

## Gauge &amp; Higgs Boson Particle Listings

Heavy Bosons Other than Higgs Bosons, Axions ( $A^0$ ) and Other Very Light Bosons

GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
GRIFOLS	90D	PR D42 3293	J.A. Grifols, E. Masso, T.G. Rizzo	(BARC, CERN+)
KIM	90	PL B240 243	G.N. Kim <i>et al.</i>	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	H. Albrecht <i>et al.</i>	(ARGUS Collab.)
BARBIERI	89B	PR D39 1229	R. Barbieri, R.N. Mohapatra	(PISA, UMD)
LANGACKER	89B	PR D40 1569	P. Langacker, S. Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	S. Odaoka <i>et al.</i>	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar <i>et al.</i>	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke <i>et al.</i>	(LBL, UCB, COLO, NWES+)
BERGSTROM	88	PL B212 386	L. Bergstrom	(STOH)
CUYPERS	88	PRL 60 1237	F. Cuypers, P.H. Frampton	(UNCCH)
DONCHESKI	88	PL B206 137	M.A. Doncheski, H. Grotch, R. Robinett	(PSU)
DONCHESKI	88B	PR D38 412	M.A. Doncheski, H. Grotch, R.W. Robinett	(PSU)
ANSARI	87D	PL B195 613	R. Ansari <i>et al.</i>	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel <i>et al.</i>	(JADE Collab.)
ARNISON	86B	EPL 1 327	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick <i>et al.</i>	(HRS Collab.)
Also	86B	PR D34 3286	M. Derrick <i>et al.</i>	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger <i>et al.</i>	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker <i>et al.</i>	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
ARNISON	83D	PL 129B 273	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma <i>et al.</i>	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr <i>et al.</i>	(LBL, NWES, TRIU)
DESHPANDE	83	PR D27 1193	N.G. Deshpande, R.J. Johnson	(OREG)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)
DIMOPOUL...	81	NP B182 77	S. Dimopoulos, S. Raby, G.L. Kane	(STAN, MICH)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)

where  $J^\mu$  is the Noether current of the spontaneously broken global symmetry.

An axion gives a natural solution to the strong  $CP$  problem: why the effective  $\theta$ -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,  $\theta_{\text{eff}}$  is the effective  $\theta$  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  $\phi_A$  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  $\phi_A$  whose minimum is at  $\phi_A = \theta_{\text{eff}} f_A$  cancelling  $\theta_{\text{eff}}$  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

## 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

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

constant  $f_A \sim 10^{12}$  GeV was found to be a good candidate of the cold dark matter component of the Universe [13](see Dark Matter review). The energy density is stored in the low-momentum modes of the axion field which are highly occupied and thus represent essentially classical field oscillations.

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

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

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

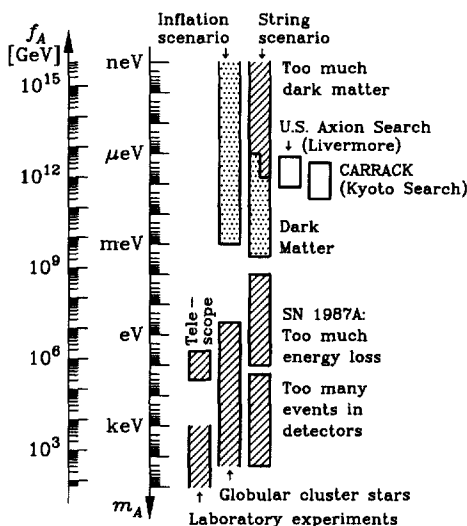
is excluded to avoid excess counts in the water Cherenkov detectors which registered the SN 1987A neutrino signal [11].

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  $\beta$  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

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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.

clusters. An unsuccessful “telescope search” for such features yields  $m_a < 3.5$  eV [13]. For  $m_a \gtrsim 30$  eV, the axion lifetime is shorter than the age of the universe.

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

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

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 potential. Because the initial misalignment angle  $\Theta_i$  can be very small or very close to  $\pi$ , 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  $\Theta_i$  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  $\mu$  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  $\alpha$  and  $\kappa$  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  $\Theta_i$  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.

