

Gauge & Higgs Boson Particle Listings

Axions (A^0) and Other Very Light Bosons

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

AXIONS AND OTHER VERY LIGHT BOSONS

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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

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

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 $\mathcal{L}_\theta = \theta_{\text{eff}} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \tilde{F}_{\mu\nu}^a$ is so small ($\theta_{\text{eff}} \lesssim 10^{-9}$) as required by the current limits on the neutron electric dipole moment, even though $\theta_{\text{eff}} \sim O(1)$ 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 $\tilde{F}_{\mu\nu}^a = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma a}$. 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

$$\mathcal{L} = \left(\theta_{\text{eff}} - \frac{\phi_A}{f_A}\right) \frac{\alpha_s}{8\pi} F^{\mu\nu a} \tilde{F}_{\mu\nu}^a, \quad (2)$$

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 $\phi_A = \theta_{\text{eff}} f_A$ cancelling θ_{eff} and solving the strong CP problem. The mass of the axion is inversely proportional to f_A as

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

The original axion model [1,5] assumes $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247 \text{ GeV}$ 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 $f_A \sim 10^{12} \text{ GeV}$ 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.

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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, $B(K^+ \rightarrow \pi^+ \phi_F) < 3 \times 10^{-10}$ [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 $\nu_1 \rightarrow \nu_2 \phi_F$ (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 $\langle\rho\rangle \approx 0.6 \times 10^4 \text{ g cm}^{-3}$ and $\langle T \rangle \approx 0.7 \times 10^8 \text{ K}$. The new energy-loss rate must not exceed about $10 \text{ ergs g}^{-1} \text{ s}^{-1}$ 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 $\langle\rho\rangle \approx 2 \times 10^5 \text{ g cm}^{-3}$ and $\langle T \rangle \approx 1 \times 10^8 \text{ K}$. 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

$$g_{Xe} \lesssim \begin{cases} 0.5 \times 10^{-12} & \text{for pseudoscalars [3]} \\ 1.3 \times 10^{-14} & \text{for scalars [4]} \end{cases}, \quad (1)$$

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

$$g_{B,L} \lesssim 10^{-23} \quad (2)$$

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]

$$g_{A\gamma} \lesssim 0.6 \times 10^{-10} \text{ GeV}^{-1}. \quad (3)$$

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,

$$3 \times 10^{-10} \lesssim g_{AN} \lesssim 3 \times 10^{-7} \quad (4)$$

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

$$10^{-6} \lesssim g_{AN} \lesssim 10^{-3} \quad (5)$$

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 $m_A = 0.62 \text{ eV} (10^7 \text{ GeV}/f_A)$, Eq. (3) yields $m_A \lesssim 0.4 \text{ eV}$ for $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limit is $m_A \lesssim 0.008 \text{ eV}$ 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 $m_A \lesssim 0.01 \text{ eV}$ as a generic limit (Fig. 1).

In the early universe, axions come into thermal equilibrium only if $f_A \lesssim 10^8 \text{ GeV}$ [12]. Some fraction of the relic axions end up in galaxies and galaxy clusters. Their decay $a \rightarrow 2\gamma$ 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 $m_a < 3.5 \text{ eV}$ [13]. For $m_a \gtrsim 30 \text{ eV}$, the axion lifetime is shorter than the age of the universe.

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

$$\Omega_A h^2 \approx 1.9 \times 3^{\pm 1} (1 \mu\text{eV}/m_A)^{1.175} \Theta_1^2 F(\Theta_1) \quad (6)$$

where h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. 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

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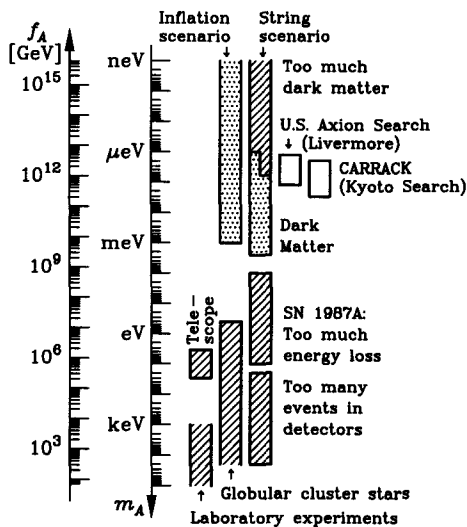


Figure 1: Astrophysical and cosmological exclusion regions (hatched) for the axion mass m_A or equivalently, the Peccei-Quinn scale f_A . An “open end” of an exclusion bar means that it represents a rough estimate; its exact location has not been established or it depends on detailed model assumptions. 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.

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 $\Theta_i^2 F(\Theta_i) \sim 1$ to avoid fine-tuning the initial conditions.

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 $T_{\text{reheat}} > f_A$, 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]

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

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 $m_A = 6\text{--}2500 \mu\text{eV}$ 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 Haggmann, 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)

(by C. Hagmann, K. van Bibber, and L.J. Rosenberg)

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 searches where the axion is assumed to be dark matter, searches where the Sun is presumed to be a source of axions, and purely laboratory experiments. 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-photon coupling $g_{A\gamma}$, to which the present review is confined. As discussed in Part II of this Review by G. Raffelt, the lower bound derives from a cosmological overclosure argument, and the upper bound from SN1987A [2]. Limits from stellar evolution overlap seamlessly above that, connecting with accelerator-based limits which 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 $g_\gamma = (E/N - 1.92)/2$, where E/N is a model-dependent number. It is noteworthy however, that two quite distinct models lead to axion-photon couplings which are not very different. For 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], $g_\gamma = -0.96$. The Lagrangian $L = g_{A\gamma} \mathbf{E} \cdot \mathbf{B} \phi_A$, 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, $k_\gamma - k_A \sim m_A^2/2\omega \ll \omega$, 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].

Below are discussed several experimental techniques constraining $g_{A\gamma}$, and their results. Also included are recent but yet-unpublished results, and projected sensitivities for experiments soon to be upgraded.

III.1. Microwave cavity experiments: Possibly the most promising avenue to the discovery of the axion presumes that axions constitute a significant fraction of the dark matter halo of our galaxy. The maximum likelihood density for the Cold Dark Matter (CDM) component of our galactic halo is $\rho_{\text{CDM}} = 7.5 \times 10^{-25} \text{ g/cm}^3 (450 \text{ MeV/cm}^3)$ [6]. 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

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abundant [2]. As shown by Sikivie [7], halo axions may be detected by their resonant conversion into a quasi-monochromatic microwave signal in a high- Q cavity permeated by a strong 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 ultra-fine structure due to axions recently fallen into the galaxy and not yet thermalized [8]. The feasibility of the technique was established in early experiments of small sensitive volume, $V = O(1 \text{ liter})$ [9,10] with High Electron Mobility Transistor (HEMT) amplifiers, which set limits on axions in the mass range $4.5 < m_A < 16.3 \mu\text{eV}$, but at power sensitivity levels 2–3 orders of magnitude too high to see KSVZ and DFSZ axions (the conversion power $P_{A \rightarrow \gamma} \propto g_{A\gamma}^2$). A recent large-scale experiment ($B \sim 7.5 \text{ T}, V \sim 200 \text{ liter}$) has achieved sensitivity to KSVZ axions over a narrow mass range $2.77 < m_A < 3.3 \mu\text{eV}$, and continues to take data [11]. The exclusion regions shown in Fig. 1 for Refs. [9–12] are all normalized to the best-fit Cold Dark Matter density $\rho_{\text{CDM}} = 7.5 \times 10^{-25} \text{ g/cm}^3 (450 \text{ MeV/cm}^3)$, and 90% CL. Recent developments in DC SQUID amplifiers [12] and Rydberg atom single-quantum detectors [13] promise dramatic improvements in noise temperature, which will enable rapid scanning of the axion mass range at or below the DFSZ limit. The region of the microwave cavity experiments is shown in detail in Fig. 2.

