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

NODE=S029

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NODE=S029

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

NODE=S029AXA

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

NODE=S029AXA

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[1] LOVE	08	CLEO	$\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$, or $\tau^+\tau^-$
>0.2	BARROSO	82	ASTR	Standard Axion
>0.25	[2] RAFFELT	82	ASTR	Standard Axion
>0.2	[3] DICUS	78C	ASTR	Standard Axion
	MIKAELIAN	78	ASTR	Stellar emission
>0.3	[3] SATO	78	ASTR	Standard Axion
>0.2	VYSOTSKII	78	ASTR	Standard Axion

NODE=S029AXA

[1] LOVE 08 show mass-dependent limits on B($\Upsilon \rightarrow \gamma A^0$) B($A^0 \rightarrow \mu^+\mu^-$) or $\tau^+\tau^-$ on their Fig. 3.

NODE=S029AXA;LINKAGE=LO

[2] Lower bound from 5.5 MeV γ-ray line from the sun.

NODE=S029AXA;LINKAGE=B

[3] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

NODE=S029AXA;LINKAGE=A

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

NODE=S029AD2

Limits are for branching ratios.

NODE=S029AD2

NODE=S029AD2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[4] PARK	05	HYCP	$\Sigma^+ \rightarrow p A^0$, $A^0 \rightarrow \mu^+\mu^-$	
$<7 \times 10^{-10}$	90	[5] ADLER	04	B787	$K^+ \rightarrow \pi^+ X^0$	
$<7.3 \times 10^{-11}$	90	[6] ANISIMOVSK...	04	B949	$K^+ \rightarrow \pi^+ X^0$	
$<4.5 \times 10^{-11}$	90	[7] ADLER	02C	B787	$K^+ \rightarrow \pi^+ X^0$	
$<4 \times 10^{-5}$	90	[8] ADLER	01	B787	$K^+ \rightarrow \pi^+ \pi^0 A^0$	
$<4.9 \times 10^{-5}$	90	AMMAR	01B	CLEO	$B^\pm \rightarrow \pi^\pm (K^\pm) X^0$	
$<5.3 \times 10^{-5}$	90	AMMAR	01B	CLEO	$B^0 \rightarrow K^0_S X^0$	OCCUR=2
$<3.3 \times 10^{-5}$	90	[9] ALTEGOER	98	NOMD	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 120$ MeV	
$<5.0 \times 10^{-8}$	90	[10] KITCHING	97	B787	$K^+ \rightarrow \pi^+ X^0$ ($X^0 \rightarrow \gamma\gamma$)	
$<5.2 \times 10^{-10}$	90	[11] ADLER	96	B787	$K^+ \rightarrow \pi^+ X^0$	
$<2.8 \times 10^{-4}$	90	[12] AMSLER	96B	CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 65$ MeV	
$<3 \times 10^{-4}$	90	[12] AMSLER	96B	CBAR	$\eta \rightarrow \gamma X^0$, m_{X^0}= 50–200 MeV	OCCUR=2
$<4 \times 10^{-5}$	90	[12] AMSLER	96B	CBAR	$\eta' \rightarrow \gamma X^0$, m_{X^0}= 50–925 MeV	OCCUR=3
$<6 \times 10^{-5}$	90	[12] AMSLER	94B	CBAR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=65–125 MeV	
$<6 \times 10^{-5}$	90	[12] AMSLER	94B	CBAR	$\eta \rightarrow \gamma X^0$, m_{X^0}=200–525 MeV	OCCUR=2
$<7 \times 10^{-3}$	90	[13] MEIJERDREES	94	CNTR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=25 MeV	
$<2 \times 10^{-3}$	90	[13] MEIJERDREES	94	CNTR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=100 MeV	OCCUR=2
$<2 \times 10^{-7}$	90	[14] ATIYA	93B	B787	Sup. by ADLER 04	
$<3 \times 10^{-13}$		[15] NG	93	COSM	$\pi^0 \rightarrow \gamma X^0$	
$<1.1 \times 10^{-8}$	90	[16] ALLIEGRO	92	SPEC	$K^+ \rightarrow \pi^+ X^0$ ($X^0 \rightarrow e^+e^-$)	
$<5 \times 10^{-4}$	90	[17] ATIYA	92	B787	$\pi^0 \rightarrow \gamma X^0$	
$<4 \times 10^{-6}$	90	[18] MEIJERDREES	92	SPEC	$\pi^0 \rightarrow \gamma X^0$, $X^0 \rightarrow e^+e^-$, m_{X^0}= 100 MeV	
$<1 \times 10^{-7}$	90	[19] ATIYA	90B	B787	Sup. by KITCHING 97	
$<1.3 \times 10^{-8}$	90	[20] KORENCHE...	87	SPEC	$\pi^+ \rightarrow e^+\nu A^0$ ($A^0 \rightarrow e^+e^-$)	
$<1 \times 10^{-9}$	90	[21] EICHLER	86	SPEC	Stopped $\pi^+ \rightarrow e^+\nu A^0$	OCCUR=2
$<2 \times 10^{-5}$	90	[22] YAMAZAKI	84	SPEC	For 160<m<260 MeV	
$<(1.5–4) \times 10^{-6}$	90	[22] YAMAZAKI	84	SPEC	K decay, $m_{X^0} \ll 100$ MeV	OCCUR=2
		[23] ASANO	82	CNTR	Stopped $K^+ \rightarrow \pi^+ X^0$	
		[24] ASANO	81B	CNTR	Stopped $K^+ \rightarrow \pi^+ X^0$	
		[25] ZHITNITSKII	79		Heavy axion	

[4] PARK 05 found three candidate events for $\Sigma^+ \to p\mu^+\mu^-$ in the HyperCP experiment. Due to a narrow spread in dimuon mass, they hypothesize the events as a possible signal of a new boson. It can be interpreted as an axion-like particle with $m_{A^0} = 214.3 \pm 0.5$ MeV and the branching fraction $B(\Sigma^+ \to pA^0) \times B(A^0 \to \mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$. NODE=S029AD2;LINKAGE=PA

[5] 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. NODE=S029AD2;LINKAGE=AL

[6] ANISIMOVSKY 04 bound is for m_{X^0}=0. NODE=S029AD2;LINKAGE=AN

[7] ADLER 02C bound is for m_{X^0} <60 MeV. See Fig. 2 for limits at higher masses. NODE=S029AD2;LINKAGE=LC

[8] 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. NODE=S029AD2;LINKAGE=AD

[9] 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. NODE=S029AD2;LINKAGE=M

[10] KITCHING 97 limit is for $B(K^+ \to \pi^+ X^0) \cdot B(X^0 \to \gamma\gamma)$ 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. NODE=S029AD2;LINKAGE=TK

[11] 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. NODE=S029AD2;LINKAGE=K4

[12] AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution. NODE=S029AD2;LINKAGE=K

[13] 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. NODE=S029AD2;LINKAGE=L

[14] 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. NODE=S029AD2;LINKAGE=I2

[15] NG 93 studied the production of X^0 via $\gamma\gamma \to \pi^0 \to \gamma X^0$ 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. NODE=S029AD2;LINKAGE=J

[16] 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. NODE=S029AD2;LINKAGE=F

[17] 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. NODE=S029AD2;LINKAGE=H

[18] 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. NODE=S029AD2;LINKAGE=E

[19] ATIYA 90B limit is for $B(K^+ \to \pi^+ X^0) \cdot B(X^0 \to \gamma\gamma)$ 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. NODE=S029AD2;LINKAGE=K2

[20] KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and $B(A^0 \to e^+e^-) = 1$. NODE=S029AD2;LINKAGE=A

[21] EICHLER 86 looked for $\pi^+ \to e^+\nu A^0$ followed by $A^0 \to e^+e^-$. 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. NODE=S029AD2;LINKAGE=T

[22] YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+ X$. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not. NODE=S029AD2;LINKAGE=R

[23] ASANO 82 at KEK set limits for $B(K^+ \to \pi^+ X^0)$ for m_{X^0} <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(X^0 \to n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s. NODE=S029AD2;LINKAGE=G

