

# Axions ( $A^0$ ) and Other Very Light Bosons, Searches for

See the related review(s):

[Axions and Other Similar Particles](#)

## $A^0$ (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

| VALUE (MeV)   | DOCUMENT ID          | TECN | COMMENT               |
|---|----------------------|------|-----------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |                      |      |                       |
| >0.2  | BARROSO              | 82   | ASTR Standard Axion   |
| >0.25   | <sup>1</sup> RAFFELT | 82   | ASTR Standard Axion   |
| >0.2  | <sup>2</sup> DICUS   | 78C  | ASTR Standard Axion   |
|   | MIKAELIAN            | 78   | ASTR Stellar emission |
| >0.3  | <sup>2</sup> SATO    | 78   | ASTR Standard Axion   |
| >0.2  | VYSOTSKII            | 78   | ASTR Standard Axion   |

<sup>1</sup> Lower bound from 5.5 MeV  $\gamma$ -ray line from the sun.

<sup>2</sup> Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

## $A^0$ (Axion) and Other Light Boson ( $X^0$ ) Searches in Hadron Decays

Limits are for branching ratios.

| VALUE   | CL% | DOCUMENT ID                  | TECN      | COMMENT  |
|---|-----|------------------------------|-----------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                              |           |  |
| <2 $\times 10^{-10}$  | 95  | <sup>1</sup> AAIJ            | 17AQ LHCb | $B^+ \rightarrow K^+ X^0$ ( $X^0 \rightarrow \mu^+ \mu^-$ )                          |
| <3.7 $\times 10^{-8}$   | 90  | <sup>2</sup> AHN             | 17 KOTO   | $K_L^0 \rightarrow \pi^0 X^0$ , $m_{X^0} = 135$ MeV                                  |
| <6 $\times 10^{-11}$  | 90  | <sup>3</sup> BATLEY          | 17 NA48   | $K^\pm \rightarrow \pi^\pm X^0$ ( $X^0 \rightarrow \mu^+ \mu^-$ )                    |
|   |     | <sup>4</sup> WON             | 16 BELL   | $\eta \rightarrow \gamma X^0$ ( $X^0 \rightarrow \pi^+ \pi^-$ )                      |
| <1 $\times 10^{-9}$   | 95  | <sup>5</sup> AAIJ            | 15AZ LHCb | $B^0 \rightarrow K^{*0} X^0$ ( $X^0 \rightarrow \mu^+ \mu^-$ )                       |
| <1.5 $\times 10^{-6}$   | 90  | <sup>6</sup> ADLARSON        | 13 WASA   | $\pi^0 \rightarrow \gamma X^0$ ( $X^0 \rightarrow e^+ e^-$ ),<br>$m_{X^0} = 100$ MeV |
| <2 $\times 10^{-8}$   | 90  | <sup>7</sup> BABUSCI         | 13B KLOE  | $\phi \rightarrow \eta X^0$ ( $X^0 \rightarrow e^+ e^-$ )                            |
|   |     | <sup>8</sup> ARCHILLI        | 12 KLOE   | $\phi \rightarrow \eta X^0$ , $X^0 \rightarrow e^+ e^-$                              |
| <2 $\times 10^{-15}$  | 90  | <sup>9</sup> GNINENKO        | 12A BDMP  | $\pi^0 \rightarrow \gamma X^0$ ( $X^0 \rightarrow e^+ e^-$ )                         |
| <3 $\times 10^{-14}$  | 90  | <sup>10</sup> GNINENKO       | 12B BDMP  | $\eta(\eta') \rightarrow \gamma X^0$ ( $X^0 \rightarrow e^+ e^-$ )                   |
| <7 $\times 10^{-10}$  | 90  | <sup>11</sup> ADLER          | 04 B787   | $K^+ \rightarrow \pi^+ X^0$  |
| <7.3 $\times 10^{-11}$  | 90  | <sup>12</sup> ANISIMOVSK..04 | B949      | $K^+ \rightarrow \pi^+ X^0$  |
| <4.5 $\times 10^{-11}$  | 90  | <sup>13</sup> ADLER          | 02C B787  | $K^+ \rightarrow \pi^+ X^0$  |
| <4 $\times 10^{-5}$   | 90  | <sup>14</sup> ADLER          | 01 B787   | $K^+ \rightarrow \pi^+ \pi^0 A^0$  |
| <4.9 $\times 10^{-5}$   | 90  | AMMAR                        | 01B CLEO  | $B^\pm \rightarrow \pi^\pm (K^\pm) X^0$  |
| <5.3 $\times 10^{-5}$   | 90  | AMMAR                        | 01B CLEO  | $B^0 \rightarrow K_S^0 X^0$  |
| <3.3 $\times 10^{-5}$   | 90  | <sup>15</sup> ALTEGOER       | 98 NOMD   | $\pi^0 \rightarrow \gamma X^0$ , $m_{X^0} < 120$ MeV                                 |
| <5.0 $\times 10^{-8}$   | 90  | <sup>16</sup> KITCHING       | 97 B787   | $K^+ \rightarrow \pi^+ X^0$ ( $X^0 \rightarrow \gamma \gamma$ )                      |
| <5.2 $\times 10^{-10}$  | 90  | <sup>17</sup> ADLER          | 96 B787   | $K^+ \rightarrow \pi^+ X^0$  |

|                                   |    |                              |          |  |
|-----------------------------------|----|------------------------------|----------|--|
| $<2.8 \times 10^{-4}$             | 90 | 18 AMSLER                    | 96B CBAR | $\pi^0 \rightarrow \gamma X^0, m_{X^0} < 65 \text{ MeV}$   |
| $<3 \times 10^{-4}$               | 90 | 18 AMSLER                    | 96B CBAR | $\eta \rightarrow \gamma X^0, m_{X^0} = 50\text{--}200 \text{ MeV}$                                  |
| $<4 \times 10^{-5}$               | 90 | 18 AMSLER                    | 96B CBAR | $\eta' \rightarrow \gamma X^0, m_{X^0} = 50\text{--}925 \text{ MeV}$                                 |
| $<6 \times 10^{-5}$               | 90 | 18 AMSLER                    | 94B CBAR | $\pi^0 \rightarrow \gamma X^0, m_{X^0} = 65\text{--}125 \text{ MeV}$                                 |
| $<6 \times 10^{-5}$               | 90 | 18 AMSLER                    | 94B CBAR | $\eta \rightarrow \gamma X^0, m_{X^0} = 200\text{--}525 \text{ MeV}$                                 |
| $<7 \times 10^{-3}$               | 90 | 19 MEIJERDREES <sup>94</sup> | CNTR     | $\pi^0 \rightarrow \gamma X^0, m_{X^0} = 25 \text{ MeV}$   |
| $<2 \times 10^{-3}$               | 90 | 19 MEIJERDREES <sup>94</sup> | CNTR     | $\pi^0 \rightarrow \gamma X^0, m_{X^0} = 100 \text{ MeV}$  |
| $<2 \times 10^{-7}$               | 90 | 20 ATIYA                     | 93B B787 | Sup. by ADLER 04   |
| $<3 \times 10^{-13}$              |    | 21 NG                        | 93 COSM  | $\pi^0 \rightarrow \gamma X^0$   |
| $<1.1 \times 10^{-8}$             | 90 | 22 ALLIEGRO                  | 92 SPEC  | $K^+ \rightarrow \pi^+ X^0 (X^0 \rightarrow e^+ e^-)$  |
| $<5 \times 10^{-4}$               | 90 | 23 ATIYA                     | 92 B787  | $\pi^0 \rightarrow \gamma X^0$   |
| $<1 \times 10^{-12}$              | 95 | 24 BARABASH                  | 92 BDMP  | $\pi^\pm \rightarrow e^\pm \nu X^0 (X^0 \rightarrow e^+ e^-, \gamma\gamma), m_{X^0} = 8 \text{ MeV}$ |
| $<1 \times 10^{-12}$              | 95 | 25 BARABASH                  | 92 BDMP  | $K^\pm \rightarrow \pi^\pm X^0 (X^0 \rightarrow e^+ e^-, \gamma\gamma), m_{X^0} = 10 \text{ MeV}$    |
| $<1 \times 10^{-11}$              | 95 | 26 BARABASH                  | 92 BDMP  | $K_L^0 \rightarrow \pi^0 X^0 (X^0 \rightarrow e^+ e^-, \gamma\gamma), m_{X^0} = 10 \text{ MeV}$      |
| $<1 \times 10^{-14}$              | 95 | 27 BARABASH                  | 92 BDMP  | $\eta' \rightarrow \eta X^0 (X^0 \rightarrow e^+ e^-, \gamma\gamma), m_{X^0} = 10 \text{ MeV}$       |
| $<4 \times 10^{-6}$               | 90 | 28 MEIJERDREES <sup>92</sup> | SPEC     | $\pi^0 \rightarrow \gamma X^0 (X^0 \rightarrow e^+ e^-), m_{X^0} = 100 \text{ MeV}$                  |
| $<1 \times 10^{-7}$               | 90 | 29 ATIYA                     | 90B B787 | Sup. by KITCHING 97  |
| $<1.3 \times 10^{-8}$             | 90 | 30 KORENCHE...               | 87 SPEC  | $\pi^+ \rightarrow e^+ \nu A^0 (A^0 \rightarrow e^+ e^-)$  |
| $<1 \times 10^{-9}$               | 90 | 31 EICHLER                   | 86 SPEC  | Stopped $\pi^+ \rightarrow e^+ \nu A^0$  |
| $<2 \times 10^{-5}$               | 90 | 32 YAMAZAKI                  | 84 SPEC  | For $160 < m < 260 \text{ MeV}$  |
| $<(1.5\text{--}4) \times 10^{-6}$ | 90 | 32 YAMAZAKI                  | 84 SPEC  | $K$ decay, $m_{X^0} \ll 100 \text{ MeV}$   |
|                                   |    | 33 ASANO                     | 82 CNTR  | Stopped $K^+ \rightarrow \pi^+ X^0$  |
|                                   |    | 34 ASANO                     | 81B CNTR | Stopped $K^+ \rightarrow \pi^+ X^0$  |
|                                   |    | 35 ZHITNITSKII               | 79       | Heavy axion  |

<sup>1</sup> The limit is for  $\tau_{X^0} = 10 \text{ ps}$ . See their Fig. 4 for limits in the range of  $m_{X^0} = 250\text{--}4700 \text{ MeV}$  and  $\tau_{X^0} = 0.1\text{--}1000 \text{ ps}$ .

<sup>2</sup> The limit as a function of  $m_{X^0}$  from 0 to 250 MeV is provided in their Fig. 5.

<sup>3</sup> The limit is for  $m_{X^0} = 216 \text{ MeV}$  and  $\tau_{X^0} \leq 10 \text{ ps}$ . See their Fig. 4(c) for limits in the range of  $m_{X^0} = 211\text{--}354 \text{ MeV}$  and longer lifetimes.

<sup>4</sup> WON 16 look for a vector boson coupled to baryon number. Derived limits on  $\alpha' < 10^{-3}\text{--}10^{-2}$  for  $m_{X^0} = 290\text{--}520 \text{ MeV}$  at 95% CL. See their Fig. 4 for mass-dependent limits.

<sup>5</sup> The limit is for  $\tau_{X^0} = 10 \text{ ps}$  and  $m_{X^0} = 214\text{--}4350 \text{ MeV}$ . See their Fig. 4 for mass- and lifetime-dependent limits.

<sup>6</sup> Limits between  $2.0 \times 10^{-5}$  and  $1.5 \times 10^{-6}$  are obtained for  $m_{X^0} = 20\text{--}100 \text{ MeV}$  (see their Fig. 8). Angular momentum conservation requires that  $X^0$  has spin  $\geq 1$ .

<sup>7</sup> The limit is for  $B(\phi \rightarrow \eta X^0) \cdot B(X^0 \rightarrow e^+ e^-)$  and applies to  $m_{X^0} = 410 \text{ MeV}$ . It is derived by analyzing  $\eta \rightarrow \pi^0 \pi^0 \pi^0$  and  $\pi^- \pi^+ \pi^0$ . Limits between  $1 \times 10^{-6}$  and  $2 \times 10^{-8}$  are obtained for  $m_{X^0} \leq 450 \text{ MeV}$  (see their Fig. 6).

<sup>8</sup> ARCHILLI 12 analyzed  $\eta \rightarrow \pi^+ \pi^- \pi^0$  decays. Derived limits on  $\alpha'/\alpha < 2 \times 10^{-5}$  for  $m_{X^0} = 50\text{--}420 \text{ MeV}$  at 90% CL. See their Fig. 8 for mass-dependent limits.

- <sup>9</sup> This limit is for  $B(\pi^0 \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow e^+ e^-)$  and applies for  $m_{X^0} = 90$  MeV and  $\tau_{X^0} \simeq 1 \times 10^{-8}$  sec. Limits between  $10^{-8}$  and  $2 \times 10^{-15}$  are obtained for  $m_{X^0} = 3$ –120 MeV and  $\tau_{X^0} = 1 \times 10^{-11}$ –1 sec. See their Fig. 3 for limits at different masses and lifetimes.
- <sup>10</sup> This limit is for  $B(\eta \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow e^+ e^-)$  and applies for  $m_{X^0} = 100$  MeV and  $\tau_{X^0} \simeq 6 \times 10^{-9}$  sec. Limits between  $10^{-5}$  and  $3 \times 10^{-14}$  are obtained for  $m_{X^0} \lesssim 550$  MeV and  $\tau_{X^0} = 10^{-10}$ –10 sec. See their Fig. 5 for limits at different mass and lifetime and for  $\eta'$  decays.
- <sup>11</sup> This limit applies for a mass near 180 MeV. For other masses in the range  $m_{X^0} = 150$ –250 MeV the limit is less restrictive, but still improves ADLER 02C and ATIYA 93B.
- <sup>12</sup> ANISIMOVSKY 04 bound is for  $m_{X^0}=0$ .
- <sup>13</sup> ADLER 02C bound is for  $m_{X^0} < 60$  MeV. See Fig. 2 for limits at higher masses.
- <sup>14</sup> The quoted limit is for  $m_{X^0} = 0$ –80 MeV. See their Fig. 5 for the limit at higher mass. The branching fraction limit assumes pure phase space decay distributions.
- <sup>15</sup> ALTEGOER 98 looked for  $X^0$  from  $\pi^0$  decay which penetrate the shielding and convert to  $\pi^0$  in the external Coulomb field of a nucleus.
- <sup>16</sup> KITCHING 97 limit is for  $B(K^+ \rightarrow \pi^+ X^0) \cdot B(X^0 \rightarrow \gamma\gamma)$  and applies for  $m_{X^0} \simeq 50$  MeV,  $\tau_{X^0} < 10^{-10}$  s. Limits are provided for  $0 < m_{X^0} < 100$  MeV,  $\tau_{X^0} < 10^{-8}$  s.
- <sup>17</sup> ADLER 96 looked for a peak in missing-mass distribution. This work is an update of ATIYA 93. The limit is for massless stable  $X^0$  particles and extends to  $m_{X^0}=80$  MeV at the same level. See paper for dependence on finite lifetime.
- <sup>18</sup> AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.
- <sup>19</sup> The MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of  $X^0$  decay modes. It applies to  $\tau(X^0) > 10^{-23}$  sec.
- <sup>20</sup> ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable  $X^0$  of  $m_{X^0}=150$ –250 MeV, and the limit becomes stronger ( $10^{-8}$ ) for  $m_{X^0}=180$ –240 MeV.
- <sup>21</sup> NG 93 studied the production of  $X^0$  via  $\gamma\gamma \rightarrow \pi^0 \rightarrow \gamma X^0$  in the early universe at  $T \simeq 1$  MeV. The bound on extra neutrinos from nucleosynthesis  $\Delta N_\nu < 0.3$  (WALKER 91) is employed. It applies to  $m_{X^0} \ll 1$  MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier  $X^0$ .
- <sup>22</sup> ALLIEGRO 92 limit applies for  $m_{X^0}=150$ –340 MeV and is the branching ratio times the decay probability. Limit is  $< 1.5 \times 10^{-8}$  at 99%CL.
- <sup>23</sup> ATIYA 92 looked for a peak in missing mass distribution. The limit applies to  $m_{X^0}=0$ –130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires  $X^0$  to be a vector particle.
- <sup>24</sup> BARABASH 92 is a beam dump experiment that searched for a light Higgs. Limits between  $1 \times 10^{-12}$  and  $1 \times 10^{-7}$  are obtained for  $3 < m_{X^0} < 40$  MeV.
- <sup>25</sup> Limits between  $1 \times 10^{-12}$  and 1 are obtained for  $4 < m_{X^0} < 69$  MeV.
- <sup>26</sup> Limits between  $1 \times 10^{-11}$  and  $5 \times 10^{-3}$  are obtained for  $4 < m_{X^0} < 63$  MeV.
- <sup>27</sup> Limits between  $1 \times 10^{-14}$  and 1 are obtained for  $3 < m_{X^0} < 82$  MeV.
- <sup>28</sup> MEIJERDREES 92 limit applies for  $\tau_{X^0} = 10^{-23}$ – $10^{-11}$  sec. Limits between  $2 \times 10^{-4}$  and  $4 \times 10^{-6}$  are obtained for  $m_{X^0} = 25$ –120 MeV. Angular momentum conservation requires that  $X^0$  has spin  $\geq 1$ .
- <sup>29</sup> ATIYA 90B limit is for  $B(K^+ \rightarrow \pi^+ X^0) \cdot B(X^0 \rightarrow \gamma\gamma)$  and applies for  $m_{X^0} = 50$  MeV,  $\tau_{X^0} < 10^{-10}$  s. Limits are also provided for  $0 < m_{X^0} < 100$  MeV,  $\tau_{X^0} < 10^{-8}$  s.

- <sup>30</sup> KORENCHENKO 87 limit assumes  $m_{A^0} = 1.7$  MeV,  $\tau_{A^0} \lesssim 10^{-12}$  s, and  $B(A^0 \rightarrow e^+ e^-) = 1$ .
- <sup>31</sup> EICHLER 86 looked for  $\pi^+ \rightarrow e^+ \nu A^0$  followed by  $A^0 \rightarrow e^+ e^-$ . Limits on the branching fraction depend on the mass and lifetime of  $A^0$ . The quoted limits are valid when  $\tau(A^0) \gtrsim 3. \times 10^{-10}$  s if the decays are kinematically allowed.
- <sup>32</sup> YAMAZAKI 84 looked for a discrete line in  $K^+ \rightarrow \pi^+ X$ . Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.
- <sup>33</sup> ASANO 82 at KEK set limits for  $B(K^+ \rightarrow \pi^+ X^0)$  for  $m_{X^0} < 100$  MeV as  $BR < 4. \times 10^{-8}$  for  $\tau(X^0 \rightarrow n\gamma\text{'s}) > 1. \times 10^{-9}$  s,  $BR < 1.4 \times 10^{-6}$  for  $\tau < 1. \times 10^{-9}$  s.
- <sup>34</sup> ASANO 81B is KEK experiment. Set  $B(K^+ \rightarrow \pi^+ X^0) < 3.8 \times 10^{-8}$  at CL = 90%.
- <sup>35</sup> ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 ( $3 < m < 40$  MeV) contradicts experimental muon anomalous magnetic moments.

## $A^0$ (Axion) Searches in Quarkonium Decays

Decay or transition of quarkonium. Limits are for branching ratio.

| VALUE | CL% | DOCUMENT ID | TECN | COMMENT |
|-------|-----|-------------|------|---------|
|-------|-----|-------------|------|---------|

• • • We do not use the following data for averages, fits, limits, etc. • • •

|                        |    |                         |          |  |
|------------------------|----|-------------------------|----------|--|
| $< 2.8 \times 10^{-8}$ | 90 | <sup>1</sup> ABLIKIM    | 16E BES3 | $J/\psi \rightarrow A^0 \gamma (A^0 \rightarrow \mu^+ \mu^-)$  |
| $< 4 \times 10^{-7}$   | 90 | <sup>2</sup> ABLIKIM    | 12 BES3  | $J/\psi \rightarrow A^0 \gamma (A^0 \rightarrow \mu^+ \mu^-)$  |
| $< 4.0 \times 10^{-5}$ | 90 | <sup>3</sup> ANTREASYAN | 90C CBAL | $\Upsilon(1S) \rightarrow A^0 \gamma$                          |
| $< 5 \times 10^{-5}$   | 90 | <sup>4</sup> DRUZHININ  | 87 ND    | $\phi \rightarrow A^0 \gamma (A^0 \rightarrow e^+ e^-)$        |
| $< 2 \times 10^{-3}$   | 90 | <sup>5</sup> DRUZHININ  | 87 ND    | $\phi \rightarrow A^0 \gamma (A^0 \rightarrow \gamma \gamma)$  |
| $< 7 \times 10^{-6}$   | 90 | <sup>6</sup> DRUZHININ  | 87 ND    | $\phi \rightarrow A^0 \gamma (A^0 \rightarrow \text{missing})$ |
| $< 1.4 \times 10^{-5}$ | 90 | <sup>7</sup> EDWARDS    | 82 CBAL  | $J/\psi \rightarrow A^0 \gamma$                                |

<sup>1</sup> ABLIKIM 16E limits between  $2.8\text{--}495.3 \times 10^{-8}$  were obtained for  $0.212 \text{ GeV} < m_{A^0} < 3.0$  GeV. See their Fig. 5 for mass-dependent limits.

<sup>2</sup> ABLIKIM 12 derived limits between  $4 \times 10^{-7}\text{--}2.1 \times 10^{-5}$  for  $0.212 \text{ GeV} < m_{A^0} < 3.0$  GeV. See their Fig. 2(c) for mass-dependent limits.

<sup>3</sup> ANTREASYAN 90C assume that  $A^0$  does not decay in the detector.

<sup>4</sup> The first DRUZHININ 87 limit is valid when  $\tau_{A^0}/m_{A^0} < 3 \times 10^{-13}$  s/MeV and  $m_{A^0} < 20$  MeV.

<sup>5</sup> The second DRUZHININ 87 limit is valid when  $\tau_{A^0}/m_{A^0} < 5 \times 10^{-13}$  s/MeV and  $m_{A^0} < 20$  MeV.

<sup>6</sup> The third DRUZHININ 87 limit is valid when  $\tau_{A^0}/m_{A^0} > 7 \times 10^{-12}$  s/MeV and  $m_{A^0} < 200$  MeV.

<sup>7</sup> EDWARDS 82 looked for  $J/\psi \rightarrow \gamma A^0$  decays by looking for events with a single  $\gamma$  [of energy  $\sim 1/2$  the  $J/\psi(1S)$  mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

## $A^0$ (Axion) Searches in Positronium Decays

Decay or transition of positronium. Limits are for branching ratio.

| VALUE   | CL% | DOCUMENT ID            | TECN    | COMMENT  |
|---|-----|------------------------|---------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                        |         |  |
| $<4.4 \times 10^{-5}$   | 90  | <sup>1</sup> BADERT... | 02 CNTR | $\alpha\text{-Ps} \rightarrow \gamma X_1 X_2, m_{X_1} + m_{X_2} \leq 900 \text{ keV}$              |
| $<2 \times 10^{-4}$   | 90  | MAENO                  | 95 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} = 850\text{--}1013 \text{ keV}$                  |
| $<3.0 \times 10^{-4}$   | 90  | <sup>2</sup> ASAI      | 94 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} = 30\text{--}500 \text{ keV}$                    |
| $<2.8 \times 10^{-5}$   | 90  | <sup>3</sup> AKOPYAN   | 91 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma (A^0 \rightarrow \gamma\gamma), m_{A^0} < 30 \text{ keV}$ |
| $<1.1 \times 10^{-6}$   | 90  | <sup>4</sup> ASAI      | 91 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} < 800 \text{ keV}$                               |
| $<3.8 \times 10^{-4}$   | 90  | GNINENKO               | 90 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} < 30 \text{ keV}$                                |
| $<(1\text{--}5) \times 10^{-4}$   | 95  | <sup>5</sup> TSUCHIAKI | 90 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} = 300\text{--}900 \text{ keV}$                   |
| $<6.4 \times 10^{-5}$   | 90  | <sup>6</sup> ORITO     | 89 CNTR | $\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} < 30 \text{ keV}$                                |
|   |     | <sup>7</sup> AMALDI    | 85 CNTR | Ortho-positronium  |
|   |     | <sup>8</sup> CARBONI   | 83 CNTR | Ortho-positronium  |

<sup>1</sup> BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles.

<sup>2</sup> The ASAI 94 limit is based on inclusive photon spectrum and is independent of  $A^0$  decay modes.

<sup>3</sup> The AKOPYAN 91 limit applies for a short-lived  $A^0$  with  $\tau_{A^0} < 10^{-13} m_{A^0} [\text{keV}] \text{ s}$ .

<sup>4</sup> ASAI 91 limit translates to  $g_{A^0 e^+ e^-}^2 / 4\pi < 1.1 \times 10^{-11}$  (90% CL) for  $m_{A^0} < 800 \text{ keV}$ .

<sup>5</sup> The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of  $A^0$  decay modes.

<sup>6</sup> ORITO 89 limit translates to  $g_{A^0 e e}^2 / 4\pi < 6.2 \times 10^{-10}$ . Somewhat more sensitive limits are obtained for larger  $m_{A^0}$ :  $B < 7.6 \times 10^{-6}$  at 100 keV.

<sup>7</sup> AMALDI 85 set limits  $B(A^0 \gamma) / B(\gamma\gamma\gamma) < (1\text{--}5) \times 10^{-6}$  for  $m_{A^0} = 900\text{--}100 \text{ keV}$  which are about 1/10 of the CARBONI 83 limits.

<sup>8</sup> CARBONI 83 looked for orthopositronium  $\rightarrow A^0 \gamma$ . Set limit for  $A^0$  electron coupling squared,  $g(e e A^0)^2 / (4\pi) < 6. \times 10^{-10}\text{--}7. \times 10^{-9}$  for  $m_{A^0}$  from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from  $g\text{--}2$  experiments.

## $A^0$ (Axion) Search in Photoproduction

| VALUE | DOCUMENT ID | COMMENT |
|-------|-------------|---------|
|-------|-------------|---------|

● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●

<sup>1</sup> BASSOMPIE... 95  $m_{A^0} = 1.8 \pm 0.2 \text{ MeV}$

<sup>1</sup> BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of  $e^+ e^-$  pairs in the region  $m_{e^+ e^-} = 1.8 \pm 0.2 \text{ MeV}$ . They obtained bounds on the production rate  $A^0$  for  $\tau(A^0) = 10^{-18}\text{--}10^{-9} \text{ sec}$ . They also found an excess of events in the range  $m_{e^+ e^-} = 2.1\text{--}3.5 \text{ MeV}$ .

