ABE	97S	PRL 79 2192	F. Abe *et al.*	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe *et al.*	(CDF Collab.)
ABE	97X	PRL 79 4327	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	97Q	PL B412 201	M. Acciarri *et al.*	(L3 Collab.)
ARIMA	97	PR D55 19	T. Arima *et al.*	(VENUS Collab.)
BARENBOIM	97	PR D55 4213	G. Barenboim *et al.*	(VALE, IFIC)
DEANDREA	97	PL B409 277	A. Deandrea	(MARS)
DERRICK	97	ZPHY C73 613	M. Derrick *et al.*	(ZEUS Collab.)
GROSSMAN	97	PR D55 2768	Y. Grossman, Z. Ligeti, E. Nardi	(REHO, CIT)
JADACH	97	PL B408 281	S. Jadach, B.F.L. Ward, Z. Was	(CERN, INPK+)
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ABACHI	96C	PRL 76 3271	S. Abachi *et al.*	(D0 Collab.)
ABACHI	96D	PL B385 471	S. Abachi *et al.*	(D0 Collab.)
ABREU	96T	ZPHY C72 179	P. Abreu *et al.*	(DELPHI Collab.)
ADAM	96C	PL B380 471	W. Adam *et al.*	(DELPHI Collab.)
AID	96B	PL B369 173	S. Aid *et al.*	(H1 Collab.)
ALLET	96	PL B383 139	M. Allet *et al.*	(VILL, LEUV, LOUV, WISC)
ABACHI	95E	PL B358 405	S. Abachi *et al.*	(D0 Collab.)
ABE	95M	PRL 74 2900	F. Abe *et al.*	(CDF Collab.)
ABE	95N	PRL 74 3538	F. Abe *et al.*	(CDF Collab.)
BALEST	95	PR D51 2053	R. Balest *et al.*	(CLEO Collab.)
KUZNETSOV	95	PRL 75 794	I.A. Kuznetsov *et al.*	(PNPI, KIAE, HARV+)
KUZNETSOV	95B	PAN 58 2113	A.V. Kuznetsov, N.V. Mikheev	(YARO)
		Translated from YAF 58 2228.		
MIZUKOSHI	95	NP B443 20	J.K. Mizukoshi, O.J.P. Eboli, M.C. Gonzalez-Garcia	
ABREU	94O	ZPHY C64 183	P. Abreu *et al.*	(DELPHI Collab.)
BHATTACH...	94	PL B336 100	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
Also	94B	PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
BHATTACH...	94B	PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
DAVIDSON	94	ZPHY C61 613	S. Davidson, D. Bailey, B.A. Campbell	(CFPA+)
KUZNETSOV	94	PL B329 295	A.V. Kuznetsov, N.V. Mikheev	(YARO)
KUZNETSOV	94B	JETPL 60 315	I.A. Kuznetsov *et al.*	(PNPI, KIAE, HARV+)
		Translated from ZETFP 60 311.		
LEURER	94	PR D50 536	M. Leurer	(REHO)
LEURER	94B	PR D49 333	M. Leurer	(REHO)
Also	93	PRL 71 1324	M. Leurer	(REHO)
MAHANTA	94	PL B337 128	U. Mahanta	(MEHTA)
SEVERIJNS	94	PRL 73 611 (erratum)	N. Severijns *et al.*	(LOUV, WISC, LEUV+)
VILAIN	94B	PL B332 465	P. Vilain *et al.*	(CHARM II Collab.)
ABE	93C	PL B302 119	K. Abe *et al.*	(VENUS Collab.)
ABE	93D	PL B304 373	T. Abe *et al.*	(TOPAZ Collab.)
ABE	93G	PRL 71 2542	F. Abe *et al.*	(CDF Collab.)
ABREU	93J	PL B316 620	P. Abreu *et al.*	(DELPHI Collab.)
ACTON	93E	PL B311 391	P.D. Acton *et al.*	(OPAL Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti *et al.*	(UA2 Collab.)
BHATTACH...	93	PR D47 R3693	G. Bhattacharyya *et al.*	(CALC, JADA, ICTP+)
BUSKULIC	93F	PL B308 425	D. Buskulic *et al.*	(ALEPH Collab.)
DERRICK	93	PL B306 173	M. Derrick *et al.*	(ZEUS Collab.)
RIZZO	93	PR D48 4470	T.G. Rizzo	(ANL)
SEVERIJNS	93	PRL 70 4047	N. Severijns *et al.*	(LOUV, WISC, LEUV+)
Also	94	PRL 73 611 (erratum)	N. Severijns *et al.*	(LOUV, WISC, LEUV+)
STERNER	93	PL B303 385	K.L. Sterner *et al.*	(AMY Collab.)
ABREU	92D	ZPHY C53 555	P. Abreu *et al.*	(DELPHI Collab.)
ADRIANI	92F	PL B292 472	O. Adriani *et al.*	(L3 Collab.)
DECAMP	92	PRPL 216 253	D. Decamp *et al.*	(ALEPH Collab.)
IMAZATO	92	PRL 69 877	J. Imazato *et al.*	(KEK, INUS, TOKY+)
MISHRA	92	PRL 68 3499	S.R. Mishra *et al.*	(COLU, CHIC, FNAL+)
POLAK	92B	PR D46 3871	J. Polak, M. Zralek	(SILES)
ACTON	91	PL B268 122	D.P. Acton *et al.*	(OPAL Collab.)
ACTON	91B	PL B273 338	D.P. Acton *et al.*	(OPAL Collab.)
ADEVA	91D	PL B262 155	B. Adeva *et al.*	(L3 Collab.)
AQUINO	91	PL B261 280	M. Aquino, A. Fernandez, A. Garcia	(CINV, PUEB)
COLANGELO	91	PL B253 154	P. Colangelo, G. Nardulli	(BARI)
CUYPERS	91	PL B259 173	F. Cuypers, A.F. Falk, P.H. Frampton	(DURH, HARV+)
FARAGGI	91	MPL A6 61	A.E. Faraggi, D.V. Nanopoulos	(TAMU)
POLAK	91	NP B363 385	J. Polak, M. Zralek	(SILES)
RIZZO	91	PR D44 202	T.G. Rizzo	(WISC, ISU)
WALKER	91	APJ 376 51	T.P. Walker *et al.*	(HSCA, OSU, CHIC+)
ABE	90F	PL B246 297	K. Abe *et al.*	(VENUS Collab.)
ABE	90H	PR D41 1722	F. Abe *et al.*	(CDF Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy *et al.*	(OPAL Collab.)
ANTREASYAN	90C	PL B251 204	D. Antreasyan *et al.*	(Crystal Ball Collab.)
GONZALEZ-G...	90D	PL B240 163	M.C. Gonzalez-Garcia, J.W.F. Valle	(VALE)
GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
GRIFOLS	90D	PR D42 3293	J.A. Grifols, E. Masso, T.G. Rizzo	(BARC, CERN+)
KIM	90	PL B240 243	G.N. Kim *et al.*	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	C. Albajar *et al.*	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	H. Albrecht *et al.*	(ARGUS Collab.)
BARBIERI	89B	PR D39 1229	R. Barbieri, R.N. Mohapatra	(PISA, UMD)
LANGACKER	89B	PR D40 1569	P. Langacker, S. Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	S. Odaka *et al.*	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar *et al.*	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke *et al.*	(LBL, UCB, COLO, NWES+)
BERGSTROM	88	PL B212 386	L. Bergstrom	(STOH)
CUYPERS	88	PRL 60 1237	F. Cuypers, P.H. Frampton	(UNCCH)
DONCHESKI	88	PL B206 137	M.A. Doncheski, H. Grotch, R. Robinett	(PSU)
DONCHESKI	88B	PR D38 412	M.A. Doncheski, H. Grotch, R.W. Robinett	(PSU)
ANSARI	87D	PL B195 613	R. Ansari *et al.*	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel *et al.*	(JADE Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend *et al.*	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick *et al.*	(HRS Collab.)
Also	86B	PR D34 3286	M. Derrick *et al.*	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio *et al.*	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	A. Jodidio *et al.*	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva *et al.*	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger *et al.*	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker *et al.*	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva *et al.*	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend *et al.*	(CELLO Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr *et al.*	(LBL, NWES, TRIU)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)

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

AXIONS AND OTHER VERY LIGHT BOSONS

Written October 1997 by H. Murayama (University of California, Berkeley) Part I; April 1998 by G. Raffelt (Max-Planck Institute, München) Part II; and April 1998 by C. Hagmann, K. van Bibber (Lawrence Livermore National Laboratory), and L.J. Rosenberg (Massachusetts Institute of Technology) Part III.

This review is divided into three parts:

Part I (Theory)
Part II (Astrophysical Constraints)
Part III (Experimental Limits)

AXIONS AND OTHER VERY LIGHT BOSONS, PART I (THEORY)

(by H. Murayama)

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. They arise if there is a global continuous symmetry in the theory that is spontaneously broken in the vacuum. If the symmetry is exact, it results in a massless Nambu–Goldstone (NG) boson. If there is a small explicit breaking of the symmetry, either already in the Lagrangian or due to quantum mechanical effects such as anomalies, the would-be NG boson acquires a finite mass; then it is called a pseudo-NG boson. Typical examples are axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries. This Review provides brief descriptions of each of them and their motivations.

One common characteristic for all these particles is that their coupling to the Standard Model particles are suppressed by the energy scale of symmetry breaking, *i.e.* the decay constant f, where the interaction is described by the Lagrangian

$$\mathcal{L} = \frac{1}{f}(\partial_\mu \phi) J^\mu , \tag{1}$$

where J^μ is the Noether current of the spontaneously broken global symmetry.