[24] ASANO 81B is KEK experiment. Set $B(K^+ \to \pi^+ X^0) < 3.8 \times 10^{-8}$ at CL = 90%. NODE=S029AD2;LINKAGE=C

[25] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 ($3 < m < 40$ MeV) contradicts experimental muon anomalous magnetic moments. NODE=S029AD2;LINKAGE=B

A^0 (Axion) Searches in Quarkonium Decays

NODE=S029AXQ

Decay or transition of quarkonium. Limits are for branching ratio. NODE=S029AXQ

NODE=S029AXQ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.3 \times 10^{-5}$	90	[26] BALEST	95	CLEO	$\Upsilon(1S) \to A^0\gamma$	
$<4.0 \times 10^{-5}$	90	ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to A^0\gamma$	
		[27] ANTREASYAN	90C	RVUE		OCCUR=2
$<5 \times 10^{-5}$	90	[28] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to e^+e^-$)	
$<2 \times 10^{-3}$	90	[29] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to \gamma\gamma$)	OCCUR=2
$<7 \times 10^{-6}$	90	[30] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to$ missing)	OCCUR=3
$<3.1 \times 10^{-4}$	90	[31] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+e^-$)	
$<4 \times 10^{-4}$	90	[31] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to \mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-)	OCCUR=2

$<8 \times 10^{-4}$	90	[32] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$	OCCUR=3
$<1.3 \times 10^{-3}$	90	[33] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+e^-$, $\gamma\gamma$)	OCCUR=4
$<2. \times 10^{-3}$	90	[34] BOWCOCK	86	CLEO	$\Upsilon(2S) \to \Upsilon(1S) \to A^0$	
$<5. \times 10^{-3}$	90	[35] MAGERAS	86	CUSB	$\Upsilon(1S) \to A^0\gamma$	
$<3. \times 10^{-4}$	90	[36] ALAM	83	CLEO	$\Upsilon(1S) \to A^0\gamma$	
$<9.1 \times 10^{-4}$	90	[37] NICZYPORUK	83	LENA	$\Upsilon(1S) \to A^0\gamma$	
$<1.4 \times 10^{-5}$	90	[38] EDWARDS	82	CBAL	$J/\psi \to A^0\gamma$	
$<3.5 \times 10^{-4}$	90	[39] SIVERTZ	82	CUSB	$\Upsilon(1S) \to A^0\gamma$	
$<1.2 \times 10^{-4}$	90	[39] SIVERTZ	82	CUSB	$\Upsilon(3S) \to A^0\gamma$	OCCUR=2

[26] BALEST 95 looked for a monochromatic γ from $\Upsilon(1S)$ decay. The bound is for $m_{A^0} <$ 5.0 GeV. See Fig. 7 in the paper for bounds for heavier m_{A^0}. They also quote a bound on branching ratios 10^{-3}–10^{-5} of three-body decay $\gamma X\overline{X}$ for $0<m_X < 3.1$ GeV. NODE=S029AXQ;LINKAGE=A

[27] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon$, J/ψ) is the reduction factor for $\Gamma(V \to A^0\gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \to ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \to ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$. NODE=S029AXQ;LINKAGE=J6

[28] 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. NODE=S029AXQ;LINKAGE=E1

[29] 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. NODE=S029AXQ;LINKAGE=F1

[30] 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. NODE=S029AXQ;LINKAGE=H1

[31] $\tau_{A^0} < 1 \times 10^{-13}$s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \to \gamma\gamma$ when $m_{A^0} < 100$ MeV. NODE=S029AXQ;LINKAGE=X

[32] $\tau_{A^0} > 1 \times 10^{-7}$s. NODE=S029AXQ;LINKAGE=Y

[33] Independent of τ_{A^0}. NODE=S029AXQ;LINKAGE=Z

[34] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to A^0\gamma$. The limit for $B(\Upsilon(1S) \to A^0\gamma)B(A^0 \to e^+e^-)$ depends on m_{A^0} and τ_{A^0}. The quoted limit for m_{A^0}=1.8 MeV is at $\tau_{A^0} \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m_e < m_{A^0} < 2m_\mu$ when the results of this experiment are combined with the results of ALAM 83. NODE=S029AXQ;LINKAGE=V

[35] MAGERAS 86 looked for $\Upsilon(1S) \to \gamma A^0$ ($A^0 \to e^+e^-$). The quoted branching fraction limit is for m_{A^0} = 1.7 MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$s where the limit is the worst. NODE=S029AXQ;LINKAGE=W

[36] ALAM 83 is at CESR. This limit combined with limit for $B(J/\psi \to A^0\gamma)$ (EDWARDS 82) excludes standard axion. NODE=S029AXQ;LINKAGE=N

[37] NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $B(\Upsilon \to A^0\gamma)$ derived from $B(J/\psi(1S) \to A^0\gamma)$ limit (EDWARDS 82) excludes standard axion. NODE=S029AXQ;LINKAGE=Q

[38] EDWARDS 82 looked for $J/\psi \to \gamma A^0$ 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. NODE=S029AXQ;LINKAGE=J

[39] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \to \gamma A^0$, A^0 undetected. Limit for $1S$ ($3S$) is valid for m_{A^0} <7 GeV (4 GeV). NODE=S029AXQ;LINKAGE=L

A^0 (Axion) Searches in Positronium Decays

NODE=S029AXD

Decay or transition of positronium. Limits are for branching ratio. NODE=S029AXD

NODE=S029AXD

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4 \times 10^{-5}$	90	[40] BADERT...	02	CNTR	o-Ps $\to \gamma X_1 X_2$, $m_{X_1}+m_{X_2} \leq$ 900 keV
$<2 \times 10^{-4}$	90	MAENO	95	CNTR	o-Ps $\to A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0 \times 10^{-3}$	90	[41] ASAI	94	CNTR	o-Ps $\to A^0\gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[42] AKOPYAN	91	CNTR	o-Ps $\to A^0\gamma$ ($A^0 \to \gamma\gamma$), $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	[43] ASAI	91	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} < 800$ 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	[44] TSUCHIAKI	90	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} =$ 300–900 keV
$<6.4 \times 10^{-5}$	90	[45] ORITO	89	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} < 30$ keV
		[46] AMALDI	85	CNTR	Ortho-positronium
		[47] CARBONI	83	CNTR	Ortho-positronium

[40] BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles. NODE=S029AXD;LINKAGE=DB

[41] The ASAI 94 limit is based on inclusive photon spectrum and is independent of A^0 decay modes. NODE=S029AXD;LINKAGE=C

[42] The AKOPYAN 91 limit applies for a short-lived A^0 with $\tau_{A^0} < 10^{-13}\, m_{A^0}$ [keV] s. NODE=S029AXD;LINKAGE=B

[43] 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. NODE=S029AXD;LINKAGE=A1

[44] The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes. NODE=S029AXD;LINKAGE=A

[45] 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. NODE=S029AXD;LINKAGE=GX

[46] 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. NODE=S029AXD;LINKAGE=AM

[47] 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. NODE=S029AXD;LINKAGE=O

A^0 (Axion) Search in Photoproduction

NODE=S029AXG
NODE=S029AXG

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[48] BASSOMPIE...	95	$m_{A^0} = 1.8 \pm 0.2$ MeV

[48] 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. NODE=S029AXG;LINKAGE=BB