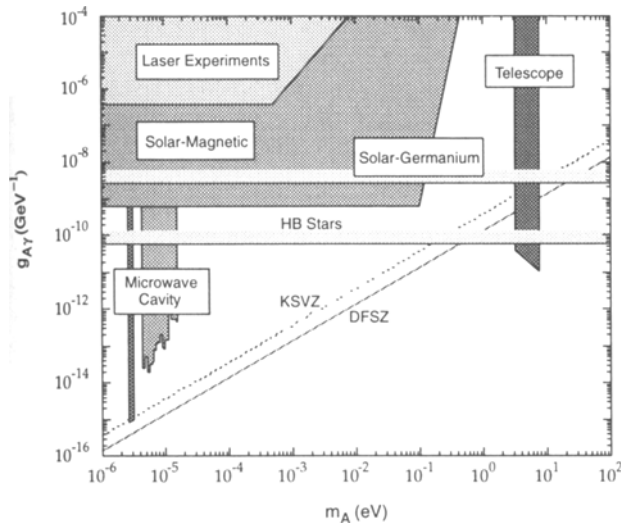


Figure 1: Exclusion region in mass vs. axion-photon coupling ($m_A, g_{A\gamma}$) for various experiments. The limit set by globular cluster Horizontal Branch Stars (“HB Stars”) is shown for Ref. 2.

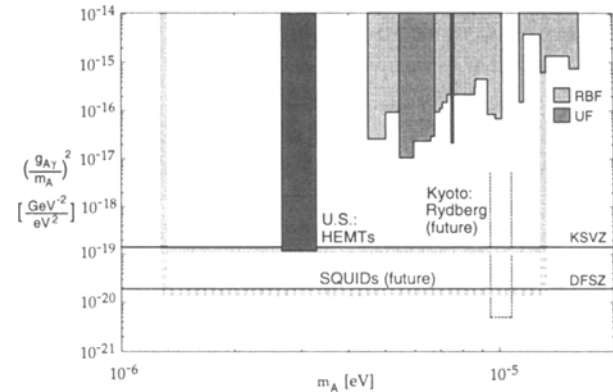


Figure 2: Exclusion region from the microwave cavity experiments, where the plot is flattened by presenting $(g_{A\gamma}/m_A)^2$ vs. m_A . The first-generation experiments (Rochester-BNL-FNAL, “RBF” [9]; University of Florida, “UF” [10]) and the US large-scale experiment in progress (“US” [11]) are all HEMT-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 [12] (shaded dashed line). The expected performance of the Kyoto experiment based on a Rydberg atom single-quantum receiver (dotted line) is also shown [13].

III.2. Telescope search for eV axions: For axions of mass greater than about 10^{-1} eV , their cosmological abundance is no longer dominated by vacuum misalignment or string radiation mechanisms, but rather by thermal production. Their contribution to the critical density is small, $\Omega \sim 0.01 (m_A/\text{eV})$. However, the spontaneous-decay lifetime of axions, $\tau(A \rightarrow 2\gamma) \sim 10^{25} \text{ sec} (m_A/\text{eV})^{-5}$ while irrelevant for μeV axions, is short enough to afford a powerful constraint on such thermally produced axions in the eV 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 $I_A \sim 10^{-17} (m_A/3 \text{ eV})^7 \text{ erg cm}^{-2} \text{ arcsec}^{-2} \text{ \AA}^{-1} \text{ sec}^{-1}$ for DFSZ axions, comparable to the continuum night emission. 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 [14]; no such line was observed between $3100\text{--}8300 \text{ \AA} (m_A = 3\text{--}8 \text{ eV})$ 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. 1 to easily exclude DFSZ axions throughout the mass range.

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III.3. A search for solar axions: As with the telescope search for thermally produced axions above, 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 to photons in a large magnetic field. However, their average energy is ~ 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 a gas, $m_\gamma = \omega_{\text{pl}}$, thus permitting the axion and photon dispersion relationships to be matched [15]. A first simple implementation of this proposal was carried out using a conventional dipole magnet with a conversion volume of variable-pressure helium gas and a xenon proportional chamber as the x-ray detector [16]. The magnet was fixed in orientation to take data for ~ 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 $0.03 \text{ eV} < m_A < 0.11$ eV (95% CL). A more ambitious experiment has recently been commissioned, using a superconducting magnet on a telescope mount to track the Sun continuously. A preliminary exclusion limit of $g_{A\gamma} < 6 \times 10^{-10} \text{GeV}^{-1}$ (95% CL) has been set for $m_A < 0.03$ eV [17].

Another search for solar axions has been carried out, using a single crystal germanium detector. It exploits 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 [18].

III.4. Photon regeneration (“invisible light shining through walls”): Photons propagating through a transverse field (with $\mathbf{E} \parallel \mathbf{B}$) 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 $\Pi \sim (1/4)(g_{A\gamma} B l)^2$. 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 [19]. The overall probability $P(\gamma \rightarrow A \rightarrow \gamma) = \Pi^2$. Such an experiment has been carried out, utilizing two magnets of length $l = 4.4$ m and $B = 3.7$ T. Axions with mass $m_A < 10^{-3}$ eV, and $g_{A\gamma} > 6.7 \times 10^{-7} \text{GeV}^{-1}$ were excluded at 95% CL [20,21]. 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 [22]. First, as the E_{\parallel} component, but not the 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 a 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 can be a mixing of virtual axions in the E_{\parallel} state, but not for the E_{\perp} state. This will lead to light which 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 magnets described in Sec. (III.4) above [21,23]. As in the case of photon regeneration, the observables are boosted linearly by the number of passes the laser beam makes in an optical cavity within the magnet. The polarization-rotation resulted in a stronger limit than that from ellipticity, $g_{A\gamma} < 3.6 \times 10^{-7} \text{GeV}^{-1}$ (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 . There are two experiments in construction with greatly improved sensitivity which while still far from being able to detect standard axions, should measure the QED “light-by-light” contribution for the first time [24,25]. The overall envelope for limits from the laser-based experiments in Sec. (III.4) and Sec. (III.5) is shown schematically in Fig. 1.

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<1.1 × 10 ⁻⁸	90	10 ALLIEGRO	92 SPEC	$K^+ \rightarrow \pi^+ A^0$ ($A^0 \rightarrow e^+ e^-$)
<5 × 10 ⁻⁴	90	11 ATIYA	92 B787	$\pi^0 \rightarrow \gamma X^0$
<4 × 10 ⁻⁶	90	12 MEIJERDREES	92 SPEC	$\pi^0 \rightarrow \gamma X^0$, $X^0 \rightarrow e^+ e^-$, $m_{X^0} = 100$ MeV
<1 × 10 ⁻⁷	90	13 ATIYA	90B B787	Sup. by KITCH- ING 97
<1.3 × 10 ⁻⁸	90	14 KORENCHEN...	87 SPEC	$\pi^+ \rightarrow e^+ \nu A^0$ ($A^0 \rightarrow e^+ e^-$)
<1 × 10 ⁻⁹	90	0 15 EICHLER	86 SPEC	Stopped $\pi^+ \rightarrow$ $e^+ \nu A^0$
<2 × 10 ⁻⁵	90	16 YAMAZAKI	84 SPEC	For $160 < m < 260$ MeV
<(1.5-4) × 10 ⁻⁶	90	16 YAMAZAKI	84 SPEC	K decay, $m_{A^0} \ll$ 100 MeV
	0	17 ASANO	82 CNTR	Stopped $K^+ \rightarrow$ $\pi^+ A^0$
	0	18 ASANO	81B CNTR	Stopped $K^+ \rightarrow$ $\pi^+ A^0$
		19 ZHITNITSKII	79	Heavy axion

