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

AXIONS AND OTHER VERY LIGHT BOSONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. These have been proposed to solve a variety of mostly theoretical concerns. Typical examples are pseudo-Goldstone bosons like axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries.

In QCD, SU(3) gauge invariance does not forbid a term $\theta(g_s^2/32\pi^2)F^{\mu\nu a}\widetilde{F}^a_{\mu\nu}$ in Lagrangian. However, CP invariance is broken if $\theta \neq 0$ or π, and the parameter θ has to be small $\lesssim 10^{-9}$ in order not to generate too large elecric dilopole moment of neutron. This is called strong CP problem. Peccei-Quinn symmetry gives a natural solution to the strong CP problem. The axion mass and its coupling to stable particles are inversely proportional to the scale of Peccei-Quinn symmetry breaking, f_A. The original axion model [1,5] assumed $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and had two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings were completely fixed in terms of one parameter, the ratio of the vacuum expectation values of the two Higgs fields. The result of extensive experimental searches for such an axion have been negative [6].

Observation of a narrow-peak structure in positron spectra from heavy ion collisions [7] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A \sim v$, but drop the constraints of tree-level flavor conservation, were proposed [8]. Extensive searches for this particle, $A^0(1.8$ MeV), ended up with another negative result [9].

Another way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [10,11]. See the note on Invisible Axions later in this section.

Familons arise when there is a global horizontal symmetry (a symmetry which interchanges different generations)

broken spontaneously. They could be either scalars or pseudoscalars. An SU(3) horizontal symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger horizontal symmetries with separate groups of left-handed and right-handed fields, one also has pseudo-scalar familons. Some of them have flavor-off-diagonal couplings such as $\partial_\mu \phi_F \overline{d}\gamma^\mu s/F$ or $\partial_\mu \phi_F \overline{e}\gamma^\mu \mu/F$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor-changing processes. For instance, $\mathrm{B}(K^+ \to \pi^+ \phi_F) < 1.7 \times 10^{-9}$ [12] gives $F_{K\pi} > 1.3 \times 10^{11}$ GeV [2].

If there is a global lepton number symmetry and if it breaks spontaneously, there is a Majoron. The triplet Majoron model [4] has a weak-triplet Higgs boson, and the Majoron couples to Z. The original version is now excluded by the invisible Z decay width. The model would remain viable if there were an additional singlet Higgs boson and if the Majoron were mainly a singlet [13]. In the singlet Majoron model [3], lepton number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos that acquire Majorana masses. The left-handed neutrino masses are generated by a "seesaw" mechanism [14]. The scale of lepton number breaking can be much higher than the electroweak scale in this case. Astrophysical constraints require the decay constant to be $\gtrsim 10^9$ GeV [15].

Other light bosons (scalar, pseudoscalar or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see [16].

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

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

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

[1] Lower bound from 5.5 MeV γ-ray line from the sun.
[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

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

Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6 \times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\pi^0 \to \gamma X^0$, m_{X^0}=65–125 MeV

<6	$\times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\eta \to \gamma X^0$, m_{X^0}=200–525 MeV	
<0.007		90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=25 MeV	
<0.002		90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=100 MeV	
<1.7	$\times 10^{-9}$	90		[5] ATIYA	93	B787	$K^+ \to \pi^+ A^0$	
<2	$\times 10^{-7}$	90		[6] ATIYA	93B	B787	$K^+ \to \pi^+ A^0$	
<3	$\times 10^{-13}$			[7] NG	93	COSM	$\pi^0 \to \gamma X^0$	
<1.1	$\times 10^{-8}$	90		[8] ALLIEGRO	92	SPEC	$K^+ \to \pi^+ A^0$ $(A^0 \to e^+ e^-)$	
<5	$\times 10^{-4}$	90		[9] ATIYA	92	B787	$\pi^0 \to \gamma X^0$	
<4	$\times 10^{-6}$	90		[10] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$, $X^0 \to e^+ e^-$, m_{X^0}= 100 MeV	
<1	$\times 10^{-7}$	90		[11] ATIYA	90B	B787	$K^+ \to \pi^+ A^0$, $(A^0 \to \gamma\gamma)$	
<1.3	$\times 10^{-8}$	90		[12] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ $(A^0 \to e^+ e^-)$	
<1	$\times 10^{-9}$	90	0	[13] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$	
<2	$\times 10^{-5}$	90		[14] YAMAZAKI	84	SPEC	For 160<m<260 MeV	
$<(1.5$–$4) \times 10^{-6}$		90		[14] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV	
			0	[15] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$	
			0	[16] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$	
				[17] ZHITNITSKII	79		Heavy axion	

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

[4] The MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of X^0 decay modes. It applies to $\tau(X^0) > 10^{-23}$ sec.

[5] ATIYA 93 looked for a peak in missing mass distribution. The limit is for massless stable A^0 particles and extends to m_{A^0}=80 MeV at the same level. See paper for dependence on finite lifetime.

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

[7] NG 93 studied the production of X^0 via $\gamma\gamma \to \pi^0 \to \gamma X^0$ in the early universe at $T \simeq 1$ MeV. The bound on extra neutrinos from nucleosyntheis $\Delta N_\nu < 0.3$ (WALKER 91) is employed. It applies to $m_{X^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier X^0.

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

[9] ATIYA 92 looked for a peak in missing mass distribution. The limit applies to m_{X^0}=0–130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires X^0 to be a vector particle.

[10] MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}$–10^{-11} sec. Limits between 2×10^{-4} and 4×10^{-6} are obtained for m_{X^0} = 25–120 MeV. Angular momentum conservation requires that X^0 has spin ≥ 1.

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

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

[13] 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.

[14] 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.

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

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

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

A^0 (Axion) Searches in Quarkonium Decays

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

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.3\times10^{-5}$	90		[18] BALEST	95	CLEO	$\Upsilon(1S)\to A^0\gamma$
$<4.0\times10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S)\to A^0\gamma$
			[19] ANTREASYAN	90C	RVUE	
$<5\times10^{-5}$	90		[20] DRUZHININ	87	ND	$\phi\to A^0\gamma$ $(A^0\to e^+e^-)$
$<2\times10^{-3}$	90		[21] DRUZHININ	87	ND	$\phi\to A^0\gamma$ $(A^0\to\gamma\gamma)$
$<7\times10^{-6}$	90		[22] DRUZHININ	87	ND	$\phi\to A^0\gamma$ $(A^0\to$ missing)
$<3.1\times10^{-4}$	90	0	[23] ALBRECHT	86D	ARG	$\Upsilon(1S)\to A^0\gamma$ $(A^0\to e^+e^-)$
$<4\times10^{-4}$	90	0	[23] ALBRECHT	86D	ARG	$\Upsilon(1S)\to A^0\gamma$ $(A^0\to\mu^+\mu^-,$ $\pi^+\pi^-, K^+K^-)$
$<8\times10^{-4}$	90	1	[24] ALBRECHT	86D	ARG	$\Upsilon(1S)\to A^0\gamma$
$<1.3\times10^{-3}$	90	0	[25] ALBRECHT	86D	ARG	$\Upsilon(1S)\to A^0\gamma$ $(A^0\to e^+e^-,\gamma\gamma)$
$<2.\times10^{-3}$	90		[26] BOWCOCK	86	CLEO	$\Upsilon(2S)\to\Upsilon(1S)\to A^0$
$<5.\times10^{-3}$	90		[27] MAGERAS	86	CUSB	$\Upsilon(1S)\to A^0\gamma$
$<3.\times10^{-4}$	90		[28] ALAM	83	CLEO	$\Upsilon(1S)\to A^0\gamma$
$<9.1\times10^{-4}$	90		[29] NICZYPORUK	83	LENA	$\Upsilon(1S)\to A^0\gamma$
$<1.4\times10^{-5}$	90		[30] EDWARDS	82	CBAL	$J/\psi\to A^0\gamma$
$<3.5\times10^{-4}$	90		[31] SIVERTZ	82	CUSB	$\Upsilon(1S)\to A^0\gamma$
$<1.2\times10^{-4}$	90		[31] SIVERTZ	82	CUSB	$\Upsilon(3S)\to A^0\gamma$