A^0 (Axion) Production in Hadron Collisions

NODE=S029AXP

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$. NODE=S029AXP

NODE=S029AXP

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[49] JAIN	07	CNTR	$A^0 \rightarrow e^+ e^-$
			[50] AHMAD	97	SPEC	e^+ production
			[51] LEINBERGER	97	SPEC	$A^0 \rightarrow e^+ e^-$
			[52] GANZ	96	SPEC	$A^0 \rightarrow e^+ e^-$
			[53] KAMEL	96	EMUL	^{32}S emulsion, $A^0 \rightarrow e^+ e^-$
			[54] BLUEMLEIN	92	BDMP	$A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$
			[55] MEIJERDREES	92	SPEC	$\pi^- p \rightarrow n A^0$, $A^0 \rightarrow e^+ e^-$
			[56] BLUEMLEIN	91	BDMP	$A^0 \rightarrow e^+ e^-$, 2γ
			[57] FAISSNER	89	OSPK	Beam dump, $A^0 \rightarrow e^+ e^-$
			[58] DEBOER	88	RVUE	$A^0 \rightarrow e^+ e^-$
			[59] EL-NADI	88	EMUL	$A^0 \rightarrow e^+ e^-$
			[60] FAISSNER	88	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[61] BADIER	86	BDMP	$A^0 \rightarrow e^+ e^-$
$<2. \times 10^{-11}$	90	0	[62] BERGSMA	85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[62] BERGSMA	85	CHRM	CERN beam dump OCCUR=2
		24	[63] FAISSNER	83	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[64] FAISSNER	83B	RVUE	LAMPF beam dump
			[65] FRANK	83B	RVUE	LAMPF beam dump
			[66] HOFFMAN	83	CNTR	$\pi p \rightarrow n A^0$ ($A^0 \rightarrow e^+ e^-$)
			[67] FETSCHER	82	RVUE	See FAISSNER 81B
		12	[68] FAISSNER	81	OSPK	CERN PS ν wideband
		15	[69] FAISSNER	81B	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$

		8	[70] KIM	81	OSPK	26 GeV $pN \to A^0 X$	
		0	[71] FAISSNER	80	OSPK	Beam dump, $A^0 \to e^+ e^-$	
$<1. \times 10^{-8}$	90		[72] JACQUES	80	HLBC	28 GeV protons	
$<1. \times 10^{-14}$	90		[72] JACQUES	80	HLBC	Beam dump	OCCUR=2
			[73] SOUKAS	80	CALO	28 GeV p beam dump	
			[74] BECHIS	79	CNTR		
$<1. \times 10^{-8}$	90		[75] COTEUS	79	OSPK	Beam dump	
$<1. \times 10^{-3}$	95		[76] DISHAW	79	CALO	400 GeV pp	
$<1. \times 10^{-8}$	90		ALIBRAN	78	HYBR	Beam dump	
$<6. \times 10^{-9}$	95		ASRATYAN	78B	CALO	Beam dump	
$<1.5 \times 10^{-8}$	90		[77] BELLOTTI	78	HLBC	Beam dump	
$<5.4 \times 10^{-14}$	90		[77] BELLOTTI	78	HLBC	m_{A^0}=1.5 MeV	OCCUR=2
$<4.1 \times 10^{-9}$	90		[77] BELLOTTI	78	HLBC	m_{A^0}=1 MeV	OCCUR=3
$<1. \times 10^{-8}$	90		[78] BOSETTI	78B	HYBR	Beam dump	
			[79] DONNELLY	78			
$<0.5 \times 10^{-8}$	90		HANSL	78D	WIRE	Beam dump	
			[80] MICELMAC...	78			
			[81] VYSOTSKII	78			

[49] JAIN 07 claims evidence for $A^0 \to e^+ e^-$ 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. NODE=S029AXP;LINKAGE=JA

[50] 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. NODE=S029AXP;LINKAGE=LA

[51] 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. NODE=S029AXP;LINKAGE=LL

[52] 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. NODE=S029AXP;LINKAGE=G1

[53] 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. NODE=S029AXP;LINKAGE=KL

[54] 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. NODE=S029AXP;LINKAGE=NN

[55] MEIJERDREES 92 give $\Gamma(\pi^- p \to n A^0) \cdot B(A^0 \to e^+ e^-)/\Gamma(\pi^- p \to \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0} = 100$ MeV, $\tau_{A^0} = 10^{-11}$–10^{-23} sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25$–136 MeV. NODE=S029AXP;LINKAGE=Z

[56] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \to e^+ e^-$, 2γ are found. Fig. 6 gives the excluded region in m_{A^0}-x plane ($x=\tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m_{A^0} < 3.2$ MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$. NODE=S029AXP;LINKAGE=A2

[57] FAISSNER 89 searched for $A^0 \to e^+ e^-$ 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. NODE=S029AXP;LINKAGE=F2

[58] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass $\sim$ 1.1, $\sim$ 2.1, and $\sim$ 9 MeV, lifetimes 10^{-16}–10^{-15} s decaying to $e^+ e^-$ and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism. NODE=S029AXP;LINKAGE=X

[59] 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 $\sim$ 4 GeV/c/nucleon. NODE=S029AXP;LINKAGE=W

[60] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \to \gamma\gamma$. 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. NODE=S029AXP;LINKAGE=F1

[61] 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. NODE=S029AXP;LINKAGE=A1

[62] BERGSMA 85 look for $A^0 \to 2\gamma$, $e^+ e^-$, $\mu^+ \mu^-$. 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, NODE=S029AXP;LINKAGE=T

where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, m_{A^0} <180 keV and τ >0.037 s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[63] 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. NODE=S029AXP;LINKAGE=P

[64] 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. NODE=S029AXP;LINKAGE=Q

[65] 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. NODE=S029AXP;LINKAGE=R

[66] 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. NODE=S029AXP;LINKAGE=S

[67] 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. NODE=S029AXP;LINKAGE=O

[68] FAISSNER 81 see excess μe events. Suggest axion interactions. NODE=S029AXP;LINKAGE=L

[69] 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. NODE=S029AXP;LINKAGE=M

[70] 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. NODE=S029AXP;LINKAGE=N

[71] 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 $m_{A^0} < 2m_{e^-}$. NODE=S029AXP;LINKAGE=I

[72] 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. NODE=S029AXP;LINKAGE=J

[73] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump. NODE=S029AXP;LINKAGE=K

[74] 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. NODE=S029AXP;LINKAGE=F

[75] COTEUS 79 is a beam dump experiment at BNL. NODE=S029AXP;LINKAGE=G

[76] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles. NODE=S029AXP;LINKAGE=H

[77] 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×(mass^{-4}). Third value uses data of PL 60B 401 and quotes $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67}$ cm^4. NODE=S029AXP;LINKAGE=A

[78] BOSETTI 78B quotes $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67}$ cm^4. NODE=S029AXP;LINKAGE=B

[79] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative. NODE=S029AXP;LINKAGE=C

[80] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below). NODE=S029AXP;LINKAGE=D

[81] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants. NODE=S029AXP;LINKAGE=E

A^0 (Axion) Searches in Reactor Experiments

NODE=S029AXR

NODE=S029AXR

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

VALUE	DOCUMENT ID		TECN	COMMENT
	[82] CHANG	07		Primakoff or Compton
	[83] ALTMANN	95	CNTR	Reactor; $A^0 \rightarrow e^+ e^-$
	[84] KETOV	86	SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	[85] KOCH	86	SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	[86] DATAR	82	CNTR	Light water reactor
	[87] VUILLEUMIER	81	CNTR	Reactor, $A^0 \rightarrow 2\gamma$

[82] 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. NODE=S029AXR;LINKAGE=CH

[83] 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 $\omega(A^0)/\omega(\gamma)\ \times$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. NODE=S029AXR;LINKAGE=C

[84] 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. NODE=S029AXR;LINKAGE=A

[85] 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. NODE=S029AXR;LINKAGE=B

[86] DATAR 82 looked for $A^0 \rightarrow 2\gamma$ in neutron capture ($np \rightarrow dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $\left[(I = 0) - (I = 1)\right]$ result, assert nonexistence of standard A^0. NODE=S029AXR;LINKAGE=I

[87] VUILLEUMIER 81 is at Grenoble reactor. Set limit m_{A^0} <280 keV. NODE=S029AXR;LINKAGE=D

