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

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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).

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	[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 Stable Particle Decays

Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6 \times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\pi^0 \to \gamma X^0$, m_{X^0}=65–125 MeV
$<6 \times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\eta \to \gamma X^0$, m_{X^0}=200–525 MeV
<0.007	90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=25 MeV
<0.002	90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=100 MeV
$<1.7 \times 10^{-9}$	90		[5] ATIYA	93	CNTR	$K^+ \to \pi^+ A^0$
$<2 \times 10^{-7}$	90		[6] ATIYA	93B	CNTR	$K^+ \to \pi^+ A^0$
$<3 \times 10^{-13}$			[7] NG	93	COSM	$\pi^0 \to \gamma X^0$
$<1.1 \times 10^{-8}$	90		[8] ALLIEGRO	92	SPEC	$K^+ \to \pi^+ A^0$ $(A^0 \to e^+ e^-)$
$<5 \times 10^{-4}$	90		[9] ATIYA	92	CNTR	$\pi^0 \to \gamma X^0$
$<4 \times 10^{-6}$	90		[10] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$, $X^0 \to e^+ e^-$, m_{X^0}= 100 MeV
$<1 \times 10^{-7}$	90		[11] ATIYA	90B	CNTR	$K^+ \to \pi^+ A^0$, $(A^0 \to \gamma\gamma)$
$<1.3 \times 10^{-8}$	90		[12] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ $(A^0 \to e^+ e^-)$
$<1 \times 10^{-9}$	90	0	[13] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[14] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5–4) \times 10^{-6}$	90		[14] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV
		0	[15] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$
		0	[16] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$
			[17] ZHITNITSKII	79		Heavy axion

[3] AMSLER 94B looked for a peak in missing-mass distribution.

[4] 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.

[5] ATIYA 93 looked for a peak in missing mass distribution. 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.

[6] 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.

[7] 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 nucleosyntheis $\Delta N_\nu < 0.3$ (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.

[8] 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.

[9] 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.

[10] 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.

[11] ATIYA 90B limit is for B($K^+ \rightarrow \pi^+ A^0$)·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.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] ASANO 81B is KEK experiment. Set B($K^+ \rightarrow \pi^+ A^0$) $< 3.8 \times 10^{-8}$ at CL = 90%.

[17] 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. • • •						
$<4.0 \times 10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow A^0\gamma$
			[18] ANTREASYAN	90C	RVUE	
$<5 \times 10^{-5}$	90		[19] DRUZHININ	87	ND	$\phi \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+ e^-$)
$<2 \times 10^{-3}$	90		[20] DRUZHININ	87	ND	$\phi \rightarrow \gamma A^0$ ($A^0 \rightarrow \gamma\gamma$)
$<7 \times 10^{-6}$	90		[21] DRUZHININ	87	ND	$\phi \rightarrow \gamma A^0$ ($A^0 \rightarrow$ missing)
$<3.1 \times 10^{-4}$	90	0	[22] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+ e^-$)
$<4 \times 10^{-4}$	90	0	[22] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow \mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-)
$<8 \times 10^{-4}$	90	1	[23] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$
$<1.3 \times 10^{-3}$	90	0	[24] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+ e^-$, $\gamma\gamma$)
$<2. \times 10^{-3}$	90		[25] BOWCOCK	86	CLEO	$\Upsilon(2S) \rightarrow \Upsilon(1S) \rightarrow A^0$
$<5. \times 10^{-3}$	90		[26] MAGERAS	86	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
$<3. \times 10^{-4}$	90		[27] ALAM	83	CLEO	$\Upsilon(1S) \rightarrow A^0\gamma$
$<9.1 \times 10^{-4}$	90		[28] NICZYPORUK	83	LENA	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.4 \times 10^{-5}$	90		[29] EDWARDS	82	CBAL	$J/\psi \rightarrow A^0\gamma$
$<3.5 \times 10^{-4}$	90		[30] SIVERTZ	82	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.2 \times 10^{-4}$	90		[30] SIVERTZ	82	CUSB	$\Upsilon(3S) \rightarrow A^0\gamma$

[18] 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/ψ) 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 $0.00075 < x < 44$.

[19] 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.

[20] 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.

[21] 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.

[22] $\tau_{A^0} < 1 \times 10^{-13}$s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma\gamma$ when $m_{A^0} < 100$ MeV.

[23] $\tau_{A^0} > 1 \times 10^{-7}$s.

[24] Independent of τ_{A^0}.

[25] 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.

[26] 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.

[27] ALAM 83 is at CESR. This limit combined with limit for B($J/\psi \rightarrow A^0\gamma$) (EDWARDS 82) excludes standard axion.

[28] 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.

[29] 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.

[30] 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.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-4}$	90	MAENO	95	CNTR	o-Ps $\rightarrow A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0 \times 10^{-3}$	90	[31] ASAI	94	CNTR	o-Ps $\rightarrow A^0\gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[32] AKOPYAN	91	CNTR	o-Ps $\rightarrow A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$), $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	[33] ASAI	91	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO	90	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} <$ 30 keV
$<(1\text{–}5) \times 10^{-4}$	95	[34] TSUCHIAKI	90	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} =$ 300–900 keV
$<6.4 \times 10^{-5}$	90	[35] ORITO	89	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} < 30$ keV
		[36] AMALDI	85	CNTR	Ortho-positronium
		[37] CARBONI	83	CNTR	Ortho-positronium

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

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

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

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

[35] ORITO 89 limit translates to $g^2_{A^0 ee}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger m_{A^0}: $B < 7.6 \times 10^{-6}$ at 100 keV.

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

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

A^0 (Axion) Search in Photoproduction

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[38] BASSOMPIE... 93	m_{A^0}= 1.8 MeV

[38] BASSOMPIERRE 93 looked for a peak in invariant mass of e^+e^- at 1.8 MeV in photoproduction on an aligned Ge crystal. They quote a bound on the portion of possible resonance contribution of 10^{-3} for $\tau_{X^0} < 4\times 10^{-13}$ s.