## $A^0$ (Axion) Production in Hadron Collisions

Limits are for  $\sigma(A^0) / \sigma(\pi^0)$ .

| <u>VALUE</u>  | <u>CL%</u> | <u>EVTS</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>  |
|---|------------|-------------|--------------------|-------------|---|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |            |             |                    |             |   |
|   |            |             | 1 JAIN             | 07          | CNTR $A^0 \rightarrow e^+ e^-$                                  |
|   |            |             | 2 AHMAD            | 97          | SPEC $e^+$ production   |
|   |            |             | 3 LEINBERGER       | 97          | SPEC $A^0 \rightarrow e^+ e^-$                                  |
|   |            |             | 4 GANZ             | 96          | SPEC $A^0 \rightarrow e^+ e^-$                                  |
|   |            |             | 5 KAMEL            | 96          | EMUL $^{32}\text{S}$ emulsion, $A^0 \rightarrow e^+ e^-$        |
|   |            |             | 6 BLUEMLEIN        | 92          | BDMP $A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$                    |
|   |            |             | 7 MEIJERDREES      | 92          | SPEC $\pi^- p \rightarrow n A^0, A^0 \rightarrow e^+ e^-$       |
|   |            |             | 8 BLUEMLEIN        | 91          | BDMP $A^0 \rightarrow e^+ e^-, 2\gamma$                         |
|   |            |             | 9 FAISSNER         | 89          | OSPK Beam dump,   |
|   |            |             | 10 DEBOER          | 88          | RVUE $A^0 \rightarrow e^+ e^-$                                  |
|   |            |             | 11 EL-NADI         | 88          | EMUL $A^0 \rightarrow e^+ e^-$                                  |
|   |            |             | 12 FAISSNER        | 88          | OSPK Beam dump, $A^0 \rightarrow 2\gamma$                       |
|   |            |             | 13 BADIER          | 86          | BDMP $A^0 \rightarrow e^+ e^-$                                  |
| $<2. \times 10^{-11}$   | 90         | 0           | 14 BERGSMA         | 85          | CHRM CERN beam dump   |
| $<1. \times 10^{-13}$   | 90         | 0           | 14 BERGSMA         | 85          | CHRM CERN beam dump   |
|   |            | 24          | 15 FAISSNER        | 83          | OSPK Beam dump, $A^0 \rightarrow 2\gamma$                       |
|   |            |             | 16 FAISSNER        | 83B         | RVUE LAMPF beam dump  |
|   |            |             | 17 FRANK           | 83B         | RVUE LAMPF beam dump  |
|   |            |             | 18 HOFFMAN         | 83          | CNTR $\pi p \rightarrow n A^0$<br>( $A^0 \rightarrow e^+ e^-$ ) |
|   |            |             | 19 FETSCHER        | 82          | RVUE See FAISSNER 81B   |
|   |            | 12          | 20 FAISSNER        | 81          | OSPK CERN PS $\nu$ wideband                                     |
|   |            | 15          | 21 FAISSNER        | 81B         | OSPK Beam dump, $A^0 \rightarrow 2\gamma$                       |
|   |            | 8           | 22 KIM             | 81          | OSPK 26 GeV $pN \rightarrow A^0 X$                              |
|   |            | 0           | 23 FAISSNER        | 80          | OSPK Beam dump,<br>$A^0 \rightarrow e^+ e^-$                    |
| $<1. \times 10^{-8}$  | 90         |             | 24 JACQUES         | 80          | HLBC 28 GeV protons   |
| $<1. \times 10^{-14}$   | 90         |             | 24 JACQUES         | 80          | HLBC Beam dump  |
|   |            |             | 25 SOUKAS          | 80          | CALO 28 GeV $p$ beam dump                                       |
|   |            |             | 26 BECHIS          | 79          | CNTR  |
| $<1. \times 10^{-8}$  | 90         |             | 27 COTEUS          | 79          | OSPK Beam dump  |
| $<1. \times 10^{-3}$  | 95         |             | 28 DISHAW          | 79          | CALO 400 GeV $pp$   |
| $<1. \times 10^{-8}$  | 90         |             | ALIBRAN            | 78          | HYBR Beam dump  |
| $<6. \times 10^{-9}$  | 95         |             | ASRATYAN           | 78B         | CALO Beam dump  |
| $<1.5 \times 10^{-8}$   | 90         |             | 29 BELLOTTI        | 78          | HLBC Beam dump  |
| $<5.4 \times 10^{-14}$  | 90         |             | 29 BELLOTTI        | 78          | HLBC $m_{A^0}=1.5$ MeV  |
| $<4.1 \times 10^{-9}$   | 90         |             | 29 BELLOTTI        | 78          | HLBC $m_{A^0}=1$ MeV  |
| $<1. \times 10^{-8}$  | 90         |             | 30 BOSETTI         | 78B         | HYBR Beam dump  |
|   |            |             | 31 DONNELLY        | 78          |   |
| $<0.5 \times 10^{-8}$   | 90         |             | HANSL              | 78D         | WIRE Beam dump  |
|   |            |             | 32 MICELMAC...     | 78          |   |
|   |            |             | 33 VYSOTSKII       | 78          |   |

- <sup>1</sup> JAIN 07 claims evidence for  $A^0 \rightarrow e^+e^-$  produced in  $^{207}\text{Pb}$  collision on nuclear emulsion (Ag/Br) for  $m(A^0) = 7 \pm 1$  or  $19 \pm 1$  MeV and  $\tau(A^0) \leq 10^{-13}$  s.
- <sup>2</sup> AHMAD 97 reports a result of APEX Collaboration which studied positron production in  $^{238}\text{U}+^{232}\text{Ta}$  and  $^{238}\text{U}+^{181}\text{Ta}$  collisions, without requiring a coincident electron. No narrow lines were found for  $250 < E_{e^+} < 750$  keV.
- <sup>3</sup> LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy  $e^+e^-$ -line at  $\sim 635$  keV in  $^{238}\text{U}+^{181}\text{Ta}$  collision. Limits on the production probability for a narrow sum-energy  $e^+e^-$  line are set. See their Table 2.
- <sup>4</sup> GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of  $e^+e^-$  pairs from  $^{238}\text{U}+^{181}\text{Ta}$  and  $^{238}\text{U}+^{232}\text{Th}$  collisions at GSI. See Table 2 for limits both for back-to-back and isotropic configurations of  $e^+e^-$  pairs. These limits rule out the existence of peaks in the  $e^+e^-$  sum-energy distribution, reported by an earlier version of this experiment.
- <sup>5</sup> KAMEL 96 looked for  $e^+e^-$  pairs from the collision of  $^{32}\text{S}$  (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity  $m_{e^+e^-} > 2$  MeV.
- <sup>6</sup> BLUEMLEIN 92 is a proton beam dump experiment at Serpukhov with a secondary target to induce Bethe-Heitler production of  $e^+e^-$  or  $\mu^+\mu^-$  from the produce  $A^0$ . See Fig. 5 for the excluded region in  $m_{A^0}$ - $x$  plane. For the standard axion,  $0.3 < x < 25$  is excluded at 95% CL. If combined with BLUEMLEIN 91,  $0.008 < x < 32$  is excluded.
- <sup>7</sup> MEIJERDREES 92 give  $\Gamma(\pi^-p \rightarrow nA^0) \cdot B(A^0 \rightarrow e^+e^-) / \Gamma(\pi^-p \rightarrow \text{all}) < 10^{-5}$  (90% CL) for  $m_{A^0} = 100$  MeV,  $\tau_{A^0} = 10^{-11}$ – $10^{-23}$  sec. Limits ranging from  $2.5 \times 10^{-3}$  to  $10^{-7}$  are given for  $m_{A^0} = 25$ – $136$  MeV.
- <sup>8</sup> BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for  $A^0 \rightarrow e^+e^-$ ,  $2\gamma$  are found. Fig. 6 gives the excluded region in  $m_{A^0}$ - $x$  plane ( $x = \tan\beta = v_2/v_1$ ). Standard axion is excluded for  $0.2 < m_{A^0} < 3.2$  MeV for most  $x > 1$ ,  $0.2$ – $11$  MeV for most  $x < 1$ .
- <sup>9</sup> FAISSNER 89 searched for  $A^0 \rightarrow e^+e^-$  in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass  $2m_e$ – $20$  MeV is excluded. Lower limit on  $f_{A^0}$  of  $\simeq 10^4$  GeV is given for  $m_{A^0} = 2m_e$ – $20$  MeV.
- <sup>10</sup> DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass  $\sim 1.1$ ,  $\sim 2.1$ , and  $\sim 9$  MeV, lifetimes  $10^{-16}$ – $10^{-15}$  s decaying to  $e^+e^-$  and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with  $\pi^0$  Dalitz decay. DEBOER 89B is a reply which contests the criticism.
- <sup>11</sup> EL-NADI 88 claim the existence of a neutral particle decaying into  $e^+e^-$  with mass  $1.60 \pm 0.59$  MeV, lifetime  $(0.15 \pm 0.01) \times 10^{-14}$  s, which is produced in heavy ion interactions with emulsion nuclei at  $\sim 4$  GeV/c/nucleon.
- <sup>12</sup> FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for  $A^0 \rightarrow \gamma\gamma$ . A standard axion decaying to  $2\gamma$  is excluded except for a region  $x \simeq 1$ . Lower limit on  $f_{A^0}$  of  $10^2$ – $10^3$  GeV is given for  $m_{A^0} = 0.1$ – $1$  MeV.
- <sup>13</sup> BADIÉ 86 did not find long-lived  $A^0$  in 300 GeV  $\pi^-$  Beam Dump Experiment that decays into  $e^+e^-$  in the mass range  $m_{A^0} = (20$ – $200)$  MeV, which excludes the  $A^0$  decay constant  $f(A^0)$  in the interval (60–600) GeV. See their figure 6 for excluded region on  $f(A^0)$ - $m_{A^0}$  plane.
- <sup>14</sup> BERGSMA 85 look for  $A^0 \rightarrow 2\gamma, e^+e^-, \mu^+\mu^-$ . First limit above is for  $m_{A^0} = 1$  MeV; second is for 200 MeV. See their figure 4 for excluded region on  $f_{A^0}$ - $m_{A^0}$  plane, where  $f_{A^0}$  is  $A^0$  decay constant. For Peccei-Quinn PECCEI 77  $A^0$ ,  $m_{A^0} < 180$  keV and

- $\tau > 0.037$  s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.
- 15 FAISSNER 83 observed 19  $1\text{-}\gamma$  and 12  $2\text{-}\gamma$  events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.
  - 16 FAISSNER 83B extrapolate SIN  $\gamma$  signal to LAMPF  $\nu$  experimental condition. Resulting 370  $\gamma$ 's are not at variance with LAMPF upper limit of 450  $\gamma$ 's. Derived from LAMPF limit that  $[d\sigma(A^0)/d\omega \text{ at } 90^\circ] m_{A^0}/\tau_{A^0} < 14 \times 10^{-35} \text{ cm}^2 \text{ sr}^{-1} \text{ MeV ms}^{-1}$ . See comment on FRANK 83B.
  - 17 FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450  $\gamma$ 's. See comment on FAISSNER 83B.
  - 18 HOFFMAN 83 set CL = 90% limit  $d\sigma/dt B(e^+ e^-) < 3.5 \times 10^{-32} \text{ cm}^2/\text{GeV}^2$  for  $140 < m_{A^0} < 160$  MeV. Limit assumes  $\tau(A^0) < 10^{-9}$  s.
  - 19 FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since  $2\text{-}\gamma$  peak rate remarkably decreases if iron wall is set in front of the decay region.
  - 20 FAISSNER 81 see excess  $\mu e$  events. Suggest axion interactions.
  - 21 FAISSNER 81B is SIN 590 MeV proton beam dump. Observed  $14.5 \pm 5.0$  events of  $2\gamma$  decay of long-lived neutral penetrating particle with  $m_{2\gamma} \lesssim 1$  MeV. Axion interpretation with  $\eta\text{-}A^0$  mixing gives  $m_{A^0} = 250 \pm 25$  keV,  $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$  s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEK-SEEV 82B, CAVAINAC 83, and ANANEV 85.
  - 22 KIM 81 analyzed 8 candidates for  $A^0 \rightarrow 2\gamma$  obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is  $(0.86 \sim 5.6) \times 10^{-3}$  s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.
  - 23 FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for  $A^0 \rightarrow e^+ e^-$  decay. Assuming  $A^0/\pi^0 = 5.5 \times 10^{-7}$ , obtained decay rate limit  $20/(A^0 \text{ mass})$  MeV/s (CL = 90%), which is about  $10^{-7}$  below theory and interpreted as upper limit to  $m_{A^0} < 2m_{e^-}$ .
  - 24 JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events  $[\sigma(\text{production})\sigma(\text{interaction}) < 7. \times 10^{-68} \text{ cm}^4$ , CL = 90%]. Second limit is from nonobservation of axion decays into  $2\gamma$ 's or  $e^+ e^-$ , and for axion mass a few MeV.
  - 25 SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.
  - 26 BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either  $2\gamma$  or  $e^+ e^-$ . No signal found. CL = 90% limits for model parameter(s) are given.
  - 27 COTEUS 79 is a beam dump experiment at BNL.
  - 28 DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.
  - 29 BELLOTTI 78 first value comes from search for  $A^0 \rightarrow e^+ e^-$ . Second value comes from search for  $A^0 \rightarrow 2\gamma$ , assuming mass  $< 2m_{e^-}$ . For any mass satisfying this, limit is above value  $\times (\text{mass}^{-4})$ . Third value uses data of PL 60B 401 and quotes  $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67} \text{ cm}^4$ .
  - 30 BOSETTI 78B quotes  $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67} \text{ cm}^4$ .
  - 31 DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.



- <sup>32</sup> MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).  
<sup>33</sup> VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

## $A^0$ (Axion) Searches in Reactor Experiments

| VALUE   | DOCUMENT ID                 | TECN | COMMENT                                 |
|---|-----------------------------|------|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • |                             |      |   |
|   | <sup>1</sup> CHANG 07       |      | Primakoff or Compton                    |
|   | <sup>2</sup> ALTMANN 95     | CNTR | Reactor; $A^0 \rightarrow e^+ e^-$      |
|   | <sup>3</sup> KETOV 86       | SPEC | Reactor, $A^0 \rightarrow \gamma\gamma$ |
|   | <sup>4</sup> KOCH 86        | SPEC | Reactor; $A^0 \rightarrow \gamma\gamma$ |
|   | <sup>5</sup> DATAR 82       | CNTR | Light water reactor                     |
|   | <sup>6</sup> VUILLEUMIER 81 | CNTR | Reactor, $A^0 \rightarrow 2\gamma$      |

<sup>1</sup> CHANG 07 looked for monochromatic photons from Primakoff or Compton conversion of axions from the Kuo-Sheng reactor due to axion coupling to photon or electron, respectively. The search places model-independent limits on the products  $G_{A\gamma\gamma} G_{ANN}$  and  $G_{Aee} G_{ANN}$  for  $m(A^0)$  less than the MeV range.

<sup>2</sup> ALTMANN 95 looked for  $A^0$  decaying into  $e^+ e^-$  from the Bugey5 nuclear reactor. They obtain an upper limit on the  $A^0$  production rate of  $\omega(A^0)/\omega(\gamma) \times B(A^0 \rightarrow e^+ e^-) < 10^{-16}$  for  $m_{A^0} = 1.5$  MeV at 90% CL. The limit is weaker for heavier  $A^0$ . In the case of a standard axion, this limit excludes a mass in the range  $2m_e < m_{A^0} < 4.8$  MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances  $Z^0$  in the  $(m_{X^0}, f_{X^0})$  plane.

<sup>3</sup> KETOV 86 searched for  $A^0$  at the Rovno nuclear power plant. They found an upper limit on the  $A^0$  production probability of  $0.8 [100 \text{ keV}/m_{A^0}]^6 \times 10^{-6}$  per fission. In the standard axion model, this corresponds to  $m_{A^0} > 150$  keV. Not valid for  $m_{A^0} \gtrsim 1$  MeV.

<sup>4</sup> KOCH 86 searched for  $A^0 \rightarrow \gamma\gamma$  at nuclear power reactor Biblis A. They found an upper limit on the  $A^0$  production rate of  $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$  (CL=95%). Standard axion with  $m_{A^0} = 250$  keV gives  $10^{-5}$  for the ratio. Not valid for  $m_{A^0} > 1022$  keV.

<sup>5</sup> DATAR 82 looked for  $A^0 \rightarrow 2\gamma$  in neutron capture ( $np \rightarrow dA^0$ ) at Tarapur 500 MW reactor. Sensitive to sum of  $l = 0$  and  $l = 1$  amplitudes. With ZEHNDER 81 [ $(l = 0) - (l = 1)$ ] result, assert nonexistence of standard  $A^0$ .

<sup>6</sup> VUILLEUMIER 81 is at Grenoble reactor. Set limit  $m_{A^0} < 280$  keV.

## $A^0$ (Axion) and Other Light Boson ( $X^0$ ) Searches in Nuclear Transitions

Limits are for branching ratio.

| VALUE   | CL% | DOCUMENT ID             | TECN | COMMENT   |
|---|-----|-------------------------|------|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • |     |                         |      |   |
| $< 8.5 \times 10^{-6}$  | 90  | <sup>1</sup> DERBIN 02  | CNTR | $^{125m}\text{Te}$ decay                              |
|   |     | <sup>2</sup> DEBOER 97C | RVUE | M1 transitions  |
| $< 5.5 \times 10^{-10}$   | 95  | <sup>3</sup> TSUNODA 95 | CNTR | $^{252}\text{Cf}$ fission, $A^0 \rightarrow ee$       |
| $< 1.2 \times 10^{-6}$  | 95  | <sup>4</sup> MINOWA 93  | CNTR | $^{139}\text{La}^* \rightarrow ^{139}\text{La}A^0$    |
| $< 2 \times 10^{-4}$  | 90  | <sup>5</sup> HICKS 92   | CNTR | $^{35}\text{S}$ decay, $A^0 \rightarrow \gamma\gamma$ |
| $< 1.5 \times 10^{-9}$  | 95  | <sup>6</sup> ASANUMA 90 | CNTR | $^{241}\text{Am}$ decay                               |

|                            |    |              |     |      |   |
|----------------------------|----|--------------|-----|------|---|
| $<(0.4-10) \times 10^{-3}$ | 95 | 7 DEBOER     | 90  | CNTR | ${}^8\text{Be}^* \rightarrow {}^8\text{Be}A^0,$<br>$A^0 \rightarrow e^+e^-$   |
| $<(0.2-1) \times 10^{-3}$  | 90 | 8 BINI       | 89  | CNTR | ${}^{16}\text{O}^* \rightarrow {}^{16}\text{O}X^0,$<br>$X^0 \rightarrow e^+e^-$   |
|                            |    | 9 AVIGNONE   | 88  | CNTR | $\text{Cu}^* \rightarrow \text{Cu}A^0 (A^0 \rightarrow 2\gamma,$<br>$A^0 e \rightarrow \gamma e, A^0 Z \rightarrow \gamma Z)$ |
| $< 1.5 \times 10^{-4}$     | 90 | 10 DATAR     | 88  | CNTR | ${}^{12}\text{C}^* \rightarrow {}^{12}\text{C}A^0,$<br>$A^0 \rightarrow e^+e^-$   |
| $< 5 \times 10^{-3}$       | 90 | 11 DEBOER    | 88C | CNTR | ${}^{16}\text{O}^* \rightarrow {}^{16}\text{O}X^0,$<br>$X^0 \rightarrow e^+e^-$   |
| $< 3.4 \times 10^{-5}$     | 95 | 12 DOEHNER   | 88  | SPEC | ${}^2\text{H}^*, A^0 \rightarrow e^+e^-$  |
| $< 4 \times 10^{-4}$       | 95 | 13 SAVAGE    | 88  | CNTR | Nuclear decay (isovector)   |
| $< 3 \times 10^{-3}$       | 95 | 13 SAVAGE    | 88  | CNTR | Nuclear decay (isoscalar)   |
| $<10.6 \times 10^{-2}$     | 90 | 14 HALLIN    | 86  | SPEC | ${}^6\text{Li}$ isovector decay   |
| $<10.8$                    | 90 | 14 HALLIN    | 86  | SPEC | ${}^{10}\text{B}$ isoscalar decays  |
| $< 2.2$                    | 90 | 14 HALLIN    | 86  | SPEC | ${}^{14}\text{N}$ isoscalar decays  |
| $< 4 \times 10^{-4}$       | 90 | 15 SAVAGE    | 86B | CNTR | ${}^{14}\text{N}^*$   |
|                            |    | 16 ANANEV    | 85  | CNTR | $\text{Li}^*, \text{deut}^* A^0 \rightarrow 2\gamma$  |
|                            |    | 17 CAVIGNAC  | 83  | CNTR | ${}^{97}\text{Nb}^*, \text{deut}^* \text{ transition}$<br>$A^0 \rightarrow 2\gamma$   |
|                            |    | 18 ALEKSEEV  | 82B | CNTR | $\text{Li}^*, \text{deut}^* \text{ transition}$<br>$A^0 \rightarrow 2\gamma$  |
|                            |    | 19 LEHMANN   | 82  | CNTR | $\text{Cu}^* \rightarrow \text{Cu}A^0 (A^0 \rightarrow 2\gamma)$  |
|                            |    | 20 ZEHNDER   | 82  | CNTR | $\text{Li}^*, \text{Nb}^* \text{ decay, } n\text{-capt.}$   |
|                            |    | 21 ZEHNDER   | 81  | CNTR | $\text{Ba}^* \rightarrow \text{Ba}A^0 (A^0 \rightarrow 2\gamma)$  |
|                            |    | 22 CALAPRICE | 79  |      | Carbon  |

<sup>1</sup> DERBIN 02 looked for the axion emission in an M1 transition in  ${}^{125m}\text{Te}$  decay. They looked for a possible presence of a shifted energy spectrum in gamma rays due to the undetected axion.

<sup>2</sup> DEBOER 97C reanalyzed the existent data on Nuclear M1 transitions and find that a 9 MeV boson decaying into  $e^+e^-$  would explain the excess of events with large opening angles. See also DEBOER 01 for follow-up experiments.

<sup>3</sup> TSUNODA 95 looked for axion emission when  ${}^{252}\text{Cf}$  undergoes a spontaneous fission, with the axion decaying into  $e^+e^-$ . The bound is for  $m_{A^0}=40$  MeV. It improves to  $2.5 \times 10^{-5}$  for  $m_{A^0}=200$  MeV.

<sup>4</sup> MINOWA 93 studied chain process,  ${}^{139}\text{Ce} \rightarrow {}^{139}\text{La}^*$  by electron capture and M1 transition of  ${}^{139}\text{La}^*$  to the ground state. It does not assume decay modes of  $A^0$ . The bound applies for  $m_{A^0} < 166$  keV.

<sup>5</sup> HICKS 92 bound is applicable for  $\tau_{X^0} < 4 \times 10^{-11}$  sec.

<sup>6</sup> The ASANUMA 90 limit is for the branching fraction of  $X^0$  emission per  ${}^{241}\text{Am}$   $\alpha$  decay and valid for  $\tau_{X^0} < 3 \times 10^{-11}$  s.

<sup>7</sup> The DEBOER 90 limit is for the branching ratio  ${}^8\text{Be}^* (18.15 \text{ MeV}, 1^+) \rightarrow {}^8\text{Be}A^0,$   
 $A^0 \rightarrow e^+e^-$  for the mass range  $m_{A^0} = 4-15$  MeV.

<sup>8</sup> The BINI 89 limit is for the branching fraction of  ${}^{16}\text{O}^* (6.05 \text{ MeV}, 0^+) \rightarrow {}^{16}\text{O}X^0,$   
 $X^0 \rightarrow e^+e^-$  for  $m_X = 1.5-3.1$  MeV.  $\tau_{X^0} \lesssim 10^{-11}$  s is assumed. The spin-parity of  $X$  is restricted to  $0^+$  or  $1^-$ .

<sup>9</sup> AVIGNONE 88 looked for the 1115 keV transition  $\text{C}^* \rightarrow \text{Cu}A^0$ , either from  $A^0 \rightarrow 2\gamma$  in-flight decay or from the secondary  $A^0$  interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for  $m_{A^0} < 1.1$  MeV.

- <sup>10</sup> DATAR 88 rule out light pseudoscalar particle emission through its decay  $A^0 \rightarrow e^+ e^-$  in the mass range 1.02–2.5 MeV and lifetime range  $10^{-13}$ – $10^{-8}$  s. The above limit is for  $\tau = 5 \times 10^{-13}$  s and  $m = 1.7$  MeV; see the paper for the  $\tau$ - $m$  dependence of the limit.
- <sup>11</sup> The limit is for the branching fraction of  $^{16}\text{O}^*(6.05 \text{ MeV}, 0^+) \rightarrow ^{16}\text{O}X^0$ ,  $X^0 \rightarrow e^+ e^-$  against internal pair conversion for  $m_{X^0} = 1.7$  MeV and  $\tau_{X^0} < 10^{-11}$  s. Similar limits are obtained for  $m_{X^0} = 1.3$ – $3.2$  MeV. The spin parity of  $X^0$  must be either  $0^+$  or  $1^-$ . The limit at 1.7 MeV is translated into a limit for the  $X^0$ -nucleon coupling constant:  $g_{X^0 NN}^2/4\pi < 2.3 \times 10^{-9}$ .
- <sup>12</sup> The DOEHNER 88 limit is for  $m_{A^0} = 1.7$  MeV,  $\tau(A^0) < 10^{-10}$  s. Limits less than  $10^{-4}$  are obtained for  $m_{A^0} = 1.2$ – $2.2$  MeV.
- <sup>13</sup> SAVAGE 88 looked for  $A^0$  that decays into  $e^+ e^-$  in the decay of the 9.17 MeV  $J^P = 2^+$  state in  $^{14}\text{N}$ , 17.64 MeV state  $J^P = 1^+$  in  $^8\text{Be}$ , and the 18.15 MeV state  $J^P = 1^+$  in  $^8\text{Be}$ . This experiment constrains the isovector coupling of  $A^0$  to hadrons, if  $m_{A^0} = (1.1 \rightarrow 2.2)$  MeV and the isoscalar coupling of  $A^0$  to hadrons, if  $m_{A^0} = (1.1 \rightarrow 2.6)$  MeV. Both limits are valid only if  $\tau(A^0) \lesssim 1 \times 10^{-11}$  s.
- <sup>14</sup> Limits are for  $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi\text{M1})$ ; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of  $e^+ e^-$  pairs. Valid for  $\tau_{A^0} < 2 \times 10^{-11}$  s.  $^6\text{Li}$  isovector decay data strongly disfavor PECCEI 86 model I, whereas the  $^{10}\text{B}$  and  $^{14}\text{N}$  isoscalar decay data strongly reject PECCEI 86 model II and III.
- <sup>15</sup> SAVAGE 86B looked for  $A^0$  that decays into  $e^+ e^-$  in the decay of the 9.17 MeV  $J^P = 2^+$  state in  $^{14}\text{N}$ . Limit on the branching fraction is valid if  $\tau_{A^0} \lesssim 1 \times 10^{-11}$  s for  $m_{A^0} = (1.1$ – $1.7)$  MeV. This experiment constrains the iso-vector coupling of  $A^0$  to hadrons.
- <sup>16</sup> ANANEV 85 with IBR-2 pulsed reactor exclude standard  $A^0$  at CL = 95% masses below 470 keV ( $\text{Li}^*$  decay) and below  $2m_e$  for deuteron\* decay.
- <sup>17</sup> CAVAINAC 83 at Bugey reactor exclude axion at any  $m_{^{97}\text{Nb}^* \text{decay}}$  and axion with  $m_{A^0}$  between 275 and 288 keV (deuteron\* decay).
- <sup>18</sup> ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard  $A^0$  at CL = 95% mass-ranges  $m_{A^0} < 400$  keV ( $\text{Li}^*$  decay) and  $330 \text{ keV} < m_{A^0} < 2.2$  MeV. (deuteron\* decay).
- <sup>19</sup> LEHMANN 82 obtained  $A^0 \rightarrow 2\gamma$  rate  $< 6.2 \times 10^{-5}/\text{s}$  (CL = 95%) excluding  $m_{A^0}$  between 100 and 1000 keV.
- <sup>20</sup> ZEHNDER 82 used Gosgen 2.8GW light-water reactor to check  $A^0$  production. No  $2\gamma$  peak in  $\text{Li}^*$ ,  $\text{Nb}^*$  decay (both single  $p$  transition) nor in  $n$  capture (combined with previous  $\text{Ba}^*$  negative result) rules out standard  $A^0$ . Set limit  $m_{A^0} < 60$  keV for any  $A^0$ .
- <sup>21</sup> ZEHNDER 81 looked for  $\text{Ba}^* \rightarrow A^0\text{Ba}$  transition with  $A^0 \rightarrow 2\gamma$ . Obtained  $2\gamma$  coincidence rate  $< 2.2 \times 10^{-5}/\text{s}$  (CL = 95%) excluding  $m_{A^0} > 160$  keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.
- <sup>22</sup> CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.
-

**$A^0$  (Axion) Limits from Its Electron Coupling**Limits are for  $\tau(A^0 \rightarrow e^+ e^-)$ .

| <u>VALUE (s)</u>  | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>                                      |
|---|------------|--------------------|-------------|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • |            |                    |             |   |
| none $4 \times 10^{-16}$ – $4.5 \times 10^{-12}$                              | 90         | 1 BROSS            | 91 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |
|   |            | 2 GUO              | 90 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |
|   |            | 3 BJORKEN          | 88 CALO     | $A \rightarrow e^+ e^-$ or<br>$2\gamma$             |
|   |            | 4 BLINOV           | 88 MD1      | $ee \rightarrow eeA^0$<br>( $A^0 \rightarrow ee$ )  |
| none $1 \times 10^{-14}$ – $1 \times 10^{-10}$                                | 90         | 5 RIORDAN          | 87 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |
| none $1 \times 10^{-14}$ – $1 \times 10^{-11}$                                | 90         | 6 BROWN            | 86 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |
| none $6 \times 10^{-14}$ – $9 \times 10^{-11}$                                | 95         | 7 DAVIER           | 86 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |
| none $3 \times 10^{-13}$ – $1 \times 10^{-7}$                                 | 90         | 8 KONAKA           | 86 BDMP     | $eN \rightarrow eA^0 N$<br>( $A^0 \rightarrow ee$ ) |

<sup>1</sup> The listed BROSS 91 limit is for  $m_{A^0} = 1.14$  MeV.  $B(A^0 \rightarrow e^+ e^-) = 1$  assumed. Excluded domain in the  $\tau_{A^0}$ – $m_{A^0}$  plane extends up to  $m_{A^0} \approx 7$  MeV (see Fig. 5). Combining with electron  $g-2$  constraint, axions coupling only to  $e^+ e^-$  ruled out for  $m_{A^0} < 4.8$  MeV (90% CL).

<sup>2</sup> GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with  $g-2$  constraint, axions coupling only to  $e^+ e^-$  are ruled out for  $m_{A^0} < 2.7$  MeV (90% CL).

<sup>3</sup> BJORKEN 88 reports limits on axion parameters ( $f_A$ ,  $m_A$ ,  $\tau_A$ ) for  $m_{A^0} < 200$  MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

<sup>4</sup> BLINOV 88 assume zero spin,  $m = 1.8$  MeV and lifetime  $< 5 \times 10^{-12}$  s and find  $\Gamma(A^0 \rightarrow \gamma\gamma)B(A^0 \rightarrow e^+ e^-) < 2$  eV (CL=90%).

<sup>5</sup> Assumes  $A^0 \gamma\gamma$  coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for  $m_{A^0} < 15$  MeV.

<sup>6</sup> Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for  $m_{A^0} < 15$  MeV are shown in their figure 3.

<sup>7</sup>  $m_{A^0} = 1.8$  MeV assumed. The excluded domain in the  $\tau_{A^0}$ – $m_{A^0}$  plane extends up to  $m_{A^0} \approx 14$  MeV, see their figure 4.

<sup>8</sup> The limits are obtained from their figure 3. Also given is the limit on the  $A^0 \gamma\gamma$ – $A^0 e^+ e^-$  coupling plane by assuming Primakoff production.