³ ADLER 97 bound is for massless A^0 .⁴ KITCHING 97 limit is for $B(K^+ \rightarrow \pi^+ A^0) \cdot B(A^0 \rightarrow \gamma\gamma)$ and applies for $m_{A^0} \approx 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.⁵ 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.⁶ AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.⁷ 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.⁸ 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.⁹ NG 93 studied the production of X^0 via $\gamma\gamma \rightarrow \pi^0 \rightarrow \gamma X^0$ in the early universe at $T \approx 1$ 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 .¹⁰ 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.¹¹ 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.¹² 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 .¹³ ATIYA 90B limit is for $B(K^+ \rightarrow \pi^+ A^0) \cdot B(A^0 \rightarrow \gamma\gamma)$ 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.¹⁴ KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and $B(A^0 \rightarrow e^+ e^-) = 1$.¹⁵ 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 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.¹⁶ 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.¹⁷ ASANO 82 at KEK set limits for $B(K^+ \rightarrow \pi^+ A^0)$ for $m_{A^0} < 100$ MeV as $BR < 4 \times 10^{-8}$ for $\tau(A^0 \rightarrow n\gamma's) > 1 \times 10^{-9}$ s, $BR < 1.4 \times 10^{-6}$ for $\tau < 1 \times 10^{-9}$ s.¹⁸ ASANO 81B is KEK experiment. Set $B(K^+ \rightarrow \pi^+ A^0) < 3.8 \times 10^{-8}$ at CL = 90%.¹⁹ ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 ($3 < m < 40$ MeV) contradicts experimental muon anomalous magnetic moments. **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
>0.2	BARROSO 82	ASTR	Standard Axion
>0.25	¹ RAFFELT 82	ASTR	Standard Axion
>0.2	² DICUS 78C	ASTR	Standard Axion
>0.3	MIKAELIAN 78	ASTR	Stellar emission
>0.2	² SATO 78	ASTR	Standard Axion
	VYSOTSKII 78	ASTR	Standard Axion

¹ Lower bound from 5.5 MeV γ -ray line from the sun.² Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission. **A^0 (Axion) and Other Light Boson (X^0) Searches in Stable Particle Decays**

Limits are for branching ratios.

VALUE	CL% EVTS	DOCUMENT ID	TECN	COMMENT
<3.0 × 10 ⁻¹⁰	90	³ ADLER 97	B787	$K^+ \rightarrow \pi^+ A^0$
<5.0 × 10 ⁻⁸	90	⁴ KITCHING 97	B787	$K^+ \rightarrow \pi^+ A^0$ ($A^0 \rightarrow \gamma\gamma$)
<5.2 × 10 ⁻¹⁰	90	⁵ ADLER 96	B787	$K^+ \rightarrow \pi^+ A^0$
<2.8 × 10 ⁻⁴	90	⁶ AMSLER 96B	CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} < 65$ MeV
<3 × 10 ⁻⁴	90	⁶ AMSLER 96B	CBAR	$\eta \rightarrow \gamma X^0$, $m_{X^0} =$ 50-200 MeV
<4 × 10 ⁻⁵	90	⁶ AMSLER 96B	CBAR	$\eta' \rightarrow \gamma X^0$, $m_{X^0} = 50-925$ MeV
<6 × 10 ⁻⁵	90	⁶ AMSLER 94B	CBAR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} = 65-125$ MeV
<6 × 10 ⁻⁵	90	⁶ AMSLER 94B	CBAR	$\eta \rightarrow \gamma X^0$, $m_{X^0} = 200-525$ MeV
<0.007	90	⁷ MEIJERDREES94	CNTR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} = 25$ MeV
<0.002	90	⁷ MEIJERDREES94	CNTR	$\pi^0 \rightarrow \gamma X^0$, $m_{X^0} = 100$ MeV
<2 × 10 ⁻⁷	90	⁸ ATIYA 93B	B787	$K^+ \rightarrow \pi^+ A^0$
<3 × 10 ⁻¹³		⁹ NG 93	COSM	$\pi^0 \rightarrow \gamma X^0$

 A^0 (Axion) Searches in Quarkonium Decays

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

VALUE	CL% EVTS	DOCUMENT ID	TECN	COMMENT
<1.3 × 10 ⁻⁵	90	²⁰ BALEST 95	CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
<4.0 × 10 ⁻⁵	90	ANTREASYAN 90C	CBAL	$\Upsilon(1S) \rightarrow A^0 \gamma$
		21 ANTREASYAN 90C	RVUE	
<5 × 10 ⁻⁵	90	²² DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma$ ($A^0 \rightarrow e^+ e^-$)
<2 × 10 ⁻³	90	²³ DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma$ ($A^0 \rightarrow \gamma\gamma$)
<7 × 10 ⁻⁶	90	²⁴ DRUZHININ 87	ND	$\phi \rightarrow A^0 \gamma$ ($A^0 \rightarrow$ missing)
<3.1 × 10 ⁻⁴	90	0 ²⁵ ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ ($A^0 \rightarrow e^+ e^-$)

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$<4 \times 10^{-4}$	90	0	25	ALBRECHT	86D	ARG	$T(1S) \rightarrow A^0 \gamma$ ($A^0 \rightarrow \mu^+ \mu^-$, $\pi^+ \pi^-$, $K^+ K^-$)
$<8 \times 10^{-4}$	90	1	26	ALBRECHT	86D	ARG	$T(1S) \rightarrow A^0 \gamma$
$<1.3 \times 10^{-3}$	90	0	27	ALBRECHT	86D	ARG	$T(1S) \rightarrow A^0 \gamma$ ($A^0 \rightarrow e^+ e^-, \gamma \gamma$)
$<2 \times 10^{-3}$	90		28	BOWCOCK	86	CLEO	$T(2S) \rightarrow T(1S) \rightarrow A^0 \gamma$
$<5 \times 10^{-3}$	90		29	MAGERAS	86	CUSB	$T(1S) \rightarrow A^0 \gamma$
$<3 \times 10^{-4}$	90		30	ALAM	83	CLEO	$T(1S) \rightarrow A^0 \gamma$
$<9.1 \times 10^{-4}$	90		31	NICZYPORUK	83	LENA	$T(1S) \rightarrow A^0 \gamma$
$<1.4 \times 10^{-5}$	90		32	EDWARDS	82	CBAL	$J/\psi \rightarrow A^0 \gamma$
$<3.5 \times 10^{-4}$	90		33	SIVERTZ	82	CUSB	$T(1S) \rightarrow A^0 \gamma$
$<1.2 \times 10^{-4}$	90		33	SIVERTZ	82	CUSB	$T(3S) \rightarrow A^0 \gamma$

²⁰ BALEST 95 looked for a monochromatic γ from $T(1S)$ 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 $\gamma X \bar{X}$ for $0 < m_X < 3.1$ GeV.

²¹ The combined limit of ANTREASIAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_T C_{J/\psi} > 0.09$, where C_V ($V = T, J/\psi$)

is the reduction factor for $\Gamma(V \rightarrow A^0 \gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_T = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \rightarrow ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \rightarrow ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

²² 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.

²³ 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.

²⁴ 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.

²⁵ $\tau_{A^0} < 1 \times 10^{-13}$ s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma \gamma$ when $m_{A^0} < 100$ MeV.

²⁶ $\tau_{A^0} > 1 \times 10^{-7}$ s.

²⁷ Independent of τ_{A^0} .

²⁸ BOWCOCK 86 looked for A^0 that decays into $e^+ e^-$ in the cascade decay $T(2S) \rightarrow T(1S) \pi^+ \pi^-$ followed by $T(1S) \rightarrow A^0 \gamma$. The limit for $B(T(1S) \rightarrow A^0 \gamma) B(A^0 \rightarrow e^+ e^-)$ depends on m_{A^0} and τ_{A^0} . The quoted limit for $m_{A^0} = 1.8$ MeV is at $\tau_{A^0} \sim 2 \times 10^{-12}$ s, where the limit is the worst. The same limit 2×10^{-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.

²⁹ MAGERAS 86 looked for $T(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+ e^-$). The quoted branching fraction limit is for $m_{A^0} = 1.7$ MeV, at $\tau(A^0) \sim 4 \times 10^{-13}$ s where the limit is the worst.

³⁰ ALAM 83 is at CESR. This limit combined with limit for $B(J/\psi \rightarrow A^0 \gamma)$ (EDWARDS 82) excludes standard axion.