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. • • •						
			[39] BLUEMLEIN	92	BDMP	$A^0 N_Z \to \ell^+\ell^- N_Z$
			[40] MEIJERDREES	92	SPEC	$\pi^- p \to nA^0$, $A^0 \to e^+e^-$
			[41] BLUEMLEIN	91	BDMP	$A^0 \to e^+e^-$, 2γ
			[42] FAISSNER	89	OSPK	Beam dump, $A^0 \to e^+e^-$
			[43] DEBOER	88	RVUE	$A^0 \to e^+e^-$
			[44] EL-NADI	88	EMUL	$A^0 \to e^+e^-$
			[45] FAISSNER	88	OSPK	Beam dump, $A^0 \to 2\gamma$
			[46] BADIER	86	BDMP	$A^0 \to e^+e^-$
$<2.\times 10^{-11}$	90	0	[47] BERGSMA	85	CHRM	CERN beam dump
$<1.\times 10^{-13}$	90	0	[47] BERGSMA	85	CHRM	CERN beam dump
		24	[48] FAISSNER	83	OSPK	Beam dump, $A^0 \to 2\gamma$
			[49] FAISSNER	83B	RVUE	LAMPF beam dump
			[50] FRANK	83B	RVUE	LAMPF beam dump
			[51] HOFFMAN	83	CNTR	$\pi p \to nA^0$ ($A^0 \to e^+e^-$)
			[52] FETSCHER	82	RVUE	See FAISSNER 81B
		12	[53] FAISSNER	81	OSPK	CERN PS ν wideband
		15	[54] FAISSNER	81B	OSPK	Beam dump, $A^0 \to 2\gamma$
		8	[55] KIM	81	OSPK	26 GeV $pN \to A^0 X$
		0	[56] FAISSNER	80	OSPK	Beam dump, $A^0 \to e^+e^-$
$<1.\times 10^{-8}$	90		[57] JACQUES	80	HLBC	28 GeV protons
$<1.\times 10^{-14}$	90		[57] JACQUES	80	HLBC	Beam dump
			[58] SOUKAS	80	CALO	28 GeV p beam dump
			[59] BECHIS	79	CNTR	
$<1.\times 10^{-8}$	90		[60] COTEUS	79	OSPK	Beam dump
$<1.\times 10^{-3}$	95		[61] 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		[62] BELLOTTI	78	HLBC	Beam dump
$<5.4\times 10^{-14}$	90		[62] BELLOTTI	78	HLBC	m_{A^0}=1.5 MeV
$<4.1\times 10^{-9}$	90		[62] BELLOTTI	78	HLBC	m_{A^0}=1 MeV
$<1.\times 10^{-8}$	90		[63] BOSETTI	78B	HYBR	Beam dump
			[64] DONNELLY	78		
$<0.5\times 10^{-8}$	90		HANSL	78D	WIRE	Beam dump
			[65] MICELMAC...	78		
			[66] VYSOTSKII	78		

[39] 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.

[40] MEIJERDREES 92 give $\Gamma(\pi^- p \to nA^0)\cdot B(A^0 \to e^+e^-)/\Gamma(\pi^- p \to \text{all}) < 10^{-5}$ (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.

[41] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \to e^+e^-$, 2γ 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 $x < 1$.

[42] 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.

[43] 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.

[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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.

[49] 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 $[d\sigma(A^0)/d\omega$ at $90°]\, m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[50] 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.

[51] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B$(e^+ e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for $140 < m_{A^0} < 160$ MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[52] 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.

[53] FAISSNER 81 see excess μe events. Suggest axion interactions.

[54] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ 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 ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[55] 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.

[56] 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 $20/(A^0$ mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

[57] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interactaction}) < 7. \times 10^{-68}$ cm^4, CL = 90%$]$. Second limit is from nonobservation of axion decays into 2γ's or $e^+ e^-$, and for axion mass a few MeV.

[58] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[59] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2γ or $e^+ e^-$. No signal found. CL = 90% limits for model parameter(s) are given.

[60] COTEUS 79 is a beam dump experiment at BNL.

[61] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[62] 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$\times$(mass^{-4}). Third value uses data of PL 60B 401 and quotes σ(production)σ(interaction) $< 10^{-67}$ cm^4.
[63] BOSETTI 78B quotes σ(production)σ(interaction) $< 2. \times 10^{-67}$ cm^4.
[64] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.
[65] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).
[66] 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. • • •				
	[67] KETOV	86	SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	[68] KOCH	86	SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	[69] DATAR	82	CNTR	Light water reactor
	[70] VUILLEUMIER	81	CNTR	Reactor, $A^0 \rightarrow 2\gamma$

