

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

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

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

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

¹ Lower bound from 5.5 MeV γ -ray line from the sun.

² 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 Meson Decays

Limits are for branching ratios.

<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. ● ● ●					
<4.5 $\times 10^{-11}$	90		³ ADLER	02C B787	$K^+ \rightarrow \pi^+ A^0$
<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	$B^0 \rightarrow K_S^0 X^0$
<1.1 $\times 10^{-10}$	90		⁴ ADLER	00 B787	$K^+ \rightarrow \pi^+ A^0$
<3.3 $\times 10^{-5}$	90		⁵ ALTEGOER	98 NOMD	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 120$ MeV
<5.0 $\times 10^{-8}$	90		⁶ KITCHING	97 B787	$K^+ \rightarrow \pi^+ A^0$ ($A^0 \rightarrow \gamma\gamma$)
<5.2 $\times 10^{-10}$	90		⁷ ADLER	96 B787	$K^+ \rightarrow \pi^+ A^0$
<2.8 $\times 10^{-4}$	90		⁸ AMSLER	96B CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 65$ MeV
<3 $\times 10^{-4}$	90		⁸ AMSLER	96B CBAR	$\eta \rightarrow \gamma X^0$, $m_{X^0} =$ 50–200 MeV
<4 $\times 10^{-5}$	90		⁸ AMSLER	96B CBAR	$\eta' \rightarrow \gamma X^0$, $m_{X^0} = 50$ –925 MeV
<6 $\times 10^{-5}$	90		⁸ AMSLER	94B CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} = 65$ –125 MeV

<6	$\times 10^{-5}$	90	⁸ AMSLER	94B CBAR	$\eta \rightarrow \gamma X^0$, $m_{X^0}=200-525$ MeV
<0.007		90	⁹ MEIJERDREES	94 CNTR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0}=25$ MeV
<0.002		90	⁹ MEIJERDREES	94 CNTR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0}=100$ MeV
<2	$\times 10^{-7}$	90	¹⁰ ATIYA	93B B787	$K^+ \rightarrow \pi^+ A^0$
<3	$\times 10^{-13}$		¹¹ NG	93 COSM	$\pi^0 \rightarrow \gamma X^0$
<1.1	$\times 10^{-8}$	90	¹² ALLIEGRO	92 SPEC	$K^+ \rightarrow \pi^+ A^0$ ($A^0 \rightarrow e^+ e^-$)
<5	$\times 10^{-4}$	90	¹³ ATIYA	92 B787	$\pi^0 \rightarrow \gamma X^0$
<4	$\times 10^{-6}$	90	¹⁴ MEIJERDREES	92 SPEC	$\pi^0 \rightarrow \gamma X^0$, $X^0 \rightarrow e^+ e^-$, $m_{X^0}=100$ MeV
<1	$\times 10^{-7}$	90	¹⁵ ATIYA	90B B787	Sup. by KITCH- ING 97
<1.3	$\times 10^{-8}$	90	¹⁶ KORENCHE...	87 SPEC	$\pi^+ \rightarrow e^+ \nu A^0$ ($A^0 \rightarrow e^+ e^-$)
<1	$\times 10^{-9}$	90	0 ¹⁷ EICHLER	86 SPEC	Stopped $\pi^+ \rightarrow$ $e^+ \nu A^0$
<2	$\times 10^{-5}$	90	¹⁸ YAMAZAKI	84 SPEC	For $160 < m < 260$ MeV
<(1.5-4)	$\times 10^{-6}$	90	¹⁸ YAMAZAKI	84 SPEC	K decay, $m_{A^0} \ll$ 100 MeV
			0 ¹⁹ ASANO	82 CNTR	Stopped $K^+ \rightarrow$ $\pi^+ A^0$
			0 ²⁰ ASANO	81B CNTR	Stopped $K^+ \rightarrow$ $\pi^+ A^0$
			²¹ ZHITNITSKII	79	Heavy axion

³ ADLER 02C bound is for $m_{A^0} < 60$ MeV. See Fig. 2 for limits at higher masses.

⁴ ADLER 00 bound is for massless A^0 .

⁵ ALTEGOER 98 looked for X^0 from π^0 decay which penetrate the shielding and convert to π^0 in the external Coulomb field of a nucleus.

⁶ KITCHING 97 limit is for $B(K^+ \rightarrow \pi^+ A^0) \cdot B(A^0 \rightarrow \gamma\gamma)$ and applies for $m_{A^0} \simeq 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.

⁷ ADLER 96 looked for a peak in missing-mass distribution. This work is an update of ATIYA 93. The limit is for massless stable A^0 particles and extends to $m_{A^0}=80$ MeV at the same level. See paper for dependence on finite lifetime.

⁸ AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.

⁹ 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.

¹⁰ ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable A^0 of $m_{A^0}=150-250$ MeV, and the limit becomes stronger (10^{-8}) for $m_{A^0}=180-240$ MeV.

¹¹ 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 .

¹² ALLIEGRO 92 limit applies for $m_{A^0}=150-340$ MeV and is the branching ratio times the decay probability. Limit is $< 1.5 \times 10^{-8}$ at 99%CL.