**Search for  $A^0$  (Axion) Resonance in Bhabha Scattering**The limit is for  $\Gamma(A^0)[B(A^0 \rightarrow e^+e^-)]^2$ .

| VALUE ( $10^{-3}$ eV)   | CL% | DOCUMENT ID             | TECN     | COMMENT                           |
|---|-----|-------------------------|----------|-----------------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                         |          |                                   |
| < 1.3   | 97  | <sup>1</sup> HALLIN     | 92 CNTR  | $m_{A^0} = 1.75\text{--}1.88$ MeV |
| none 0.0016–0.47  | 90  | <sup>2</sup> HENDERSON  | 92C CNTR | $m_{A^0} = 1.5\text{--}1.86$ MeV  |
| < 2.0   | 90  | <sup>3</sup> WU         | 92 CNTR  | $m_{A^0} = 1.56\text{--}1.86$ MeV |
| < 0.013   | 95  | TSERTOS                 | 91 CNTR  | $m_{A^0} = 1.832$ MeV             |
| none 0.19–3.3   | 95  | <sup>4</sup> WIDMANN    | 91 CNTR  | $m_{A^0} = 1.78\text{--}1.92$ MeV |
| < 5   | 97  | BAUER                   | 90 CNTR  | $m_{A^0} = 1.832$ MeV             |
| none 0.09–1.5   | 95  | <sup>5</sup> JUDGE      | 90 CNTR  | $m_{A^0} = 1.832$ MeV,<br>elastic |
| < 1.9   | 97  | <sup>6</sup> TSERTOS    | 89 CNTR  | $m_{A^0} = 1.82$ MeV              |
| <(10–40)  | 97  | <sup>6</sup> TSERTOS    | 89 CNTR  | $m_{A^0} = 1.51\text{--}1.65$ MeV |
| <(1–2.5)  | 97  | <sup>6</sup> TSERTOS    | 89 CNTR  | $m_{A^0} = 1.80\text{--}1.86$ MeV |
| < 31  | 95  | LORENZ                  | 88 CNTR  | $m_{A^0} = 1.646$ MeV             |
| < 94  | 95  | LORENZ                  | 88 CNTR  | $m_{A^0} = 1.726$ MeV             |
| < 23  | 95  | LORENZ                  | 88 CNTR  | $m_{A^0} = 1.782$ MeV             |
| < 19  | 95  | LORENZ                  | 88 CNTR  | $m_{A^0} = 1.837$ MeV             |
| < 3.8   | 97  | <sup>7</sup> TSERTOS    | 88 CNTR  | $m_{A^0} = 1.832$ MeV             |
|   |     | <sup>8</sup> VANKLINKEN | 88 CNTR  |                                   |
|   |     | <sup>9</sup> MAIER      | 87 CNTR  |                                   |
| <2500   | 90  | MILLS                   | 87 CNTR  | $m_{A^0} = 1.8$ MeV               |
|   |     | <sup>10</sup> VONWIMMER | 87 CNTR  |                                   |

<sup>1</sup> HALLIN 92 quote limits on lifetime,  $8 \times 10^{-14} - 5 \times 10^{-13}$  sec depending on mass, assuming  $B(A^0 \rightarrow e^+e^-) = 100\%$ . They say that TSERTOS 91 overstated their sensitivity by a factor of 3.

<sup>2</sup> HENDERSON 92C exclude axion with lifetime  $\tau_{A^0} = 1.4 \times 10^{-12} - 4.0 \times 10^{-10}$  s, assuming  $B(A^0 \rightarrow e^+e^-) = 100\%$ . HENDERSON 92C also exclude a vector boson with  $\tau = 1.4 \times 10^{-12} - 6.0 \times 10^{-10}$  s.

<sup>3</sup> WU 92 quote limits on lifetime  $> 3.3 \times 10^{-13}$  s assuming  $B(A^0 \rightarrow e^+e^-) = 100\%$ . They say that TSERTOS 89 overestimate the limit by a factor of  $\pi/2$ . WU 92 also quote a bound for vector boson,  $\tau > 8.2 \times 10^{-13}$  s.

<sup>4</sup> WIDMANN 91 bound applies exclusively to the case  $B(A^0 \rightarrow e^+e^-) = 1$ , since the detection efficiency varies substantially as  $\Gamma(A^0)_{\text{total}}$  changes. See their Fig. 6.

<sup>5</sup> JUDGE 90 excludes an elastic pseudoscalar  $e^+e^-$  resonance for  $4.5 \times 10^{-13}$  s  $< \tau(A^0) < 7.5 \times 10^{-12}$  s (95% CL) at  $m_{A^0} = 1.832$  MeV. Comparable limits can be set for  $m_{A^0} = 1.776\text{--}1.856$  MeV.

<sup>6</sup> See also TSERTOS 88B in references.

<sup>7</sup> The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

<sup>8</sup> VANKLINKEN 88 looked for relatively long-lived resonance ( $\tau = 10^{-10}\text{--}10^{-12}$  s). The sensitivity is not sufficient to exclude such a narrow resonance.

<sup>9</sup> MAIER 87 obtained limits  $R\Gamma \lesssim 60$  eV (100 eV) at  $m_{A^0} \simeq 1.64$  MeV (1.83 MeV) for energy resolution  $\Delta E_{\text{cm}} \simeq 3$  keV, where  $R$  is the resonance cross section normalized to that of Bhabha scattering, and  $\Gamma = \Gamma_{e^+e^-}^2 / \Gamma_{\text{total}}$ . For a discussion implying that  $\Delta E_{\text{cm}} \simeq 10$  keV, see TSERTOS 89.

<sup>10</sup>VONWIMMERSPERG 87 measured Bhabha scattering for  $E_{\text{cm}} = 1.37\text{--}1.86$  MeV and found a possible peak at 1.73 with  $\int \sigma dE_{\text{cm}} = 14.5 \pm 6.8$  keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.

### Search for $A^0$ (Axion) Resonance in $e^+e^- \rightarrow \gamma\gamma$

The limit is for  $\Gamma(A^0 \rightarrow e^+e^-) \cdot \Gamma(A^0 \rightarrow \gamma\gamma) / \Gamma_{\text{total}}$

| VALUE ( $10^{-3}$ eV)   | CL% | DOCUMENT ID          | TECN | COMMENT                                |
|---|-----|----------------------|------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                      |      |  |
| < 0.18  | 95  | VO                   | 94   | CNTR $m_{A^0} = 1.1$ MeV               |
| < 1.5   | 95  | VO                   | 94   | CNTR $m_{A^0} = 1.4$ MeV               |
| < 12  | 95  | VO                   | 94   | CNTR $m_{A^0} = 1.7$ MeV               |
| < 6.6   | 95  | <sup>1</sup> TRZASKA | 91   | CNTR $m_{A^0} = 1.8$ MeV               |
| < 4.4   | 95  | WIDMANN              | 91   | CNTR $m_{A^0} = 1.78\text{--}1.92$ MeV |
|   |     | <sup>2</sup> FOX     | 89   | CNTR                                   |
| < 0.11  | 95  | <sup>3</sup> MINOWA  | 89   | CNTR $m_{A^0} = 1.062$ MeV             |
| < 33  | 97  | CONNELL              | 88   | CNTR $m_{A^0} = 1.580$ MeV             |
| < 42  | 97  | CONNELL              | 88   | CNTR $m_{A^0} = 1.642$ MeV             |
| < 73  | 97  | CONNELL              | 88   | CNTR $m_{A^0} = 1.782$ MeV             |
| < 79  | 97  | CONNELL              | 88   | CNTR $m_{A^0} = 1.832$ MeV             |

<sup>1</sup>TRZASKA 91 also give limits in the range  $(6.6\text{--}30) \times 10^{-3}$  eV (95%CL) for  $m_{A^0} = 1.6\text{--}2.0$  MeV.

<sup>2</sup>FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ( $< 9 \times 10^{-5}$  of two-photon annihilation at rest).

<sup>3</sup>Similar limits are obtained for  $m_{A^0} = 1.045\text{--}1.085$  MeV.

### Search for $X^0$ (Light Boson) Resonance in $e^+e^- \rightarrow \gamma\gamma\gamma$

The limit is for  $\Gamma(X^0 \rightarrow e^+e^-) \cdot \Gamma(X^0 \rightarrow \gamma\gamma\gamma) / \Gamma_{\text{total}}$ . C invariance forbids spin-0  $X^0$  coupling to both  $e^+e^-$  and  $\gamma\gamma\gamma$ .

| VALUE ( $10^{-3}$ eV)   | CL% | DOCUMENT ID          | TECN | COMMENT                              |
|---|-----|----------------------|------|--------------------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                      |      |                                      |
| < 0.2   | 95  | <sup>1</sup> VO      | 94   | CNTR $m_{X^0} = 1.1\text{--}1.9$ MeV |
| < 1.0   | 95  | <sup>2</sup> VO      | 94   | CNTR $m_{X^0} = 1.1$ MeV             |
| < 2.5   | 95  | <sup>2</sup> VO      | 94   | CNTR $m_{X^0} = 1.4$ MeV             |
| < 120   | 95  | <sup>2</sup> VO      | 94   | CNTR $m_{X^0} = 1.7$ MeV             |
| < 3.8   | 95  | <sup>3</sup> SKALSEY | 92   | CNTR $m_{X^0} = 1.5$ MeV             |

<sup>1</sup>VO 94 looked for  $X^0 \rightarrow \gamma\gamma\gamma$  decaying at rest. The precise limits depend on  $m_{X^0}$ . See Fig. 2(b) in paper.

<sup>2</sup>VO 94 looked for  $X^0 \rightarrow \gamma\gamma\gamma$  decaying in flight.

<sup>3</sup>SKALSEY 92 also give limits 4.3 for  $m_{X^0} = 1.54$  and 7.5 for 1.64 MeV. The spin of  $X^0$  is assumed to be one.

**Light Boson ( $X^0$ ) Search in Nonresonant  $e^+e^-$  Annihilation at Rest**Limits are for the ratio of  $n\gamma + X^0$  production relative to  $\gamma\gamma$ .

| VALUE (units $10^{-6}$ )  | CL% | DOCUMENT ID          | TECN    | COMMENT  |
|---|-----|----------------------|---------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                      |         |  |
| < 4.2   | 90  | <sup>1</sup> MITSUI  | 96 CNTR | $\gamma X^0$                                     |
| < 4   | 68  | <sup>2</sup> SKALSEY | 95 CNTR | $\gamma X^0$                                     |
| <40   | 68  | <sup>3</sup> SKALSEY | 95 RVUE | $\gamma X^0$                                     |
| < 0.18  | 90  | <sup>4</sup> ADACHI  | 94 CNTR | $\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$ |
| < 0.26  | 90  | <sup>5</sup> ADACHI  | 94 CNTR | $\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$ |
| < 0.33  | 90  | <sup>6</sup> ADACHI  | 94 CNTR | $\gamma X^0, X^0 \rightarrow \gamma\gamma\gamma$ |

<sup>1</sup> MITSUI 96 looked for a monochromatic  $\gamma$ . The bound applies for a vector  $X^0$  with  $C=-1$  and  $m_{X^0} < 200$  keV. They derive an upper bound on  $e e X^0$  coupling and hence on the branching ratio  $B(\sigma\text{-Ps} \rightarrow \gamma\gamma X^0) < 6.2 \times 10^{-6}$ . The bounds weaken for heavier  $X^0$ .

<sup>2</sup> SKALSEY 95 looked for a monochromatic  $\gamma$  without an accompanying  $\gamma$  in  $e^+e^-$  annihilation. The bound applies for scalar and vector  $X^0$  with  $C = -1$  and  $m_{X^0} = 100\text{--}1000$  keV.

<sup>3</sup> SKALSEY 95 reinterpreted the bound on  $\gamma A^0$  decay of  $\sigma\text{-Ps}$  by ASAI 91 where 3% of delayed annihilations are not from  $^3S_1$  states. The bound applies for scalar and vector  $X^0$  with  $C = -1$  and  $m_{X^0} = 0\text{--}800$  keV.

<sup>4</sup> ADACHI 94 looked for a peak in the  $\gamma\gamma$  invariant mass distribution in  $\gamma\gamma\gamma\gamma$  production from  $e^+e^-$  annihilation. The bound applies for  $m_{X^0} = 70\text{--}800$  keV.

<sup>5</sup> ADACHI 94 looked for a peak in the missing-mass mass distribution in  $\gamma\gamma$  channel, using  $\gamma\gamma\gamma\gamma$  production from  $e^+e^-$  annihilation. The bound applies for  $m_{X^0} < 800$  keV.

<sup>6</sup> ADACHI 94 looked for a peak in the missing mass distribution in  $\gamma\gamma\gamma$  channel, using  $\gamma\gamma\gamma\gamma$  production from  $e^+e^-$  annihilation. The bound applies for  $m_{X^0} = 200\text{--}900$  keV.

**Searches for Goldstone Bosons ( $X^0$ )**

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

| VALUE   | CL% | DOCUMENT ID           | TECN    | COMMENT  |
|---|-----|-----------------------|---------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                       |         |  |
| <9 $\times 10^{-6}$   | 90  | <sup>1</sup> BAYES    | 15 TWST | $\mu^+ \rightarrow e^+ X^0$ , Familon                            |
|   |     | <sup>2</sup> LATTANZI | 13 COSM | Majoron dark matter decay  |
|   |     | <sup>3</sup> LESSA    | 07 RVUE | Meson, $\ell$ decays to Majoron                                  |
|   |     | <sup>4</sup> DIAZ     | 98 THEO | $H^0 \rightarrow X^0 X^0, A^0 \rightarrow X^0 X^0 X^0$ , Majoron |
|   |     | <sup>5</sup> BOBRAKOV | 91      | Electron quasi-magnetic interaction                              |
| <3.3 $\times 10^{-2}$   | 95  | <sup>6</sup> ALBRECHT | 90E ARG | $\tau \rightarrow \mu X^0$ . Familon                             |
| <1.8 $\times 10^{-2}$   | 95  | <sup>6</sup> ALBRECHT | 90E ARG | $\tau \rightarrow e X^0$ . Familon                               |
| <6.4 $\times 10^{-9}$   | 90  | <sup>7</sup> ATIYA    | 90 B787 | $K^+ \rightarrow \pi^+ X^0$ . Familon                            |
| <1.4 $\times 10^{-5}$   | 90  | <sup>8</sup> BALKE    | 88 CNTR | $\mu^+ \rightarrow e^+ X^0$ . Familon                            |
| <1.1 $\times 10^{-9}$   | 90  | <sup>9</sup> BOLTON   | 88 CBOX | $\mu^+ \rightarrow e^+ \gamma X^0$ . Familon                     |

|                       |    |    |              |     |      |   |
|-----------------------|----|----|--------------|-----|------|---|
|                       |    | 10 | CHANDA       | 88  | ASTR | Sun, Majoron  |
|                       |    | 11 | CHOI         | 88  | ASTR | Majoron, SN 1987A                                   |
| $<5 \times 10^{-6}$   | 90 | 12 | PICCIOTTO    | 88  | CNTR | $\pi \rightarrow e\nu X^0$ , Majoron                |
| $<1.3 \times 10^{-9}$ | 90 | 13 | GOLDMAN      | 87  | CNTR | $\mu \rightarrow e\gamma X^0$ . Familon             |
| $<3 \times 10^{-4}$   | 90 | 14 | BRYMAN       | 86B | RVUE | $\mu \rightarrow e X^0$ . Familon                   |
| $<1 \times 10^{-10}$  | 90 | 15 | EICHLER      | 86  | SPEC | $\mu^+ \rightarrow e^+ X^0$ . Familon               |
| $<2.6 \times 10^{-6}$ | 90 | 16 | JODIDIO      | 86  | SPEC | $\mu^+ \rightarrow e^+ X^0$ . Familon               |
|                       |    | 17 | BALTRUSAIT.. | 85  | MRK3 | $\tau \rightarrow \ell X^0$ . Familon               |
|                       |    | 18 | DICUS        | 83  | COSM | $\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$ |

- <sup>1</sup> BAYES 15 limits are the average over  $m_{X^0} = 13\text{--}80$  MeV for the isotropic decay distribution of positrons. See their Fig. 4 and Table II for the mass-dependent limits as well as the dependence on the decay anisotropy. In particular, they find a limit  $< 58 \times 10^{-6}$  at 90% CL for massless familons and for the same asymmetry as normal muon decay, a case not covered by JODIDIO 86.
- <sup>2</sup> LATTANZI 13 use WMAP 9 year data as well as X-ray and  $\gamma$ -ray observations to derive limits on decaying majoron dark matter. A limit on the decay width  $\Gamma(X^0 \rightarrow \nu\bar{\nu}) < 6.4 \times 10^{-19} \text{ s}^{-1}$  at 95% CL is found if majorons make up all of the dark matter.
- <sup>3</sup> LESSA 07 consider decays of the form Meson  $\rightarrow \ell\nu$  Majoron and  $\ell \rightarrow \ell'\nu\bar{\nu}$  Majoron and use existing data to derive limits on the neutrino-Majoron Yukawa couplings  $g_{\alpha\beta}$  ( $\alpha, \beta = e, \mu, \tau$ ). Their best limits are  $|g_{e\alpha}|^2 < 5.5 \times 10^{-6}$ ,  $|g_{\mu\alpha}|^2 < 4.5 \times 10^{-5}$ ,  $|g_{\tau\alpha}|^2 < 5.5 \times 10^{-2}$  at CL = 90%.
- <sup>4</sup> DIAZ 98 studied models of spontaneously broken lepton number with both singlet and triplet Higgses. They obtain limits on the parameter space from invisible decay  $Z \rightarrow H^0 A^0 \rightarrow X^0 X^0 X^0 X^0$  and  $e^+e^- \rightarrow ZH^0$  with  $H^0 \rightarrow X^0 X^0$ .
- <sup>5</sup> BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit  $x_e^2 < 2 \times 10^{-4}$  (95%CL) is found for the effective anomalous magneton parametrized as  $x_e(G_F/8\pi\sqrt{2})^{1/2}$ .
- <sup>6</sup> ALBRECHT 90E limits are for  $B(\tau \rightarrow \ell X^0)/B(\tau \rightarrow \ell\nu\bar{\nu})$ . Valid for  $m_{X^0} < 100$  MeV. The limits rise to 7.1% (for  $\mu$ ), 5.0% (for  $e$ ) for  $m_{X^0} = 500$  MeV.
- <sup>7</sup> ATIYA 90 limit is for  $m_{X^0} = 0$ . The limit  $B < 1 \times 10^{-8}$  holds for  $m_{X^0} < 95$  MeV. For the reduction of the limit due to finite lifetime of  $X^0$ , see their Fig. 3.
- <sup>8</sup> BALKE 88 limits are for  $B(\mu^+ \rightarrow e^+ X^0)$ . Valid for  $m_{X^0} < 80$  MeV and  $\tau_{X^0} > 10^{-8}$  sec.
- <sup>9</sup> BOLTON 88 limit corresponds to  $F > 3.1 \times 10^9$  GeV, which does not depend on the chirality property of the coupling.
- <sup>10</sup> CHANDA 88 find  $v_T < 10$  MeV for the weak-triplet Higgs vacuum expectation value in Gelmini-Roncadelli model, and  $v_S > 5.8 \times 10^6$  GeV in the singlet Majoron model.
- <sup>11</sup> CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling  $h$  in the range  $2 \times 10^{-5} < h < 3 \times 10^{-4}$  for the interaction  $L_{\text{int}} = \frac{1}{2} i h \bar{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$ . For several families of neutrinos, the limit applies for  $(\sum h_i^4)^{1/4}$ .
- <sup>12</sup> PICCIOTTO 88 limit applies when  $m_{X^0} < 55$  MeV and  $\tau_{X^0} > 2\text{ns}$ , and it decreases to  $4 \times 10^{-7}$  at  $m_{X^0} = 125$  MeV, beyond which no limit is obtained.
- <sup>13</sup> GOLDMAN 87 limit corresponds to  $F > 2.9 \times 10^9$  GeV for the family symmetry breaking scale from the Lagrangian  $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu (a + b\gamma_5) \psi_e \partial_\mu \phi_{X^0}$  with  $a^2 + b^2 = 1$ . This is not as sensitive as the limit  $F > 9.9 \times 10^9$  GeV derived from the search for  $\mu^+ \rightarrow e^+ X^0$  by JODIDIO 86, but does not depend on the chirality property of the coupling.



- <sup>14</sup> Limits are for  $\Gamma(\mu \rightarrow e X^0)/\Gamma(\mu \rightarrow e \nu \bar{\nu})$ . Valid when  $m_{X^0} = 0-93.4, 98.1-103.5$  MeV.
- <sup>15</sup> EICHLER 86 looked for  $\mu^+ \rightarrow e^+ X^0$  followed by  $X^0 \rightarrow e^+ e^-$ . Limits on the branching fraction depend on the mass and and lifetime of  $X^0$ . The quoted limits are valid when  $\tau_{X^0} \lesssim 3. \times 10^{-10}$  s if the decays are kinematically allowed.
- <sup>16</sup> JODIDIO 86 corresponds to  $F > 9.9 \times 10^9$  GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian  $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$ .
- <sup>17</sup> BALTRUSAITIS 85 search for light Goldstone boson( $X^0$ ) of broken U(1). CL = 95% limits are  $B(\tau \rightarrow \mu^+ X^0)/B(\tau \rightarrow \mu^+ \nu \nu) < 0.125$  and  $B(\tau \rightarrow e^+ X^0)/B(\tau \rightarrow e^+ \nu \nu) < 0.04$ . Inferred limit for the symmetry breaking scale is  $m > 3000$  TeV.
- <sup>18</sup> The primordial heavy neutrino must decay into  $\nu$  and familon,  $f_A$ , early so that the red-shifted decay products are below critical density, see their table. In addition,  $K \rightarrow \pi f_A$  and  $\mu \rightarrow e f_A$  are unseen. Combining these excludes  $m_{\text{heavy}\nu}$  between  $5 \times 10^{-5}$  and  $5 \times 10^{-4}$  MeV ( $\mu$  decay) and  $m_{\text{heavy}\nu}$  between  $5 \times 10^{-5}$  and 0.1 MeV ( $K$ -decay).

### Majoron Searches in Neutrinoless Double $\beta$ Decay

Limits are for the half-life of neutrinoless  $\beta\beta$  decay with a Majoron emission.  
 No experiment currently claims any such evidence. Only the best or comparable limits for each isotope are reported. Also see the reviews ZUBER 98 and FAESSLER 98B.

| $t_{1/2}(10^{21} \text{ yr})$   | CL%       | ISOTOPE                 | TRANSITION   | METHOD  | DOCUMENT ID                 |
|---|-----------|-------------------------|--------------|---|-----------------------------|
| <b>&gt;7200</b>   | <b>90</b> | <b><sup>128</sup>Te</b> |              | <b>CNTR</b>   | <sup>1</sup> BERNATOW... 92 |
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |           |                         |              |   |                             |
| > 420   | 90        | <sup>76</sup> Ge        | $0\nu 1\chi$ | GERDA   | <sup>2</sup> AGOSTINI 15A   |
| > 400   | 90        | <sup>100</sup> Mo       | $0\nu 1\chi$ | NEMO-3  | <sup>3</sup> ARNOLD 15      |
| >1200   | 90        | <sup>136</sup> Xe       | $0\nu 1\chi$ | EXO-200   | <sup>4</sup> ALBERT 14A     |
| >2600   | 90        | <sup>136</sup> Xe       | $0\nu 1\chi$ | KamLAND-Zen   | <sup>5</sup> GANDO 12       |
| > 16  | 90        | <sup>130</sup> Te       | $0\nu 1\chi$ | NEMO-3  | <sup>6</sup> ARNOLD 11      |
| > 1.9   | 90        | <sup>96</sup> Zr        | $2\nu 1\chi$ | NEMO-3  | <sup>7</sup> ARGYRIADES 10  |
| > 1.52  | 90        | <sup>150</sup> Nd       | $0\nu 1\chi$ | NEMO-3  | <sup>8</sup> ARGYRIADES 09  |
| > 27  | 90        | <sup>100</sup> Mo       | $0\nu 1\chi$ | NEMO-3  | <sup>9</sup> ARNOLD 06      |
| > 15  | 90        | <sup>82</sup> Se        | $0\nu 1\chi$ | NEMO-3  | <sup>10</sup> ARNOLD 06     |
| > 14  | 90        | <sup>100</sup> Mo       | $0\nu 1\chi$ | NEMO-3  | <sup>11</sup> ARNOLD 04     |
| > 12  | 90        | <sup>82</sup> Se        | $0\nu 1\chi$ | NEMO-3  | <sup>12</sup> ARNOLD 04     |
| > 2.2   | 90        | <sup>130</sup> Te       | $0\nu 1\chi$ | Cryog. det.   | <sup>13</sup> ARNABOLDI 03  |
| > 0.9   | 90        | <sup>130</sup> Te       | $0\nu 2\chi$ | Cryog. det.   | <sup>14</sup> ARNABOLDI 03  |
| > 8   | 90        | <sup>116</sup> Cd       | $0\nu 1\chi$ | CdWO <sub>4</sub> scint.                            | <sup>15</sup> DANEVICH 03   |
| > 0.8   | 90        | <sup>116</sup> Cd       | $0\nu 2\chi$ | CdWO <sub>4</sub> scint.                            | <sup>16</sup> DANEVICH 03   |
| > 500   | 90        | <sup>136</sup> Xe       | $0\nu 1\chi$ | Liquid Xe Scint.                                    | <sup>17</sup> BERNABEI 02D  |
| > 5.8   | 90        | <sup>100</sup> Mo       | $0\nu 1\chi$ | ELEGANT V   | <sup>18</sup> FUSHIMI 02    |
| > 0.32  | 90        | <sup>100</sup> Mo       | $0\nu 1\chi$ | Liq. Ar ioniz.                                      | <sup>19</sup> ASHITKOV 01   |
| > 0.0035  | 90        | <sup>160</sup> Gd       | $0\nu 1\chi$ | <sup>160</sup> Gd <sub>2</sub> SiO <sub>5</sub> :Ce | <sup>20</sup> DANEVICH 01   |
| > 0.013   | 90        | <sup>160</sup> Gd       | $0\nu 2\chi$ | <sup>160</sup> Gd <sub>2</sub> SiO <sub>5</sub> :Ce | <sup>21</sup> DANEVICH 01   |
| > 2.3   | 90        | <sup>82</sup> Se        | $0\nu 1\chi$ | NEMO 2  | <sup>22</sup> ARNOLD 00     |
| > 0.31  | 90        | <sup>96</sup> Zr        | $0\nu 1\chi$ | NEMO 2  | <sup>23</sup> ARNOLD 00     |
| > 0.63  | 90        | <sup>82</sup> Se        | $0\nu 2\chi$ | NEMO 2  | <sup>24</sup> ARNOLD 00     |

|   |       |    |                   |      |        |    |          |    |
|---|-------|----|-------------------|------|--------|----|----------|----|
| > | 0.063 | 90 | <sup>96</sup> Zr  | 0ν2χ | NEMO 2 | 24 | ARNOLD   | 00 |
| > | 0.16  | 90 | <sup>100</sup> Mo | 0ν2χ | NEMO 2 | 24 | ARNOLD   | 00 |
| > | 2.4   | 90 | <sup>82</sup> Se  | 0ν1χ | NEMO 2 | 25 | ARNOLD   | 98 |
| > | 7.2   | 90 | <sup>136</sup> Xe | 0ν2χ | TPC    | 26 | LUESCHER | 98 |
| > | 7.91  | 90 | <sup>76</sup> Ge  |      | SPEC   | 27 | GUENTHER | 96 |
| > | 17    | 90 | <sup>76</sup> Ge  |      | CNTR   |    | BECK     | 93 |

- <sup>1</sup> BERNATOWICZ 92 studied double-β decays of <sup>128</sup>Te and <sup>130</sup>Te, and found the ratio  $\tau(^{130}\text{Te})/\tau(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$  in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of <sup>128</sup>Te of  $(7.7 \pm 0.4) \times 10^{24}$  year. We calculated 90% CL limit as  $(7.7-1.28 \times 0.4=7.2) \times 10^{24}$ .
- <sup>2</sup> AGOSTINI 15A analyze a 20.3 kg yr of data set of the GERDA calorimeter to determine  $g_{\nu\chi} < 3.4-8.7 \times 10^{-5}$  on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.
- <sup>3</sup> ARNOLD 15 use the NEMO-3 tracking calorimeter with 3.43 kg yr exposure to determine the limit on Majoron emission. The limit corresponds to  $g_{\nu\chi} < 1.6-3.0 \times 10^{-4}$ . The spread reflects different nuclear matrix elements. Supersedes ARNOLD 06.
- <sup>4</sup> ALBERT 14A utilize 100 kg yr of exposure of the EXO-200 tracking calorimeter to place a limit on the  $g_{\nu\chi} < 0.8-1.7 \times 10^{-5}$  on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.
- <sup>5</sup> GANDO 12 use the KamLAND-Zen detector to obtain the limit on the 0νχ decay with Majoron emission. It implies that the coupling constant  $g_{\nu\chi} < 0.8-1.6 \times 10^{-5}$  depending on the nuclear matrix elements used.
- <sup>6</sup> ARNOLD 11 use the NEMO-3 detector to obtain the reported limit on Majoron emission. It implies that the coupling constant  $g_{\nu\chi} < 0.6-1.6 \times 10^{-4}$  depending on the nuclear matrix element used. Supersedes ARNABOLDI 03.
- <sup>7</sup> ARGYRIADES 10 use the NEMO-3 tracking detector and <sup>96</sup>Zr to derive the reported limit. No limit for the Majoron electron coupling is given.
- <sup>8</sup> ARGYRIADES 09 use <sup>150</sup>Nd data taken with the NEMO-3 tracking detector. The reported limit corresponds to  $\langle g_{\nu\chi} \rangle < 1.7-3.0 \times 10^{-4}$  using a range of nuclear matrix elements that include the effect of nuclear deformation.
- <sup>9</sup> ARNOLD 06 use <sup>100</sup>Mo data taken with the NEMO-3 tracking detector. The reported limit corresponds to  $\langle g_{\nu\chi} \rangle < (0.4-1.8) \times 10^{-4}$  using a range of matrix element calculations. Superseded by ARNOLD 15.
- <sup>10</sup> NEMO-3 tracking calorimeter is used in ARNOLD 06. Reported half-life limit for <sup>82</sup>Se corresponds to  $\langle g_{\nu\chi} \rangle < (0.66-1.9) \times 10^{-4}$  using a range of matrix element calculations. Supersedes ARNOLD 04.
- <sup>11</sup> ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to  $\langle g_{\nu\chi} \rangle < (0.5-0.9)10^{-4}$  using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03. Superseded by ARNOLD 06.
- <sup>12</sup> ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to  $\langle g_{\nu\chi} \rangle < (0.7-1.6)10^{-4}$  using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.
- <sup>13</sup> Supersedes ALESSANDRELLO 00. Array of TeO<sub>2</sub> crystals in high resolution cryogenic calorimeter. Some enriched in <sup>130</sup>Te. Derive  $\langle g_{\nu\chi} \rangle < 17-33 \times 10^{-5}$  depending on matrix element.
- <sup>14</sup> Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search.
- <sup>15</sup> Limit for the 0νχ decay with Majoron emission of <sup>116</sup>Cd using enriched CdWO<sub>4</sub> scintillators.  $\langle g_{\nu\chi} \rangle < 4.6-8.1 \times 10^{-5}$  depending on the matrix element. Supersedes DANEVICH 00.
- <sup>16</sup> Limit for the 0ν2χ decay of <sup>116</sup>Cd. Supersedes DANEVICH 00.