An axion gives a natural solution to the strong CP problem: why the effective θ-parameter in the QCD Lagrangian $\mathcal{L}_\theta = \theta_{\mathit{eff}} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \widetilde{F}^a_{\mu\nu}$ is so small ($\theta_{\mathit{eff}} \lesssim 10^{-9}$) as required by the current limits on the neutron electric dipole moment, even though $\theta_{\mathit{eff}} \sim O(1)$ is perfectly allowed by the QCD gauge invariance. Here, θ_{eff} is the effective θ parameter after the diagonalization of the quark masses, and $F^{\mu\nu a}$ is the gluon field strength and $\widetilde{F}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma a}$. An axion is a pseudo-NG boson of a spontaneously broken Peccei–Quinn symmetry, which is an exact symmetry at the classical level, but is broken quantum mechanically due to the triangle anomaly with the gluons. The definition of the Peccei–Quinn symmetry is model dependent. As a result of the triangle anomaly, the axion acquires an effective coupling to gluons

$$\mathcal{L} = \left(\theta_{\mathit{eff}} - \frac{\phi_A}{f_A} \right) \frac{\alpha_s}{8\pi} F^{\mu\nu a} \widetilde{F}^a_{\mu\nu} , \tag{2}$$

where ϕ_A is the axion field. It is often convenient to *define* the axion decay constant f_A with this Lagrangian [6]. The QCD nonperturbative 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 inversely proportional to f_A as

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

The original axion model [1,5] assumes $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter ($\tan\beta$): the ratio of the vacuum expectation values of two Higgs fields. This model is excluded after extensive experimental searches for such an axion [7]. Observation of a narrow-peak structure in positron spectra from heavy ion collisions [8] 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 [9]. Extensive searches for this particle, $A^0(1.8\text{ MeV})$, ended up with another negative result [10].

The popular way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 coupling becomes weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [11,12]. Two classes of models are discussed commonly in the literature. One introduces new heavy quarks which carry Peccei–Quinn charge while the usual quarks and leptons do not (KSVZ axion or "hadronic axion") [11]. The other does not need additional quarks but requires two Higgs doublets, and all quarks and leptons carry Peccei–Quinn charges (DFSZ axion or "GUT-axion") [12]. All models contain at least one electroweak singlet scalar boson which acquires an expectation value and breaks Peccei–Quinn symmetry. The invisible axion with a large decay constant $f_A \sim 10^{12}$ GeV was found to be a good candidate of the cold dark matter component of the Universe [13](see Dark Matter review). The energy density is stored in the low-momentum modes of the axion field which are highly occupied and thus represent essentially classical field oscillations.

The constraints on the invisible axion from astrophysics are derived from interactions of the axion with either photons, electrons or nucleons. The strengths of the interactions are model dependent (*i.e.*, not a function of f_A only), and hence one needs to specify a model in order to place lower bounds on f_A. Such constraints will be discussed in Part II. Serious experimental searches for an invisible axion are underway; they typically rely on axion-photon coupling, and some of them assume that the axion is the dominant component of our galactic halo density. Part III will discuss experimental techniques and limits.

Familons arise when there is a global family symmetry broken spontaneously. A family symmetry interchanges generations or acts on different generations differently. Such a symmetry may explain the structure of quark and lepton masses and their mixings. A familon could be either a scalar or a pseudoscalar. For instance, an SU(3) family symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger family symmetries with separate groups of left-handed and right-handed fields, one also has pseudoscalar familons. Some of them have flavor-off-diagonal couplings such as $\partial_\mu \phi_F \bar{d}\gamma^\mu s/F_{ds}$ or $\partial_\mu \phi_F \bar{e}\gamma^\mu \mu/F_{\mu e}$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor-changing processes. For instance, $\mathrm{B}(K^+ \to \pi^+\phi_F) < 3 \times 10^{-10}$ [14] gives $F_{ds} > 3.4 \times 10^{11}$ GeV [15]. The constraints on familons primarily coupled to third generation are quite weak [15].

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 Majoron couples to Z. It is now excluded by the Z invisible-decay width. The model is viable if there is an additional singlet Higgs boson and if the Majoron is mainly a singlet [16]. In the singlet Majoron model [3], lepton-number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos which acquire Majorana masses. The left-handed neutrino masses are generated by a "seesaw" mechanism [17]. 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 [18].

There is revived interest in a long-lived neutrino, to improve Big-Bang Nucleosynthesis [19] or large scale structure formation theories [20]. Since a decay of neutrinos into electrons or photons is severely constrained, these scenarios require a familon (Majoron) mode $\nu_1 \to \nu_2 \phi_F$ (see, *e.g.*, Ref. 15 and references therein).

Other light bosons (scalar, pseudoscalar, or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see Ref. 21.

It has been widely argued that a fundamental theory will not possess global symmetries; gravity, for example, is expected to violate them. Global symmetries such as baryon number arise by accident, typically as a consequence of gauge symmetries. It has been noted [22] that the Peccei-Quinn symmetry, from this perspective, must also arise by accident and must hold to an extraordinary degree of accuracy in order to solve the strong CP problem. Possible resolutions to this problem, however, have been discussed [22,23]. String theory also provides sufficiently good symmetries, especially using a large compactification radius motivated by recent developments in M-theory [24].

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AXIONS AND OTHER VERY LIGHT BOSONS: PART II (ASTROPHYSICAL CONSTRAINTS)

(by G.G. Raffelt)

Low-mass weakly-interacting particles (neutrinos, gravitons, axions, baryonic or leptonic gauge bosons, *etc.*) are produced in hot plasmas and thus represent an energy-loss channel for stars. The strength of the interaction with photons, electrons, and nucleons can be constrained from the requirement that stellar-evolution time scales are not modified beyond observational limits. For detailed reviews see Refs. [1,2].

The energy-loss rates are steeply increasing functions of temperature T and density ρ. Because the new channel has to compete with the standard neutrino losses which tend to increase even faster, the best limits arise from low-mass stars, notably from horizontal-branch (HB) stars which have a helium-burning core of about 0.5 solar masses at $\langle\rho\rangle \approx 0.6\times10^4\,\mathrm{g\,cm^{-3}}$ and $\langle T\rangle \approx 0.7\times10^8\,\mathrm{K}$. The new energy-loss rate must not exceed about $10\,\mathrm{ergs\,g^{-1}\,s^{-1}}$ to avoid a conflict with the observed number ratio of HB stars in globular clusters. Likewise the ignition of helium in the degenerate cores of the preceding red-giant phase is delayed too much unless the same constraint holds at $\langle\rho\rangle \approx 2\times10^5\,\mathrm{g\,cm^{-3}}$ and $\langle T\rangle \approx 1\times10^8\,\mathrm{K}$. The white-dwarf luminosity function also yields useful bounds.

The new bosons X^0 interact with electrons and nucleons with a dimensionless strength g. For scalars it is a Yukawa coupling, for new gauge bosons (*e.g.*, from a baryonic or leptonic gauge symmetry) a gauge coupling. Axion-like pseudoscalars couple derivatively as $f^{-1}\bar\psi\gamma_\mu\gamma_5\psi\,\partial^\mu\phi_X$ with f an energy scale. Usually this is equivalent to $(2m/f)\bar\psi\gamma_5\psi\,\phi_X$ with m the mass of the fermion ψ so that $g = 2m/f$. For the coupling to electrons, globular-cluster stars yield the constraint

$$g_{Xe} \lesssim \left\{ \begin{array}{ll} 0.5\times10^{-12} & \text{for pseudoscalars [3]}\ , \\ 1.3\times10^{-14} & \text{for scalars [4]}\ , \end{array} \right. \tag{1}$$

if $m_X \lesssim 10\,\mathrm{keV}$. The Compton process $\gamma + {}^4\mathrm{He} \to {}^4\mathrm{He} + X^0$ limits the coupling to nucleons to $g_{XN} \lesssim 0.4\times10^{-10}$ [4].

Scalar and vector bosons mediate long-range forces which are severely constrained by "fifth-force" experiments [5]. In the massless case the best limits come from tests of the equivalence principle in the solar system, leading to

$$g_{B,L} \lesssim 10^{-23} \tag{2}$$

for a baryonic or leptonic gauge coupling [6].

In analogy to neutral pions, axions A^0 couple to photons as $g_{A\gamma}\mathbf{E}\cdot\mathbf{B}\,\phi_A$ which allows for the Primakoff conversion $\gamma \leftrightarrow A^0$ in external electromagnetic fields. The most restrictive limit arises from globular-cluster stars [2]

$$g_{A\gamma} \lesssim 0.6\times10^{-10}\,\mathrm{GeV}^{-1}\ . \tag{3}$$

The often-quoted “red-giant limit” [7] is slightly weaker.

The duration of the SN 1987A neutrino signal of a few seconds proves that the newborn neutron star cooled mostly by neutrinos rather than through an “invisible channel” such as right-handed (sterile) neutrinos or axions [8]. Therefore,

$$3\times10^{-10} \lesssim g_{AN} \lesssim 3\times10^{-7} \tag{4}$$

is excluded for the pseudoscalar Yukawa coupling to nucleons [2]. The “strong” coupling side is allowed because axions then escape only by diffusion, quenching their efficiency as an energy-loss channel [9]. Even then the range

$$10^{-6} \lesssim g_{AN} \lesssim 10^{-3} \tag{5}$$

is excluded to avoid excess counts in the water Cherenkov detectors which registered the SN 1987A neutrino signal [11].

In terms of the Peccei-Quinn scale f_A, the axion couplings to nucleons and photons are $g_{AN} = C_N m_N/f_A$ ($N = n$ or p) and $g_{A\gamma} = (\alpha/2\pi f_A)\,(E/N - 1.92)$ where C_N and E/N are model-dependent numerical parameters of order unity. With $m_A = 0.62\,\mathrm{eV}\,(10^7\,\mathrm{GeV}/f_A)$, Eq. (3) yields $m_A \lesssim 0.4\,\mathrm{eV}$ for $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limit is $m_A \lesssim 0.008\,\mathrm{eV}$ for KSVZ axions while it varies between about 0.004 and 0.012 eV for DFSZ axions, depending on the angle β which measures the ratio of two Higgs vacuum expectation values [10]. In view of the large uncertainties it is good enough to remember $m_A \lesssim 0.01\,\mathrm{eV}$ as a generic limit (Fig. 1).

