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

A REVIEW GOES HERE – Check our WWW List of Reviews

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 Hadron Decays

Limits are for branching ratios.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[1] WON	16	BELL	$\eta \to \gamma X^0$ ($X^0 \to \pi^+\pi^-$)
$<1 \times 10^{-9}$	95	[2] AAIJ	15AZ	LHCB	$B^0 \to K^{*0} X^0$ ($X^0 \to \mu^+\mu^-$)
$<1.5 \times 10^{-6}$	90	[3] ADLARSON	13	WASA	$\pi^0 \to \gamma X^0$ ($X^0 \to e^+e^-$), m_{X^0} = 100 MeV
$<2 \times 10^{-8}$	90	[4] BABUSCI	13B	KLOE	$\phi \to \eta X^0$ ($X^0 \to e^+e^-$)
		[5] ARCHILLI	12	KLOE	$\phi \to \eta X^0$, $X^0 \to e^+e^-$
$<2 \times 10^{-15}$	90	[6] GNINENKO	12A	BDMP	$\pi^0 \to \gamma X^0$ ($X^0 \to e^+e^-$)
$<3 \times 10^{-14}$	90	[7] GNINENKO	12B	BDMP	$\eta(\eta') \to \gamma X^0$ ($X^0 \to e^+e^-$)
$<7 \times 10^{-10}$	90	[8] ADLER	04	B787	$K^+ \to \pi^+ X^0$
$<7.3 \times 10^{-11}$	90	[9] ANISIMOVSK...	04	B949	$K^+ \to \pi^+ X^0$
$<4.5 \times 10^{-11}$	90	[10] ADLER	02C	B787	$K^+ \to \pi^+ X^0$
$<4 \times 10^{-5}$	90	[11] ADLER	01	B787	$K^+ \to \pi^+\pi^0 A^0$
$<4.9 \times 10^{-5}$	90	AMMAR	01B	CLEO	$B^\pm \to \pi^\pm(K^\pm) X^0$
$<5.3 \times 10^{-5}$	90	AMMAR	01B	CLEO	$B^0 \to K^0_S X^0$
$<3.3 \times 10^{-5}$	90	[12] ALTEGOER	98	NOMD	$\pi^0 \to \gamma X^0$, $m_{X^0} <$ 120 MeV
$<5.0 \times 10^{-8}$	90	[13] KITCHING	97	B787	$K^+ \to \pi^+ X^0$ ($X^0 \to \gamma\gamma$)
$<5.2 \times 10^{-10}$	90	[14] ADLER	96	B787	$K^+ \to \pi^+ X^0$
$<2.8 \times 10^{-4}$	90	[15] AMSLER	96B	CBAR	$\pi^0 \to \gamma X^0$, $m_{X^0} <$ 65 MeV
$<3 \times 10^{-4}$	90	[15] AMSLER	96B	CBAR	$\eta \to \gamma X^0$, m_{X^0}= 50–200 MeV
$<4 \times 10^{-5}$	90	[15] AMSLER	96B	CBAR	$\eta' \to \gamma X^0$, m_{X^0}= 50–925 MeV
$<6 \times 10^{-5}$	90	[15] AMSLER	94B	CBAR	$\pi^0 \to \gamma X^0$, m_{X^0}=65–125 MeV

$<6 \times 10^{-5}$	90	[15] AMSLER	94B	CBAR	$\eta \to \gamma X^0$, m_{X^0}=200–525 MeV
$<7 \times 10^{-3}$	90	[16] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=25 MeV
$<2 \times 10^{-3}$	90	[16] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=100 MeV
$<2 \times 10^{-7}$	90	[17] ATIYA	93B	B787	Sup. by ADLER 04
$<3 \times 10^{-13}$		[18] NG	93	COSM	$\pi^0 \to \gamma X^0$
$<1.1 \times 10^{-8}$	90	[19] ALLIEGRO	92	SPEC	$K^+ \to \pi^+ X^0$ ($X^0 \to e^+ e^-$)
$<5 \times 10^{-4}$	90	[20] ATIYA	92	B787	$\pi^0 \to \gamma X^0$
$<1 \times 10^{-12}$	95	[21] BARABASH	92	BDMP	$\pi^\pm \to e^\pm \nu X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), m_{X^0} = 8 MeV
$<1 \times 10^{-12}$	95	[22] BARABASH	92	BDMP	$K^\pm \to \pi^\pm X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), m_{X^0} = 10 MeV
$<1 \times 10^{-11}$	95	[23] BARABASH	92	BDMP	$K_L^0 \to \pi^0 X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), m_{X^0} = 10 MeV
$<1 \times 10^{-14}$	95	[24] BARABASH	92	BDMP	$\eta' \to \eta X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), m_{X^0} = 10 MeV
$<4 \times 10^{-6}$	90	[25] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$ ($X^0 \to e^+ e^-$), m_{X^0}= 100 MeV
$<1 \times 10^{-7}$	90	[26] ATIYA	90B	B787	Sup. by KITCHING 97
$<1.3 \times 10^{-8}$	90	[27] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ ($A^0 \to e^+ e^-$)
$<1 \times 10^{-9}$	90	[28] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90	[29] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5–4) \times 10^{-6}$	90	[29] YAMAZAKI	84	SPEC	K decay, $m_{X^0} \ll$ 100 MeV
		[30] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ X^0$
		[31] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ X^0$
		[32] ZHITNITSKII	79		Heavy axion

[1] WON 16 look for a vector boson coupled to baryon number. Derived limits on α' $<$ 10^{-3}–10^{-2} for m_{X^0} = 290–520 MeV at 95% CL. See their Fig. 4 for mass-dependent limits.

[2] The limit is for τ_{X^0} = 10 ps and m_{X^0} = 214–4350 MeV. See their Fig. 4 for mass- and lifetime-dependent limits.

[3] Limits between 2.0×10^{-5} and 1.5×10^{-6} are obtained for m_{X^0} = 20–100 MeV (see their Fig. 8). Angular momentum conservation requires that X^0 has spin $\geq$ 1.

[4] The limit is for B($\phi \to \eta X^0$)·B($X^0 \to e^+ e^-$) and applies to m_{X^0} = 410 MeV. It is derived by analyzing $\eta \to \pi^0 \pi^0 \pi^0$ and $\pi^- \pi^+ \pi^0$. Limits between 1×10^{-6} and 2×10^{-8} are obtained for $m_{X^0} \leq$ 450 MeV (see their Fig. 6).

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

[6] This limit is for B($\pi^0 \to \gamma X^0$)·B($X^0 \to e^+ e^-$) and applies for m_{X^0} = 90 MeV and $\tau_{X^0} \simeq 1 \times 10^{-8}$ sec. Limits between 10^{-8} and 2×10^{-15} are obtained for m_{X^0} = 3–120 MeV and $\tau_{X^0} = 1 \times 10^{-11}$–1 sec. See their Fig. 3 for limits at different masses and lifetimes.

[7] This limit is for B($\eta \to \gamma X^0$)·B($X^0 \to e^+ e^-$) and applies for m_{X^0} = 100 MeV and $\tau_{X^0} \simeq 6 \times 10^{-9}$ sec. Limits between 10^{-5} and 3×10^{-14} are obtained for $m_{X^0} \lesssim$ 550 MeV and $\tau_{X^0} = 10^{-10}$–10 sec. See their Fig. 5 for limits at different mass and lifetime and for η' decays.

[8] This limit applies for a mass near 180 MeV. For other masses in the range m_{X^0} = 150–250 MeV the limit is less restrictive, but still improves ADLER 02C and ATIYA 93B.

[9] ANISIMOVSKY 04 bound is for m_{X^0}=0.

[10] ADLER 02C bound is for m_{X^0} <60 MeV. See Fig. 2 for limits at higher masses.

[11] The quoted limit is for m_{X^0} = 0–80 MeV. See their Fig. 5 for the limit at higher mass. The branching fraction limit assumes pure phase space decay distributions.

[12] 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.

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

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

[15] AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.

[16] 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.

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

[18] 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.

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

[20] 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.

[21] BARABASH 92 is a beam dump experiment that searched for a light Higgs. Limits between 1×10^{-12} and 1×10^{-7} are obtained for $3 < m_{X^0} < 40$ MeV.

[22] Limits between 1×10^{-12} and 1 are obtained for $4 < m_{X^0} < 69$ MeV.

[23] Limits between 1×10^{-11} and 5×10^{-3} are obtained for $4 < m_{X^0} < 63$ MeV.

[24] Limits between 1×10^{-14} and 1 are obtained for $3 < m_{X^0} < 82$ MeV.

[25] 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.

[26] ATIYA 90B limit is for B($K^+ \rightarrow \pi^+ X^0$)·B($X^0 \rightarrow \gamma\gamma$) and applies for $m_{X^0} = 50$ MeV, $\tau_{X^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{X^0} < 100$ MeV, $\tau_{X^0} < 10^{-8}$ s.

[27] KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and B($A^0 \rightarrow e^+ e^-) = 1$.

[28] 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.

[29] 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.

[30] ASANO 82 at KEK set limits for B($K^+ \rightarrow \pi^+ X^0$) for m_{X^0} <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(X^0 \rightarrow n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s.

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

[32] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 ($3 < m < 40$ MeV) contradicts experimental muon anomalous magnetic moments.

A^0 (Axion) Searches in Quarkonium Decays

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

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.8 \times 10^{-8}$	90	[1] ABLIKIM	16E	BES3	$J/\psi \rightarrow A^0\gamma$ ($A^0 \rightarrow \mu^+\mu^-$)
$<4 \times 10^{-7}$	90	[2] ABLIKIM	12	BES3	$J/\psi \rightarrow A^0\gamma$ ($A^0 \rightarrow \mu^+\mu^-$)
$<4.0 \times 10^{-5}$	90	[3] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow A^0\gamma$
$<5 \times 10^{-5}$	90	[4] DRUZHININ	87	ND	$\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow e^+e^-$)
$<2 \times 10^{-3}$	90	[5] DRUZHININ	87	ND	$\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$)
$<7 \times 10^{-6}$	90	[6] DRUZHININ	87	ND	$\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow$ missing)
$<1.4 \times 10^{-5}$	90	[7] EDWARDS	82	CBAL	$J/\psi \rightarrow A^0\gamma$

[1] ABLIKIM 16E limits between 2.8–495.3×10^{-8} were obtained for 0.212 GeV $< m_{A^0} <$ 3.0 GeV. See their Fig. 5 for mass-dependent limits.

[2] ABLIKIM 12 derived limits between 4×10^{-7}–2.1×10^{-5} for 0.212 GeV $< m_{A^0} <$ 3.0 GeV. See their Fig. 2(c) for mass-dependent limits.

[3] ANTREASYAN 90C assume that A^0 does not decay in the detector.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

A^0 (Axion) Searches in Positronium Decays

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

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

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

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

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

[4] 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.

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

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

[7] 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.

[8] CARBONI 83 looked for orthopositronium $\rightarrow A^0 \gamma$. Set limit for A^0 electron coupling squared, $g(e e A^0)^2/(4\pi) < 6. \times 10^{-10}$–$7. \times 10^{-9}$ 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. • • •		
	[1] BASSOMPIE... 95	$m_{A^0} = 1.8 \pm 0.2$ MeV

[1] 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. • • •						
			[1] JAIN	07	CNTR	$A^0 \rightarrow e^+ e^-$
			[2] AHMAD	97	SPEC	e^+ production
			[3] LEINBERGER	97	SPEC	$A^0 \rightarrow e^+ e^-$
			[4] GANZ	96	SPEC	$A^0 \rightarrow e^+ e^-$
			[5] KAMEL	96	EMUL	^{32}S emulsion, $A^0 \rightarrow e^+ e^-$
			[6] BLUEMLEIN	92	BDMP	$A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$
			[7] MEIJERDREES	92	SPEC	$\pi^- p \rightarrow n A^0$, $A^0 \rightarrow e^+ e^-$
			[8] BLUEMLEIN	91	BDMP	$A^0 \rightarrow e^+ e^-$, 2γ
			[9] FAISSNER	89	OSPK	Beam dump, $A^0 \rightarrow e^+ e^-$
			[10] DEBOER	88	RVUE	$A^0 \rightarrow e^+ e^-$
			[11] EL-NADI	88	EMUL	$A^0 \rightarrow e^+ e^-$
			[12] FAISSNER	88	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[13] BADIER	86	BDMP	$A^0 \rightarrow e^+ e^-$
$<2. \times 10^{-11}$	90	0	[14] BERGSMA	85	CHRM	CERN beam dump

$<1. \times 10^{-13}$	90	0	[14] BERGSMA	85	CHRM	CERN beam dump
		24	[15] FAISSNER	83	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[16] FAISSNER	83B	RVUE	LAMPF beam dump
			[17] FRANK	83B	RVUE	LAMPF beam dump
			[18] HOFFMAN	83	CNTR	$\pi p \rightarrow n A^0$ ($A^0 \rightarrow e^+ e^-$)
			[19] FETSCHER	82	RVUE	See FAISSNER 81B
		12	[20] FAISSNER	81	OSPK	CERN PS ν wideband
		15	[21] FAISSNER	81B	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
		8	[22] KIM	81	OSPK	26 GeV $p N \rightarrow A^0 X$
		0	[23] FAISSNER	80	OSPK	Beam dump, $A^0 \rightarrow e^+ e^-$
$<1. \times 10^{-8}$	90		[24] JACQUES	80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[24] JACQUES	80	HLBC	Beam dump
			[25] SOUKAS	80	CALO	28 GeV p beam dump
			[26] BECHIS	79	CNTR	
$<1. \times 10^{-8}$	90		[27] COTEUS	79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[28] DISHAW	79	CALO	400 GeV $p p$
$<1. \times 10^{-8}$	90		ALIBRAN	78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN	78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[29] BELLOTTI	78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[29] BELLOTTI	78	HLBC	m_{A^0}=1.5 MeV
$<4.1 \times 10^{-9}$	90		[29] BELLOTTI	78	HLBC	m_{A^0}=1 MeV
$<1. \times 10^{-8}$	90		[30] BOSETTI	78B	HYBR	Beam dump
			[31] DONNELLY	78		
$<0.5 \times 10^{-8}$	90		HANSL	78D	WIRE	Beam dump
			[32] MICELMAC...	78		
			[33] VYSOTSKII	78		

[1] JAIN 07 claims evidence for $A^0 \rightarrow e^+ e^-$ produced in ^{207}Pb collision on nuclear emulsion (Ag/Br) for $m(A^0) = 7 \pm 1$ or 19 ± 1 MeV and $\tau(A^0) \leq 10^{-13}$ s.

[2] AHMAD 97 reports a result of APEX Collaboration which studied positron production in ^{238}U+^{232}Ta and ^{238}U+^{181}Ta collisions, without requiring a coincident electron. No narrow lines were found for $250 < E_{e^+} < 750$ keV.