- 17 BERNABEI 02D obtain limit for  $0\nu\chi$  decay with Majoron emission of  $^{136}\text{Xe}$  using liquid Xe scintillation detector. They derive  $\langle g_{\nu\chi} \rangle < 2.0\text{--}3.0 \times 10^{-5}$  with several nuclear matrix elements.
- 18 Replaces TANAKA 93. FUSHIMI 02 derive half-life limit for the  $0\nu\chi$  decay by means of tracking calorimeter ELEGANT V. Considering various matrix element calculations, a range of limits for the Majoron-neutrino coupling is given:  $\langle g_{\nu\chi} \rangle < (6.3\text{--}360) \times 10^{-5}$ .
- 19 ASHITKOV 01 result for  $0\nu\chi$  of  $^{100}\text{Mo}$  is less stringent than ARNOLD 00.
- 20 DANEVICH 01 obtain limit for the  $0\nu\chi$  decay with Majoron emission of  $^{160}\text{Gd}$  using  $\text{Gd}_2\text{SiO}_5\text{:Ce}$  crystal scintillators.
- 21 DANEVICH 01 obtain limit for the  $0\nu 2\chi$  decay with 2 Majoron emission of  $^{160}\text{Gd}$ .
- 22 ARNOLD 00 reports limit for the  $0\nu\chi$  decay with Majoron emission derived from tracking calorimeter NEMO 2. Using  $^{82}\text{Se}$  source:  $\langle g_{\nu\chi} \rangle < 1.6 \times 10^{-4}$ . Matrix element from GUENTHER 96.
- 23 Using  $^{96}\text{Zr}$  source:  $\langle g_{\nu\chi} \rangle < 2.6 \times 10^{-4}$ . Matrix element from ARNOLD 99.
- 24 ARNOLD 00 reports limit for the  $0\nu 2\chi$  decay with two Majoron emission derived from tracking calorimeter NEMO 2.
- 25 ARNOLD 98 determine the limit for  $0\nu\chi$  decay with Majoron emission of  $^{82}\text{Se}$  using the NEMO-2 tracking detector. They derive  $\langle g_{\nu\chi} \rangle < 2.3\text{--}4.3 \times 10^{-4}$  with several nuclear matrix elements.
- 26 LUESCHER 98 report a limit for the  $0\nu$  decay with Majoron emission of  $^{136}\text{Xe}$  using Xe TPC. This result is more stringent than BARABASH 89. Using the matrix elements of ENGEL 88, they obtain a limit on  $\langle g_{\nu\chi} \rangle$  of  $2.0 \times 10^{-4}$ .
- 27 See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.

### Invisible $A^0$ (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$  is usually assumed ( $v_j =$  vacuum expectation values). For a review of these limits, see RAFFELT 91 and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

| <u>VALUE (eV)</u>   | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>              |
|---|------------|--------------------|-------------|-----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |            |                    |             |                             |
| < 0.67  | 95         | 1 ARCHIDIACO...13A | COSM        | K, hot dark matter          |
| none $0.7\text{--}3 \times 10^5$  |            | 2 CADAMURO 11      | COSM        | D abundance                 |
| <105  | 90         | 3 DERBIN 11A       | CNTR        | D, solar axion              |
|   |            | 4 ANDRIAMON...10   | CAST        | K, solar axions             |
| < 0.72  | 95         | 5 HANNESTAD 10     | COSM        | K, hot dark matter          |
|   |            | 6 ANDRIAMON..09    | CAST        | K, solar axions             |
| <191  | 90         | 7 DERBIN 09A       | CNTR        | K, solar axions             |
| <334  | 95         | 8 KEKEZ 09         | HPGE        | K, solar axions             |
| < 1.02  | 95         | 9 HANNESTAD 08     | COSM        | K, hot dark matter          |
| < 1.2   | 95         | 10 HANNESTAD 07    | COSM        | K, hot dark matter          |
| < 0.42  | 95         | 11 MELCHIORRI 07A  | COSM        | K, hot dark matter          |
| < 1.05  | 95         | 12 HANNESTAD 05A   | COSM        | K, hot dark matter          |
| 3 to 20   |            | 13 MOROI 98        | COSM        | K, hot dark matter          |
| < 0.007   |            | 14 BORISOV 97      | ASTR        | D, neutron star             |
| < 4   |            | 15 KACHELRIESS 97  | ASTR        | D, neutron star cooling     |
| <(0.5–6) $\times 10^{-3}$   |            | 16 KEIL 97         | ASTR        | SN 1987A                    |
| < 0.018   |            | 17 RAFFELT 95      | ASTR        | D, red giant                |
| < 0.010   |            | 18 ALTHERR 94      | ASTR        | D, red giants, white dwarfs |
|   |            | 19 CHANG 93        | ASTR        | K, SN 1987A                 |

|                                     |             |     |      |   |
|-------------------------------------|-------------|-----|------|---|
| < 0.01                              | WANG        | 92  | ASTR | D, white dwarf  |
| < 0.03                              | WANG        | 92C | ASTR | D, C-O burning  |
| none 3–8                            | 20 BERSHADY | 91  | ASTR | D, K,<br>intergalactic light                              |
| < 10                                | 21 KIM      | 91C | COSM | D, K, mass density of<br>the universe, super-<br>symmetry |
| < $1 \times 10^{-3}$                | 22 RAFFELT  | 91B | ASTR | D,K, SN 1987A   |
| none $10^{-3}$ – $3$                | 23 RESSELL  | 91  | ASTR | K, intergalactic light                                    |
|                                     | BURROWS     | 90  | ASTR | D,K, SN 1987A   |
|                                     | 24 ENGEL    | 90  | ASTR | D,K, SN 1987A   |
| < 0.02                              | 25 RAFFELT  | 90D | ASTR | D, red giant  |
| < $1 \times 10^{-3}$                | 26 BURROWS  | 89  | ASTR | D,K, SN 1987A   |
| < $(1.4\text{--}10) \times 10^{-3}$ | 27 ERICSON  | 89  | ASTR | D,K, SN 1987A   |
| < $3.6 \times 10^{-4}$              | 28 MAYLE    | 89  | ASTR | D,K, SN 1987A   |
| < 12                                | CHANDA      | 88  | ASTR | D, Sun  |
| < $1 \times 10^{-3}$                | RAFFELT     | 88  | ASTR | D,K, SN 1987A   |
|                                     | 29 RAFFELT  | 88B | ASTR | red giant   |
| < 0.07                              | FRIEMAN     | 87  | ASTR | D, red giant  |
| < 0.7                               | 30 RAFFELT  | 87  | ASTR | K, red giant  |
| < 2–5                               | TURNER      | 87  | COSM | K, thermal production                                     |
| < 0.01                              | 31 DEARBORN | 86  | ASTR | D, red giant  |
| < 0.06                              | RAFFELT     | 86  | ASTR | D, red giant  |
| < 0.7                               | 32 RAFFELT  | 86  | ASTR | K, red giant  |
| < 0.03                              | RAFFELT     | 86B | ASTR | D, white dwarf  |
| < 1                                 | 33 KAPLAN   | 85  | ASTR | K, red giant  |
| < 0.003–0.02                        | IWAMOTO     | 84  | ASTR | D, K, neutron star  |
| > $1 \times 10^{-5}$                | ABBOTT      | 83  | COSM | D,K, mass density of<br>the universe                      |
| > $1 \times 10^{-5}$                | DINE        | 83  | COSM | D,K, mass density of<br>the universe                      |
| < 0.04                              | ELLIS       | 83B | ASTR | D, red giant  |
| > $1 \times 10^{-5}$                | PRESKILL    | 83  | COSM | D,K, mass density of<br>the universe                      |
| < 0.1                               | BARROSO     | 82  | ASTR | D, red giant  |
| < 1                                 | 34 FUKUGITA | 82  | ASTR | D, stellar cooling  |
| < 0.07                              | FUKUGITA    | 82B | ASTR | D, red giant  |

<sup>1</sup> ARCHIDIACONO 13A is analogous to HANNESTAD 05A. The limit is based on the CMB temperature power spectrum of the Planck data, the CMB polarization from the WMAP 9-yr data, the matter power spectrum from SDSS-DR7, and the local Hubble parameter measurement by the Carnegie Hubble program.

<sup>2</sup> CADAMURO 11 use the deuterium abundance to show that the  $m_{A0}$  range 0.7 eV – 300 keV is excluded for axions, complementing HANNESTAD 10.

<sup>3</sup> DERBIN 11A look for solar axions produced by Compton and bremsstrahlung processes, in the resonant excitation of  $^{169}\text{Tm}$ , constraining the axion-electron  $\times$  axion nucleon couplings.

<sup>4</sup> ANDRIAMONJE 10 search for solar axions produced from  $^7\text{Li}$  (478 keV) and  $\text{D}(p,\gamma)^3\text{He}$  (5.5 MeV) nuclear transitions. They show limits on the axion-photon coupling for two reference values of the axion-nucleon coupling for  $m_A < 100$  eV.

<sup>5</sup> This is an update of HANNESTAD 08 including 7 years of WMAP data.

<sup>6</sup> ANDRIAMONJE 09 look for solar axions produced from the thermally excited 14.4 keV level of  $^{57}\text{Fe}$ . They show limits on the axion-nucleon  $\times$  axion-photon coupling assuming  $m_A < 0.03$  eV.

- <sup>7</sup> DERBIN 09A look for Primakoff-produced solar axions in the resonant excitation of  $^{169}\text{Tm}$ , constraining the axion-photon  $\times$  axion-nucleon couplings.
- <sup>8</sup> KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used.
- <sup>9</sup> This is an update of HANNESTAD 07 including 5 years of WMAP data.
- <sup>10</sup> This is an update of HANNESTAD 05A with new cosmological data, notably WMAP (3 years) and baryon acoustic oscillations (BAO). Lyman- $\alpha$  data are left out, in contrast to HANNESTAD 05A and MELCHIORRI 07A, because it is argued that systematic errors are large. It uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component.
- <sup>11</sup> MELCHIORRI 07A is analogous to HANNESTAD 05A, with updated cosmological data, notably WMAP (3 years). Uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component. Leaving out Lyman- $\alpha$  data, a conservative limit is 1.4 eV.
- <sup>12</sup> HANNESTAD 05A puts an upper limit on the mass of hadronic axion because in this mass range it would have been thermalized and contribute to the hot dark matter component of the universe. The limit is based on the CMB anisotropy from WMAP, SDSS large scale structure, Lyman  $\alpha$ , and the prior Hubble parameter from HST Key Project. A  $\chi^2$  statistic is used. Neutrinos are assumed not to contribute to hot dark matter.
- <sup>13</sup> MOROI 98 points out that a KSVZ axion of this mass range (see CHANG 93) can be a viable hot dark matter of Universe, as long as the model-dependent  $g_{A\gamma}$  is accidentally small enough as originally emphasized by KAPLAN 85; see Fig. 1.
- <sup>14</sup> BORISOV 97 bound is on the axion-electron coupling  $g_{ae} < 1 \times 10^{-13}$  from the photo-production of axions off of magnetic fields in the outer layers of neutron stars.
- <sup>15</sup> KACHELRIESS 97 bound is on the axion-electron coupling  $g_{ae} < 1 \times 10^{-10}$  from the production of axions in strongly magnetized neutron stars. The authors also quote a stronger limit,  $g_{ae} < 9 \times 10^{-13}$  which is strongly dependent on the strength of the magnetic field in white dwarfs.
- <sup>16</sup> KEIL 97 uses new measurements of the axial-vector coupling strength of nucleons, as well as a reanalysis of many-body effects and pion-emission processes in the core of the neutron star, to update limits on the invisible-axion mass.
- <sup>17</sup> RAFFELT 95 reexamined the constraints on axion emission from red giants due to the axion-electron coupling. They improve on DEARBORN 86 by taking into proper account degeneracy effects in the bremsstrahlung rate. The limit comes from requiring the red giant core mass at helium ignition not to exceed its standard value by more than 5% (0.025 solar masses).
- <sup>18</sup> ALTHERR 94 bound is on the axion-electron coupling  $g_{ae} < 1.5 \times 10^{-13}$ , from energy loss via axion emission.
- <sup>19</sup> CHANG 93 updates ENGEL 90 bound with the Kaplan-Manohar ambiguity in  $z=m_u/m_d$  (see the Note on the Quark Masses in the Quark Particle Listings). It leaves the window  $f_A=3 \times 10^5-3 \times 10^6$  GeV open. The constraint from Big-Bang Nucleosynthesis is satisfied in this window as well.
- <sup>20</sup> BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from  $2\gamma$  decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.
- <sup>21</sup> KIM 91C argues that the bound from the mass density of the universe will change drastically for the supersymmetric models due to the entropy production of saxion (scalar component in the axionic chiral multiplet) decay. Note that it is an *upperbound* rather than a lowerbound.
- <sup>22</sup> RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.
- <sup>23</sup> RESSELL 91 uses absence of any intracluster line emission to set limit.
- <sup>24</sup> ENGEL 90 rule out  $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$ , which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to  $2.5 \times 10^{-3} \text{ eV} \lesssim m_{A0} \lesssim 2.5 \times 10^4 \text{ eV}$ . The constraint is loose in the middle of the range, i.e. for  $g_{AN} \sim 10^{-6}$ .
- <sup>25</sup> RAFFELT 90D is a re-analysis of DEARBORN 86.

- <sup>26</sup> The region  $m_{A^0} \gtrsim 2$  eV is also allowed.
- <sup>27</sup> ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.
- <sup>28</sup> MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.
- <sup>29</sup> RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars  $\epsilon < 100 \text{ erg g}^{-1} \text{ s}^{-1}$ , which gives a firmer basis for the axion limits based on red giant cooling.
- <sup>30</sup> RAFFELT 87 also gives a limit  $g_{A\gamma} < 1 \times 10^{-10} \text{ GeV}^{-1}$ .
- <sup>31</sup> DEARBORN 86 also gives a limit  $g_{A\gamma} < 1.4 \times 10^{-11} \text{ GeV}^{-1}$ .
- <sup>32</sup> RAFFELT 86 gives a limit  $g_{A\gamma} < 1.1 \times 10^{-10} \text{ GeV}^{-1}$  from red giants and  $< 2.4 \times 10^{-9} \text{ GeV}^{-1}$  from the sun.
- <sup>33</sup> KAPLAN 85 says  $m_{A^0} < 23$  eV is allowed for a special choice of model parameters.
- <sup>34</sup> FUKUGITA 82 gives a limit  $g_{A\gamma} < 2.3 \times 10^{-10} \text{ GeV}^{-1}$ .

### Search for Relic Invisible Axions

Limits are for  $[G_{A\gamma\gamma}/m_{A^0}]^2 \rho_A$  where  $G_{A\gamma\gamma}$  denotes the axion two-photon coupling,

$$L_{\text{int}} = -\frac{G_{A\gamma\gamma}}{4} \phi_A F_{\mu\nu} \tilde{F}^{\mu\nu} = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}, \text{ and } \rho_A \text{ is the axion energy density near the earth.}$$

| VALUE | CL% | DOCUMENT ID | TECN | COMMENT |
|-------|-----|-------------|------|---------|
|-------|-----|-------------|------|---------|

• • • We do not use the following data for averages, fits, limits, etc. • • •

|                         |      |                       |    |      |   |
|-------------------------|------|-----------------------|----|------|---|
|                         |      | <sup>1</sup> BRANCA   | 17 | AURG | $m_{S^0} = 3.5\text{--}3.9 \text{ peV}$   |
| $< 3 \times 10^{-42}$   | 90   | <sup>2</sup> BRUBAKER | 17 |      | $m_{A^0} = 23.55\text{--}24.0 \text{ } \mu\text{eV}$                              |
| $< 1.0 \times 10^{-29}$ | 95   | <sup>3</sup> CHOI     | 17 |      | $m_{A^0} = 24.7\text{--}29.1 \text{ } \mu\text{eV}$                               |
| $< 8.6 \times 10^{-42}$ | 90   | <sup>4</sup> HOSKINS  | 16 | ADMX | $m_{A^0} = 3.36\text{--}3.52 \text{ or } 3.55\text{--}3.69 \text{ } \mu\text{eV}$ |
|                         |      | <sup>5</sup> BECK     | 13 |      | $m_{A^0} = 0.11 \text{ meV}$  |
| $< 3.5 \times 10^{-43}$ |      | <sup>6</sup> HOSKINS  | 11 | ADMX | $m_{A^0} = 3.3\text{--}3.69 \times 10^{-6} \text{ eV}$                            |
| $< 2.9 \times 10^{-43}$ | 90   | <sup>7</sup> ASZTALOS | 10 | ADMX | $m_{A^0} = 3.34\text{--}3.53 \times 10^{-6} \text{ eV}$                           |
| $< 1.9 \times 10^{-43}$ | 97.7 | <sup>8</sup> DUFFY    | 06 | ADMX | $m_{A^0} = 1.98\text{--}2.17 \times 10^{-6} \text{ eV}$                           |
| $< 5.5 \times 10^{-43}$ | 90   | <sup>9</sup> ASZTALOS | 04 | ADMX | $m_{A^0} = 1.9\text{--}3.3 \times 10^{-6} \text{ eV}$                             |
|                         |      | <sup>10</sup> KIM     | 98 | THEO |   |
| $< 2 \times 10^{-41}$   |      | <sup>11</sup> HAGMANN | 90 | CNTR | $m_{A^0} = (5.4\text{--}5.9)10^{-6} \text{ eV}$                                   |
| $< 6.3 \times 10^{-42}$ | 95   | <sup>12</sup> WUENSCH | 89 | CNTR | $m_{A^0} = (4.5\text{--}10.2)10^{-6} \text{ eV}$                                  |
| $< 5.4 \times 10^{-41}$ | 95   | <sup>12</sup> WUENSCH | 89 | CNTR | $m_{A^0} = (11.3\text{--}16.3)10^{-6} \text{ eV}$                                 |

<sup>1</sup> BRANCA 17 look for modulations of the fine-structure constant and the electron mass due to moduli dark matter by using the cryogenic resonant-mass AURIGA detector. The limit on the assumed dilatonic coupling implies  $G_{S\gamma\gamma} < 1.5 \times 10^{-24} \text{ GeV}^{-1}$  for the scalar to two-photon coupling. See Fig. 5 for the mass-dependent limits.

<sup>2</sup> BRUBAKER 17 used a microwave cavity detector at the Yale Wright Laboratory to search for dark matter axions. See Fig. 3 for the mass-dependent limits.

<sup>3</sup> CHOI 17 used a microwave cavity detector with toroidal geometry. See Fig. 4 for their mass-dependent limits.

<sup>4</sup> HOSKINS 16 is analogous to DUFFY 06. See Fig. 12 for mass-dependent limits in terms of the local dark matter density.

- <sup>5</sup> BECK 13 argues that dark-matter axions passing through Earth may generate a small observable signal in resonant S/N/S Josephson junctions. A measurement by HOFFMANN 04 [Physical Review **B70** 180503 (2004)] is interpreted in terms of subdominant dark matter axions with  $m_{A^0} = 0.11$  meV.
- <sup>6</sup> HOSKINS 11 is analogous to DUFFY 06. See Fig. 4 for the mass-dependent limit in terms of the local density.
- <sup>7</sup> ASZTALOS 10 used the upgraded detector of ASZTALOS 04 to search for halo axions. See their Fig. 5 for the  $m_{A^0}$  dependence of the limit.
- <sup>8</sup> DUFFY 06 used the upgraded detector of ASZTALOS 04, while assuming a smaller velocity dispersion than the isothermal model as in Eq. (8) of their paper. See Fig. 10 of their paper on the axion mass dependence of the limit.
- <sup>9</sup> ASZTALOS 04 looked for a conversion of halo axions to microwave photons in magnetic field. At 90% CL, the KSVZ axion cannot have a local halo density more than  $0.45 \text{ GeV/cm}^3$  in the quoted mass range. See Fig. 7 of their paper on the axion mass dependence of the limit.
- <sup>10</sup> KIM 98 calculated the axion-to-photon couplings for various axion models and compared them to the HAGMANN 90 bounds. This analysis demonstrates a strong model dependence of  $G_{A\gamma\gamma}$  and hence the bound from relic axion search.
- <sup>11</sup> HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.
- <sup>12</sup> WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagnetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with  $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14} \text{ MeV}^{-4}$  (the three generation DFSZ model) and  $\rho_A = 300 \text{ MeV/cm}^3$  that makes up galactic halos gives  $(G_{A\gamma\gamma}/m_{A^0})^2 \rho_A = 4 \times 10^{-44}$ . Note that our definition of  $G_{A\gamma\gamma}$  is  $(1/4\pi)$  smaller than that of WUENSCH 89.

### Invisible $A^0$ (Axion) Limits from Photon Coupling

Limits are for the modulus of the axion-two-photon coupling  $G_{A\gamma\gamma}$  defined by  $L = -G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$ . For scalars  $S^0$  the limit is on the coupling constant in  $L = G_{S\gamma\gamma} \phi_S (\mathbf{E}^2 - \mathbf{B}^2)$ . The relation between  $G_{A\gamma\gamma}$  and  $m_{A^0}$  is not used unless stated otherwise, i.e., many of these bounds apply to low-mass axion-like particles (ALPs), not to QCD axions.

| VALUE ( $\text{GeV}^{-1}$ )   | CL% | DOCUMENT ID        | TECN | COMMENT                                 |
|---|-----|--------------------|------|---|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                    |      |   |
| $<6.6 \times 10^{-11}$  | 95  | 1 ADE 17           | CMB  | Axion-like particles                    |
|   |     | 2 ANASTASSO... 17  | CAST | $m_{A^0} < 0.02 \text{ eV}$             |
|   |     | 3 DOLAN 17         | RVUE | Axion-like particles                    |
| $<2.51 \times 10^{-4}$  | 95  | 4 INADA 17         | LSW  | $m_{A^0} < 0.1 \text{ eV}$              |
| $>1.5 \times 10^{-11}$  | 95  | 5 KOHRI 17         | ASTR | $m_{A^0} = 0.7\text{--}50 \text{ neV}$  |
| $<2.6 \times 10^{-12}$  | 95  | 6 MARSH 17         | ASTR | $m_{A^0} \leq 10^{-13} \text{ eV}$      |
| $<6 \times 10^{-13}$  |     | 7 TIWARI 17        | COSM | $m_{A^0} \leq 10^{-15} \text{ eV}$      |
| $<5 \times 10^{-12}$  | 95  | 8 AJELLO 16        | ASTR | $m_{A^0} = 0.5\text{--}5 \text{ neV}$   |
| $<1.2 \times 10^{-7}$   | 95  | 9 DELLA-VALLE 16   | LASR | $m_{A^0} = 1.3 \text{ meV}$             |
| $<7.2 \times 10^{-8}$   | 95  | 10 DELLA-VALLE 16  | LASR | $m_{A^0} < 0.5 \text{ meV}$             |
| $<8 \times 10^{-4}$   |     | 11 JAECKEL 16      | ALPS | $m_{A^0} = 0.1\text{--}100 \text{ GeV}$ |
| $<6 \times 10^{-21}$  |     | 12 LEEFER 16       |      | $m_{S^0} < 10^{-18} \text{ eV}$         |
|   |     | 13 ANASTASSO... 15 | CAST | Chameleons                              |

|                                     |      |    |               |     |      |   |
|-------------------------------------|------|----|---------------|-----|------|---|
| $<1.47 \times 10^{-10}$             | 95   | 14 | ARIK          | 15  | CAST | $m_{A^0} = 0.39\text{--}0.42$ eV            |
| $<3.5 \times 10^{-8}$               | 95   | 15 | BALLOU        | 15  | LSW  | $m_{A^0} < 2 \times 10^{-4}$ eV             |
|                                     |      | 16 | BRAX          | 15  | ASTR | $m_{S^0} < 4 \times 10^{-12}$ eV            |
| $<5.42 \times 10^{-4}$              | 95   | 17 | HASEBE        | 15  | LASR | $m_{A^0} = 0.15$ eV                         |
|                                     |      | 18 | MILLEA        | 15  | COSM | Axion-like particles                        |
|                                     |      | 19 | VANTILBURG    | 15  |      | Dilaton-like dark matter                    |
| $<4.1 \times 10^{-10}$              | 99.7 | 20 | VINYOLES      | 15  | ASTR | $m_{A^0} = 0.6\text{--}185$ eV              |
| $<3.3 \times 10^{-10}$              | 95   | 21 | ARIK          | 14  | CAST | $m_{A^0} = 0.64\text{--}1.17$ eV            |
| $<6.6 \times 10^{-11}$              | 95   | 22 | AYALA         | 14  | ASTR | Globular clusters                           |
| $<1.4 \times 10^{-7}$               | 95   | 23 | DELLA-VALLE   | 14  | LASR | $m_{A^0} = 1$ meV                           |
|                                     |      | 24 | EJLLI         | 14  | COSM | $m_{A^0} = 2.66\text{--}48.8$ $\mu$ eV      |
| $<8 \times 10^{-8}$                 | 95   | 25 | PUGNAT        | 14  | LSW  | $m_{A^0} < 0.3$ meV                         |
| $<1 \times 10^{-11}$                |      | 26 | REESMAN       | 14  | ASTR | $m_{A^0} < 1 \times 10^{-10}$ eV            |
| $<2.1 \times 10^{-11}$              | 95   | 27 | ABRAMOWSKI13A | 13A | IACT | $m_{A^0} = 15\text{--}60$ neV               |
| $<2.15 \times 10^{-9}$              | 95   | 28 | ARMENGAUD     | 13  | EDEL | $m_{A^0} < 200$ eV                          |
| $<4.5 \times 10^{-8}$               | 95   | 29 | BETZ          | 13  | LSW  | $m_{A^0} = 7.2 \times 10^{-6}$ eV           |
| $<8 \times 10^{-11}$                |      | 30 | FRIEDLAND     | 13  | ASTR | Red giants                                  |
| $>2 \times 10^{-11}$                |      | 31 | MEYER         | 13  | ASTR | $m_{A^0} < 1 \times 10^{-7}$ eV             |
| $<8.3 \times 10^{-12}$              | 95   | 32 | WOUTERS       | 13  | ASTR | $m_{A^0} < 7 \times 10^{-12}$ eV            |
|                                     |      | 33 | CADAMURO      | 12  | COSM | Axion-like particles                        |
| $<2.5 \times 10^{-13}$              | 95   | 34 | PAYEZ         | 12  | ASTR | $m_{A^0} < 4.2 \times 10^{-14}$ eV          |
| $<2.3 \times 10^{-10}$              | 95   | 35 | ARIK          | 11  | CAST | $m_{A^0} = 0.39\text{--}0.64$ eV            |
| $<6.5 \times 10^{-8}$               | 95   | 36 | EHRET         | 10  | ALPS | $m_{A^0} < 0.7$ meV                         |
| $<2.4 \times 10^{-9}$               | 95   | 37 | AHMED         | 09A | CDMS | $m_{A^0} < 100$ eV                          |
| $<1.2\text{--}2.8 \times 10^{-10}$  | 95   | 38 | ARIK          | 09  | CAST | $m_{A^0} = 0.02\text{--}0.39$ eV            |
|                                     |      | 39 | CHOU          | 09  |      | Chameleons                                  |
| $<7 \times 10^{-10}$                |      | 40 | GONDOLO       | 09  | ASTR | $m_{A^0} < \text{few keV}$                  |
| $<1.3 \times 10^{-6}$               | 95   | 41 | AFANASEV      | 08  |      | $m_{S^0} < 1$ meV                           |
| $<3.5 \times 10^{-7}$               | 99.7 | 42 | CHOU          | 08  |      | $m_{A^0} < 0.5$ meV                         |
| $<1.1 \times 10^{-6}$               | 99.7 | 43 | FOUCHE        | 08  |      | $m_{A^0} < 1$ meV                           |
| $<5.6\text{--}13.4 \times 10^{-10}$ | 95   | 44 | INOUE         | 08  |      | $m_{A^0} = 0.84\text{--}1.00$ eV            |
| $<5 \times 10^{-7}$                 |      | 45 | ZAVATTINI     | 08  |      | $m_{A^0} < 1$ meV                           |
| $<8.8 \times 10^{-11}$              | 95   | 46 | ANDRIAMON..07 | 07  | CAST | $m_{A^0} < 0.02$ eV                         |
| $<1.25 \times 10^{-6}$              | 95   | 47 | ROBILLIARD    | 07  |      | $m_{A^0} < 1$ meV                           |
| $2\text{--}5 \times 10^{-6}$        |      | 48 | ZAVATTINI     | 06  |      | $m_{A^0} = 1\text{--}1.5$ meV               |
| $<1.1 \times 10^{-9}$               | 95   | 49 | INOUE         | 02  |      | $m_{A^0} = 0.05\text{--}0.27$ eV            |
| $<2.78 \times 10^{-9}$              | 95   | 50 | MORALES       | 02B |      | $m_{A^0} < 1$ keV                           |
| $<1.7 \times 10^{-9}$               | 90   | 51 | BERNABEI      | 01B |      | $m_{A^0} < 100$ eV                          |
| $<1.5 \times 10^{-4}$               | 90   | 52 | ASTIER        | 00B | NOMD | $m_{A^0} < 40$ eV                           |
|                                     |      | 53 | MASSO         | 00  | THEO | induced $\gamma$ coupling                   |
| $<2.7 \times 10^{-9}$               | 95   | 54 | AVIGNONE      | 98  | SLAX | $m_{A^0} < 1$ keV                           |
| $<6.0 \times 10^{-10}$              | 95   | 55 | MORIYAMA      | 98  |      | $m_{A^0} < 0.03$ eV                         |
| $<3.6 \times 10^{-7}$               | 95   | 56 | CAMERON       | 93  |      | $m_{A^0} < 10^{-3}$ eV,<br>optical rotation |



|                       |      |                |    |  |
|-----------------------|------|----------------|----|--|
| $<6.7 \times 10^{-7}$ | 95   | 57 CAMERON     | 93 | $m_{A^0} < 10^{-3}$ eV,<br>photon regeneration |
| $<3.6 \times 10^{-9}$ | 99.7 | 58 LAZARUS     | 92 | $m_{A^0} < 0.03$ eV                            |
| $<7.7 \times 10^{-9}$ | 99.7 | 58 LAZARUS     | 92 | $m_{A^0} = 0.03\text{--}0.11$ eV               |
| $<7.7 \times 10^{-7}$ | 99   | 59 RUOSO       | 92 | $m_{A^0} < 10^{-3}$ eV                         |
| $<2.5 \times 10^{-6}$ |      | 60 SEMERTZIDIS | 90 | $m_{A^0} < 7 \times 10^{-4}$ eV                |