In the early universe, axions come into thermal equilibrium only if $f_A \lesssim 10^8\,\mathrm{GeV}$ [12]. Some fraction of the relic axions end up in galaxies and galaxy clusters. Their decay $a \to 2\gamma$ contributes to the cosmic extragalactic background light and to line emissions from galactic dark-matter haloes and galaxy clusters. An unsuccessful “telescope search” for such features yields $m_a < 3.5\,\mathrm{eV}$ [13]. For $m_a \gtrsim 30\,\mathrm{eV}$, the axion lifetime is shorter than the age of the universe.

For $f_A \gtrsim 10^8$ GeV cosmic axions are produced nonthermally. If inflation occurred after the Peccei-Quinn symmetry breaking or if $T_{\mathrm{reheat}} < f_A$, the “misalignment mechanism” [14] leads to a contribution to the cosmic critical density of

$$\Omega_A h^2 \approx 1.9\times3^{\pm1}\,(1\,\mu\mathrm{eV}/m_A)^{1.175}\,\Theta_{\mathrm{i}}^2 F(\Theta_{\mathrm{i}}) \tag{6}$$

where h is the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The stated range reflects recognized uncertainties of the cosmic conditions at the QCD phase transition and of the temperature-dependent axion mass. The function $F(\Theta)$ with $F(0) = 1$ and $F(\pi) = \infty$ accounts for anharmonic corrections to the axion potential. Because the initial misalignment angle Θ_{i} can be very small or very close to π, there is no real prediction for the mass of dark-matter axions even though one would expect $\Theta_{\mathrm{i}}^2 F(\Theta_{\mathrm{i}}) \sim 1$ to avoid fine-tuning the initial conditions.

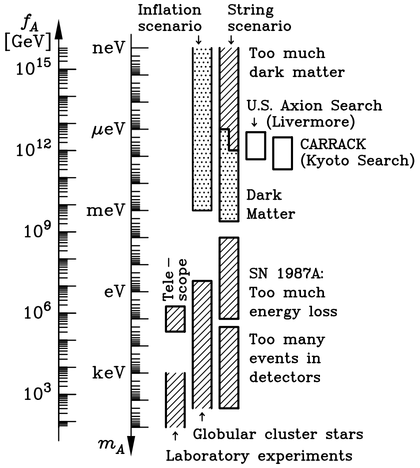

Figure 1: Astrophysical and cosmological exclusion regions (hatched) for the axion mass m_A or equivalently, the Peccei-Quinn scale f_A. An “open end” of an exclusion bar means that it represents a rough estimate; its exact location has not been established or it depends on detailed model assumptions. The globular cluster limit depends on the axion-photon coupling; it was assumed that $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limits depend on the axion-nucleon couplings; the shown case corresponds to the KSVZ model and approximately to the DFSZ model. The dotted “inclusion regions” indicate where axions could plausibly be the cosmic dark matter. Most of the allowed range in the inflation scenario requires fine-tuned initial conditions. In the string scenario the plausible dark-matter range is controversial as indicated by the step in the low-mass end of the “inclusion bar” (see main text for a discussion). Also shown is the projected sensitivity range of the search experiments for galactic dark-matter axions.

A possible fine-tuning of Θ_{i} is limited by inflation-induced quantum fluctuations which in turn lead to temperature fluctuations of the cosmic microwave background [15,16]. In a broad class of inflationary models one thus finds an upper limit to m_A where axions could be the dark matter. According to the most recent discussion [16] it is about 10^{-3} eV (Fig. 1).

If inflation did not occur at all or if it occurred before the Peccei-Quinn symmetry breaking with $T_{\mathrm{reheat}} > f_A$, cosmic axion strings form by the Kibble mechanism [17]. Their motion is damped primarily by axion emission rather than gravitational waves. After axions acquire a mass at the QCD phase transition they quickly become nonrelativistic and thus form a cold dark matter component. Battye and Shellard [18] found that the dominant source of axion radiation are string loops rather than long strings. At a cosmic time t the average loop creation size is parametrized as $\langle \ell \rangle = \alpha t$ while the radiation power is $P = \kappa\mu$ with μ the renormalized string tension. The loop contribution to the cosmic axion density is [18]

$$\Omega_A h^2 \approx 88 \times 3^{\pm 1} \left[(1+\alpha/\kappa)^{3/2} - 1\right] \, (1\,\mu\mathrm{eV}/m_A)^{1.175} \; , \quad (7)$$

where the stated nominal uncertainty has the same source as in Eq. (6). The values of α and κ are not known, but probably $0.1 < \alpha/\kappa < 1.0$ [18], taking the expression in square brackets to 0.15–1.83. If axions are the dark matter, we have

$$0.05 \lesssim \Omega_A h^2 \lesssim 0.50 \; , \quad (8)$$

where it was assumed that the universe is older than 10 Gyr, that the dark-matter density is dominated by axions with $\Omega_A \gtrsim 0.2$, and that $h \gtrsim 0.5$. This implies m_A = 6–2500 μeV for the plausible mass range of dark-matter axions (Fig. 1).

Contrary to Ref. 18, Sikivie *et al.* [19] find that the motion of global strings is strongly damped, leading to a flat axion spectrum. In Battye and Shellard's treatment the axion radiation is strongly peaked at wavelengths of order the loop size. In Sikivie *et al.*'s picture more of the string radiation goes into kinetic axion energy which is redshifted so that ultimately there are fewer axions. In this scenario the contributions from string decay and vacuum realignment are of the same order of magnitude; they are both given by Eq. (6) with Θ_i of order one. As a consequence, Sikivie *et al.* allow for a plausible range of dark-matter axions which reaches to smaller masses as indicated in Fig. 1.

The work of both groups implies that the low-mass end of the plausible mass interval in the string scenario overlaps with the projected sensitivity range of the U.S. search experiment for galactic dark-matter axions (Livermore) [20] and of the Kyoto search experiment CARRACK [21] as indicated in Fig. 1. (See also Part III of this Review by Hagmann, van Bibber, and Rosenberg.)

In summary, a variety of robust astrophysical arguments and laboratory experiments (Fig. 1) indicate that $m_A \lesssim 10^{-2}$ eV. The exact value of this limit may change with a more sophisticated treatment of supernova physics and/or the observation of the neutrino signal from a future galactic supernova, but a dramatic modification is not expected unless someone puts forth a completely new argument. The stellar-evolution limits shown in Fig. 1 depend on the axion couplings to various particles and thus can be irrelevant in fine-tuned models where, for example, the axion-photon coupling strictly vanishes. For nearly any m_A in the range generically allowed by stellar evolution, axions could be the cosmic dark matter, depending on the cosmological scenario realized in nature. It appears that our only practical chance to discover these "invisible" particles rests with the ongoing or future search experiments for galactic dark-matter.

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AXIONS AND OTHER VERY LIGHT BOSONS, PART III (EXPERIMENTAL LIMITS)

(Revised November 2003 by C. Hagmann, K. van Bibber,
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In this section we review the experimental methodology and limits on light axions and light pseudoscalars in general. (A comprehensive overview of axion theory is given by H. Murayama in the Part I of this Review, whose notation we follow [1].) Within its scope are purely laboratory experiments, searches where the axion is assumed to be halo dark matter, and searches where the Sun is presumed to be a source of axions. We restrict the discussion to axions of mass $m_A < O(\text{eV})$, as the allowed range for the axion mass is nominally $10^{-6} < m_A < 10^{-2}$ eV. Experimental work in this range predominantly has been through the axion-to-two-photon coupling $g_{A\gamma}$, to which the present review is largely confined. As discussed in Part II of this Review by G. Raffelt, the lower bound to the axion mass derives from a cosmological overclosure argument, and the upper bound most restrictively from SN1987A [2]. Limits from stellar evolution overlap seamlessly above that, connecting with accelerator-based limits that ruled out the original axion. There, it was assumed that the Peccei-Quinn symmetry-breaking scale was the electroweak scale, *i.e.,* $f_A \sim 250$ GeV, implying axions of mass $m_A \sim O(100\,\text{keV})$. These earlier limits from nuclear transitions, particle decays, *etc.,* while not discussed here, are included in the Listings.

While the axion mass is well-determined by the Peccei-Quinn scale, *i.e.,* $m_A = 0.62\,\text{eV}(10^7\,\text{GeV}/f_A)$, the axion-photon coupling $g_{A\gamma}$ is not: $g_{A\gamma} = (\alpha/\pi f_A)g_\gamma$, with $g_\gamma = (E/N - 1.92)/2$, and where E/N is a model-dependent number. It is noteworthy, however, that quite distinct models lead to axion-photon couplings that are not very different. For example, in the case of axions imbedded in Grand Unified Theories, the DFSZ axion [3], $g_\gamma = 0.37$, whereas in one popular implementation of the "hadronic" class of axions, the KSVZ axion [4], $g_\gamma = -0.96$. Hence, between these two models, rates for axion-photon processes $\sim g^2_{A\gamma}$ differ by less than a factor of 10. The Lagrangian $\mathcal{L} = g_{A\gamma}\mathbf{E}\cdot\mathbf{B}\phi_A$, with ϕ_A the axion field, permits the conversion of an axion into a single real photon in an external electromagnetic field, *i.e.,* a Primakoff interaction. In the case of relativistic axions, $k_\gamma - k_A \sim m^2_A/2\omega$, pertinent to several experiments below, coherent axion-photon mixing in long magnetic fields results in significant conversion probability even for very weakly coupled axions [5]. This mixing of photons and axions has been posited to explain dimming from distant supernovae and the apparent long interstellar attenuation length of the most energetic cosmic rays [6].