[18] 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.

[19] 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 $5\times10^{-5}<x<260$. 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 $0.00075<x<44$.

[20] The first DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0}<3\times10^{-13}$ s/MeV and $m_{A^0}<20$ MeV.

[21] The second DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0}<5\times10^{-13}$ s/MeV and $m_{A^0}<20$ MeV.

[22] The third DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0}>7\times10^{-12}$ s/MeV and $m_{A^0}<200$ MeV.

[23] $\tau_{A^0}<1\times10^{-13}$s and $m_{A^0}<1.5$ GeV. Applies for $A^0\to\gamma\gamma$ when $m_{A^0}<100$ MeV.

[24] $\tau_{A^0}>1\times10^{-7}$s.

[25] Independent of τ_{A^0}.

[26] 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 $\tau_{A^0}\sim2.\times10^{-12}$s, where the limit is the worst. The same limit $2.\times10^{-3}$ 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.

[27] 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 $\tau(A^0)\sim4.\times10^{-13}$s where the limit is the worst.

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

[29] 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.

[30] EDWARDS 82 looked for $J/\psi\to\gamma A^0$ decays by looking for events with a single γ [of energy $\sim1/2$ the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

[31] 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).

A^0 (Axion) Searches in Positronium Decays

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

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

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

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

[34] 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.

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

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

[37] 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.

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

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

[40] 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.

[41] 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.

[42] 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 $x < 1$.

[43] 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.

[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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, 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.

[49] 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.

[50] FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ's are not at variance with LAMPF upper limit of 450 γ's. Derived from LAMPF limit that $[d\sigma(A^0)/d\omega$ at $90°]\, m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[51] 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.

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

[53] 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.

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

[55] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with η-A^0 mixing gives $m_{A^0} = 250 \pm 25$ keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[56] KIM 81 analyzed 8 candidates for $A^0 \to 2\gamma$ 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.

[57] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \to e^+e^-$ 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 $m_{A^0} < 2m_{e^-}$.

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

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

[60] 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.

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

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

[63] BELLOTTI 78 first value comes from search for $A^0 \to e^+e^-$. Second value comes from search for $A^0 \to 2\gamma$, 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.

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

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

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

[67] 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. • • •				
	[68] ALTMANN	95	CNTR	Reactor; $A^0 \to e^+e^-$
	[69] KETOV	86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[70] KOCH	86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[71] DATAR	82	CNTR	Light water reactor
	[72] VUILLEUMIER	81	CNTR	Reactor, $A^0 \to 2\gamma$

[68] 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 $\omega(A^0)/\omega(\gamma) \times B(A^0 \to e^+e^-) < 10^{-16}$ 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.

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

[70] KOCH 86 searched for $A^0 \to \gamma\gamma$ 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.

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

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

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

Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 5.5 \times 10^{-10}$	95		[73] TSUNODA	95	CNTR	^{252}Cf fission, $A^0 \to ee$
$< 1.2 \times 10^{-6}$	95		[74] MINOWA	93	CNTR	^{139}La$^* \to {}^{139}$LaA^0
$< 2 \times 10^{-4}$	90		[75] HICKS	92	CNTR	^{35}S decay, $A^0 \to \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[76] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4\text{–}10) \times 10^{-3}$	95		[77] DEBOER	90	CNTR	^{8}Be$^* \to {}^8$BeA^0, $A^0 \to e^+e^-$
$<(0.2\text{–}1) \times 10^{-3}$	90		[78] BINI	89	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+e^-$
			[79] AVIGNONE	88	CNTR	Cu$^* \to$ CuA^0 ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[80] DATAR	88	CNTR	^{12}C$^* \to {}^{12}$CA^0, $A^0 \to e^+e^-$
$< 5 \times 10^{-3}$	90		[81] DEBOER	88C	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+e^-$
$< 3.4 \times 10^{-5}$	95		[82] DOEHNER	88	SPEC	^{2}H*, $A^0 \to e^+e^-$
$< 4 \times 10^{-4}$	95		[83] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[83] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[84] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90		[84] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[84] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[85] SAVAGE	86B	CNTR	^{14}N*
			[86] ANANEV	85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[87] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \to 2\gamma$
			[88] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[89] LEHMANN	82	CNTR	Cu$^* \to$ CuA^0 ($A^0 \to 2\gamma$)
		0	[90] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.
		0	[91] ZEHNDER	81	CNTR	Ba$^* \to$ BaA^0 ($A^0 \to 2\gamma$)
			[92] CALAPRICE	79		Carbon

[73] 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.

[74] 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.

[75] HICKS 92 bound is applicable for $\tau_{X^0} < 4\times10^{-11}$ sec.

[76] The ASANUMA 90 limit is for the branching fraction of X^0 emission per ^{241}Am α decay and valid for $\tau_{X^0} < 3\times10^{-11}$ s.

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

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

[79] 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.

[80] 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 $\tau = 5\times10^{-13}$ s and m = 1.7 MeV; see the paper for the τ-m dependence of the limit.

[81] The limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\rightarrow$ ^{16}O X^0, $X^0 \rightarrow e^+e^-$ against internal pair conversion for m_{X^0} = 1.7 MeV and $\tau_{X^0} < 10^{-11}$ s. Similar limits are obtained for m_{X^0} = 1.3–3.2 MeV. The spin parity of X^0 must be either 0^+ or 1^-. The limit at 1.7 MeV is translated into a limit for the X^0-nucleon coupling constant: $g^2_{X^0NN}/4\pi < 2.3\times10^{-9}$.

[82] 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.

[83] 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 $\tau(A^0) \lesssim 1\times10^{-11}$ s.

[84] 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 $\tau_{A^0} < 2\times10^{-11}$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.

[85] 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 $\tau_{A^0} \lesssim 1.\times10^{-11}$s for m_{A^0} = (1.1–1.7) MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.

[86] 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.