- <sup>1</sup>ADE 17 look for cosmic birefringence from axion-like particles using CMB polarization data taken by the BICEP2 and Keck Array experiments. They set a limit  $G_{A\gamma\gamma}H_I < 7.2 \times 10^{-2}$  at 95 %CL for  $m_{A^0} < 10^{-28}$  eV, where  $H_I$  is the Hubble parameter during inflation.
- <sup>2</sup>ANASTASSOPOULOS 17 looked for solar axions by the CAST axion helioscope in the vacuum phase, and supersedes ANDRIAMONJE 07.
- <sup>3</sup>DOLAN 17 update existing limits on  $G_{A\gamma\gamma}$  for axion-like particles. See their Fig. 2 for mass-dependent limits.
- <sup>4</sup>INADA 17 search for axions with an x-ray LSW at Spring-8. See their Fig. 4 for mass-dependent limits.
- <sup>5</sup>KOHRI 17 attributed to axion-photon oscillations the excess of cosmic infrared background observed by the CIBER experiment. See their Fig. 5 for the region preferred by their scenario.
- <sup>6</sup>MARSH 17 is similar to WOUTERS 13, using Chandra observations of M87. See their Fig. 6 for mass-dependent limits.
- <sup>7</sup>TIWARI 17 use observed limits of the cosmic distance-duality relation to constrain the photon-ALP mixing based on 3D simulations of the magnetic field configuration. The quoted value is for the averaged magnetic field of 1nG with a coherent length of 1 Mpc. See their Fig. 5 for mass-dependent limits.
- <sup>8</sup>AJELLO 16 look for irregularities in the energy spectrum of the NGC1275 measured by Fermi LAT, assuming photon-ALP mixing in the intra-cluster and Galactic magnetic fields. See their Fig. 2 for mass-dependent limits.
- <sup>9</sup>DELLA-VALLE 16 look for the birefringence induced by axion-like particles. See their Fig. 14 for mass-dependent limits.
- <sup>10</sup>DELLA-VALLE 16 look for the dichroism induced by axion-like particles. See their Fig. 14 for mass-dependent limits.
- <sup>11</sup>JAECKEL 16 use the LEP data of  $Z \rightarrow 2\gamma$  and  $Z \rightarrow 3\gamma$  to constrain the ALP production via  $e^+e^- \rightarrow Z \rightarrow A^0\gamma (A^0 \rightarrow \gamma\gamma)$ , assuming the ALP coupling with two hypercharge bosons. See their Fig. 4 for mass-dependent limits.
- <sup>12</sup>LEEFER 16 derived limits by using radio-frequency spectroscopy of dysprosium and atomic clock measurements. See their Fig. 1 for mass-dependent limits as well as limits on Yukawa-type couplings of the scalar to the electron and nucleons.
- <sup>13</sup>ANASTASSOPOULOS 15 search for solar chameleons with CAST and derived limits on the chameleon coupling to photons and matter. See their Fig. 12 for the exclusion region.
- <sup>14</sup>ARIK 15 is analogous to ARIK 09, and search for solar axions for  $m_{A^0}$  around 0.2 and 0.4 eV. See their Figs. 1 and 3 for the mass-dependent limits.
- <sup>15</sup>Based on OSQAR photon regeneration experiment. See their Fig. 6 for mass-dependent limits on scalar and pseudoscalar bosons.
- <sup>16</sup>BRAX 15 derived limits on conformal and disformal couplings of a scalar to photons by searching for a chaotic absorption pattern in the X-ray and UV bands of the Hydra A galaxy cluster and a BL lac object, respectively. See their Fig. 8.
- <sup>17</sup>HASEBE 15 look for an axion via a four-wave mixing process at quasi-parallel colliding laser beams. They also derived limits on a scalar coupling to photons  $G_{S\gamma\gamma} < 2.62 \times 10^{-4}$  GeV<sup>-1</sup> at  $m_{S^0} = 0.15$  eV. See their Figs. 11 and 12 for mass-dependent limits.

- 18 MILLEA 15 is similar to CADAMURO 12, including the Planck data and the latest inferences of primordial deuterium abundance. See their Fig. 3 for mass-dependent limits.
- 19 VANTILBURG 15 look for harmonic variations in the dysprosium transition frequency data, induced by coherent oscillations of the fine-structure constant due to dilaton-like dark matter, and set the limits,  $G_{S\gamma\gamma} < 6 \times 10^{-27} \text{ GeV}^{-1}$  at  $m_{S^0} = 6 \times 10^{-23} \text{ eV}$ . See their Fig. 4 for mass-dependent limits between  $1 \times 10^{-24} < m_{S^0} < 1 \times 10^{-15} \text{ eV}$ .
- 20 VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations. See their Fig. 9.
- 21 ARIK 14 is similar to ARIK 11. See their Fig. 2 for mass-dependent limits.
- 22 AYALA 14 derived the limit from the helium-burning lifetime of horizontal-branch stars based on number counts in globular clusters.
- 23 DELLA-VALLE 14 use the new PVLAS apparatus to set a limit on vacuum magnetic birefringence induced by axion-like particles. See their Fig. 6 for the mass-dependent limits.
- 24 EJLLI 14 set limits on a product of primordial magnetic field and the axion mass using CMB distortion induced by resonant axion production from CMB photons. See their Fig. 1 for limits applying specifically to the DFSZ and KSVZ axion models.
- 25 PUGNAT 14 is analogous to EHRET 10. See their Fig. 5 for mass-dependent limits on scalar and pseudoscalar bosons.
- 26 REESMAN 14 derive limits by requiring effects of axion-photon interconversion on gamma-ray spectra from distant blazars to be no larger than errors in the best-fit optical depth based on a certain extragalactic background light model. See their Fig. 5 for mass-dependent limits.
- 27 ABRAMOWSKI 13A look for irregularities in the energy spectrum of the BL Lac object PKS 2155–304 measured by H.E.S.S. The limits depend on assumed magnetic field around the source. See their Fig. 7 for mass-dependent limits.
- 28 ARMENGAUD 13 is analogous to AVIGNONE 98. See Fig. 6 for the limit.
- 29 BETZ 13 performed a microwave-based light shining through the wall experiment. See their Fig. 13 for mass-dependent limits.
- 30 FRIEDLAND 13 derived the limit by considering blue-loop suppression of the evolution of red giants with 7–12 solar masses.
- 31 MEYER 13 attributed to axion-photon oscillations the observed excess of very high-energy  $\gamma$ -rays with respect to predictions based on extragalactic background light models. See their Fig. 4 for mass-dependent lower limits for various magnetic field configurations.
- 32 WOUTERS 13 look for irregularities in the X-ray spectrum of the Hydra cluster observed by Chandra. See their Fig. 4 for mass-dependent limits.
- 33 CADAMURO 12 derived cosmological limits on  $G_{A\gamma\gamma}$  for axion-like particles. See their Fig. 1 for mass-dependent limits.
- 34 PAYEZ 12 derive limits from polarization measurements of quasar light (see their Fig. 3). The limits depend on assumed magnetic field strength in galaxy clusters. The limits depend on assumed magnetic field and electron density in the local galaxy supercluster.
- 35 ARIK 11 search for solar axions using  $^3\text{He}$  buffer gas in CAST, continuing from the  $^4\text{He}$  version of ARIK 09. See Fig. 2 for the exact mass-dependent limits.
- 36 ALPS is a photon regeneration experiment. See their Fig. 4 for mass-dependent limits on scalar and pseudoscalar bosons.
- 37 AHMED 09A is analogous to AVIGNONE 98.
- 38 ARIK 09 is the  $^4\text{He}$  filling version of the CAST axion helioscope in analogy to INOUE 02 and INOUE 08. See their Fig. 7 for mass-dependent limits.
- 39 CHOU 09 use the GammeV apparatus in the afterglow mode to search for chameleons, (pseudo)scalar bosons with a mass depending on the environment. For pseudoscalars they exclude at  $3\sigma$  the range  $2.6 \times 10^{-7} \text{ GeV}^{-1} < G_{A\gamma\gamma} < 4.2 \times 10^{-6} \text{ GeV}^{-1}$  for vacuum  $m_{A^0}$  roughly below 6 meV for density scaling index exceeding 0.8.

- 40 GONDOLO 09 use the all-flavor measured solar neutrino flux to constrain solar interior temperature and thus energy losses.
- 41 LIPSS photon regeneration experiment, assuming scalar particle  $S^0$ . See Fig. 4 for mass-dependent limits.
- 42 CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 3 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06.
- 43 FOUICHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits.
- 44 INOUE 08 is an extension of INOUE 02 to larger axion masses, using the Tokyo axion helioscope. See their Fig. 4 for mass-dependent limits.
- 45 ZAVATTINI 08 is an upgrade of ZAVATTINI 06, see their Fig. 8 for mass-dependent limits. They now exclude the parameter range where ZAVATTINI 06 had seen a positive signature.
- 46 ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. Supersedes ZIOUTAS 05.
- 47 ROBILLIARD 07 perform a photon regeneration experiment with a pulsed laser and pulsed magnetic field. See their Fig. 4 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06 with a CL exceeding 99.9%.
- 48 ZAVATTINI 06 propagate a laser beam in a magnetic field and observe dichroism and birefringence effects that could be attributed to an axion-like particle. This result is now excluded by ROBILLIARD 07, ZAVATTINI 08, and CHOU 08.
- 49 INOUE 02 looked for Primakoff conversion of solar axions in 4T superconducting magnet into X ray.
- 50 MORALES 02B looked for the coherent conversion of solar axions to photons via the Primakoff effect in Germanium detector.
- 51 BERNABEI 01B looked for Primakoff coherent conversion of solar axions into photons via Bragg scattering in NaI crystal in DAMA dark matter detector.
- 52 ASTIER 00B looked for production of axions from the interaction of high-energy photons with the horn magnetic field and their subsequent re-conversion to photons via the interaction with the NOMAD dipole magnetic field.
- 53 MASSO 00 studied limits on axion-proton coupling using the induced axion-photon coupling through the proton loop and CAMERON 93 bound on the axion-photon coupling using optical rotation. They obtained the bound  $g_p^2/4\pi < 1.7 \times 10^{-9}$  for the coupling  $g_p \bar{p} \gamma_5 p \phi_A$ .
- 54 AVIGNONE 98 result is based on the coherent conversion of solar axions to photons via the Primakoff effect in a single crystal germanium detector.
- 55 Based on the conversion of solar axions to X-rays in a strong laboratory magnetic field.
- 56 Experiment based on proposal by MAIANI 86.
- 57 Experiment based on proposal by VANBIBBER 87.
- 58 LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.
- 59 RUOSO 92 experiment is based on the proposal by VANBIBBER 87.
- 60 SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to  $m_{A^0} = 4 \times 10^{-3}$  where  $G_{A\gamma\gamma} < 1 \times 10^{-4} \text{ GeV}^{-1}$ .
-

### Limit on Invisible $A^0$ (Axion) Electron Coupling

The limit is for  $g_{Aee} \phi_A \bar{e}(i\gamma_5)e$ , or equivalently, the dipole-dipole potential

$-\frac{g_{Aee}^2}{16\pi m_e^2} ((\sigma_1 \cdot \sigma_2) - 3(\sigma_1 \cdot \mathbf{n})(\sigma_2 \cdot \mathbf{n}))/r^3$  where  $\mathbf{n}=\mathbf{r}/r$  and the sign of the potential was corrected based on DAIDO 17.

| VALUE   | CL% | DOCUMENT ID      | TECN     | COMMENT                     |
|---|-----|------------------|----------|-----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                  |          |                             |
| $<4.5 \times 10^{-13}$  | 90  | 1 ABGRALL        | 17 HPGE  | $m_{A^0} = 11.8$ keV        |
| $<3.5 \times 10^{-12}$  | 90  | 2 AKERIB         | 17B LUX  | Solar axions                |
| $<4.2 \times 10^{-13}$  | 90  | 3 AKERIB         | 17B LUX  | $m_{A^0} = 1-16$ keV        |
| $<2.3 \times 10^{-13}$  | 90  | 4 APRILE         | 17B X100 | $m_{A^0} = 6$ keV           |
| $<4 \times 10^{-4}$   | 90  | 5 FICEK          | 17       | $m_{A^0} < 1$ keV           |
| $<4.35 \times 10^{-12}$   | 90  | 6 FU             | 17A PNDX | Solar axions                |
| $<4.3 \times 10^{-14}$  | 90  | 7 FU             | 17A PNDX | $m_{A^0} = 2$ keV           |
| $<5 \times 10^{-13}$  | 90  | 8 LIU            | 17A CDEX | $m_{A^0} = 13$ keV          |
| $<2.5 \times 10^{-11}$  | 90  | 9 LIU            | 17A CDEX | Solar axions                |
| $<0.15$   | 95  | 10 LUO           | 17       | $m_{A^0} = 300$ eV          |
| $<3.3 \times 10^{-13}$  | 68  | 11 BATTICH       | 16 ASTR  | White dwarf cooling         |
| $<7 \times 10^{-13}$  |     | 12 CORSICO       | 16 ASTR  | White dwarf cooling         |
| $<1.39 \times 10^{-11}$   | 90  | 13 YOON          | 16 KIMS  | Solar axions                |
| $<7.4 \times 10^{-9}$   | 95  | 14 TERRANO       | 15       | $m_{A^0} < 30$ $\mu$ eV     |
| $<8 \times 10^{-13}$  | 90  | 15 ABE           | 14F XMAS | $m_{A^0} = 60$ keV          |
| $<7.7 \times 10^{-12}$  | 90  | 16 APRILE        | 14B X100 | Solar axions                |
|   |     | 17 APRILE        | 14B X100 | $m_{A^0} = 5-7$ keV         |
| $< 0.96-8.2 \times 10^{-8}$   | 90  | 18 DERBIN        | 14 CNTR  | $m_{A^0} = 0.1-1$ MeV       |
| $<2.8 \times 10^{-13}$  | 99  | 19 MILLER-BER... | 14 ASTR  | White dwarf cooling         |
| $<5.4 \times 10^{-11}$  | 90  | 20 ABE           | 13D XMAS | Solar axions                |
| $<1.07 \times 10^{-12}$   | 90  | 21 ARMENGAUD     | 13 EDEL  | $m_{A^0} = 12.5$ keV        |
| $<2.59 \times 10^{-11}$   | 90  | 22 ARMENGAUD     | 13 EDEL  | Solar axions                |
|   |     | 23 BARTH         | 13 CAST  | Solar axions                |
| $< 1.4-9.7 \times 10^{-7}$  | 90  | 24 DERBIN        | 13 CNTR  | $m_{A^0} = 0.1-1$ MeV       |
| $<1.5 \times 10^{-8}$   | 68  | 25 HECKEL        | 13       | $m_{A^0} \leq 0.1$ $\mu$ eV |
| $<4.3 \times 10^{-13}$  | 95  | 26 VIAUX         | 13A ASTR | Low-mass red giants         |
| $<7 \times 10^{-13}$  | 95  | 27 CORSICO       | 12 ASTR  | White dwarf cooling         |
| $<2.2 \times 10^{-10}$  | 90  | 28 DERBIN        | 12 CNTR  | Solar axions                |
| $< 0.02-1 \times 10^{-10}$  | 90  | 29 AALSETH       | 11 CNTR  | $m_{A^0} = 0.3-8$ keV       |
| $<1.4 \times 10^{-12}$  | 90  | 30 AHMED         | 09A CDMS | $m_{A^0} = 2.5$ keV         |
| $<4 \times 10^{-9}$   |     | 31 DAVOUDIASL    | 09 ASTR  | Earth cooling               |
| $<2.7 \times 10^{-8}$   | 66  | 32 NI            | 94       | Induced magnetism           |
|   |     | 32 CHUI          | 93       | Induced magnetism           |
| $<3.6 \times 10^{-7}$   | 66  | 33 PAN           | 92       | Torsion pendulum            |
| $<2.9 \times 10^{-8}$   | 95  | 32 BOBRAKOV      | 91       | Induced magnetism           |
| $<1.9 \times 10^{-6}$   | 66  | 34 WINELAND      | 91 NMR   |                             |
| $<7 \times 10^{-7}$   | 66  | 33 RITTER        | 90       | Torsion pendulum            |
| $<6.6 \times 10^{-8}$   | 95  | 32 VOROBYOV      | 88       | Induced magnetism           |

- <sup>1</sup> ABGRALL 17 is analogous to AHMED 09A using the MAJORANA DEMONSTRATOR. See their Fig. 2 for limits between  $6 \text{ keV} < m_{A^0} < 97 \text{ keV}$ .
- <sup>2</sup> AKERIB 17B is analogous to LIU 17A.
- <sup>3</sup> AKERIB 17B is analogous to AHMED 09A. See their Fig. 7 for mass-dependent limits.
- <sup>4</sup> APRILE 17B is analogous to AHMED 09A. They found a bug in their code and needed to correct the limits in Fig. 7 of APRILE 14B. See their Fig. 1 for the corrected limits between  $1 \text{ keV} < m_{A^0} < 40 \text{ keV}$ .
- <sup>5</sup> FICEK 17 look for spin-dependent interactions between electrons by comparing precision spectroscopic measurements in  $^4\text{He}$  with theoretical calculations. See their Fig. 1 for limits up to  $m_{A^0} = 10 \text{ keV}$ .
- <sup>6</sup> FU 17A is analogous to LIU 17A. See their Fig. 3 for mass-dependent limits.
- <sup>7</sup> FU 17A is analogous to AHMED 09A. See their Fig. 4 for mass-dependent limits.
- <sup>8</sup> LIU 17A is analogous to AHMED 09A. See their Fig. 9 for limits between  $0.25 \text{ keV} < m_{A^0} < 20 \text{ keV}$ .
- <sup>9</sup> LIU 17A look for solar axions produced from Compton, bremsstrahlung, atomic-recombination and deexcitation channels, and set a limit for  $m_{A^0} < 1 \text{ keV}$ .
- <sup>10</sup> LUO 17 use a recent measurement of the dipole-dipole interaction between two iron atoms at the nanometer scale and set a limit for  $m_{A^0} < 1 \text{ keV}$ . See their Fig. 3 for mass-dependent limits.
- <sup>11</sup> BATTICH 16 is analogous to CORSICO 16 and used the pulsating DB white dwarf PG 1351+489.
- <sup>12</sup> CORSICO 16 studied the cooling rate of the pulsating DA white dwarf L19-2 based on an asteroseismic model.
- <sup>13</sup> YOON 16 look for solar axions with the axio-electric effect in CsI(Tl) crystals and set a limit for  $m_{A^0} < 1 \text{ keV}$ .
- <sup>14</sup> TERRANO 15 used a torsion pendulum and rotating attractor with 20-pole electron-spin distributions. See their Fig. 4 for a mass-dependent limit up to  $m_{A^0} = 500 \mu\text{eV}$ .
- <sup>15</sup> ABE 14F set limits on the axioelectric effect in the XMASS detector assuming the pseudoscalar constitutes all the local dark matter. See their Fig. 3 for limits between  $m_{A^0} = 40\text{--}120 \text{ keV}$ .
- <sup>16</sup> APRILE 14B look for solar axions using the XENON100 detector.
- <sup>17</sup> APRILE 14B is analogous to AHMED 09A. Their Fig. 7 was later found to be incorrect due to a bug in their code. See Fig. 1 in APRILE 17B for the corrected limits.
- <sup>18</sup> DERBIN 14 is an update of DERBIN 13 with a BGO scintillating bolometer. See their Fig. 3 for mass-dependent limits.
- <sup>19</sup> MILLER-BERTOLAMI 14 studied the impact of axion emission on white dwarf cooling in a self-consistent way.
- <sup>20</sup> ABE 13D is analogous to DERBIN 12, using the XMASS detector.
- <sup>21</sup> ARMENGAUD 13 is similar to AALSETH 11. See their Fig. 10 for limits between  $3 \text{ keV} < m_{A^0} < 100 \text{ keV}$ .
- <sup>22</sup> ARMENGAUD 13 is similar to DERBIN 12, and take account of axio-recombination and axio-deexcitation effects. See their Fig. 12 for mass-dependent limits.
- <sup>23</sup> BARTH 13 search for solar axions produced by axion-electron coupling, and obtained the limit,  $g_{Aee} \cdot G_{A\gamma\gamma} < 8.1 \times 10^{-23} \text{ GeV}^{-1}$  at 95%CL.
- <sup>24</sup> DERBIN 13 looked for 5.5 MeV solar axions produced in  $pd \rightarrow ^3\text{He } A^0$  in a BGO detector through the axioelectric effect. See their Fig. 4 for mass-dependent limits.
- <sup>25</sup> HECKEL 13 studied the influence of 2 or 4 stationary sources each containing  $6.0 \times 10^{24}$  polarized electrons, on a rotating torsion pendulum containing  $9.8 \times 10^{24}$  polarized electrons. See their Fig. 4 for mass-dependent limits.
- <sup>26</sup> VIAUX 13A constrain axion emission using the observed brightness of the tip of the red-giant branch in the globular cluster M5.

- 27 CORSICO 12 attributed the excessive cooling rate of the pulsating white dwarf R548 to emission of axions with  $g_{Aee} \simeq 4.8 \times 10^{-13}$ .
- 28 DERBIN 12 look for solar axions with the axio-electric effect in a Si(Li) detector. The solar production is based on Compton and bremsstrahlung processes.
- 29 AALSETH 11 is analogous to AHMED 09A. See their Fig. 4 for mass-dependent limits.
- 30 AHMED 09A assume keV-mass pseudoscalars are the local dark matter and constrain the axio-electric effect in the CDMS detector. See their Fig. 5 for mass-dependent limits.
- 31 DAVOUDI ASL 09 use geophysical constraints on Earth cooling by axion emission.
- 32 These experiments measured induced magnetization of a bulk material by the spin-dependent potential generated from other bulk material with aligned electron spins, where the magnetic field is shielded with superconductor. The sign of the limit set by CHUI 93 is opposite to that of the axion-mediated dipole-dipole potential.
- 33 These experiments used a torsion pendulum to measure the potential between two bulk matter objects where the spins are polarized but without a net magnetic field in either of them. The limits reflect the corrected sign of the dipole-dipole potential.
- 34 WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

### Invisible $A^0$ (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

| VALUE (eV)  | CL% | DOCUMENT ID        | TECN | COMMENT                        |
|---|-----|--------------------|------|--------------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                    |      |                                |
|   |     | 1 ABEL             | 17   | Neutron EDM                    |
| < 93  | 90  | 2 ABGRALL          | 17   | HPGE Solar axion               |
| < 70  | 90  | 3 FU               | 17A  | PNDX Solar axion               |
|   |     | 4 KLIMCHITSK...17A |      | Casimir effect                 |
| < 177   | 90  | 5 LIU              | 17A  | CDEX Solar axion               |
| < 1 × 10 <sup>2</sup>   | 95  | 6 GAVRILYUK        | 15   | CNTR Solar axion               |
|   |     | 7 KLIMCHITSK...15  |      | Casimir-less                   |
|   |     | 8 BEZERRA          | 14   | Casimir effect                 |
|   |     | 9 BEZERRA          | 14A  | Casimir effect                 |
|   |     | 10 BEZERRA         | 14B  | Casimir effect                 |
|   |     | 11 BEZERRA         | 14C  | Casimir effect                 |
|   |     | 12 BLUM            | 14   | COSM <sup>4</sup> He abundance |
|   |     | 13 LEINSON         | 14   | ASTR Neutron star cooling      |
| < 2.50 × 10 <sup>2</sup>  | 95  | 14 ALESSANDRIA     | 13   | CNTR Solar axion               |
| < 1.55 × 10 <sup>2</sup>  | 90  | 15 ARMENGAUD       | 13   | EDEL Solar axion               |
| < 8.6 × 10 <sup>3</sup>   | 90  | 16 BELLI           | 12   | CNTR Solar axion               |
| < 1.4 × 10 <sup>4</sup>   | 90  | 17 BELLINI         | 12B  | BORX Solar axion               |
| < 1.45 × 10 <sup>2</sup>  | 95  | 18 DERBIN          | 11   | CNTR Solar axion               |
|   |     | 19 BELLINI         | 08   | CNTR Solar axion               |
|   |     | 20 ADELBERGER      | 07   | Test of Newton's law           |

<sup>1</sup> ABEL 17 look for a time-oscillating neutron EDM and an axion-wind spin-precession effect respectively induced by axion dark matter couplings to gluons and nucleons. See their Fig. 4 for limits in the range of  $m_{A^0} = 10^{-24}$ – $10^{-17}$  eV.

<sup>2</sup> ABGRALL 17 limit assumes the hadronic axion model used in ALESSANDRIA 13. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.

<sup>3</sup> FU 17A look for the 14.4 keV <sup>57</sup>Fe solar axions. The limit assumes the DFSZ axion model. See their Fig. 3 for mass-dependent limits on the axion-electron coupling.

- <sup>4</sup> KLIMCHITSKAYA 17A use the differential measurement of the Casimir force between a Ni-coated sphere and Au and Ni sectors of the structured disc to constrain the axion coupling to nucleons for  $2.61 \text{ meV} < m_{A^0} < 0.9 \text{ eV}$ . See their Figs. 1 and 2 for mass dependent limits.
- <sup>5</sup> LIU 17 is analogous to ALESSANDRIA 13. The limit assumes the hadronic axion model. See their Fig. 6(b) for the limit on product of axion couplings to electrons and nucleons.
- <sup>6</sup> GAVRILYUK 15 look for solar axions emitted by the M1 transition of  $^{83}\text{Kr}$  (9.4 keV). The mass bound assumes  $m_u/m_d = 0.56$  and  $S = 0.5$ .
- <sup>7</sup> KLIMCHITSKAYA 15 use the measurement of differential forces between a test mass and rotating source masses of Au and Si to constrain the force due to two-axion exchange for  $1.7 \times 10^{-3} < m_{A^0} < 0.9 \text{ eV}$ . See their Figs. 1 and 2 for mass dependent limits.
- <sup>8</sup> BEZERRA 14 use the measurement of the thermal Casimir-Polder force between a Bose-Einstein condensate of  $^{87}\text{Rb}$  atoms and a  $\text{SiO}_2$  plate to constrain the force mediated by exchange of two pseudoscalars for  $0.1 \text{ meV} < m_{A^0} < 0.3 \text{ eV}$ . See their Fig. 2 for the mass-dependent limit on pseudoscalar coupling to nucleons.
- <sup>9</sup> BEZERRA 14A is analogous to BEZERRA 14. They use the measurement of the Casimir pressure between two Au-coated plates to constrain pseudoscalar coupling to nucleons for  $1 \times 10^{-3} \text{ eV} < m_{A^0} < 15 \text{ eV}$ . See their Figs. 1 and 2 for the mass-dependent limit.
- <sup>10</sup> BEZERRA 14B is analogous to BEZERRA 14. BEZERRA 14B use the measurement of the normal and lateral Casimir forces between sinusoidally corrugated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for  $1 \text{ eV} < m_{A^0} < 20 \text{ eV}$ . See their Figs. 1–3 for mass-dependent limits.
- <sup>11</sup> BEZERRA 14C is analogous to BEZERRA 14. They use the measurement of the gradient of the Casimir force between Au- and Ni-coated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for  $3 \times 10^{-5} \text{ eV} < m_{A^0} < 1 \text{ eV}$ . See their Figs. 1, 3, and 4 for the mass-dependent limits.
- <sup>12</sup> BLUM 14 studied effects of an oscillating strong  $CP$  phase induced by axion dark matter on the primordial  $^4\text{He}$  abundance. See their Fig. 1 for mass-dependent limits.
- <sup>13</sup> LEINSON 14 attributes the excessive cooling rate of the neutron star in Cassiopeia A to axion emission from the superfluid core, and found  $C_n^2 m_{A^0}^2 \simeq 5.7 \times 10^{-6} \text{ eV}^2$ , where  $C_n$  is the effective Peccei-Quinn charge of the neutron.
- <sup>14</sup> ALESSANDRIA 13 used the CUORE experiment to look for 14.4 keV solar axions produced from the M1 transition of thermally excited  $^{57}\text{Fe}$  nuclei in the solar core, using the axio-electric effect. The limit assumes the hadronic axion model. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.
- <sup>15</sup> ARMENGAUD 13 is analogous to ALESSANDRIA 13. The limit assumes the hadronic axion model. See their Fig. 8 for the limit on product of axion couplings to electrons and nucleons.
- <sup>16</sup> BELLI 12 looked for solar axions emitted by the M1 transition of  $^7\text{Li}^*$  (478 keV) after the electron capture of  $^7\text{Be}$ , using the resonant excitation  $^7\text{Li}$  in the LiF crystal. The mass bound assumes  $m_u/m_d = 0.55$ ,  $m_u/m_s = 0.029$ , and the flavor-singlet axial vector matrix element  $S = 0.4$ .
- <sup>17</sup> BELLINI 12B looked for 5.5 MeV solar axions produced in the  $pd \rightarrow ^3\text{He} A^0$ . The limit assumes the hadronic axion model. See their Figs. 6 and 7 for mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.
- <sup>18</sup> DERBIN 11 looked for solar axions emitted by the M1 transition of thermally excited  $^{57}\text{Fe}$  nuclei in the Sun, using their possible resonant capture on  $^{57}\text{Fe}$  in the laboratory. The mass bound assumes  $m_u/m_d = 0.56$  and the flavor-singlet axial vector matrix element  $S = 3F - D \simeq 0.5$ .
- <sup>19</sup> BELLINI 08 consider solar axions emitted in the M1 transition of  $^7\text{Li}^*$  (478 keV) and look for a peak at 478 keV in the energy spectra of the Counting Test Facility (CTF), a Borexino prototype. For  $m_{A^0} < 450 \text{ keV}$  they find mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.