[3] LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy $e^+ e^-$-line at $\sim$ 635 keV in ^{238}U+^{181}Ta collision. Limits on the production probability for a narrow sum-energy $e^+ e^-$ line are set. See their Table 2.

[4] GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of $e^+ e^-$ pairs from ^{238}U+^{181}Ta and ^{238}U+^{232}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.

[5] 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.

[6] 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.

[7] MEIJERDREES 92 give $\Gamma(\pi^- p \rightarrow n A^0) \cdot B(A^0 \rightarrow e^+ e^-)/\Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0} = 100$ MeV, $\tau_{A^0} = 10^{-11}$–10^{-23} sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25$–136 MeV.

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

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] BERGSMA 85 look for $A^0 \rightarrow 2\gamma$, e^+e^-, $\mu^+\mu^-$. First limit above is for $m_{A^0} = 1$ MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0}-m_{A^0}$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, $m_{A^0} <180$ keV and $\tau >0.037$ s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[15] FAISSNER 83 observed 19 1-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.

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

[17] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 γ's. See comment on FAISSNER 83B.

[18] 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.

[19] 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.

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

[21] 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 82B, CAVAIGNAC 83, and ANANEV 85.

[22] KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86\sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[23] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+ e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit $20/(A^0$ mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

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

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

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

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

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

[29] BELLOTTI 78 first value comes from search for $A^0 \rightarrow e^+ e^-$. Second value comes from search for $A^0 \rightarrow 2\gamma$, assuming mass $<2m_{e^-}$. For any mass satisfying this, limit is above value$\times$(mass^{-4}). Third value uses data of PL 60B 401 and quotes $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67}$ cm^4.

[30] BOSETTI 78B quotes $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67}$ cm^4.

[31] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[32] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[33] 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. • • •				
	[1] CHANG	07		Primakoff or Compton
	[2] ALTMANN	95	CNTR	Reactor; $A^0 \rightarrow e^+ e^-$
	[3] KETOV	86	SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	[4] KOCH	86	SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	[5] DATAR	82	CNTR	Light water reactor
	[6] VUILLEUMIER	81	CNTR	Reactor, $A^0 \rightarrow 2\gamma$

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

[2] ALTMANN 95 looked for A^0 decaying into $e^+ e^-$ from the Bugey 5 nuclear reactor. They obtain an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma) \times \text{B}(A^0 \rightarrow e^+ e^-) < 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier A^0. In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$

MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances Z^0 in the (m_{X^0}, f_{X^0}) plane.

[3] 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 $\left[100\ \text{keV}/m_{A^0}\right]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to $m_{A^0} > 150$ keV. Not valid for $m_{A^0} \gtrsim$ 1 MeV.

[4] 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.

[5] DATAR 82 looked for $A^0 \rightarrow 2\gamma$ in neutron capture ($n p \rightarrow d A^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $\left[(I = 0) - (I = 1)\right]$ result, assert nonexistence of standard A^0.

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

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

Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 8.5 \times 10^{-6}$	90	[1] DERBIN	02	CNTR	^{125m}Te decay
		[2] DEBOER	97C	RVUE	M1 transitions
$< 5.5 \times 10^{-10}$	95	[3] TSUNODA	95	CNTR	^{252}Cf fission, $A^0 \rightarrow ee$
$< 1.2 \times 10^{-6}$	95	[4] MINOWA	93	CNTR	$^{139}\text{La}^* \rightarrow {}^{139}\text{La}\,A^0$
$< 2 \times 10^{-4}$	90	[5] HICKS	92	CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$
$< 1.5 \times 10^{-9}$	95	[6] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4\text{–}10) \times 10^{-3}$	95	[7] DEBOER	90	CNTR	$^8\text{Be}^* \rightarrow {}^8\text{Be}\,A^0$, $A^0 \rightarrow e^+e^-$
$<(0.2\text{–}1) \times 10^{-3}$	90	[8] BINI	89	CNTR	$^{16}\text{O}^* \rightarrow {}^{16}\text{O}\,X^0$, $X^0 \rightarrow e^+e^-$
		[9] 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	[10] DATAR	88	CNTR	$^{12}\text{C}^* \rightarrow {}^{12}\text{C}\,A^0$, $A^0 \rightarrow e^+e^-$
$< 5 \times 10^{-3}$	90	[11] DEBOER	88C	CNTR	$^{16}\text{O}^* \rightarrow {}^{16}\text{O}\,X^0$, $X^0 \rightarrow e^+e^-$
$< 3.4 \times 10^{-5}$	95	[12] DOEHNER	88	SPEC	$^2\text{H}^*$, $A^0 \rightarrow e^+e^-$
$< 4 \times 10^{-4}$	95	[13] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95	[13] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
$<10.6 \times 10^{-2}$	90	[14] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90	[14] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90	[14] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	[15] SAVAGE	86B	CNTR	$^{14}\text{N}^*$
		[16] ANANEV	85	CNTR	Li*, deut* $A^0 \rightarrow 2\gamma$
		[17] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \rightarrow 2\gamma$
		[18] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \rightarrow 2\gamma$
		[19] LEHMANN	82	CNTR	$\text{Cu}^* \rightarrow \text{Cu}\,A^0$ ($A^0 \rightarrow 2\gamma$)

[20] ZEHNDER	82	CNTR	Li^*, Nb^* decay, n-capt.
[21] ZEHNDER	81	CNTR	$Ba^* \rightarrow Ba A^0$ ($A^0 \rightarrow 2\gamma$)
[22] CALAPRICE	79		Carbon

[1] 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.

[2] 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.

[3] 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.

[4] 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.

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

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

[7] 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.

[8] 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^-.

[9] AVIGNONE 88 looked for the 1115 keV transition $C^* \rightarrow Cu A^0$, 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.

[10] 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.

[11] 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: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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).

[18] 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).

[19] 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.

[20] ZEHNDER 82 used Gosgen 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.

[21] ZEHNDER 81 looked for Ba* $\rightarrow$ A^0 Ba 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.

[22] 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	[1] BROSS	91	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$
		[2] GUO	90	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$
		[3] BJORKEN	88	CALO	$A \rightarrow e^+e^-$ or 2γ
		[4] BLINOV	88	MD1	$ee \rightarrow eeA^0$ $(A^0 \rightarrow ee)$
none 1×10^{-14}–1×10^{-10}	90	[5] RIORDAN	87	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$
none 1×10^{-14}–1×10^{-11}	90	[6] BROWN	86	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$
none 6×10^{-14}–9×10^{-11}	95	[7] DAVIER	86	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$
none 3×10^{-13}–1×10^{-7}	90	[8] KONAKA	86	BDMP	$eN \rightarrow eA^0N$ $(A^0 \rightarrow ee)$

[1] 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).

[2] 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).

[3] 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.
[4] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \to \gamma\gamma)\mathrm{B}(A^0 \to e^+ e^-) < 2$ eV (CL=90%).
[5] 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.
[6] 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.
[7] $m_{A^0} = 1.8$ MeV assumed. The excluded domain in the $\tau_{A^0}-m_{A^0}$ plane extends up to $m_{A^0} \approx 14$ MeV, see their figure 4.
[8] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma - A^0 e^+ e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha Scattering

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

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 1.3	97	[1] HALLIN	92	CNTR	$m_{A^0} = 1.75$–1.88 MeV
none 0.0016–0.47	90	[2] HENDERSON	92C	CNTR	$m_{A^0} = 1.5$–1.86 MeV
$<$ 2.0	90	[3] 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	[4] 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	[5] JUDGE	90	CNTR	$m_{A^0} = 1.832$ MeV, elastic
$<$ 1.9	97	[6] TSERTOS	89	CNTR	$m_{A^0} = 1.82$ MeV
$<$(10–40)	97	[6] TSERTOS	89	CNTR	$m_{A^0} = 1.51$–1.65 MeV
$<$(1–2.5)	97	[6] 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	[7] TSERTOS	88	CNTR	$m_{A^0} = 1.832$ MeV
		[8] VANKLINKEN	88	CNTR	
		[9] MAIER	87	CNTR	
$<$2500	90	MILLS	87	CNTR	$m_{A^0} = 1.8$ MeV
		[10] VONWIMMER...	87	CNTR	

[1] HALLIN 92 quote limits on lifetime, $8 \times 10^{-14} - 5 \times 10^{-13}$ sec depending on mass, assuming $\mathrm{B}(A^0 \to e^+ e^-) = 100\%$. They say that TSERTOS 91 overstated their sensitivity by a factor of 3.
[2] HENDERSON 92C exclude axion with lifetime $\tau_{A^0}=1.4 \times 10^{-12} - 4.0 \times 10^{-10}$ s, assuming $\mathrm{B}(A^0 \to e^+ e^-)=100\%$. HENDERSON 92C also exclude a vector boson with $\tau=1.4 \times 10^{-12} - 6.0 \times 10^{-10}$ s.

[3] WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming B($A^0 \to e^+ e^-$)=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.

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

[5] JUDGE 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 $m_{A^0} = 1.776$–1.856 MeV.

[6] See also TSERTOS 88B in references.

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

[8] 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.

[9] 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.

[10] VONWIMMERSPERG 87 measured Bhabha scattering for $E_{\text{cm}} = 1.37$–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 $e^+ e^- \to \gamma\gamma$

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

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	[1] TRZASKA	91	CNTR	$m_{A^0} = 1.8$ MeV
$<$ 4.4	95	WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV
		[2] FOX	89	CNTR	
$<$ 0.11	95	[3] 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

[1] 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.

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

[3] Similar limits are obtained for $m_{A^0} = 1.045$–1.085 MeV.

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

The limit is for $\Gamma(X^0 \to e^+e^-)\cdot\Gamma(X^0 \to \gamma\gamma\gamma)/\Gamma_{\text{total}}$. 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	[1] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV
$<$ 1.0	95	[2] VO	94	CNTR	m_{X^0}=1.1 MeV
$<$ 2.5	95	[2] VO	94	CNTR	m_{X^0}=1.4 MeV
$<$120	95	[2] VO	94	CNTR	m_{X^0}=1.7 MeV
$<$ 3.8	95	[3] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV

[1] VO 94 looked for $X^0 \to \gamma\gamma\gamma$ decaying at rest. The precise limits depend on m_{X^0}. See Fig. 2(b) in paper.

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

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

Light Boson (X^0) Search in Nonresonant e^+e^- Annihilation at Rest

Limits are for the ratio of $n\gamma + X^0$ production relative to $\gamma\gamma$.

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

[1] 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 eeX^0 coupling and hence on the branching ratio B(o-Ps $\to \gamma\gamma X^0$)$< 6.2 \times 10^{-6}$. The bounds weaken for heavier X^0.

[2] 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} = 100–1000 keV.

[3] SKALSEY 95 reinterpreted the bound on γA^0 decay of o-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} = 0–800 keV.

[4] 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} = 70–800 keV.

[5] 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.

[6] 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} = 200–900 keV.

Searches for Goldstone Bosons (X^0)

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

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9 \times 10^{-6}$	90	[1] BAYES	15	TWST	$\mu^+ \rightarrow e^+ X^0$, Familon
		[2] LATTANZI	13	COSM	Majoron dark matter decay
		[3] LESSA	07	RVUE	Meson, ℓ decays to Majoron
		[4] DIAZ	98	THEO	$H^0 \rightarrow X^0 X^0$, $A^0 \rightarrow X^0 X^0 X^0$, Majoron
		[5] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3 \times 10^{-2}$	95	[6] ALBRECHT	90E	ARG	$\tau \rightarrow \mu X^0$. Familon
$<1.8 \times 10^{-2}$	95	[6] ALBRECHT	90E	ARG	$\tau \rightarrow e X^0$. Familon
$<6.4 \times 10^{-9}$	90	[7] ATIYA	90	B787	$K^+ \rightarrow \pi^+ X^0$. Familon
$<1.4 \times 10^{-5}$	90	[8] BALKE	88	CNTR	$\mu^+ \rightarrow e^+ X^0$. Familon
$<1.1 \times 10^{-9}$	90	[9] BOLTON	88	CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon
		[10] CHANDA	88	ASTR	Sun, Majoron
		[11] CHOI	88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90	[12] PICCIOTTO	88	CNTR	$\pi \rightarrow e \nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90	[13] GOLDMAN	87	CNTR	$\mu \rightarrow e \gamma X^0$. Familon
$<3 \times 10^{-4}$	90	[14] BRYMAN	86B	RVUE	$\mu \rightarrow e X^0$. Familon
$<1 \times 10^{-10}$	90	[15] EICHLER	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
$<2.6 \times 10^{-6}$	90	[16] JODIDIO	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
		[17] BALTRUSAIT...	85	MRK3	$\tau \rightarrow \ell X^0$. Familon
		[18] DICUS	83	COSM	$\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$

[1] BAYES 15 limits are the average over $m_{X^0} = 13$–80 MeV for the isotropic decay distribution of positrons. See their Fig. 4 and Table II for the mass-dependent limits as well as the dependence on the decay anisotropy. In particular, they find a limit $< 58 \times 10^{-6}$ at 90% CL for massless familons and for the same asymmetry as normal muon decay, a case not covered by JODIDIO 86.

[2] LATTANZI 13 use WMAP 9 year data as well as X-ray and γ-ray observations to derive limits on decaying majoron dark matter. A limit on the decay width $\Gamma(X^0 \rightarrow \nu\overline{\nu}) < 6.4 \times 10^{-19}$ s^{-1} at 95% CL is found if majorons make up all of the dark matter.

[3] LESSA 07 consider decays of the form Meson $\rightarrow \ell\nu$Majoron and $\ell \rightarrow \ell' \nu\overline{\nu}$Majoron and use existing data to derive limits on the neutrino-Majoron Yukawa couplings $g_{\alpha\beta}$ (α,β=e,μ,τ). Their best limits are $|g_{e\alpha}|^2 < 5.5 \times 10^{-6}$, $|g_{\mu\alpha}|^2 < 4.5 \times 10^{-5}$, $|g_{\tau\alpha}|^2 < 5.5 \times 10^{-2}$ at CL = 90%.

[4] 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 $H^0 \rightarrow X^0 X^0$.

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

[6] 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.

[7] 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.

[8] BALKE 88 limits are for B($\mu^+ \rightarrow e^+ X^0$). Valid for $m_{X^0} < 80$ MeV and $\tau_{X^0} > 10^{-8}$ sec.

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

[10] CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vacuum expectation value in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.

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

[12] 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.

[13] 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.

[14] 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.

[15] 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.

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

[17] 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.