[87] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m_{^{97}\text{Nb*decay}}$ and axion with m_{A^0} between 275 and 288 keV (deuteron* decay).

[88] 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).

[89] LEHMANN 82 obtained $A^0 \rightarrow 2\gamma$ rate $< 6.2\times10^{-5}$/s (CL = 95%) excluding m_{A^0} between 100 and 1000 keV.

[90] ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li*, Nb* decay (both single p transition) nor in n capture (combined with previous Ba* negative result) rules out standard A^0. Set limit m_{A^0} <60 keV for any A^0.

[91] ZEHNDER 81 looked for Ba* $\rightarrow$ A^0 Ba transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ coincidence rate $< 2.2\times10^{-5}$/s (CL = 95%) excluding m_{A^0} >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[92] 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 $\tau(A^0 \to e^+e^-)$.

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	[93] BROSS	91	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[94] GUO	90	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[95] BJORKEN	88	CALO	$A \to e^+e^-$ or 2γ
		[96] BLINOV	88	MD1	$ee \to eeA^0$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-10}	90	[97] RIORDAN	87	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-11}	90	[98] BROWN	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 6×10^{-14}–9×10^{-11}	95	[99] DAVIER	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 3×10^{-13}–1×10^{-7}	90	[100] KONAKA	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$

[93] The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. $B(A^0 \to e^+e^-) = 1$ 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).

[94] 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).

[95] 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.

[96] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5\times10^{-12}$ s and find $\Gamma(A^0 \to \gamma\gamma)B(A^0 \to e^+e^-) < 2$ eV (CL=90%).

[97] 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.

[98] 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.

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

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

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

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

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.3	97	[101] HALLIN	92	CNTR	m_{A^0} = 1.75–1.88 MeV
none 0.0016–0.47	90	[102] HENDERSON	92C	CNTR	m_{A^0}= 1.5–1.86 MeV
< 2.0	90	[103] 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	[104] 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	[105] JUDGE	90	CNTR	m_{A^0} = 1.832 MeV, elastic
< 1.9	97	[106] TSERTOS	89	CNTR	m_{A^0} = 1.82 MeV
<(10–40)	97	[106] TSERTOS	89	CNTR	m_{A^0} = 1.51–1.65 MeV
<(1–2.5)	97	[106] 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	[107] TSERTOS	88	CNTR	m_{A^0} = 1.832 MeV
		[108] VANKLINKEN	88	CNTR	
		[109] MAIER	87	CNTR	
<2500	90	MILLS	87	CNTR	m_{A^0} = 1.8 MeV
		[110] VONWIMMER..	87	CNTR	

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

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

[103] 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.

[104] 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.

[105] 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.

[106] See also TSERTOS 88B in references.

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

[108] 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.

[109] 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.

[110] 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	[111] TRZASKA	91	CNTR	$m_{A^0} = 1.8$ MeV
< 4.4	95	WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV
		[112] FOX	89	CNTR	
< 0.11	95	[113] 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

[111] 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.

[112] 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).

[113] 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	[114] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV
< 1.0	95	[115] VO	94	CNTR	m_{X^0}=1.1 MeV
< 2.5	95	[115] VO	94	CNTR	m_{X^0}=1.4 MeV
<120	95	[115] VO	94	CNTR	m_{X^0}=1.7 MeV
< 3.8	95	[116] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV

[114] 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.

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

[116] 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	68	[117] SKALSEY	95	CNTR	γX^0
<40	68	[118] SKALSEY	95	RVUE	γX^0
< 0.18	90	[119] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \to \gamma\gamma$
< 0.26	90	[120] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \to \gamma\gamma$
< 0.33	90	[121] ADACHI	94	CNTR	γX^0, $X^0 \to \gamma\gamma\gamma$

[117] 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.

[118] 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.

[119] 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.

[120] 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.

[121] 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%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[122] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3\times10^{-2}$	95		[123] ALBRECHT	90E	ARG	$\tau \to \mu X^0$. Familon
$<1.8\times10^{-2}$	95		[123] ALBRECHT	90E	ARG	$\tau \to e X^0$. Familon
$<6.4\times10^{-9}$	90		[124] ATIYA	90	B787	$K^+ \to \pi^+ X^0$. Familon
$<1.1\times10^{-9}$	90		[125] BOLTON	88	CBOX	$\mu^+ \to e^+\gamma X^0$. Familon
			[126] CHANDA	88	ASTR	Sun, Majoron
			[127] CHOI	88	ASTR	Majoron, SN 1987A
$<5\times10^{-6}$	90		[128] PICCIOTTO	88	CNTR	$\pi \to e\nu X^0$, Majoron
$<1.3\times10^{-9}$	90		[129] GOLDMAN	87	CNTR	$\mu \to e\gamma X^0$. Familon
$<3\times10^{-4}$	90		[130] BRYMAN	86B	RVUE	$\mu \to e X^0$. Familon
$<1.\times10^{-10}$	90	0	[131] EICHLER	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
$<2.6\times10^{-6}$	90		[132] JODIDIO	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
			[133] BALTRUSAIT..	85	MRK3	$\tau \to \ell X^0$. Familon
			[134] DICUS	83	COSM	ν(hvy) $\to \nu$(light) X^0

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

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

[124] 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.

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

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

[127] CHOI 88 used the observed neutrino flux from the supernova SN1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{\rm int} = \frac{1}{2} ih\overline{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[128] 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.

[129] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{\rm int} = (1/F)\overline{\psi}_\mu \gamma^\mu (a + b\gamma_5) \psi_e \partial_\mu \phi_{X^0}$ 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 $\mu^+ \to e^+ X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

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

[131] EICHLER 86 looked for $\mu^+ \to e^+ X^0$ followed by $X^0 \to e^+ e^-$. 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.

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

[133] BALTRUSAITIS 85 search for light Goldstone boson(X^0) of broken U(1). CL = 95% limits are B($\tau \to \mu^+ X^0$)/B($\tau \to \mu^+ \nu\nu$) <0.125 and B($\tau \to e^+ X^0$)/B($\tau \to e^+ \nu\nu$) <0.04. Inferred limit for the symmetry breaking scale is m >3000 TeV.

[134] 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, $K \to \pi f_A$ and $\mu \to e f_A$ are unseen. Combining these excludes $m_{\rm heavy\nu}$ between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\rm heavy\nu}$ between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission. Previous indications for neutrinoless double beta decay with majoron emission have been superseded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 7.2 x 10^{24}	90	[135] BERNATOW...	92	CNTR	^{128}Te
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 1.7 x 10^{22}	90	BECK	93	CNTR	^{76}Ge
> 7.9 x 10^{20}	68	[136] TANAKA	93	SPEC	^{100}Mo
> 1.9 x 10^{20}	68	BARABASH	89	CNTR	^{136}Xe
> 1.0 x 10^{21}	90	FISHER	89	CNTR	^{76}Ge
> 3.3 x 10^{20}	90	ALSTON-...	88	CNTR	^{100}Mo
(6 ±1) x 10^{20}		AVIGNONE	87	CNTR	^{76}Ge
> 1.4 x 10^{21}	90	CALDWELL	87	CNTR	^{76}Ge
> 4.4 x 10^{20}	90	ELLIOTT	87	SPEC	^{82}Se
> 1.2 x 10^{21}	90	FISHER	87	CNTR	^{76}Ge
		[137] VERGADOS	82	CNTR	

[135] 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 $(7.7\text{–}1.28 \times 0.4\text{=}7.2) \times 10^{24}$.