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

NODE=S029ANT

Limits are for branching ratio. NODE=S029ANT

NODE=S029ANT

VALUE	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 8.5 \times 10^{-6}$	90	[88] DERBIN	02	CNTR	^{125m}Te decay	
		[89] DEBOER	97C	RVUE	M1 transitions	
$< 5.5 \times 10^{-10}$	95	[90] TSUNODA	95	CNTR	^{252}Cf fission, $A^0 \rightarrow ee$	
$< 1.2 \times 10^{-6}$	95	[91] MINOWA	93	CNTR	^{139}La$^* \rightarrow {}^{139}$LaA^0	
$< 2 \times 10^{-4}$	90	[92] HICKS	92	CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$	
$< 1.5 \times 10^{-9}$	95	[93] ASANUMA	90	CNTR	^{241}Am decay	
$<(0.4\text{–}10) \times 10^{-3}$	95	[94] DEBOER	90	CNTR	^{8}Be$^* \rightarrow {}^8$BeA^0, $A^0 \rightarrow e^+e^-$	
$<(0.2\text{–}1) \times 10^{-3}$	90	[95] BINI	89	CNTR	^{16}O$^* \rightarrow {}^{16}$OX^0, $X^0 \rightarrow e^+e^-$	
		[96] AVIGNONE	88	CNTR	Cu$^* \rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$, $A^0 e \rightarrow \gamma e$, $A^0 Z \rightarrow \gamma Z$)	
$< 1.5 \times 10^{-4}$	90	[97] DATAR	88	CNTR	^{12}C$^* \rightarrow {}^{12}$CA^0, $A^0 \rightarrow e^+e^-$	
$< 5 \times 10^{-3}$	90	[98] DEBOER	88C	CNTR	^{16}O$^* \rightarrow {}^{16}$OX^0, $X^0 \rightarrow e^+e^-$	
$< 3.4 \times 10^{-5}$	95	[99] DOEHNER	88	SPEC	^{2}H*, $A^0 \rightarrow e^+e^-$	
$< 4 \times 10^{-4}$	95	[100] SAVAGE	88	CNTR	Nuclear decay (isovector)	
$< 3 \times 10^{-3}$	95	[100] SAVAGE	88	CNTR	Nuclear decay (isoscalar)	OCCUR=2
$<10.6 \times 10^{-2}$	90	[101] HALLIN	86	SPEC	^{6}Li isovector decay	
<10.8	90	[101] HALLIN	86	SPEC	^{10}B isoscalar decays	OCCUR=2
< 2.2	90	[101] HALLIN	86	SPEC	^{14}N isoscalar decays	OCCUR=3
$< 4 \times 10^{-4}$	90	[102] SAVAGE	86B	CNTR	^{14}N*	
		[103] ANANEV	85	CNTR	Li*, deut* $A^0 \rightarrow 2\gamma$	
		[104] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \rightarrow 2\gamma$	
		[105] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \rightarrow 2\gamma$	
		[106] LEHMANN	82	CNTR	Cu$^* \rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$)	
		[107] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.	
		[108] ZEHNDER	81	CNTR	Ba$^* \rightarrow$ BaA^0 ($A^0 \rightarrow 2\gamma$)	
		[109] CALAPRICE	79		Carbon	

[88] 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. NODE=S029ANT;LINKAGE=ER

[89] 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. NODE=S029ANT;LINKAGE=W

[90] 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. NODE=S029ANT;LINKAGE=J

[91] 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. NODE=S029ANT;LINKAGE=D

[92] HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec. NODE=S029ANT;LINKAGE=V

[93] The ASANUMA 90 limit is for the branching fraction of X^0 emission per ^{241}Amα decay and valid for $\tau_{X^0} < 3 \times 10^{-11}$ s. NODE=S029ANT;LINKAGE=I

[94] 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. NODE=S029ANT;LINKAGE=BB

[95] 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^-. NODE=S029ANT;LINKAGE=H

[96] AVIGNONE 88 looked for the 1115 keV transition C* $\rightarrow$ CuA^0, either from $A^0 \rightarrow 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV. NODE=S029ANT;LINKAGE=G

[97] 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. NODE=S029ANT;LINKAGE=T

[98] 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: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$. NODE=S029ANT;LINKAGE=DX

[99] 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. NODE=S029ANT;LINKAGE=C

[100] 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. NODE=S029ANT;LINKAGE=B

[101] 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. NODE=S029ANT;LINKAGE=AA

[102] 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. NODE=S029ANT;LINKAGE=U

[103] 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. NODE=S029ANT;LINKAGE=S

[104] 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). NODE=S029ANT;LINKAGE=P

[105] 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). NODE=S029ANT;LINKAGE=F

[106] 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. NODE=S029ANT;LINKAGE=K

[107] 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. NODE=S029ANT;LINKAGE=M

[108] ZEHNDER 81 looked for Ba* $\rightarrow$ A^0Ba transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81. NODE=S029ANT;LINKAGE=E

[109] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV. NODE=S029ANT;LINKAGE=A

A^0 (Axion) Limits from Its Electron Coupling

NODE=S029AXE

Limits are for $\tau(A^0 \rightarrow e^+e^-)$.

NODE=S029AXE

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

NODE=S029AXE

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

none 4×10^{-16}–4.5×10^{-12}	90	[110] BROSS	91	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$
		[111] GUO	90	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$
		[112] BJORKEN	88	CALO	$A \rightarrow e^+ e^-$ or 2γ
		[113] BLINOV	88	MD1	$e e \rightarrow e e A^0$ $(A^0 \rightarrow e e)$
none 1×10^{-14}–1×10^{-10}	90	[114] RIORDAN	87	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$
none 1×10^{-14}–1×10^{-11}	90	[115] BROWN	86	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$
none 6×10^{-14}–9×10^{-11}	95	[116] DAVIER	86	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$
none 3×10^{-13}–1×10^{-7}	90	[117] KONAKA	86	BDMP	$e N \rightarrow e A^0 N$ $(A^0 \rightarrow e e)$

[110] 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). NODE=S029AXE;LINKAGE=G

[111] 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). NODE=S029AXE;LINKAGE=F

[112] 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. NODE=S029AXE;LINKAGE=V

[113] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \rightarrow \gamma\gamma)$B($A^0 \rightarrow e^+ e^-$) < 2 eV (CL=90%). NODE=S029AXE;LINKAGE=BL

[114] 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. NODE=S029AXE;LINKAGE=D

[115] 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. NODE=S029AXE;LINKAGE=C

[116] $m_{A^0} = 1.8$ 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. NODE=S029AXE;LINKAGE=A

[117] 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. NODE=S029AXE;LINKAGE=B

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

NODE=S029AEE

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

NODE=S029AEE
NODE=S029AEE

VALUE (10^{-3} eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 1.3	97	[118] HALLIN	92	CNTR	$m_{A^0} = 1.75$–1.88 MeV	
none 0.0016–0.47	90	[119] HENDERSON	92C	CNTR	$m_{A^0} = 1.5$–1.86 MeV	
$<$ 2.0	90	[120] 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	[121] 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	[122] JUDGE	90	CNTR	$m_{A^0} = 1.832$ MeV, elastic	
$<$ 1.9	97	[123] TSERTOS	89	CNTR	$m_{A^0} = 1.82$ MeV	
$<$(10–40)	97	[123] TSERTOS	89	CNTR	$m_{A^0} = 1.51$–1.65 MeV	OCCUR=2
$<$(1–2.5)	97	[123] TSERTOS	89	CNTR	$m_{A^0} = 1.80$–1.86 MeV	OCCUR=3
$<$ 31	95	LORENZ	88	CNTR	$m_{A^0} = 1.646$ MeV	
$<$ 94	95	LORENZ	88	CNTR	$m_{A^0} = 1.726$ MeV	OCCUR=2
$<$ 23	95	LORENZ	88	CNTR	$m_{A^0} = 1.782$ MeV	OCCUR=3
$<$ 19	95	LORENZ	88	CNTR	$m_{A^0} = 1.837$ MeV	OCCUR=4
$<$ 3.8	97	[124] TSERTOS	88	CNTR	$m_{A^0} = 1.832$ MeV	
		[125] VANKLINKEN	88	CNTR		
		[126] MAIER	87	CNTR		
$<$2500	90	MILLS	87	CNTR	$m_{A^0} = 1.8$ MeV	
		[127] VONWIMMER.	87	CNTR		