[18] 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.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
>7200	**90**	**^{128}Te**		**CNTR**	[1] BERNATOW...	92
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 420	90	^{76}Ge	$0\nu1\chi$	GERDA	[2] AGOSTINI	15A
> 400	90	^{100}Mo	$0\nu1\chi$	NEMO-3	[3] ARNOLD	15
>1200	90	^{136}Xe	$0\nu1\chi$	EXO-200	[4] ALBERT	14A
>2600	90	^{136}Xe	$0\nu1\chi$	KamLAND-Zen	[5] GANDO	12
> 16	90	^{130}Te	$0\nu1\chi$	NEMO-3	[6] ARNOLD	11
> 1.9	90	^{96}Zr	$2\nu1\chi$	NEMO-3	[7] ARGYRIADES	10
> 1.52	90	^{150}Nd	$0\nu1\chi$	NEMO-3	[8] ARGYRIADES	09
> 27	90	^{100}Mo	$0\nu1\chi$	NEMO-3	[9] ARNOLD	06
> 15	90	^{82}Se	$0\nu1\chi$	NEMO-3	[10] ARNOLD	06

> 14	90	^{100}Mo	$0\nu1\chi$	NEMO-3	[11] ARNOLD	04
> 12	90	^{82}Se	$0\nu1\chi$	NEMO-3	[12] ARNOLD	04
> 2.2	90	^{130}Te	$0\nu1\chi$	Cryog. det.	[13] ARNABOLDI	03
> 0.9	90	^{130}Te	$0\nu2\chi$	Cryog. det.	[14] ARNABOLDI	03
> 8	90	^{116}Cd	$0\nu1\chi$	$CdWO_4$ scint.	[15] DANEVICH	03
> 0.8	90	^{116}Cd	$0\nu2\chi$	$CdWO_4$ scint.	[16] DANEVICH	03
> 500	90	^{136}Xe	$0\nu1\chi$	Liquid Xe Scint.	[17] BERNABEI	02D
> 5.8	90	^{100}Mo	$0\nu1\chi$	ELEGANT V	[18] FUSHIMI	02
> 0.32	90	^{100}Mo	$0\nu1\chi$	Liq. Ar ioniz.	[19] ASHITKOV	01
> 0.0035	90	^{160}Gd	$0\nu1\chi$	$^{160}Gd_2SiO_5$:Ce	[20] DANEVICH	01
> 0.013	90	^{160}Gd	$0\nu2\chi$	$^{160}Gd_2SiO_5$:Ce	[21] DANEVICH	01
> 2.3	90	^{82}Se	$0\nu1\chi$	NEMO 2	[22] ARNOLD	00
> 0.31	90	^{96}Zr	$0\nu1\chi$	NEMO 2	[23] ARNOLD	00
> 0.63	90	^{82}Se	$0\nu2\chi$	NEMO 2	[24] ARNOLD	00
> 0.063	90	^{96}Zr	$0\nu2\chi$	NEMO 2	[24] ARNOLD	00
> 0.16	90	^{100}Mo	$0\nu2\chi$	NEMO 2	[24] ARNOLD	00
> 2.4	90	^{82}Se	$0\nu1\chi$	NEMO 2	[25] ARNOLD	98
> 7.2	90	^{136}Xe	$0\nu2\chi$	TPC	[26] LUESCHER	98
> 7.91	90	^{76}Ge		SPEC	[27] GUENTHER	96
> 17	90	^{76}Ge		CNTR	BECK	93

[1] BERNATOWICZ 92 studied double-β decays of ^{128}Te and ^{130}Te, and found the ratio $\tau(^{130}\mathrm{Te})/\tau(^{128}\mathrm{Te}) = (3.52 \pm 0.11) \times 10^{-4}$ 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 $(7.7–1.28 \times 0.4=7.2) \times 10^{24}$.

[2] AGOSTINI 15A analyze a 20.3 kg yr of data set of the GERDA calorimeter to determine $g_{\nu\chi} <$ 3.4–8.7 $\times 10^{-5}$ on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.

[3] ARNOLD 15 use the NEMO-3 tracking calorimeter with 3.43 kg yr exposure to determine the limit on Majoron emission. The limit corresponds to $g_{\nu\chi} <$ 1.6–3.0 $\times 10^{-4}$. The spread reflects different nuclear matrix elements. Supersedes ARNOLD 06.

[4] ALBERT 14A utilize 100 kg yr of exposure of the EXO-200 tracking calorimeter to place a limit on the $g_{\nu\chi} <$ 0.8–1.7 $\times 10^{-5}$ on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.

[5] GANDO 12 use the KamLAND-Zen detector to obtain the limit on the $0\nu\chi$ decay with Majoron emission. It implies that the coupling constant $g_{\nu\chi} <$ 0.8–1.6 $\times 10^{-5}$ depending on the nuclear matrix elements used.

[6] ARNOLD 11 use the NEMO-3 detector to obtain the reported limit on Majoron emission. It implies that the coupling constant $g_{\nu\chi} <$ 0.6–1.6 $\times 10^{-4}$ depending on the nuclear matrix element used. Supercedes ARNABOLDI 03.

[7] ARGYRIADES 10 use the NEMO-3 tracking detector and ^{96}Zr to derive the reported limit. No limit for the Majoron electron coupling is given.

[8] ARGYRIADES 09 use ^{150}Nd data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu\chi} \rangle <$ 1.7–3.0 $\times 10^{-4}$ using a range of nuclear matrix elements that include the effect of nuclear deformation.

[9] ARNOLD 06 use ^{100}Mo data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu\chi} \rangle <$ (0.4–1.8) $\times 10^{-4}$ using a range of matrix element calculations. Superseded by ARNOLD 15.

[10] NEMO-3 tracking calorimeter is used in ARNOLD 06 . Reported half-life limit for ^{82}Se corresponds to $\langle g_{\nu\chi}\rangle$ $<$ (0.66–1.9)$\times 10^{-4}$ using a range of matrix element calculations. Supersedes ARNOLD 04.

[11] ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu\chi}\rangle$ $<$ (0.5–0.9)10^{-4} using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03. Superseded by ARNOLD 06.

[12] ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu\chi}\rangle$ $<$ (0.7–1.6)10^{-4} using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.

[13] Supersedes ALESSANDRELLO 00. Array of TeO_2 crystals in high resolution cryogenic calorimeter. Some enriched in ^{130}Te. Derive $\langle g_{\nu\chi}\rangle$ $<$ 17–33 $\times 10^{-5}$ depending on matrix element.

[14] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search.

[15] Limit for the $0\nu\chi$ decay with Majoron emission of ^{116}Cd using enriched $CdWO_4$ scintillators. $\langle g_{\nu\chi}\rangle$ $<$ 4.6–8.1 $\times 10^{-5}$ depending on the matrix element. Supersedes DANEVICH 00.

[16] Limit for the $0\nu2\chi$ decay of ^{116}Cd. Supersedes DANEVICH 00.

[17] BERNABEI 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.

[18] Replaces TANAKA 93. FUSHIMI 02 derive half-life limit for the $0\nu\chi$ decay by means of tracking calorimeter ELEGANT V. Considering various matrix element calculations, a range of limits for the Majoron-neutrino coupling is given: $\langle g_{\nu\chi}\rangle$ $<$(6.3–360) $\times 10^{-5}$.

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

[20] DANEVICH 01 obtain limit for the $0\nu\chi$ decay with Majoron emission of ^{160}Gd using Gd_2SiO_5:Ce crystal scintillators.

[21] DANEVICH 01 obtain limit for the $0\nu2\chi$ decay with 2 Majoron emission of ^{160}Gd.

[22] ARNOLD 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.

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

[24] ARNOLD 00 reports limit for the $0\nu2\chi$ decay with two Majoron emission derived from tracking calorimeter NEMO 2.

[25] ARNOLD 98 determine the limit for $0\nu_{\chi}$ decay with Majoron emission of ^{82}Se using the NEMO-2 tracking detector. They derive $\langle g_{\nu_{\chi}}\rangle$ $<$ 2.3–4.3 $\times 10^{-4}$ with several nuclear matrix elements.

[26] 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 $\times 10^{-4}$.

[27] See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.

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

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

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 0.67	95	[1] ARCHIDIACO...	13A	COSM	K, hot dark matter
none 0.7–3 $\times 10^5$		[2] CADAMURO	11	COSM	D abundance
$<$105	90	[3] DERBIN	11A	CNTR	D, solar axion
		[4] ANDRIAMON...	10	CAST	K, solar axions
$<$ 0.72	95	[5] HANNESTAD	10	COSM	K, hot dark matter
		[6] ANDRIAMON...	09	CAST	K, solar axions
$<$191	90	[7] DERBIN	09A	CNTR	K, solar axions
$<$334	95	[8] KEKEZ	09	HPGE	K, solar axions
$<$ 1.02	95	[9] HANNESTAD	08	COSM	K, hot dark matter
$<$ 1.2	95	[10] HANNESTAD	07	COSM	K, hot dark matter
$<$ 0.42	95	[11] MELCHIORRI	07A	COSM	K, hot dark matter
$<$ 1.05	95	[12] HANNESTAD	05A	COSM	K, hot dark matter
3 to 20		[13] MOROI	98	COSM	K, hot dark matter
$<$ 0.007		[14] BORISOV	97	ASTR	D, neutron star
$<$ 4		[15] KACHELRIESS	97	ASTR	D, neutron star cooling
$<(0.5–6) \times 10^{-3}$		[16] KEIL	97	ASTR	SN 1987A
$<$ 0.018		[17] RAFFELT	95	ASTR	D, red giant
$<$ 0.010		[18] ALTHERR	94	ASTR	D, red giants, white dwarfs
		[19] CHANG	93	ASTR	K, SN 1987A
$<$ 0.01		WANG	92	ASTR	D, white dwarf
$<$ 0.03		WANG	92C	ASTR	D, C-O burning
none 3–8		[20] BERSHADY	91	ASTR	D, K, intergalactic light
$<$ 10		[21] KIM	91C	COSM	D, K, mass density of the universe, supersymmetry
		[22] RAFFELT	91B	ASTR	D,K, SN 1987A
$<$ 1 $\times 10^{-3}$		[23] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3		BURROWS	90	ASTR	D,K, SN 1987A
		[24] ENGEL	90	ASTR	D,K, SN 1987A
$<$ 0.02		[25] RAFFELT	90D	ASTR	D, red giant
$<$ 1 $\times 10^{-3}$		[26] BURROWS	89	ASTR	D,K, SN 1987A
$<(1.4–10) \times 10^{-3}$		[27] ERICSON	89	ASTR	D,K, SN 1987A
$<$ 3.6 $\times 10^{-4}$		[28] MAYLE	89	ASTR	D,K, SN 1987A
$<$ 12		CHANDA	88	ASTR	D, Sun
$<$ 1 $\times 10^{-3}$		RAFFELT	88	ASTR	D,K, SN 1987A
		[29] RAFFELT	88B	ASTR	red giant
$<$ 0.07		FRIEMAN	87	ASTR	D, red giant
$<$ 0.7		[30] RAFFELT	87	ASTR	K, red giant
$<$ 2–5		TURNER	87	COSM	K, thermal production
$<$ 0.01		[31] DEARBORN	86	ASTR	D, red giant
$<$ 0.06		RAFFELT	86	ASTR	D, red giant
$<$ 0.7		[32] RAFFELT	86	ASTR	K, red giant
$<$ 0.03		RAFFELT	86B	ASTR	D, white dwarf

< 1	[33]	KAPLAN	85	ASTR	K, red giant
< 0.003–0.02		IWAMOTO	84	ASTR	D, K, neutron star
$> 1 \times 10^{-5}$		ABBOTT	83	COSM	D,K, mass density of 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	[34]	FUKUGITA	82	ASTR	D, stellar cooling
< 0.07		FUKUGITA	82B	ASTR	D, red giant

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

[2] CADAMURO 11 use the deuterium abundance to show that the m_{A^0} range 0.7 eV – 300 keV is excluded for axions, complementing HANNESTAD 10.

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

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

[5] This is an update of HANNESTAD 08 including 7 years of WMAP data.

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

[7] DERBIN 09A look for Primakoff-produced solar axions in the resonant excitation of ^{169}Tm, constraining the axion-photon $\times$ axion-nucleon couplings.

[8] KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used.

[9] This is an update of HANNESTAD 07 including 5 years of WMAP data.

[10] This is an update of HANNESTAD 05A with new cosmological data, notably WMAP (3 years) and baryon acoustic oscillations (BAO). Lyman-α data are left out, in contrast to HANNESTAD 05A and MELCHIORRI 07A, because it is argued that systematic errors are large. It uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component.

[11] MELCHIORRI 07A is analogous to HANNESTAD 05A, with updated cosmological data, notably WMAP (3 years). Uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component. Leaving out Lyman-α data, a conservative limit is 1.4 eV.

[12] HANNESTAD 05A puts an upper limit on the mass of hadronic axion because in this mass range it would have been thermalized and contribute to the hot dark matter component of the universe. The limit is based on the CMB anisotropy from WMAP, SDSS large scale structure, Lyman α, and the prior Hubble parameter from HST Key Project. A χ^2 statistic is used. Neutrinos are assumed not to contribute to hot dark matter.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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).

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

[19] CHANG 93 updates ENGEL 90 bound with the Kaplan-Manohar ambiguity in $z=m_u/m_d$ (see the Note on the Quark Masses in the Quark Particle Listings). It leaves the window $f_A=3\times10^5$–3×10^6 GeV open. The constraint from Big-Bang Nucleosynthesis is satisfied in this window as well.

[20] 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.

[21] 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.

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

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

[24] 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 $g_{AN} \sim 10^{-6}$.

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

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

[27] 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.

[28] 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.

[29] 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.

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

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

[32] 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.

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

[34] 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, $L_{\rm int} = -\frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\widetilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, 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. • • •					
		[1] BRANCA	17	AURG	$m_{S^0} = 3.5$–3.9 peV
$<3 \times 10^{-42}$	90	[2] BRUBAKER	17		$m_{A^0} = 23.55$–$24.0\ \mu$eV
$<8.6 \times 10^{-42}$	90	[3] HOSKINS	16	ADMX	m_{A^0} =3.36–3.52 or 3.55–3.69 μeV
		[4] BECK	13		$m_{A^0} = 0.11$ meV
$<3.5 \times 10^{-43}$		[5] HOSKINS	11	ADMX	$m_{A^0} = 3.3$–3.69×10^{-6} eV
$<2.9 \times 10^{-43}$	90	[6] ASZTALOS	10	ADMX	$m_{A^0} = 3.34$–3.53×10^{-6} eV
$<1.9 \times 10^{-43}$	97.7	[7] DUFFY	06	ADMX	$m_{A^0} = 1.98$–2.17×10^{-6} eV
$<5.5 \times 10^{-43}$	90	[8] ASZTALOS	04	ADMX	$m_{A^0} = 1.9$–3.3×10^{-6} eV
		[9] KIM	98	THEO	
$<2 \times 10^{-41}$		[10] HAGMANN	90	CNTR	$m_{A^0} = (5.4$–$5.9)10^{-6}$ eV
$<6.3 \times 10^{-42}$	95	[11] WUENSCH	89	CNTR	$m_{A^0} = (4.5$–$10.2)10^{-6}$ eV
$<5.4 \times 10^{-41}$	95	[11] WUENSCH	89	CNTR	$m_{A^0} = (11.3$–$16.3)10^{-6}$ eV

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

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

[3] HOSKINS 16 is analogous to DUFFY 06. See Fig. 12 for mass-dependent limits in terms of the local dark matter density.