[67] 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.
[68] 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.
[69] 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 $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I = 0) - (I = 1)]$ result, assert nonexistence of standard A^0.
[70] 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%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.2 \times 10^{-6}$	95		[71] MINOWA	93	CNTR	^{139}La$^* \rightarrow {}^{139}$LaA^0
$< 2 \times 10^{-4}$	90		[72] HICKS	92	CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[73] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4\text{–}10) \times 10^{-3}$	95		[74] DEBOER	90	CNTR	^{8}Be$^* \rightarrow {}^8$BeA^0, $A^0 \rightarrow e^+ e^-$
$<(0.2\text{–}1) \times 10^{-3}$	90		[75] BINI	89	CNTR	^{16}O$^* \rightarrow {}^{16}$OX^0, $X^0 \rightarrow e^+ e^-$
			[76] AVIGNONE	88	CNTR	Cu$^* \rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$, $A^0 e \rightarrow \gamma e$, $A^0 Z \rightarrow \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[77] DATAR	88	CNTR	^{12}C$^* \rightarrow {}^{12}$CA^0, $A^0 \rightarrow e^+ e^-$
$< 5 \times 10^{-3}$	90		[78] DEBOER	88C	CNTR	^{16}O$^* \rightarrow {}^{16}$OX^0, $X^0 \rightarrow e^+ e^-$
$< 3.4 \times 10^{-5}$	95		[79] DOEHNER	88	SPEC	^{2}H*, $A^0 \rightarrow e^+ e^-$
$< 4 \times 10^{-4}$	95		[80] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[80] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[81] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90		[81] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[81] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[82] SAVAGE	86B	CNTR	^{14}N*
			[83] ANANEV	85	CNTR	Li*, deut* $A^0 \rightarrow 2\gamma$
			[84] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \rightarrow 2\gamma$
			[85] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \rightarrow 2\gamma$
			[86] LEHMANN	82	CNTR	Cu$^* \rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$)
		0	[87] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.
		0	[88] ZEHNDER	81	CNTR	Ba$^* \rightarrow$ BaA^0 ($A^0 \rightarrow 2\gamma$)
			[89] CALAPRICE	79		Carbon

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

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

[73] 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.

[74] The DEBOER 90 limit is for the branching ratio ^{8}Be* (18.15 MeV, 1^+) $\rightarrow$ ^{8}BeA^0, $A^0 \rightarrow e^+ e^-$ for the mass range m_{A^0} = 4–15 MeV.

[75] The BINI 89 limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\rightarrow$ ^{16}OX^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^-.

[76] AVIGNONE 88 looked for the 1115 keV transition C* $\rightarrow$ CuA^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.

[77] 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.

[78] The limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\rightarrow$ ^{16}OX^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: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[79] 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.

[80] 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 ^{8}Be, and the 18.15 MeV state $J^P = 1^+$ in ^{8}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.

[81] 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}Li 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.

[82] 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.

[83] 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.

[84] CAVAIGNAC 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).

[85] 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 keV $< m_{A^0} <$2.2 MeV. (deuteron* decay).

[86] LEHMANN 82 obtained $A^0 \rightarrow 2\gamma$ rate $< 6.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} between 100 and 1000 keV.

[87] 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.

[88] ZEHNDER 81 looked for Ba* $\rightarrow$ A^0Ba transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[89] 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 $\tau(A^0 \rightarrow e^+ e^-)$.

VALUE (s)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*

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

none 4×10^{-16}–4.5×10^{-12}	90	[90] BROSS	91	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)
		[91] GUO	90	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)
		[92] BJORKEN	88	CALO	$A \rightarrow e^+e^-$ or 2γ
		[93] BLINOV	88	MD1	$ee \rightarrow eeA^0$ ($A^0 \rightarrow ee$)
none 1×10^{-14}–1×10^{-10}	90	[94] RIORDAN	87	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)
none 1×10^{-14}–1×10^{-11}	90	[95] BROWN	86	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)
none 6×10^{-14}–9×10^{-11}	95	[96] DAVIER	86	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)
none 3×10^{-13}–1×10^{-7}	90	[97] KONAKA	86	BDMP	$eN \rightarrow eA^0 N$ ($A^0 \rightarrow ee$)

[90] 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).

[91] 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).

[92] 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.

[93] 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%).

[94] 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.

[95] 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.

[96] $m_{A^0} = 1.8$ 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.

[97] 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 Scattering

The limit is for $\Gamma(A^0)[\text{B}(A^0 \rightarrow e^+e^-)]^2$.

VALUE (10^{-3} eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 1.3	97	[98] HALLIN	92	CNTR	$m_{A^0} = 1.75$–1.88 MeV
none 0.0016–0.47	90	[99] HENDERSON	92C	CNTR	$m_{A^0} = 1.5$–1.86 MeV
$<$ 2.0	90	[100] WU	92	CNTR	$m_{A^0} = 1.56$–1.86 MeV
$<$ 0.013	95	TSERTOS	91	CNTR	$m_{A^0} = 1.832$ MeV
none 0.19–3.3	95	[101] WIDMANN	91	CNTR	$m_{A^0} = 1.78$–1.92 MeV
$<$ 5	97	BAUER	90	CNTR	$m_{A^0} = 1.832$ MeV
none 0.09–1.5	95	[102] JUDGE	90	CNTR	$m_{A^0} = 1.832$ MeV, elastic
$<$ 1.9	97	[103] TSERTOS	89	CNTR	$m_{A^0} = 1.82$ MeV
$<$(10–40)	97	[103] TSERTOS	89	CNTR	$m_{A^0} = 1.51$–1.65 MeV
$<$(1–2.5)	97	[103] TSERTOS	89	CNTR	$m_{A^0} = 1.80$–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	[104] TSERTOS	88	CNTR	$m_{A^0} = 1.832$ MeV
		[105] VANKLINKEN	88	CNTR	
		[106] MAIER	87	CNTR	
$<$2500	90	MILLS	87	CNTR	$m_{A^0} = 1.8$ MeV
		[107] VONWIMMER.	87	CNTR	

[98] 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.

[99] HENDERSON 92C exclude axion with lifetime $\tau_{A^0}=1.4\times10^{-12}-4.0\times10^{-10}$ s, assuming B($A^0 \rightarrow e^+e^-$)=100%. HENDERSON 92C also exclude a vector boson with $\tau=1.4\times10^{-12}-6.0\times10^{-10}$ s.

[100] WU 92 quote limits on lifetime $> 3.3\times10^{-13}$ 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, $\tau > 8.2\times10^{-13}$ s.

[101] 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.

[102] JUDGE 90 excludes an elastic pseudoscalar e^+e^- resonance for 4.5×10^{-13} s $< \tau(A^0) < 7.5\times10^{-12}$ s (95% CL) at m_{A^0} = 1.832 MeV. Comparable limits can be set for m_{A^0} = 1.776–1.856 MeV.