[118] HALLIN 92 quote limits on lifetime, $8 \times 10^{-14} - 5 \times 10^{-13}$ sec depending on mass, assuming B($A^0 \rightarrow e^+ e^-$) = 100%. They say that TSERTOS 91 overstated their sensitivity by a factor of 3. NODE=S029AEE;LINKAGE=H

[119] HENDERSON 92C exclude axion with lifetime τ_{A^0}=$1.4 \times 10^{-12} - 4.0 \times 10^{-10}$ s, assuming B($A^0 \rightarrow e^+ e^-$)=100%. HENDERSON 92C also exclude a vector boson with τ=$1.4 \times 10^{-12} - 6.0 \times 10^{-10}$ s. NODE=S029AEE;LINKAGE=K

[120] WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming B($A^0 \rightarrow e^+ e^-$)=100%. They say that TSERTOS 89 overestimate the limit by a factor of $\pi/2$. WU 92 also quote a bound for vector boson, $\tau > 8.2 \times 10^{-13}$ s. NODE=S029AEE;LINKAGE=J

[121] WIDMANN 91 bound applies exclusively to the case B($A^0 \rightarrow e^+ e^-$)=1, since the detection efficiency varies substantially as $\Gamma(A^0)_{\text{total}}$ changes. See their Fig. 6. NODE=S029AEE;LINKAGE=I

[122] 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. NODE=S029AEE;LINKAGE=G

[123] See also TSERTOS 88B in references. NODE=S029AEE;LINKAGE=F

[124] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3. NODE=S029AEE;LINKAGE=E

[125] 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. NODE=S029AEE;LINKAGE=D

[126] 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. NODE=S029AEE;LINKAGE=A

[127] VONWIMMERSPERG 87 measured Bhabha scattering for E_{cm} = 1.37–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}}$ = 14.5 ± 6.8 keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88. NODE=S029AEE;LINKAGE=C

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

NODE=S029AEG

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

NODE=S029AEG

NODE=S029AEG

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	OCCUR=2
<12	95	VO	94	CNTR	m_{A^0}=1.7 MeV	OCCUR=3
< 6.6	95	[128] TRZASKA	91	CNTR	m_{A^0} = 1.8 MeV	
< 4.4	95	WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV	
		[129] FOX	89	CNTR		
< 0.11	95	[130] 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	OCCUR=2
<73	97	CONNELL	88	CNTR	m_{A^0} = 1.782 MeV	OCCUR=3
<79	97	CONNELL	88	CNTR	m_{A^0} = 1.832 MeV	OCCUR=4

[128] 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. NODE=S029AEG;LINKAGE=C

[129] 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). NODE=S029AEG;LINKAGE=B

[130] Similar limits are obtained for m_{A^0} = 1.045–1.085 MeV. NODE=S029AEG;LINKAGE=A

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

NODE=S029XEG

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

NODE=S029XEG

NODE=S029XEG

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.2	95	[131] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV	
< 1.0	95	[132] VO	94	CNTR	m_{X^0}=1.1 MeV	OCCUR=2
< 2.5	95	[132] VO	94	CNTR	m_{X^0}=1.4 MeV	OCCUR=3
<120	95	[132] VO	94	CNTR	m_{X^0}=1.7 MeV	OCCUR=4
< 3.8	95	[133] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV	

[131] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying at rest. The precise limits depend on m_{X^0}. See Fig. 2(b) in paper. NODE=S029XEG;LINKAGE=B

[132] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight. NODE=S029XEG;LINKAGE=C

[133] 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. NODE=S029XEG;LINKAGE=A

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

NODE=S029XGE

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

NODE=S029XGE
NODE=S029XGE

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 4.2	90	[134] MITSUI	96	CNTR	γX^0	
$<$ 4	68	[135] SKALSEY	95	CNTR	γX^0	
$<$40	68	[136] SKALSEY	95	RVUE	γX^0	OCCUR=2
$<$ 0.18	90	[137] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$	
$<$ 0.26	90	[138] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$	OCCUR=2
$<$ 0.33	90	[139] ADACHI	94	CNTR	γX^0, $X^0 \rightarrow \gamma\gamma\gamma$	OCCUR=3

[134] 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 $ee X^0$ coupling and hence on the branching ratio B(o-Ps $\rightarrow \gamma\gamma X^0$)$< 6.2 \times 10^{-6}$. The bounds weaken for heavier X^0. NODE=S029XGE;LINKAGE=F

[135] 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. NODE=S029XGE;LINKAGE=A

[136] 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. NODE=S029XGE;LINKAGE=B

[137] 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. NODE=S029XGE;LINKAGE=C

[138] 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. NODE=S029XGE;LINKAGE=D

[139] 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. NODE=S029XGE;LINKAGE=E

Searches for Goldstone Bosons (X^0)

NODE=S029GB

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

NODE=S029GB
NODE=S029GB

VALUE	CL%	DOCUMENT ID		TECN	COMMENT	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[140] LESSA	07	RVUE	Meson, ℓ decays to Majoron	
		[141] DIAZ	98	THEO	$H^0 \rightarrow X^0 X^0$, $A^0 \rightarrow X^0 X^0 X^0$, Majoron	
		[142] BOBRAKOV	91		Electron quasi-magnetic interaction	
$<3.3 \times 10^{-2}$	95	[143] ALBRECHT	90E	ARG	$\tau \rightarrow \mu X^0$. Familon	
$<1.8 \times 10^{-2}$	95	[143] ALBRECHT	90E	ARG	$\tau \rightarrow e X^0$. Familon	OCCUR=2
$<6.4 \times 10^{-9}$	90	[144] ATIYA	90	B787	$K^+ \rightarrow \pi^+ X^0$. Familon	
$<1.1 \times 10^{-9}$	90	[145] BOLTON	88	CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon	
		[146] CHANDA	88	ASTR	Sun, Majoron	
		[147] CHOI	88	ASTR	Majoron, SN 1987A	
$<5 \times 10^{-6}$	90	[148] PICCIOTTO	88	CNTR	$\pi \rightarrow e\nu X^0$, Majoron	
$<1.3 \times 10^{-9}$	90	[149] GOLDMAN	87	CNTR	$\mu \rightarrow e\gamma X^0$. Familon	
$<3 \times 10^{-4}$	90	[150] BRYMAN	86B	RVUE	$\mu \rightarrow e X^0$. Familon	
$<1 \times 10^{-10}$	90	[151] EICHLER	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon	
$<2.6 \times 10^{-6}$	90	[152] JODIDIO	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon	
		[153] BALTRUSAIT...	85	MRK3	$\tau \rightarrow \ell X^0$. Familon	
		[154] DICUS	83	COSM	$\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$	

[140] 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 $g_{\alpha\beta}$ ($\alpha,\beta=e,\mu,\tau$). Their best limits are $|g_{e\alpha}|^2 < 5.5 \times 10^{-6}$, $|g_{\mu\alpha}|^2 < 4.5 \times 10^{-5}$, $|g_{\tau\alpha}|^2 < 5.5 \times 10^{-2}$ at CL = 90%. NODE=S029GB;LINKAGE=LE

[141] 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 $H^0 \rightarrow X^0 X^0$. NODE=S029GB;LINKAGE=J

[142] 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 $x_e (G_F/8\pi\sqrt{2})^{1/2}$. NODE=S029GB;LINKAGE=A2

[143] 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. NODE=S029GB;LINKAGE=I

[144] 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. NODE=S029GB;LINKAGE=H

[145] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling. NODE=S029GB;LINKAGE=G

[146] 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. NODE=S029GB;LINKAGE=Z

[147] 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 $(\Sigma h_i^4)^{1/4}$. NODE=S029GB;LINKAGE=E

[148] 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. NODE=S029GB;LINKAGE=F

[149] 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. NODE=S029GB;LINKAGE=A

[150] 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. NODE=S029GB;LINKAGE=B1

[151] 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. NODE=S029GB;LINKAGE=T

[152] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F) \, \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$. NODE=S029GB;LINKAGE=D

[153] 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. NODE=S029GB;LINKAGE=C

[154] 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). NODE=S029GB;LINKAGE=A1

Majoron Searches in Neutrinoless Double β Decay

NODE=S029MT

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission.