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

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

INVISIBLE A^0 (AXION)

As discussed in the note on "Axions and Other Light Bosons," the so-called invisible axion models decouple the scale of the Peccei–Quinn symmetry breaking from the electroweak scale, and avoid the constraints from negative accelerator searches for the axion. Two classes of models are discussed commonly in the literature. One introduces new heavy quarks that carry Peccei–Quinn charge while the usual quarks and leptons do not (KSVZ axions or "hadronic" axions) [1]. The other does not need additional quarks but requires two Higgs doublets, and all quarks and leptons carry Peccei–Quinn charges (DFSZ axions or "GUT" axions) [2]. All models contain at least one electroweak singlet scalar boson that acquires an expectation value and breaks the Peccei–Quinn symmetry.

The common property of all axion models is the effective coupling

$$\mathcal{L} = \left(\theta_{\mathit{eff}} - \frac{\phi_A}{f_A}\right) \frac{g_s^2}{32\pi^2}\, F^{\mu\nu a}\, \widetilde{F}^a_{\mu\nu} \ , \tag{1}$$

where ϕ_A is the axion field, θ_{eff} is the effective QCD vacuum angle after the diagonalization of the quark masses, g_s the QCD coupling constant, $F^{\mu\nu a}$ the gluon field strength and $\widetilde{F}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\, F^{\rho\sigma a}$. It is often convenient to *define* the axion decay constant f_A with this Lagrangian [3]. The QCD instanton effect induces a potential for ϕ_A whose minimum is at $\phi_A = \theta_{\mathit{eff}} f_A$, cancelling θ_{eff} and solving the strong CP problem. The mass of the axion is related to f_A by

$$m_A = 0.62 \times 10^{-3}\mathrm{eV} \ \times (10^{10}\mathrm{GeV}/f_A) \ . \tag{2}$$

The constraints on the axion mass from various experiments, astrophysics, and cosmology are derived from the interactions of the axion with either photons, electrons, or nucleons. We use the following notation for their coupling constants $G_{A\gamma\gamma}$ and G_{Aff},

$$\mathcal{L}_{A\gamma\gamma} = -\frac{1}{4} G_{A\gamma\gamma}\phi_A\, F^{\mu\nu}\, \widetilde{F}_{\mu\nu} = G_{A\gamma\gamma}\, \phi_A \boldsymbol{E}\cdot\boldsymbol{B} \ , \tag{3}$$

$$\mathcal{L}_{Aff} = G_{Aff}\, \partial_\mu \phi_A\, \overline{f}\gamma^\mu\gamma_5\, f \ , \tag{4}$$

for $f = e, p, n$. The relations of these coupling constants to f_A (and m_A) are model dependent, and are listed in Table 1.

Table 1: The coupling constants of the axion to the matter particles in DFSZ and KSVZ models, taken from Ref. [5] where the results of Ref. [6] were used. These dimensionless coupling constants are related to those in the Lagrangian by $G_{Aii} = c_i/2f_A$ for $i = \gamma, e, p, n$. The parameter β is an arbitrary angle whose tangent is defined by the ratio between the expectation values of the two Higgs doublets in the DFSZ model. A rational number E/N in the KSVZ model depends on the number of new quarks and their charges. The coupling to nucleons are subject to certain ambiguities in hadronic matrix elements [4] that are not shown here. All entries have small uncertainties from the current quark masses.

	DFSZ	KSVZ
c_γ	0.0017	$0.0023(E/N - 1.92)$
c_e	$(1/3)\cos^2\beta$	0
c_p	$-0.10 - 0.45\cos^2\beta$	-0.39
c_n	$-0.18 + 0.39\cos^2\beta$	$+0.04$

For illustrative purposes, we depict various constraints on f_A (and m_A) for the case of the KSVZ model in Fig. 1, using only representative constraints. What follows is a brief discussion of each of the constraints shown in the figure. The bounds on the DFSZ axion are similar.

Astrophysics puts a lower bound on f_A, because a small f_A leads to a large coupling of the axion to nucleons, electrons, and photons and thus to a large "exotic" energy-loss rate. In horizontal-branch (HB) stars, the Primakoff process $\gamma + ({}^4He, e^-) \to ({}^4He, e^-) + A^0$ would be the dominant axionic energy-loss mechanism. It would accelerate the consumption of nuclear fuel and thus shorten the helium-burning lifetime of these stars. The observable number fraction of HB stars in globular clusters would be significantly reduced relative to theoretical expectations unless $G_{A\gamma\gamma} < 0.6 \times 10^{-10}$ GeV^{-1} [5]. The duration of the neutrino burst from supernova (SN) 1987A observed at the Kamiokande and IMB detectors was consistent with expectations, while axion emission would have cooled the core and shortened the burst duration [7]. The dominant emission process is axion bremsstrahlung in nucleon-nucleon collisions, a process that needs to be calculated in a hot and dense nuclear medium where many-body effects are important. Early calculations overestimated the emission