<sup>20</sup> ADELBERGER 07 use precision tests of Newton’s law to constrain a force contribution from the exchange of two pseudoscalars. See their Fig. 5 for limits on the pseudoscalar coupling to nucleons, relevant for  $m_{A^0}$  below about 1 meV.

### Axion Limits from $T$ -violating Medium-Range Forces

The limit is for the coupling  $g = g_p g_s$  in a  $T$ -violating potential between nucleons or nucleon and electron of the form  $V = \frac{g\hbar^2}{8\pi m_p} (\boldsymbol{\sigma} \cdot \hat{\boldsymbol{r}}) \left( \frac{1}{r^2} + \frac{1}{\lambda r} \right) e^{-r/\lambda}$ , where  $g_p$  and  $g_s$  are dimensionless scalar and pseudoscalar coupling constants and  $\lambda = \hbar/(m_A c)$  is the range of the force.

| <u>VALUE</u> | <u>DOCUMENT ID</u>  | <u>TECN</u> | <u>COMMENT</u>  |
|--------------|---|-------------|---|
| • • •        | We do not use the following data for averages, fits, limits, etc. • • • |             |   |
| 1            | STADNIK   | 18          | THEO atomic and molecular EDMs                        |
| 2            | CRESCINI  | 17          | SQID paramagnetic GSO crystal                         |
| 3            | AFACH   | 15          | ultracold neutrons                                    |
| 4            | STADNIK   | 15          | THEO nucleon spin contributions for nuclei            |
| 5            | TERRANO   | 15          | torsion pendulum                                      |
| 6            | BULATOWICZ  | 13          | NMR polarized $^{129}\text{Xe}$ and $^{131}\text{Xe}$ |
| 7            | CHU   | 13          | polarized $^3\text{He}$                               |
| 8            | TULLNEY   | 13          | SQID polarized $^3\text{He}$ and $^{129}\text{Xe}$    |
| 9            | RAFFELT   | 12          | stellar energy loss                                   |
| 10           | HOEDL   | 11          | torsion pendulum                                      |
| 11           | PETUKHOV  | 10          | polarized $^3\text{He}$                               |
| 12           | SEREBROV  | 10          | ultracold neutrons                                    |
| 13           | IGNATOVICH  | 09          | RVUE ultracold neutrons                               |
| 14           | SEREBROV  | 09          | RVUE ultracold neutrons                               |
| 15           | BAESSLER  | 07          | ultracold neutrons                                    |
| 16           | HECKEL  | 06          | torsion pendulum                                      |
| 17           | NI  | 99          | paramagnetic Tb F <sub>3</sub>                        |
| 18           | POSPELOV  | 98          | THEO neutron EDM                                      |
| 19           | YODIN   | 96          |   |
| 20           | RITTER  | 93          | torsion pendulum                                      |
| 21           | VENEMA  | 92          | nuclear spin-precession frequencies                   |
| 22           | WINELAND  | 91          | NMR   |

<sup>1</sup> STADNIK 18 used atomic and molecular EDM experiments to derive limits on the product of the pseudoscalar couplings to electron and the scalar coupling to nucleon and electron. See their Fig. 2 for mass-dependent limits, which improved on the laboratory bounds for  $m_{A^0} > 0.01$  eV.

<sup>2</sup> CRESCINI 17 use the QUAX- $g_p g_s$  experiment to look for variation of a paramagnetic GSO crystal magnetization when rotating lead disks are positioned near the crystal, and find  $g = g_p^e g_s^N < 4.3 \times 10^{-30}$  for  $\lambda = 0.1\text{--}0.2$  m at 95% CL. See their Fig. 6 for limits as a function of  $\lambda$ .

<sup>3</sup> AFACH 15 look for a change of spin precession frequency of ultracold neutrons when a magnetic field with opposite directions is applied, and find  $g < 2.2 \times 10^{-27} (\text{m}/\lambda)^2$  at 95% CL for  $1 \mu\text{m} < \lambda < 5$  mm. See their Fig. 3 for their limits.

<sup>4</sup> STADNIK 15 studied proton and neutron spin contributions for nuclei and derive the limits  $g < 10^{-28}\text{--}10^{-23}$  for  $\lambda > 3 \times 10^{-4}$  m using the data of TULLNEY 13. See their Figs. 1 and 2 for  $\lambda$ -dependent limits.

<sup>5</sup> TERRANO 15 used a torsion pendulum and rotating attractor, and derived a restrictive limit on the product of the pseudoscalar coupling to electron and the scalar coupling to



- nucleons,  $g < 9 \times 10^{-29} - 5 \times 10^{-26}$  for  $m_{A0} < 1.5-400 \mu\text{eV}$ . See their Fig. 5 for mass-dependent limits.
- 6 BULATOWICZ 13 looked for NMR frequency shifts in polarized  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  when a zirconia rod is positioned near the NMR cell, and find  $g < 1 \times 10^{-19} - 1 \times 10^{-24}$  for  $\lambda = 0.01-1 \text{ cm}$ . See their Fig. 4 for their limits.
  - 7 CHU 13 look for a shift of the spin precession frequency of polarized  $^3\text{He}$  in the presence of an unpolarized mass, in analogy to YODIN 96. See Fig. 3 for limits on  $g$  in the approximate  $m_{A0}$  range 0.02–2 meV.
  - 8 TULLNEY 13 look for a shift of the precession frequency difference between the colocated  $^3\text{He}$  and  $^{129}\text{Xe}$  in the presence an unpolarized mass, and derive limits  $g < 3 \times 10^{-29} - 2 \times 10^{-22}$  for  $\lambda > 3 \times 10^{-4} \text{ m}$ . See their Fig. 3 for  $\lambda$ -dependent limits.
  - 9 RAFFELT 12 show that the pseudoscalar couplings to electron and nucleon and the scalar coupling to nucleon are individually constrained by stellar energy-loss arguments and searches for anomalous monopole-monopole forces, together providing restrictive constraints on  $g$ . See their Figs. 2 and 3 for results.
  - 10 HOEDL 11 use a novel torsion pendulum to study the force by the polarized electrons of an external magnet. In their Fig. 3 they show restrictive limits on  $g$  in the approximate  $m_{A0}$  range 0.03–10 meV.
  - 11 PETUKHOV 10 use spin relaxation of polarized  $^3\text{He}$  and find  $g < 3 \times 10^{-23} (\text{cm}/\lambda)^2$  at 95% CL for the force range  $\lambda = 10^{-4}-1 \text{ cm}$ .
  - 12 SEREBROV 10 use spin precession of ultracold neutrons close to bulk matter and find  $g < 2 \times 10^{-21} (\text{cm}/\lambda)^2$  at 95% CL for the force range  $\lambda = 10^{-4}-1 \text{ cm}$ .
  - 13 IGNATOVICH 09 use data on depolarization of ultracold neutrons in material traps. They show  $\lambda$ -dependent limits in their Fig. 1.
  - 14 SEREBROV 09 uses data on depolarization of ultracold neutrons stored in material traps and finds  $g < 2.96 \times 10^{-21} (\text{cm}/\lambda)^2$  for the force range  $\lambda = 10^{-3}-1 \text{ cm}$  and  $g < 3.9 \times 10^{-22} (\text{cm}/\lambda)^2$  for  $\lambda = 10^{-4}-10^{-3} \text{ cm}$ , each time at 95% CL, significantly improving on BAESSLER 07.
  - 15 BAESSLER 07 use the observation of quantum states of ultracold neutrons in the Earth's gravitational field to constrain  $g$  for an interaction range  $1 \mu\text{m}$ –a few mm. See their Fig. 3 for results.
  - 16 HECKEL 06 studied the influence of unpolarized bulk matter, including the laboratory's surroundings or the Sun, on a torsion pendulum containing about  $9 \times 10^{22}$  polarized electrons. See their Fig. 4 for limits on  $g$  as a function of interaction range.
  - 17 NI 99 searched for a  $T$ -violating medium-range force acting on paramagnetic  $\text{Tb F}_3$  salt. See their Fig. 1 for the result.
  - 18 POSPELOV 98 studied the possible contribution of  $T$ -violating Medium-Range Force to the neutron electric dipole moment, which is possible when axion interactions violate  $CP$ . The size of the force among nucleons must be smaller than gravity by a factor of  $2 \times 10^{-10} (1 \text{ cm}/\lambda_A)$ , where  $\lambda_A = \hbar/m_A c$ .
  - 19 YODIN 96 compared the precession frequencies of atomic  $^{199}\text{Hg}$  and  $\text{Cs}$  when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.
  - 20 RITTER 93 studied the influence of bulk mass with polarized electrons on an unpolarized torsion pendulum, providing limits in the interaction range from 1 to 100 cm.
  - 21 VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of  $^{199}\text{Hg}$  and  $^{201}\text{Hg}$  atoms.
  - 22 WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored  $^9\text{Be}^+$  ions using nuclear magnetic resonance.
-

### Hidden Photons: Kinetic Mixing Parameter Limits

Hidden photons limits are listed for the first time, including only the most recent papers. Suggestions for previous important results are welcome. Limits are on the kinetic mixing parameter  $\chi$  which is defined by the Lagrangian

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\chi}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{m_{\gamma'}^2}{2} A'_\mu A'^\mu,$$

where  $A_\mu$  and  $A'_\mu$  are the photon and hidden-photon fields with field strengths  $F_{\mu\nu}$  and  $F'_{\mu\nu}$ , respectively, and  $m_{\gamma'}$  is the hidden-photon mass.

| VALUE   | CL%  | DOCUMENT ID     | TECN      | COMMENT  |
|---|------|-----------------|-----------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |      |                 |           |  |
| $<3.1 \times 10^{-14}$  | 90   | 1 ABGRALL       | 17 HPGE   | $m_{\gamma'} = 11.8 \text{ keV}$               |
| $<6 \times 10^{-4}$   | 90   | 2 ABLIKIM       | 17AA BES3 | $m_{\gamma'} = 1.5\text{--}3.4 \text{ GeV}$    |
| $<7 \times 10^{-15}$  | 90   | 3 ANGLOHER      | 17 CRES   | $m_{\gamma'} = 0.3\text{--}0.7 \text{ keV}$    |
| $<1.2 \times 10^{-4}$   | 90   | 4 BANERJEE      | 17 NA64   | $m_{\gamma'} = 0.002\text{--}0.4 \text{ GeV}$  |
| $<2 \times 10^{-11}$  |      | 5 CHANG         | 17 ASTR   | $m_{\gamma'} = 15 \text{ MeV}$                 |
| $<4.5 \times 10^{-3}$   | 90   | 6 DUBININA      | 17 EMUL   | $m_{\gamma'} = 1.1\text{--}24 \text{ MeV}$     |
| $<4 \times 10^{-4}$   | 90   | 7 LEES          | 17E BABR  | $m_{\gamma'} = 4.7 \text{ GeV}$                |
|   |      | 8 AAD           | 16AG ATLS | $m_{\gamma'} = 0.1\text{--}2 \text{ GeV}$      |
| $<4.4 \times 10^{-4}$   | 90   | 9 ANASTASI      | 16 KLOE   | $m_{\gamma'} = 527\text{--}987 \text{ MeV}$    |
| $<1.7 \times 10^{-6}$   | 95   | 10 KHACHATRY... | 16 CMS    | $m_{\gamma'} = 2 \text{ GeV}$                  |
| $<7 \times 10^{-4}$   | 90   | 11 LEES         | 16F BABR  | $m_{\gamma'} = 0.212\text{--}10 \text{ GeV}$   |
| $<4 \times 10^{-2}$   | 95   | 12 AAD          | 15CD ATLS | $m_{\gamma'} = 15\text{--}55 \text{ GeV}$      |
| $<1.4 \times 10^{-3}$   | 90   | 13 ADARE        | 15        | $m_{\gamma'} = 30\text{--}90 \text{ MeV}$      |
|   |      | 14 AN           | 15A       | $m_{\gamma'} = 12 \text{ eV} - 40 \text{ keV}$ |
|   |      | 15 ANASTASI     | 15 KLOE   | $m_{\gamma'} = 2m_\mu - 1 \text{ GeV}$         |
| $<1.7 \times 10^{-3}$   | 90   | 16 ANASTASI     | 15A KLOE  | $m_{\gamma'} = 5\text{--}320 \text{ MeV}$      |
| $<4.2 \times 10^{-4}$   | 90   | 17 BATLEY       | 15A NA48  | $m_{\gamma'} = 36 \text{ MeV}$                 |
|   |      | 18 JAEGLE       | 15 BELL   | $m_{\gamma'} = 0.1\text{--}3.5 \text{ GeV}$    |
| $<3 \times 10^{-13}$  |      | 19 KAZANAS      | 15 ASTR   | $m_{\gamma'} = 2m_e - 100 \text{ MeV}$         |
|   |      | 20 SUZUKI       | 15        | $m_{\gamma'} = 1.9\text{--}4.3 \text{ eV}$     |
| $<2.3 \times 10^{-13}$  | 99.7 | 21 VINYOLES     | 15 ASTR   | $m_{\gamma'} = 8 \text{ eV}$                   |
|   |      | 22 ABE          | 14F XMAS  | $m_{\gamma'} = 40\text{--}120 \text{ keV}$     |
| $<1.8 \times 10^{-3}$   | 90   | 23 AGAKISHIEV   | 14 HDES   | $m_{\gamma'} = 63 \text{ MeV}$                 |
| $<9.0 \times 10^{-4}$   | 90   | 24 BABUSCI      | 14 KLOE   | $m_{\gamma'} = 969 \text{ MeV}$                |
|   |      | 25 BATELL       | 14 BDMP   | $m_{\gamma'} = 10^{-3}\text{--}1 \text{ GeV}$  |
| $<1.3 \times 10^{-7}$   | 95   | 26 BLUEMLEIN    | 14 BDMP   | $m_{\gamma'} = 0.6 \text{ GeV}$                |
| $<3 \times 10^{-18}$  |      | 27 FRADETTE     | 14 COSM   | $m_{\gamma'} = 50\text{--}300 \text{ MeV}$     |
| $<3.5 \times 10^{-4}$   | 90   | 28 LEES         | 14J BABR  | $m_{\gamma'} = 0.2 \text{ GeV}$                |
| $<9 \times 10^{-4}$   | 95   | 29 MERKEL       | 14 A1     | $m_{\gamma'} = 40\text{--}300 \text{ MeV}$     |

|                           |    |                |          |   |
|---------------------------|----|----------------|----------|---|
| <3 × 10 <sup>-15</sup>    |    | 30 AN          | 13B ASTR | $m_{\gamma'} = 2 \text{ keV}$                   |
| <7 × 10 <sup>-14</sup>    |    | 31 AN          | 13C XE10 | $m_{\gamma'} = 100 \text{ eV}$                  |
| <8 × 10 <sup>-4</sup>     |    | 32 DIAMOND     | 13 BDMP  | $m_{\gamma'} = 30\text{--}250 \text{ MeV}$      |
| <2.2 × 10 <sup>-13</sup>  |    | 33 HORVAT      | 13 HPGE  | $m_{\gamma'} = 230 \text{ eV}$                  |
| <8.06 × 10 <sup>-5</sup>  | 95 | 34 INADA       | 13 LSW   | $m_{\gamma'} = 0.04 \text{ eV--}26 \text{ keV}$ |
| <2 × 10 <sup>-10</sup>    | 95 | 35 MIZUMOTO    | 13       | $m_{\gamma'} = 1 \text{ eV}$                    |
| <1.7 × 10 <sup>-7</sup>   |    | 36 PARKER      | 13 LSW   | $m_{\gamma'} = 53 \mu\text{eV}$                 |
| <5.32 × 10 <sup>-15</sup> |    | 37 PARKER      | 13       | $m_{\gamma'} = 53 \mu\text{eV}$                 |
| <1 × 10 <sup>-15</sup>    |    | 38 REDONDO     | 13 ASTR  | $m_{\gamma'} = 2 \text{ keV}$                   |
| <8 × 10 <sup>-8</sup>     | 90 | 39 GNINENKO    | 12A BDMP | $m_{\gamma'} = 1\text{--}135 \text{ MeV}$       |
| <1 × 10 <sup>-7</sup>     | 90 | 40 GNINENKO    | 12B CHRM | $m_{\gamma'} = 1\text{--}500 \text{ MeV}$       |
| <1 × 10 <sup>-3</sup>     | 90 | 41 ABRAHAMY... | 11       | $m_{\gamma'} = 175\text{--}250 \text{ MeV}$     |
| <9 × 10 <sup>-8</sup>     | 95 | 42 BLUEMLEIN   | 11 BDMP  | $m_{\gamma'} = 70 \text{ MeV}$                  |
| <1 × 10 <sup>-7</sup>     |    | 43 BJORKEN     | 09 BDMP  | $m_{\gamma'} = 2\text{--}400 \text{ MeV}$       |
| <5 × 10 <sup>-9</sup>     |    | 44 BJORKEN     | 09 ASTR  | $m_{\gamma'} = 2\text{--}50 \text{ MeV}$        |

<sup>1</sup> ABGRALL 17 is analogous to ABE 14F using the MAJORANA DEMONSTRATOR. See their Fig. 3 for limits between  $6 \text{ keV} < m_{\gamma'} < 97 \text{ keV}$ .

<sup>2</sup> ABLIKIM 17AA look for  $e^+e^- \rightarrow \gamma\gamma'$  ( $\gamma' \rightarrow e^+e^-$  or  $\mu^+\mu^-$ ). Limits between  $10^{-3}$  and  $10^{-4}$  are obtained (see their Fig. 3).

<sup>3</sup> ANGLOHER 17 is analogous to ABE 14F. The quoted limit is at  $m_{\gamma'} = 0.7 \text{ keV}$ . See their Fig. 8 for mass-dependent limits.

<sup>4</sup> BANERJEE 17 look for invisible decays of hidden photons produced in the reaction  $e^-Z \rightarrow e^-Z\gamma'$ . The quoted limit applies to  $m_{\gamma'} = 2 \text{ MeV}$ . See their Fig. 3 for mass-dependent limits.

<sup>5</sup> CHANG 17 examine the hidden photon emission from SN1987A, including the effects of finite temperature and density on  $\chi$  and obtain limits  $\chi (m_{\gamma'}/\text{MeV}) \lesssim 3 \times 10^{-9}$  for  $m_{\gamma'} < 15 \text{ MeV}$  and  $\chi \lesssim 10^{-9}$  for  $m_{\gamma'} = 15\text{--}120 \text{ MeV}$ .

<sup>6</sup> DUBININA 17 look for  $\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e\gamma'$  ( $\gamma' \rightarrow e^+e^-$ ) in a nuclear photoemulsion. The quoted limit applies to  $m_{\gamma'} = 1.1 \text{ MeV}$ . Limits between  $4.5 \times 10^{-3}$  and  $10^{-2}$  are obtained (see their Fig. 3).

<sup>7</sup> LEES 17E look for invisible decays of hidden photons produced in the reaction  $e^+e^- \rightarrow \gamma\gamma'$ . See their Fig. 5 for limits in the mass range  $m_{\gamma'} \leq 8 \text{ GeV}$ .

<sup>8</sup> AAD 16AG look for hidden photons promptly decaying into collimated electrons and/or muons, assuming that they are produced in the cascade decays of squarks or the Higgs boson. See their Fig. 10 and Fig.13 for their limits on the cross section times branching fractions.

<sup>9</sup> ANASTASI 16 look for the decay  $\gamma' \rightarrow \pi^+\pi^-$  in the reaction  $e^+e^- \rightarrow \gamma\gamma'$ . Limits between  $4.3 \times 10^{-3}$  and  $4.4 \times 10^{-4}$  are obtained for  $527 < m_{\gamma'} < 987 \text{ MeV}$  (see their Fig. 9).

<sup>10</sup> KHACHATRYAN 16 look for  $\gamma' \rightarrow \mu^+\mu^-$  in a dark SUSY scenario where the SM-like Higgs boson decays into a pair of the visible lightest neutralinos with mass  $10 \text{ GeV}$ , both of which decay into  $\gamma'$  and a hidden neutralino with mass  $1 \text{ GeV}$ . See the right panel in their Fig. 2.

- <sup>11</sup> LEES 16F looked for a hidden photon coupled only to the second and third generations of leptons in the reaction  $e^+e^- \rightarrow \mu^+\mu^-\gamma'$  ( $\gamma' \rightarrow \mu^+\mu^-$ ) using data collected by BABAR detector, and derived limits on the hidden photon gauge coupling as low as  $7 \times 10^{-4}$  for  $m_{\gamma'} = 0.212\text{--}10$  GeV. See their Fig. 5 for the mass-dependent limits.
- <sup>12</sup> AAD 15CD look for  $H \rightarrow Z\gamma' \rightarrow 4\ell$  with the ATLAS detector at LHC and find  $\chi < 4\text{--}17 \times 10^{-2}$  for  $m_{\gamma'} = 15\text{--}55$  GeV. See their Fig. 6.
- <sup>13</sup> ADARE 15 look for a hidden photon in  $\pi^0, \eta^0 \rightarrow \gamma e^+ e^-$  at the PHENIX experiment. See their Fig. 4 for mass-dependent limits.
- <sup>14</sup> AN 15A derived limits from the absence of ionization signals in the XENON10 and XENON100 experiments, assuming hidden photons constitute all the local dark matter. Their best limit is  $\chi < 1.3 \times 10^{-15}$  at  $m_{\gamma'} = 18$  eV. See their Fig. 1 for mass-dependent limits.
- <sup>15</sup> ANASTASI 15 look for a production of a hidden photon and a hidden Higgs boson with the KLOE detector at DAΦNE, where the hidden photon decays into a pair of muons and the hidden Higgs boson lighter than  $m_{\gamma'}$  escape detection. See their Figs. 6 and 7 for mass-dependent limits on a product of the hidden fine structure constant and the kinetic mixing.
- <sup>16</sup> ANASTASI 15A look for the decay  $\gamma' \rightarrow e^+e^-$  in the reaction  $e^+e^- \rightarrow e^+e^-\gamma$ . Limits between  $1.7 \times 10^{-3}$  and  $1 \times 10^{-2}$  are obtained for  $m_{\gamma'} = 5\text{--}320$  MeV (see their Fig. 7).
- <sup>17</sup> BATLEY 15A look for  $\pi^0 \rightarrow \gamma\gamma'$  ( $\gamma' \rightarrow e^+e^-$ ) at the NA48/2 experiment. Limits between  $4.2 \times 10^{-4}$  and  $8.8 \times 10^{-3}$  are obtained for  $m_{\gamma'} = 9\text{--}120$  MeV (see their Fig. 4).
- <sup>18</sup> JAEGLER 15 look for the decay  $\gamma' \rightarrow e^+e^-, \mu^+\mu^-,$  or  $\pi^+\pi^-$  in the dark Higgstrahlung channel,  $e^+e^- \rightarrow \gamma' H'$  ( $H' \rightarrow \gamma'\gamma'$ ) at the BELLE experiment. They set limits on a product of the branching fraction and the Born cross section as well as a product of the hidden fine structure constant and the kinetic mixing. See their Figs. 3 and 4.
- <sup>19</sup> KAZANAS 15 set limits by studying the decay of hidden photons  $\gamma' \rightarrow e^+e^-$  inside and near the progenitor star of SN1987A. See their Fig. 6 for mass-dependent limits.
- <sup>20</sup> SUZUKI 15 looked for hidden-photon dark matter with a dish antenna and derived limits assuming they constitute all the local dark matter. Their limits are  $\chi < 6 \times 10^{-12}$  for  $m_{\gamma'} = 1.9\text{--}4.3$  eV. See their Fig. 7 for mass-dependent limits.
- <sup>21</sup> VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations, and set the limits  $\chi m_{\gamma'} < 1.8 \times 10^{-12}$  eV for  $m_{\gamma'} = 3 \times 10^{-5}\text{--}8$  eV. See their Fig. 11.
- <sup>22</sup> ABE 14F look for the photoelectric-like interaction in the XMASS detector assuming the hidden photon constitutes all the local dark matter. Limits between  $2 \times 10^{-13}$  and  $1 \times 10^{-12}$  are obtained. See their Fig. 3 for mass-dependent limits.
- <sup>23</sup> AGAKISHIEV 14 look for hidden photons  $\gamma' \rightarrow e^+e^-$  at the HADES experiment, and set limits on  $\chi$  for  $m_{\gamma'} = 0.02\text{--}0.6$  GeV. See their Fig. 5 for mass-dependent limits.
- <sup>24</sup> BABUSCI 14 look for the decay  $\gamma' \rightarrow \mu^+\mu^-$  in the reaction  $e^+e^- \rightarrow \mu^+\mu^-\gamma$ . Limits between  $4 \times 10^{-3}$  and  $9.0 \times 10^{-4}$  are obtained for  $520 \text{ MeV} < m_{\gamma'} < 980$  MeV (see their Fig. 7).
- <sup>25</sup> BATELL 14 derived limits from the electron beam dump experiment at SLAC (E-137) by searching for events with recoil electrons by sub-GeV dark matter produced from the decay of the hidden photon. Limits at the level of  $10^{-4}\text{--}10^{-1}$  are obtained for  $m_{\gamma'} = 10^{-3}\text{--}1$  GeV, depending on the dark matter mass and the hidden gauge coupling (see their Fig. 2).

- 26 BLUEMLEIN 14 analyzed the beam dump data taken at the U-70 accelerator to look for  $\gamma'$ -bremsstrahlung and the subsequent decay into muon pairs and hadrons. See their Fig. 4 for mass-dependent excluded region.
- 27 FRADETTE 14 studied effects of decay of relic hidden photons on BBN and CMB to set constraints on very small values of the kinetic mixing. See their Figs. 4 and 7 for mass-dependent excluded regions.
- 28 LEES 14J look for hidden photons in the reaction  $e^+e^- \rightarrow \gamma\gamma'$  ( $\gamma' \rightarrow e^+e^-, \mu^+\mu^-$ ). Limits at the level of  $10^{-4}$ – $10^{-3}$  are obtained for  $0.02 \text{ GeV} < m_{\gamma'} < 10.2 \text{ GeV}$ . See their Fig. 4 for mass-dependent limits.
- 29 MERKEL 14 look for  $\gamma' \rightarrow e^+e^-$  at the A1 experiment at the Mainz Microtron (MAMI). See their Fig. 3 for mass-dependent limits.
- 30 AN 13B examined the stellar production of hidden photons, correcting an important error of the production rate of the longitudinal mode which now dominates. See their Fig. 2 for mass-dependent limits based on solar energy loss.
- 31 AN 13C use the solar flux of hidden photons to set a limit on the atomic ionization rate in the XENON10 experiment. They find  $\chi m_{\gamma'} < 3 \times 10^{-12} \text{ eV}$  for  $m_{\gamma'} < 1 \text{ eV}$ . See their Fig. 2 for mass-dependent limits.
- 32 DIAMOND 13 analyzed the beam dump data taken at the SLAC millicharge experiment to constrain a hidden photon invisibly decaying into lighter long-lived particles, which undergo elastic scattering off nuclei in the detector. Limits between  $8 \times 10^{-4}$ – $2 \times 10^{-2}$  are obtained. The quoted limit is applied when the dark gauge coupling is set equal to the electromagnetic coupling. See their Fig.4 for mass-dependent limits.
- 33 HORVAT 13 look for hidden-photo-electric effect in HPGe detectors induced by solar hidden photons. See their Fig. 3 for mass-dependent limits.
- 34 INADA 13 search for hidden photons using an intense X-ray beamline at SPring-8. See their Fig. 4 for mass-dependent limits.
- 35 MIZUMOTO 13 look for solar hidden photons. See their Fig. 5 for mass-dependent limits.
- 36 PARKER 13 look for hidden photons using a cryogenic resonant microwave cavity. See their Fig.5 for mass-dependent limits.
- 37 PARKER 13 derived a limit for the hidden photon CDM with a randomly oriented hidden photon field.
- 38 REDONDO 13 examined the solar emission of hidden photons including the enhancement factor for the longitudinal mode pointed out by AN 13B, and also updated stellar-energy loss arguments. See their Fig.3 for mass-dependent limits, including a review of the currently best limits from other arguments.
- 39 GNINENKO 12A obtained bounds on  $B(\pi^0 \rightarrow \gamma\gamma') \cdot B(\gamma' \rightarrow e^+e^-)$  from the NOMAD and PS191 neutrino experiments, and derived limits between  $8 \times 10^{-8}$ – $2 \times 10^{-4}$ . See their Fig.4 for mass-dependent excluded regions.
- 40 GNINENKO 12B used the data taken at the CHARM experiment to constrain the decay,  $\eta(\eta') \rightarrow \gamma\gamma'$  ( $\gamma' \rightarrow e^+e^-$ ), and derived limits between  $1 \times 10^{-7}$ – $1 \times 10^{-4}$ . See their Fig.4 for mass-dependent excluded region.
- 41 ABRAHAMYAN 11 look for  $\gamma' \rightarrow e^+e^-$  in the electron-nucleon fixed-target experiment at the Jefferson Laboratory (APEX). See their Fig. 5 for mass-dependent limits.
- 42 BLUEMLEIN 11 analyzed the beam dump data taken at the U-70 accelerator to look for  $\pi^0 \rightarrow \gamma\gamma'$  ( $\gamma' \rightarrow e^+e^-$ ). See their Fig. 5 for mass-dependent limits.
- 43 BJORKEN 09 analyzed the beam dump data taken at E137, E141, and E774 to constrain a hidden photon produced by bremsstrahlung, subsequently decaying into  $e^+e^-$ , and derived limits between  $10^{-7}$  and  $10^{-2}$ . See their Fig. 1 for mass-dependent excluded region.
- 44 BJORKEN 09 required the energy loss in the  $\gamma'$  emission from the core of SN1987A not to exceed  $10^{53} \text{ erg/s}$ , and derived limits between  $5 \times 10^{-9}$  and  $2 \times 10^{-6}$ . See their Fig. 1 for mass-dependent excluded region.