NODE=S029MT

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.

NODE=S029MT

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID		
>7200	**90**	**^{128}Te**		**CNTR**	[155] BERNATOW...	92	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 27	90	^{100}Mo	$0\nu1\chi$	NEMO-3	[156] ARNOLD	06	
> 15	90	^{82}Se	$0\nu1\chi$	NEMO-3	[157] ARNOLD	06	OCCUR=2
> 14	90	^{100}Mo	$0\nu1\chi$	NEMO-3	[158] ARNOLD	04	
> 12	90	^{82}Se	$0\nu1\chi$	NEMO-3	[159] ARNOLD	04	OCCUR=2
> 2.2	90	^{130}Te	$0\nu1\chi$	Cryog. det.	[160] ARNABOLDI	03	
> 0.9	90	^{130}Te	$0\nu2\chi$	Cryog. det.	[161] ARNABOLDI	03	OCCUR=2
> 8	90	^{116}Cd	$0\nu1\chi$	$CdWO_4$ scint.	[162] DANEVICH	03	
> 0.8	90	^{116}Cd	$0\nu2\chi$	$CdWO_4$ scint.	[163] DANEVICH	03	OCCUR=2
> 500	90	^{136}Xe	$0\nu\chi$	Liquid Xe Scint.	[164] BERNABEI	02D	
> 5.8	90	^{100}Mo	$0\nu\chi$	ELEGANT V	[165] FUSHIMI	02	
> 0.32	90	^{100}Mo	$0\nu\chi$	Liq. Ar ioniz.	[166] ASHITKOV	01	
> 0.0035	90	^{160}Gd	$0\nu\chi$	$^{160}Gd_2SiO_5$:Ce	[167] DANEVICH	01	
> 0.013	90	^{160}Gd	$0\nu2\chi$	$^{160}Gd_2SiO_5$:Ce	[168] DANEVICH	01	OCCUR=2
> 2.3	90	^{82}Se	$0\nu\chi$	NEMO 2	[169] ARNOLD	00	
> 0.31	90	^{96}Zr	$0\nu\chi$	NEMO 2	[170] ARNOLD	00	OCCUR=2
> 0.63	90	^{82}Se	$0\nu2\chi$	NEMO 2	[171] ARNOLD	00	OCCUR=5
> 0.063	90	^{96}Zr	$0\nu2\chi$	NEMO 2	[171] ARNOLD	00	OCCUR=6

>	0.16	90	^{100}Mo	$0\nu 2\chi$	NEMO 2	[171] ARNOLD	00	OCCUR=7
>	2.4	90	^{82}Se	$0\nu\chi$	NEMO 2	[172] ARNOLD	98	
>	7.2	90	^{136}Xe	$0\nu 2\chi$	TPC	[173] LUESCHER	98	
>	7.91	90	^{76}Ge		SPEC	[174] GUENTHER	96	
>	17	90	^{76}Ge		CNTR	BECK	93	

[155] BERNATOWICZ 92 studied double-β decays of ^{128}Te and ^{130}Te, and found the ratio $\tau(^{130}\text{Te})/\tau(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$ in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of ^{128}Te of $(7.7 \pm 0.4) \times 10^{24}$ year. We calculated 90% CL limit as $(7.7–1.28 \times 0.4=7.2) \times 10^{24}$. NODE=S029MT;LINKAGE=A

[156] 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. Supersedes ARNOLD 04. NODE=S029MT;LINKAGE=AM

[157] 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. NODE=S029MT;LINKAGE=AS

[158] 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. NODE=S029MT;LINKAGE=A1

[159] 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. NODE=S029MT;LINKAGE=A2

[160] 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. NODE=S029MT;LINKAGE=RO

[161] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. NODE=S029MT;LINKAGE=RP

[162] 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. NODE=S029MT;LINKAGE=VI

[163] Limit for the $0\nu 2\chi$ decay of ^{116}Cd. Supersedes DANEVICH 00. NODE=S029MT;LINKAGE=VJ

[164] 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. NODE=S029MT;LINKAGE=D5

[165] 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) $\times 10^{-5}$. NODE=S029MT;LINKAGE=FM

[166] ASHITKOV 01 result for $0\nu\chi$ of ^{100}Mo is less stringent than ARNOLD 00. NODE=S029MT;LINKAGE=SH

[167] DANEVICH 01 obtain limit for the $0\nu\chi$ decay with Majoron emission of ^{160}Gd using Gd_2SiO_5:Ce crystal scintillators. NODE=S029MT;LINKAGE=TH

[168] DANEVICH 01 obtain limit for the $0\nu 2\chi$ decay with 2 Majoron emission of ^{160}Gd. NODE=S029MT;LINKAGE=TI

[169] 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. NODE=S029MT;LINKAGE=K1

[170] Using ^{96}Zr source: $\langle g_{\nu\chi}\rangle < 2.6 \times 10^{-4}$. Matrix element from ARNOLD 99. NODE=S029MT;LINKAGE=K2

[171] ARNOLD 00 reports limit for the $0\nu 2\chi$ decay with two Majoron emission derived from tracking calorimeter NEMO 2. NODE=S029MT;LINKAGE=K5

[172] 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. NODE=S029MT;LINKAGE=RN

[173] LUESCHER 98 report a limit for the 0ν decay with Majoron emission of ^{136}Xe using Xe TPC. This result is more stringent than BARABASH 89. Using the matrix elements of ENGEL 88, they obtain a limit on $\langle g_{\nu\chi}\rangle$ of 2.0×10^{-4}. NODE=S029MT;LINKAGE=LT

[174] See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models. NODE=S029MT;LINKAGE=C

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

NODE=S029IAA

$v_1 = v_2$ 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. NODE=S029IAA

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

NODE=S029IAA

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

<334	95	[175]	KEKEZ	09	HPGE	K, solar axions	
$<$ 1.02	95	[176]	HANNESTAD	08	COSM	K, hot dark matter	
$<$ 1.2	95	[177]	HANNESTAD	07	COSM	K, hot dark matter	
$<$ 0.42	95	[178]	MELCHIORRI	07A	COSM	K, hot dark matter	
$<$ 1.05	95	[179]	HANNESTAD	05A	COSM	K, hot dark matter	
3 to 20		[180]	MOROI	98	COSM	K, hot dark matter	
$<$ 0.007		[181]	BORISOV	97	ASTR	D, neutron star	
$<$ 4		[182]	KACHELRIESS	97	ASTR	D, neutron star cooling	
$<(0.5\text{–}6) \times 10^{-3}$		[183]	KEIL	97	ASTR	SN 1987A	
$<$ 0.018		[184]	RAFFELT	95	ASTR	D, red giant	
$<$ 0.010		[185]	ALTHERR	94	ASTR	D, red giants, white dwarfs	
		[186]	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		[187]	BERSHADY	91	ASTR	D, K, intergalactic light	
$<$ 10		[188]	KIM	91C	COSM	D, K, mass density of the universe, supersymmetry	
		[189]	RAFFELT	91B	ASTR	D,K, SN 1987A	
$<$ 1 $\times 10^{-3}$		[190]	RESSELL	91	ASTR	K, intergalactic light	
none 10^{-3}–3			BURROWS	90	ASTR	D,K, SN 1987A	
		[191]	ENGEL	90	ASTR	D,K, SN 1987A	
$<$ 0.02		[192]	RAFFELT	90D	ASTR	D, red giant	
$<$ 1 $\times 10^{-3}$		[193]	BURROWS	89	ASTR	D,K, SN 1987A	
$<(1.4\text{–}10) \times 10^{-3}$		[194]	ERICSON	89	ASTR	D,K, SN 1987A	
$<$ 3.6 $\times 10^{-4}$		[195]	MAYLE	89	ASTR	D,K, SN 1987A	
$<$ 12			CHANDA	88	ASTR	D, Sun	
$<$ 1 $\times 10^{-3}$			RAFFELT	88	ASTR	D,K, SN 1987A	
		[196]	RAFFELT	88B	ASTR	red giant	
$<$ 0.07			FRIEMAN	87	ASTR	D, red giant	
$<$ 0.7		[197]	RAFFELT	87	ASTR	K, red giant	
$<$ 2–5			TURNER	87	COSM	K, thermal production	
$<$ 0.01		[198]	DEARBORN	86	ASTR	D, red giant	
$<$ 0.06			RAFFELT	86	ASTR	D, red giant	
$<$ 0.7		[199]	RAFFELT	86	ASTR	K, red giant	OCCUR=2
$<$ 0.03			RAFFELT	86B	ASTR	D, white dwarf	
$<$ 1		[200]	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		[201]	FUKUGITA	82	ASTR	D, stellar cooling	
$<$ 0.07			FUKUGITA	82B	ASTR	D, red giant	