- ¹³ 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.
- ¹⁴ MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}-10^{-11}$ sec. Limits between 2×10^{-4} and 4×10^{-6} are obtained for $m_{X^0} = 25-120$ MeV. Angular momentum conservation requires that X^0 has spin ≥ 1 .
- ¹⁵ ATIYA 90B limit is for $B(K^{\mp} \rightarrow \pi^{\pm} A^0) \cdot B(A^0 \rightarrow \gamma\gamma)$ and applies for $m_{A^0} = 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.
- ¹⁶ KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and $B(A^0 \rightarrow e^+ e^-) = 1$.
- ¹⁷ 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 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.
- ¹⁸ 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.
- ¹⁹ ASANO 82 at KEK set limits for $B(K^+ \rightarrow \pi^+ A^0)$ for $m_{A^0} < 100$ MeV as $BR < 4. \times 10^{-8}$ for $\tau(A^0 \rightarrow n\gamma's) > 1. \times 10^{-9}$ s, $BR < 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$ s.
- ²⁰ ASANO 81B is KEK experiment. Set $B(K^+ \rightarrow \pi^+ A^0) < 3.8 \times 10^{-8}$ at CL = 90%.
- ²¹ 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%	EVTS	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
$< 1.3 \times 10^{-5}$	90		²² BALEST 95	CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 4.0 \times 10^{-5}$	90		ANTREASYAN 90C	CBAL	$\Upsilon(1S) \rightarrow A^0 \gamma$
			²³ ANTREASYAN 90C	RVUE	
$< 5 \times 10^{-5}$	90		²⁴ DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma$ $(A^0 \rightarrow e^+ e^-)$
$< 2 \times 10^{-3}$	90		²⁵ DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma (A^0 \rightarrow \gamma\gamma)$
$< 7 \times 10^{-6}$	90		²⁶ DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma$ $(A^0 \rightarrow \text{missing})$
$< 3.1 \times 10^{-4}$	90	0	²⁷ ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ $(A^0 \rightarrow e^+ e^-)$
$< 4 \times 10^{-4}$	90	0	²⁷ ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ $(A^0 \rightarrow \mu^+ \mu^-,$ $\pi^+ \pi^-, K^+ K^-)$
$< 8 \times 10^{-4}$	90	1	²⁸ ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 1.3 \times 10^{-3}$	90	0	²⁹ ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ $(A^0 \rightarrow e^+ e^-, \gamma\gamma)$
$< 2. \times 10^{-3}$	90		³⁰ BOWCOCK 86	CLEO	$\Upsilon(2S) \rightarrow \Upsilon(1S) \rightarrow A^0$
$< 5. \times 10^{-3}$	90		³¹ MAGERAS 86	CUSB	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 3. \times 10^{-4}$	90		³² ALAM 83	CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 9.1 \times 10^{-4}$	90		³³ NICZYPORUK 83	LENA	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 1.4 \times 10^{-5}$	90		³⁴ EDWARDS 82	CBAL	$J/\psi \rightarrow A^0 \gamma$
$< 3.5 \times 10^{-4}$	90		³⁵ SIVERTZ 82	CUSB	$\Upsilon(1S) \rightarrow A^0 \gamma$
$< 1.2 \times 10^{-4}$	90		³⁵ SIVERTZ 82	CUSB	$\Upsilon(3S) \rightarrow A^0 \gamma$

- 22 BALEST 95 looked for a monochromatic γ from $\Upsilon(1S)$ decay. The bound is for $m_{A^0} < 5.0$ GeV. See Fig. 7 in the paper for bounds for heavier m_{A^0} . They also quote a bound on branching ratios 10^{-3} – 10^{-5} of three-body decay $\gamma X \bar{X}$ for $0 < m_X < 3.1$ GeV.
- 23 The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon, J/\psi$) is the reduction factor for $\Gamma(V \rightarrow A^0 \gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \rightarrow ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \rightarrow ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.
- 24 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.
- 25 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.
- 26 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.
- 27 $\tau_{A^0} < 1 \times 10^{-13}$ s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma\gamma$ when $m_{A^0} < 100$ MeV.
- 28 $\tau_{A^0} > 1 \times 10^{-7}$ s.
- 29 Independent of τ_{A^0} .
- 30 BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \rightarrow A^0\gamma$. The limit for $B(\Upsilon(1S) \rightarrow A^0\gamma)B(A^0 \rightarrow e^+e^-)$ depends on m_{A^0} and τ_{A^0} . The quoted limit for $m_{A^0}=1.8$ MeV is at $\tau_{A^0} \sim 2. \times 10^{-12}$ s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m_e < m_{A^0} < 2m_\mu$ when the results of this experiment are combined with the results of ALAM 83.
- 31 MAGERAS 86 looked for $\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+e^-$). The quoted branching fraction limit is for $m_{A^0} = 1.7$ MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$ s where the limit is the worst.
- 32 ALAM 83 is at CESR. This limit combined with limit for $B(J/\psi \rightarrow A^0\gamma)$ (EDWARDS 82) excludes standard axion.
- 33 NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $B(\Upsilon \rightarrow A^0\gamma)$ derived from $B(J/\psi(1S) \rightarrow A^0\gamma)$ limit (EDWARDS 82) excludes standard axion.
- 34 EDWARDS 82 looked for $J/\psi \rightarrow \gamma A^0$ decays by looking for events with a single γ [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.
- 35 SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \rightarrow \gamma A^0$, A^0 undetected. Limit for 1S (3S) is valid for $m_{A^0} < 7$ GeV (4 GeV).
-

A^0 (Axion) Searches in Positronium Decays

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

<u>VALUE</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. ● ● ●				
$<4.4 \times 10^{-5}$	90	³⁶ BADERT...	02 CNTR	$\alpha\text{-Ps} \rightarrow \gamma X_1 X_2,$ $m_{X_1} + m_{X_2} \leq 900$ keV
$<2 \times 10^{-4}$	90	MAENO	95 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 850\text{--}1013$ keV
$<3.0 \times 10^{-3}$	90	³⁷ ASAI	94 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 30\text{--}500$ keV
$<2.8 \times 10^{-5}$	90	³⁸ AKOPYAN	91 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ $(A^0 \rightarrow \gamma\gamma),$ $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	³⁹ ASAI	91 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma,$ $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO	90 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} <$ 30 keV
$<(1\text{--}5) \times 10^{-4}$	95	⁴⁰ TSUCHIAKI	90 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma, m_{A^0} =$ 300–900 keV
$<6.4 \times 10^{-5}$	90	⁴¹ ORITO	89 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma,$ $m_{A^0} < 30$ keV
		⁴² AMALDI	85 CNTR	Ortho-positronium
		⁴³ CARBONI	83 CNTR	Ortho-positronium

³⁶ BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles.

³⁷ The ASAI 94 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

³⁸ The AKOPYAN 91 limit applies for a short-lived A^0 with $\tau_{A^0} < 10^{-13} m_{A^0}$ [keV] s.

³⁹ ASAI 91 limit translates to $g_{A^0 e^+ e^-}^2 / 4\pi < 1.1 \times 10^{-11}$ (90%CL) for $m_{A^0} < 800$ keV.

⁴⁰ The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

⁴¹ 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.

⁴² AMALDI 85 set limits $B(A^0 \gamma) / B(\gamma\gamma\gamma) < (1\text{--}5) \times 10^{-6}$ for $m_{A^0} = 900\text{--}100$ keV which are about 1/10 of the CARBONI 83 limits.