[103] See also TSERTOS 88B in references.

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

[105] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}$–10^{-12} s). The sensitivity is not sufficient to exclude such a narrow resonance.

[106] 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 $\Gamma = \Gamma^2_{ee}/\Gamma_{\text{total}}$. For a discussion implying that $\Delta E_{\text{cm}} \simeq$ 10 keV, see TSERTOS 89.

[107] VONWIMMERSPERG 87 measured Bhabha scattering for E_{cm} = 1.37–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}}$ = 14.5 ± 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	[108] TRZASKA	91	CNTR	m_{A^0} = 1.8 MeV
< 4.4	95	WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV
		[109] FOX	89	CNTR	
< 0.11	95	[110] 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

[108] TRZASKA 91 also give limits in the range (6.6–30) $\times 10^{-3}$ eV (95%CL) for m_{A^0} = 1.6–2.0 MeV.

[109] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($< 9\times10^{-5}$ of two-photon annihilation at rest).

[110] Similar limits are obtained for m_{A^0} = 1.045–1.085 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	[111] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV
< 1.0	95	[112] VO	94	CNTR	m_{X^0}=1.1 MeV
< 2.5	95	[112] VO	94	CNTR	m_{X^0}=1.4 MeV
<120	95	[112] VO	94	CNTR	m_{X^0}=1.7 MeV
< 3.8	95	[113] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV

[111] 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.

[112] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.

[113] 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.

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. • • •						
			[114] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3 \times 10^{-2}$	95		[115] ALBRECHT	90E	ARG	$\tau \rightarrow \mu X^0$. Familon
$<1.8 \times 10^{-2}$	95		[115] ALBRECHT	90E	ARG	$\tau \rightarrow e X^0$. Familon
$<6.4 \times 10^{-9}$	90		[116] ATIYA	90	CNTR	$K^+ \rightarrow \pi^+ X^0$. Familon
$<1.1 \times 10^{-9}$	90		[117] BOLTON	88	CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon
			[118] CHANDA	88	ASTR	Sun, Majoron
			[119] CHOI	88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90		[120] PICCIOTTO	88	CNTR	$\pi \rightarrow e \nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90		[121] GOLDMAN	87	CNTR	$\mu \rightarrow e \gamma X^0$. Familon
$<3 \times 10^{-4}$	90		[122] BRYMAN	86B	RVUE	$\mu \rightarrow e X^0$. Familon
$<1. \times 10^{-10}$	90	0	[123] EICHLER	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
$<2.6 \times 10^{-6}$	90		[124] JODIDIO	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
			[125] BALTRUSAIT...	85	MRK3	$\tau \rightarrow \ell X^0$. Familon
			[126] DICUS	83	COSM	$\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$

[114] 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 $x_e (G_F/8\pi\sqrt{2})^{1/2}$.

[115] ALBRECHT 90E limits are for $B(\tau \rightarrow \ell X^0)/B(\tau \rightarrow \ell \nu \overline{\nu})$. 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.

[116] 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.

[117] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.

[118] 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.

[119] 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 $L_{\text{int}} = \frac{1}{2} i h \overline{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[120] PICCIOTTO 88 limit applies when $m_{X^0} < 55$ MeV and $\tau_{X^0} > 2$ns, and it decreases to 4×10^{-7} at $m_{X^0} = 125$ MeV, beyond which no limit is obtained.

[121] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{\text{int}} = (1/F) \overline{\psi}_\mu \gamma^\mu (a + b\gamma_5) \psi_e \partial_\mu \phi_{X^0}$ 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.

[122] Limits are for $\Gamma(\mu \rightarrow e X^0)/\Gamma(\mu \rightarrow e \nu \overline{\nu})$. Valid when $m_{X^0} = $ 0–93.4, 98.1–103.5 MeV.

[123] 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.

[124] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F) \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.

[125] 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.

[126] 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.

Previous indications for neutrinoless double beta decay with majoron emission have been superseded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	CL%	DOCUMENT ID		TECN	COMMENT
> 7.2 × 10^{24}	90	[127] BERNATOW...	92	CNTR	^{128}Te

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

$> 1.7 \times 10^{22}$	90	BECK	93	CNTR	^{76}Ge
$> 7.9 \times 10^{20}$	68	[128] TANAKA	93	SPEC	^{100}Mo
$> 1.9 \times 10^{20}$	68	BARABASH	89	CNTR	^{136}Xe
$> 1.0 \times 10^{21}$	90	FISHER	89	CNTR	^{76}Ge
$> 3.3 \times 10^{20}$	90	ALSTON-...	88	CNTR	^{100}Mo
$(6 \pm 1) \times 10^{20}$		AVIGNONE	87	CNTR	^{76}Ge
$> 1.4 \times 10^{21}$	90	CALDWELL	87	CNTR	^{76}Ge
$> 4.4 \times 10^{20}$	90	ELLIOTT	87	SPEC	^{82}Se
$> 1.2 \times 10^{21}$	90	FISHER	87	CNTR	^{76}Ge
		[129] VERGADOS	82	CNTR	

[127] BERNATOWICZ 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 $(7.7–1.28 \times 0.4{=}7.2) \times 10^{24}$.

[128] TANAKA 93 also quote limit 5.3×10^{19} years on two Majoron emission.

[129] VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H, of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca.

MINIREVIEW GOES HERE

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

$v_1 = v_2$ is usually assumed (v_i = vacuum expectation values). For a review of these limits, see RAFFELT 90C and TURNER 90.