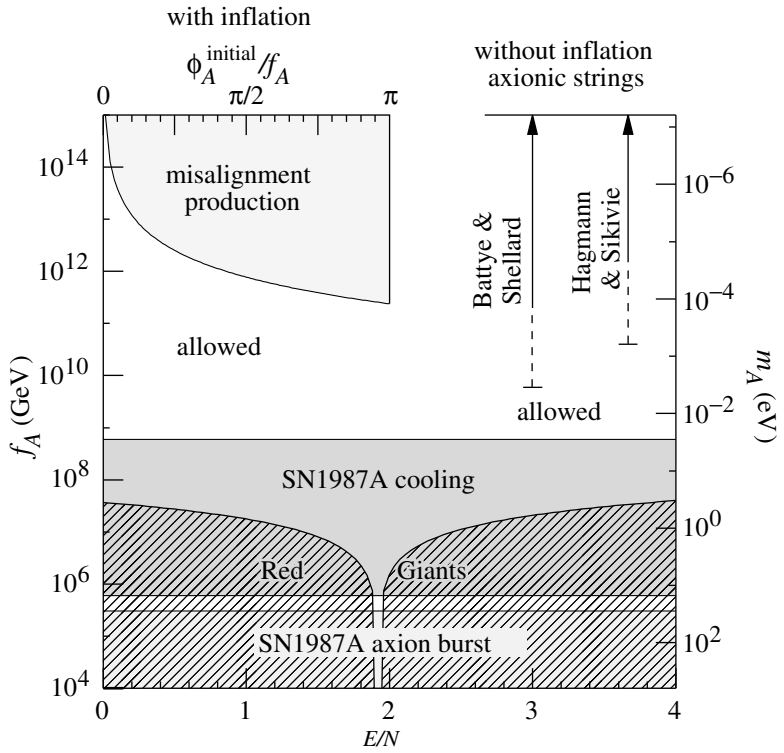

Figure 1: An illustration of the astrophysical and cosmological constraints on the axion decay constant f_A (and equivalently on m_A) in the KSVZ model. The constraint on the DSFZ model is similar except for the small window at $f_A \sim 10^6$ GeV, and one needs inflation. Shaded regions are excluded based on the arguments given in the text, though both sides have large uncertainties. The lower bound on f_A from red giants depends on the parameter E/N. All the other constraints do not. If there is inflation, there is an upper bound on f_A from misalignment production, which depends on the initial value of the axion field $\phi_A^{\rm initial}$ after inflation is over. If there is not, cosmic strings generated by Peccei–Quinn symmetry breaking produce axions, which contribute to the present mass density. Estimates of the resulting mass density vary. Here, upper bounds on f_A from two groups are shown, each of them with rather large ambiguity shown by dashed lines.

rate to some extent. A more realistic treatment leads to a somewhat diminished limit of about $f_A > 0.6 \times 10^9$ GeV [8], [9], although the treatment of many-body effects in this result is still under study. The cooling argument does not exclude $f_A \lesssim 0.6 \times 10^6$ GeV; in this range of f_A, the axions produced

in the SN core are trapped [10]. Still, $f_A \lesssim 0.3 \times 10^6$ GeV is excluded because the trapped axions result in a burst similar to that of the neutrinos and can produce signals in water Cherenkov detectors [11]. For KSVZ axions with $E/N \approx 2$, there exists an apparent small window between these two SN arguments.

Cosmology usually puts an upper bound on f_A, because the predicted cosmic mass density in axions is proportional to $f_A^{1.175}$. The DFSZ model and the KSVZ model with more than one new quark leads to domain walls that have to be diluted away by inflation. On the other hand, the axion field does not know during inflation where the true minimum of its potential is, and is "misaligned" [12]. It begins a coherent oscillation from its misaligned initial value after the QCD phase transition and contributes to the present energy density [13] as $\Omega_a h^2 \simeq 0.2(f_A/10^{12}\ \text{GeV})^{1.175}(\phi_A^{\text{initial}}/2\pi f_A)^2 \leq 1$ for a small misalignment $\phi_A^{\text{initial}}/f_A \lesssim 1$. The KSVZ model with a single new quark does not produce domain walls and does not need inflation. Without inflation, there are cosmic strings created at the time of the Peccei–Quinn symmetry breaking, that emit axions and eventually decay (or collapse). There is an ongoing controversy on the estimate of the relic energy density of the emitted axions [14]. Furthermore, cosmological bounds change if there is additional entropy production [15] or a dissipation of the coherent oscillation into lighter particles [16].

It has been widely argued that a fundmental theory will not possess global symmetries; gravity, for example, is expected to violate them. Global symmetries such as baryon number typically arise as an indirect consequence of gauge symmetries and renormalizability (accidental symmetry). It has been noted [17] that the Peccei-Quinn symmetry, from this perspective, must also arise as an accidental one and must hold to an extraordinary degree of accuracy in order to solve the strong CP problem. See, for example, Ref. [17] for a possible resolution to this problem; string theory also provides sufficiently good symmetries (see for a review, [18]).

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

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

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.018	[138] RAFFELT	95	ASTR	D, red giant
< 0.010	[139] ALTHERR	94	ASTR	D, red giants, white dwarfs
< 0.01	WANG	92	ASTR	D, white dwarf
< 0.03	WANG	92C	ASTR	D, C-O burning
none 3–8	[140] BERSHADY	91	ASTR	D, K, intergalactic light
<10	[141] KIM	91C	COSM	D, K, mass density of the universe, supersymmetry
	[142] RAFFELT	91B	ASTR	D,K, SN 1987A
$< 1 \times 10^{-3}$	[143] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS	90	ASTR	D,K, SN 1987A
	[144] ENGEL	90	ASTR	D,K, SN 1987A
< 0.02	[145] RAFFELT	90D	ASTR	D, red giant
$< 1 \times 10^{-3}$	[146] BURROWS	89	ASTR	D,K, SN 1987A
$<(1.4–10) \times 10^{-3}$	[147] ERICSON	89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[148] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[149] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[150] RAFFELT	87	ASTR	K, red giant
$< 2–5$	TURNER	87	COSM	K, thermal production
< 0.01	[151] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[152] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[153] 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	[154] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[138] 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).

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

[140] 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.

[141] 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.

[142] RAFFELT 91B argue that previous SN1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

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

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

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

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

[147] 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.

[148] 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.

[149] 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.

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

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

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

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

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

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-41}$		[155] HAGMANN	90	CNTR	m_{A^0} = (5.4–5.9)10^{-6} eV
$<1.3 \times 10^{-42}$	95	[156] WUENSCH	89	CNTR	m_{A^0} = (4.5–10.2)10^{-6} eV
$<2 \times 10^{-41}$	95	[156] WUENSCH	89	CNTR	m_{A^0} = (11.3–16.3)10^{-6} eV

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

[156] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and $\rho_A = 300$ MeV/cm^3 that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2 \rho_A = 4 \times 10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Invisible A^0 (Axion) Limits from Photon Coupling

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

VALUE (GeV^{-1})	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-7}$	95	[157] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[158] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[159] LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[159] LAZARUS	92	m_{A^0}= 0.03–0.11 eV
$<7.7 \times 10^{-7}$	99	[160] RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[161] SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

[157] Experiment based on proposal by MAIANI 86.

[158] Experiment based on proposal by VANBIBBER 87.

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

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

[161] SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to $m_{A^0} = 4 \times 10^{-3}$ where $G_{A\gamma\gamma} < 1 \times 10^{-4}$ GeV^{-1}.

Limit on Invisible A^0 (Axion) Electron Coupling

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

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

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.3\times10^{-5}$	66	[162] NI	94		Induced magnetism
$<6.7\times10^{-5}$	66	[162] CHUI	93		Induced magnetism
$<3.6\times10^{-4}$	66	[163] PAN	92		Torsion pendulum
$<2.7\times10^{-5}$	95	[162] BOBRAKOV	91		Induced magnetism
$<1.9\times10^{-3}$	66	[164] WINELAND	91	NMR	
$<8.9\times10^{-4}$	66	[163] RITTER	90		Torsion pendulum
$<6.6\times10^{-5}$	95	[162] VOROBYOV	88		Induced magnetism

[162] 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.

[163] 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.