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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  $\phi_A$  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

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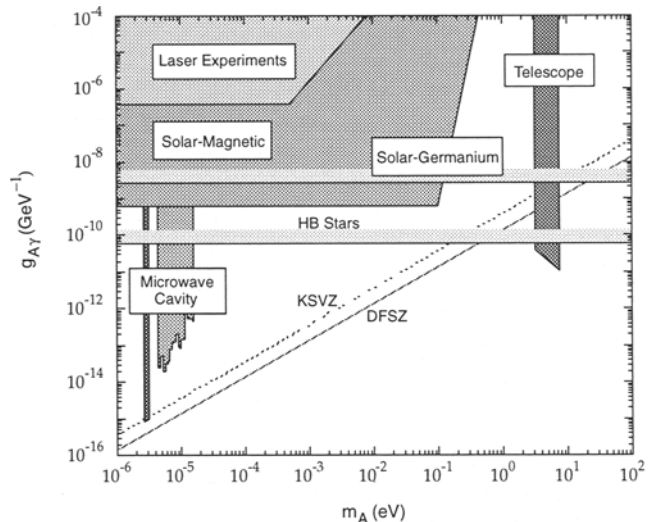
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mixing in long magnetic fields results in significant conversion probability even for very weakly coupled axions [5].

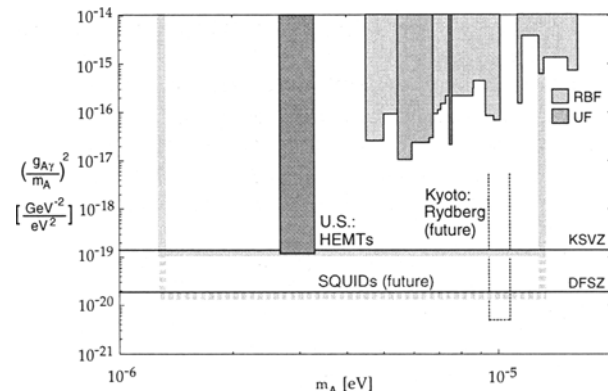
Below are discussed several experimental techniques constraining  $g_{A\gamma}$ , and their results. Also included are recent but yet-unpublished results, and projected sensitivities for experiments soon to be upgraded.

**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 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.

**III.2. Telescope search for eV axions:** For axions of mass greater than about  $10^{-1} \text{ eV}$ , 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  $\mu\text{eV}$  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,



**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].

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.

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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 3100–8300 Å ( $m_A = 3\text{--}8$  eV) after “on-off field” subtraction of the atmospheric molecular background spectra. A limit everywhere stronger than  $g_{A\gamma} < 10^{-10}\text{GeV}^{-1}$  is set, which is seen from Fig. 1 to easily exclude DFSZ axions throughout the mass range.

**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  $\sim 4$  keV, implying an oscillation length in the vacuum of  $2\pi(m_A^2/2\omega)^{-1} \sim O(\text{mm})$ , precluding the mixing from achieving its theoretically maximum value in any practical magnet. It was recognized that one could endow the photon with an effective mass in 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  $\sim 1000$  sec/day. Axions were excluded for  $g_{A\gamma} < 3.6 \times 10^{-9}\text{GeV}^{-1}$  for  $m_A < 0.03$  eV, and  $g_{A\gamma} < 7.7 \times 10^{-9}\text{GeV}^{-1}$  for  $0.03\text{ eV} < m_A < 0.11$  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  $\Pi$  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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<6 × 10 <sup>-5</sup>	90	7 AMSLER	94B CBAR	$\eta \rightarrow \gamma X^0$ , $m_{X^0}=200-525$ MeV
<0.007	90	8 MEIJERDREES94	CNTR	$\pi^0 \rightarrow \gamma X^0$ , $m_{X^0}=25$ MeV
<0.002	90	8 MEIJERDREES94	CNTR	$\pi^0 \rightarrow \gamma X^0$ , $m_{X^0}=100$ MeV
<2 × 10 <sup>-7</sup>	90	9 ATIYA	93B B787	$K^+ \rightarrow \pi^+ A^0$
<3 × 10 <sup>-13</sup>	90	10 NG	93 COSM	$\pi^0 \rightarrow \gamma X^0$
<1.1 × 10 <sup>-8</sup>	90	11 ALLIEGRO	92 SPEC	$K^+ \rightarrow \pi^+ A^0$ ( $A^0 \rightarrow e^+ e^-$ )
<5 × 10 <sup>-4</sup>	90	12 ATIYA	92 B787	$\pi^0 \rightarrow \gamma X^0$
<4 × 10 <sup>-6</sup>	90	13 MEIJERDREES92	SPEC	$\pi^0 \rightarrow \gamma X^0$ , $X^0 \rightarrow e^+ e^-$ , $m_{X^0}=100$ MeV
<1 × 10 <sup>-7</sup>	90	14 ATIYA	90B B787	Sup. by KITCH- ING 97
<1.3 × 10 <sup>-8</sup>	90	15 KORENCHEN...	87 SPEC	$\pi^+ \rightarrow e^+ \nu A^0$ ( $A^0 \rightarrow e^+ e^-$ )
<1 × 10 <sup>-9</sup>	90	0	16 EICHLER	86 SPEC Stopped $\pi^+ \rightarrow$ $e^+ \nu A^0$
<2 × 10 <sup>-5</sup>	90	17 YAMAZAKI	84 SPEC	For $160 < m < 260$ MeV
<(1.5-4) × 10 <sup>-6</sup>	90	17 YAMAZAKI	84 SPEC	$K$ decay, $m_{A^0} \ll$ 100 MeV
		0	18 ASANO	82 CNTR Stopped $K^+ \rightarrow$ $\pi^+ A^0$
		0	19 ASANO	81B CNTR Stopped $K^+ \rightarrow$ $\pi^+ A^0$
			20 ZHITNITSKII	79 Heavy axion