⁴³ 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

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●		
	⁴⁴ BASSOMPIE... 95	$m_{A^0} = 1.8 \pm 0.2$ MeV

⁴⁴ BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of e^+e^- pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate A^0 for $\tau(A^0) = 10^{-18}$ – 10^{-9} sec. They also found an excess of events in the range $m_{e^+e^-} = 2.1$ – 3.5 MeV.

A^0 (Axion) Production in Hadron Collisions

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

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
			45 AHMAD	97 SPEC	e^+ production
			46 LEINBERGER	97 SPEC	$A^0 \rightarrow e^+e^-$
			47 GANZ	96 SPEC	$A^0 \rightarrow e^+e^-$
			48 KAMEL	96 EMUL	^{32}S emulsion, $A^0 \rightarrow e^+e^-$
			49 BLUEMLEIN	92 BDMP	$A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$
			50 MEIJERDREES	92 SPEC	$\pi^- p \rightarrow n A^0, A^0 \rightarrow e^+e^-$
			51 BLUEMLEIN	91 BDMP	$A^0 \rightarrow e^+e^-, 2\gamma$
			52 FAISSNER	89 OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
			53 DEBOER	88 RVUE	$A^0 \rightarrow e^+e^-$
			54 EL-NADI	88 EMUL	$A^0 \rightarrow e^+e^-$
			55 FAISSNER	88 OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			56 BADIER	86 BDMP	$A^0 \rightarrow e^+e^-$
$<2. \times 10^{-11}$	90	0	57 BERGSMA	85 CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	57 BERGSMA	85 CHRM	CERN beam dump
		24	58 FAISSNER	83 OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			59 FAISSNER	83B RVUE	LAMPF beam dump
			60 FRANK	83B RVUE	LAMPF beam dump
			61 HOFFMAN	83 CNTR	$\pi p \rightarrow n A^0$ ($A^0 \rightarrow e^+e^-$)
			62 FETSCHER	82 RVUE	See FAISSNER 81B
		12	63 FAISSNER	81 OSPK	CERN PS ν wideband
		15	64 FAISSNER	81B OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
		8	65 KIM	81 OSPK	26 GeV $pN \rightarrow A^0 X$
		0	66 FAISSNER	80 OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
$<1. \times 10^{-8}$	90		67 JACQUES	80 HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		67 JACQUES	80 HLBC	Beam dump
			68 SOUKAS	80 CALO	28 GeV p beam dump
			69 BECHIS	79 CNTR	
$<1. \times 10^{-8}$	90		70 COTEUS	79 OSPK	Beam dump
$<1. \times 10^{-3}$	95		71 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		72 BELLOTTI	78 HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		72 BELLOTTI	78 HLBC	$m_{A^0}=1.5$ MeV
$<4.1 \times 10^{-9}$	90		72 BELLOTTI	78 HLBC	$m_{A^0}=1$ MeV

$<1. \times 10^{-8}$	90	73 BOSETTI	78B HYBR	Beam dump
		74 DONNELLY	78	
$<0.5 \times 10^{-8}$	90	HANSL	78D WIRE	Beam dump
		75 MICELMAC...	78	
		76 VYSOTSKII	78	

- 45 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.
- 46 LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy e^+e^- -line at ~ 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.
- 47 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.
- 48 KAMEL 96 looked for e^+e^- pairs from the collision of ^{32}S (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity $m_{ee} > 2$ MeV.
- 49 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.
- 50 MEIJERDREES 92 give $\Gamma(\pi^- p \rightarrow nA^0) \cdot \text{B}(A^0 \rightarrow e^+e^-) / \Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0} = 100$ MeV, $\tau_{A^0} = 10^{-11}-10^{-23}$ sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25-136$ MeV.
- 51 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 $x < 1$.
- 52 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.
- 53 DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass ~ 1.1 , ~ 2.1 , and ~ 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 π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism.
- 54 EL-NADI 88 claim the existence of a neutral particle decaying into e^+e^- with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at ~ 4 GeV/c/nucleon.
- 55 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 2γ 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.
- 56 BADIER 86 did not find long-lived A^0 in 300 GeV π^- 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.

- 57 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.
- 58 FAISSNER 83 observed 19 1- γ and 12 2- γ 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.
- 59 FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ 's are not at variance with LAMPF upper limit of 450 γ '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.
- 60 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 γ 's. See comment on FAISSNER 83B.
- 61 HOFFMAN 83 set CL = 90% limit $d\sigma/dt \text{ B}(e^+e^-) < 3.5 \times 10^{-32} \text{ cm}^2/\text{GeV}^2$ for $140 < m_{A^0} < 160$ MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.
- 62 FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2- γ peak rate remarkably decreases if iron wall is set in front of the decay region.
- 63 FAISSNER 81 see excess μe events. Suggest axion interactions.
- 64 FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2 γ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with η - 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 82, CAVIGNAC 83, and ANANEV 85.
- 65 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.
- 66 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 $m_{A^0} < 2m_{e^-}$.
- 67 JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interaction}) < 7. \times 10^{-68} \text{ cm}^4, \text{ CL} = 90\%]$. Second limit is from nonobservation of axion decays into 2 γ 's or e^+e^- , and for axion mass a few MeV.
- 68 SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.
- 69 BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2 γ or e^+e^- . No signal found. CL = 90% limits for model parameter(s) are given.
- 70 COTEUS 79 is a beam dump experiment at BNL.
- 71 DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.
- 72 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 $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67} \text{ cm}^4$.

- ⁷³ BOSETTI 78B quotes $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67} \text{ cm}^4$.
⁷⁴ DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.
⁷⁵ MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).
⁷⁶ 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

<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. ● ● ●			
	⁷⁷ ALTMANN 95	CNTR	Reactor; $A^0 \rightarrow e^+ e^-$
	⁷⁸ KETOV 86	SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	⁷⁹ KOCH 86	SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	⁸⁰ DATAR 82	CNTR	Light water reactor
	⁸¹ VUILLEUMIER 81	CNTR	Reactor, $A^0 \rightarrow 2\gamma$
⁷⁷ 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 $m_{A^0} = 1.5 \text{ MeV}$ 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 $2m_e < m_{A^0} < 4.8 \text{ MeV}$ 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.			
⁷⁸ 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 $m_{A^0} > 150 \text{ keV}$. Not valid for $m_{A^0} \gtrsim 1 \text{ MeV}$.			
⁷⁹ 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 $m_{A^0} = 250 \text{ keV}$ gives 10^{-5} for the ratio. Not valid for $m_{A^0} > 1022 \text{ keV}$.			
⁸⁰ 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 .			
⁸¹ VUILLEUMIER 81 is at Grenoble reactor. Set limit $m_{A^0} < 280 \text{ keV}$.			