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

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

ALTMANN	95	ZPHY C68 221	+Declais, v. Feilitzsch+	(MUNT, LAPP, CPPM)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
BASSOMPIE...	95	PL B355 584	Bassompierre, Bologna+	(LAPP, LCGT, LYON)
MAENO	95	PL B351 574	+Fujikawa, Kataoka, Nishihara+	(TOKY)
RAFFELT	95	PR D51 1495	+Weiss	(MPIM, MPIA)
SKALSEY	95	PR D51 6292	+Conti	(MICH)
TSUNODA	95	EPL 30 273	+Nakamura, Orito, Minowa	(TOKY)
ADACHI	94	PR A49 3201	+Chiba, Hirose, Nagayama+	(TMU)
ALTHERR	94	ASP 2 175	+Petitgirard, del Rio Gaztelurrutia	(CERN, LAPP, DFAB)
AMSLER	94B	PL B333 271	+Armstrong, Ould-Saada+	(Crystal Barrel Collab.)
ASAI	94	PL B323 90	+Shigekuni, Sanuki, Orito	(TOKY)
MEIJERDREES	94	PR D49 4937	Meijer Drees, Waltham+	(BRCO, OREG, TRIU)
NI	94	Physica B194 153	+Chui, Pan, Cheng	(NTHU)
VO	94	PR C49 1551	+Kelly, Wohn, Hill+	(ISU, LBL, LLNL, UCD)
ATIYA	93	PRL 70 2521	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
Also	93C	PRL 71 305 (erratum)	Atiya, Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
ATIYA	93B	PR D48 R1	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
BASSOMPIE...	93	EPL 22 239	Bassompierre, Bologna+	(LAPP, TORI, LYON)
BECK	93	PRL 70 2853	+Bensch, Bockholt, Heusser, Hirsch+	(MPIH, KIAE, SASSO)
CAMERON	93	PR D47 3707	+Cantatore, Melissinos+	(ROCH, BNL, FNAL, TRST)
CHUI	93	PRL 71 3247	+Ni	(NTHU)
MINOWA	93	PRL 71 4120	+Inoue, Asanuma, Imamura	(TOKY)
NG	93	PR D48 2941		(AST)
TANAKA	93	PR D48 5412	+Ejiri	(OSAK)
ALLIEGRO	92	PRL 68 278	+Campagnari+	(BNL, FNAL, PSI, WASH, YALE)
ATIYA	92	PRL 69 733	+Chiang, Frank, Haggerty, Ito+	(BNL, LANL, PRIN, TRIU)
BERNATOW...	92	PRL 69 2341	Bernatowicz, Brannon, Brazzle, Cowsik+	(WUSL, TATA)
BLUEMLEIN	92	IJMP A7 3835	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
HALLIN	92	PR D45 3955	+Calaprice, McPherson, Saettler	(PRIN)
HENDERSON	92C	PRL 69 1733	+Asoka-Kumar, Greenberg, Lynn+	(YALE, BNL)
HICKS	92	PL B276 423	+Alburger	(OHIO, BNL)
LAZARUS	92	PRL 69 2333	+Smith, Cameron, Melissinos+	(BNL, ROCH, FNAL)
MEIJERDREES	92	PRL 68 3845	Meijer Drees, Waltham+	(SINDRUM I Collab.)
PAN	92	MPL 7 1287	+Ni, Chen	(NTHU)
RUOSO	92	ZPHY C56 505	+Cameron, Cantatore+	(ROCH, BNL, FNAL, TRST)
SKALSEY	92	PRL 68 456	+Kolata	(MICH, NDAM)
WANG	92	MPL A7 1497		(ILL)
WANG	92C	PL B291 97		(ILL)
WU	92	PRL 69 1729	+Asoka-Kumar, Greenberg, Henderson+	(BNL, YALE, CUNY)
AKOPYAN	91	PL B272 443	+Atoyan, Gninenko, Sukhov	(INRM)
ASAI	91	PRL 66 2440	+Orito, Yoshimura, Haga	(ICEPP)
BERSHADY	91	PRL 66 1398	+Ressell, Turner	(CHIC, FNAL, EFI)
BLUEMLEIN	91	ZPHY C51 341	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
BOBRAKOV	91	JETPL 53 294	+Borisov, Lasakov, Serebrov, Tal'daev, Trofimova	(PNPI)

Translated from ZETFP 53 283.