<sup>3</sup> ALTEGOER 98 looked for  $X^0$  from  $\pi^0$  decay which penetrate the shielding and convert to  $\pi^0$  in the external Coulomb field of a nucleus.  
<sup>4</sup> ADLER 97 bound is for massless  $A^0$ .  
<sup>5</sup> 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.  
<sup>6</sup> 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.  
<sup>7</sup> AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.  
<sup>8</sup> 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.  
<sup>9</sup> 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.  
<sup>10</sup> 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  $X^0$ .  
<sup>11</sup> 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.  
<sup>12</sup> 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.  
<sup>13</sup> MEIJERDREES 92 limit applies for  $\tau_{X^0} = 10^{-23}-10^{-11}$  sec. Limits between  $2 \times 10^{-4}$  and  $4 \times 10^{-6}$  are obtained for  $m_{X^0} = 25-120$  MeV. Angular momentum conservation requires that  $X^0$  has spin  $\geq 1$ .  
<sup>14</sup> 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.  
<sup>15</sup> KORENCHENKO 87 limit assumes  $m_{A^0} = 1.7$  MeV,  $\tau_{A^0} \lesssim 10^{-12}$  s, and  $B(A^0 \rightarrow e^+ e^-) = 1$ .  
<sup>16</sup> 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.  
<sup>17</sup> 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.  
<sup>18</sup> 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.  
<sup>19</sup> ASANO 81B is KEK experiment. Set  $B(K^+ \rightarrow \pi^+ A^0) < 3.8 \times 10^{-8}$  at CL = 90%.  
<sup>20</sup> 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
• • • We do not use the following data for averages, fits, limits, etc. • • •			
>0.2	BARROSO 82	ASTR	Standard Axion
>0.25	<sup>1</sup> RAFFELT 82	ASTR	Standard Axion
>0.2	<sup>2</sup> DICUS 78c	ASTR	Standard Axion
	MIKAELIAN 78	ASTR	Stellar emission
>0.3	<sup>2</sup> SATO 78	ASTR	Standard Axion
>0.2	VYSOTSKII 78	ASTR	Standard Axion
<sup>1</sup> Lower bound from 5.5 MeV $\gamma$ -ray line from the sun.			
<sup>2</sup> Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.			

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

Limits are for branching ratios.