[4] BECK 13 argues that dark-matter axions passing through Earth may generate a small observable signal in resonant S/N/S Josephson junctions. A measurement by HOFFMANN 04 [Physical Review **B70** 180503 (2004)] is interpreted in terms of subdominant dark matter axions with $m_{A^0} = 0.11$ meV.

[5] HOSKINS 11 is analogous to DUFFY 06. See Fig. 4 for the mass-dependent limit in terms of the local density.

[6] ASZTALOS 10 used the upgraded detector of ASZTALOS 04 to search for halo axions. See their Fig. 5 for the m_{A^0} dependence of the limit.

[7] DUFFY 06 used the upgraded detector of ASZTALOS 04, while assuming a smaller velocity dispersion than the isothermal model as in Eq. (8) of their paper. See Fig. 10 of their paper on the axion mass dependence of the limit.

[8] ASZTALOS 04 looked for a conversion of halo axions to microwave photons in magnetic field. At 90% CL, the KSVZ axion cannot have a local halo density more than 0.45 GeV/cm^3 in the quoted mass range. See Fig. 7 of their paper on the axion mass dependence of the limit.

[9] 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.

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

[11] 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 $[G_{A\gamma\gamma}/m_{A^0}]^2 =$

2×10^{-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 modulus of the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = -G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$. For scalars S^0 the limit is on the coupling constant in $L = G_{S\gamma\gamma}\phi_S(\mathbf{E}^2 - \mathbf{B}^2)$. The relation between $G_{A\gamma\gamma}$ and m_{A^0} is not used unless stated otherwise, i.e., many of these bounds apply to low-mass axion-like particles (ALPs), not to QCD axions.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6 \times 10^{-13}$		[1] TIWARI	17	COSM	$m_{A^0} \leq 10^{-15}$ eV
$<5 \times 10^{-12}$	95	[2] AJELLO	16	ASTR	$m_{A^0} = 0.5$–5 neV
$<1.2 \times 10^{-7}$	95	[3] DELLA-VALLE	16	LASR	$m_{A^0} = 1.3$ meV
$<7.2 \times 10^{-8}$	95	[4] DELLA-VALLE	16	LASR	$m_{A^0} < 0.5$ meV
$<8 \times 10^{-4}$		[5] JAECKEL	16	ALPS	$m_{A^0} = 0.1$–100 GeV
$<6 \times 10^{-21}$		[6] LEEFER	16		$m_{S^0} < 10^{-18}$ eV
		[7] ANASTASSO...	15	CAST	Chameleons
$<1.47 \times 10^{-10}$	95	[8] ARIK	15	CAST	$m_{A^0} = 0.39$–0.42 eV
$<3.5 \times 10^{-8}$	95	[9] BALLOU	15	LSW	$m_{A^0} < 2 \times 10^{-4}$ eV
		[10] BRAX	15	ASTR	$m_{S^0} < 4 \times 10^{-12}$ eV
$<5.42 \times 10^{-4}$	95	[11] HASEBE	15	LASR	$m_{A^0} = 0.15$ eV
		[12] MILLEA	15	COSM	Axion-like particles
		[13] VANTILBURG	15		Dilaton-like dark matter
$<4.1 \times 10^{-10}$	99.7	[14] VINYOLES	15	ASTR	$m_{A^0} = 0.6$–185 eV
$<3.3 \times 10^{-10}$	95	[15] ARIK	14	CAST	$m_{A^0} = 0.64$–1.17 eV
$<6.6 \times 10^{-11}$	95	[16] AYALA	14	ASTR	Globular clusters
$<1.4 \times 10^{-7}$	95	[17] DELLA-VALLE	14		$m_{A^0} = 1$ meV
		[18] EJLLI	14	COSM	$m_{A^0} = 2.66$–48.8 μeV
$<8 \times 10^{-8}$	95	[19] PUGNAT	14	LSW	$m_{A^0} < 0.3$ meV
$<1 \times 10^{-11}$		[20] REESMAN	14	ASTR	$m_{A^0} < 1 \times 10^{-10}$ eV
$<2.1 \times 10^{-11}$	95	[21] ABRAMOWSKI	13A	IACT	$m_{A^0} = 15$–60 neV
$<2.15 \times 10^{-9}$	95	[22] ARMENGAUD	13	EDEL	$m_{A^0} < 200$ eV
$<4.5 \times 10^{-8}$	95	[23] BETZ	13	LSW	$m_{A^0} = 7.2 \times 10^{-6}$ eV
$<8 \times 10^{-11}$		[24] FRIEDLAND	13	ASTR	Red giants
$>2 \times 10^{-11}$		[25] MEYER	13	ASTR	$m_{A^0} < 1 \times 10^{-7}$ eV
$<8.3 \times 10^{-12}$	95	[26] WOUTERS	13	ASTR	$m_{A^0} < 7 \times 10^{-12}$ eV
		[27] CADAMURO	12	COSM	Axion-like particles
$<2.5 \times 10^{-13}$	95	[28] PAYEZ	12	ASTR	$m_{A^0} < 4.2 \times 10^{-14}$ eV
$<2.3 \times 10^{-10}$	95	[29] ARIK	11	CAST	$m_{A^0} = 0.39$–0.64 eV
$<6.5 \times 10^{-8}$	95	[30] EHRET	10	ALPS	$m_{A^0} < 0.7$ meV
$<2.4 \times 10^{-9}$	95	[31] AHMED	09A	CDMS	$m_{A^0} < 100$ eV

< 1.2–2.8×10^{-10}	95	[32] ARIK	09	CAST	$m_{A^0} = 0.02$–0.39 eV
		[33] CHOU	09		Chameleons
$<7 \times 10^{-10}$		[34] GONDOLO	09	ASTR	$m_{A^0} <$ few keV
$<1.3 \times 10^{-6}$	95	[35] AFANASEV	08		$m_{S^0} < 1$ meV
$<3.5 \times 10^{-7}$	99.7	[36] CHOU	08		$m_{A^0} < 0.5$ meV
$<1.1 \times 10^{-6}$	99.7	[37] FOUCHE	08		$m_{A^0} < 1$ meV
< 5.6–13.4×10^{-10}	95	[38] INOUE	08		$m_{A^0} = 0.84$–1.00 eV
$<5 \times 10^{-7}$		[39] ZAVATTINI	08		$m_{A^0} < 1$ meV
$<8.8 \times 10^{-11}$	95	[40] ANDRIAMON...	07	CAST	$m_{A^0} < 0.02$ eV
$<1.25 \times 10^{-6}$	95	[41] ROBILLIARD	07		$m_{A^0} < 1$ meV
2–5×10^{-6}		[42] ZAVATTINI	06		$m_{A^0} = 1$–1.5 meV
$<1.1 \times 10^{-9}$	95	[43] INOUE	02		$m_{A^0} = 0.05$–0.27 eV
$<2.78 \times 10^{-9}$	95	[44] MORALES	02B		$m_{A^0} <1$ keV
$<1.7 \times 10^{-9}$	90	[45] BERNABEI	01B		$m_{A^0} <100$ eV
$<1.5 \times 10^{-4}$	90	[46] ASTIER	00B	NOMD	$m_{A^0} <40$ eV
		[47] MASSO	00	THEO	induced γ coupling
$<2.7 \times 10^{-9}$	95	[48] AVIGNONE	98	SLAX	$m_{A^0} < 1$ keV
$<6.0 \times 10^{-10}$	95	[49] MORIYAMA	98		$m_{A^0} < 0.03$ eV
$<3.6 \times 10^{-7}$	95	[50] CAMERON	93		$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[51] CAMERON	93		$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[52] LAZARUS	92		$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[52] LAZARUS	92		$m_{A^0} = 0.03$–0.11 eV
$<7.7 \times 10^{-7}$	99	[53] RUOSO	92		$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[54] SEMERTZIDIS	90		$m_{A^0} < 7 \times 10^{-4}$ eV

[1] TIWARI 17 use observed limits of the cosmic distance-duality relation to constrain the photon-ALP mixing based on 3D simulations of the magnetic field configuration. The quoted value is for the averaged magnetic field of 1nG with a coherent length of 1 Mpc. See their Fig. 5 for mass-dependent limits.

[2] AJELLO 16 look for irregularities in the energy spectrum of the NGC1275 measured by Fermi LAT, assuming photon-ALP mixing in the intra-cluster and Galactic magnetic felds. See their Fig. 2 for mass-dependent limits.

[3] DELLA-VALLE 16 look for the birefringence induced by axion-like particles. See their Fig. 14 for mass-dependent limits.

[4] DELLA-VALLE 16 look for the dichroism induced by axion-like particles. See their Fig. 14 for mass-dependent limits.

[5] JAECKEL 16 use the LEP data of $Z \to 2\gamma$ and $Z \to 3\gamma$ to constrain the ALP production via $e^+ e^- \to Z \to A^0 \gamma$ ($A^0 \to \gamma\gamma$), assuming the ALP coupling with two hypercharge bosons. See their Fig. 4 for mass-dependent limits.

[6] LEEFER 16 derived limits by using radio-frequency spectroscopy of dysprosium and atomic clock measurements. See their Fig. 1 for mass-dependent limits as well as limits on Yukawa-type couplings of the scalar to the electron and nucleons.

[7] ANASTASSOPOULOS 15 search for solar chameleons with CAST and derived limits on the chameleon coupling to photons and matter. See their Fig. 12 for the exclusion region.

[8] ARIK 15 is analogous to ARIK 09, and search for solar axions for m_{A^0} around 0.2 and 0.4 eV. See their Figs. 1 and 3 for the mass-dependent limits.

[9] Based on OSQAR photon regeneration experiment. See their Fig. 6 for mass-dependent limits on scalar and pseudoscalar bosons.

[10] BRAX 15 derived limits on conformal and disformal couplings of a scalar to photons by searching for a chaotic absorption pattern in the X-ray and UV bands of the Hydra A galaxy cluster and a BL lac object, respectively. See their Fig. 8.

[11] HASEBE 15 look for an axion via a four-wave mixing process at quasi-parallel colliding laser beams. They also derived limits on a scalar coupling to photons $G_{S\gamma\gamma} < 2.62 \times 10^{-4}$ GeV^{-1} at $m_{S^0} = 0.15$ eV. See their Figs. 11 and 12 for mass-dependent limits.

[12] MILLEA 15 is similar to CADAMURO 12, including the Planck data and the latest inferences of primordial deuterium abundance. See their Fig. 3 for mass-dependent limits.

[13] VANTILBURG 15 look for harmonic variations in the dyprosium transition frequency data, induced by coherent oscillations of the fine-structure constant due to dilaton-like dark matter, and set the limits, $G_{S\gamma\gamma} < 6 \times 10^{-27}$ GeV^{-1} at $m_{S^0} = 6 \times 10^{-23}$ eV. See their Fig. 4 for mass-dependent limits between $1 \times 10^{-24} < m_{S^0} < 1 \times 10^{-15}$ eV.

[14] VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations. See their Fig. 9.

[15] ARIK 14 is similar to ARIK 11. See their Fig. 2 for mass-dependent limits.

[16] AYALA 14 derived the limit from the helium-burning lifetime of horizontal-branch stars based on number counts in globular clusters.

[17] DELLA-VALLE 14 use the new PVLAS apparatus to set a limit on vacuum magnetic birefringence induced by axion-like particles. See their Fig. 6 for the mass-dependent limits.

[18] EJLLI 14 set limits on a product of primordial magnetic field and the axion mass using CMB distortion induced by resonant axion production from CMB photons. See their Fig. 1 for limits applying specifically to the DFSZ and KSVZ axion models.

[19] PUGNAT 14 is analogous to EHRET 10. See their Fig. 5 for mass-dependent limits on scalar and pseudoscalar bosons.

[20] REESMAN 14 derive limits by requiring effects of axion-photon interconversion on gamma-ray spectra from distant blazars to be no larger than errors in the best-fit optical depth based on a certain extragalactic background light model. See their Fig. 5 for mass-dependent limits.

[21] ABRAMOWSKI 13A look for irregularities in the energy spectrum of the BL Lac object PKS 2155–304 measured by H.E.S.S. The limits depend on assumed magnetic field around the source. See their Fig. 7 for mass-dependent limits.

[22] ARMENGAUD 13 is analogous to AVIGNONE 98. See Fig. 6 for the limit.

[23] BETZ 13 performed a microwave-based light shining through the wall experiment. See their Fig. 13 for mass-dependent limits.

[24] FRIEDLAND 13 derived the limit by considering blue-loop suppression of the evolution of red giants with 7–12 solar masses.

[25] MEYER 13 attributed to axion-photon oscillations the observed excess of very high-energy γ-rays with respect to predictions based on extragalactic background light models. See their Fig.4 for mass-dependent lower limits for various magnetic field configurations.

[26] WOUTERS 13 look for irregularities in the X-ray spectrum of the Hydra cluster observed by Chandra. See their Fig. 4 for mass-dependent limits.

[27] CADAMURO 12 derived cosmological limits on $G_{A\gamma\gamma}$ for axion-like particles. See their Fig. 1 for mass-dependent limits.

[28] PAYEZ 12 derive limits from polarization measurements of quasar light (see their Fig. 3). The limits depend on assumed magnetic field strength in galaxy clusters. The limits depend on assumed magnetic field and electron density in the local galaxy supercluster.

[29] ARIK 11 search for solar axions using ^{3}He buffer gas in CAST, continuing from the ^{4}He version of ARIK 09. See Fig. 2 for the exact mass-dependent limits.

[30] ALPS is a photon regeneration experiment. See their Fig. 4 for mass-dependent limits on scalar and pseudoscalar bosons.

[31] AHMED 09A is analogous to AVIGNONE 98.

[32] ARIK 09 is the ^{4}He filling version of the CAST axion helioscope in analogy to INOUE 02 and INOUE 08. See their Fig. 7 for mass-dependent limits.

[33] CHOU 09 use the GammeV apparatus in the afterglow mode to search for chameleons, (pseudo)scalar bosons with a mass depending on the environment. For pseudoscalars they exclude at 3σ the range 2.6×10^{-7} GeV^{-1} $<$ $G_{A\gamma\gamma}$ $<$ 4.2×10^{-6} GeV^{-1} for vacuum m_{A^0} roughly below 6 meV for density scaling index exceeding 0.8.

[34] GONDOLO 09 use the all-flavor measured solar neutrino flux to constrain solar interior temperature and thus energy losses.