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.01	WANG	92	ASTR	D, white dwarf
< 0.03	WANG	92C	ASTR	D, C-O burning
none 3–8	[130] BERSHADY	91	ASTR	D, K, intergalactic light
<10	[131] KIM	91C	COSM	D, K, mass density of the universe, supersymmetry
	[132] RAFFELT	91B	ASTR	D,K, SN 1987A
$< 1 \times 10^{-3}$	[133] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS	90	ASTR	D,K, SN 1987A
	[134] ENGEL	90	ASTR	D,K, SN 1987A
< 0.02	[135] RAFFELT	90D	ASTR	D, red giant
$< 1 \times 10^{-3}$	[136] BURROWS	89	ASTR	D,K, SN 1987A
$<(1.4–10) \times 10^{-3}$	[137] ERICSON	89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[138] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[139] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[140] RAFFELT	87	ASTR	K, red giant
$< 2–5$	TURNER	87	COSM	K, thermal production
< 0.01	[141] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[142] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[143] 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	[144] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[130] 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.

[131] 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.

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

[133] RESSELL 91 uses absence of any intracluster line emission to set limit.

[134] 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 2.5×10^{-3} eV $\lesssim m_{A^0} \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

[135] RAFFELT 90D is a re-analysis of DEARBORN 86.

[136] The region $m_{A^0} \gtrsim 2$ eV is also allowed.

[137] 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.

[138] 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.

[139] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg g^{-1} s^{-1}, which gives a firmer basis for the axion limits based on red giant cooling.

[140] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV^{-1}.

[141] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV^{-1}.

[142] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}$ GeV^{-1} from red giants and $< 2.4\times10^{-9}$ GeV^{-1} from the sun.

[143] KAPLAN 85 says $m_{A^0} < 23$ eV is allowed for a special choice of model parameters.

[144] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ 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, $L_{\text{int}} = \frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\widetilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, and ρ_A 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. • • •					
$<2 \times 10^{-41}$		[145] HAGMANN	90	CNTR	$m_{A^0} = (5.4\text{–}5.9)10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[146] WUENSCH	89	CNTR	$m_{A^0} = (4.5\text{–}10.2)10^{-6}$ eV
$<2 \times 10^{-41}$	95	[146] WUENSCH	89	CNTR	$m_{A^0} = (11.3\text{–}16.3)10^{-6}$ eV

[145] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.

[146] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and $\rho_A = 300$ 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*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-7}$	95	[147] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[148] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[149] LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[149] LAZARUS	92	$m_{A^0} = 0.03\text{–}0.11$ eV
$<7.7 \times 10^{-7}$	99	[150] RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[151] SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

[147] Experiment based on proposal by MAIANI 86.

[148] Experiment based on proposal by VANBIBBER 87.

[149] LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.

[150] RUOSO 92 experiment is based on the proposal by VANBIBBER 87.
[151] 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 $G_{Aee}\partial_\mu\phi_A\overline{e}\gamma^\mu\gamma_5 e$ in GeV^{-1}, or equivalenty, the dipole-dipole potential $\frac{G^2_{Aee}}{4\pi}$ $((\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1\cdot\boldsymbol{n})\,(\boldsymbol{\sigma}_2\cdot\boldsymbol{n}))/r^3$ where $\boldsymbol{n}=\boldsymbol{r}/r$.

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

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.9 \times 10^{-5}$	95	[152] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[153] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[154] RITTER	90		Torsion pendulum
$<6.4 \times 10^{-5}$	95	[152] VOROBYOV	88		Induced magnetism

[152] 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.
[153] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.
[154] RITTER 90 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.