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

Limits are for branching ratio.

<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. ● ● ●					
$< 8.5 \times 10^{-6}$	90		⁸² DERBIN	02 CNTR	^{125m}Te decay
			⁸³ DEBOER	97C RVUE	M1 transitions
$< 5.5 \times 10^{-10}$	95		⁸⁴ TSUNODA	95 CNTR	^{252}Cf fission, $A^0 \rightarrow ee$
$< 1.2 \times 10^{-6}$	95		⁸⁵ MINOWA	93 CNTR	$^{139}\text{La}^* \rightarrow ^{139}\text{La}A^0$
$< 2 \times 10^{-4}$	90		⁸⁶ HICKS	92 CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		⁸⁷ ASANUMA	90 CNTR	^{241}Am decay
$< (0.4-10) \times 10^{-3}$	95		⁸⁸ DEBOER	90 CNTR	$^8\text{Be}^* \rightarrow ^8\text{Be}A^0$, $A^0 \rightarrow e^+ e^-$

$<(0.2-1) \times 10^{-3}$	90	89 BINI	89 CNTR	$^{16}\text{O}^* \rightarrow ^{16}\text{O}X^0,$ $X^0 \rightarrow e^+e^-$
		90 AVIGNONE	88 CNTR	$\text{Cu}^* \rightarrow \text{Cu}A^0 (A^0 \rightarrow$ $2\gamma, A^0 e \rightarrow \gamma e,$ $A^0 Z \rightarrow \gamma Z)$
$< 1.5 \times 10^{-4}$	90	91 DATAR	88 CNTR	$^{12}\text{C}^* \rightarrow ^{12}\text{C}A^0,$ $A^0 \rightarrow e^+e^-$
$< 5 \times 10^{-3}$	90	92 DEBOER	88C CNTR	$^{16}\text{O}^* \rightarrow ^{16}\text{O}X^0,$ $X^0 \rightarrow e^+e^-$
$< 3.4 \times 10^{-5}$	95	93 DOEHNER	88 SPEC	$^2\text{H}^*, A^0 \rightarrow e^+e^-$
$< 4 \times 10^{-4}$	95	94 SAVAGE	88 CNTR	Nuclear decay (isovec- tor)
$< 3 \times 10^{-3}$	95	94 SAVAGE	88 CNTR	Nuclear decay (isoscalar)
< 0.106	90	95 HALLIN	86 SPEC	^6Li isovector decay
< 10.8	90	95 HALLIN	86 SPEC	^{10}B isoscalar decays
< 2.2	90	95 HALLIN	86 SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0 96 SAVAGE	86B CNTR	$^{14}\text{N}^*$
		97 ANANEV	85 CNTR	$\text{Li}^*, \text{deut}^* A^0 \rightarrow 2\gamma$
		98 CAVAIGNAC	83 CNTR	$^{97}\text{Nb}^*, \text{deut}^* \text{ transition}$ $A^0 \rightarrow 2\gamma$
		99 ALEKSEEV	82B CNTR	$\text{Li}^*, \text{deut}^* \text{ transition}$ $A^0 \rightarrow 2\gamma$
		100 LEHMANN	82 CNTR	$\text{Cu}^* \rightarrow \text{Cu}A^0$ $(A^0 \rightarrow 2\gamma)$
		0 101 ZEHNDER	82 CNTR	$\text{Li}^*, \text{Nb}^* \text{ decay, } n\text{-capt.}$
		0 102 ZEHNDER	81 CNTR	$\text{Ba}^* \rightarrow \text{Ba}A^0$ $(A^0 \rightarrow 2\gamma)$
		103 CALAPRICE	79	Carbon

82 DERBIN 02 looked for the axion emission in an M1 transition in ^{125m}Te decay. They looked for a possible presence of a shifted energy spectrum in gamma rays due to the undetected axion.

83 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.

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

85 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.

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

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

88 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.

89 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^- .

90 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.

- 91 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 τ - m dependence of the limit.
- 92 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: $g_{X^0 NN}^2/4\pi < 2.3 \times 10^{-9}$.
- 93 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.
- 94 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}N , 17.64 MeV state $J^P = 1^+$ in ^8Be , and the 18.15 MeV state $J^P = 1^+$ in ^8Be . 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.
- 95 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. ^6Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the ^{10}B and ^{14}N isoscalar decay data strongly reject PECCEI 86 model II and III.
- 96 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}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.
- 97 ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li^* decay) and below $2m_e$ for deuteron* decay.
- 98 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).
- 99 ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges $m_{A^0} < 400$ keV (Li^* decay) and $330 \text{ keV} < m_{A^0} < 2.2$ MeV. (deuteron* decay).
- 100 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.
- 101 ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li^* , Nb^* decay (both single p transition) nor in n capture (combined with previous Ba^* negative result) rules out standard A^0 . Set limit $m_{A^0} < 60$ keV for any A^0 .
- 102 ZEHNDER 81 looked for $\text{Ba}^* \rightarrow A^0\text{Ba}$ transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ 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.
- 103 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 4×10^{-16} – 4.5×10^{-12}	90	104 BROSS	91 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		105 GUO	90 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		106 BJORKEN	88 CALO	$A \rightarrow e^+e^-$ or 2γ
		107 BLINOV	88 MD1	$ee \rightarrow eeA^0$ ($A^0 \rightarrow ee$)
none 1×10^{-14} – 1×10^{-10}	90	108 RIORDAN	87 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 1×10^{-14} – 1×10^{-11}	90	109 BROWN	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 6×10^{-14} – 9×10^{-11}	95	110 DAVIER	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 3×10^{-13} – 1×10^{-7}	90	111 KONAKA	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)

¹⁰⁴ 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 τ_{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).