Below are discussed several experimental techniques constraining $g_{A\gamma}$, and their results. Also included are recent unpublished results, and projected sensitivities of experiments soon to be upgraded or made operational. Recent reviews describe these experiments in greater detail [7].

III.1. Microwave cavity experiments: Perhaps the most promising avenue to the discovery of the axion presumes that axions constitute a significant fraction of the local dark matter halo in our galaxy. An estimate for the Cold Dark matter (CDM) component of our local galactic halo is $\rho_{\text{CDM}} = 7.5\times10^{-25}\text{g/cm}^3$ $(450\,\text{MeV/cm}^3)$ [8]. That the CDM halo is in fact made of axions (rather than, *e.g.,* WIMPs) is in principle an independent assumption. However should very light axions exist, they would almost necessarily be cosmologically abundant [2]. As shown by Sikivie [9] and Krauss *et al.* [10], halo axions may be detected by their resonant conversion into a quasi-monochromatic microwave signal in a high-Q cavity permeated by a strong static magnetic field. The cavity is tunable and the signal is maximum when the frequency $\nu = m_A(1 + O(10^{-6}))$, the width of the peak representing the virial distribution of thermalized axions in the galactic gravitational potential. The signal may possess finer structure due to axions recently fallen into the galaxy and not yet thermalized [11]. The feasibility of the technique was established in early experiments of small sensitive volume, $V = O(1\,\text{liter})$ [12] with HFET amplifiers, setting limits in the mass range $4.5 < m_A < 16.3$ μeV, but lacking by 2–3 orders of magnitude the sensitivity to detect KSVZ and DFSZ axions (the conversion power $P_{A\to\gamma} \propto g^2_{A\gamma}$). ADMX, a later experiment ($B \sim 7.8$ T, $V \sim 200$ liter) has achieved sensitivity to KSVZ axions over the mass range 1.9–3.3 μeV, and continues to operate [13]. The exclusion regions shown in Figure 1 for Refs. 12,13 are all normalized to the CDM density $\rho_{\text{CDM}} = 7.5\times10^{-25}\text{g/cm}^3$ $(450\,\text{MeV/cm}^3)$ and 90% CL. A near quantum-limited low noise DC SQUID amplifier [14] is being installed in the upgraded ADMX experiment. A Rydberg atom single-quantum detector [15] is being commissioned in a new RF cavity axion search [16]. These new technologies promise dramatic improvements in experimental sensitivity, which should enable rapid scanning of the axion mass range at or better than the sensitivity required to detect DFSZ axions. The search region of the microwave cavity experiments is shown in detail in Figure 1.

III.2 Optical and Radio Telescope searches: For axions of mass greater than about 10^{-1} eV, their cosmological abundance is no longer dominated by vacuum misalignment of string radiation mechanisms, but rather by thermal emission. Their contribution to critical density is small $\Omega \sim 0.01(m_A/\text{eV})$. However, the spontaneous-decay lifetime of axions, $\tau(A \to 2\gamma) \sim 10^{25}\text{sec}(m_A/\text{eV})^{-5}$ while irrelevant for μeV axions, is short enough to afford a powerful constraint on such thermally produced axions in the eV mass range, by looking for a quasi-monochromatic photon line from galactic clusters. This line, corrected for Doppler shift, would be at half the axion mass and its width would be consistent with the observed virial motion, typically $\Delta\lambda/\lambda \sim 10^{-2}$. The expected line intensity would be of the order $I_A \sim 10^{-17}(m_A/3\,\text{eV})^7\text{erg}\,\text{cm}^{-2}\text{arcsec}^{-2}\text{Å}^{-1}\text{sec}^{-1}$ for DFSZ axions, comparable to the continuum night emission.

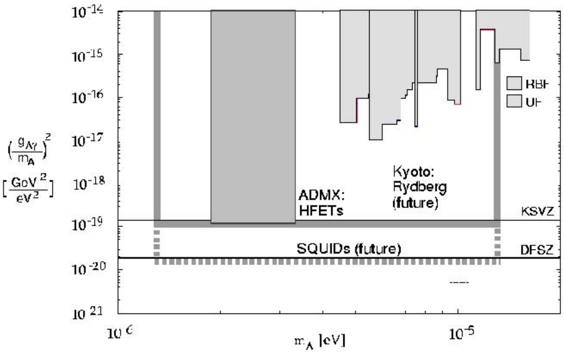

Figure 1: Exclusion region from the microwave cavity experiments, where the plot is flattened by presenting $(g_{A\gamma}/m_A)^2$ versus m_A. The first-generation experiments ("RBF" and "UF" [12]) and in-progress "ADMX" [13] are all HFET-based. Shown also is the full mass range to be covered by the latter experiment (shaded line), and the improved sensitivity when upgraded with DC SQUID amplifiers [14] (shaded dashed line). The expected sensitivity of "CARRACK II" based on a Rydberg single-quantum receiver (dotted line) is also shown in Ref. 16.

The conservative assumption is made that the relative density of thermal axions fallen into the cluster gravitational potential reflects their overall cosmological abundance. A search for thermal axions in three rich Abell clusters was carried out at Kitt Peak National Laboratory [17]; no such line was observed between 3100–8300 Å (m_A = 3–8 eV) after on-off field subtraction of the atmospheric molecular background spectra. A limit everywhere stronger than $g_{A\gamma} < 10^{-10}\text{GeV}^{-1}$ is set, which is seen from Fig. 2 to easily exclude DFSZ axions throughout the mass range.

Similar in principle to the optical telescope search, microwave photons from spontaneous axion decay in halos of astrophysical objects may be searched for with a radio telescope. One group [18] aimed the Haystack radio dish at several nearby dwarf galaxies. The expected signal is a narrow spectral line with the expected virial width, Doppler shift, and intensity distribution about the center of the galaxies. They reported limits of $g_{A\gamma} < 1.0 \times 10^{-9}\text{GeV}^{-1}$ for $m_A \sim$ few×100 μeV. They propose an interferometric radio telescope search with sensitivity near $g_{A\gamma}$ of 10^{-10}GeV^{-1}.

III.3 A search for solar axions: As with the telescope search for thermally produced axions, the search for solar axions was stimulated by the possibility of there being a "1 eV window" for hadronic axions (*i.e.*, axions with no tree-level coupling to leptons), a "window" subsequently closed by an improved understanding of the evolution of globular cluster stars and SN1987A [2]. Hadronic axions would be copiously produced within our Sun's interior by a Primakoff process. Their flux at the Earth of $\sim 10^{12}\text{cm}^{-2}\text{sec}^{-1}(m_A/\text{eV})^2$, which is independent of the details of the solar model, is sufficient for a definitive test via the axion reconversion into photons in a large magnetic field. However, their average energy is $\sim$ 4 keV, implying an oscillation length in the vacuum of $2\pi(m_A^2/2\omega)^{-1} \sim O(\text{mm})$, precluding the mixing from achieving its theoretically maximum value in any practical magnet. It was recognized that one could endow the photon with an effective mass in the gas, $m_\gamma = \omega_{\text{pl}}$, thus permitting the axion and photon dispersion relations to be matched [5]. A first simple implementation of this proposal was carried out using a conventional dipole magnet with a conversion volume of variable-pressure gas and a xenon proportional chamber as the x-ray detector [19]. The magnet was fixed in orientation to take data for $\sim$ 1000 sec/day. Axions were excluded for $g_{A\gamma} < 3.6 \times 10^{-9}\text{GeV}^{-1}$ for $m_A < 0.03$ eV, and $g_{A\gamma} < 7.7 \times 10^{-9}\text{GeV}^{-1}$ for $0.03 < m_A < 0.11$ eV (95% CL). A more sensitive experiment (Tokyo axion helioscope) has been completed, using a superconducting magnet on a telescope mount to track the sun continuously. This gives an exclusion limit of $g_{A\gamma} < 6 \times 10^{-10}\text{GeV}^{-1}$ for $m_A < 0.3$ eV [20]. A new experiment CAST (CERN Axion Solar Telescope), using a decommissioned LHC dipole magnet, is taking first data [21]. The projected sensitivity $g_{A\gamma} < 10^{-10}\text{GeV}^{-1}$ for $m_A < 1$ eV, is about that of the globular cluster bounds.

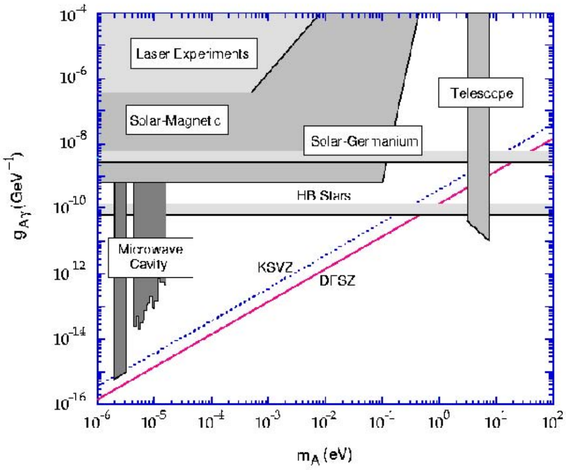

Figure 2: Exclusion region in mass versus axion-photon coupling $(m_A, g_{A\gamma})$ for various experiments. The limit set by globular cluster Horizontal Branch Stars ("HB Stars") is shown in Ref. 2.