³¹ NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $B(T \rightarrow A^0 \gamma)$ derived from $B(J/\psi(1S) \rightarrow A^0 \gamma)$ limit (EDWARDS 82) excludes standard axion.

³² EDWARDS 82 looked for $J/\psi \rightarrow \gamma A^0$ decays by looking for events with a single γ [of energy $\sim 1/2$ the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

³³ SIVERTZ 82 is CESR experiment. Looked for $T \rightarrow \gamma A^0$, A^0 undetected. Limit for 1S (3S) is valid for $m_{A^0} < 7$ GeV (4 GeV).

A^0 (Axion) Searches in Positronium Decays

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

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2 \times 10^{-4}$	90	MAENO	95	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 850\text{--}1013$ keV
$<3.0 \times 10^{-3}$	90	34 ASAI	94	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 30\text{--}500$ keV
$<2.8 \times 10^{-5}$	90	35 AKOPYAN	91	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$ ($A^0 \rightarrow \gamma \gamma$), $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	36 ASAI	91	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO	90	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 30$ keV
$<(1\text{--}5) \times 10^{-4}$	95	37 TSUCHIYAKI	90	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} = 300\text{--}900$ keV
$<6.4 \times 10^{-5}$	90	38 ORITO	89	CNTR $o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 30$ keV
		39 AMALDI	85	CNTR Ortho-positronium
		40 CARBONI	83	CNTR Ortho-positronium

³⁴ The ASAI 94 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

³⁵ The AKOPYAN 91 limit applies for a short-lived A^0 with $\tau_{A^0} < 10^{-13}$ m_{A^0} [keV] s.

³⁶ ASAI 91 limit translates to $g_{A^0 e e}^2 / 4\pi < 1.1 \times 10^{-11}$ (90%CL) for $m_{A^0} < 800$ keV.

³⁷ The TSUCHIYAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

³⁸ ORITO 89 limit translates to $g_{A^0 e e}^2 / 4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger m_{A^0} : $B < 7.6 \times 10^{-6}$ at 100 keV.

³⁹ AMALDI 85 set limits $B(A^0 \gamma) / B(\gamma \gamma) < (1\text{--}5) \times 10^{-6}$ for $m_{A^0} = 900\text{--}100$ keV which are about 1/10 of the CARBONI 83 limits.

⁴⁰ CARBONI 83 looked for orthopositronium $\rightarrow A^0 \gamma$. Set limit for A^0 electron coupling squared, $g(e e A^0)^2 / (4\pi) < 6 \times 10^{-10}$ - 7×10^{-9} for m_{A^0} from 150-900 keV (CL = 99.7%). This is about 1/10 of the bound from $g\text{--}2$ experiments.

A^0 (Axion) Search in Photoproduction

VALUE DOCUMENT ID COMMENT

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

⁴¹ BASSOMPIERRE... 95 $m_{A^0} = 1.8 \pm 0.2$ MeV

⁴¹ 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 $m_{e^+ e^-} = 2.1\text{--}3.5$ 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. • • •

⁴² AHMAD 97 SPEC e^+ production

⁴³ LEINBERGER 97 SPEC $A^0 \rightarrow e^+ e^-$

⁴⁴ GANZ 96 SPEC $A^0 \rightarrow e^+ e^-$

⁴⁵ KAMEL 96 EMUL ^{32}S emulsion, $A^0 \rightarrow e^+ e^-$

⁴⁶ BLUEMLEIN 92 BDMP $A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$

⁴⁷ MEIJERDREES 92 SPEC $\pi^- p \rightarrow n A^0, A^0 \rightarrow e^+ e^-$

⁴⁸ BLUEMLEIN 91 BDMP $A^0 \rightarrow e^+ e^-, 2\gamma$

⁴⁹ FAISSNER 89 OSPK Beam dump, $A^0 \rightarrow e^+ e^-$

⁵⁰ DEBOER 88 RVUE $A^0 \rightarrow e^+ e^-$

⁵¹ EL-NADI 88 EMUL $A^0 \rightarrow e^+ e^-$

⁵² FAISSNER 88 OSPK Beam dump, $A^0 \rightarrow 2\gamma$

⁵³ BADIER 86 BDMP $A^0 \rightarrow e^+ e^-$

⁵⁴ BERGSMAN 85 CHRM CERN beam dump

⁵⁴ BERGSMAN 85 CHRM CERN beam dump

⁵⁵ FAISSNER 83 OSPK Beam dump, $A^0 \rightarrow 2\gamma$

⁵⁶ FAISSNER 83B RVUE LAMPF beam dump

⁵⁷ FRANK 83B RVUE LAMPF beam dump

⁵⁸ HOFFMAN 83 CNTR $\pi p \rightarrow n A^0$
($A^0 \rightarrow e^+ e^-$)

⁵⁹ FETSCHER 82 RVUE See FAISSNER 81B

⁶⁰ FAISSNER 81 OSPK CERN PS ν wideband

⁶¹ FAISSNER 81B OSPK Beam dump, $A^0 \rightarrow 2\gamma$

⁶² KIM 81 OSPK 26 GeV $pN \rightarrow A^0 X$

⁶³ FAISSNER 80 OSPK Beam dump, $A^0 \rightarrow e^+ e^-$

$<1 \times 10^{-8}$ 90 64 JACQUES 80 HLBC 28 GeV protons

$<1 \times 10^{-14}$ 90 64 JACQUES 80 HLBC Beam dump

65 SOUKAS 80 CALO 28 GeV p beam dump

66 BECHIS 79 CNTR

$<1 \times 10^{-8}$ 90 67 COTEUS 79 OSPK Beam dump

$<1 \times 10^{-3}$ 95 68 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 69 BELLOTTI 78 HLBC Beam dump

$<5.4 \times 10^{-14}$ 90 69 BELLOTTI 78 HLBC $m_{A^0} = 1.5$ MeV

$<4.1 \times 10^{-9}$ 90 69 BELLOTTI 78 HLBC $m_{A^0} = 1$ MeV

$<1 \times 10^{-8}$ 90 70 BOSETTI 78B HYBR Beam dump

71 DONNELLY 78

$<0.5 \times 10^{-8}$ 90 HANSL 78D WIRE Beam dump

72 MICELMAC... 78

73 VYSOTSKI 78

⁴² AHMAD 97 reports a result of APEX Collaboration which studied positron production in $^{238}\text{U} + ^{232}\text{Ta}$ and $^{238}\text{U} + ^{181}\text{Ta}$ collisions, without requiring a coincident electron. No narrow lines were found for $250 < E_{e^+} < 750$ keV.

⁴³ LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy $e^+ e^-$ line at ~ 635 keV in $^{238}\text{U} + ^{181}\text{Ta}$ collision. Limits on the production probability for a narrow sum-energy $e^+ e^-$ line are set. See their Table 2.

⁴⁴ GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of $e^+ e^-$ pairs from $^{238}\text{U} + ^{181}\text{Ta}$ and $^{238}\text{U} + ^{232}\text{Th}$ 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.

⁴⁵ 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 $m_{e e} > 2$ MeV.

⁴⁶ 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.