[175] KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used. NODE=S029IAA;LINKAGE=KE

[176] This is an update of HANNESTAD 07 including 5 years of WMAP data. NODE=S029IAA;LINKAGE=AN

[177] 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. NODE=S029IAA;LINKAGE=HN

[178] 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. NODE=S029IAA;LINKAGE=ME

[179] 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. NODE=S029IAA;LINKAGE=HA

[180] 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. NODE=S029IAA;LINKAGE=T

[181] 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. NODE=S029IAA;LINKAGE=P

[182] 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. NODE=S029IAA;LINKAGE=Q

[183] 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. NODE=S029IAA;LINKAGE=R

[184] 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). NODE=S029IAA;LINKAGE=F

[185] ALTHERR 94 bound is on the axion-electron coupling $g_{ae} < 1.5 \times 10^{-13}$, from energy loss via axion emission. NODE=S029IAA;LINKAGE=K

[186] 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. NODE=S029IAA;LINKAGE=U

[187] 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. NODE=S029IAA;LINKAGE=AB

[188] 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. NODE=S029IAA;LINKAGE=O

[189] RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes. NODE=S029IAA;LINKAGE=N

[190] RESSELL 91 uses absence of any intracluster line emission to set limit. NODE=S029IAA;LINKAGE=M

[191] 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 $g_{AN} \sim 10^{-6}$. NODE=S029IAA;LINKAGE=L

[192] RAFFELT 90D is a re-analysis of DEARBORN 86. NODE=S029IAA;LINKAGE=J

[193] The region $m_{A^0} \gtrsim 2$ eV is also allowed. NODE=S029IAA;LINKAGE=AA

[194] 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. NODE=S029IAA;LINKAGE=I

[195] 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. NODE=S029IAA;LINKAGE=A

[196] 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. NODE=S029IAA;LINKAGE=H

[197] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV^{-1}. NODE=S029IAA;LINKAGE=B

[198] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV^{-1}. NODE=S029IAA;LINKAGE=C

[199] 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. NODE=S029IAA;LINKAGE=G

[200] KAPLAN 85 says $m_{A^0} < 23$ eV is allowed for a special choice of model parameters. NODE=S029IAA;LINKAGE=D

[201] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV^{-1}. NODE=S029IAA;LINKAGE=E

Search for Relic Invisible Axions

NODE=S029AXI

Limits are for $[G_{A\gamma\gamma}/m_{A^0}]^2\rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\mathrm{int}} = \frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\widetilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, and ρ_A is the axion energy density near the earth. NODE=S029AXI

NODE=S029AXI

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.9 \times 10^{-43}$	97.7	[202] DUFFY	06	CNTR	$m_{A^0} = 1.98$–2.17×10^{-6} eV
$<5.5 \times 10^{-43}$	90	[203] ASZTALOS	04	CNTR	$m_{A^0} = 1.9$–3.3×10^{-6} eV
		[204] KIM	98	THEO	
$<2 \times 10^{-41}$		[205] HAGMANN	90	CNTR	$m_{A^0} = (5.4$–$5.9)10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[206] WUENSCH	89	CNTR	$m_{A^0} = (4.5$–$10.2)10^{-6}$ eV
$<2 \times 10^{-41}$	95	[206] WUENSCH	89	CNTR	$m_{A^0} = (11.3$–$16.3)10^{-6}$ eV

OCCUR=2

[202] 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. NODE=DUFFY;LINKAGE=DU

[203] 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. NODE=S029AXI;LINKAGE=AS

[204] 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. NODE=S029AXI;LINKAGE=D

[205] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83. NODE=S029AXI;LINKAGE=B

[206] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagnetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ 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. NODE=S029AXI;LINKAGE=A

Invisible A^0 (Axion) Limits from Photon Coupling

NODE=S029IAG

Limits are for the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$. Related limits from astrophysics can be found in the "Invisible A^0 (Axion) Mass Limits from Astrophysics and Cosmology" section. NODE=S029IAG

NODE=S029IAG

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.2–2.8×10^{-10}	95	[207] ARIK	09	CAST	$m_{A^0} = 0.02$–0.39 eV	
$<3.5 \times 10^{-7}$	99.7	[208] CHOU	08		$m_{A^0} < 0.5$ meV	
$<1.1 \times 10^{-6}$	99.7	[209] FOUCHE	08		$m_{A^0} < 1$ meV	
< 5.6–13.4×10^{-10}	95	[210] INOUE	08		$m_{A^0} = 0.84$–1.00 eV	
$<5 \times 10^{-7}$		[211] ZAVATTINI	08		$m_{A^0} < 1$ meV	
$<8.8 \times 10^{-11}$	95	[212] ANDRIAMON...	07	CAST	$m_{A^0} < 0.02$ eV	
$<1.25 \times 10^{-6}$	95	[213] ROBILLIARD	07		$m_{A^0} < 1$ meV	
2–5×10^{-6}		[214] ZAVATTINI	06		$m_{A^0} = 1$–1.5 meV	
$<1.1 \times 10^{-9}$	95	[215] INOUE	02		$m_{A^0} = 0.05$–0.27 eV	
$<2.78 \times 10^{-9}$	95	[216] MORALES	02B		$m_{A^0} <1$ keV	
$<1.7 \times 10^{-9}$	90	[217] BERNABEI	01B		$m_{A^0} <100$ eV	
$<1.5 \times 10^{-4}$	90	[218] ASTIER	00B	NOMD	$m_{A^0} <40$ eV	
		[219] MASSO	00	THEO	induced γ coupling	
$<2.7 \times 10^{-9}$	95	[220] AVIGNONE	98	SLAX	$m_{A^0} < 1$ keV	
$<6.0 \times 10^{-10}$	95	[221] MORIYAMA	98		$m_{A^0} < 0.03$ eV	
$<3.6 \times 10^{-7}$	95	[222] CAMERON	93		$m_{A^0} < 10^{-3}$ eV, optical rotation	
$<6.7 \times 10^{-7}$	95	[223] CAMERON	93		$m_{A^0} < 10^{-3}$ eV, photon regeneration	OCCUR=2
$<3.6 \times 10^{-9}$	99.7	[224] LAZARUS	92		$m_{A^0} < 0.03$ eV	
$<7.7 \times 10^{-9}$	99.7	[224] LAZARUS	92		$m_{A^0} = 0.03$–0.11 eV	OCCUR=2
$<7.7 \times 10^{-7}$	99	[225] RUOSO	92		$m_{A^0} < 10^{-3}$ eV	
$<2.5 \times 10^{-6}$		[226] SEMERTZIDIS	90		$m_{A^0} < 7 \times 10^{-4}$ eV	

[207] 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. NODE=S029IAG;LINKAGE=AR

[208] CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 3 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06. NODE=S029IAG;LINKAGE=HO

[209] FOUCHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits. NODE=S029IAG;LINKAGE=FO

[210] 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. NODE=S029IAG;LINKAGE=IO