Other searches for solar axions have been carried out using crystal germanium detectors. These exploit the coherent conversion of axions into photons when their angle of incidence satisfies a Bragg condition with a crystalline plane. Analysis of 1.94 kg-yr of data from a 1 kg germanium detector yields a bound of $g_{A\gamma} < 2.7 \times 10^{-9}\text{GeV}^{-1}$ (95% CL) independent of mass up to $m_A \sim 1$ keV [22]. Analysis of 0.2 kg-yr of data from a 0.234 kg germanium detector yields a bound of $g_{A\gamma} < 2.8 \times 10^{-9}\mathrm{GeV}^{-1}$ (95% CL) [23]. A general study of sensitivities [24] concludes these crystal detectors are unlikely to compete with axion bounds arising from globular clusters [25] or helioseismology [26].

III.4 Photon regeneration ("invisible light shining through walls"): Photons propagating through a transverse field (with $\mathbf{E}\|\mathbf{B}$ may convert into axions. For light axions with $m_A^2 l/2\omega \ll 2\pi$, where l is the length of the magnetic field, the axion beam produced is colinear and coherent with the photon beam, and the conversion probability Π is given by $\Pi \sim (1/4)(g_{A\gamma}Bl)^2$. An ideal implementation for this limit is a laser beam propagating down a long, superconducting dipole magnet like those for high-energy physics accelerators. If another such dipole magnet is set up in line with the first, with an optical barrier interposed between them, then photons may be regenerated from the pure axion beam in the second magnet and detected [27]. The overall probability $P(\gamma \to A \to \gamma) = \Pi^2$. such an experiment has been carried our, utilizing two magnets of length $l = 4.4$ m and $B = 3.7$ T. Axions with mass $m_A < 10^{-3}$ eV, and $g_{A\gamma} > 6.7 \times 10^{-7}\mathrm{GeV}^{-1}$ were excluded at 95% CL [28]. With sufficient effort, limits comparable to those from stellar evolution would be achievable. Due to the $g_{A\gamma}^4$ rate suppression, however, it does not seem feasible to reach standard axion couplings.

III.5 Polarization experiments: The existence of axions can affect the polarization of light propagating through a transverse magnetic field in two ways [29]. First, as the $\mathbf{E}_{\|}$ component, but not the $\mathbf{E}_{\perp}$ component will be depleted by the production of real axions, there will be in general a small rotation of the polarization vector of linearly polarized light. This effect will be constant for all sufficiently light m_A such that the oscillation length is much longer than the magnet $m_A^2 l/2\omega \ll 2\pi$. For heavier axions, the effect oscillates and diminishes with increasing m_A, and vanishes for $m_A > \omega$. The second effect is birefringence of the vacuum, again because there could be a mixing of virtual axions in the $\mathbf{E}_{\|}$ state, but not for the $\mathbf{E}_{\perp}$ state. This will lead to light that is initially linearly polarized becoming elliptically polarized. Higher-order QED also induces vacuum birefringence, and is much stronger than the contribution due to axions. A search for both polarization-rotation and induced ellipticity has been carried out with the same dipole magnets described above [30]. As in the case of photon regeneration, the observables are boosted linearly by the number of passes of the laser beam in the optical cavity within the magnet. The polarization-rotation resulted in a stronger limit than that from ellipticity, $g_{A\gamma} < 3.6 \times 10^{-7}\mathrm{GeV}^{-1}$ (95% CL) for $m_A < 5 \times 10^{-4}$ eV. The limits from ellipticity are better at higher masses, as they fall off smoothly and do not terminate at m_A. Current experiments with greatly improved sensitivity that, while still far from being able to detect standard axions, have measured the QED "light-by-light" contribution for the first time [31]. The overall envelope for limits from the laser-based experiments is shown schematically in Fig. 2.

III.6 Non-Newtonian monopole-dipole couplings: Axions mediate a CP violating monopole-dipole Yukawa-type gravitational interaction potential ($g_s g_p\, \hat{\sigma} \cdot \hat{r}\, \mathrm{e}^{-r/\lambda}$) between spin and matter [32] where $g_s g_p$ is the product of couplings at the scalar and polarized vertices and λ is the range of the force. Two experiments placed upper limits on the product coupling $g_s g_p$ in a system of magnetized media and test masses. One experiment [33] had peak sensitivity near 100 mm (2 μeV axion mass) another [34] had peak sensitivity near 10 mm (20 μeV axion mass). Both lacked sensitivity by 10 orders of magnitude of the sensitivity required to detect couplings implied by the existing limits on a neutron EDM.

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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 Meson 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. • • •						
$<4.5 \times 10^{-11}$	90		[3] ADLER	02C	B787	$K^+ \rightarrow \pi^+ A^0$
$<4.9 \times 10^{-5}$	90		AMMAR	01B	CLEO	$B^\pm \rightarrow \pi^\pm (K^\pm) X^0$
$<5.3 \times 10^{-5}$	90		AMMAR	01B	CLEO	$B^0 \rightarrow K^0_S X^0$
$<1.1 \times 10^{-10}$	90		[4] ADLER	00	B787	$K^+ \rightarrow \pi^+ A^0$
$<3.3 \times 10^{-5}$	90		[5] ALTEGOER	98	NOMD	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 120$ MeV
$<5.0 \times 10^{-8}$	90		[6] KITCHING	97	B787	$K^+ \rightarrow \pi^+ A^0$ $(A^0 \rightarrow \gamma\gamma)$
$<5.2 \times 10^{-10}$	90		[7] ADLER	96	B787	$K^+ \rightarrow \pi^+ A^0$
$<2.8 \times 10^{-4}$	90		[8] AMSLER	96B	CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 65$ MeV
$<3 \times 10^{-4}$	90		[8] AMSLER	96B	CBAR	$\eta \rightarrow \gamma X^0$, $m_{X^0}=$ 50–200 MeV
$<4 \times 10^{-5}$	90		[8] AMSLER	96B	CBAR	$\eta' \rightarrow \gamma X^0$, $m_{X^0}=$ 50–925 MeV
$<6 \times 10^{-5}$	90		[8] AMSLER	94B	CBAR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=65–125 MeV
$<6 \times 10^{-5}$	90		[8] AMSLER	94B	CBAR	$\eta \rightarrow \gamma X^0$, m_{X^0}=200–525 MeV
<0.007	90		[9] MEIJERDREES	94	CNTR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=25 MeV
<0.002	90		[9] MEIJERDREES	94	CNTR	$\pi^0 \rightarrow \gamma X^0$, m_{X^0}=100 MeV
$<2 \times 10^{-7}$	90		[10] ATIYA	93B	B787	$K^+ \rightarrow \pi^+ A^0$
$<3 \times 10^{-13}$			[11] NG	93	COSM	$\pi^0 \rightarrow \gamma X^0$
$<1.1 \times 10^{-8}$	90		[12] ALLIEGRO	92	SPEC	$K^+ \rightarrow \pi^+ A^0$ $(A^0 \rightarrow e^+ e^-)$
$<5 \times 10^{-4}$	90		[13] ATIYA	92	B787	$\pi^0 \rightarrow \gamma X^0$
$<4 \times 10^{-6}$	90		[14] MEIJERDREES	92	SPEC	$\pi^0 \rightarrow \gamma X^0$, $X^0 \rightarrow e^+ e^-$, $m_{X^0}=$ 100 MeV
$<1 \times 10^{-7}$	90		[15] ATIYA	90B	B787	Sup. by KITCHING 97
$<1.3 \times 10^{-8}$	90		[16] KORENCHE...	87	SPEC	$\pi^+ \rightarrow e^+ \nu A^0$ $(A^0 \rightarrow e^+ e^-)$
$<1 \times 10^{-9}$	90	0	[17] EICHLER	86	SPEC	Stopped $\pi^+ \rightarrow e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[18] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5\text{–}4) \times 10^{-6}$	90		[18] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV
		0	[19] ASANO	82	CNTR	Stopped $K^+ \rightarrow \pi^+ A^0$
		0	[20] ASANO	81B	CNTR	Stopped $K^+ \rightarrow \pi^+ A^0$
			[21] ZHITNITSKII	79		Heavy axion

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

[4] ADLER 00 bound is for massless A^0.

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

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

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

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

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

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

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

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

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

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

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

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

[17] EICHLER 86 looked for $\pi^+ \rightarrow e^+ \nu A^0$ followed by $A^0 \rightarrow e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of A^0. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

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

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

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

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

A^0 (Axion) Searches in Quarkonium Decays

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

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.3 \times 10^{-5}$	90		[22] BALEST	95	CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<4.0 \times 10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow A^0 \gamma$
			[23] ANTREASYAN	90C	RVUE	
$<5 \times 10^{-5}$	90		[24] DRUZHININ	87	ND	$\phi \rightarrow A^0 \gamma$ $(A^0 \rightarrow e^+ e^-)$
$<2 \times 10^{-3}$	90		[25] DRUZHININ	87	ND	$\phi \rightarrow A^0 \gamma$ $(A^0 \rightarrow \gamma\gamma)$
$<7 \times 10^{-6}$	90		[26] DRUZHININ	87	ND	$\phi \rightarrow A^0 \gamma$ $(A^0 \rightarrow$ missing)
$<3.1 \times 10^{-4}$	90	0	[27] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ $(A^0 \rightarrow e^+ e^-)$
$<4 \times 10^{-4}$	90	0	[27] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ $(A^0 \rightarrow \mu^+ \mu^-, \pi^+ \pi^-, K^+ K^-)$

$<8 \times 10^{-4}$	90	1	[28] ALBRECHT 86D	ARG	$\Upsilon(1S) \to A^0\gamma$
$<1.3 \times 10^{-3}$	90	0	[29] ALBRECHT 86D	ARG	$\Upsilon(1S) \to A^0\gamma$ $(A^0 \to e^+e^-, \gamma\gamma)$
$<2. \times 10^{-3}$	90		[30] BOWCOCK 86	CLEO	$\Upsilon(2S) \to \Upsilon(1S) \to A^0$
$<5. \times 10^{-3}$	90		[31] MAGERAS 86	CUSB	$\Upsilon(1S) \to A^0\gamma$
$<3. \times 10^{-4}$	90		[32] ALAM 83	CLEO	$\Upsilon(1S) \to A^0\gamma$
$<9.1 \times 10^{-4}$	90		[33] NICZYPORUK 83	LENA	$\Upsilon(1S) \to A^0\gamma$
$<1.4 \times 10^{-5}$	90		[34] EDWARDS 82	CBAL	$J/\psi \to A^0\gamma$
$<3.5 \times 10^{-4}$	90		[35] SIVERTZ 82	CUSB	$\Upsilon(1S) \to A^0\gamma$
$<1.2 \times 10^{-4}$	90		[35] SIVERTZ 82	CUSB	$\Upsilon(3S) \to A^0\gamma$

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

[23] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon, J/\psi$) is the reduction factor for $\Gamma(V \to A^0\gamma)$ 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 $0.00075 < x < 44$.