See key on page 213

Gauge & Higgs Boson Particle Listings
Axions (A^0) and Other Very Light Bosons

- 47 MEIJERDREES 92 give $\Gamma(\pi^- p \rightarrow n A^0) B(A^0 \rightarrow e^+ e^-) / \Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0} = 100$ MeV, $\tau_{A^0} = 10^{-11} - 10^{-23}$ sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25-136$ MeV.
- 48 BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \rightarrow e^+ e^-$, 2γ are found. Fig. 6 gives the excluded region in m_{A^0} - x plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m_{A^0} < 3.2$ MeV for most $x > 1$, $0.2-11$ MeV for most $x < 1$.
- 49 FAISSNER 89 searched for $A^0 \rightarrow e^+ e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m_e - 20$ MeV is excluded. Lower limit on f_{A^0} of $\approx 10^4$ GeV is given for $m_{A^0} = 2m_e - 20$ MeV.
- 50 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.
- 51 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.
- 52 FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \rightarrow \gamma\gamma$. A standard axion decaying to 2γ is excluded except for a region $x \approx 1$. Lower limit on f_{A^0} of $10^2 - 10^3$ GeV is given for $m_{A^0} = 0.1-1$ MeV.
- 53 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.
- 54 BERGSMA 85 look for $A^0 \rightarrow 2\gamma, e^+ e^-, \mu^+ \mu^-$. First limit above is for $m_{A^0} = 1$ MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0} - m_{A^0}$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 $A^0, m_{A^0} < 180$ keV and $\tau > 0.037$ s. (CL = 90%). For the axion of FAISSNER 81b at 250 keV, BERGSMA 85 expect 15 events but observe zero.
- 55 FAISSNER 83 observed 19 $1-\gamma$ and 12 $2-\gamma$ 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.
- 56 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 $[d\sigma(A^0)/d\omega] m_{A^0} / \tau_{A^0} < 14 \times 10^{-35}$ cm² sr⁻¹ MeV ms⁻¹. See comment on FRANK 83b.
- 57 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.
- 58 HOFFMAN 83 set CL = 90% limit $d\sigma/d\Omega B(e^+ e^-) < 3.5 \times 10^{-32}$ cm²/GeV² for $140 < m_{A^0} < 160$ MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.
- 59 FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since $2-\gamma$ peak rate remarkably decreases if iron wall is set in front of the decay region.
- 60 FAISSNER 81 see excess μe events. Suggest axion interactions.
- 61 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 $\eta-A^0$ 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, CAVIGNAC 83, and ANANEV 85.
- 62 KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86 \sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.
- 63 FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+ e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit $20/(A^0 \text{ mass})$ MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m_{A^0} < 2m_e$.
- 64 JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interaction}) < 7. \times 10^{-68}$ cm⁴, CL = 90%]. Second limit is from nonobservation of axion decays into 2γ 's or $e^+ e^-$, and for axion mass a few MeV.
- 65 SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.
- 66 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.
- 67 COTEUS 79 is a beam dump experiment at BNL.
- 68 DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.
- 69 BELLOTTI 78 first value comes from search for $A^0 \rightarrow e^+ e^-$. Second value comes from search for $A^0 \rightarrow 2\gamma$, assuming mass $< 2m_e$. For any mass satisfying this, limit is above value $\times (\text{mass}^{-4})$. Third value uses data of PL 60B 401 and quotes $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67}$ cm⁴.
- 70 BOSETTI 78b quotes $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67}$ cm⁴.
- 71 DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.
- 72 MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).
- 73 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. • • •			
	74	ALTMANN 95	CNTR Reactor; $A^0 \rightarrow e^+ e^-$
	75	KETOV 86	SPEC Reactor, $A^0 \rightarrow \gamma\gamma$
	76	KOCH 86	SPEC Reactor; $A^0 \rightarrow \gamma\gamma$
	77	DATAR 82	CNTR Light water reactor
	78	VUILLEUMIER 81	CNTR Reactor, $A^0 \rightarrow 2\gamma$
74 ALTMANN 95 looked for A^0 decaying into $e^+ e^-$ from the Bugey5 nuclear reactor. They obtain an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma) \times B(A^0 \rightarrow e^+ e^-) < 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier A^0 . In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances Z^0 in the (m_{X^0}, f_{X^0}) plane.			
75 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.			
76 KOCH 86 searched for $A^0 \rightarrow \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m_{A^0} = 250$ keV gives 10^{-5} for the ratio. Not valid for $m_{A^0} > 1022$ keV.			
77 DATAR 82 looked for $A^0 \rightarrow 2\gamma$ in neutron capture ($n p \rightarrow d A^0$) at Tarapur 500 MW reactor. Sensitive to sum of $l = 0$ and $l = 1$ amplitudes. With ZEHNDER 81 ($l = 0$ - ($l = 1$)) result, assert nonexistence of standard A^0 .			
78 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. • • •					
			79	DEBOER 97c	RVUE M1 transitions
			80	TSUNODA 95	CNTR ²⁵² Cf fission, $A^0 \rightarrow ee$
			81	MINOWA 93	CNTR ¹³⁹ La* \rightarrow ¹³⁹ La A^0
			82	HICKS 92	CNTR ³⁵ S decay, $A^0 \rightarrow \gamma\gamma$
			83	ASANUMA 90	CNTR ²⁴¹ Am decay
			84	DEBOER 90	CNTR ⁸ Be* \rightarrow ⁸ Be A^0
			85	BINI 89	CNTR ¹⁶ O* \rightarrow ¹⁶ O X^0 , $X^0 \rightarrow e^+ e^-$
			86	AVIGNONE 88	CNTR Cu* \rightarrow Cu A^0 ($A^0 \rightarrow 2\gamma, A^0 e \rightarrow \gamma e, A^0 Z \rightarrow \gamma Z$)
			87	DATAR 88	CNTR ¹² C* \rightarrow ¹² C A^0
			88	DEBOER 88c	CNTR ¹⁶ O* \rightarrow ¹⁶ O X^0 , $X^0 \rightarrow e^+ e^-$
			89	DOEHNER 88	SPEC ² H*, $A^0 \rightarrow e^+ e^-$
			90	SAVAGE 88	CNTR Nuclear decay (isovector)
			90	SAVAGE 88	CNTR Nuclear decay (isoscalar)
			91	HALLIN 86	SPEC ⁶ Li isovector decay
			91	HALLIN 86	SPEC ¹⁰ B isoscalar decays
			91	HALLIN 86	SPEC ¹⁴ N isoscalar decays
			92	SAVAGE 86b	CNTR ¹⁴ N*
			93	ANANEV 85	CNTR Li*, deut* $A^0 \rightarrow 2\gamma$
			94	CAVIGNAC 83	CNTR ⁹⁷ Nb*, deut* transition $A^0 \rightarrow 2\gamma$
			95	ALEKSEEV 82b	CNTR Li*, deut* transition $A^0 \rightarrow 2\gamma$
			96	LEHMANN 82	CNTR Cu* \rightarrow Cu A^0 ($A^0 \rightarrow 2\gamma$)
			97	ZEHNDER 82	CNTR Li*, Nb* decay, n-capt.
			98	ZEHNDER 81	CNTR Ba* \rightarrow Ba A^0 ($A^0 \rightarrow 2\gamma$)
			99	CALAPRICE 79	Carbon
79 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.					
80 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.					
81 MINOWA 93 studied chain process, ¹³⁹ Ce \rightarrow ¹³⁹ La* by electron capture and M1 transition of ¹³⁹ La* to the ground state. It does not assume decay modes of A^0 . The bound applies for $m_{A^0} < 166$ keV.					
82 HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec.					
83 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.					
84 The DEBOER 90 limit is for the branching ratio ⁸ Be* (18.15 MeV, 1 ⁺) \rightarrow ⁸ Be A^0 , $A^0 \rightarrow e^+ e^-$ for the mass range $m_{A^0} = 4-15$ MeV.					
85 The BINI 89 limit is for the branching fraction of ¹⁶ O* (6.05 MeV, 0 ⁺) \rightarrow ¹⁶ O X^0 , $X^0 \rightarrow e^+ e^-$ for $m_X = 1.5-3.1$ MeV. $\tau_{X^0} \lesssim 10^{-11}$ s is assumed. The spin-parity of X is restricted to 0 ⁺ or 1 ⁻ .					