REFERENCES FOR Searches for Axions ( $A^0$ ) and Other Very Light Bosons

|               |      |                                |  |
|---------------|------|--------------------------------|--|
| STADNIK       | 18   | PRL 120 013202                 | Y.V. Stadnik, V.A. Dzuba, V.V. Flambaum              |
| AAIJ          | 17AQ | PR D95 071101                  | R. Aaij <i>et al.</i> (LHCb Collab.)                 |
| ABEL          | 17   | PR X7 041034                   | C. Abel <i>et al.</i> (nEDM Collab.)                 |
| ABGRALL       | 17   | PRL 118 161801                 | N. Abgrall <i>et al.</i> (MAJORANA Collab.)          |
| ABLIKIM       | 17AA | PL B774 252                    | M. Ablikim <i>et al.</i> (BES III Collab.)           |
| ADE           | 17   | PR D96 102003                  | P.A.R. Ade <i>et al.</i> (BICEP2/Keck Array Collab.) |
| AHN           | 17   | PTEP 2017 021C01               | J.K. Ahn <i>et al.</i> (KOTO Collab.)                |
| AKERIB        | 17B  | PRL 118 261301                 | D.S. Akerib <i>et al.</i> (LUX Collab.)              |
| ANASTASSO...  | 17   | NATP 13 584                    | V. Anastassopoulos <i>et al.</i> (CAST Collab.)      |
| ANGLOHER      | 17   | EPJ C77 299                    | G. Angloher <i>et al.</i> (CRESST-II Collab.)        |
| APRILE        | 17B  | PR D95 029904                  | E. Aprile <i>et al.</i> (XENON100 Collab.)           |
| BANERJEE      | 17   | PRL 118 011802                 | D. Banerjee <i>et al.</i> (NA64 Collab.)             |
| BATLEY        | 17   | PL B769 67                     | J.R. Batley <i>et al.</i> (NA48/2 Collab.)           |
| BRANCA        | 17   | PRL 118 021302                 | A. Branca <i>et al.</i> (AURIGA Collab.)             |
| BRUBAKER      | 17   | PRL 118 061302                 | B.M. Brubaker <i>et al.</i> (YALE, UCB, NIST+)       |
| CHANG         | 17   | JHEP 1701 107                  | J.H. Chang, R. Essig, S.D. McDermott (STON)          |
| CHOI          | 17   | PR D96 061102                  | J. Choi <i>et al.</i> (CAPP-ACTION Collab.)          |
| CRESCINI      | 17   | PL B773 677                    | N. Crescini <i>et al.</i> (QUAX-gpgs Collab.)        |
| DAIDO         | 17   | PL B772 127                    | R. Daido, F. Takahashi                               |
| DOLAN         | 17   | JHEP 1712 094                  | Matthew J. Dolan <i>et al.</i>                       |
| DUBININA      | 17   | PAN 80 461                     | V.V. Dubinina <i>et al.</i>                          |
| FICEK         | 17   | PR A95 032505                  | F. Ficek <i>et al.</i>                               |
| FU            | 17A  | PRL 119 181806                 | C. Fu <i>et al.</i> (PandaX-II Collab.)              |
| INADA         | 17   | PRL 118 071803                 | T. Inada <i>et al.</i>                               |
| KLIMCHITSK... | 17A  | PR D95 123013                  | G.L. Klimchitskaya, V.M. Mostepanenko                |
| KOHR          | 17   | PR D96 051701                  | K. Kohri, H. Kodama (KEK, KYOT)                      |
| LEES          | 17E  | PRL 119 131804                 | J.P. Lees <i>et al.</i> (BABAR Collab.)              |
| LIU           | 17   | PL B766 117                    | X.-H. Liu (TINT)                                     |
| LIU           | 17A  | PR D95 052006                  | S.K. Liu <i>et al.</i> (CDEX Collab.)                |
| LUO           | 17   | PR D96 055028                  | P. Luo <i>et al.</i>                                 |
| MARSH         | 17   | JCAP 1712 036                  | M.C.D. Marsh <i>et al.</i>                           |
| TIWARI        | 17   | PR D95 023005                  | P. Tiwari (Technion)                                 |
| AAD           | 16AG | JHEP 1602 062                  | G. Aad <i>et al.</i> (ATLAS Collab.)                 |
| ABLIKIM       | 16E  | PR D93 052005                  | M. Ablikim <i>et al.</i> (BES III Collab.)           |
| AJELLO        | 16   | PRL 116 161101                 | M. Ajello <i>et al.</i> (Fermi-LAT Collab.)          |
| ANASTASI      | 16   | PL B757 356                    | A. Anastasi <i>et al.</i> (KLOE-2 Collab.)           |
| BATTICH       | 16   | JCAP 1608 062                  | T. Battich <i>et al.</i>                             |
| CORSICO       | 16   | JCAP 1607 036                  | A.H. Corsico <i>et al.</i>                           |
| DELLA-VALLE   | 16   | EPJ C76 24                     | F. Della Valle <i>et al.</i> (PVLAS Collab.)         |
| HOSKINS       | 16   | PR D94 082001                  | J. Hoskins <i>et al.</i> (ADMX Collab.)              |
| JAECKEL       | 16   | PL B753 482                    | J. Jaeckel, M. Spannowsky (HEID, DURH)               |
| KHACHATRY...  | 16   | PL B752 146                    | V. Khachatryan <i>et al.</i> (CMS Collab.)           |
| LEEFER        | 16   | PRL 117 271601                 | N. Leefer <i>et al.</i> (MAINZ, BONN, LBL, UCB+)     |
| LEES          | 16F  | PR D94 011102                  | J.P. Lees <i>et al.</i> (BABAR Collab.)              |
| WON           | 16   | PR D94 092006                  | E. Won <i>et al.</i> (BELLE Collab.)                 |
| YOON          | 16   | JHEP 1606 011                  | Y.S. Yoon <i>et al.</i> (KIMS Collab.)               |
| AAD           | 15CD | PR D92 092001                  | G. Aad <i>et al.</i> (ATLAS Collab.)                 |
| AAIJ          | 15AZ | PRL 115 161802                 | R. Aaij <i>et al.</i> (LHCb Collab.)                 |
| ADARE         | 15   | PR C91 031901                  | A. Adare <i>et al.</i> (PHENIX Collab.)              |
| AFACH         | 15   | PL B745 58                     | S. Afach <i>et al.</i> (ETH, PSI, CAEN, +)           |
| AGOSTINI      | 15A  | EPJ C75 416                    | M. Agostini <i>et al.</i> (GERDA Collab.)            |
| AN            | 15A  | PL B747 331                    | H. An <i>et al.</i> (CIT, VICT, VIEN)                |
| ANASTASI      | 15   | PL B747 365                    | A. Anastasi <i>et al.</i> (KLOE-2 Collab.)           |
| ANASTASI      | 15A  | PL B750 633                    | A. Anastasi <i>et al.</i> (KLOE-2 Collab.)           |
| ANASTASSO...  | 15   | PL B749 172                    | V. Anastassopoulos <i>et al.</i> (CAST Collab.)      |
| ARIK          | 15   | PR D92 021101                  | M. Arik <i>et al.</i> (CAST Collab.)                 |
| ARNOLD        | 15   | PR D92 072011                  | R. Arnold <i>et al.</i> (NEMO-3 Collab.)             |
| BALLOU        | 15   | PR D92 092002                  | R. Ballou <i>et al.</i> (OSQAR Collab.)              |
| BATLEY        | 15A  | PL B746 178                    | J.R. Batley <i>et al.</i> (NA48/2 Collab.)           |
| BAYES         | 15   | PR D91 052020                  | R. Bayes <i>et al.</i> (TWIST Collab.)               |
| BRAX          | 15   | PR D92 083501                  | P. Brax, P. Brun, D. Wouters (SACL, SACL5)           |
| GAVRILYUK     | 15   | JETPL 101 664                  | Yu.M. Gavriluk <i>et al.</i>                         |
|               |      | Translated from ZETFP 101 739. |  |
| HASEBE        | 15   | PTEP 2015 073C01               | T. Hasebe <i>et al.</i>                              |
| JAEGLE        | 15   | PRL 114 211801                 | I. Jaegle <i>et al.</i> (BELLE Collab.)              |
| KAZANAS       | 15   | NP B890 17                     | D. Kazanas <i>et al.</i>                             |
| KLIMCHITSK... | 15   | EPJ C75 164                    | G.L. Klimchitskaya, V.M. Mostepanenko                |
| MILLEA        | 15   | PR D92 023010                  | M. Millea, L. Knox, B. Fields (UCD, ILL)             |
| STADNIK       | 15   | EPJ C75 110                    | Y.V. Stadnik, V.V. Flambaum (SYDN)                   |

|               |     |                               |                                     |                        |
|---------------|-----|-------------------------------|-------------------------------------|------------------------|
| SUZUKI        | 15  | JCAP 1509 042                 | J. Suzuki <i>et al.</i>             |                        |
| TERRANO       | 15  | PRL 115 201801                | W.A. Terrano <i>et al.</i>          | (WASH)                 |
| VANTILBURG    | 15  | PRL 115 011802                | K. Van Tilburg <i>et al.</i>        |                        |
| VINYOLES      | 15  | JCAP 1510 015                 | N. Vinyoles <i>et al.</i>           |                        |
| ABE           | 14F | PRL 113 121301                | K. Abe <i>et al.</i>                | (XMASS Collab.)        |
| AGAKISHIEV    | 14  | PL B731 265                   | G. Agakishiev <i>et al.</i>         | (HADES Collab.)        |
| ALBERT        | 14A | PR D90 092004                 | J.B. Albert <i>et al.</i>           | (EXO-200 Collab.)      |
| APRILE        | 14B | PR D90 062009                 | E. Aprile <i>et al.</i>             | (XENON100 Collab.)     |
| ARIK          | 14  | PRL 112 091302                | M. Arik <i>et al.</i>               | (CAST Collab.)         |
| AYALA         | 14  | PRL 113 191302                | A. Ayala <i>et al.</i>              |                        |
| BABUSCI       | 14  | PL B736 459                   | D. Babusci <i>et al.</i>            | (KLOE-2 Collab.)       |
| BATELL        | 14  | PRL 113 171802                | B. Batell, R. Essig, Z. Surujon     | (EFI, STON)            |
| BEZERRA       | 14  | PR D89 035010                 | V.B. Bezerra <i>et al.</i>          |                        |
| BEZERRA       | 14A | EPJ C74 2859                  | V.B. Bezerra <i>et al.</i>          |                        |
| BEZERRA       | 14B | PR D90 055013                 | V.B. Bezerra <i>et al.</i>          |                        |
| BEZERRA       | 14C | PR D89 075002                 | V.B. Bezerra <i>et al.</i>          |                        |
| BLUEMLEIN     | 14  | PL B731 320                   | J. Bluemlein, J. Brunner            | (CPPM, DESY)           |
| BLUM          | 14  | PL B737 30                    | K. Blum <i>et al.</i>               | (IAS, PRIN)            |
| DELLA-VALLE   | 14  | PR D90 092003                 | F. Della Valle <i>et al.</i>        | (PVLAS Collab.)        |
| DERBIN        | 14  | EPJ C74 3035                  | A.V. Derbin <i>et al.</i>           |                        |
| EJLLI         | 14  | PR D90 123527                 | D. Ejlli                            |                        |
| FRADETTE      | 14  | PR D90 035022                 | A. Fradette <i>et al.</i>           |                        |
| LEES          | 14J | PRL 113 201801                | J.P. Lees <i>et al.</i>             | (BABAR Collab.)        |
| LEINSON       | 14  | JCAP 1408 031                 | L. Leinson                          |                        |
| MERKEL        | 14  | PRL 112 221802                | H. Merkel <i>et al.</i>             | (A1 at MAMI)           |
| MILLER-BER... | 14  | JCAP 1410 069                 | M.M. Miller Bertolami <i>et al.</i> |                        |
| PUGNAT        | 14  | EPJ C74 3027                  | P. Pignat <i>et al.</i>             | (OSQAR Collab.)        |
| REESMAN       | 14  | JCAP 1408 021                 | R. Reesman <i>et al.</i>            | (OSU)                  |
| ABE           | 13D | PL B724 46                    | K. Abe <i>et al.</i>                | (XMASS Collab.)        |
| ABRAMOWSKI    | 13A | PR D88 102003                 | A. Abramowski <i>et al.</i>         | (H.E.S.S. Collab.)     |
| ADLARSON      | 13  | PL B726 187                   | P. Adlarson <i>et al.</i>           | (WASA-at-COSY Collab.) |
| ALESSANDRIA   | 13  | JCAP 1305 007                 | F. Alessandria <i>et al.</i>        | (CUORE Collab.)        |
| AN            | 13B | PL B725 190                   | H. An, M. Pospelov, J. Pradler      |                        |
| AN            | 13C | PRL 111 041302                | H. An, M. Pospelov, J. Pradler      |                        |
| ARCHIDIACO... | 13A | JCAP 1310 020                 | M. Archidiacono <i>et al.</i>       |                        |
| ARMENGAUD     | 13  | JCAP 1311 067                 | E. Armengaud <i>et al.</i>          | (EDELWEISS-II Collab.) |
| BABUSCI       | 13B | PL B720 111                   | D. Babusci <i>et al.</i>            | (KLOE-2 Collab.)       |
| BARTH         | 13  | JCAP 1305 010                 | K. Barth <i>et al.</i>              | (CAST Collab.)         |
| BECK          | 13  | PRL 111 231801                | C. Beck                             |                        |
| BETZ          | 13  | PR D88 075014                 | M. Betz <i>et al.</i>               | (CROWS Collab.)        |
| BULATOWICZ    | 13  | PRL 111 102001                | M. Bulatowicz <i>et al.</i>         |                        |
| CHU           | 13  | PR D87 011105                 | P.-H. Chu <i>et al.</i>             | (DUKE, IND, SJTU)      |
| DERBIN        | 13  | EPJ C73 2490                  | A. V. Derbin <i>et al.</i>          |                        |
| DIAMOND       | 13  | PRL 111 221803                | M.D. Diamond, P. Schuster           |                        |
| FRIEDLAND     | 13  | PRL 110 061101                | A. Friedland, M. Giannotti, M. Wise |                        |
| HECKEL        | 13  | PRL 111 151802                | B. R. Heckel <i>et al.</i>          |                        |
| HORVAT        | 13  | PL B721 220                   | R. Horvat <i>et al.</i>             |                        |
| INADA         | 13  | PL B722 301                   | T. Inada <i>et al.</i>              |                        |
| LATTANZI      | 13  | PR D88 063528                 | M. Lattanzi <i>et al.</i>           |                        |
| MEYER         | 13  | PR D87 035027                 | M. Meyer, D. Horns, M. Raue         |                        |
| MIZUMOTO      | 13  | JCAP 1307 013                 | T. Mizumoto <i>et al.</i>           |                        |
| PARKER        | 13  | PR D88 112004                 | S. Parker <i>et al.</i>             |                        |
| REDONDO       | 13  | JCAP 1308 034                 | J. Redondo, G. Raffelt              |                        |
| TULLNEY       | 13  | PRL 111 100801                | K. Tullney <i>et al.</i>            |                        |
| VIAUX         | 13A | PRL 111 231301                | N. Viaux <i>et al.</i>              |                        |
| WOUTERS       | 13  | APJ 772 44                    | D. Wouters, P. Brun                 | (SACL)                 |
| ABLIKIM       | 12  | PR D85 092012                 | M. Ablikim <i>et al.</i>            | (BES III Collab.)      |
| ARCHILLI      | 12  | PL B706 251                   | F. Archilli <i>et al.</i>           | (KLOE-2 Collab.)       |
| BELLI         | 12  | PL B711 41                    | P. Belli <i>et al.</i>              | (DAMA-KIEV)            |
| BELLINI       | 12B | PR D85 092003                 | G. Bellini <i>et al.</i>            | (Borexino Collab.)     |
| CADAMURO      | 12  | JCAP 1202 032                 | D. Cadamuro <i>et al.</i>           | (MPIM)                 |
| CORSICO       | 12  | JCAP 1212 010                 | A.H. Corsico <i>et al.</i>          | (LAPL, RGSUL, WASH+)   |
| DERBIN        | 12  | JETPL 95 339                  | A.V. Derbin <i>et al.</i>           | (PNPI)                 |
|               |     | Translated from ZETFP 95 379. |                                     |                        |
| GANDO         | 12  | PR C86 021601                 | A. Gando <i>et al.</i>              | (KamLAND-Zen Collab.)  |
| GNINENKO      | 12A | PR D85 055027                 | S.N. Gninenko                       | (INRM)                 |
| GNINENKO      | 12B | PL B713 244                   | S.N. Gninenko                       | (INRM)                 |
| PAYEZ         | 12  | JCAP 1207 041                 | A. Payez <i>et al.</i>              | (LIEG)                 |
| RAFFELT       | 12  | PR D86 015001                 | G. Raffelt                          | (MPIM)                 |
| AALSETH       | 11  | PRL 106 131301                | C.E. Aalseth <i>et al.</i>          | (CoGeNT Collab.)       |
| ABRAHAMY...   | 11  | PRL 107 191804                | S. Abrahamyan <i>et al.</i>         |                        |

|               |     |                               |                                      |                     |
|---------------|-----|-------------------------------|--------------------------------------|---------------------|
| ARIK          | 11  | PRL 107 261302                | M. Arik <i>et al.</i>                | (CAST Collab.)      |
| ARNOLD        | 11  | PRL 107 062504                | R. Arnold <i>et al.</i>              | (NEMO-3 Collab.)    |
| BLUEMLEIN     | 11  | PL B701 155                   | J. Bluemlein, J. Brunner             | (DESY)              |
| CADAMURO      | 11  | JCAP 1102 003                 | D. Cadamuro <i>et al.</i>            | (MPIM, AARHUS)      |
| DERBIN        | 11  | PAN 74 596                    | A.V. Derbin <i>et al.</i>            | (PNPI)              |
| DERBIN        | 11A | PR D83 023505                 | A.V. Derbin <i>et al.</i>            | (PNPI)              |
| HOEDL         | 11  | PRL 106 041801                | S.A. Hoedl <i>et al.</i>             | (WASH)              |
| HOSKINS       | 11  | PR D84 121302                 | J. Hoskins <i>et al.</i>             | (ADMX Collab.)      |
| ANDRIAMON...  | 10  | JCAP 1003 032                 | S. Andriamonje <i>et al.</i>         | (CAST Collab.)      |
| ARGYRIADES    | 10  | NP A847 168                   | J. Argyriades <i>et al.</i>          | (NEMO-3 Collab.)    |
| ASZTALOS      | 10  | PRL 104 041301                | S.J. Asztalos <i>et al.</i>          | (ADMX Collab.)      |
| EHRET         | 10  | PL B689 149                   | K. Ehret <i>et al.</i>               | (ALPS Collab.)      |
| HANNESTAD     | 10  | JCAP 1008 001                 | S. Hannestad <i>et al.</i>           |                     |
| PETUKHOV      | 10  | PRL 105 170401                | A.K. Petukhov <i>et al.</i>          |                     |
| SEREBROV      | 10  | JETPL 91 6                    | A. Serebrov <i>et al.</i>            |                     |
| AHMED         | 09A | PRL 103 141802                | Z. Ahmed <i>et al.</i>               | (CDMS Collab.)      |
| ANDRIAMON...  | 09  | JCAP 0912 002                 | S. Andriamonje <i>et al.</i>         |                     |
| ARGYRIADES    | 09  | PR C80 032501                 | J. Argyriades <i>et al.</i>          | (NEMO-3 Collab.)    |
| ARIK          | 09  | JCAP 0902 008                 | E. Arik <i>et al.</i>                | (CAST Collab.)      |
| BJORKEN       | 09  | PR D80 075018                 | J. Bjorken <i>et al.</i>             |                     |
| CHOU          | 09  | PRL 102 030402                | A.S. Chou <i>et al.</i>              | (GammeV Collab.)    |
| DAVOUDIASEL   | 09  | PR D79 095024                 | H. Davoudiasl, P. Huber              |                     |
| DERBIN        | 09A | PL B678 181                   | A.V. Derbin <i>et al.</i>            |                     |
| GONDOLLO      | 09  | PR D79 107301                 | P. Gondolo, G. Raffelt               | (UTAH, MPIM)        |
| IGNATOVICH    | 09  | EPJ C64 19                    | V.K. Ignatovich, Y.N. Pokotilovski   | (JINR)              |
| KEKEZ         | 09  | PL B671 345                   | D. Kekez <i>et al.</i>               |                     |
| SEREBROV      | 09  | PL B680 423                   | A. Serebrov                          | (PNPI)              |
| AFANASEV      | 08  | PRL 101 120401                | A. Afanasev <i>et al.</i>            |                     |
| BELLINI       | 08  | EPJ C54 61                    | G. Bellini <i>et al.</i>             | (Borexino Collab.)  |
| CHOU          | 08  | PRL 100 080402                | A.S. Chou <i>et al.</i>              | (GammeV Collab.)    |
| FOUCHE        | 08  | PR D78 032013                 | M. Fouche <i>et al.</i>              |                     |
| HANNESTAD     | 08  | JCAP 0804 019                 | S. Hannestad <i>et al.</i>           |                     |
| INOUE         | 08  | PL B668 93                    | Y. Inoue <i>et al.</i>               |                     |
| ZAVATTINI     | 08  | PR D77 032006                 | E. Zavattini <i>et al.</i>           | (PVLAS Collab.)     |
| ADELBERGER    | 07  | PRL 98 131104                 | E.G. Adelberger <i>et al.</i>        |                     |
| ANDRIAMON...  | 07  | JCAP 0704 010                 | S. Andriamonje <i>et al.</i>         | (CAST Collab.)      |
| BAESSLER      | 07  | PR D75 075006                 | S. Baessler <i>et al.</i>            |                     |
| CHANG         | 07  | PR D75 052004                 | H.M. Chang <i>et al.</i>             | (TEXONO Collab.)    |
| HANNESTAD     | 07  | JCAP 0708 015                 | S. Hannestad <i>et al.</i>           |                     |
| JAIN          | 07  | JP G34 129                    | P.L. Jain, G. Singh                  |                     |
| LESSA         | 07  | PR D75 094001                 | A.P. Lessa, O.L.G. Peres             |                     |
| MELCHIORRI    | 07A | PR D76 041303                 | A. Melchiorri, O. Mena, A. Slosar    |                     |
| ROBILLIARD    | 07  | PRL 99 190403                 | C. Robilliard <i>et al.</i>          |                     |
| ARNOLD        | 06  | NP A765 483                   | R. Arnold <i>et al.</i>              | (NEMO-3 Collab.)    |
| DUFFY         | 06  | PR D74 012006                 | L.D. Duffy <i>et al.</i>             |                     |
| HECKEL        | 06  | PRL 97 021603                 | B.R. Heckel <i>et al.</i>            |                     |
| ZAVATTINI     | 06  | PRL 96 110406                 | E. Zavattini <i>et al.</i>           | (PVLAS Collab.)     |
| HANNESTAD     | 05A | JCAP 0507 002                 | S. Hannestad, A. Mirizzi, G. Raffelt |                     |
| ZIOUTAS       | 05  | PRL 94 121301                 | K. Zioutas <i>et al.</i>             | (CAST Collab.)      |
| ADLER         | 04  | PR D70 037102                 | S. Adler <i>et al.</i>               | (BNL E787 Collab.)  |
| ANISIMOVSK... | 04  | PRL 93 031801                 | V.V. Anisimovsky <i>et al.</i>       | (BNL E949 Collab.)  |
| ARNOLD        | 04  | JETPL 80 377                  | R. Arnold <i>et al.</i>              | (NEMO-3 Collab.)    |
| ASZTALOS      | 04  | PR D69 011101                 | S.J. Asztalos <i>et al.</i>          |                     |
| HOFFMANN      | 04  | PR B70 180503                 | C. Hoffmann <i>et al.</i>            |                     |
| ARNABOLDI     | 03  | PL B557 167                   | C. Arnaboldi <i>et al.</i>           |                     |
| CIVITARESE    | 03  | NP A729 867                   | O. Civitarese, J. Suhonen            |                     |
| DANEVICH      | 03  | PR C68 035501                 | F.A. Danevich <i>et al.</i>          |                     |
| ADLER         | 02C | PL B537 211                   | S. Adler <i>et al.</i>               | (BNL E787 Collab.)  |
| BADERT...     | 02  | PL B542 29                    | A. Badertscher <i>et al.</i>         |                     |
| BERNABEI      | 02D | PL B546 23                    | R. Bernabei <i>et al.</i>            | (DAMA Collab.)      |
| DERBIN        | 02  | PAN 65 1302                   | A.V. Derbin <i>et al.</i>            |                     |
| FUSHIMI       | 02  | PL B531 190                   | K. Fushimi <i>et al.</i>             | (ELEGANT V Collab.) |
| INOUE         | 02  | PL B536 18                    | Y. Inoue <i>et al.</i>               |                     |
| MORALES       | 02B | ASP 16 325                    | A. Morales <i>et al.</i>             | (COSME Collab.)     |
| ADLER         | 01  | PR D63 032004                 | S. Adler <i>et al.</i>               | (BNL E787 Collab.)  |
| AMMAR         | 01B | PRL 87 271801                 | R. Ammar <i>et al.</i>               | (CLEO Collab.)      |
| ASHITKOV      | 01  | JETPL 74 529                  | V.D. Ashitkov <i>et al.</i>          |                     |
|               |     | Translated from ZETFP 74 601. |                                      |                     |