[24] The first DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 3 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[25] The second DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 5 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[26] The third DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} > 7 \times 10^{-12}$ s/MeV and $m_{A^0} < 200$ MeV.

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

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

[29] Independent of τ_{A^0}.

[30] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ 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.

[31] 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.

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

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

[34] 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.

[35] 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. • • •				
$<4.4 \times 10^{-5}$	90	[36] 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	[37] ASAI 94	CNTR	o-Ps $\to A^0\gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[38] 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	[39] 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
$<(1–5) \times 10^{-4}$	95	[40] TSUCHIAKI 90	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} =$ 300–900 keV
$<6.4 \times 10^{-5}$	90	[41] ORITO 89	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} < 30$ keV
		[42] AMALDI 85	CNTR	Ortho-positronium
		[43] CARBONI 83	CNTR	Ortho-positronium

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

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

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

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

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

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

[42] 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.

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

A^0 (Axion) Search in Photoproduction

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

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

A^0 (Axion) Production in Hadron Collisions

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

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[45] AHMAD 97	SPEC	e^+ production
			[46] LEINBERGER 97	SPEC	$A^0 \to e^+e^-$
			[47] GANZ 96	SPEC	$A^0 \to e^+e^-$
			[48] KAMEL 96	EMUL	^{32}S emulsion, $A^0 \to e^+e^-$
			[49] BLUEMLEIN 92	BDMP	$A^0 N_Z \to \ell^+\ell^- N_Z$
			[50] MEIJERDREES 92	SPEC	$\pi^- p \to n A^0$, $A^0 \to e^+e^-$
			[51] BLUEMLEIN 91	BDMP	$A^0 \to e^+e^-$, 2γ
			[52] FAISSNER 89	OSPK	Beam dump, $A^0 \to e^+e^-$
			[53] DEBOER 88	RVUE	$A^0 \to e^+e^-$
			[54] EL-NADI 88	EMUL	$A^0 \to e^+e^-$
			[55] FAISSNER 88	OSPK	Beam dump, $A^0 \to 2\gamma$
			[56] BADIER 86	BDMP	$A^0 \to e^+e^-$
$<2. \times 10^{-11}$	90	0	[57] BERGSMA 85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[57] BERGSMA 85	CHRM	CERN beam dump
		24	[58] FAISSNER 83	OSPK	Beam dump, $A^0 \to 2\gamma$
			[59] FAISSNER 83B	RVUE	LAMPF beam dump
			[60] FRANK 83B	RVUE	LAMPF beam dump
			[61] HOFFMAN 83	CNTR	$\pi p \to n A^0$ $(A^0 \to e^+e^-)$
			[62] FETSCHER 82	RVUE	See FAISSNER 81B
		12	[63] FAISSNER 81	OSPK	CERN PS ν wideband
		15	[64] FAISSNER 81B	OSPK	Beam dump, $A^0 \to 2\gamma$
		8	[65] KIM 81	OSPK	26 GeV $pN \to A^0 X$
		0	[66] FAISSNER 80	OSPK	Beam dump, $A^0 \to e^+e^-$
$<1. \times 10^{-8}$	90		[67] JACQUES 80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[67] JACQUES 80	HLBC	Beam dump
			[68] SOUKAS 80	CALO	28 GeV p beam dump
			[69] BECHIS 79	CNTR	
$<1. \times 10^{-8}$	90		[70] COTEUS 79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[71] DISHAW 79	CALO	400 GeV pp
$<1. \times 10^{-8}$	90		ALIBRAN 78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN 78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[72] BELLOTTI 78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[72] BELLOTTI 78	HLBC	m_{A^0}=1.5 MeV
$<4.1 \times 10^{-9}$	90		[72] BELLOTTI 78	HLBC	m_{A^0}=1 MeV
$<1. \times 10^{-8}$	90		[73] BOSETTI 78B	HYBR	Beam dump
			[74] DONNELLY 78		
$<0.5 \times 10^{-8}$	90		HANSL 78D	WIRE	Beam dump
			[75] MICELMAC... 78		
			[76] VYSOTSKII 78		

[45] AHMAD 97 reports a result of APEX Collaboration which studied positron production in ^{238}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.

[46] 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.

[47] 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.

[48] KAMEL 96 looked for e^+e^- pairs from the collision of ^{32}S (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity $m_{ee} > 2$ MeV.

[49] BLUEMLEIN 92 is a proton beam dump experiment at Serpukhov with a secondary target to induce Bethe-Heitler production of e^+e^- or $\mu^+\mu^-$ from the produce A^0.

See Fig. 5 for the excluded region in m_{A^0}-x plane. For the standard axion, $0.3 < x < 25$ is excluded at 95% CL. If combined with BLUEMLEIN 91, $0.008 < x < 32$ is excluded.

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

[51] 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 $x < 1$.

[52] 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.

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

[54] EL-NADI 88 claim the existence of a neutral particle decaying into $e^+ e^-$ with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at ~ 4 GeV/c/nucleon.

[55] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \to \gamma\gamma$. 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.

[56] BADIER 86 did not find long-lived A^0 in 300 GeV π^- Beam Dump Experiment that decays into $e^+ e^-$ in the mass range $m_{A^0} = (20$–$200)$ MeV, which excludes the A^0 decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-m_{A^0} plane.

[57] BERGSMA 85 look for $A^0 \to 2\gamma$, $e^+ e^-$, $\mu^+ \mu^-$. 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 $\tau > 0.037$ s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[58] FAISSNER 83 observed 19 1-γ and 12 2-γ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

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

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

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

[62] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-γ peak rate remarkably decreases if iron wall is set in front of the decay region.

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

[64] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 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.

[65] 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.

[66] 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 $m_{A^0} < 2m_{e^-}$.

[67] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interaction}) < 7. \times 10^{-68}$ 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.

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

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

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

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

[72] BELLOTTI 78 first value comes from search for $A^0 \to e^+ e^-$. 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.

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

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

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

[76] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

A^0 (Axion) Searches in Reactor Experiments

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[77] ALTMANN 95	CNTR	Reactor; $A^0 \to e^+ e^-$
	[78] KETOV 86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[79] KOCH 86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[80] DATAR 82	CNTR	Light water reactor
	[81] VUILLEUMIER 81	CNTR	Reactor, $A^0 \to 2\gamma$

[77] 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.

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

[79] 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.

[80] DATAR 82 looked for $A^0 \to 2\gamma$ in neutron capture ($np \to d A^0$) 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.

[81] 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. • • •					
$< 8.5 \times 10^{-6}$	90		[82] DERBIN 02	CNTR	^{125m}Te decay
			[83] DEBOER 97C	RVUE	M1 transitions
$< 5.5 \times 10^{-10}$	95		[84] TSUNODA 95	CNTR	^{252}Cf fission, $A^0 \to ee$
$< 1.2 \times 10^{-6}$	95		[85] MINOWA 93	CNTR	^{139}La$^* \to {}^{139}$LaA^0
$< 2 \times 10^{-4}$	90		[86] HICKS 92	CNTR	^{35}S decay, $A^0 \to \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[87] ASANUMA 90	CNTR	^{241}Am decay
$<(0.4$–$10) \times 10^{-3}$	95		[88] DEBOER 90	CNTR	^{8}Be$^* \to {}^8$BeA^0, $A^0 \to e^+ e^-$
$<(0.2$–$1) \times 10^{-3}$	90		[89] BINI 89	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+ e^-$
			[90] 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		[91] DATAR 88	CNTR	^{12}C$^* \to {}^{12}$CA^0, $A^0 \to e^+ e^-$
$< 5 \times 10^{-3}$	90		[92] DEBOER 88C	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+ e^-$
$< 3.4 \times 10^{-5}$	95		[93] DOEHNER 88	SPEC	^{2}H*, $A^0 \to e^+ e^-$
$< 4 \times 10^{-4}$	95		[94] SAVAGE 88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[94] SAVAGE 88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[95] HALLIN 86	SPEC	^{6}Li isovector decay
<10.8	90		[95] HALLIN 86	SPEC	^{10}B isoscalar decays
< 2.2	90		[95] HALLIN 86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[96] SAVAGE 86B	CNTR	^{14}N*
			[97] ANANEV 85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[98] CAVAIGNAC 83	CNTR	^{97}Nb*, deut* transition $A^0 \to 2\gamma$
			[99] ALEKSEEV 82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[100] LEHMANN 82	CNTR	Cu$^* \to$ CuA^0 ($A^0 \to 2\gamma$)
		0	[101] ZEHNDER 82	CNTR	Li*, Nb* decay, n-capt.
		0	[102] ZEHNDER 81	CNTR	Ba$^* \to$ BaA^0 ($A^0 \to 2\gamma$)
			[103] CALAPRICE 79		Carbon

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

[83] DEBOER 97C reanalyzed the existent data on Nuclear M1 transitions and find that a 9 MeV boson decaying into $e^+ e^-$ would explain the excess of events with large opening angles. See also DEBOER 01 for follow-up experiments.

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

[85] MINOWA 93 studied chain process, ^{139}Ce $\to {}^{139}$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.