Gauge & Higgs Boson Particle Listings

Axions (A^0) and Other Very Light Bosons

- 86** AVIGNONE 88 looked for the 1115 keV transition $C^* \rightarrow CuA^0$, either from $A^0 \rightarrow 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV.
- 87** DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \rightarrow e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range 10^{-13} – 10^{-8} s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m = 1.7$ MeV; see the paper for the τ - m dependence of the limit.
- 88** The limit is for the branching fraction of $^{16}O^*(6.05 \text{ MeV}, 0^+) \rightarrow ^{16}O\chi^0, \chi^0 \rightarrow e^+e^-$ against internal pair conversion for $m_{\chi^0} = 1.7$ MeV and $\tau_{\chi^0} < 10^{-11}$ s. Similar limits are obtained for $m_{\chi^0} = 1.3$ – 3.2 MeV. The spin parity of χ^0 must be either 0^+ or 1^- . The limit at 1.7 MeV is translated into a limit for the χ^0 -nucleon coupling constant: $g_{\chi^0 NN}^2/4\pi < 2.3 \times 10^{-9}$.
- 89** 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.
- 90** 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 8Be , and the 18.15 MeV state $J^P = 1^+$ in 8Be . This experiment constrains the isovector coupling of A^0 to hadrons, if $m_{A^0} = (1.1 \rightarrow 2.2)$ MeV and the isoscalar coupling of A^0 to hadrons, if $m_{A^0} = (1.1 \rightarrow 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.
- 91** Limits are for $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of e^+e^- pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$ s. 6Li 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.
- 92** 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.
- 93** 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.
- 94** CAVAIGNAC 83 at Bugey reactor exclude axion at any $m_{97}Nb^*$ decay and axion with m_{A^0} between 275 and 288 keV (deuteron* decay).
- 95** 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).
- 96** LEHMANN 82 obtained $A^0 \rightarrow 2\gamma$ rate $< 6.2 \times 10^{-5}/s$ (CL = 95%) excluding m_{A^0} between 100 and 1000 keV.
- 97** ZEHNDER 82 used Goergen 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 .
- 98** ZEHNDER 81 looked for $Ba^* \rightarrow A^0Ba$ transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}/s$ (CL = 95%) excluding $m_{A^0} > 160$ keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.
- 99** CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

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

VALUE (s)	CL%	DOCUMENT ID	TECN	COMMENT
none 4×10^{-16} – 4.5×10^{-12}	90	100 BROSS	91 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		101 GUO	90 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		102 BJORKEN	88 CALO	$A \rightarrow e^+e^-$ or 2γ
		103 BLINOV	88 MD1	$ee \rightarrow eeA^0$ ($A^0 \rightarrow ee$)
none 1×10^{-14} – 1×10^{-10}	90	104 RIORDAN	87 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 1×10^{-14} – 1×10^{-11}	90	105 BROWN	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 6×10^{-14} – 9×10^{-11}	95	106 DAVIER	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 3×10^{-13} – 1×10^{-7}	90	107 KONAKA	86 BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
100 The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. $B(A^0 \rightarrow e^+e^-) = 1$ assumed. Excluded domain in the τ_{A^0} - m_{A^0} plane extends up to $m_{A^0} \approx 7$ MeV (see Fig. 5). Combining with electron g -2 constraint, axions coupling only to e^+e^- ruled out for $m_{A^0} < 4.8$ MeV (90%CL).				
101 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).				
102 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.				
103 BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \rightarrow \gamma\gamma)B(A^0 \rightarrow e^+e^-) < 2$ eV (CL=90%).				
104 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.				
105 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.				
106 $m_{A^0} \approx 1.8$ 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.				

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

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

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

VALUE (10^{-3} eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 1.3	97	108 HALLIN	92 CNTR	$m_{A^0} = 1.75$ – 1.88 MeV
none 0.0016–0.47	90	109 HENDERSON	92C CNTR	$m_{A^0} = 1.5$ – 1.86 MeV
< 2.0	90	110 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	111 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	112 JUDGE	90 CNTR	$m_{A^0} = 1.832$ MeV, elastic
< 1.9	97	113 TSERTOS	89 CNTR	$m_{A^0} = 1.82$ MeV
$< (10$ – $40)$	97	113 TSERTOS	89 CNTR	$m_{A^0} = 1.51$ – 1.65 MeV
$< (1$ – $2.5)$	97	113 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	114 TSERTOS	88 CNTR	$m_{A^0} = 1.832$ MeV
		115 VANKLINKEN	88 CNTR	
		116 MAIER	87 CNTR	
< 2500	90	MILLS	87 CNTR	$m_{A^0} = 1.8$ MeV
		117 VONWIMMER.87	CNTR	

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

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

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

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

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

113 See also TSERTOS 88B in references.

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

115 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.

116 MAIER 87 obtained limits $R \lesssim 60$ eV (100 eV) at $m_{A^0} \approx 1.64$ MeV (1.83 MeV) for energy resolution $\Delta E_{\text{cm}} \approx 3$ keV, where R is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma_{ee}^2/\Gamma_{\text{total}}$. For a discussion implying that $\Delta E_{\text{cm}} \approx 10$ keV, see TSERTOS 89.

117 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 $e^+e^- \rightarrow \gamma\gamma$

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

VALUE (10^{-3} eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.18	95	VO	94 CNTR	$m_{A^0} = 1.1$ MeV
< 1.5	95	VO	94 CNTR	$m_{A^0} = 1.4$ MeV
< 12	95	VO	94 CNTR	$m_{A^0} = 1.7$ MeV
< 6.6	95	118 TRZASKA	91 CNTR	$m_{A^0} = 1.8$ MeV
< 4.4	95	WIDMANN	91 CNTR	$m_{A^0} = 1.78$ – 1.92 MeV
		119 FOX	89 CNTR	
< 0.11	95	120 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

118 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.

119 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).

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

See key on page 213

Gauge & Higgs Boson Particle Listings
Axions (A^0) and Other Very Light BosonsSearch for X^0 (Light Boson) Resonance in $e^+e^- \rightarrow \gamma\gamma\gamma$

The limit is for $\Gamma(X^0 \rightarrow e^+e^-)\Gamma(X^0 \rightarrow \gamma\gamma\gamma)/\Gamma_{\text{total}}$. 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	121 VO	94 CNTR	$m_{X^0}=1.1-1.9$ MeV
< 1.0	95	122 VO	94 CNTR	$m_{X^0}=1.1$ MeV
< 2.5	95	122 VO	94 CNTR	$m_{X^0}=1.4$ MeV
<120	95	122 VO	94 CNTR	$m_{X^0}=1.7$ MeV
< 3.8	95	123 SKALSEY	92 CNTR	$m_{X^0}=1.5$ MeV
121 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.				
122 VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.				
123 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	124 MITSUI	96 CNTR	γX^0
< 4	68	125 SKALSEY	95 CNTR	γX^0
<40	68	126 SKALSEY	95 RVUE	γX^0
< 0.18	90	127 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.26	90	128 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.33	90	129 ADACHI	94 CNTR	$\gamma X^0, X^0 \rightarrow \gamma\gamma\gamma$
124 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 $B(o\text{-Ps} \rightarrow \gamma\gamma X^0) < 6.2 \times 10^{-6}$. The bounds weaken for heavier X^0 .				
125 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.				
126 SKALSEY 95 reinterpreted the bound on γA^0 decay of $o\text{-Ps}$ 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.				
127 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.				
128 ADACHI 94 looked for a peak in the missing-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.				
129 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. • • •					
			130 BOBRAKOV	91	Electron quasi-magnetic interaction
< 3.3×10^{-2}	95		131 ALBRECHT	90E ARG	$\tau \rightarrow \mu X^0$, Familion
< 1.8×10^{-2}	95		131 ALBRECHT	90E ARG	$\tau \rightarrow e X^0$, Familion
< 6.4×10^{-9}	90		132 ATIYA	90 B787	$K^+ \rightarrow \pi^+ X^0$, Familion
< 1.1×10^{-9}	90		133 BOLTON	88 CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$, Familion
			134 CHANDA	88 ASTR	Sun, Majoron
			135 CHOI	88 ASTR	Majoron, SN 1987A
< 5×10^{-6}	90		136 PICCIOTTO	88 CNTR	$\pi \rightarrow e\nu X^0$, Majoron
< 1.3×10^{-9}	90		137 GOLDMAN	87 CNTR	$\mu \rightarrow e\gamma X^0$, Familion
< 3×10^{-4}	90		138 BRYMAN	86B RVUE	$\mu \rightarrow e X^0$, Familion
< 1×10^{-10}	90	0	139 EICHLER	86 SPEC	$\mu^+ \rightarrow e^+ X^0$, Familion
< 2.6×10^{-6}	90		140 JODIDIO	86 SPEC	$\mu^+ \rightarrow e^+ X^0$, Familion
			141 BALTRUSAIT..85	MRK3	$\tau \rightarrow \ell X^0$, Familion
			142 DICUS	83 COSM	$\nu(h\nu\gamma) \rightarrow \nu(\text{light}) X^0$
130 BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $\chi_e^2 < 2 \times 10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $\chi_e(G_F/8\pi\sqrt{2})^{1/2}$.					
131 ALBRECHT 90E limits are for $B(\tau \rightarrow \ell X^0)/B(\tau \rightarrow \ell\nu\bar{\nu})$. 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.					
132 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.					
133 BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.					
134 CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.					
135 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 $L_{\text{int}} = \frac{1}{2} h \bar{\nu}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\sum h_i^2)^{1/4}$.