¹⁰⁵ 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).

¹⁰⁶ BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_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.

¹⁰⁷ 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%).

¹⁰⁸ 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.

¹⁰⁹ 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.

¹¹⁰ $m_{A^0} = 1.8$ MeV assumed. The excluded domain in the τ_{A^0} – m_{A^0} plane extends up to $m_{A^0} \approx 14$ MeV, see their figure 4.

¹¹¹ The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$ – $A^0e^+e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha ScatteringThe 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	¹¹² HALLIN	92 CNTR	$m_{A^0} = 1.75\text{--}1.88$ MeV
none 0.0016–0.47	90	¹¹³ HENDERSON	92C CNTR	$m_{A^0} = 1.5\text{--}1.86$ MeV
< 2.0	90	¹¹⁴ 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	¹¹⁵ 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	¹¹⁶ JUDGE	90 CNTR	$m_{A^0} = 1.832$ MeV, elastic
< 1.9	97	¹¹⁷ TSERTOS	89 CNTR	$m_{A^0} = 1.82$ MeV
<(10–40)	97	¹¹⁷ TSERTOS	89 CNTR	$m_{A^0} = 1.51\text{--}1.65$ MeV
<(1–2.5)	97	¹¹⁷ 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	¹¹⁸ TSERTOS	88 CNTR	$m_{A^0} = 1.832$ MeV
		¹¹⁹ VANKLINKEN	88 CNTR	
		¹²⁰ MAIER	87 CNTR	
<2500	90	MILLS	87 CNTR	$m_{A^0} = 1.8$ MeV
		¹²¹ VONWIMMER	87 CNTR	

¹¹²HALLIN 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.

¹¹³HENDERSON 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.

¹¹⁴WU 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.

¹¹⁵WIDMANN 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.

¹¹⁶JUDGE 90 excludes an elastic pseudoscalar e^+e^- resonance for 4.5×10^{-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.

¹¹⁷See also TSERTOS 88B in references.

¹¹⁸The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

¹¹⁹VANKLINKEN 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.

¹²⁰MAIER 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.

¹²¹VONWIMMERSPERG 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	¹²² TRZASKA	91 CNTR	$m_{A^0} = 1.8$ MeV
< 4.4	95	WIDMANN	91 CNTR	$m_{A^0} = 1.78\text{--}1.92$ MeV
		¹²³ FOX	89 CNTR	
< 0.11	95	¹²⁴ 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

¹²²TRZASKA 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.

¹²³FOX 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).

¹²⁴Similar 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	¹²⁵ VO	94 CNTR	$m_{X^0} = 1.1\text{--}1.9$ MeV
< 1.0	95	¹²⁶ VO	94 CNTR	$m_{X^0} = 1.1$ MeV
< 2.5	95	¹²⁶ VO	94 CNTR	$m_{X^0} = 1.4$ MeV
< 120	95	¹²⁶ VO	94 CNTR	$m_{X^0} = 1.7$ MeV
< 3.8	95	¹²⁷ SKALSEY	92 CNTR	$m_{X^0} = 1.5$ MeV

¹²⁵VO 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.

¹²⁶VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.

¹²⁷SKALSEY 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	128 MITSUI	96 CNTR	γX^0
< 4	68	129 SKALSEY	95 CNTR	γX^0
<40	68	130 SKALSEY	95 RVUE	γX^0
< 0.18	90	131 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.26	90	132 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.33	90	133 ADACHI	94 CNTR	$\gamma X^0, X^0 \rightarrow \gamma\gamma\gamma$
128 MITSUI 96 looked for a monochromatic γ . 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 .				
129 SKALSEY 95 looked for a monochromatic γ without an accompanying γ in e^+e^- annihilation. The bound applies for scalar and vector X^0 with $C = -1$ and $m_{X^0} = 100\text{--}1000$ keV.				
130 SKALSEY 95 reinterpreted the bound on γA^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.				
131 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.				
132 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.				
133 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%	EVTS	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
			134 DIAZ	98 THEO	$H^0 \rightarrow X^0 X^0, A^0 \rightarrow X^0 X^0 X^0$, Majoron interaction
			135 BOBRAKOV	91	Electron quasi-magnetic interaction
< 3.3×10^{-2}	95		136 ALBRECHT	90E ARG	$\tau \rightarrow \mu X^0$. Familon
< 1.8×10^{-2}	95		136 ALBRECHT	90E ARG	$\tau \rightarrow e X^0$. Familon
< 6.4×10^{-9}	90		137 ATIYA	90 B787	$K^+ \rightarrow \pi^+ X^0$. Familon
< 1.1×10^{-9}	90		138 BOLTON	88 CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon
			139 CHANDA	88 ASTR	Sun, Majoron
			140 CHOI	88 ASTR	Majoron, SN 1987A
< 5×10^{-6}	90		141 PICCIOTTO	88 CNTR	$\pi \rightarrow e\nu X^0$, Majoron

- | | | | | | | |
|-----------------------|----|-----|---------|--------------|------|---|
| $<1.3 \times 10^{-9}$ | 90 | 142 | GOLDMAN | 87 | CNTR | $\mu \rightarrow e\gamma X^0$. Familon |
| $<3 \times 10^{-4}$ | 90 | 143 | BRYMAN | 86B | RVUE | $\mu \rightarrow eX^0$. Familon |
| $<1. \times 10^{-10}$ | 90 | 0 | 144 | EICHLER | 86 | SPEC $\mu^+ \rightarrow e^+ X^0$. Familon |
| $<2.6 \times 10^{-6}$ | 90 | | 145 | JODIDIO | 86 | SPEC $\mu^+ \rightarrow e^+ X^0$. Familon |
| | | | 146 | BALTRUSAITIS | 85 | MRK3 $\tau \rightarrow \ell X^0$. Familon |
| | | | 147 | DICUS | 83 | COSM $\nu(h\nu) \rightarrow \nu(\text{light})X^0$ |
- 134 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 $Z \rightarrow H^0 A^0 \rightarrow X^0 X^0 X^0 X^0 X^0$ and $e^+ e^- \rightarrow Z H^0$ with $H^0 \rightarrow X^0 X^0$.
- 135 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 $x_e(G_F/8\pi\sqrt{2})^{1/2}$.
- 136 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 μ), 5.0% (for e) for $m_{X^0} = 500$ MeV.
- 137 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.
- 138 BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.
- 139 CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.
- 140 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 $(\sum h_i^4)^{1/4}$.
- 141 PICCIOTTO 88 limit applies when $m_{X^0} < 55$ MeV and $\tau_{X^0} > 2\text{ns}$, and it decreases to 4×10^{-7} at $m_{X^0} = 125$ MeV, beyond which no limit is obtained.
- 142 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.
- 143 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.
- 144 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.
- 145 JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.
- 146 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.
- 147 The primordial heavy neutrino must decay into ν 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 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\text{heavy}\nu}$ between 5×10^{-5} and 0.1 MeV (K -decay).