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

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

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

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

[90] AVIGNONE 88 looked for the 1115 keV transition $\text{C}^* \to \text{Cu}A^0$, either from $A^0 \to 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV.

[91] DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \to e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range 10^{-13}–10^{-8} s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m = 1.7$ MeV; see the paper for the τ-m dependence of the limit.

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

[93] The DOEHNER 88 limit is for $m_{A^0} = 1.7$ MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than 10^{-4} are obtained for $m_{A^0} = 1.2$–2.2 MeV.

[94] SAVAGE 88 looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N, 17.64 MeV state $J^P = 1^+$ in ^{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 $m_{A^0} = (1.1 \to 2.2)$ MeV and the isoscalar coupling of A^0 to hadrons, if $m_{A^0} = (1.1 \to 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[95] Limits are for $\Gamma(A^0(1.8\ \text{MeV}))/\Gamma(\pi\text{M}1)$; 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.

[96] SAVAGE 86B looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N. Limit on the branching fraction is valid if $\tau_{A^0} \lesssim 1. \times 10^{-11}$s for $m_{A^0} = (1.1$–$1.7)$ MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.

[97] ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li* decay) and below $2m_e$ for deuteron* decay.

[98] 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).

[99] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges m_{A^0} <400 keV (Li* decay) and 330 keV $< m_{A^0} <$2.2 MeV. (deuteron* decay).

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

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

[102] ZEHNDER 81 looked for $\text{Ba}^* \to A^0\text{Ba}$ transition with $A^0 \to 2\gamma$. 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.

[103] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

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

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	[104] BROSS	91	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[105] GUO	90	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[106] BJORKEN	88	CALO	$A \to e^+e^-$ or 2γ
		[107] BLINOV	88	MD1	$ee \to eeA^0$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-10}	90	[108] RIORDAN	87	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-11}	90	[109] BROWN	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 6×10^{-14}–9×10^{-11}	95	[110] DAVIER	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 3×10^{-13}–1×10^{-7}	90	[111] KONAKA	86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$

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

[105] GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with $g-2$ constraint, axions coupling only to e^+e^- are ruled out for $m_{A^0} < 2.7$ MeV (90% CL).

[106] BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_A) for $m_{A^0} < 200$ MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

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

[108] Assumes $A^0\gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for $m_{A^0} < 15$ MeV.

[109] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for $m_{A^0} < 15$ MeV are shown in their figure 3.

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

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

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

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

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.3	97	[112] HALLIN	92	CNTR	$m_{A^0} = 1.75$–1.88 MeV
none 0.0016–0.47	90	[113] HENDERSON	92C	CNTR	$m_{A^0} = 1.5$–1.86 MeV
< 2.0	90	[114] 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	[115] 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	[116] JUDGE	90	CNTR	$m_{A^0} = 1.832$ MeV, elastic
< 1.9	97	[117] TSERTOS	89	CNTR	$m_{A^0} = 1.82$ MeV
<(10–40)	97	[117] TSERTOS	89	CNTR	$m_{A^0} = 1.51$–1.65 MeV
<(1–2.5)	97	[117] 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	[118] TSERTOS	88	CNTR	$m_{A^0} = 1.832$ MeV
		[119] VANKLINKEN	88	CNTR	
		[120] MAIER	87	CNTR	
<2500	90	MILLS	87	CNTR	$m_{A^0} = 1.8$ MeV
		[121] VONWIMMER.	87	CNTR	

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

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

[114] WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming $\text{B}(A^0 \to e^+e^-) = 100\%$. 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.

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

[116] 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.

[117] See also TSERTOS 88B in references.

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

[119] 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.

[120] 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.

[121] 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	[122] TRZASKA	91	CNTR	$m_{A^0} = 1.8$ MeV
< 4.4	95	WIDMANN	91	CNTR	$m_{A^0} = 1.78$–1.92 MeV
		[123] FOX	89	CNTR	
< 0.11	95	[124] MINOWA	89	CNTR	$m_{A^0} = 1.062$ MeV
<33	97	CONNELL	88	CNTR	$m_{A^0} = 1.580$ MeV
<42	97	CONNELL	88	CNTR	$m_{A^0} = 1.642$ MeV
<73	97	CONNELL	88	CNTR	$m_{A^0} = 1.782$ MeV
<79	97	CONNELL	88	CNTR	$m_{A^0} = 1.832$ MeV

[122] 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.

[123] 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).

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

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

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

VALUE (10^{-3} eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.2	95	[125] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV
< 1.0	95	[126] VO	94	CNTR	m_{X^0}=1.1 MeV
< 2.5	95	[126] VO	94	CNTR	m_{X^0}=1.4 MeV
<120	95	[126] VO	94	CNTR	m_{X^0}=1.7 MeV
< 3.8	95	[127] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV

[125] 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.

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

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

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

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

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.2	90	[128] MITSUI	96	CNTR	γX^0
< 4	68	[129] SKALSEY	95	CNTR	γX^0
<40	68	[130] SKALSEY	95	RVUE	γX^0
< 0.18	90	[131] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$
< 0.26	90	[132] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$
< 0.33	90	[133] ADACHI	94	CNTR	γX^0, $X^0 \rightarrow \gamma\gamma\gamma$

[128] MITSUI 96 looked for a monochromatic γ. The bound applies for a vector X^0 with C=-1 and m_{X^0} <200 keV. They derive an upper bound on eeX^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.

[129] SKALSEY 95 looked for a monochromatic γ without an accompanying γ in $e^+ e^-$ annihilation. The bound applies for scalar and vector X^0 with $C = -1$ and m_{X^0} = 100–1000 keV.

[130] 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.

[131] ADACHI 94 looked for a peak in the $\gamma\gamma$ invariant mass distribution in $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for m_{X^0} = 70–800 keV.

[132] ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for m_{X^0} <800 keV.

[133] ADACHI 94 looked for a peak in the missing mass distribution in $\gamma\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for m_{X^0} = 200–900 keV.

Searches for Goldstone Bosons (X^0)

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

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[134] DIAZ	98	THEO	$H^0 \rightarrow X^0 X^0$, $A^0 \rightarrow X^0 X^0 X^0$, Majoron
			[135] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3 \times 10^{-2}$	95		[136] ALBRECHT	90E	ARG	$\tau \rightarrow \mu X^0$. Familon
$<1.8 \times 10^{-2}$	95		[136] ALBRECHT	90E	ARG	$\tau \rightarrow e X^0$. Familon
$<6.4 \times 10^{-9}$	90		[137] ATIYA	90	B787	$K^+ \rightarrow \pi^+ X^0$. Familon
$<1.1 \times 10^{-9}$	90		[138] BOLTON	88	CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon
			[139] CHANDA	88	ASTR	Sun, Majoron
			[140] CHOI	88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90		[141] PICCIOTTO	88	CNTR	$\pi \rightarrow e\nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90		[142] GOLDMAN	87	CNTR	$\mu \rightarrow e\gamma X^0$. Familon
$<3 \times 10^{-4}$	90		[143] BRYMAN	86B	RVUE	$\mu \rightarrow e X^0$. Familon
$<1. \times 10^{-10}$	90	0	[144] EICHLER	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
$<2.6 \times 10^{-6}$	90		[145] JODIDIO	86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
			[146] BALTRUSAIT...	85	MRK3	$\tau \rightarrow \ell X^0$. Familon
			[147] DICUS	83	COSM	ν(hvy) $\rightarrow \nu$(light)X^0

[134] DIAZ 98 studied models of spontaneously broken lepton number with both singlet and triplet Higgses. They obtain limits on the parameter space from invisible decay $Z \rightarrow H^0 A^0 \rightarrow X^0 X^0 X^0 X^0 X^0$ and $e^+ e^- \rightarrow Z H^0$ with $H^0 \rightarrow X^0 X^0$.

[135] BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $x_e^2 < 2 \times 10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $x_e(G_F/8\pi\sqrt{2})^{1/2}$.

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

[137] ATIYA 90 limit is for $m_{X^0} = 0$. The limit $B < 1 \times 10^{-8}$ holds for $m_{X^0} < 95$ MeV. For the reduction of the limit due to finite lifetime of X^0, see their Fig. 3.

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

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

[140] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{\text{int}} = \frac{1}{2} ih\overline{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

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

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

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

[144] EICHLER 86 looked for $\mu^+ \rightarrow e^+ X^0$ followed by $X^0 \rightarrow e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of X^0. The quoted limits are valid when $\tau_{X^0} \lesssim 3. \times 10^{-10}$ s if the decays are kinematically allowed.

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

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

[147] The primordial heavy neutrino must decay into ν and familon, f_A, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \rightarrow \pi f_A$ and $\mu \rightarrow e f_A$ are unseen. Combining these excludes $m_{\text{heavy}\nu}$ between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\text{heavy}\nu}$ between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission.
No experiment currently claims any such evidence. Only the best or comparable limits for each isotope are reported. Also see the reviews ZUBER 98 and FAESSLER 98B.