- 136 PICCIOTTO 88 limit applies when $m_{X^0} < 55$ MeV and $\tau_{X^0} > 2$ ns, and it decreases to 4×10^{-7} at $m_{X^0} = 125$ MeV, beyond which no limit is obtained.
- 137 GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu (a + b\gamma_5) \psi_e \theta_\mu \phi_X$ 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.
- 138 Limits are for $\Gamma(\mu \rightarrow e X^0)/\Gamma(\mu \rightarrow e\nu\bar{\nu})$. Valid when $m_{X^0} = 0-93.4, 98.1-103.5$ MeV.
- 139 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 the 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.
- 140 JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu \psi_e \theta^\mu \phi_X$.
- 141 BALTRUSAITIS 85 search for light Goldstone boson (X^0) of broken U(1). CL = 95% limits are $B(\tau \rightarrow \mu^+ X^0)/B(\tau \rightarrow \mu^+ \nu\bar{\nu}) < 0.125$ and $B(\tau \rightarrow e^+ X^0)/B(\tau \rightarrow e^+ \nu\bar{\nu}) < 0.04$. Inferred limit for the symmetry breaking scale is $m > 3000$ TeV.
- 142 The primordial heavy neutrino must decay into ν and familion, f_A , early so that the red-shifted decay products are below critical density, see their table. In addition, $K \rightarrow \pi f_A$ and $\mu \rightarrow e f_A$ are unseen. Combining these excludes $m_{\text{heavy}\nu}$ between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\text{heavy}\nu}$ between 5×10^{-5} and 0.1 MeV (K -decay).

Majoron Searches in Neutrinoless Double β Decay

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

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

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
> 7.2	$\times 10^{24}$	90	143 BERNATOW...	92 CNTR 128Te
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 7.91	$\times 10^{21}$	90	144 GUENTHER	96 SPEC 76Ge
> 1.7	$\times 10^{22}$	90	BECK	93 CNTR 76Ge
> 7.9	$\times 10^{20}$	68	145 TANAKA	93 SPEC 100Mo
> 1.9	$\times 10^{20}$	68	BARABASH	89 CNTR 136Xe
> 1.0	$\times 10^{21}$	90	FISHER	89 CNTR 76Ge
> 3.3	$\times 10^{20}$	90	ALSTON...	88 CNTR 100Mo
(6 \pm 1) $\times 10^{20}$			AVIGNONE	87 CNTR 76Ge
> 1.4	$\times 10^{21}$	90	CALDWELL	87 CNTR 76Ge
> 4.4	$\times 10^{20}$	90	ELLIOTT	87 SPEC 82Se
> 1.2	$\times 10^{21}$	90	FISHER	87 CNTR 76Ge
			146 VERGADOS	82 CNTR

- 143 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 $(7.7-1.28 \times 0.4=7.2) \times 10^{24}$.
- 144 See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.
- 145 TANAKA 93 also quote limit 5.3×10^{19} years on two Majoron emission.
- 146 VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H , of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca .

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

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

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 0.007	147 BORISOV	97 ASTR	D, neutron star
< 4	148 KACHELRIESS	97 ASTR	D, neutron star cooling
< $(0.5-6) \times 10^{-3}$	149 KEIL	97 ASTR	SN 1987A
< 0.018	150 RAFFELT	95 ASTR	D, red giant
< 0.010	151 ALTHERR	94 ASTR	D, red giants, white dwarfs
< 0.01	WANG	92 ASTR	D, white dwarf
< 0.03	WANG	92C ASTR	D, C-O burning
none 3-8	152 BERSHADY	91 ASTR	D, K, Intergalactic light
< 10	153 KIM	91C COSM	D, K, mass density of the universe, super-symmetry
< 1	154 RAFFELT	91B ASTR	D, K, SN 1987A
none 10^{-3-3}	155 RESSELL	91 ASTR	K, Intergalactic light
	BURROWS	90 ASTR	D, K, SN 1987A
< 0.02	156 ENGEL	90 ASTR	D, K, SN 1987A
< 1	157 RAFFELT	90D ASTR	D, red giant
< $(1.4-10) \times 10^{-3}$	158 BURROWS	89 ASTR	D, K, SN 1987A
< 3.6×10^{-4}	159 ERICSON	89 ASTR	D, K, SN 1987A
< 12	160 MAYLE	89 ASTR	D, K, SN 1987A
	CHANDA	88 ASTR	D, Sun

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Axions (A^0) and Other Very Light Bosons

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 1	$\times 10^{-3}$	161 RAFFELT	88 ASTR	D, K, SN 1987A
< 0.07		162 RAFFELT	88B ASTR	red giant
< 0.7		FRIEMAN	87 ASTR	D, red giant
< 2-5		163 DEARBORN	87 ASTR	K, red giant
< 0.01		TURNER	87 COSM	K, thermal production
< 0.06		164 RAFFELT	86 ASTR	D, red giant
< 0.7		164 RAFFELT	86 ASTR	K, red giant
< 0.03		RAFFELT	86B ASTR	D, white dwarf
< 1		165 KAPLAN	85 ASTR	K, red giant
< 0.003-0.02		IWAMOTO	84 ASTR	D, K, neutron star
> 1	$\times 10^{-5}$	ABBOTT	83 COSM	D, K, mass density of the universe
> 1	$\times 10^{-5}$	DINE	83 COSM	D, K, mass density of the universe
< 0.04		ELLIS	83B ASTR	D, red giant
> 1	$\times 10^{-5}$	PRESKILL	83 COSM	D, K, mass density of the universe
< 0.1		BARROSO	82 ASTR	D, red giant
< 1		166 FUKUGITA	82 ASTR	D, stellar cooling
< 0.07		FUKUGITA	82B ASTR	D, red giant

147 BORISOV 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-13}$ from the photo-production of axions off of electric fields in the outer layers of neutron stars.

148 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.

149 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.

150 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).

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

152 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.

153 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.

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

155 RESSELL 91 uses absence of any intracolor line emission to set limit.

156 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 $2.5 \times 10^{-3} \text{ eV} \lesssim m_{A^0} \lesssim 2.5 \times 10^4 \text{ eV}$. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

157 RAFFELT 90D is a re-analysis of DEARBORN 86.

158 The region $m_{A^0} \gtrsim 2 \text{ eV}$ is also allowed.

159 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.

160 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.