[35] LIPSS photon regeneration experiment, assuming scalar particle S^0. See Fig. 4 for mass-dependent limits.

[36] CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 3 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06.

[37] FOUCHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits.

[38] INOUE 08 is an extension of INOUE 02 to larger axion masses, using the Tokyo axion helioscope. See their Fig. 4 for mass-dependent limits.

[39] ZAVATTINI 08 is an upgrade of ZAVATTINI 06, see their Fig. 8 for mass-dependent limits. They now exclude the parameter range where ZAVATTINI 06 had seen a positive signature.

[40] ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. Supersedes ZIOUTAS 05.

[41] ROBILLIARD 07 perform a photon regeneration experiment with a pulsed laser and pulsed magnetic field. See their Fig. 4 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06 with a CL exceeding 99.9%.

[42] ZAVATTINI 06 propagate a laser beam in a magnetic field and observe dichroism and birefringence effects that could be attributed to an axion-like particle. This result is now excluded by ROBILLIARD 07, ZAVATTINI 08, and CHOU 08.

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

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

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

[46] 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.

[47] 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 $g_p \overline{p} \gamma_5 p \phi_A$.

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

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

[50] Experiment based on proposal by MAIANI 86.

[51] Experiment based on proposal by VANBIBBER 87.

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

[53] RUOSO 92 experiment is based on the proposal by VANBIBBER 87.

[54] 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 equivalently, 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 $\boldsymbol{n}=\boldsymbol{r}/r$.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.2 \times 10^{-10}$	68	[1] BATTICH	16	ASTR	White dwarf cooling
$<7 \times 10^{-10}$		[2] CORSICO	16	ASTR	White dwarf cooling
$<1.36 \times 10^{-8}$	90	[3] YOON	16	KIMS	Solar axions
$<7.3 \times 10^{-6}$	95	[4] TERRANO	15		$m_{A^0} < 30\ \mu$eV
$<7.8 \times 10^{-10}$	90	[5] ABE	14F	XMAS	$m_{A^0} = 60$ keV
$<7.5 \times 10^{-9}$	90	[6] APRILE	14B	X100	Solar axions
$<1 \times 10^{-9}$	90	[7] APRILE	14B	X100	$m_{A^0} = 5$–7 keV
$<$ 0.94–8.0 $\times 10^{-5}$	90	[8] DERBIN	14	CNTR	$m_{A^0} = 0.1$–1 MeV
$<3 \times 10^{-10}$	99	[9] MILLER-BER...	14	ASTR	White dwarf cooling
$<5.3 \times 10^{-8}$	90	[10] ABE	13D	XMAS	Solar axions
$<1.05 \times 10^{-9}$	90	[11] ARMENGAUD	13	EDEL	$m_{A^0} = 12.5$ keV
$<2.53 \times 10^{-8}$	90	[12] ARMENGAUD	13	EDEL	Solar axions
		[13] BARTH	13	CAST	Solar axions
$<$ 1.4–9.5 $\times 10^{-4}$	90	[14] DERBIN	13	CNTR	$m_{A^0} = 0.1$–1 MeV
$<2.9 \times 10^{-5}$	68	[15] HECKEL	13		$m_{A^0} \leq 0.1\ \mu$eV
$<4.2 \times 10^{-10}$	95	[16] VIAUX	13A	ASTR	Low-mass red giants
$<7 \times 10^{-10}$	95	[17] CORSICO	12	ASTR	White dwarf cooling
$<2.2 \times 10^{-7}$	90	[18] DERBIN	12	CNTR	Solar axions
$<$ 0.02–1 $\times 10^{-7}$	90	[19] AALSETH	11	CNTR	$m_{A^0} = 0.3$–8 keV
$<1.4 \times 10^{-9}$	90	[20] AHMED	09A	CDMS	$m_{A^0} = 2.5$ keV
$<3 \times 10^{-6}$		[21] DAVOUDIASL	09	ASTR	Earth cooling
$<5.3 \times 10^{-5}$	66	[22] NI	94		Induced magnetism
$<6.7 \times 10^{-5}$	66	[22] CHUI	93		Induced magnetism
$<3.6 \times 10^{-4}$	66	[23] PAN	92		Torsion pendulum
$<2.7 \times 10^{-5}$	95	[22] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[24] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[23] RITTER	90		Torsion pendulum
$<6.6 \times 10^{-5}$	95	[22] VOROBYOV	88		Induced magnetism

[1] BATTICH 16 is analogous to CORSICO 16 and used the pulsating DB white dwarf PG 1351+489.

[2] CORSICO 16 studied the cooling rate of the pulsating DA white dwarf L19-2 based on an asteroseismic model.

[3] YOON 16 look for solar axions with the axio-electric effect in CsI(Tl) crystals and set a limit for $m_{A^0} < 1$ keV.

[4] TERRANO 15 used a torsion pendulum and rotating attractor with 20-pole electron-spin distributions. See their Fig. 4 for a mass-dependent limit up to $m_{A^0} = 500\ \mu$eV.

[5] ABE 14F set limits on the axioelectric effect in the XMASS detector assuming the pseudoscalar constitutes all the local dark matter. See their Fig. 3 for limits between $m_{A^0} = 40$–120 keV.

[6] APRILE 14B look for solar axions using the XENON100 detector.

[7] APRILE 14B is analogous to AHMED 09A. See their Fig. 7 for limits between 1 keV $< m_{A^0} < 35$ keV.

[8] DERBIN 14 is an update of DERBIN 13 with a BGO scintillating bolometer. See their Fig. 3 for mass-dependent limits.
[9] MILLER-BERTOLAMI 14 studied the impact of axion emission on white dwarf cooling in a self-consistent way.
[10] ABE 13D is analogous to DERBIN 12, using the XMASS detector.
[11] ARMENGAUD 13 is similar to AALSETH 11. See their Fig. 10 for limits between 3 keV $< m_{A^0} <$ 100 keV.
[12] ARMENGAUD 13 is similar to DERBIN 12, and take account of axio-recombination and axio-deexcitation effects. See their Fig. 12 for mass-dependent limits.
[13] BARTH 13 search for solar axions produced by axion-electron coupling, and obtained the limit, $G_{Aee} \cdot G_{A\gamma\gamma} <$ 7.9 $\times 10^{-20}$ GeV^{-2} at 95%CL.
[14] DERBIN 13 looked for 5.5 MeV solar axions produced in $pd \rightarrow {}^3\text{He}\, A^0$ in a BGO detector through the axioelectric effect. See their Fig. 4 for mass-dependent limits.
[15] HECKEL 13 studied the influence of 2 or 4 stationary sources each containing 6.0×10^{24} polarized electrons, on a rotating torsion pendulum containing 9.8×10^{24} polarized electrons. See their Fig. 4 for mass-dependent limits.
[16] VIAUX 13A constrain axion emission using the observed brightness of the tip of the red-giant branch in the globular cluster M5.
[17] CORSICO 12 attributed the excessive cooling rate of the pulsating white dwarf R548 to emission of axions with $G_{Aee} \simeq 5 \times 10^{-10}$.
[18] DERBIN 12 look for solar axions with the axio-electric effect in a Si(Li) detector. The solar production is based on Compton and bremsstrahlung processes.
[19] AALSETH 11 is analogous to AHMED 09A. See their Fig. 4 for mass-dependent limits.
[20] AHMED 09A assume keV-mass pseudoscalars are the local dark matter and constrain the axio-electric effect in the CDMS detector. See their Fig. 5 for mass-dependent limits.
[21] DAVOUDIASL 09 use geophysical constraints on Earth cooling by axion emission.
[22] 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.
[23] 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.
[24] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^2$	95	[1] GAVRILYUK	15	CNTR	Solar axion
		[2] KLIMCHITSK...	15		Casimir-less
		[3] BEZERRA	14		Casimir effect
		[4] BEZERRA	14A		Casimir effect
		[5] BEZERRA	14B		Casimir effect
		[6] BEZERRA	14C		Casimir effect
		[7] BLUM	14	COSM	^{4}He abundance
		[8] LEINSON	14	ASTR	Neutron star cooling

$<2.50 \times 10^{2}$	95	9 ALESSANDRIA	13	CNTR	Solar axion
$<1.55 \times 10^{2}$	90	10 ARMENGAUD	13	EDEL	Solar axion
$<8.6 \times 10^{3}$	90	11 BELLI	12	CNTR	Solar axion
$<1.41 \times 10^{2}$	90	12 BELLINI	12B	BORX	Solar axion
$<1.45 \times 10^{2}$	95	13 DERBIN	11	CNTR	Solar axion
		14 BELLINI	08	CNTR	Solar axion
		15 ADELBERGER	07		Test of Newton's law

[1] GAVRILYUK 15 look for solar axions emitted by the M1 transition of ^{83}Kr (9.4 keV). The mass bound assumes $m_u/m_d = 0.56$ and $S = 0.5$.

[2] KLIMCHITSKAYA 15 use the measurement of differential forces between a test mass and rotating source masses of Au and Si to constrain the force due to two-axion exchange for $1.7 \times 10^{-3} < m_{A^0} < 0.9$ eV. See their Figs. 1 and 2 for mass dependent limits.

[3] BEZERRA 14 use the measurement of the thermal Casimir-Polder force between a Bose-Einstein condensate of ^{87}Rb atoms and a SiO_2 plate to constrain the force mediated by exchange of two pseudoscalars for 0.1 meV $< m_{A^0} <$ 0.3 eV. See their Fig. 2 for the mass-dependent limit on pseudoscalar coupling to nucleons.

[4] BEZERRA 14A is analogous to BEZERRA 14. They use the measurement of the Casimir pressure between two Au-coated plates to constrain pseudoscalar coupling to nucleons for 1×10^{-3} eV $< m_{A^0} <$ 15 eV. See their Figs. 1 and 2 for the mass-dependent limit.

[5] BEZERRA 14B is analogous to BEZERRA 14. BEZERRA 14B use the measurement of the normal and lateral Casimir forces between sinusoidally corrugated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for 1 eV $< m_{A^0} <$ 20 eV. See their Figs. 1–3 for mass-dependent limits.

[6] BEZERRA 14C is analogous to BEZERRA 14. They use the measurement of the gradient of the Casimir force between Au- and Ni-coated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for 3×10^{-5} eV $< m_{A_0} <$ 1 eV. See their Figs. 1, 3, and 4 for the mass-dependent limits.

[7] BLUM 14 studied effects of an oscillating strong CP phase induced by axion dark matter on the primordial ^{4}He abundance. See their Fig. 1 for mass-dependent limits.

[8] LEINSON 14 attributes the excessive cooling rate of the neutron star in Cassiopeia A to axion emission from the superfluid core, and found $C_n^2\, m_{A^0}^2 \simeq 5.7 \times 10^{-6}$ eV^2, where C_n is the effective Peccei-Quinn charge of the neutron.

[9] ALESSANDRIA 13 used the CUORE experiment to look for 14.4 keV solar axions produced from the M1 transition of thermally excited ^{57}Fe nuclei in the solar core, using the axio-electric effect. The limit assumes the hadronic axion model. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.

[10] ARMENGAUD 13 is analogous to ALESSANDRIA 13. The limit assumes the hadronic axion model. See their Fig. 8 for the limit on product of axion couplings to electrons and nucleons.

[11] BELLI 12 looked for solar axions emitted by the M1 transition of ^{7}Li* (478 keV) after the electron capture of ^{7}Be, using the resonant excitation ^{7}Li in the LiF crystal. The mass bound assumes $m_u/m_d = 0.55$, $m_u/m_s = 0.029$, and the flavor-singlet axial vector matrix element $S = 0.4$.

[12] BELLINI 12B looked for 5.5 MeV solar axions produced in the $p d \rightarrow {}^{3}\text{He}\, A^0$. The limit assumes the hadronic axion model. See their Figs. 4 and 5 for mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.

[13] DERBIN 11 looked for solar axions emitted by the M1 transition of thermally excited ^{57}Fe nuclei in the Sun, using their possible resonant capture on ^{57}Fe in the laboratory. The mass bound assumes $m_u/m_d = 0.56$ and the flavor-singlet axial vector matrix element $S = 3F - D \simeq 0.5$.

[14] BELLINI 08 consider solar axions emitted in the M1 transition of ^{7}Li* (478 keV) and look for a peak at 478 keV in the energy spectra of the Counting Test Facility (CTF), a

Borexino prototype. For m_{A^0} < 450 keV they find mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.

[15] ADELBERGER 07 use precision tests of Newton's law to constrain a force contribution from the exchange of two pseudoscalars. See their Fig. 5 for limits on the pseudoscalar coupling to nucleons, relevant for m_{A^0} below about 1 meV.

Axion Limits from *T*-violating Medium-Range Forces

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

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[1] AFACH	15		ultracold neutrons
	[2] STADNIK	15	THEO	nucleon spin contributions for nuclei
	[3] TERRANO	15		torsion pendulum
	[4] BULATOWICZ	13	NMR	polarized ^{129}Xe and ^{131}Xe
	[5] CHU	13		polarized ^{3}He
	[6] TULLNEY	13	SQID	polarized ^{3}He and ^{129}Xe
	[7] RAFFELT	12		stellar energy loss
	[8] HOEDL	11		torsion pendulum
	[9] PETUKHOV	10		polarized ^{3}He
	[10] SEREBROV	10		ultracold neutrons
	[11] IGNATOVICH	09	RVUE	ultracold neutrons
	[12] SEREBROV	09	RVUE	ultracold neutrons
	[13] BAESSLER	07		ultracold neutrons
	[14] HECKEL	06		torsion pendulum
	[15] NI	99		paramagnetic Tb F_3
	[16] POSPELOV	98	THEO	neutron EDM
	[17] YOUDIN	96		
	[18] RITTER	93		torsion pendulum
	[19] VENEMA	92		nuclear spin-precession frequencies
	[20] WINELAND	91	NMR	

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

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

[3] TERRANO 15 used a torsion pendulum and rotating attractor, and derived a restrictive limit on the product of the pseudoscalar coupling to electron and the scalar coupling to nucleons, $g < 9 \times 10^{-29}$–5×10^{-26} for $m_{A^0} <$ 1.5–400 μeV. See their Fig. 5 for mass-dependent limits.

[4] BULATOWICZ 13 looked for NMR frequency shifts in polarized ^{129}Xe and ^{131}Xe when a zirconia rod is positioned near the NMR cell, and find $g < 1 \times 10^{-19}$–1×10^{-24} for λ = 0.01–1 cm. See their Fig. 4 for their limits.

[5] CHU 13 look for a shift of the spin precession frequency of polarized ^{3}He in the presence of an unpolarized mass, in analogy to YOUDIN 96. See Fig. 3 for limits on g in the approximate m_{A^0} range 0.02–2 meV.

[6] TULLNEY 13 look for a shift of the precession frequency difference between the colocated ^{3}He and ^{129}Xe in the presence an unpolarized mass, and derive limits g $< 3\times10^{-29}$–2×10^{-22} for $\lambda > 3\times10^{-4}$ m. See their Fig. 3 for λ-dependent limits.