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

MAENO	95	PL B (to be pub.)	+Fujikawa, Kataoka, Nishihara+	(TOKY)
AMSLER	94B	PL B333 271	+Armstrong, Augustin, Baker+	(CBAR Collab.)
ASAI	94	PL B323 90	+Shigekuni, Sanuki, Orito	(TOKY)
MEIJERDREES	94	PR D49 4937	Meijer Drees, Waltham+	(BRCO, OREG, TRIU)
VO	94	PR C49 1551	+Kelly, Wohn, Hill+	(ISU, LBL, LLNL, UCD)
ATIYA	93	PRL 70 2521	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
Also	93C	PRL 71 305 (erratum)	Atiya, Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
ATIYA	93B	PR D48 R1	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
BASSOMPIE...	93	EPL 22 239	Bassompierre, Bologna+	(LAPP, TORI, LYON)
BECK	93	PRL 70 2853	+Bensch, Bockholt, Heusser, Hirsch+	(MPIH, KIAE, SASSO)
CAMERON	93	PR D47 3707	+Cantatore, Melissinos+	(ROCH, BNL, FNAL, TRST)
MINOWA	93	PRL 71 4120	+Inoue, Asanuma, Imamura	(TOKY)
NG	93	PR D48 2941		(AST)
TANAKA	93	PR D48 5412	+Ejiri	(OSAK)
ALLIEGRO	92	PRL 68 278	+Campagnari+	(BNL, FNAL, PSI, WASH, YALE)
ATIYA	92	PRL 69 733	+Chiang, Frank, Haggerty, Ito+	(BNL, LANL, PRIN, TRIU)
BERNATOW...	92	PRL 69 2341	Bernatowicz, Brannon, Brazzle, Cowsik+	(WUSL, TATA)
BLUEMLEIN	92	IJMP A7 3835	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
HALLIN	92	PR D45 3955	+Calaprice, McPherson, Saettler	(PRIN)
HENDERSON	92C	PRL 69 1733	+Asoka-Kumar, Greenberg, Lynn+	(YALE, BNL)
HICKS	92	PL B276 423	+Alburger	(OHIO, BNL)
LAZARUS	92	PRL 69 2333	+Smith, Cameron, Melissinos+	(BNL, ROCH, FNAL)
MEIJERDREES	92	PRL 68 3845	Meijer Drees, Waltham+	(SINDRUM I Collab.)
RUOSO	92	ZPHY C56 505	+Cameron, Cantatore+	(ROCH, BNL, FNAL, TRST)
SKALSEY	92	PRL 68 456	+Kolata	(MICH, NDAM)
WANG	92	MPL A7 1497		(ILL)
WANG	92C	PL B291 97		(ILL)
WU	92	PRL 69 1729	+Asoka-Kumar, Greenberg, Henderson+	(BNL, YALE, CUNY)
AKOPYAN	91	PL B272 443	+Atoyan, Gninenko, Sukhov	(INRM)
ASAI	91	PRL 66 2440	+Orito, Yoshimura, Haga	(ICEPP)
BERSHADY	91	PRL 66 1398	+Ressell, Turner	(CHIC, FNAL, EFI)
BLUEMLEIN	91	ZPHY C51 341	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
BOBRAKOV	91	JETPL 53 294	+Borisov, Lasakov, Serebrov, Tal'daev, Trofimova	(PNPI)
		Translated from ZETFP 53 283.		
BROSS	91	PRL 67 2942	+Crisler, Pordes, Volk, Errede, Wrbanek	(FNAL, ILL)
KIM	91C	PRL 67 3465		(SEOUL)
RAFFELT	91B	PRL 67 2605	+Seckel	(MPIM, BART)
RESSELL	91	PR D44 3001		(CHIC, FNAL)
TRZASKA	91	PL B269 54	+Dejbakhsh, Dutta, Li, Cormier	(TAMU)
TSERTOS	91	PL B266 259	+Kienle, Judge, Schreckenbach	(ILLG, GSI)
WALKER	91	APJ 376 51	+Steigman, Schramm, Olive+	(HSCA, OSU, CHIC, MINN)
WIDMANN	91	ZPHY A340 209	+Bauer, Connell, Maier, Major+	(STUT, GSI, STUTM)
WINELAND	91	PRL 67 1735	+Bollinger, Heinzen, Itano, Raizen	(NBSB)
ALBRECHT	90E	PL B246 278	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ANTREASYAN	90C	PL B251 204	+Bartels, Besset, Bieler, Bienlein+	(Crystal Ball Collab.)
ASANUMA	90	PL B237 588	+Minowa, Tsukamoto, Orito, Tsunoda	(TOKY)
ATIYA	90	PRL 64 21	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL 787 Collab.)
ATIYA	90B	PRL 65 1188	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL 787 Collab.)
BAUER	90	NIM B50 300	+Briggmann, Carstanjen, Connell, et al	(STUT, VILL, GSI)
BURROWS	90	PR D42 3297	+Ressell, Turner	(ARIZ, CHIC, FNAL)
DEBOER	90	JPG 16 L1	de Boer, Lehmann, Steyaert	(LVLN)
ENGEL	90	PRL 65 960	+Seckel, Hayes	(BART, LANL)
GNINENKO	90	PL B237 287	+Klubakov, Poblaguev, Postoev	(INRM)
GUO	90	PR D41 2924	+Kaplan, Alde+	(NIU, LANL, FNAL, CASE, TEXA)
HAGMANN	90	PR D42 1297	+Sikivie, Sullivan, Tanner	(FLOR)
JUDGE	90	PRL 65 972	+Krusche, Schreckenbach, Tsertos, Kienle	(ILLG, GSI)