BROSS	91	PRL 67 2942	+Crisler, Pordes, Volk, Errede, Wrbanek	(FNAL, ILL)
KIM	91C	PRL 67 3465		(SEOUL)
RAFFELT	91B	PRL 67 2605	+Seckel	(MPIM, BART)
RESSELL	91	PR D44 3001		(CHIC, FNAL)
TRZASKA	91	PL B269 54	+Dejbakhsh, Dutta, Li, Cormier	(TAMU)
TSERTOS	91	PL B266 259	+Kienle, Judge, Schreckenbach	(ILLG, GSI)
WALKER	91	APJ 376 51	+Steigman, Schramm, Olive+	(HSCA, OSU, CHIC, MINN)
WIDMANN	91	ZPHY A340 209	+Bauer, Connell, Maier, Major+	(STUT, GSI, STUTM)
WINELAND	91	PRL 67 1735	+Bollinger, Heinzen, Itano, Raizen	(NBSB)
ALBRECHT	90E	PL B246 278	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ANTREASYAN	90C	PL B251 204	+Bartels, Besset, Bieler, Bienlein+	(Crystal Ball Collab.)
ASANUMA	90	PL B237 588	+Minowa, Tsukamoto, Orito, Tsunoda	(TOKY)
ATIYA	90	PRL 64 21	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL 787 Collab.)
ATIYA	90B	PRL 65 1188	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL 787 Collab.)
BAUER	90	NIM B50 300	+Briggmann, Carstanjen, Connell, et al.	(STUT, VILL, GSI)
BURROWS	90	PR D42 3297	+Ressell, Turner	(ARIZ, CHIC, FNAL)
DEBOER	90	JPG 16 L1	de Boer, Lehmann, Steyaert	(LOUV)
ENGEL	90	PRL 65 960	+Seckel, Hayes	(BART, LANL)
GNINENKO	90	PL B237 287	+Klubakov, Poblaguev, Postoev	(INRM)
GUO	90	PR D41 2924	+Kaplan, Alde+	(NIU, LANL, FNAL, CASE, TEXA)
HAGMANN	90	PR D42 1297	+Sikivie, Sullivan, Tanner	(FLOR)
JUDGE	90	PRL 65 972	+Krusche, Schreckenbach, Tsertos, Kienle	(ILLG, GSI)
RAFFELT	90C	PRPL 198 1		(MPIM)
RAFFELT	90D	PR D41 1324		(MPIM)
RITTER	90	PR D42 977	+Goldblum, Ni, Gillies, Speake	(VIRG)
SEMERTZIDIS	90	PRL 64 2988	+Cameron, Cantatore+	(ROCH, BNL, FNAL, TRST)
TSUCHIAKI	90	PL B236 81	+Orito, Yoshida, Minowa	(ICEPP)
TURNER	90	PRPL 197 67		(FNAL)
BARABASH	89	PL B223 273	+Kuzminov, Lobashev, Novikov+	(ITEP, INRM)
BINI	89	PL B221 99	+Fazzini, Giannatiempo, Poggi, Sona+	(FIRZ, CERN, AARH)
BURROWS	89	PR D39 1020	+Turner, Brinkmann	(ARIZ, CHIC, FNAL, BOCH)
Also	88	PRL 60 1797	Turner	(FNAL, EFI)
DEBOER	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
ERICSON	89	PL B219 507	+Mathiot	(CERN, IPN)
FAISSNER	89	ZPHY C44 557	+Heinrigs, Preussger, Reitz, Samm+	(AACH3, BERL, PSI)
FISHER	89	PL B218 257	+Boehm, Bovet, Egger+	(CIT, NEUC, PSI)
FOX	89	PR C39 288	+Kemper, Cottle, Zingarelli	(FSU)
MAYLE	89	PL B219 515	+Wilson, Ellis+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
Also	88	PL B203 188	Mayle, Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA	89	PRL 62 1091	+Orito, TIsuchiaki, TIsukamoto	(ICEPP)
ORITO	89	PRL 63 597	+Yoshimura, Haga, Minowa, Tsuchiaki	(ICEPP)
PERKINS	89	PRL 62 2638		(OXF)
TSERTOS	89	PR D40 1397	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
VANBIBBER	89	PR D39 2089	Van Bibber, McIntyre, Morris, Raffelt	(LLL, TAMU, LBL)
WUENSCH	89	PR D40 3153	+De Panfilis-Wuensch, Semertzidis+	(ROCH, BNL, FNAL)
Also	87	PRL 59 839	De Panfilis, Melissinos, Moskowitz+	(ROCH, BNL, FNAL)
ALSTON-...	88	PRL 60 1928	Alston-Garnjost, Dougherty+	(LBL, MTHO, UNM)
AVIGNONE	88	PR D37 618	+Baktash, Barker, Calaprice+	(PRIN, SCUC, ORNL, WASH)
BJORKEN	88	PR D38 3375	+Ecklund, Nelson, Abashian+	(FNAL, SLAC, VPI)
BLINOV	88	SJNP 47 563	+Bondar, Bukin, Vorobyev, Groshev+	(NOVO)
		Translated from YAF 47 889.		
BOLTON	88	PR D38 2077	+Cooper, Frank, Hallin+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 56 2461	Bolton, Bowman, Cooper+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 57 3241	Grosnick, Wright, Bolton+	(CHIC, LANL, STAN, TEMP)
CHANDA	88	PR D37 2714	+Nieves, Pal	(UMD, UPR, MASA)
CHOI	88	PR D37 3225	+Kim, Kim, Lam	(JHU)
CONNELL	88	PRL 60 2242	+Fearick, Hoernle, Sideras-Haddad, Sellschop	(WITW)
DATAR	88	PR C37 250	+Fortier, Gales, Hourani+	(IPN)
DEBOER	88	PRL 61 1274	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2644 erratum	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2638	Perkins	(OXF)
Also	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
DEBOER	88C	JPG 14 L131	de Boer, Deutsch, Lehmann, Prieels, Steyaert	(LOUV)
DOEHNER	88	PR D38 2722	+Last, Arnold, Freedman, Dubbers	(HEIDP, ANL, ILLG)
DOI	88	PR D37 2575	+Kotani, Takasugi	(OSAK)
EL-NADI	88	PRL 61 1271	+Badawy	(CAIR)
FAISSNER	88	ZPHY C37 231	+Heinrigs, Preussger, Reitz, Samm+	(AACH3, BERL, SIN)
HATSUDA	88B	PL B203 469	+Yoshimura	(KEK)
LORENZ	88	PL B214 10	+Mageras, Stiegler, Huszar	(MPIM, PSI)
MAYLE	88	PL B203 188	+Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
RAFFELT	88	PRL 60 1793	+Seckel	(UCB, LLL, UCSC)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)
SAVAGE	88	PR D37 1134	+Filippone, Mitchell	(CIT)
TSERTOS	88	PL B207 273	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
TSERTOS	88B	ZPHY A331 103	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
VANKLINKEN	88	PL B205 223	van Klinken, Meiring, de Boer, Schaafsma+	(GRON, GSI)
VANKLINKEN	88B	PRL 60 2442	van Klinken	(GRON)
VONWIMMER...	88	PRL 60 2443	von Wimmersperg	(BNL)
VOROBYOV	88	PL B208 146	+Gitarts	(NOVO)
AVIGNONE	87	AIP Conf. 1987	+Brodzinski, Miley, Reeves	(SCUC, PNL)
AIP Conf.	Proc.	Salt Lake City, UT		
CALDWELL	87	PRL 59 419	+Eisberg, Grumm, Witherell+	(UCSB, LBL)
DRUZHININ	87	ZPHY C37 1	+Dubrovin, Eidelman, Golubev+	(NOVO)
ELLIOTT	87	PRL 59 1649	+Hahn, Moe	(UCI)
FISHER	87	PL B192 460	+Boehm, Bovet, Egger+	(CIT, NEUC, SIN)
FRIEMAN	87	PR D36 2201	+Dimopoulos, Turner	(SLAC, STAN, FNAL, EFI)
GOLDMAN	87	PR D36 1543	+Hallin, Hoffman+	(LANL, CHIC, STAN, TEMP)
KORENCHE...	87	SJNP 46 192	Korenchenko, Kostin, Mzhaviya+	(JINR)
		Translated from YAF 46 313.		