[7] RAFFELT 12 show that the pseudoscalar couplings to electron and nucleon and the scalar coupling to nucleon are individually constrained by stellar energy-loss arguments and searches for anomalous monopole-monopole forces, together providing restrictive constraints on g. See their Figs. 2 and 3 for results.

[8] HOEDL 11 use a novel torsion pendulum to study the force by the polarized electrons of an external magnet. In their Fig. 3 they show restrictive limits on g in the approximate m_{A^0} range 0.03–10 meV.

[9] PETUKHOV 10 use spin relaxation of polarized ^{3}He and find $g < 3\times10^{-23}$ (cm/λ)^2 at 95% CL for the force range $\lambda = 10^{-4}$–1 cm.

[10] SEREBROV 10 use spin precession of ultracold neutrons close to bulk matter and find $g < 2\times10^{-21}$ (cm/λ)^2 at 95% CL for the force range $\lambda = 10^{-4}$–1 cm.

[11] IGNATOVICH 09 use data on depolarization of ultracold neutrons in material traps. They show λ-dependent limits in their Fig. 1.

[12] SEREBROV 09 uses data on depolarization of ultracold neutrons stored in material traps and finds $g < 2.96\times10^{-21}$ (cm/λ)^2 for the force range $\lambda = 10^{-3}$–1 cm and $g < 3.9\times10^{-22}$ (cm/λ)^2 for $\lambda = 10^{-4}$–10^{-3} cm, each time at 95% CL, significantly improving on BAESSLER 07.

[13] BAESSLER 07 use the observation of quantum states of ultracold neutrons in the Earth's gravitational field to constrain g for an interaction range 1 μm–a few mm. See their Fig. 3 for results.

[14] HECKEL 06 studied the influence of unpolarized bulk matter, including the laboratory's surroundings or the Sun, on a torsion pendulum containing about 9×10^{22} polarized electrons. See their Fig. 4 for limits on g as a function of interaction range.

[15] NI 99 searched for a T-violating medium-range force acting on paramagnetic Tb F_3 salt. See their Fig. 1 for the result.

[16] 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 cm/λ_A), where $\lambda_A=\hbar/m_A c$.

[17] YOUDIN 96 compared the precession frequencies of atomic ^{199}Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.

[18] RITTER 93 studied the influence of bulk mass with polarized electrons on an unpolarized torsion pendulum, providing limits in the interaction range from 1 to 100 cm.

[19] VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of ^{199}Hg and ^{201}Hg atoms.

[20] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored ^{9}Be$^+$ ions using nuclear magnetic resonance.

Hidden Photons: Kinetic Mixing Parameter Limits

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

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

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

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.2 \times 10^{-4}$	90	[1] BANERJEE	17	NA64	$m_{\gamma'}$ = 0.002–0.4 GeV
		[2] AAD	16AG	ATLS	$m_{\gamma'}$ = 0.1–2 GeV
$<4.4 \times 10^{-4}$	90	[3] ANASTASI	16	KLOE	$m_{\gamma'}$ = 527–987 MeV
$<1.7 \times 10^{-6}$	95	[4] KHACHATRY...	16	CMS	$m_{\gamma'}$ = 2 GeV
$<7 \times 10^{-4}$	90	[5] LEES	16F	BABR	$m_{\gamma'}$ = 0.212–10 GeV
$<4 \times 10^{-2}$	95	[6] AAD	15CD	ATLS	$m_{\gamma'}$ = 15–55 GeV
$<1.4 \times 10^{-3}$	90	[7] ADARE	15		$m_{\gamma'}$ = 30–90 MeV
		[8] AN	15A		$m_{\gamma'}$ = 12 eV - 40 keV
		[9] ANASTASI	15	KLOE	$m_{\gamma'} = 2m_{\mu}$ - 1 GeV
$<1.7 \times 10^{-3}$	90	[10] ANASTASI	15A	KLOE	$m_{\gamma'}$ = 5–320 MeV
$<4.2 \times 10^{-4}$	90	[11] BATLEY	15A	NA48	$m_{\gamma'}$ = 36 MeV
		[12] JAEGLE	15	BELL	$m_{\gamma'}$ = 0.1–3.5 GeV
$<3 \times 10^{-13}$		[13] KAZANAS	15	ASTR	$m_{\gamma'} = 2m_e - 100$ MeV
		[14] SUZUKI	15		$m_{\gamma'}$ = 1.9–4.3 eV
$<2.3 \times 10^{-13}$	99.7	[15] VINYOLES	15	ASTR	$m_{\gamma'}$ = 8 eV
		[16] ABE	14F	XMAS	$m_{\gamma'}$ = 40–120 keV
$<1.8 \times 10^{-3}$	90	[17] AGAKISHIEV	14	HDES	$m_{\gamma'}$ = 63 MeV
$<9.0 \times 10^{-4}$	90	[18] BABUSCI	14	KLOE	$m_{\gamma'}$ = 969 MeV
		[19] BATELL	14	BDMP	$m_{\gamma'} = 10^{-3}$–1 GeV
$<1.3 \times 10^{-7}$	95	[20] BLUEMLEIN	14	BDMP	$m_{\gamma'}$ = 0.6 GeV
$<3 \times 10^{-18}$		[21] FRADETTE	14	COSM	$m_{\gamma'}$ = 50–300 MeV
$<3.5 \times 10^{-4}$	90	[22] LEES	14J	BABR	$m_{\gamma'}$ = 0.2 GeV
$<9 \times 10^{-4}$	95	[23] MERKEL	14	A1	$m_{\gamma'}$ = 40–300 MeV
$<3 \times 10^{-15}$		[24] AN	13B	ASTR	$m_{\gamma'}$ = 2 keV
$<7 \times 10^{-14}$		[25] AN	13C	XE10	$m_{\gamma'}$ = 100 eV
$<8 \times 10^{-4}$		[26] DIAMOND	13	BDMP	$m_{\gamma'}$ = 30–250 MeV
$<2.2 \times 10^{-13}$		[27] HORVAT	13	HPGE	$m_{\gamma'}$ = 230 eV
$<8.06 \times 10^{-5}$	95	[28] INADA	13	LSW	$m_{\gamma'}$ = 0.04 eV−26 keV
$<2 \times 10^{-10}$	95	[29] MIZUMOTO	13		$m_{\gamma'}$ = 1 eV
$<1.7 \times 10^{-7}$		[30] PARKER	13	LSW	$m_{\gamma'}$ = 53 μeV
$<5.32 \times 10^{-15}$		[31] PARKER	13		$m_{\gamma'}$ = 53 μeV
$<1 \times 10^{-15}$		[32] REDONDO	13	ASTR	$m_{\gamma'}$ = 2 keV
$<8 \times 10^{-8}$	90	[33] GNINENKO	12A	BDMP	$m_{\gamma'}$ = 1–135 MeV
$<1 \times 10^{-7}$	90	[34] GNINENKO	12B	CHRM	$m_{\gamma'}$ = 1–500 MeV
$<1 \times 10^{-3}$	90	[35] ABRAHAMY...	11		$m_{\gamma'}$ = 175–250 MeV
$<9 \times 10^{-8}$	95	[36] BLUEMLEIN	11	BDMP	$m_{\gamma'}$ = 70 MeV

$<1 \times 10^{-7}$	[37] BJORKEN	09	BDMP	$m_{\gamma'} = 2$–400 MeV
$<5 \times 10^{-9}$	[38] BJORKEN	09	ASTR	$m_{\gamma'} = 2$–50 MeV

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

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

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

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

[5] LEES 16F looked for a hidden photon coupled only to the second and third generations of leptons in the reaction $e^+ e^- \rightarrow \mu^+ \mu^- \gamma'$ ($\gamma' \rightarrow \mu^+ \mu^-$) using data collected by BABAR detector, and derived limits on the hidden photon gauge coupling as low as 7×10^{-4} for $m_{\gamma'} = 0.212$–10 GeV. See their Fig. 5 for the mass-dependent limits.

[6] AAD 15CD look for $H \rightarrow Z \gamma' \rightarrow 4\ell$ with the ATLAS detector at LHC and find $\chi < 4$–17×10^{-2} for $m_{\gamma'} = 15$–55 GeV. See their Fig. 6.

[7] ADARE 15 look for a hidden photon in π^0, $\eta^0 \rightarrow \gamma e^+ e^-$ at the PHENIX experiment. See their Fig. 4 for mass-dependent limits.

[8] AN 15A derived limits from the absence of ionization signals in the XENON10 and XENON100 experiments, assuming hidden photons constitute all the local dark matter. Their best limit is $\chi < 1.3 \times 10^{-15}$ at $m_{\gamma'} = 18$ eV. See their Fig. 1 for mass-dependent limits.

[9] ANASTASI 15 look for a production of a hidden photon and a hidden Higgs boson with the KLOE detector at DAΦNE, where the hidden photon decays into a pair of muons and the hidden Higgs boson lighter than $m_{\gamma'}$ escape detection. See their Figs. 6 and 7 for mass-dependent limits on a product of the hidden fine structure constant and the kinetic mixing.

[10] ANASTASI 15A look for the decay $\gamma' \rightarrow e^+ e^-$ in the reaction $e^+ e^- \rightarrow e^+ e^- \gamma$. Limits between 1.7×10^{-3} and 1×10^{-2} are obtained for $m_{\gamma'} = 5$–320 MeV (see their Fig. 7).

[11] BATLEY 15A look for $\pi^0 \rightarrow \gamma \gamma'$ ($\gamma' \rightarrow e^+ e^-$) at the NA48/2 experiment. Limits between 4.2×10^{-4} and 8.8×10^{-3} are obtained for $m_{\gamma'} = 9$–120 MeV (see their Fig. 4).

[12] JAEGLE 15 look for the decay $\gamma' \rightarrow e^+ e^-$, $\mu^+ \mu^-$, or $\pi^+ \pi^-$ in the dark Higgsstrahlung channel, $e^+ e^- \rightarrow \gamma' H'$ ($H' \rightarrow \gamma' \gamma'$) at the BELLE experiment. They set limits on a product of the branching fraction and the Born cross section as well as a product of the hidden fine structure constant and the kinetic mixing. See their Figs. 3 and 4.

[13] KAZANAS 15 set limits by studying the decay of hidden photons $\gamma' \rightarrow e^+ e^-$ inside and near the progenitor star of SN1987A. See their Fig. 6 for mass-dependent limits.

[14] SUZUKI 15 looked for hidden-photon dark matter with a dish antenna and derived limits assuming they constitute all the local dark matter. Their limits are $\chi < 6 \times 10^{-12}$ for $m_{\gamma'} = 1.9$–4.3 eV. See their Fig. 7 for mass-dependent limits.

[15] VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations, and set the limits $\chi m_{\gamma'} < 1.8 \times 10^{-12}$ eV for $m_{\gamma'} = 3 \times 10^{-5}$–8 eV. See their Fig. 11.

[16] ABE 14F look for the photoelectric-like interaction in the XMASS detector assuming the hidden photon constitutes all the local dark matter. Limits between 2×10^{-13} and 1×10^{-12} are obtained. See their Fig. 3 for mass-dependent limits.

[17] AGAKISHIEV 14 look for hidden photons $\gamma' \rightarrow e^+ e^-$ at the HADES experiment, and set limits on χ for $m_{\gamma'} = 0.02$–0.6 GeV. See their Fig. 5 for mass-dependent limits.

[18] BABUSCI 14 look for the decay $\gamma' \rightarrow \mu^+ \mu^-$ in the reaction $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$. Limits between 4×10^{-3} and 9.0×10^{-4} are obtained for 520 MeV $< m_{\gamma'} <$ 980 MeV (see their Fig. 7).

[19] BATELL 14 derived limits from the electron beam dump experiment at SLAC (E-137) by searching for events with recoil electrons by sub-GeV dark matter produced from the decay of the hidden photon. Limits at the level of 10^{-4}–10^{-1} are obtained for $m_{\gamma'} = 10^{-3}$–1 GeV, depending on the dark matter mass and the hidden gauge coupling (see their Fig. 2).

[20] BLUEMLEIN 14 analyzed the beam dump data taken at the U-70 accelerator to look for γ'-bremsstrahlung and the subsequent decay into muon pairs and hadrons. See their Fig. 4 for mass-dependent excluded region.

[21] FRADETTE 14 studied effects of decay of relic hidden photons on BBN and CMB to set constraints on very small values of the kinetic mixing. See their Figs. 4 and 7 for mass-dependent excluded regions.

[22] LEES 14J look for hidden photons in the reaction $e^+ e^- \rightarrow \gamma \gamma'$ ($\gamma' \rightarrow e^+ e^-$, $\mu^+ \mu^-$). Limits at the level of 10^{-4}–10^{-3} are obtained for 0.02 GeV $< m_{\gamma'} <$ 10.2 GeV. See their Fig. 4 for mass-dependent limits.

[23] MERKEL 14 look for $\gamma' \rightarrow e^+ e^-$ at the A1 experiment at the Mainz Microtron (MAMI). See their Fig. 3 for mass-dependent limits.

[24] AN 13B examined the stellar production of hidden photons, correcting an important error of the production rate of the longitudinal mode which now dominates. See their Fig. 2 for mass-dependent limits based on solar energy loss.

[25] AN 13C use the solar flux of hidden photons to set a limit on the atomic ionization rate in the XENON10 experiment. They find $\chi\, m_{\gamma'} < 3 \times 10^{-12}$ eV for $m_{\gamma'} < 1$ eV. See their Fig. 2 for mass-dependent limits.

[26] DIAMOND 13 analyzed the beam dump data taken at the SLAC millicharge experiment to constrain a hidden photon invisibly decaying into lighter long-lived particles, which undergo elastic scattering off nuclei in the detector. Limits between 8×10^{-4}–2×10^{-2} are obtained. The quoted limit is applied when the dark gauge coupling is set equal to the electromagnetic coupling. See their Fig.4 for mass-dependent limits.

[27] HORVAT 13 look for hidden-photo-electric effect in HPGe detectors induced by solar hidden photons. See their Fig. 3 for mass-dependent limits.

[28] INADA 13 search for hidden photons using an intense X-ray beamline at SPring-8. See their Fig. 4 for mass-dependent limits.

[29] MIZUMOTO 13 look for solar hidden photons. See their Fig. 5 for mass-dependent limits.

[30] PARKER 13 look for hidden photons using a cryogenic resonant microwave cavity. See their Fig.5 for mass-dependent limits.

[31] PARKER 13 derived a limit for the hidden photon CDM with a randomly oriented hidden photon field.

[32] REDONDO 13 examined the solar emission of hidden photons including the enhancement factor for the longitudinal mode pointed out by AN 13B, and also updated stellar-energy loss arguments. See their Fig.3 for mass-dependent limits, including a review of the currently best limits from other arguments.