RAFFELT 90C PRPL 198 1 (MPIM)
RAFFELT 90D PR D41 1324 (MPIM)
RITTER 90 PR D42 977 +Goldblum, Ni, Gillies, Speake (VIRG)
SEMERTZIDIS 90 PRL 64 2988 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
TSUCHIAKI 90 PL B236 81 +Orito, Yoshida, Minowa (ICEPP)
TURNER 90 PRPL 197 67 (FNAL)
BARABASH 89 PL B223 273 +Kuzminov, Lobashev, Novikov+ (ITEP, INRM)
BINI 89 PL B221 99 +Fazzini, Giannatiempo, Poggi, Sona+(FIRZ, CERN, AARH)
BURROWS 89 PR D39 1020 +Turner, Brinkmann (ARIZ, CHIC, FNAL, BOCH)
Also 88 PRL 60 1797 Turner (FNAL, EFI)
DEBOER 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
ERICSON 89 PL B219 507 +Mathiot (CERN, IPN)
FAISSNER 89 ZPHY C44 557 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, PSI)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
FOX 89 PR C39 288 +Kemper, Cottle, Zingarelli (FSU)
MAYLE 89 PL B219 515 +Wilson, Ellis+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
Also 88 PL B203 188 Mayle, Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA 89 PRL 62 1091 +Orito, TIsuchiaki, TIsukamoto (ICEPP)
ORITO 89 PRL 63 597 +Yoshimura, Haga, Minowa, Tsuchiaki (ICEPP)
PERKINS 89 PRL 62 2638 (OXF)
TSERTOS 89 PR D40 1397 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANBIBBER 89 PR D39 2089 Van Bibber, McIntyre, Morris, Raffelt (LLL, TAMU, LBL)
WUENSCH 89 PR D40 3153 +De Panfilis-Wuensch, Semertzidis+ (ROCH, BNL, FNAL)
Also 87 PRL 59 839 De Panfilis, Melissinos, Moskowitz+ (ROCH, BNL, FNAL)
ALSTON-... 88 PRL 60 1928 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM)
AVIGNONE 88 PR D37 618 +Baktash, Barker, Calaprice+(PRIN, SCUC, ORNL, WASH)
BJORKEN 88 PR D38 3375 +Ecklund, Nelson, Abashian+ (FNAL, SLAC, VPI)
BLINOV 88 SJNP 47 563 +Bondar, Bukin, Vorobyev, Groshev+ (NOVO)
Translated from YAF 47 889.
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
CHANDA 88 PR D37 2714 +Nieves, Pal (UMD, UPR, MASA)
CHOI 88 PR D37 3225 +Kim, Kim, Lam (JHU)
CONNELL 88 PRL 60 2242 +Fearick, Hoernle, Sideras-Haddad, Sellschop (WITW)
DATAR 88 PR C37 250 +Fortier, Gales, Hourani+ (IPN)
DEBOER 88 PRL 61 1274 de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2644 erratum de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2638 Perkins (OXF)
Also 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
DEBOER 88C JPG 14 L131 de Boer, Deutsch, Lehmann, Prieels, Steyaert (LVLN)
DOEHNER 88 PR D38 2722 +Last, Arnold, Freedman, Dubbers (HEIDP, ANL, ILLG)
DOI 88 PR D37 2575 +Kotani, Takasugi (OSAK)
EL-NADI 88 PRL 61 1271 +Badawy (CAIR)
FAISSNER 88 ZPHY C37 231 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, SIN)
HATSUDA 88B PL B203 469 +Yoshimura (KEK)
LORENZ 88 PL B214 10 +Mageras, Stiegler, Huszar (MPIM, PSI)
MAYLE 88 PL B203 188 +Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO 88 PR D37 1131 +Ahmad, Britton, Bryman, Clifford+ (TRIU, CNRC)
RAFFELT 88 PRL 60 1793 +Seckel (UCB, LLL, UCSC)
RAFFELT 88B PR D37 549 +Dearborn (UCB, LLL)
SAVAGE 88 PR D37 1134 +Filippone, Mitchell (CIT)
TSERTOS 88 PL B207 273 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
TSERTOS 88B ZPHY A331 103 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANKLINKEN 88 PL B205 223 van Klinken, Meiring, de Boer, Schaafsma+ (GRON, GSI)
VANKLINKEN 88B PRL 60 2442 van Klinken (GRON)
VONWIMMER... 88 PRL 60 2443 von Wimmersperg (BNL)
VOROBYOV 88 PL B208 146 +Gitarts (NOVO)
AVIGNONE 87 AIP Conf. 1987 +Brodzinski, Miley, Reeves (SCUC, PNL)
AIP Conf. Proc. Salt Lake City, UT
CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ELLIOTT 87 PRL 59 1649 +Hahn, Moe (UCI)
FISHER 87 PL B192 460 +Boehm, Bovet, Egger+ (CIT, NEUC, SIN)
FRIEMAN 87 PR D36 2201 +Dimopoulos, Turner (SLAC, STAN, FNAL, EFI)
GOLDMAN 87 PR D36 1543 +Hallin, Hoffman+ (LANL, CHIC, STAN, TEMP)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
MAIER 87 ZPHY A326 527 +Bauer, Briggmann, Carstanjen+ (STUT, GSI)
MILLS 87 PR D36 707 +Levy (BELL)
RAFFELT 87 PR D36 2211 +Dearborn (LLL, UCB)
RIORDAN 87 PRL 59 755 +Krasny, Lang, Barbaro, Bodek+ (ROCH, CIT+)
TURNER 87 PRL 59 2489 (FNAL, EFI)
VANBIBBER 87 PRL 59 759 Van Bibber, Dagdeviren, Koonin+(LLL, CIT, MIT, STAN)
VONWIMMER... 87 PRL 59 266 von Wimmersperg, Connell, Hoernle, Sideras-Haddad(WITW)
ALBRECHT 86D PL B179 403 +Binder, Boeckmann+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BOWCOCK 86 PRL 56 2676 +Giles, Hassard, Kinoshita+ (CLEO Collab.)
BROWN 86 PRL 57 2101 + (FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN 86B PRL 57 2787 +Clifford (TRIU)
DAVIER 86 PL B180 295 +Jeanjean, Nguyen Ngoc (LALO)
DEARBORN 86 PRL 56 26 +Schramm, Steigman (LLL, CHIC, FNAL, BART)
EICHLER 86 PL B175 101 +Felawka, Kraus, Niebuhr+ (SINDRUM Collab.)
HALLIN 86 PRL 57 2105 +Calparice, Dunford, McDonald (PRIN)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
KETOV 86 JETPL 44 146 +Klimov, Nikolaev, Mikaelyan+ (KIAE)
Translated from ZETFP 44 114.