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

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

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

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

165 KAPLAN 85 says $m_{A^0} < 23 \text{ eV}$ is allowed for a special choice of model parameters.

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

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

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 2	$\times 10^{-41}$	167 HAGMANN	90 CNTR	$m_{A^0} = (5.4-5.9)10^{-6} \text{ eV}$
< 1.3	$\times 10^{-42}$	95 168 WUENSCH	89 CNTR	$m_{A^0} = (4.5-10.2)10^{-6} \text{ eV}$
< 2	$\times 10^{-41}$	95 168 WUENSCH	89 CNTR	$m_{A^0} = (11.3-16.3)10^{-6} \text{ eV}$

167 HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.

168 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 $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14} \text{ MeV}^{-4}$ (the three generation DFSZ model) and $\rho_A = 300 \text{ MeV}/\text{cm}^3$ that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2 \rho_A = 4 \times 10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Invisible A^0 (Axion) Limits from Photon Coupling

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

VALUE (GeV ⁻¹)	CL%	DOCUMENT ID	COMMENT
< 3.6 $\times 10^{-7}$	95	169 CAMERON	93 $m_{A^0} < 10^{-3} \text{ eV}$, optical rotation
< 6.7 $\times 10^{-7}$	95	170 CAMERON	93 $m_{A^0} < 10^{-3} \text{ eV}$, photon regeneration
< 3.6 $\times 10^{-9}$	99.7	171 LAZARUS	92 $m_{A^0} < 0.03 \text{ eV}$
< 7.7 $\times 10^{-9}$	99.7	171 LAZARUS	92 $m_{A^0} = 0.03-0.11 \text{ eV}$
< 7.7 $\times 10^{-7}$	99	172 RUOSO	92 $m_{A^0} < 10^{-3} \text{ eV}$
< 2.5 $\times 10^{-6}$		173 SEMERTZIDIS	90 $m_{A^0} < 7 \times 10^{-4} \text{ eV}$

169 Experiment based on proposal by MAIANI 86.

170 Experiment based on proposal by VANBIBBER 87.

171 LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.

172 RUOSO 92 experiment is based on the proposal by VANBIBBER 87.

173 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 $G_{A\gamma\gamma} < 1 \times 10^{-4} \text{ GeV}^{-1}$.

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee} \phi_A \mathbf{E} \cdot \mathbf{E}$ in GeV^{-1} , or equivalently, the dipole-dipole potential $\frac{G_{Aee}^2}{4\pi} ((\sigma_1 \cdot \sigma_2) - 3(\sigma_1 \cdot \mathbf{n})(\sigma_2 \cdot \mathbf{n}))/r^3$ where $\mathbf{n} = \mathbf{r}/r$.

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

VALUE (GeV ⁻¹)	CL%	DOCUMENT ID	TECN	COMMENT
< 5.3 $\times 10^{-5}$	66	174 NI	94	Induced magnetism
< 6.7 $\times 10^{-5}$	66	174 CHUI	93	Induced magnetism
< 3.6 $\times 10^{-4}$	66	175 PAN	92	Torsion pendulum
< 2.7 $\times 10^{-5}$	95	174 BOBRKOV	91	Induced magnetism
< 1.9 $\times 10^{-3}$	66	176 WINELAND	91	NMR
< 8.9 $\times 10^{-4}$	66	175 RITTER	90	Torsion pendulum
< 6.6 $\times 10^{-5}$	95	174 VOROBYOV	88	Induced magnetism

174 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.

175 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.

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

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 $V = \frac{g\hbar^2}{8\pi m_p} (\sigma \cdot \hat{r}) (\frac{1}{r^2} + \frac{m_{AC}}{\hbar r}) e^{-m_{AC}r/\hbar}$

VALUE	DOCUMENT ID
177	YOU DIN 96

177 YOU DIN 96 compared the precession frequencies of atomic ¹⁹⁹Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.

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

ADLER	97	PRL 79 2204	S. Adler+	(BNL 787 Collab.)
AHMAD	97	PRL 78 618	I. Ahmad+	(APEX Collab.)
BORISOV	97	JETP 83 868	+Grishinia	(MOSU)
DEBOER	97C	JP G23 L85	F.W.N. de Boer+	
KACHELRIESS	97	PR D56 1313	+Wilke, Wunner	(BOCH)
KEIL	97	PR D56 2419	W. Keil+	
KITCHING	97	PRL 79 4079	P. Kitching+	(BNL 787 Collab.)
LEINBERGER	97	PL B394 16	U. Leinberger+	(ORANGE Collab.)
ADLER	96	PRL 76 1421	+Atiya, Chiang, Frank, Haggerty, Kycia+	(BNL 787 Collab.)
AMSLER	96B	ZPHY C70 219	+Armstrong, Baker, Barnett+	(Crystal Barrel Collab.)
GANZ	96	PL B389 4	+Baer, Balanda+ (GSI, HEID, FRAN, JAGL, MPIH)	
GUENTHER	96	PR D54 3641	+Helming, Heusser, Hirsch+	(MPIH, SASSO)
KAMEL	96	PL B368 291		(SHAMS)
MITSUI	96	EPL 33 111	+Maki, Asai, Ishisaki+	(TOKY)
YOU DIN	96	PRL 77 2170	+Krause, Jagannathan, Hunter+	(AMHT, WASH)
ALTMANN	95	ZPHY C68 221	+Declais, v. Felitsch+	(MUNT, LAPP, CPM)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
BASSOMPIE...	95	PL B355 584	Bassompierre, Bologna+	(LAPP, LCGT, LYON)
MAENO	95	PL B351 574	+Fujikawa, Kataoka, Nishihara+	(TOKY)
RAFFELT	95	PR D51 1495	+Weiss	(MPIH, MPIA)
SKALSEY	95	PR D51 6292	+Conti	(MICH)
TSUNODA	95	EPL 30 273	+Nakamura, Orito, Minowa	(TOKY)
ADACHI	94	PR A49 3201	+Chiba, Hirose, Nagayama+	(TMU)
ALTHERR	94	ASP 2 175	+Pettigirard, del Rio Gazteurrutia	(CERN, LAPP, DFAB)
AMSLER	94B	PL B333 278	+Armstrong, Ould-Saada+	(Crystal Barrel Collab.)
ASAI	94	PL B323 90	+Shigekuni, Sasaki, Orto	(TOKY)
MEIJERDREES	94	PR D49 4937	Meijer Drees, Waltham+	(BRCO, OREG, TRIU)
NI	94	Physica B194 153	+Chui, Pan, Cheng	(NTHU)
VO	94	PR C49 1551	+Kelly, Wohn, Hill+	(ISU, LBL, LLNL, UCD)
ATIYA	93	PRL 70 2521	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
Also	93C	PRL 71 305 (erratum)	Atiya, Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
ATIYA	93B	PR D48 R1	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
BASSOMPIE...	93	EPL 22 239	Bassompierre, Bologna+	(LAPP, TORI, LYON)
BECK	93	PRL 70 2853	+Bensch, Bockholt, Heusser, Hirsch+(MPIH, KIAE, SASSO)	

See key on page 213

Gauge & Higgs Boson Particle Listings
Axions (A^0) and Other Very Light Bosons

Table with columns for Name, ID, Conference, and Affiliation. Entries include Cameron, Chui, Minowa, Tanaka, Alliegro, Atiya, Bernatowicz..., Bluemlein, Hallin, Henderson, Hicks, Lazarus, Meljerdrees, Pan, Ruoso, Skalsey, Wang, Wang, Wu, Akopyan, Asai, Bershad, Bershad, Bluemlein, Brobrakov, Kobrakov, Kim, Raffelt, Ressell, Trzaska, Tsertos, Walker, Widmann, Wineland, Albrecht, Antreasyan, Asanuma, Atiya, Bauer, Burrows, Deboer, Engel, Gueonko, Guo, Hagmann, Judge, Raffelt, Ritter, Semertzidis, Tsuchiaki, Turner, Barabash, Bin, Burrows, Deboer, Ericson, Faisner, Fisher, Fox, Mayle, Minowa, Orito, Perkins, Tsertos, Vanbibber, Wuensch, Alston..., Avignon, Bjorken, Blinov, Bolton, Chanda, Choi, Connell, Datar, Deboer, Doehner, Dol, El-Nadi, Faisner, Hatsuda, Lorenz, Mayle, Picciotto, Raffelt, Savage, Tsertos, Tsertos, Vanklinken, Vanklinken, Vonwimmer..., Vorobyov, Avignone, Caldwell, Dzubov, Elliott, Fisher.

OTHER RELATED PAPERS

Table with columns for Name, ID, Conference, and Affiliation. Entries include Srednicki, Bardeen, Tye.