VALUE	CL% EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.3 × 10 <sup>-5</sup>	90	3 ALTEGOER	98 NOMD	$\pi^0 \rightarrow \gamma X^0$ , $m_{X^0} < 120$ MeV
<3.0 × 10 <sup>-10</sup>	90	4 ADLER	97 B787	$K^+ \rightarrow \pi^+ A^0$
<5.0 × 10 <sup>-8</sup>	90	5 KITCHING	97 B787	$K^+ \rightarrow \pi^+ A^0$ ( $A^0 \rightarrow \gamma\gamma$ )
<5.2 × 10 <sup>-10</sup>	90	6 ADLER	96 B787	$K^+ \rightarrow \pi^+ A^0$
<2.8 × 10 <sup>-4</sup>	90	7 AMSLER	96B CBAR	$\pi^0 \rightarrow \gamma X^0$ , $m_{X^0} < 65$ MeV
<3 × 10 <sup>-4</sup>	90	7 AMSLER	96B CBAR	$\eta \rightarrow \gamma X^0$ , $m_{X^0}=$ 50-200 MeV
<4 × 10 <sup>-5</sup>	90	7 AMSLER	96B CBAR	$\eta' \rightarrow \gamma X^0$ , $m_{X^0}=50-925$ MeV
<6 × 10 <sup>-5</sup>	90	7 AMSLER	94B CBAR	$\pi^0 \rightarrow \gamma X^0$ , $m_{X^0}=65-125$ MeV

### $A^0$ (Axion) Searches in Quarkonium Decays

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

VALUE	CL% EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.3 × 10 <sup>-5</sup>	90	21 BALEST	95 CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
<4.0 × 10 <sup>-5</sup>	90	ANTREASYAN 90C	CBAL	$\Upsilon(1S) \rightarrow A^0 \gamma$
		22 ANTREASYAN 90C	RVUE	
<5 × 10 <sup>-5</sup>	90	23 DRUZHININ	87 ND	$\phi \rightarrow A^0 \gamma$ ( $A^0 \rightarrow e^+ e^-$ )
<2 × 10 <sup>-3</sup>	90	24 DRUZHININ	87 ND	$\phi \rightarrow A^0 \gamma$ ( $A^0 \rightarrow \gamma\gamma$ )
<7 × 10 <sup>-6</sup>	90	25 DRUZHININ	87 ND	$\phi \rightarrow A^0 \gamma$ ( $A^0 \rightarrow$ missing)
<3.1 × 10 <sup>-4</sup>	90	0	26 ALBRECHT	86D ARG $\Upsilon(1S) \rightarrow A^0 \gamma$ ( $A^0 \rightarrow e^+ e^-$ )



# Gauge & Higgs Boson Particle Listings

## Axions ( $A^0$ ) and Other Very Light Bosons

$<4 \times 10^{-4}$	90	0	26 ALBRECHT	86D ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ ( $A^0 \rightarrow \mu^+ \mu^-$ , $\pi^+ \pi^-, K^+ K^-$ )
$<8 \times 10^{-4}$	90	1	27 ALBRECHT	86D ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<1.3 \times 10^{-3}$	90	0	28 ALBRECHT	86D ARG	$\Upsilon(1S) \rightarrow A^0 \gamma$ ( $A^0 \rightarrow e^+ e^-, \gamma \gamma$ )
$<2. \times 10^{-3}$	90		29 BOWCOCK	86 CLEO	$\Upsilon(2S) \rightarrow \Upsilon(1S) \rightarrow A^0$
$<5. \times 10^{-3}$	90		30 MAGERAS	86 CUSB	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<3. \times 10^{-4}$	90		31 ALAM	83 CLEO	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<9.1 \times 10^{-4}$	90		32 NICZYPORUK	83 LENA	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<1.4 \times 10^{-5}$	90		33 EDWARDS	82 CBAL	$J/\psi \rightarrow A^0 \gamma$
$<3.5 \times 10^{-4}$	90		34 SIVERTZ	82 CUSB	$\Upsilon(1S) \rightarrow A^0 \gamma$
$<1.2 \times 10^{-4}$	90		34 SIVERTZ	82 CUSB	$\Upsilon(3S) \rightarrow A^0 \gamma$