|              |     |                      |  |                          |
|--------------|-----|----------------------|--|--------------------------|
| BERNABEI     | 01B | PL B515 6            | R. Bernabei <i>et al.</i>                            | (DAMA Collab.)           |
| DANEVICH     | 01  | NP A694 375          | F.A. Danevich <i>et al.</i>                          |                          |
| DEBOER       | 01  | JP G27 L29           | F.W.N. de Boer <i>et al.</i>                         |                          |
| STOICA       | 01  | NP A694 269          | S. Stoica, H.V. Klapdor-Kleingrothous                |                          |
| ALESSAND...  | 00  | PL B486 13           | A. Alessandrello <i>et al.</i>                       |                          |
| ARNOLD       | 00  | NP A678 341          | R. Arnold <i>et al.</i>                              |                          |
| ASTIER       | 00B | PL B479 371          | P. Astier <i>et al.</i>                              | (NOMAD Collab.)          |
| DANEVICH     | 00  | PR C62 045501        | F.A. Danevich <i>et al.</i>                          |                          |
| MASSO        | 00  | PR D61 011701        | E. Masso   |                          |
| ARNOLD       | 99  | NP A658 299          | R. Arnold <i>et al.</i>                              | (NEMO Collab.)           |
| NI           | 99  | PRL 82 2439          | W.-T. Ni <i>et al.</i>                               |                          |
| SIMKOVIC     | 99  | PR C60 055502        | F. Simkovic <i>et al.</i>                            |                          |
| ALTEGOER     | 98  | PL B428 197          | J. Altegoer <i>et al.</i>                            |                          |
| ARNOLD       | 98  | NP A636 209          | R. Arnold <i>et al.</i>                              | (NEMO-2 Collab.)         |
| AVIGNONE     | 98  | PRL 81 5068          | F.T. Avignone <i>et al.</i>                          | (Solar Axion Experiment) |
| DIAZ         | 98  | NP B527 44           | M.A. Diaz <i>et al.</i>                              |                          |
| FAESSLER     | 98B | JP G24 2139          | A. Faessler, F. Simkovic                             |                          |
| KIM          | 98  | PR D58 055006        | J.E. Kim   |                          |
| LUESCHER     | 98  | PL B434 407          | R. Luescher <i>et al.</i>                            |                          |
| MORIYAMA     | 98  | PL B434 147          | S. Moriyama <i>et al.</i>                            |                          |
| MOROI        | 98  | PL B440 69           | T. Moroi, H. Murayama                                |                          |
| POSPELOV     | 98  | PR D58 097703        | M. Pospelov  |                          |
| ZUBER        | 98  | PRPL 305 295         | K. Zuber   |                          |
| AHMAD        | 97  | PRL 78 618           | I. Ahmad <i>et al.</i>                               | (APEX Collab.)           |
| BORISOV      | 97  | JETP 83 868          | A.V. Borisov, V.Y. Grishinia                         | (MOSU)                   |
| DEBOER       | 97C | JP G23 L85           | F.W.N. de Boer <i>et al.</i>                         |                          |
| KACHELRIESS  | 97  | PR D56 1313          | M. Kachelriess, C. Wilke, G. Wunner                  | (BOCH)                   |
| KEIL         | 97  | PR D56 2419          | W. Keil <i>et al.</i>                                |                          |
| KITCHING     | 97  | PRL 79 4079          | P. Kitching <i>et al.</i>                            | (BNL E787 Collab.)       |
| LEINBERGER   | 97  | PL B394 16           | U. Leinberger <i>et al.</i>                          | (ORANGE Collab.)         |
| ADLER        | 96  | PRL 76 1421          | S. Adler <i>et al.</i>                               | (BNL E787 Collab.)       |
| AMSLER       | 96B | ZPHY C70 219         | C. Amsler <i>et al.</i>                              | (Crystal Barrel Collab.) |
| GANZ         | 96  | PL B389 4            | R. Ganz <i>et al.</i>                                | (GSI, HEID, FRAN, JAGL+) |
| GUENTHER     | 96  | PR D54 3641          | M. Gunther <i>et al.</i>                             | (MPIH, SASSO)            |
| KAMEL        | 96  | PL B368 291          | S. Kamel   | (SHAMS)                  |
| MITSUI       | 96  | EPL 33 111           | T. Mitsui <i>et al.</i>                              | (TOKY)                   |
| YODIN        | 96  | PRL 77 2170          | A.N. Youdin <i>et al.</i>                            | (AMHT, WASH)             |
| ALTMANN      | 95  | ZPHY C68 221         | M. Altmann <i>et al.</i>                             | (MUNT, LAPP, CPPM)       |
| BASSOMPIE... | 95  | PL B355 584          | G. Bassompierre <i>et al.</i>                        | (LAPP, LCGT, LYON)       |
| MAENO        | 95  | PL B351 574          | T. Maeno <i>et al.</i>                               | (TOKY)                   |
| RAFFELT      | 95  | PR D51 1495          | G. Raffelt, A. Weiss                                 | (MPIM, MPIG)             |
| SKALSEY      | 95  | PR D51 6292          | M. Skalsey, R.S. Conti                               | (MICH)                   |
| TSUNODA      | 95  | EPL 30 273           | T. Tsunoda <i>et al.</i>                             | (TOKY)                   |
| ADACHI       | 94  | PR A49 3201          | S. Adachi <i>et al.</i>                              | (TMU)                    |
| ALTHERR      | 94  | ASP 2 175            | T. Altherr, E. Petitgirard, T. del Rio Gaztelurrutia |                          |
| AMSLER       | 94B | PL B333 271          | C. Amsler <i>et al.</i>                              | (Crystal Barrel Collab.) |
| ASAI         | 94  | PL B323 90           | S. Asai <i>et al.</i>                                | (TOKY)                   |
| MEIJERDREES  | 94  | PR D49 4937          | M.R. Drees <i>et al.</i>                             | (BRCO, OREG, TRIU)       |
| NI           | 94  | Physica B194 153     | W.T. Ni <i>et al.</i>                                | (NTHU)                   |
| VO           | 94  | PR C49 1551          | D.T. Vo <i>et al.</i>                                | (ISU, LBL, LLNL, UCD)    |
| ATIYA        | 93  | PRL 70 2521          | M.S. Atiya <i>et al.</i>                             | (BNL E787 Collab.)       |
| Also         |     | PRL 71 305 (erratum) | M.S. Atiya <i>et al.</i>                             | (BNL E787 Collab.)       |
| ATIYA        | 93B | PR D48 1             | M.S. Atiya <i>et al.</i>                             | (BNL E787 Collab.)       |
| BASSOMPIE... | 93  | EPL 22 239           | G. Bassompierre <i>et al.</i>                        | (LAPP, TORI, LYON)       |
| BECK         | 93  | PRL 70 2853          | M. Beck <i>et al.</i>                                | (MPIH, KIAE, SASSO)      |
| CAMERON      | 93  | PR D47 3707          | R.E. Cameron <i>et al.</i>                           | (ROCH, BNL, FNAL+)       |
| CHANG        | 93  | PL B316 51           | S. Chang, K. Choi                                    |                          |
| CHUI         | 93  | PRL 71 3247          | T.C.P. Chui, W.T. Ni                                 | (NTHU)                   |
| MINOWA       | 93  | PRL 71 4120          | M. Minowa <i>et al.</i>                              | (TOKY)                   |
| NG           | 93  | PR D48 2941          | K.W. Ng  | (AST)                    |
| RITTER       | 93  | PRL 70 701           | R.C. Ritter <i>et al.</i>                            |                          |
| TANAKA       | 93  | PR D48 5412          | J. Tanaka, H. Ejiri                                  | (OSAK)                   |
| ALLIEGRO     | 92  | PRL 68 278           | C. Alliegro <i>et al.</i>                            | (BNL, FNAL, PSI+)        |
| ATIYA        | 92  | PRL 69 733           | M.S. Atiya <i>et al.</i>                             | (BNL, LANL, PRIN+)       |
| BARABASH     | 92  | PL B295 154          | L.S. Barabash <i>et al.</i>                          | (JINR, CERN, SERP+)      |
| BERNATOW...  | 92  | PRL 69 2341          | T. Bernatowicz <i>et al.</i>                         | (WUSL, TATA)             |
| BLUEMLEIN    | 92  | IJMP A7 3835         | J. Bluemlein <i>et al.</i>                           | (BERL, BUDA, JINR+)      |
| HALLIN       | 92  | PR D45 3955          | A.L. Hallin <i>et al.</i>                            | (PRIN)                   |
| HENDERSON    | 92C | PRL 69 1733          | S.D. Henderson <i>et al.</i>                         | (YALE, BNL)              |
| HICKS        | 92  | PL B276 423          | K.H. Hicks, D.E. Alburger                            | (OHIO, BNL)              |
| LAZARUS      | 92  | PRL 69 2333          | D.M. Lazarus <i>et al.</i>                           | (BNL, ROCH, FNAL)        |

|             |     |                               |   |                          |
|-------------|-----|-------------------------------|---|--------------------------|
| MEIJERDREES | 92  | PRL 68 3845                   | R. Meijer Drees <i>et al.</i>           | (SINDRUM I Collab.)      |
| PAN         | 92  | MPL A7 1287                   | S.S. Pan, W.T. Ni, S.C. Chen            | (NTHU)                   |
| RUOSO       | 92  | ZPHY C56 505                  | G. Ruoso <i>et al.</i>                  | (ROCH, BNL, FNAL, TRST)  |
| SKALSEY     | 92  | PRL 68 456                    | M. Skalsey, J.J. Kolata                 | (MICH, NDAM)             |
| VENEMA      | 92  | PRL 68 135                    | B.J. Venema <i>et al.</i>               |                          |
| WANG        | 92  | MPL A7 1497                   | J. Wang                                 | (ILL)                    |
| WANG        | 92C | PL B291 97                    | J. Wang                                 | (ILL)                    |
| WU          | 92  | PRL 69 1729                   | X.Y. Wu <i>et al.</i>                   | (BNL, YALE, CUNY)        |
| AKOPYAN     | 91  | PL B272 443                   | M.V. Akopyan <i>et al.</i>              | (INRM)                   |
| ASAI        | 91  | PRL 66 2440                   | S. Asai <i>et al.</i>                   | (ICEPP)                  |
| BERSHADY    | 91  | PRL 66 1398                   | M.A. Bershad, M.T. Ressell, M.S. Turner | (CHIC+)                  |
| BLUEMLEIN   | 91  | ZPHY C51 341                  | J. Bluemlein <i>et al.</i>              | (BERL, BUDA, JINR+)      |
| BOBRAKOV    | 91  | JETPL 53 294                  | V.F. Bobrakov <i>et al.</i>             | (PNPI)                   |
|             |     | Translated from ZETFP 53 283. |   |                          |
| BROSS       | 91  | PRL 67 2942                   | A.D. Bross <i>et al.</i>                | (FNAL, ILL)              |
| KIM         | 91C | PRL 67 3465                   | J.E. Kim                                | (SEOUL)                  |
| RAFFELT     | 91  | PRPL 198 1                    | G.G. Raffelt                            | (MPIM)                   |
| RAFFELT     | 91B | PRL 67 2605                   | G. Raffelt, D. Seckel                   | (MPIM, BART)             |
| RESSELL     | 91  | PR D44 3001                   | M.T. Ressell                            | (CHIC, FNAL)             |
| TRZASKA     | 91  | PL B269 54                    | W.H. Trzaska <i>et al.</i>              | (TAMU)                   |
| TSERTOS     | 91  | PL B266 259                   | H. Tsertos <i>et al.</i>                | (ILLG, GSI)              |
| WALKER      | 91  | APJ 376 51                    | T.P. Walker <i>et al.</i>               | (HSCA, OSU, CHIC+)       |
| WIDMANN     | 91  | ZPHY A340 209                 | E. Widmann <i>et al.</i>                | (STUT, GSI, STUTM)       |
| WINELAND    | 91  | PRL 67 1735                   | D.J. Wineland <i>et al.</i>             | (NBSB)                   |
| ALBRECHT    | 90E | PL B246 278                   | H. Albrecht <i>et al.</i>               | (ARGUS Collab.)          |
| ANTREASYAN  | 90C | PL B251 204                   | D. Antreasyan <i>et al.</i>             | (Crystal Ball Collab.)   |
| ASANUMA     | 90  | PL B237 588                   | T. Asanuma <i>et al.</i>                | (TOKY)                   |
| ATIYA       | 90  | PRL 64 21                     | M.S. Atiya <i>et al.</i>                | (BNL E787 Collab.)       |
| ATIYA       | 90B | PRL 65 1188                   | M.S. Atiya <i>et al.</i>                | (BNL E787 Collab.)       |
| BAUER       | 90  | NIM B50 300                   | W. Bauer <i>et al.</i>                  | (STUT, VILL, GSI)        |
| BURROWS     | 90  | PR D42 3297                   | A. Burrows, M.T. Ressell, M.S. Turner   | (ARIZ+)                  |
| DEBOER      | 90  | JP G16 L1                     | F.W.N. de Boer, J. Lehmann, J. Steyaert | (LOUV)                   |
| ENGEL       | 90  | PRL 65 960                    | J. Engel, D. Seckel, A.C. Hayes         | (BART, LANL)             |
| GNINENKO    | 90  | PL B237 287                   | S.N. Gninenko <i>et al.</i>             | (INRM)                   |
| GUO         | 90  | PR D41 2924                   | R. Guo <i>et al.</i>                    | (NIU, LANL, FNAL, CASE+) |
| HAGMANN     | 90  | PR D42 1297                   | C. Haggmann <i>et al.</i>               | (FLOR)                   |
| JUDGE       | 90  | PRL 65 972                    | S.M. Judge <i>et al.</i>                | (ILLG, GSI)              |
| RAFFELT     | 90D | PR D41 1324                   | G.G. Raffelt                            | (MPIM)                   |
| RITTER      | 90  | PR D42 977                    | R.C. Ritter <i>et al.</i>               | (UVA)                    |
| SEMERTZIDIS | 90  | PRL 64 2988                   | Y.K. Semertzidis <i>et al.</i>          | (ROCH, BNL, FNAL+)       |
| TSUCHIAKI   | 90  | PL B236 81                    | M. Tsuchiaki <i>et al.</i>              | (ICEPP)                  |
| TURNER      | 90  | PRPL 197 67                   | M.S. Turner                             | (FNAL)                   |
| BARABASH    | 89  | PL B223 273                   | A.S. Barabash <i>et al.</i>             | (ITEP, INRM)             |
| BINI        | 89  | PL B221 99                    | M. Bini <i>et al.</i>                   | (FIRZ, CERN, AARH)       |
| BURROWS     | 89  | PR D39 1020                   | A. Burrows, M.S. Turner, R.P. Brinkmann | (ARIZ+)                  |
| Also        |     | PRL 60 1797                   | M.S. Turner                             | (FNAL, EFI)              |
| DEBOER      | 89B | PRL 62 2639                   | F.W.N. de Boer, R. van Dantzig          | (ANIK)                   |
| ERICSON     | 89  | PL B219 507                   | T.E.O. Ericson, J.F. Mathiot            | (CERN, IPN)              |
| FAISSNER    | 89  | ZPHY C44 557                  | H. Faissner <i>et al.</i>               | (AACH3, BERL, PSI)       |
| FOX         | 89  | PR C39 288                    | J.D. Fox <i>et al.</i>                  | (FSU)                    |
| MAYLE       | 89  | PL B219 515                   | R. Mayle <i>et al.</i>                  | (LLL, CERN, MINN, FNAL+) |
| Also        |     | PL B203 188                   | R. Mayle <i>et al.</i>                  | (LLL, CERN, MINN, FNAL+) |
| MINOWA      | 89  | PRL 62 1091                   | H. Minowa <i>et al.</i>                 | (ICEPP)                  |
| ORITO       | 89  | PRL 63 597                    | S. Orito <i>et al.</i>                  | (ICEPP)                  |
| PERKINS     | 89  | PRL 62 2638                   | D.H. Perkins                            | (OXF)                    |
| TSERTOS     | 89  | PR D40 1397                   | H. Tsertos <i>et al.</i>                | (GSI, ILLG)              |
| VANBIBBER   | 89  | PR D39 2089                   | K. van Bibber <i>et al.</i>             | (LLL, TAMU, LBL)         |
| WUENSCH     | 89  | PR D40 3153                   | W.U. Wuensch <i>et al.</i>              | (ROCH, BNL, FNAL)        |
| Also        |     | PRL 59 839                    | S. de Panfilis <i>et al.</i>            | (ROCH, BNL, FNAL)        |
| AVIGNONE    | 88  | PR D37 618                    | F.T. Avignone <i>et al.</i>             | (PRIN, SCUC, ORNL+)      |
| BALKE       | 88  | PR D37 587                    | B. Balke <i>et al.</i>                  | (LBL, UCB, COLO, NWES+)  |
| BJORKEN     | 88  | PR D38 3375                   | J.D. Bjorken <i>et al.</i>              | (FNAL, SLAC, VPI)        |
| BLINOV      | 88  | SJNP 47 563                   | A.E. Blinov <i>et al.</i>               | (NOVO)                   |
|             |     | Translated from YAF 47 889.   |   |                          |
| BOLTON      | 88  | PR D38 2077                   | R.D. Bolton <i>et al.</i>               | (LANL, STAN, CHIC+)      |
| Also        |     | PRL 56 2461                   | R.D. Bolton <i>et al.</i>               | (LANL, STAN, CHIC+)      |
| Also        |     | PRL 57 3241                   | D. Grosnick <i>et al.</i>               | (CHIC, LANL, STAN+)      |
| CHANDA      | 88  | PR D37 2714                   | R. Chanda, J.F. Nieves, P.B. Pal        | (UMD, UPR+)              |
| CHOI        | 88  | PR D37 3225                   | K. Choi <i>et al.</i>                   | (JHU)                    |
| CONNELL     | 88  | PRL 60 2242                   | S.H. Connell <i>et al.</i>              | (WITW)                   |
| DATAR       | 88  | PR C37 250                    | V.M. Datar <i>et al.</i>                | (IPN)                    |

|               |     |                               |  |                          |
|---------------|-----|-------------------------------|--|--------------------------|
| DEBOER        | 88  | PRL 61 1274                   | F.W.N. de Boer, R. van Dantzig             | (ANIK)                   |
| Also          |     | PRL 62 2644 (erratum)         | F.W.N. de Boer, R. van Dantzig             | (ANIK)                   |
| Also          |     | PRL 62 2638                   | D.H. Perkins                               | (OXF)                    |
| Also          |     | PRL 62 2639                   | F.W.N. de Boer, R. van Dantzig             | (ANIK)                   |
| DEBOER        | 88C | JP G14 L131                   | F.W.N. de Boer <i>et al.</i>               | (LOUV)                   |
| DOEHNER       | 88  | PR D38 2722                   | J. Dohner <i>et al.</i>                    | (HEIDP, ANL, ILLG)       |
| EL-NADI       | 88  | PRL 61 1271                   | M. el Nadi, O.E. Badawy                    | (CAIR)                   |
| ENGEL         | 88  | PR C37 731                    | J. Engel, P. Vogel, M.R. Zirnbauer         |                          |
| FAISSNER      | 88  | ZPHY C37 231                  | H. Faissner <i>et al.</i>                  | (AACH3, BERL, SIN)       |
| HATSUDA       | 88B | PL B203 469                   | T. Hatsuda, M. Yoshimura                   | (KEK)                    |
| LORENZ        | 88  | PL B214 10                    | E. Lorenz <i>et al.</i>                    | (MPIM, PSI)              |
| MAYLE         | 88  | PL B203 188                   | R. Mayle <i>et al.</i>                     | (LLL, CERN, MINN, FNAL+) |
| PICCIOTTO     | 88  | PR D37 1131                   | C.E. Picciotto <i>et al.</i>               | (TRIU, CNRC)             |
| RAFFELT       | 88  | PRL 60 1793                   | G. Raffelt, D. Seckel                      | (UCB, LLL, UCSC)         |
| RAFFELT       | 88B | PR D37 549                    | G.G. Raffelt, D.S.P. Dearborn              | (UCB, LLL)               |
| SAVAGE        | 88  | PR D37 1134                   | M.J. Savage, B.W. Filippone, L.W. Mitchell | (CIT)                    |
| TSERTOS       | 88  | PL B207 273                   | A. Tsertos <i>et al.</i>                   | (GSI, ILLG)              |
| TSERTOS       | 88B | ZPHY A331 103                 | A. Tsertos <i>et al.</i>                   | (GSI, ILLG)              |
| VANKLINKEN    | 88  | PL B205 223                   | J. van Klinken <i>et al.</i>               | (GRON, GSI)              |
| VANKLINKEN    | 88B | PRL 60 2442                   | J. van Klinken                             | (GRON)                   |
| VONWIMMER...  | 88  | PRL 60 2443                   | U. von Wimmersperg                         | (BNL)                    |
| VOROBYOV      | 88  | PL B208 146                   | P.V. Vorobiev, Y.I. Gitarts                | (NOVO)                   |
| DRUZHININ     | 87  | ZPHY C37 1                    | V.P. Druzhinin <i>et al.</i>               | (NOVO)                   |
| FRIEMAN       | 87  | PR D36 2201                   | J.A. Frieman, S. Dimopoulos, M.S. Turner   | (SLAC+)                  |
| GOLDMAN       | 87  | PR D36 1543                   | T. Goldman <i>et al.</i>                   | (LANL, CHIC, STAN+)      |
| KORENCHE...   | 87  | SJNP 46 192                   | S.M. Korenchenko <i>et al.</i>             | (JINR)                   |
|               |     | Translated from YAF 46 313.   |  |                          |
| MAIER         | 87  | ZPHY A326 527                 | K. Maier <i>et al.</i>                     | (STUT, GSI)              |
| MILLS         | 87  | PR D36 707                    | A.P. Mills, J. Levy                        | (BELL)                   |
| RAFFELT       | 87  | PR D36 2211                   | G.G. Raffelt, D.S.P. Dearborn              | (LLL, UCB)               |
| RIORDAN       | 87  | PRL 59 755                    | E.M. Riordan <i>et al.</i>                 | (ROCH, CIT+)             |
| TURNER        | 87  | PRL 59 2489                   | M.S. Turner                                | (FNAL, EFI)              |
| VANBIBBER     | 87  | PRL 59 759                    | K. van Bibber <i>et al.</i>                | (LLL, CIT, MIT+)         |
| VONWIMMER...  | 87  | PRL 59 266                    | U. von Wimmersperg <i>et al.</i>           | (WITW)                   |
| BADIER        | 86  | ZPHY C31 21                   | J. Badier <i>et al.</i>                    | (NA3 Collab.)            |
| BROWN         | 86  | PRL 57 2101                   | C.N. Brown <i>et al.</i>                   | (FNAL, WASH, KYOT+)      |
| BRYMAN        | 86B | PRL 57 2787                   | D.A. Bryman, E.T.H. Clifford               | (TRIU)                   |
| DAVIER        | 86  | PL B180 295                   | M. Davier, J. Jeanjean, H. Nguyen Ngoc     | (LALO)                   |
| DEARBORN      | 86  | PRL 56 26                     | D.S.P. Dearborn, D.N. Schramm, G. Steigman | (LLL+)                   |
| EICHLER       | 86  | PL B175 101                   | R.A. Eichler <i>et al.</i>                 | (SINDRUM Collab.)        |
| HALLIN        | 86  | PRL 57 2105                   | A.L. Hallin <i>et al.</i>                  | (PRIN)                   |
| JODIDIO       | 86  | PR D34 1967                   | A. Jodidio <i>et al.</i>                   | (LBL, NWES, TRIU)        |
| Also          |     | PR D37 237 (erratum)          | A. Jodidio <i>et al.</i>                   | (LBL, NWES, TRIU)        |
| KETOV         | 86  | JETPL 44 146                  | S.N. Ketov <i>et al.</i>                   | (KIAE)                   |
|               |     | Translated from ZETFP 44 114. |  |                          |
| KOCH          | 86  | NC 96A 182                    | H.R. Koch, O.W.B. Schult                   | (JULI)                   |
| KONAKA        | 86  | PRL 57 659                    | A. Konaka <i>et al.</i>                    | (KYOT, KEK)              |
| MAIANI        | 86  | PL B175 359                   | L. Maiani, R. Petronzio, E. Zavattini      | (CERN)                   |
| PECCEI        | 86  | PL B172 435                   | R.D. Peccei, T.T. Wu, T. Yanagida          | (DESY)                   |
| RAFFELT       | 86  | PR D33 897                    | G.G. Raffelt                               | (MPIM)                   |
| RAFFELT       | 86B | PL 166B 402                   | G.G. Raffelt                               | (MPIM)                   |
| SAVAGE        | 86B | PRL 57 178                    | M.J. Savage <i>et al.</i>                  | (CIT)                    |
| AMALDI        | 85  | PL 153B 444                   | U. Amaldi <i>et al.</i>                    | (CERN)                   |
| ANANEV        | 85  | SJNP 41 585                   | V.D. Ananev <i>et al.</i>                  | (JINR)                   |
|               |     | Translated from YAF 41 912.   |  |                          |
| BALTRUSAIT... | 85  | PRL 55 1842                   | R.M. Baltrusaitis <i>et al.</i>            | (Mark III Collab.)       |
| BERGSMA       | 85  | PL 157B 458                   | F. Bergsma <i>et al.</i>                   | (CHARM Collab.)          |
| KAPLAN        | 85  | NP B260 215                   | D.B. Kaplan                                | (HARV)                   |
| IWAMOTO       | 84  | PRL 53 1198                   | N. Iwamoto                                 | (UCSB, WUSL)             |
| YAMAZAKI      | 84  | PRL 52 1089                   | T. Yamazaki <i>et al.</i>                  | (INUS, KEK)              |
| ABBOTT        | 83  | PL 120B 133                   | L.F. Abbott, P. Sikivie                    | (BRAN, FLOR)             |
| CARBONI       | 83  | PL 123B 349                   | G. Carboni, W. Dahme                       | (CERN, MUNI)             |
| CAVAIGNAC     | 83  | PL 121B 193                   | J.F. Cavaignac <i>et al.</i>               | (ISNG, LAPP)             |
| DICUS         | 83  | PR D28 1778                   | D.A. Dicus, V.L. Teplitz                   | (TEXA, UMD)              |
| DINE          | 83  | PL 120B 137                   | M. Dine, W. Fischler                       | (IAS, PENN)              |
| ELLIS         | 83B | NP B223 252                   | J. Ellis, K.A. Olive                       | (CERN)                   |
| FAISSNER      | 83  | PR D28 1198                   | H. Faissner <i>et al.</i>                  | (AACH)                   |
| FAISSNER      | 83B | PR D28 1787                   | H. Faissner <i>et al.</i>                  | (AACH3)                  |
| FRANK         | 83B | PR D28 1790                   | J.S. Frank <i>et al.</i>                   | (LANL, YALE, LBL+)       |
| HOFFMAN       | 83  | PR D28 660                    | C.M. Hoffman <i>et al.</i>                 | (LANL, ARZS)             |
| PRESKILL      | 83  | PL 120B 127                   | J. Preskill, M.B. Wise, F. Wilczek         | (HARV, UCSBT)            |

|             |     |                          |   |                         |
|-------------|-----|--------------------------|---|-------------------------|
| SIKIVIE     | 83  | PRL 51 1415              | P. Sikivie                                  | (FLOR)                  |
| Also        |     | PRL 52 695 (erratum)     | P. Sikivie                                  | (FLOR)                  |
| ALEKSEEV    | 82  | JETP 55 591              | E.A. Alekseeva <i>et al.</i>                | (KIAE)                  |
|             |     | Translated from ZETF 82  | 1007.                                       |                         |
| ALEKSEEV    | 82B | JETPL 36 116             | G.D. Alekseev <i>et al.</i>                 | (MOSU, JINR)            |
|             |     | Translated from ZETFP 36 | 94.   |                         |
| ASANO       | 82  | PL 113B 195              | Y. Asano <i>et al.</i>                      | (KEK, TOKY, INUS, OSAK) |
| BARROSO     | 82  | PL 116B 247              | A. Barroso, G.C. Branco                     | (LISB)                  |
| DATAR       | 82  | PL 114B 63               | V.M. Datar <i>et al.</i>                    | (BHAB)                  |
| EDWARDS     | 82  | PRL 48 903               | C. Edwards <i>et al.</i>                    | (Crystal Ball Collab.)  |
| FETSCHER    | 82  | JP G8 L147               | W. Fetscher                                 | (ETH)                   |
| FUKUGITA    | 82  | PRL 48 1522              | M. Fukugita, S. Watamura, M. Yoshimura      | (KEK)                   |
| FUKUGITA    | 82B | PR D26 1840              | M. Fukugita, S. Watamura, M. Yoshimura      | (KEK)                   |
| LEHMANN     | 82  | PL 115B 270              | P. Lehmann <i>et al.</i>                    | (SACL)                  |
| RAFFELT     | 82  | PL 119B 323              | G. Raffelt, L. Stodolsky                    | (MPIM)                  |
| ZEHNDER     | 82  | PL 110B 419              | A. Zehnder, K. Gabathuler, J.L. Vuilleumier | (ETH+)                  |
| ASANO       | 81B | PL 107B 159              | Y. Asano <i>et al.</i>                      | (KEK, TOKY, INUS, OSAK) |
| BARROSO     | 81  | PL 106B 91               | A. Barroso, N.C. Mukhopadhyay               | (SIN)                   |
| FAISSNER    | 81  | ZPHY C10 95              | H. Faissner <i>et al.</i>                   | (AACH3)                 |
| FAISSNER    | 81B | PL 103B 234              | H. Faissner <i>et al.</i>                   | (AACH3)                 |
| KIM         | 81  | PL 105B 55               | B.R. Kim, C. Stamm                          | (AACH3)                 |
| VUILLEUMIER | 81  | PL 101B 341              | J.L. Vuilleumier <i>et al.</i>              | (CIT, MUNI)             |
| ZEHNDER     | 81  | PL 104B 494              | A. Zehnder                                  | (ETH)                   |
| FAISSNER    | 80  | PL 96B 201               | H. Faissner <i>et al.</i>                   | (AACH3)                 |
| JACQUES     | 80  | PR D21 1206              | P.F. Jacques <i>et al.</i>                  | (RUTG, STEV, COLU)      |
| SOUKAS      | 80  | PRL 44 564               | A. Soukas <i>et al.</i>                     | (BNL, HARV, ORNL, PENN) |
| BECHIS      | 79  | PRL 42 1511              | D.J. Bechis <i>et al.</i>                   | (UMD, COLU, AFRR)       |
| CALAPRICE   | 79  | PR D20 2708              | F.P. Calaprice <i>et al.</i>                | (PRIN)                  |
| COTEUS      | 79  | PRL 42 1438              | P. Coteus <i>et al.</i>                     | (COLU, ILL, BNL)        |
| DISHAW      | 79  | PL 85B 142               | J.P. Dishaw <i>et al.</i>                   | (SLAC, CIT)             |
| ZHITNITSKII | 79  | SJNP 29 517              | A.R. Zhitnitsky, Y.I. Skovpen               | (NOVO)                  |
|             |     | Translated from YAF 29   | 1001.                                       |                         |
| ALIBRAN     | 78  | PL 74B 134               | P. Alibran <i>et al.</i>                    | (Gargamelle Collab.)    |
| ASRATYAN    | 78B | PL 79B 497               | A.E. Asratyan <i>et al.</i>                 | (ITEP, SERP)            |
| BELLOTTI    | 78  | PL 76B 223               | E. Bellotti, E. Fiorini, L. Zanotti         | (MILA)                  |
| BOSETTI     | 78B | PL 74B 143               | P.C. Bosetti <i>et al.</i>                  | (BEBC Collab.)          |
| DICUS       | 78C | PR D18 1829              | D.A. Dicus <i>et al.</i>                    | (TEXA, VPI, STAN)       |
| DONNELLY    | 78  | PR D18 1607              | T.W. Donnelly <i>et al.</i>                 | (STAN)                  |
| Also        |     | PRL 37 315               | F. Reines, H.S. Gurr, H.W. Sobel            | (UCI)                   |
| Also        |     | PRL 33 179               | H.S. Gurr, F. Reines, H.W. Sobel            | (UCI)                   |
| HANSL       | 78D | PL 74B 139               | T. Hansl <i>et al.</i>                      | (CDHS Collab.)          |
| MICELMAC... | 78  | LNC 21 441               | G.V. Mitselmakher, B. Pontecorvo            | (JINR)                  |
| MIKAELIAN   | 78  | PR D18 3605              | K.O. Mikaelian                              | (FNAL, NWES)            |
| SATO        | 78  | PTP 60 1942              | K. Sato                                     | (KYOT)                  |
| VYSOTSKII   | 78  | JETPL 27 502             | M.I. Vysotsky <i>et al.</i>                 | (ASCI)                  |
|             |     | Translated from ZETFP 27 | 533.  |                         |
| YANG        | 78  | PRL 41 523               | T.C. Yang                                   | (MASA)                  |
| PECCEI      | 77  | PR D16 1791              | R.D. Peccei, H.R. Quinn                     | (STAN, SLAC)            |
| Also        |     | PRL 38 1440              | R.D. Peccei, H.R. Quinn                     | (STAN, SLAC)            |
| REINES      | 76  | PRL 37 315               | F. Reines, H.S. Gurr, H.W. Sobel            | (UCI)                   |
| GURR        | 74  | PRL 33 179               | H.S. Gurr, F. Reines, H.W. Sobel            | (UCI)                   |
| ANAND       | 53  | PRSL A22 183             | B.M. Anand                                  |                         |

### OTHER RELATED PAPERS

|           |    |             |                           |        |
|-----------|----|-------------|---------------------------|--------|
| SREDNICKI | 85 | NP B260 689 | M. Srednicki              | (UCSB) |
| BARDEEN   | 78 | PL 74B 229  | W.A. Bardeen, S.-H.H. Tye | (FNAL) |