Majoron Searches in Neutrinoless Double β 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
>7200	90 ^{128}Te		CNTR	¹⁴⁸ BERNATOW... 92
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 500	90 ^{136}Xe	$0\nu\chi$	Liquid Xe Scint.	¹⁴⁹ BERNABEI 02D
> 5.8	90 ^{100}Mo	$0\nu\chi$	ELEGANT V	¹⁵⁰ FUSHIMI 02
> 0.32	90 ^{100}Mo	$0\nu\chi$	Liq. Ar ioniz.	¹⁵¹ ASHITKOV 01
> 0.0035	90 ^{160}Gd	0ν	$^{160}\text{Gd}_2\text{SiO}_5\text{:Ce}$	¹⁵² DANEVICH 01
> 0.013	90 ^{160}Gd	$0\nu 2\chi$	$^{160}\text{Gd}_2\text{SiO}_5\text{:Ce}$	¹⁵³ DANEVICH 01
> 1.4	90 ^{130}Te	$0\nu\chi$	Cryog. det.	¹⁵⁴ ALESSAND... 00
> 0.7	90 ^{130}Te	$0\nu 2\chi$	Cryog. det.	¹⁵⁵ ALESSAND... 00
> 2.3	90 ^{82}Se	$0\nu\chi$	NEMO 2	¹⁵⁶ ARNOLD 00
> 0.31	90 ^{96}Zr	$0\nu\chi$	NEMO 2	¹⁵⁷ ARNOLD 00
> 0.63	90 ^{82}Se	$0\nu 2\chi$	NEMO 2	¹⁵⁸ ARNOLD 00
> 0.063	90 ^{96}Zr	$0\nu 2\chi$	NEMO 2	¹⁵⁸ ARNOLD 00
> 0.16	90 ^{100}Mo	$0\nu 2\chi$	NEMO 2	¹⁵⁸ ARNOLD 00
> 3.7	90 ^{116}Cd	$0\nu\chi$	$^{116}\text{CdWO}_4$ scint.	¹⁵⁹ DANEVICH 00
> 0.59	90 ^{116}Cd	$0\nu 2\chi$	$^{116}\text{CdWO}_4$ scint.	¹⁶⁰ DANEVICH 00
> 2.4	90 ^{82}Se	$0\nu\chi$	NEMO 2	¹⁶¹ ARNOLD 98
> 7.2	90 ^{136}Xe	$0\nu 2\chi$	TPC	¹⁶² LUESCHER 98
> 7.91	90 ^{76}Ge		SPEC	¹⁶³ GUENTHER 96
> 17	90 ^{76}Ge		CNTR	BECK 93

¹⁴⁸BERNATOWICZ 92 studied double- β decays of ^{128}Te and ^{130}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 ^{128}Te of $(7.7 \pm 0.4) \times 10^{24}$ year. We calculated 90% CL limit as $(7.7-1.28 \times 0.4=7.2) \times 10^{24}$.

¹⁴⁹BERNABEI 02D obtain limit for $0\nu\chi$ decay with Majoron emission of ^{136}Xe using liquid Xe scintillation detector. They derive $\langle g_{\nu\chi} \rangle < 2.0-3.0 \times 10^{-5}$ with several nuclear matrix elements.

¹⁵⁰Replaces 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: $\langle g_{\nu\chi} \rangle < (6.3-360) \times 10^{-5}$.

¹⁵¹ASHITKOV 01 result for $0\nu\chi$ of ^{100}Mo is less stringent than ARNOLD 00.

¹⁵²DANEVICH 01 obtain limit for the $0\nu\chi$ decay with Majoron emission of ^{160}Gd using $\text{Gd}_2\text{SiO}_5\text{:Ce}$ crystal scintillators.

¹⁵³DANEVICH 01 obtain limit for the $0\nu 2\chi$ decay with 2 Majoron emission of ^{160}Gd .

¹⁵⁴ALESSANDRELLO 00 obtain limit for the $0\nu\chi$ decay with Majoron emission of ^{130}Te using cryogenic calorimeter. Derive $\langle g_{\nu\chi} \rangle < 2.6-6.7 \times 10^{-4}$ with several nuclear matrix elements.

¹⁵⁵ALESSANDRELLO 00 obtain limit for the $0\nu 2\chi$ decay with two Majoron emission of ^{130}Te using cryogenic calorimeter.

¹⁵⁶ARNOLD 00 reports limit for the $0\nu\chi$ decay with Majoron emission derived from tracking calorimeter NEMO 2. Using ^{82}Se source: $\langle g_{\nu\chi} \rangle < 1.6 \times 10^{-4}$. Matrix element from GUENTHER 96.

¹⁵⁷Using ^{96}Zr source: $\langle g_{\nu\chi} \rangle < 2.6 \times 10^{-4}$. Matrix element from ARNOLD 99.