KOCH	86	NC 96A 182	+Schult	(JULI)
KONAKA	86	PRL 57 659	+Imai, Kobayashi, Masaike, Miyake+	(KYOT, KEK)
MAGERAS	86	PRL 56 2672	+Franzini, Tuts, Youssef+	(MPIM, COLU, STON)
MAIANI	86	PL B175 359	+Petronzio, Zavattini	(CERN)
PECCEI	86	PL B172 435	+Wu, Yanagida	(DESY)
RAFFELT	86	PR D33 897		(MPIM)
RAFFELT	86B	PL 166B 402		(MPIM)
SAVAGE	86B	PRL 57 178	+McKeown, Filippone, Mitchell	(CIT)
AMALDI	85	PL 153B 444	+Carboni, Jonson, Thun	(CERN)
ANANEV	85	SJNP 41 585	+Kalinina, Lushchikov, Olshevskii+	(JINR)
		Translated from YAF 41 912.		
BALTRUSAIT...	85	PRL 55 1842	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BERGSMA	85	PL 157B 458	+Dorenbosch, Allaby, Amaldi+	(CHARM Collab.)
KAPLAN	85	NP B260 215		(HARV)
IWAMOTO	84	PRL 53 1198		(UCSB, WUSL)
YAMAZAKI	84	PRL 52 1089	+Ishikawa, Taniguchi, Yamanaka+	(INUS, KEK)
ABBOTT	83	PL 120B 133	+Sikivie	(BRAN, FLOR)
ALAM	83	PR D27 1665	+	(VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI	83	PL 123B 349	+Dahme	(CERN, MUNI)
CAVAIGNAC	83	PL 121B 193	+Hoummada, Koang, Ost+	(ISNG, LAPP)
DICUS	83	PR D28 1778	+Teplitz	(TEXA, UMD)
DINE	83	PL 120B 137	+Fischler	(IAS, PENN)
ELLIS	83B	NP B223 252	+Olive	(CERN)
FAISSNER	83	PR D28 1198	+Heinrigs, Preussger, Samm	(AACH)
FAISSNER	83B	PR D28 1787	+Frenzel, Heinrigs, Preussger+	(AACH3)
FRANK	83B	PR D28 1790	+	(LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN	83	PR D28 660	+Frank, Mischke, Moir, Schardt	(LANL, ARZS)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+	(LENA Collab.)
PRESKILL	83	PL 120B 127	+Wise, Wilczek	(HARV, UCSBT)
SIKIVIE	83	PRL 51 1415		(FLOR)
Also	84	PRL 52 695 erratum	Sikivie	(FLOR)
ALEKSEEV	82	JETP 55 591	+Kartamyshev, Makarin+	(KIAE)
		Translated from ZETF 82 1007.		
ALEKSEEV	82B	JETPL 36 116	+Kalinina, Kruglov, Kulikov+	(MOSU, JINR)
		Translated from ZETFP 36 94.		
ASANO	82	PL 113B 195	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, INUS, OSAK)
BARROSO	82	PL 116B 247	+Branco	(LISB)
DATAR	82	PL 114B 63	+Baba, Betigeri, Singh	(BHAB)
EDWARDS	82	PRL 48 903	+Partridge, Peck, Porter+	(Crystal Ball Collab.)
FETSCHER	82	JPG 8 L147		(ETH)
FUKUGITA	82	PRL 48 1522	+Watamura, Yoshimura	(KEK)
FUKUGITA	82B	PR D26 1840	+Watamura, Yoshimura	(KEK)
LEHMANN	82	PL 115B 270	+Lesquoy, Muller, Zylberajch	(SACL)
RAFFELT	82	PL 119B 323	+Stodolsky	(MPIM)
SIVERTZ	82	PR D26 717	+Lee-Franzini, Horstkotte+	(CUSB Collab.)
VERGADOS	82	PL 109B 96		(CERN)
ZEHNDER	82	PL 110B 419	+Gabathuler, Vuilleumier	(ETH, SIN, CIT)
ASANO	81B	PL 107B 159	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, INUS, OSAK)
BARROSO	81	PL 106B 91	+Mukhopadhyay	(SIN)
FAISSNER	81	ZPHY C10 95	+Frenzel, Grimm, Hansl, Hoffman+	(AACH3)
FAISSNER	81B	PL 103B 234	+Frenzel, Heinrigs, Preussger+	(AACH3)
KIM	81	PL 105B 55	+Stamm	(AACH3)
VUILLEUMIER	81	PL 101B 341	+Boehm, Hahn, Kwon+	(CIT, MUNI)
ZEHNDER	81	PL 104B 494		(ETH)
FAISSNER	80	PL 96B 201	+Frenzel, Heinrigs, Preussger, Samm+	(AACH3)
JACQUES	80	PR D21 1206	+Kalelkar, Miller, Plano+	(RUTG, STEV, COLU)
SOUKAS	80	PRL 44 564	+Wanderer, Weng+	(BNL, HARV, ORNL, PENN)
BECHIS	79	PRL 42 1511	+Dombeck+	(UMD, COLU, AFRR)
CALAPRICE	79	PR D20 2708	+Dunford, Kouzes, Miller+	(PRIN)
COTEUS	79	PRL 42 1438	+Diesburg, Fine, Lee, Sokolsky+	(COLU, ILL, BNL)
DISHAW	79	PL 85B 142	+Diamant-Berger, Faessler, Liu+	(SLAC, CIT)
ZHITNITSKII	79	SJNP 29 517	+Skovpen	(NOVO)
		Translated from YAF 29 1001.		
ALIBRAN	78	PL 74B 134	+Armenise, Arnold, Bartley	(Gargamelle Collab.)
ASRATYAN	78B	PL 79B 497	+Epstein, Fakhrutdinov+	(ITEP, SERP)
BELLOTTI	78	PL 76B 223	+Fiorini, Zanotti	(MILA)
BOSETTI	78B	PL 74B 143	+Deden, Deutschmann, Fritze+	(BEBC Collab.)
DICUS	78C	PR D18 1829	+Kolb, Teplitz, Wagoner	(TEXA, VPI, STAN)
DONNELLY	78	PR D18 1607	+Freedman, Lytel, Peccei, Schwartz	(STAN)
Also	76	PRL 37 315	Reines, Gurr, Sobel	(UCI)
Also	74	PRL 33 179	Gurr, Reines, Sobel	(UCI)
HANSL	78D	PL 74B 139	+Holder, Knobloch, May, Paar+	(CDHS Collab.)
MICELMAC...	78	LNC 21 441	Micelmacher, Pontecorvo	(JINR)
MIKAELIAN	78	PR D18 3605		(FNAL, NWES)
SATO	78	PTP 60 1942		(KYOT)
VYSOTSKII	78	JETPL 27 502	+Zeldovich, Khlopov, Chechetkin	(ASCI)
		Translated from ZETFP 27 533.		
YANG	78	PRL 41 523		(MASA)
PECCEI	77	PR D16 1791	+Quinn	(STAN, SLAC)
Also	77B	PRL 38 1440	Peccei, Quinn	(STAN, SLAC)
REINES	76	PRL 37 315	+Gurr, Sobel	(UCI)
GURR	74	PRL 33 179	+Reines, Sobel	(UCI)
ANAND	53	PRSL A22 183		

OTHER RELATED PAPERS

SREDNICKI	85	NP B260 689		(UCSB)
BARDEEN	78	PL 74B 229	+Tye	(FNAL)