[33] GNINENKO 12A obtained bounds on B($\pi^0 \rightarrow \gamma\gamma'$) $\cdot$ B($\gamma' \rightarrow e^+ e^-$) from the NOMAD and PS191 neutrino experiments, and derived limits between 8×10^{-8}–2×10^{-4}. See their Fig.4 for mass-dependent excluded regions.

[34] GNINENKO 12B used the data taken at the CHARM experiment to constrain the decay, $\eta(\eta') \rightarrow \gamma\gamma'$ ($\gamma' \rightarrow e^+ e^-$), and derived limits between 1×10^{-7}–1×10^{-4}. See their Fig.4 for mass-dependent excluded region.

[35] ABRAHAMYAN 11 look for $\gamma' \rightarrow e^+ e^-$ in the electron-nucelon fixed-target experiment at the Jefferson Laboratory (APEX). See their Fig. 5 for mass-dependent limits.

[36] BLUEMLEIN 11 analyzed the beam dump data taken at the U-70 accelerator to look for $\pi^0 \rightarrow \gamma\gamma'$ ($\gamma' \rightarrow e^+ e^-$). See their Fig. 5 for mass-dependent limits.

[37] BJORKEN 09 analyzed the beam dump data taken at E137, E141, and E774 to constrain a hidden photon produced by bremsstrahlung, subsequently decaying into $e^+ e^-$, and derived limits between 10^{-7} and 10^{-2}. See their Fig. 1 for mass-dependent excluded region.

[38] BJORKEN 09 required the energy loss in the γ' emission from the core of SN1987A not to exceed 10^{53} erg/s, and derived limits between 5×10^{-9} and 2×10^{-6}. See their Fig. 1 for mass-dependent excluded region.

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

BANERJEE	17	PRL 118 011802	D. Banerjee et al.	(NA64 Collab.)
BRANCA	17	PRL 118 021302	A. Branca et al.	(AURIGA Collab.)
BRUBAKER	17	PRL 118 061302	B.M. Brubaker et al.	(YALE, UCB, NIST+)
TIWARI	17	PR D95 023005	P. Tiwari	(Technion)
AAD	16AG	JHEP 1602 062	G. Aad et al.	(ATLAS Collab.)
ABLIKIM	16E	PR D93 052005	M. Ablikim et al.	(BES III Collab.)
AJELLO	16	PRL 116 161101	M. Ajello et al.	(Fermi-LAT Collab.)
ANASTASI	16	PL B757 356	A. Anastasi et al.	(KLOE-2 Collab.)
BATTICH	16	JCAP 1608 062	T. Battich et al.	
CORSICO	16	JCAP 1607 036	A.H. Corsico et al.	
DELLA-VALLE	16	EPJ C76 24	F. Della Valle et al.	(PVLAS Collab.)
HOSKINS	16	PR D94 082001	J. Hoskins et al.	(ADMX Collab.)
JAECKEL	16	PL B753 482	J. Jaeckel, M. Spannowsky	(HEID, DURH)
KHACHATRY...	16	PL B752 146	V. Khachatryan et al.	(CMS Collab.)
LEEFER	16	PRL 117 271601	N. Leefer et al.	(MAINZ, BONN, LBL, UCB+)
LEES	16F	PR D94 011102	J.P. Lees et al.	(BABAR Collab.)
WON	16	PR D94 092006	E. Won et al.	(BELLE Collab.)
YOON	16	JHEP 1606 011	Y.S. Yoon et al.	(KIMS Collab.)
AAD	15CD	PR D92 092001	G. Aad et al.	(ATLAS Collab.)
AAIJ	15AZ	PRL 115 161802	R. Aaij et al.	(LHCb Collab.)
ADARE	15	PR C91 031901	A. Adare et al.	(PHENIX Collab.)
AFACH	15	PL B745 58	S. Afach et al.	(ETH, PSI, CAEN, +)
AGOSTINI	15A	EPJ C75 416	M. Agostini et al.	(GERDA Collab.)
AN	15A	PL B747 331	H. An et al.	(CIT, VICT, VIEN)
ANASTASI	15	PL B747 365	A. Anastasi et al.	(KLOE-2 Collab.)
ANASTASI	15A	PL B750 633	A. Anastasi et al.	(KLOE-2 Collab.)
ANASTASSO...	15	PL B749 172	V. Anastassopoulos et al.	(CAST Collab.)
ARIK	15	PR D92 021101	M. Arik et al.	(CAST Collab.)
ARNOLD	15	PR D92 072011	R. Arnold et al.	(NEMO-3 Collab.)
BALLOU	15	PR D92 092002	R. Ballou et al.	(OSQAR Collab.)
BATLEY	15A	PL B746 178	J.R. Batley et al.	(NA48/2 Collab.)
BAYES	15	PR D91 052020	R. Bayes et al.	(TWIST Collab.)
BRAX	15	PR D92 083501	P. Brax, P. Brun, D. Wouters	(SACL, SACL5)
GAVRILYUK	15	JETPL 101 664	Yu.M. Gavrilyuk et al.	
		Translated from ZETFP 101 739.		
HASEBE	15	PTEP 2015 073C01	T. Hasebe et al.	
JAEGLE	15	PRL 114 211801	I. Jaegle et al.	(BELLE Collab.)
KAZANAS	15	NP B890 17	D. Kazanas et al.	
KLIMCHITSK...	15	EPJ C75 164	G.L. Klimchitskaya, V.M. Mostepanenko	
MILLEA	15	PR D92 023010	M. Millea, L. Knox, B. Fields	(UCD, ILL)
STADNIK	15	EPJ C75 110	Y.V. Stadnik, V.V. Flambaum	(SYDN)
SUZUKI	15	JCAP 1509 042	J. Suzuki et al.	
TERRANO	15	PRL 115 201801	W.A. Terrano et al.	(WASH)
VANTILBURG	15	PRL 115 011802	K. Van Tilburg et al.	

VINYOLES	15	JCAP 1510 015	N. Vinyoles *et al.*	
ABE	14F	PRL 113 121301	K. Abe *et al.*	(XMASS Collab.)
AGAKISHIEV	14	PL B731 265	G. Agakishiev *et al.*	(HADES Collab.)
ALBERT	14A	PR D90 092004	J.B. Albert *et al.*	(EXO-200 Collab.)
APRILE	14B	PR D90 062009	E. Aprile *et al.*	(XENON100 Collab.)
ARIK	14	PRL 112 091302	M. Arik *et al.*	(CAST Collab.)
AYALA	14	PRL 113 191302	A. Ayala *et al.*	
BABUSCI	14	PL B736 459	D. Babusci *et al.*	(KLOE-2 Collab.)
BATELL	14	PRL 113 171802	B. Batell, R. Essig, Z. Surujon	(EFI, STON)
BEZERRA	14	PR D89 035010	V.B. Bezerra *et al.*	
BEZERRA	14A	EPJ C74 2859	V.B. Bezerra *et al.*	
BEZERRA	14B	PR D90 055013	V.B. Bezerra *et al.*	
BEZERRA	14C	PR D89 075002	V.B. Bezerra *et al.*	
BLUEMLEIN	14	PL B731 320	J. Bluemlein, J. Brunner	(CPPM, DESY)
BLUM	14	PL B737 30	K. Blum *et al.*	(IAS, PRIN)
DELLA-VALLE	14	PR D90 092003	F. Della Valle *et al.*	(PVLAS Collab.)
DERBIN	14	EPJ C74 3035	A.V. Derbin *et al.*	
EJLLI	14	PR D90 123527	D. Ejlli	
FRADETTE	14	PR D90 035022	A. Fradette *et al.*	
LEES	14J	PRL 113 201801	J.P. Lees *et al.*	(BABAR Collab.)
LEINSON	14	JCAP 1408 031	L. Leinson	
MERKEL	14	PRL 112 221802	H. Merkel *et al.*	(A1 at MAMI)
MILLER-BER...	14	JCAP 1410 069	M.M. Miller Bertolami *et al.*	
PUGNAT	14	EPJ C74 3027	P. Pugnat *et al.*	(OSQAR Collab.)
REESMAN	14	JCAP 1408 021	R. Reesman *et al.*	(OSU)
ABE	13D	PL B724 46	K. Abe *et al.*	(XMASS Collab.)
ABRAMOWSKI	13A	PR D88 102003	A. Abramowski *et al.*	(H.E.S.S. Collab.)
ADLARSON	13	PL B726 187	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
ALESSANDRIA	13	JCAP 1305 007	F. Alessandria *et al.*	(CUORE Collab.)
AN	13B	PL B725 190	H. An, M. Pospelov, J. Pradler	
AN	13C	PRL 111 041302	H. An, M. Pospelov, J. Pradler	
ARCHIDIACO...	13A	JCAP 1310 020	M. Archidiacono *et al.*	
ARMENGAUD	13	JCAP 1311 067	E. Armengaud *et al.*	(EDELWEISS-II Collab.)
BABUSCI	13B	PL B720 111	D. Babusci *et al.*	(KLOE-2 Collab.)
BARTH	13	JCAP 1305 010	K. Barth *et al.*	(CAST Collab.)
BECK	13	PRL 111 231801	C. Beck	
BETZ	13	PR D88 075014	M. Betz *et al.*	(CROWS Collab.)
BULATOWICZ	13	PRL 111 102001	M. Bulatowicz *et al.*	
CHU	13	PR D87 011105	P.-H. Chu *et al.*	(DUKE, IND, SJTU)
DERBIN	13	EPJ C73 2490	A. V. Derbin *et al.*	
DIAMOND	13	PRL 111 221803	M.D. Diamond, P. Schuster	
FRIEDLAND	13	PRL 110 061101	A. Friedland, M. Giannotti, M. Wise	
HECKEL	13	PRL 111 151802	B. R. Heckel *et al.*	
HORVAT	13	PL B721 220	R. Horvat *et al.*	
INADA	13	PL B722 301	T. Inada *et al.*	
LATTANZI	13	PR D88 063528	M. Lattanzi *et al.*	
MEYER	13	PR D87 035027	M. Meyer, D. Horns, M. Raue	
MIZUMOTO	13	JCAP 1307 013	T. Mizumoto *et al.*	
PARKER	13	PR D88 112004	S. Parker *et al.*	
REDONDO	13	JCAP 1308 034	J. Redondo, G. Raffelt	
TULLNEY	13	PRL 111 100801	K. Tullney *et al.*	
VIAUX	13A	PRL 111 231301	N. Viaux *et al.*	
WOUTERS	13	APJ 772 44	D. Wouters, P. Brun	(SACL)
ABLIKIM	12	PR D85 092012	M. Ablikim *et al.*	(BES III Collab.)
ARCHILLI	12	PL B706 251	F. Archilli *et al.*	(KLOE-2 Collab.)
BELLI	12	PL B711 41	P. Belli *et al.*	(DAMA-KIEV)
BELLINI	12B	PR D85 092003	G. Bellini *et al.*	(Borexino Collab.)
CADAMURO	12	JCAP 1202 032	D. Cadamuro *et al.*	(MPIM)
CORSICO	12	JCAP 1212 010	A.H. Corsico *et al.*	(LAPL, RGSUL, WASH+)
DERBIN	12	JETPL 95 339	A.V. Derbin *et al.*	(PNPI)
		Translated from ZETFP 95 379.		
GANDO	12	PR C86 021601	A. Gando *et al.*	(KamLAND-Zen Collab.)
GNINENKO	12A	PR D85 055027	S.N. Gninenko	(INRM)
GNINENKO	12B	PL B713 244	S.N. Gninenko	(INRM)
PAYEZ	12	JCAP 1207 041	A. Payez *et al.*	(LIEG)
RAFFELT	12	PR D86 015001	G. Raffelt	(MPIM)
AALSETH	11	PRL 106 131301	C.E. Aalseth *et al.*	(CoGeNT Collab.)
ABRAHAMY...	11	PRL 107 191804	S. Abrahamyan *et al.*	
ARIK	11	PRL 107 261302	M. Arik *et al.*	(CAST Collab.)
ARNOLD	11	PRL 107 062504	R. Arnold *et al.*	(NEMO-3 Collab.)
BLUEMLEIN	11	PL B701 155	J. Bluemlein, J. Brunner	(DESY)