- <sup>21</sup> BALEST 95 looked for a monochromatic  $\gamma$  from  $\Upsilon(1S)$  decay. The bound is for  $m_{A^0} < 5.0$  GeV. See Fig. 7 in the paper for bounds for heavier  $m_{A^0}$ . They also quote a bound on branching ratios  $10^{-3}$ – $10^{-5}$  of three-body decay  $\gamma X \bar{X}$  for  $0 < m_X < 3.1$  GeV.
- <sup>22</sup> The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with  $m_{A^0} < 2m_e$  at 90% CL as long as  $C_{\gamma} C_{J/\psi} > 0.09$ , where  $C_V (V = \Upsilon, J/\psi)$  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  $C_{\gamma} = C_{J/\psi} = 0.5$ , 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  $< x < 44$ .
- <sup>23</sup> 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.
- <sup>24</sup> 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.
- <sup>25</sup> 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.
- <sup>26</sup>  $\tau_{A^0} < 1 \times 10^{-13}$  s and  $m_{A^0} < 1.5$  GeV. Applies for  $A^0 \rightarrow \gamma \gamma$  when  $m_{A^0} < 100$  MeV.
- <sup>27</sup>  $\tau_{A^0} > 1 \times 10^{-7}$  s.
- <sup>28</sup> Independent of  $\tau_{A^0}$ .
- <sup>29</sup> BOWCOCK 86 looked for  $A^0$  that decays into  $e^+ e^-$  in the cascade decay  $\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$  followed by  $\Upsilon(1S) \rightarrow A^0 \gamma$ . The limit for  $B(\Upsilon(1S) \rightarrow A^0 \gamma) B(A^0 \rightarrow e^+ e^-)$  depends on  $m_{A^0}$  and  $\tau_{A^0}$ . The quoted limit for  $m_{A^0} = 1.8$  MeV is at  $\tau_{A^0} \sim 2. \times 10^{-12}$  s, where the limit is the worst. The same limit  $2. \times 10^{-3}$  applies for all lifetimes for masses  $2m_e < m_{A^0} < 2m_{\mu}$  when the results of this experiment are combined with the results of ALAM 83.
- <sup>30</sup> MAGERAS 86 looked for  $\Upsilon(1S) \rightarrow \gamma A^0$  ( $A^0 \rightarrow e^+ e^-$ ). 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.
- <sup>31</sup> ALAM 83 is at CESR. This limit combined with limit for  $B(J/\psi \rightarrow A^0 \gamma)$  (EDWARDS 82) excludes standard axion.
- <sup>32</sup> NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit  $9.2 \times 10^{-4}$  of  $B(\Upsilon \rightarrow A^0 \gamma)$  derived from  $B(J/\psi(1S) \rightarrow A^0 \gamma)$  limit (EDWARDS 82) excludes standard axion.
- <sup>33</sup> EDWARDS 82 looked for  $J/\psi \rightarrow \gamma A^0$  decays by looking for events with a single  $\gamma$  [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.
- <sup>34</sup> SIVERTZ 82 is CESR experiment. Looked for  $\Upsilon \rightarrow \gamma A^0$ ,  $A^0$  undetected. Limit for 1S (3S) is valid for  $m_{A^0} < 7$  GeV (4 GeV).

- <sup>39</sup> 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.
- <sup>40</sup> AMALDI 85 set limits  $B(A^0 \gamma) / B(\gamma \gamma \gamma) < (1-5) \times 10^{-6}$  for  $m_{A^0} = 900-100$  keV which are about 1/10 of the CARBONI 83 limits.
- <sup>41</sup> CARBONI 83 looked for orthopositronium  $\rightarrow A^0 \gamma$ . Set limit for  $A^0$  electron coupling squared,  $g(e e A^0)^2 / (4\pi) < 6. \times 10^{-10} - 7. \times 10^{-9}$  for  $m_{A^0}$  from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from  $g=2$  experiments.

### $A^0$ (Axion) Search in Photoproduction

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	<sup>42</sup> BASSOMPIERRE... 95	$m_{A^0} = 1.8 \pm 0.2$ MeV
	<sup>42</sup> BASSOMPIERRE 95	is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of $e^+ e^-$ pairs in the region $m_{e^+ e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate $A^0$ for $\tau(A^0) = 10^{-18} - 10^{-9}$ sec. They also found an excess of events in the range $m_{e^+ e^-} = 2.1-3.5$ MeV.