- 158 ARNOLD 00 reports limit for the $0\nu 2\chi$ decay with two Majoron emission derived from tracking calorimeter NEMO 2.
- 159 DANEVICH 00 obtain limit for the $0\nu \chi$ decay with Majoron emission of ^{116}Cd using enriched CdWO_4 scintillators. Derive $\langle g_{\nu\chi} \rangle < 6.5 \times 10^{-5}$ (matrix elements of ARNOLD 96) and 12×10^{-5} (matrix elements of HIRSCH 96). Replaces DANEVICH 98.
- 160 DANEVICH 00 obtain limit for the $0\nu 2\chi$ decay with two Majoron emission of ^{116}Cd using enriched CdWO_4 scintillators. Replaces DANEVICH 98.
- 161 ARNOLD 98 determine the limit for $0\nu \chi$ decay with Majoron emission of ^{82}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.
- 162 LUESCHER 98 report a limit for the 0ν decay with Majoron emission of ^{136}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 2.0×10^{-4} .
- 163 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 90C and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
3 to 20	164 MOROI	98 COSM	K, hot dark matter
< 0.007	165 BORISOV	97 ASTR	D, neutron star
< 4	166 KACHELRIESS	97 ASTR	D, neutron star cooling
<(0.5–6) × 10 ⁻³	167 KEIL	97 ASTR	SN 1987A
< 0.018	168 RAFFELT	95 ASTR	D, red giant
< 0.010	169 ALTHERR	94 ASTR	D, red giants, white dwarfs
< 0.01	170 CHANG	93 ASTR	K, SN 1987A
< 0.03	WANG	92 ASTR	D, white dwarf
none 3–8	171 WANG	92C ASTR	D, C-O burning
<10	171 BERSHADY	91 ASTR	D, K, intergalactic light
< 1 × 10 ⁻³	172 KIM	91C COSM	D, K, mass density of the universe, super-symmetry
none 10 ⁻³ –3	173 RAFFELT	91B ASTR	D,K, SN 1987A
< 0.02	174 RESSELL	91 ASTR	K, intergalactic light
< 1 × 10 ⁻³	BURROWS	90 ASTR	D,K, SN 1987A
<(1.4–10) × 10 ⁻³	175 ENGEL	90 ASTR	D,K, SN 1987A
< 3.6 × 10 ⁻⁴	176 RAFFELT	90D ASTR	D, red giant
<12	177 BURROWS	89 ASTR	D,K, SN 1987A
< 1 × 10 ⁻³	178 ERICSON	89 ASTR	D,K, SN 1987A
< 0.07	179 MAYLE	89 ASTR	D,K, SN 1987A
< 0.7	CHANDA	88 ASTR	D, Sun
	RAFFELT	88 ASTR	D,K, SN 1987A
	180 RAFFELT	88B ASTR	red giant
	FRIEMAN	87 ASTR	D, red giant
	181 RAFFELT	87 ASTR	K, red giant

< 2–5	TURNER	87	COSM	K, thermal production
< 0.01	182 DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	183 RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	184 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 the universe
> 1 $\times 10^{-5}$	DINE	83	COSM	D,K, mass density of the universe
< 0.04	ELLIS	83B	ASTR	D, red giant
> 1 $\times 10^{-5}$	PRESKILL	83	COSM	D,K, mass density of the universe
< 0.1	BARROSO	82	ASTR	D, red giant
< 1	185 FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

164 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.

165 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.

166 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.

167 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.

168 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).

169 ALTHERR 94 bound is on the axion-electron coupling $g_{ae} < 1.5 \times 10^{-13}$, from energy loss via axion emission.

170 CHANG 93 updates ENGEL 90 bound with the Kaplan-Mahohar 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.

171 BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from 2γ decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.

172 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.

173 RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

174 RESSELL 91 uses absence of any intracluster line emission to set limit.

175 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 $g_{AN} \sim 10^{-6}$.

176 RAFFELT 90D is a re-analysis of DEARBORN 86.

177 The region $m_{A0} \gtrsim 2 \text{ eV}$ is also allowed.

- 178 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.
- 179 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.
- 180 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.
- 181 RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10} \text{ GeV}^{-1}$.
- 182 DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11} \text{ GeV}^{-1}$.
- 183 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.
- 184 KAPLAN 85 says $m_{A^0} < 23 \text{ eV}$ is allowed for a special choice of model parameters.
- 185 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
$< 5.5 \times 10^{-43}$	95	186 HAGMANN	98 CNTR	$m_{A^0} = 2.9\text{--}3.3 \times 10^{-6} \text{ eV}$
		187 KIM	98 THEO	
$< 2 \times 10^{-41}$		188 HAGMANN	90 CNTR	$m_{A^0} = (5.4\text{--}5.9)10^{-6} \text{ eV}$
$< 1.3 \times 10^{-42}$	95	189 WUENSCH	89 CNTR	$m_{A^0} = (4.5\text{--}10.2)10^{-6} \text{ eV}$
$< 2 \times 10^{-41}$	95	189 WUENSCH	89 CNTR	$m_{A^0} = (11.3\text{--}16.3)10^{-6} \text{ eV}$

- 186 Based on the conversion of halo axions to microwave photons. Limit assumes $\rho_A = 0.45 \text{ GeV cm}^{-3}$. At 90%CL this result excludes a version of KSVZ axions as dark matter in the halo of our Galaxy, for the quoted axion mass range. See ASZTALOS 01 for more details.
- 187 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.
- 188 HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.
- 189 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 axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma}\phi_A\mathbf{E}\cdot\mathbf{B}$.

Related limits from astrophysics can be found in the "Invisible A^0 (Axion) Mass Limits from Astrophysics and Cosmology" section.

VALUE (GeV ⁻¹)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$<1.1 \times 10^{-9}$	95	190 INOUE	02	$m_{A^0} = 0.05\text{--}0.27$ eV
$<2.78 \times 10^{-9}$	95	191 MORALES	02B	$m_{A^0} < 1$ keV
$<1.7 \times 10^{-9}$	90	192 BERNABEI	01B	$m_{A^0} < 100$ eV
$<1.5 \times 10^{-4}$	90	193 ASTIER	00B NOMD	$m_{A^0} < 40$ eV
		194 MASSO	00 THEO	induced photon coupling
$<2.7 \times 10^{-9}$	95	195 AVIGNONE	98 SLAX	$m_{A^0} < 1$ keV
$<6.0 \times 10^{-10}$	95	196 MORIYAMA	98	$m_{A^0} < 0.03$ eV
$<3.6 \times 10^{-7}$	95	197 CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	198 CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	199 LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	199 LAZARUS	92	$m_{A^0} = 0.03\text{--}0.11$ eV
$<7.7 \times 10^{-7}$	99	200 RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		201 SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

190 INOUE 02 looked for Primakoff conversion of solar axions in 4T superconducting magnet into X ray.

191 MORALES 02B looked for the coherent conversion of solar axions to photons via the Primakoff effect in Germanium detector.