CADAMURO	11	JCAP 1102 003	D. Cadamuro *et al.*	(MPIM, AARHUS)
DERBIN	11	PAN 74 596	A.V. Derbin *et al.*	(PNPI)
		Translated from YAF 74 620.		
DERBIN	11A	PR D83 023505	A.V. Derbin *et al.*	(PNPI)
HOEDL	11	PRL 106 041801	S.A. Hoedl *et al.*	(WASH)
HOSKINS	11	PR D84 121302	J. Hoskins *et al.*	(ADMX Collab.)
ANDRIAMON...	10	JCAP 1003 032	S. Andriamonje *et al.*	(CAST Collab.)
ARGYRIADES	10	NP A847 168	J. Argyriades *et al.*	(NEMO-3 Collab.)
ASZTALOS	10	PRL 104 041301	S.J. Asztalos *et al.*	(ADMX Collab.)
EHRET	10	PL B689 149	K. Ehret *et al.*	(ALPS Collab.)
HANNESTAD	10	JCAP 1008 001	S. Hannestad *et al.*	
PETUKHOV	10	PRL 105 170401	A.K. Petukhov *et al.*	
SEREBROV	10	JETPL 91 6	A. Serebrov *et al.*	
		Translated from ZETFP 91 8.		
AHMED	09A	PRL 103 141802	Z. Ahmed *et al.*	(CDMS Collab.)
ANDRIAMON...	09	JCAP 0912 002	S. Andriamonje *et al.*	
ARGYRIADES	09	PR C80 032501	J. Argyriades *et al.*	(NEMO-3 Collab.)
ARIK	09	JCAP 0902 008	E. Arik *et al.*	(CAST Collab.)
BJORKEN	09	PR D80 075018	J. Bjorken *et al.*	
CHOU	09	PRL 102 030402	A.S. Chou *et al.*	(GammeV Collab.)
DAVOUDIASL	09	PR D79 095024	H. Davoudiasl, P. Huber	
DERBIN	09A	PL B678 181	A.V. Derbin *et al.*	
GONDOLO	09	PR D79 107301	P. Gondolo, G. Raffelt	(UTAH, MPIM)
IGNATOVICH	09	EPJ C64 19	V.K. Ignatovich, Y.N. Pokotilovski	(JINR)
KEKEZ	09	PL B671 345	D. Kekez *et al.*	
SEREBROV	09	PL B680 423	A. Serebrov	(PNPI)
AFANASEV	08	PRL 101 120401	A. Afanasev *et al.*	
BELLINI	08	EPJ C54 61	G. Bellini *et al.*	(Borexino Collab.)
CHOU	08	PRL 100 080402	A.S. Chou *et al.*	(GammeV Collab.)
FOUCHE	08	PR D78 032013	M. Fouche *et al.*	
HANNESTAD	08	JCAP 0804 019	S. Hannestad *et al.*	
INOUE	08	PL B668 93	Y. Inoue *et al.*	
ZAVATTINI	08	PR D77 032006	E. Zavattini *et al.*	(PVLAS Collab.)
ADELBERGER	07	PRL 98 131104	E.G. Adelberger *et al.*	
ANDRIAMON...	07	JCAP 0704 010	S. Andriamonje *et al.*	(CAST Collab.)
BAESSLER	07	PR D75 075006	S. Baessler *et al.*	
CHANG	07	PR D75 052004	H.M. Chang *et al.*	(TEXONO Collab.)
HANNESTAD	07	JCAP 0708 015	S. Hannestad *et al.*	
JAIN	07	JP G34 129	P.L. Jain, G. Singh	
LESSA	07	PR D75 094001	A.P. Lessa, O.L.G. Peres	
MELCHIORRI	07A	PR D76 041303	A. Melchiorri, O. Mena, A. Slosar	
ROBILLIARD	07	PRL 99 190403	C. Robilliard *et al.*	
ARNOLD	06	NP A765 483	R. Arnold *et al.*	(NEMO-3 Collab.)
DUFFY	06	PR D74 012006	L.D. Duffy *et al.*	
HECKEL	06	PRL 97 021603	B.R. Heckel *et al.*	
ZAVATTINI	06	PRL 96 110406	E. Zavattini *et al.*	(PVLAS Collab.)
HANNESTAD	05A	JCAP 0507 002	S. Hannestad, A. Mirizzi, G. Raffelt	
ZIOUTAS	05	PRL 94 121301	K. Zioutas *et al.*	(CAST Collab.)
ADLER	04	PR D70 037102	S. Adler *et al.*	(BNL E787 Collab.)
ANISIMOVSK...	04	PRL 93 031801	V.V. Anisimovsky *et al.*	(BNL E949 Collab.)
ARNOLD	04	JETPL 80 377	R. Arnold *et al.*	(NEMO-3 Collab.)
		Translated from ZETFP 80 429.		
ASZTALOS	04	PR D69 011101	S.J. Asztalos *et al.*	
HOFFMANN	04	PR B70 180503	C. Hoffmann *et al.*	
ARNABOLDI	03	PL B557 167	C. Arnaboldi *et al.*	
CIVITARESE	03	NP A729 867	O. Civitarese, J. Suhonen	
DANEVICH	03	PR C68 035501	F.A. Danevich *et al.*	
ADLER	02C	PL B537 211	S. Adler *et al.*	(BNL E787 Collab.)
BADERT...	02	PL B542 29	A. Badertscher *et al.*	
BERNABEI	02D	PL B546 23	R. Bernabei *et al.*	(DAMA Collab.)
DERBIN	02	PAN 65 1302	A.V. Derbin *et al.*	
		Translated from YAF 65 1335.		
FUSHIMI	02	PL B531 190	K. Fushimi *et al.*	(ELEGANT V Collab.)
INOUE	02	PL B536 18	Y. Inoue *et al.*	
MORALES	02B	ASP 16 325	A. Morales *et al.*	(COSME Collab.)
ADLER	01	PR D63 032004	S. Adler *et al.*	(BNL E787 Collab.)
AMMAR	01B	PRL 87 271801	R. Ammar *et al.*	(CLEO Collab.)
ASHITKOV	01	JETPL 74 529	V.D. Ashitkov *et al.*	
		Translated from ZETFP 74 601.		

BERNABEI	01B	PL B515 6	R. Bernabei *et al.*	(DAMA Collab.)
DANEVICH	01	NP A694 375	F.A. Danevich *et al.*	
DEBOER	01	JP G27 L29	F.W.N. de Boer *et al.*	
STOICA	01	NP A694 269	S. Stoica, H.V. Klapdor-Kleingrothous	
ALESSAND...	00	PL B486 13	A. Alessandrello *et al.*	
ARNOLD	00	NP A678 341	R. Arnold *et al.*	
ASTIER	00B	PL B479 371	P. Astier *et al.*	(NOMAD Collab.)
DANEVICH	00	PR C62 045501	F.A. Danevich *et al.*	
MASSO	00	PR D61 011701	E. Masso	
ARNOLD	99	NP A658 299	R. Arnold *et al.*	(NEMO Collab.)
NI	99	PRL 82 2439	W.-T. Ni *et al.*	
SIMKOVIC	99	PR C60 055502	F. Simkovic *et al.*	
ALTEGOER	98	PL B428 197	J. Altegoer *et al.*	
ARNOLD	98	NP A636 209	R. Arnold *et al.*	(NEMO-2 Collab.)
AVIGNONE	98	PRL 81 5068	F.T. Avignone *et al.*	(Solar Axion Experiment)
DIAZ	98	NP B527 44	M.A. Diaz *et al.*	
FAESSLER	98B	JP G24 2139	A. Faessler, F. Simkovic	
KIM	98	PR D58 055006	J.E. Kim	
LUESCHER	98	PL B434 407	R. Luescher *et al.*	
MORIYAMA	98	PL B434 147	S. Moriyama *et al.*	
MOROI	98	PL B440 69	T. Moroi, H. Murayama	
POSPELOV	98	PR D58 097703	M. Pospelov	
ZUBER	98	PRPL 305 295	K. Zuber	
AHMAD	97	PRL 78 618	I. Ahmad *et al.*	(APEX Collab.)
BORISOV	97	JETP 83 868	A.V. Borisov, V.Y. Grishinia	(MOSU)
DEBOER	97C	JP G23 L85	F.W.N. de Boer *et al.*	
KACHELRIESS	97	PR D56 1313	M. Kachelriess, C. Wilke, G. Wunner	(BOCH)
KEIL	97	PR D56 2419	W. Keil *et al.*	
KITCHING	97	PRL 79 4079	P. Kitching *et al.*	(BNL E787 Collab.)
LEINBERGER	97	PL B394 16	U. Leinberger *et al.*	(ORANGE Collab.)
ADLER	96	PRL 76 1421	S. Adler *et al.*	(BNL E787 Collab.)
AMSLER	96B	ZPHY C70 219	C. Amsler *et al.*	(Crystal Barrel Collab.)
GANZ	96	PL B389 4	R. Ganz *et al.*	(GSI, HEID, FRAN, JAGL+)
GUENTHER	96	PR D54 3641	M. Gunther *et al.*	(MPIH, SASSO)
KAMEL	96	PL B368 291	S. Kamel	(SHAMS)
MITSUI	96	EPL 33 111	T. Mitsui *et al.*	(TOKY)
YOUDIN	96	PRL 77 2170	A.N. Youdin *et al.*	(AMHT, WASH)
ALTMANN	95	ZPHY C68 221	M. Altmann *et al.*	(MUNT, LAPP, CPPM)
BASSOMPIE...	95	PL B355 584	G. Bassompierre *et al.*	(LAPP, LCGT, LYON)
MAENO	95	PL B351 574	T. Maeno *et al.*	(TOKY)
RAFFELT	95	PR D51 1495	G. Raffelt, A. Weiss	(MPIM, MPIG)
SKALSEY	95	PR D51 6292	M. Skalsey, R.S. Conti	(MICH)
TSUNODA	95	EPL 30 273	T. Tsunoda *et al.*	(TOKY)
ADACHI	94	PR A49 3201	S. Adachi *et al.*	(TMU)
ALTHERR	94	ASP 2 175	T. Altherr, E. Petitgirard, T. del Rio Gaztelurrutia	
AMSLER	94B	PL B333 271	C. Amsler *et al.*	(Crystal Barrel Collab.)
ASAI	94	PL B323 90	S. Asai *et al.*	(TOKY)
MEIJERDREES	94	PR D49 4937	M.R. Drees *et al.*	(BRCO, OREG, TRIU)
NI	94	Physica B194 153	W.T. Ni *et al.*	(NTHU)
VO	94	PR C49 1551	D.T. Vo *et al.*	(ISU, LBL, LLNL, UCD)
ATIYA	93	PRL 70 2521	M.S. Atiya *et al.*	(BNL E787 Collab.)
Also		PRL 71 305 (erratum)	M.S. Atiya *et al.*	(BNL E787 Collab.)
ATIYA	93B	PR D48 R1	M.S. Atiya *et al.*	(BNL E787 Collab.)
BASSOMPIE...	93	EPL 22 239	G. Bassompierre *et al.*	(LAPP, TORI, LYON)
BECK	93	PRL 70 2853	M. Beck *et al.*	(MPIH, KIAE, SASSO)
CAMERON	93	PR D47 3707	R.E. Cameron *et al.*	(ROCH, BNL, FNAL+)
CHANG	93	PL B316 51	S. Chang, K. Choi	
CHUI	93	PRL 71 3247	T.C.P. Chui, W.T. Ni	(NTHU)
MINOWA	93	PRL 71 4120	M. Minowa *et al.*	(TOKY)
NG	93	PR D48 2941	K.W. Ng	(AST)
RITTER	93	PRL 70 701	R.C. Ritter *et al.*	
TANAKA	93	PR D48 5412	J. Tanaka, H. Ejiri	(OSAK)
ALLIEGRO	92	PRL 68 278	C. Alliegro *et al.*	(BNL, FNAL, PSI+)
ATIYA	92	PRL 69 733	M.S. Atiya *et al.*	(BNL, LANL, PRIN+)
BARABASH	92	PL B295 154	L.S. Barabash *et al.*	(JINR, CERN, SERP+)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz *et al.*	(WUSL, TATA)
BLUEMLEIN	92	IJMP A7 3835	J. Bluemlein *et al.*	(BERL, BUDA, JINR+)
HALLIN	92	PR D45 3955	A.L. Hallin *et al.*	(PRIN)
HENDERSON	92C	PRL 69 1733	S.D. Henderson *et al.*	(YALE, BNL)
HICKS	92	PL B276 423	K.H. Hicks, D.E. Alburger	(OHIO, BNL)
LAZARUS	92	PRL 69 2333	D.M. Lazarus *et al.*	(BNL, ROCH, FNAL)

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

DEBOER	88	PRL 61 1274	F.W.N. de Boer, R. van Dantzig	(ANIK)
Also		PRL 62 2644 (erratum)	F.W.N. de Boer, R. van Dantzig	(ANIK)
Also		PRL 62 2638	D.H. Perkins	(OXF)
Also		PRL 62 2639	F.W.N. de Boer, R. van Dantzig	(ANIK)
DEBOER	88C	JP G14 L131	F.W.N. de Boer *et al.*	(LOUV)
DOEHNER	88	PR D38 2722	J. Dohner *et al.*	(HEIDP, ANL, ILLG)
EL-NADI	88	PRL 61 1271	M. el Nadi, O.E. Badawy	(CAIR)
ENGEL	88	PR C37 731	J. Engel, P. Vogel, M.R. Zirnbauer	
FAISSNER	88	ZPHY C37 231	H. Faissner *et al.*	(AACH3, BERL, SIN)
HATSUDA	88B	PL B203 469	T. Hatsuda, M. Yoshimura	(KEK)
LORENZ	88	PL B214 10	E. Lorenz *et al.*	(MPIM, PSI)
MAYLE	88	PL B203 188	R. Mayle *et al.*	(LLL, CERN, MINN, FNAL+)
PICCIOTTO	88	PR D37 1131	C.E. Picciotto *et al.*	(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 *et al.*	(GSI, ILLG)
TSERTOS	88B	ZPHY A331 103	A. Tsertos *et al.*	(GSI, ILLG)
VANKLINKEN	88	PL B205 223	J. van Klinken *et al.*	(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 *et al.*	(NOVO)
FRIEMAN	87	PR D36 2201	J.A. Frieman, S. Dimopoulos, M.S. Turner	(SLAC+)
GOLDMAN	87	PR D36 1543	T. Goldman *et al.*	(LANL, CHIC, STAN+)
KORENCHE...	87	SJNP 46 192	S.M. Korenchenko *et al.*	(JINR)
		Translated from YAF 46 313.		
MAIER	87	ZPHY A326 527	K. Maier *et al.*	(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 *et al.*	(ROCH, CIT+)
TURNER	87	PRL 59 2489	M.S. Turner	(FNAL, EFI)
VANBIBBER	87	PRL 59 759	K. van Bibber *et al.*	(LLL, CIT, MIT+)
VONWIMMER...	87	PRL 59 266	U. von Wimmersperg *et al.*	(WITW)
BADIER	86	ZPHY C31 21	J. Badier *et al.*	(NA3 Collab.)
BROWN	86	PRL 57 2101	C.N. Brown *et al.*	(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 *et al.*	(SINDRUM Collab.)
HALLIN	86	PRL 57 2105	A.L. Hallin *et al.*	(PRIN)
JODIDIO	86	PR D34 1967	A. Jodidio *et al.*	(LBL, NWES, TRIU)
Also		PR D37 237 (erratum)	A. Jodidio *et al.*	(LBL, NWES, TRIU)
KETOV	86	JETPL 44 146	S.N. Ketov *et al.*	(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 *et al.*	(KYOT, KEK)
MAIANI	86	PL B175 359	L. Maiani, R. Petronzio, E. Zavattini	(CERN)
PECCEI	86	PL B172 435	R.D. Peccei, T.T. Wu, T. Yanagida	(DESY)
RAFFELT	86	PR D33 897	G.G. Raffelt	(MPIM)
RAFFELT	86B	PL 166B 402	G.G. Raffelt	(MPIM)
SAVAGE	86B	PRL 57 178	M.J. Savage *et al.*	(CIT)
AMALDI	85	PL 153B 444	U. Amaldi *et al.*	(CERN)
ANANEV	85	SJNP 41 585	V.D. Ananev *et al.*	(JINR)
		Translated from YAF 41 912.		
BALTRUSAIT...	85	PRL 55 1842	R.M. Baltrusaitis *et al.*	(Mark III Collab.)
BERGSMA	85	PL 157B 458	F. Bergsma *et al.*	(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 *et al.*	(INUS, KEK)
ABBOTT	83	PL 120B 133	L.F. Abbott, P. Sikivie	(BRAN, FLOR)
CARBONI	83	PL 123B 349	G. Carboni, W. Dahme	(CERN, MUNI)
CAVAIGNAC	83	PL 121B 193	J.F. Cavaignac *et al.*	(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 *et al.*	(AACH)
FAISSNER	83B	PR D28 1787	H. Faissner *et al.*	(AACH3)
FRANK	83B	PR D28 1790	J.S. Frank *et al.*	(LANL, YALE, LBL+)
HOFFMAN	83	PR D28 660	C.M. Hoffman *et al.*	(LANL, ARZS)
PRESKILL	83	PL 120B 127	J. Preskill, M.B. Wise, F. Wilczek	(HARV, UCSBT)

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

OTHER RELATED PAPERS

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