### $A^0$ (Axion) Production In Hadron Collisions

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			<sup>43</sup> AHMAD	97 SPEC	$e^+$ production
			<sup>44</sup> LEINBERGER	97 SPEC	$A^0 \rightarrow e^+ e^-$
			<sup>45</sup> GANZ	96 SPEC	$A^0 \rightarrow e^+ e^-$
			<sup>46</sup> KAMEL	96 EMUL	$^{32}\text{S}$ emulsion, $A^0 \rightarrow e^+ e^-$
			<sup>47</sup> BLUEMLEIN	92 BDMP	$A^0 N_Z \rightarrow \ell^+ \ell^- N_Z$
			<sup>48</sup> MEIJERDREES	92 SPEC	$\pi^- p \rightarrow n A^0, A^0 \rightarrow e^+ e^-$
			<sup>49</sup> BLUEMLEIN	91 BDMP	$A^0 \rightarrow e^+ e^-, 2\gamma$
			<sup>50</sup> FAISSNER	89 OSPK	Beam dump, $A^0 \rightarrow e^+ e^-$
			<sup>51</sup> DEBOER	88 RVUE	$A^0 \rightarrow e^+ e^-$
			<sup>52</sup> EL-NADI	88 EMUL	$A^0 \rightarrow e^+ e^-$
			<sup>53</sup> FAISSNER	88 OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			<sup>54</sup> BADIER	86 BDMP	$A^0 \rightarrow e^+ e^-$
$<2. \times 10^{-11}$	90	0	<sup>55</sup> BERGSMA	85 CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	<sup>55</sup> BERGSMA	85 CHRM	CERN beam dump
		24	<sup>56</sup> FAISSNER	83 OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			<sup>57</sup> FAISSNER	83B RVUE	LAMPF beam dump
			<sup>58</sup> FRANK	83B RVUE	LAMPF beam dump
			<sup>59</sup> HOFFMAN	83 CNTR	$\pi p \rightarrow n A^0$ ( $A^0 \rightarrow e^+ e^-$ )
			<sup>60</sup> FETSCHER	82 RVUE	See FAISSNER 81B
		12	<sup>61</sup> FAISSNER	81 OSPK	CERN PS $\nu$ wideband
		15	<sup>62</sup> FAISSNER	81B OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
		8	<sup>63</sup> KIM	81 OSPK	26 GeV $pN \rightarrow A^0 X$
		0	<sup>64</sup> FAISSNER	80 OSPK	Beam dump, $A^0 \rightarrow e^+ e^-$
$<1. \times 10^{-8}$	90		<sup>65</sup> JACQUES	80 HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		<sup>65</sup> JACQUES	80 HLBC	Beam dump
			<sup>66</sup> SOUKAS	80 CALO	28 GeV $p$ beam dump
			<sup>67</sup> BECHIS	79 CNTR	
$<1. \times 10^{-8}$	90		<sup>68</sup> COTEUS	79 OSPK	Beam dump
$<1. \times 10^{-3}$	95		<sup>69</sup> 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		<sup>70</sup> BELLOTTI	78 HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		<sup>70</sup> BELLOTTI	78 HLBC	$m_{A^0} = 1.5$ MeV
$<4.1 \times 10^{-9}$	90		<sup>70</sup> BELLOTTI	78 HLBC	$m_{A^0} = 1$ MeV
$<1. \times 10^{-8}$	90		<sup>71</sup> BOSETTI	78B HYBR	Beam dump
			<sup>72</sup> DONNELLY	78	
$<0.5 \times 10^{-8}$	90		HANSL	78D WIRE	Beam dump
			<sup>73</sup> MICELMAC...	78	
			<sup>74</sup> VYSOTSKII	78	

- <sup>43</sup> AHMAD 97 reports a result of APEX Collaboration which studied positron production in  $^{238}\text{U} + ^{232}\text{Th}$  and  $^{238}\text{U} + ^{181}\text{Ta}$  collisions, without requiring a coincident electron. No narrow lines were found for  $250 < E_{e^+} < 750$  keV.
- <sup>44</sup> LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy  $e^+ e^-$  line at  $\sim 635$  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.
- <sup>45</sup> 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.
- <sup>46</sup> KAMEL 96 looked for  $e^+ e^-$  pairs from the collision of  $^{32}\text{S}$  (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity  $m_{e^+ e^-} > 2$  MeV.
- <sup>47</sup> 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.