[211] 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. NODE=S029IAG;LINKAGE=ZV

[212] ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. Supersedes ZIOUTAS 05. NODE=S029IAG;LINKAGE=AN

[213] 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%. NODE=S029IAG;LINKAGE=RO

[214] 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. NODE=S029IAG;LINKAGE=ZA

[215] INOUE 02 looked for Primakoff conversion of solar axions in 4T superconducting magnet into X ray. NODE=S029IAG;LINKAGE=IN

[216] MORALES 02B looked for the coherent conversion of solar axions to photons via the Primakoff effect in Germanium detector. NODE=S029IAG;LINKAGE=ML

[217] BERNABEI 01B looked for Primakoff coherent conversion of solar axions into photons via Bragg scattering in NaI crystal in DAMA dark matter detector. NODE=S029IAG;LINKAGE=BB

[218] 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. NODE=S029IAG;LINKAGE=GB

[219] 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 $g_p \overline{p} \gamma_5 p \phi_A$. NODE=S029IAG;LINKAGE=MS

[220] AVIGNONE 98 result is based on the coherent conversion of solar axions to photons via the Primakoff effect in a single crystal germanium detector. NODE=S029IAG;LINKAGE=FT

[221] Based on the conversion of solar axions to X-rays in a strong laboratory magnetic field. NODE=S029IAG;LINKAGE=D

[222] Experiment based on proposal by MAIANI 86. NODE=S029IAG;LINKAGE=C1

[223] Experiment based on proposal by VANBIBBER 87. NODE=S029IAG;LINKAGE=C2

[224] LAZARUS 92 experiment is based on proposal found in VANBIBBER 89. NODE=S029IAG;LINKAGE=AA

[225] RUOSO 92 experiment is based on the proposal by VANBIBBER 87. NODE=S029IAG;LINKAGE=B

[226] 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}. NODE=S029IAG;LINKAGE=A

Limit on Invisible A^0 (Axion) Electron Coupling

NODE=S029AEX

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 $\boldsymbol{n}$=$\boldsymbol{r}/r$. NODE=S029AEX

The limits below apply to invisible axion of $m_A \leq 10^{-6}$ eV. NODE=S029AEX

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.3 \times 10^{-5}$	66	[227] NI	94		Induced magnetism
$<6.7 \times 10^{-5}$	66	[227] CHUI	93		Induced magnetism
$<3.6 \times 10^{-4}$	66	[228] PAN	92		Torsion pendulum
$<2.7 \times 10^{-5}$	95	[227] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[229] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[228] RITTER	90		Torsion pendulum
$<6.6 \times 10^{-5}$	95	[227] VOROBYOV	88		Induced magnetism

[227] 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. NODE=S029AEX;LINKAGE=B4

[228] 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. NODE=S029AEX;LINKAGE=D4

[229] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance. NODE=S029AEX;LINKAGE=A4

Invisible A^0 (Axion) Limits from Nucleon Coupling

NODE=S029IAN

Limits are for the axion mass in eV. NODE=S029IAN

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1.39 \times 10^4$	90	[230] BELLI	08A	CNTR	Solar axion
		[231] BELLINI	08	CNTR	Solar axion
		[232] ADELBERGER	07		Test of Newton's law
<360	90	[233] DERBIN	07	CNTR	Solar axion
<216	95	[234] NAMBA	07	CNTR	Solar axion
$< 1.6 \times 10^4$	90	[235] DERBIN	05	CNTR	Solar axion
<400	95	[236] LJUBICIC	04	CNTR	Solar axion
$< 3.2 \times 10^4$	95	[237] KRCMAR	01	CNTR	Solar axion
<745	95	[238] KRCMAR	98	CNTR	Solar axion

NODE=S029IAN

[230] BELLI 08A is analogous to KRCMAR 01 and DERBIN 05. NODE=S029IAN;LINKAGE=BL

[231] 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. NODE=S029IAN;LINKAGE=BE

[232] 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. NODE=S029IAN;LINKAGE=AD

[233] DERBIN 07 is analogous to KRCMAR 98. NODE=S029IAN;LINKAGE=DR

[234] NAMBA 07 is analogous to KRCMAR 98. NODE=S029IAN;LINKAGE=NA

[235] DERBIN 05 bound is based on the same principle as KRCMAR 01. NODE=S029IAN;LINKAGE=DE

[236] LJUBICIC 04 looked for ejection of K-shell electrons by the axioelectric effect of 14.4 keV solar axions in a Germanium detector. The limit assumes the hadronic axion model and the same solar axion flux as in KRCMAR 98 and KRCMAR 01. NODE=S029IAN;LINKAGE=LJ

[237] KRCMAR 01 looked for solar axions emitted by the M1 transition of ^{7}Li after the electron capture by ^{7}Be and the emission of 384 keV line neutrino, using their resonant capture on ^{7}Li in the laboratory. The mass bound assumes $m_u/m_d = 0.56$ and the flavor-singlet axial-vector matrix element S=0.4. NODE=S029IAN;LINKAGE=B

[238] KRCMAR 98 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, following MORIYAMA 95B. The mass bound assumes m_u/m_d=0.56 and the flavor-singlet axial-vector matrix element $S=3F-D\simeq 0.5$. NODE=S029IAN;LINKAGE=A

Axion Limits from T-violating Medium-Range Forces

NODE=S029IAT

The limit is for the coupling g in a T-violating potential between nucleons or nucleon and electron of the form $V = \frac{g\hbar^2}{8\pi m_p}(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\,(\frac{1}{r^2}+\frac{m_A c}{\hbar r})\; e^{-m_A c r/\hbar}$ NODE=S029IAT

NODE=S029IAT

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[239] BAESSLER	07		ultracold neutrons
	[240] HECKEL	06		torsion pendulum
	[241] NI	99		paramagnetic Tb F_3
	[242] POSPELOV	98	THEO	neutron EDM
	[243] YOUDIN	96		
	[244] RITTER	93		torsion pendulum
	[245] VENEMA	92		nuclear spin-precession frequencies
	[246] WINELAND	91	NMR	

[239] 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. NODE=S029IAT;LINKAGE=BA

[240] 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. NODE=S029IAT;LINKAGE=HE

[241] NI 99 searched for a T-violating medium-range force acting on paramagnetic Tb F_3 salt. See their Fig. 1 for the result. NODE=S029IAT;LINKAGE=NI

[242] 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$/\lambda_A$), where λ_A=$\hbar/m_A c$. NODE=S029IAT;LINKAGE=B

[243] 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. NODE=S029IAT;LINKAGE=A

[244] RITTER 93 studied the influence of bulk mass with polarized electons on an unpolarized torsion pendulum, providing limits in the interaction range from 1 to 100 cm. NODE=S029IAT;LINKAGE=RI

[245] VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of ^{199}Hg and ^{201}Hg atoms. NODE=S029IAT;LINKAGE=VE

[246] 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. NODE=S029IAT;LINKAGE=WE

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Also		PRL 62 2644 (erratum)	F.W.N. de Boer, R. van Dantzig	(ANIK)	REFID=40968
Also		PRL 62 2638	D.H. Perkins	(OXF)	REFID=40970
Also		PRL 62 2639	F.W.N. de Boer, R. van Dantzig	(ANIK)	REFID=40969
DEBOER	88C	JPG 14 L131	F.W.N. de Boer *et al.*	(LOUV)	REFID=41066
DOEHNER	88	PR D38 2722	J. Dohner *et al.*	(HEIDP, ANL, ILLG)	REFID=40687
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TSERTOS	88	PL B207 273	A. Tsertos *et al.*	(GSI, ILLG)	REFID=41074
TSERTOS	88B	ZPHY A331 103	A. Tsertos *et al.*	(GSI, ILLG)	REFID=41075
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DRUZHININ	87	ZPHY C37 1	V.P. Druzhinin *et al.*	(NOVO)	REFID=40448
FRIEMAN	87	PR D36 2201	J.A. Frieman, S. Dimopoulos, M.S. Turner	(SLAC+)	REFID=40878
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