$t_{1/2}$(10^{21} yr)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*	
>7200	**90**	**^{128}Te**		**CNTR**	[148] BERNATOW...	92
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 2.2	90	^{130}Te	$0\nu1\chi$	Cryog. det.	[149] ARNABOLDI	03
> 0.9	90	^{130}Te	$0\nu2\chi$	Cryog. det.	[150] ARNABOLDI	03
> 8	90	^{116}Cd	$0\nu1\chi$	CdWO$_4$ scint.	[151] DANEVICH	03
> 0.8	90	^{116}Cd	$0\nu2\chi$	CdWO$_4$ scint.	[152] DANEVICH	03
> 500	90	^{136}Xe	$0\nu\chi$	Liquid Xe Scint.	[153] BERNABEI	02D
> 5.8	90	^{100}Mo	$0\nu\chi$	ELEGANT V	[154] FUSHIMI	02
> 0.32	90	^{100}Mo	$0\nu\chi$	Liq. Ar ioniz.	[155] ASHITKOV	01
> 0.0035	90	^{160}Gd	$0\nu\chi$	^{160}Gd$_2$SiO$_5$:Ce	[156] DANEVICH	01
> 0.013	90	^{160}Gd	$0\nu2\chi$	^{160}Gd$_2$SiO$_5$:Ce	[157] DANEVICH	01
> 2.3	90	^{82}Se	$0\nu\chi$	NEMO 2	[158] ARNOLD	00
> 0.31	90	^{96}Zr	$0\nu\chi$	NEMO 2	[159] ARNOLD	00
> 0.63	90	^{82}Se	$0\nu2\chi$	NEMO 2	[160] ARNOLD	00
> 0.063	90	^{96}Zr	$0\nu2\chi$	NEMO 2	[160] ARNOLD	00
> 0.16	90	^{100}Mo	$0\nu2\chi$	NEMO 2	[160] ARNOLD	00
> 2.4	90	^{82}Se	$0\nu\chi$	NEMO 2	[161] ARNOLD	98
> 7.2	90	^{136}Xe	$0\nu2\chi$	TPC	[162] LUESCHER	98
> 7.91	90	^{76}Ge		SPEC	[163] GUENTHER	96
> 17	90	^{76}Ge		CNTR	BECK	93

[148] 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 $(7.7–1.28 \times 0.4=7.2) \times 10^{24}$.

[149] 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.

[150] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search.

[151] 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.

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

[153] 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.

[154] 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) × 10^{-5}.

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

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

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

[158] 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.

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

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

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

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

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

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

$v_1 = v_2$ is usually assumed (v_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. • • •				
3 to 20	[164] MOROI	98	COSM	K, hot dark matter
< 0.007	[165] BORISOV	97	ASTR	D, neutron star
< 4	[166] KACHELRIESS	97	ASTR	D, neutron star cooling
<(0.5–6) × 10^{-3}	[167] KEIL	97	ASTR	SN 1987A
< 0.018	[168] RAFFELT	95	ASTR	D, red giant
< 0.010	[169] ALTHERR	94	ASTR	D, red giants, white dwarfs
	[170] 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	[171] BERSHADY	91	ASTR	D, K, intergalactic light
<10	[172] KIM	91C	COSM	D, K, mass density of the universe, supersymmetry
	[173] RAFFELT	91B	ASTR	D,K, SN 1987A
< 1 × 10^{-3}	[174] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS	90	ASTR	D,K, SN 1987A
	[175] ENGEL	90	ASTR	D,K, SN 1987A
< 0.02	[176] RAFFELT	90D	ASTR	D, red giant
< 1 × 10^{-3}	[177] BURROWS	89	ASTR	D,K, SN 1987A
<(1.4–10) × 10^{-3}	[178] ERICSON	89	ASTR	D,K, SN 1987A
< 3.6 × 10^{-4}	[179] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
< 1 × 10^{-3}	RAFFELT	88	ASTR	D,K, SN 1987A
	[180] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[181] RAFFELT	87	ASTR	K, red giant
< 2–5	TURNER	87	COSM	K, thermal production
< 0.01	[182] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[183] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[184] KAPLAN	85	ASTR	K, red giant
< 0.003–0.02	IWAMOTO	84	ASTR	D, K, neutron star
> 1 × 10^{-5}	ABBOTT	83	COSM	D,K, mass density of the universe
> 1 × 10^{-5}	DINE	83	COSM	D,K, mass density of the universe
< 0.04	ELLIS	83B	ASTR	D, red giant
> 1 × 10^{-5}	PRESKILL	83	COSM	D,K, mass density of the universe
< 0.1	BARROSO	82	ASTR	D, red giant
< 1	[185] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[164] MOROI 98 points out that a KSVZ axion of this mass range (see CHANG 93) can be a viable hot dark matter of Universe, as long as the model-dependent $g_{A\gamma}$ is accidentally small enough as originally emphasized by KAPLAN 85; see Fig. 1.

[165] BORISOV 97 bound is on the axion-electron coupling $g_{ae} < 1\times10^{-13}$ from the photo-production of axions off of magnetic fields in the outer layers of neutron stars.

[166] KACHELRIESS 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-10}$ from the production of axions in strongly magnetized neutron stars. The authors also quote a stronger limit, $g_{ae} < 9 \times 10^{-13}$ which is strongly dependent on the strength of the magnetic field in white dwarfs.

[167] KEIL 97 uses new measurements of the axial-vector coupling strength of nucleons, as well as a reanalysis of many-body effects and pion-emission processes in the core of the neutron star, to update limits on the invisible-axion mass.

[168] RAFFELT 95 reexamined the constraints on axion emission from red giants due to the axion-electron coupling. They improve on DEARBORN 86 by taking into proper account degeneracy effects in the bremsstrahlung rate. The limit comes from requiring the red giant core mass at helium ignition not to exceed its standard value by more than 5% (0.025 solar masses).

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

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

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

[172] KIM 91C argues that the bound from the mass density of the universe will change drastically for the supersymmetric models due to the entropy production of saxion (scalar component in the axionic chiral multiplet) decay. Note that it is an *upperbound* rather than a lowerbound.

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

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

[175] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to 2.5×10^{-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 $g_{AN} \sim 10^{-6}$.

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

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

[178] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.

[179] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.

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

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

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

[183] 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.

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

[185] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV^{-1}.

Search for Relic Invisible Axions

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

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.5 × 10^{-43}	95	[186] HAGMANN	98	CNTR	m_{A^0}= 2.9–3.3 × 10^{-6} eV
		[187] KIM	98	THEO	
<2 × 10^{-41}		[188] HAGMANN	90	CNTR	m_{A^0} = (5.4–5.9)10^{-6} eV
<1.3 × 10^{-42}	95	[189] WUENSCH	89	CNTR	m_{A^0} = (4.5–10.2)10^{-6} eV
<2 × 10^{-41}	95	[189] WUENSCH	89	CNTR	m_{A^0} = (11.3–16.3)10^{-6} eV

[186] Based on the conversion of halo axions to microwave photons. Limit assumes ρ_A=0.45 GeV cm^{-3}. At 90%CL this result excludes a version of KSVZ axions as dark matter in the halo of our Galaxy, for the quoted axion mass range. See ASZTALOS 01 for more details.

[187] KIM 98 calculated the axion-to-photon couplings for various axion models and compared them to the HAGMANN 90 bounds. This analysis demonstrates a strong model dependence of $G_{A\gamma\gamma}$ and hence the bound from relic axion search.

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

[189] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagnetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and ρ_A = 300 MeV/cm^3 that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2$ $\rho_A = 4\times10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Invisible A^0 (Axion) Limits from Photon Coupling

Limits are for the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma}\phi_A\mathbf{E}\cdot\mathbf{B}$.

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

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

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

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

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

[193] ASTIER 00B looked for production of axions from the interaction of high-energy photons with the horn magnetic field and their subsequent re-conversion to photons via the interaction with the NOMAD dipole magnetic field.

[194] MASSO 00 studied limits on axion-proton coupling using the induced axion-photon coupling through the proton loop and CAMERON 93 bound on the axion-photon coupling using optical rotation. They obtained the bound $g_p^2/4\pi < 1.7 \times 10^{-9}$ for the coupling $g_p \overline{p} \gamma_5 p \phi_A$.

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

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

[197] Experiment based on proposal by MAIANI 86.

[198] Experiment based on proposal by VANBIBBER 87.

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

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

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

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee} \partial_\mu \phi_A \overline{e} \gamma^\mu \gamma_5 e$ in GeV^{-1}, or equivalenty, the dipole-dipole potential $\frac{G_{Aee}^2}{4\pi}\,((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})\,(\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ 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. • • •					
$<5.3 \times 10^{-5}$	66	[202] NI	94		Induced magnetism
$<6.7 \times 10^{-5}$	66	[202] CHUI	93		Induced magnetism
$<3.6 \times 10^{-4}$	66	[203] PAN	92		Torsion pendulum
$<2.7 \times 10^{-5}$	95	[202] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[204] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[203] RITTER	90		Torsion pendulum
$<6.6 \times 10^{-5}$	95	[202] VOROBYOV	88		Induced magnetism

[202] These experiments measured induced magnetization of a bulk material by the spin-dependent potential generated from other bulk material with aligned electron spins, where the magnetic field is shielded with superconductor.

[203] These experiments used a torsion pendulum to measure the potential between two bulk matter objects where the spins are polarized but without a net magnetic field in either of them.

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

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 3.2 \times 10^4$	95	[205] KRCMAR	01	CNTR	Solar axion
<745	90	[206] KRCMAR	98	CNTR	Solar axion

[205] 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 $S=0.4$.

[206] 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 $S=3F-D \simeq 0.5$.

Axion Limits from T-violating Medium-Range Forces

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

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[207] NI	99		paramagnetic Tb F$_3$
	[208] POSPELOV	98	THEO	neutron EDM
	[209] YOUDIN	96		
	[210] RITTER	93		torsion pendulum
	[211] VENEMA	92		nuclear spin-precession frequencies
	[212] WINELAND	91	NMR	

[207] NI 99 searched for a T-violating medium-range force acting on paramagnetic Tb F$_3$ salt. See their Fig. 1 for the result.

[208] POSPELOV 98 studied the possible contribution of T-violating Medium-Range Force to the neutron electric dipole moment, which is possible when axion interactions violate CP. The size of the force among nucleons must be smaller than gravity by a factor of 2×10^{-10} (1 cm$/\lambda_A$), where $\lambda_A=\hbar/m_A c$.

[209] 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.

[210] RITTER 93 used a torsion pendulum to study the influence of bulk mass with polarized electrons on the pendulum.

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

[212] 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.

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