### $A^0$ (Axion) Searches in Positronium Decays

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-4}$	90	MAENO	95 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 850-1013$ keV
$<3.0 \times 10^{-3}$	90	<sup>35</sup> ASAI	94 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ $m_{A^0} = 30-500$ keV
$<2.8 \times 10^{-5}$	90	<sup>36</sup> AKOPYAN	91 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ ( $A^0 \rightarrow \gamma \gamma$ ), $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	<sup>37</sup> ASAI	91 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ , $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO	90 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ , $m_{A^0} < 30$ keV
$<(1-5) \times 10^{-4}$	95	<sup>38</sup> TSUCHIAKI	90 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ , $m_{A^0} = 300-900$ keV
$<6.4 \times 10^{-5}$	90	<sup>39</sup> ORITO	89 CNTR	$\alpha\text{-Ps} \rightarrow A^0 \gamma$ , $m_{A^0} < 30$ keV
		<sup>40</sup> AMALDI	85 CNTR	Ortho-positronium
		<sup>41</sup> CARBONI	83 CNTR	Ortho-positronium
		<sup>35</sup> The ASAI 94 limit is based on inclusive photon spectrum and is independent of $A^0$ decay modes.		
		<sup>36</sup> The AKOPYAN 91 limit applies for a short-lived $A^0$ with $\tau_{A^0} < 10^{-13}$ $m_{A^0}$ [keV] s.		
		<sup>37</sup> 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.		
		<sup>38</sup> The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of $A^0$ decay modes.		

See key on page 239

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Axions ( $A^0$ ) and Other Very Light Bosons