MAIER	87	ZPHY A326 527	+Bauer, Briggmann, Carstanjen+ (STUT, GSI)
MILLS	87	PR D36 707	+Levy (BELL)
RAFFELT	87	PR D36 2211	+Dearborn (LLL, UCB)
RIORDAN	87	PRL 59 755	+Krasny, Lang, Barbaro, Bodek+ (ROCH, CIT+)
TURNER	87	PRL 59 2489	(FNAL, EFI)
VANBIBBER	87	PRL 59 759	Van Bibber, Dagdeviren, Koonin+(LLL, CIT, MIT, STAN)
VONWIMMER...	87	PRL 59 266	von Wimmersperg, Connell, Hoernle, Sideras-Haddad(WITW)
ALBRECHT	86D	PL B179 403	+Binder, Boeckmann+ (ARGUS Collab.)
BADIER	86	ZPHY C31 21	+Bemporad, Boucrot, Callot+ (NA3 Collab.)
BOWCOCK	86	PRL 56 2676	+Giles, Hassard, Kinoshita+ (CLEO Collab.)
BROWN	86	PRL 57 2101	+ (FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN	86B	PRL 57 2787	+Clifford (TRIU)
DAVIER	86	PL B180 295	+Jeanjean, Nguyen Ngoc (LALO)
DEARBORN	86	PRL 56 26	+Schramm, Steigman (LLL, CHIC, FNAL, BART)
EICHLER	86	PL B175 101	+Felawka, Kraus, Niebuhr+ (SINDRUM Collab.)
HALLIN	86	PRL 57 2105	+Calparice, Dunford, McDonald (PRIN)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
KETOV	86	JETPL 44 146	+Klimov, Nikolaev, Mikaelyan+ (KIAE)
		Translated from ZETFP 44 114.	
KOCH	86	NC 96A 182	+Schult (JULI)
KONAKA	86	PRL 57 659	+Imai, Kobayashi, Masaike, Miyake+ (KYOT, KEK)
MAGERAS	86	PRL 56 2672	+Franzini, Tuts, Youssef+ (MPIM, COLU, STON)
MAIANI	86	PL B175 359	+Petronzio, Zavattini (CERN)
PECCEI	86	PL B172 435	+Wu, Yanagida (DESY)
RAFFELT	86	PR D33 897	(MPIM)
RAFFELT	86B	PL 166B 402	(MPIM)
SAVAGE	86B	PRL 57 178	+McKeown, Filippone, Mitchell (CIT)
AMALDI	85	PL 153B 444	+Carboni, Jonson, Thun (CERN)
ANANEV	85	SJNP 41 585	+Kalinina, Lushchikov, Olshevskii+ (JINR)
		Translated from YAF 41 912.	
BALTRUSAIT...	85	PRL 55 1842	Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BERGSMA	85	PL 157B 458	+Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
KAPLAN	85	NP B260 215	(HARV)
IWAMOTO	84	PRL 53 1198	(UCSB, WUSL)
YAMAZAKI	84	PRL 52 1089	+Ishikawa, Taniguchi, Yamanaka+ (INUS, KEK)
ABBOTT	83	PL 120B 133	+Sikivie (BRAN, FLOR)
ALAM	83	PR D27 1665	+ (VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI	83	PL 123B 349	+Dahme (CERN, MUNI)
CAVAIGNAC	83	PL 121B 193	+Hoummada, Koang, Ost+ (ISNG, LAPP)
DICUS	83	PR D28 1778	+Teplitz (TEXA, UMD)
DINE	83	PL 120B 137	+Fischler (IAS, PENN)
ELLIS	83B	NP B223 252	+Olive (CERN)
FAISSNER	83	PR D28 1198	+Heinrigs, Preussger, Samm (AACH)
FAISSNER	83B	PR D28 1787	+Frenzel, Heinrigs, Preussger+ (AACH3)
FRANK	83B	PR D28 1790	+ (LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN	83	PR D28 660	+Frank, Mischke, Moir, Schardt (LANL, ARZS)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+ (LENA Collab.)
PRESKILL	83	PL 120B 127	+Wise, Wilczek (HARV, UCSBT)
SIKIVIE	83	PRL 51 1415	(FLOR)
Also	84	PRL 52 695 erratum	Sikivie (FLOR)
ALEKSEEV	82	JETP 55 591	+Kartamyshev, Makarin+ (KIAE)
		Translated from ZETF 82 1007.	
ALEKSEEV	82B	JETPL 36 116	+Kalinina, Kruglov, Kulikov+ (MOSU, JINR)
		Translated from ZETFP 36 94.	
ASANO	82	PL 113B 195	+Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO	82	PL 116B 247	+Branco (LISB)
DATAR	82	PL 114B 63	+Baba, Betigeri, Singh (BHAB)
EDWARDS	82	PRL 48 903	+Partridge, Peck, Porter+ (Crystal Ball Collab.)
FETSCHER	82	JPG 8 L147	(ETH)
FUKUGITA	82	PRL 48 1522	+Watamura, Yoshimura (KEK)
FUKUGITA	82B	PR D26 1840	+Watamura, Yoshimura (KEK)
LEHMANN	82	PL 115B 270	+Lesquoy, Muller, Zylberajch (SACL)
RAFFELT	82	PL 119B 323	+Stodolsky (MPIM)
SIVERTZ	82	PR D26 717	+Lee-Franzini, Horstkotte+ (CUSB Collab.)
VERGADOS	82	PL 109B 96	(CERN)
ZEHNDER	82	PL 110B 419	+Gabathuler, Vuilleumier (ETH, SIN, CIT)
ASANO	81B	PL 107B 159	+Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO	81	PL 106B 91	+Mukhopadhyay (SIN)
FAISSNER	81	ZPHY C10 95	+Frenzel, Grimm, Hansl, Hoffman+ (AACH3)
FAISSNER	81B	PL 103B 234	+Frenzel, Heinrigs, Preussger+ (AACH3)
KIM	81	PL 105B 55	+Stamm (AACH3)
VUILLEUMIER	81	PL 101B 341	+Boehm, Hahn, Kwon+ (CIT, MUNI)
ZEHNDER	81	PL 104B 494	(ETH)
FAISSNER	80	PL 96B 201	+Frenzel, Heinrigs, Preussger, Samm+ (AACH3)
JACQUES	80	PR D21 1206	+Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
SOUKAS	80	PRL 44 564	+Wanderer, Weng+ (BNL, HARV, ORNL, PENN)
BECHIS	79	PRL 42 1511	+Dombeck+ (UMD, COLU, AFRR)
CALAPRICE	79	PR D20 2708	+Dunford, Kouzes, Miller+ (PRIN)
COTEUS	79	PRL 42 1438	+Diesburg, Fine, Lee, Sokolsky+ (COLU, ILL, BNL)
DISHAW	79	PL 85B 142	+Diamant-Berger, Faessler, Liu+ (SLAC, CIT)
ZHITNITSKII	79	SJNP 29 517	+Skovpen (NOVO)
		Translated from YAF 29 1001.	
ALIBRAN	78	PL 74B 134	+Armenise, Arnold, Bartley (Gargamelle Collab.)
ASRATYAN	78B	PL 79B 497	+Epstein, Fakhrutdinov+ (ITEP, SERP)
BELLOTTI	78	PL 76B 223	+Fiorini, Zanotti (MILA)
BOSETTI	78B	PL 74B 143	+Deden, Deutschmann, Fritze+ (BEBC Collab.)
DICUS	78C	PR D18 1829	+Kolb, Teplitz, Wagoner (TEXA, VPI, STAN)
DONNELLY	78	PR D18 1607	+Freedman, Lytel, Peccei, Schwartz (STAN)
Also	76	PRL 37 315	Reines, Gurr, Sobel (UCI)
Also	74	PRL 33 179	Gurr, Reines, Sobel (UCI)
HANSL	78D	PL 74B 139	+Holder, Knobloch, May, Paar+ (CDHS Collab.)
MICELMAC...	78	LNC 21 441	Micelmacher, Pontecorvo (JINR)
MIKAELIAN	78	PR D18 3605	(FNAL, NWES)
SATO	78	PTP 60 1942	(KYOT)
VYSOTSKII	78	JETPL 27 502	+Zeldovich, Khlopov, Chechetkin (ASCI)
		Translated from ZETFP 27 533.	

YANG	78	PRL 41 523		(MASA)
PECCEI	77	PR D16 1791	+Quinn	(STAN, SLAC)
Also	77B	PRL 38 1440	Peccei, Quinn	(STAN, SLAC)
REINES	76	PRL 37 315	+Gurr, Sobel	(UCI)
GURR	74	PRL 33 179	+Reines, Sobel	(UCI)
ANAND	53	PRSL A22 183		

OTHER RELATED PAPERS

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