192 BERNABEI 01B looked for Primakoff coherent conversion of solar axions into photons via Bragg scattering in NaI crystal in DAMA dark matter detector.

193 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.

194 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 $g_p\bar{p}\gamma_5 p\phi_A$.

195 AVIGNONE 98 result is based on the coherent conversion of solar axions to photons via the Primakoff effect in a single crystal germanium detector.

196 Based on the conversion of solar axions to X-rays in a strong laboratory magnetic field.

197 Experiment based on proposal by MAIANI 86.

198 Experiment based on proposal by VANBIBBER 87.

199 LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.

200 RUOSO 92 experiment is based on the proposal by VANBIBBER 87.

201 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 $G_{A\gamma\gamma} < 1 \times 10^{-4}$ GeV⁻¹.

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee} \partial_\mu \phi_A \bar{e} \gamma^\mu \gamma_5 e$ in GeV^{-1} , or equivalently, the dipole-dipole potential $\frac{G_{Aee}^2}{4\pi} ((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \mathbf{n})(\boldsymbol{\sigma}_2 \cdot \mathbf{n}))/r^3$ where $\mathbf{n}=\mathbf{r}/r$.

The limits below apply to invisible axion of $m_A \leq 10^{-6}$ eV.

VALUE (GeV^{-1})	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$< 5.3 \times 10^{-5}$	66	202 NI	94	Induced magnetism
$< 6.7 \times 10^{-5}$	66	202 CHUI	93	Induced magnetism
$< 3.6 \times 10^{-4}$	66	203 PAN	92	Torsion pendulum
$< 2.7 \times 10^{-5}$	95	202 BOBRAKOV	91	Induced magnetism
$< 1.9 \times 10^{-3}$	66	204 WINELAND	91	NMR
$< 8.9 \times 10^{-4}$	66	203 RITTER	90	Torsion pendulum
$< 6.6 \times 10^{-5}$	95	202 VOROBYOV	88	Induced magnetism
202 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.				
203 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.				
204 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. ● ● ●				
$< 3.2 \times 10^4$	95	205 KRCCMAR	01	CNTR Solar axion
< 745	90	206 KRCCMAR	98	CNTR Solar axion
205 KRCCMAR 01 looked for solar axions emitted by the M1 transition of ${}^7\text{Li}$ after the electron capture by ${}^7\text{Be}$ and the emission of 384 keV line neutrino, using their resonant capture on ${}^7\text{Li}$ in the laboratory. The mass bound assumes $m_U/m_D=0.56$ and the flavor-singlet axial-vector matrix element $S=0.4$.				
206 KRCCMAR 98 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, following MORIYAMA 95B. The mass bound assumes $m_U/m_D=0.56$ and the flavor-singlet axial-vector matrix element $S=3F-D \simeq 0.5$.				

Axion Limits from T -violating Medium-Range Forces

The limit is for the coupling g in a T -violating potential between nucleons or nucleon

and electron of the form
$$V = \frac{g\hbar^2}{8\pi m_p} (\boldsymbol{\sigma} \cdot \hat{\mathbf{r}}) \left(\frac{1}{r^2} + \frac{m_A c}{\hbar r} \right) e^{-m_A c r / \hbar}$$

VALUE	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
207	NI	99	paramagnetic Tb F ₃
208	POSPELOV	98	THEO neutron EDM
209	YOUDIN	96	
210	RITTER	93	torsion pendulum
211	VENEMA	92	nuclear spin-precession frequencies
212	WINELAND	91	NMR

- 207 NI 99 searched for a T -violating medium-range force acting on paramagnetic Tb F₃ salt. See their Fig. 1 for the result.
- 208 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 2×10^{-10} ($1 \text{ cm}/\lambda_A$), where $\lambda_A = \hbar/m_A c$.
- 209 YOUDIN 96 compared the precession frequencies of atomic ¹⁹⁹Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.
- 210 RITTER 93 used a torsion pendulum to study the influence of bulk mass with polarized electrons on the pendulum.
- 211 VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of ¹⁹⁹Hg and ²⁰¹Hg atoms.
- 212 WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored ⁹Be⁺ ions using nuclear magnetic resonance.

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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>	
		Translated from YAF 65 1335.		
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.)
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>	
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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>	
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ADLER	00	PRL 84 3768	S. Adler <i>et al.</i>	(BNL E787 Collab.)
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ANTREASYAN	90C	PL B251 204	D. Antreasyan <i>et al.</i>	(Crystal Ball Collab.)
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ERICSON	89	PL B219 507	T.E.O. Ericson, J.F. Mathiot	(CERN, IPN)
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DEBOER	88	PRL 61 1274	F.W.N. de Boer, R. van Dantzig	(ANIK)
Also	89	PRL 62 2644 erratum	F.W.N. de Boer, R. van Dantzig	(ANIK)
Also	89	PRL 62 2638	D.H. Perkins	(OXF)
Also	89B	PRL 62 2639	F.W.N. de Boer, R. van Dantzig	(ANIK)
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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)
ALBRECHT	86D	PL B179 403	H. Albrecht <i>et al.</i>	(ARGUS Collab.)
BADIER	86	ZPHY C31 21	J. Badier <i>et al.</i>	(NA3 Collab.)
BOWCOCK	86	PRL 56 2676	T.J.V. Bowcock <i>et al.</i>	(CLEO 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	88	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)
MAGERAS	86	PRL 56 2672	G. Mageras <i>et al.</i>	(MPIM, COLU, STON)
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)
ALAM	83	PR D27 1665	M.S. Alam <i>et al.</i>	(VAND, CORN, ITHA, HARV+)
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)
NICZYPORUK	83	ZPHY C17 197	B. Niczyporuk <i>et al.</i>	(LENA Collab.)
PRESKILL	83	PL 120B 127	J. Preskill, M.B. Wise, F. Wilczek	(HARV, UCSBT)
SIKIVIE	83	PRL 51 1415	P. Sikivie	(FLOR)
Also	84	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	JPG 8 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)
SIVERTZ	82	PR D26 717	J.M. Sivertz <i>et al.</i>	(CUSB Collab.)
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	76	PRL 37 315	F. Reines, H.S. Gurr, H.W. Sobel	(UCI)
Also	74	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	77B	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	

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