- 48 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  $2.5 \times 10^{-3}$  to  $10^{-7}$  are given for  $m_{A^0} = 25$ – $136$  MeV.
- 49 BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for  $A^0 \rightarrow e^+ e^-$ ,  $2\gamma$  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  $x < 1$ .
- 50 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.
- 51 DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass  $\sim 1.1$ ,  $\sim 2.1$ , and  $\sim 9$  MeV, lifetimes  $10^{-16}$ – $10^{-15}$  s decaying to  $e^+ e^-$  and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with  $\pi^0$  Dalitz decay. DEBOER 89b is a reply which contests the criticism.
- 52 EL-NADI 88 claim the existence of a neutral particle decaying into  $e^+ e^-$  with mass  $1.60 \pm 0.59$  MeV, lifetime  $(0.15 \pm 0.01) \times 10^{-14}$  s, which is produced in heavy ion interactions with emulsion nuclei at  $\sim 4$  GeV/c/nucleon.
- 53 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  $2\gamma$  is excluded except for a region  $x \geq 1$ . Lower limit on  $f_{A^0}$  of  $10^2$ – $10^3$  GeV is given for  $m_{A^0} = 0.1$ – $1$  MeV.
- 54 BADIER 86 did not find long-lived  $A^0$  in 300 GeV  $\pi^-$  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.
- 55 BERGSMAN 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, BERGSMAN 85 expect 15 events but observe zero.
- 56 FAISSNER 83 observed 19  $1\text{-}\gamma$  and 12  $2\text{-}\gamma$  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.
- 57 FAISSNER 83b extrapolate SIN  $\gamma$  signal to LAMPF  $\nu$  experimental condition. Resulting 370  $\gamma$ 's are not at variance with LAMPF upper limit of 450  $\gamma$ 's. Derived from LAMPF limit that  $[d\sigma(A^0)/d\omega \text{ at } 90^\circ] m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$  cm<sup>2</sup> sr<sup>-1</sup> MeV ms<sup>-1</sup>. See comment on FRANK 83b.
- 58 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  $\gamma$ 's. See comment on FAISSNER 83b.
- 59 HOFFMAN 83 set CL = 90% limit  $d\sigma/dt B(e^+ e^-) < 3.5 \times 10^{-32}$  cm<sup>2</sup>/GeV<sup>2</sup> for 140  $< m_{A^0} < 160$  MeV. Limit assumes  $\tau(A^0) < 10^{-9}$  s.
- 60 FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since  $2\text{-}\gamma$  peak rate remarkably decreases if iron wall is set in front of the decay region.
- 61 FAISSNER 81 see excess  $\mu e$  events. Suggest axion interactions.
- 62 FAISSNER 81b is SIN 590 MeV proton beam dump. Observed  $14.5 \pm 5.0$  events of  $2\gamma$  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 BERGSMAN 85. Also see in the next subsection ALEKSEEV 82, CAVAGNAC 83, and ANANEV 85.
- 63 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  $(0.86$ – $5.6) \times 10^{-3}$  s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.
- 64 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  $m_{A^0} < 2m_e$ .
- 65 JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events  $[\sigma(\text{production})\sigma(\text{interaction})] < 7. \times 10^{-68}$  cm<sup>4</sup>, CL = 90%. Second limit is from nonobservation of axion decays into  $2\gamma$ 's or  $e^+ e^-$ , and for axion mass a few MeV.
- 66 SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.
- 67 BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either  $2\gamma$  or  $e^+ e^-$ . No signal found. CL = 90% limits for model parameter(s) are given.
- 68 COTEUS 79 is a beam dump experiment at BNL.
- 69 DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.
- 70 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 values  $\times (\text{mass}^{-4})$ . Third value uses data of PL 60B 401 and quotes  $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67}$  cm<sup>4</sup>.
- 71 BOSETTI 78b quotes  $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67}$  cm<sup>4</sup>.
- 72 DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.
- 73 MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).
- 74 VYSOTSKI 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. • • •			
	75 ALTMANN	95 CNTR	Reactor; $A^0 \rightarrow e^+ e^-$
	76 KETOV	86 SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	77 KOCH	86 SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	78 DATAR	82 CNTR	Light water reactor
	79 VUILLEUMIER	81 CNTR	Reactor, $A^0 \rightarrow 2\gamma$
75 ALTMANN 95 looked for $A^0$ decaying into $e^+ e^-$ from the Bugey 5 nuclear reactor. They obtain an upper limit on the $A^0$ production rate of $\omega(A^0)/\omega(\gamma) \times B(A^0 \rightarrow e^+ e^-) < 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier $A^0$ . In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances $Z^0$ in the $(m_{X^0}, f_{X^0})$ plane.			
76 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.			
77 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.			
78 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 $A^0$ .			
79 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. • • •					
			80 DEBOER	97c RVUE	M1 transitions
			81 TSUNODA	95 CNTR	$^{252}\text{Cf}$ fission, $A^0 \rightarrow ee$
			82 MINOWA	93 CNTR	$^{139}\text{La}^* \rightarrow ^{139}\text{La} A^0$
			83 HICKS	92 CNTR	$^{35}\text{S}$ decay, $A^0 \rightarrow \gamma\gamma$
			84 ASANUMA	90 CNTR	$^{241}\text{Am}$ decay
			85 DEBOER	90 CNTR	$^8\text{Be}^* \rightarrow ^8\text{Be} A^0$ , $A^0 \rightarrow e^+ e^-$ , $X^0 \rightarrow e^+ e^-$
			86 BINI	89 CNTR	$^{16}\text{O}^* \rightarrow ^{16}\text{O} X^0$ , $X^0 \rightarrow e^+ e^-$
			87 AVIGNONE	88 CNTR	$\text{Cu}^* \rightarrow \text{Cu} A^0$ ( $A^0 \rightarrow 2\gamma$ , $A^0 e \rightarrow \gamma e$ , $A^0 Z \rightarrow \gamma Z$ )
			88 DATAR	88 CNTR	$^{12}\text{C}^* \rightarrow ^{12}\text{C} A^0$ , $A^0 \rightarrow e^+ e^-$
			89 DEBOER	88c CNTR	$^{16}\text{O}^* \rightarrow ^{16}\text{O} X^0$ , $X^0 \rightarrow e^+ e^-$
			90 DOEHNER	88 SPEC	$^2\text{H}^*$ , $A^0 \rightarrow e^+ e^-$
			91 SAVAGE	88 CNTR	Nuclear decay (isovector)
			91 SAVAGE	88 CNTR	Nuclear decay (isoscalar)
			92 HALLIN	86 SPEC	$^6\text{Li}$ isovector decay
			92 HALLIN	86 SPEC	$^{10}\text{B}$ isoscalar decays
			92 HALLIN	86 SPEC	$^{14}\text{N}$ isoscalar decays
			93 SAVAGE	86b CNTR	$^{14}\text{N}^*$
			94 ANANEV	85 CNTR	$\text{Li}^*$ , deut* $A^0 \rightarrow 2\gamma$
			95 CAVAGNAC	83 CNTR	$^{97}\text{Nb}^*$ , deut* transition $A^0 \rightarrow 2\gamma$
			96 ALEKSEEV	82b CNTR	$\text{Li}^*$ , deut* transition $A^0 \rightarrow 2\gamma$
			97 LEHMANN	82 CNTR	$\text{Cu}^* \rightarrow \text{Cu} A^0$ ( $A^0 \rightarrow 2\gamma$ )
			98 ZEHNDER	82 CNTR	$\text{Li}^*$ , $\text{Nb}^*$ decay, $n$ -capt.
			99 ZEHNDER	81 CNTR	$\text{Ba}^* \rightarrow \text{Ba} A^0$ ( $A^0 \rightarrow 2\gamma$ )
			100 CALAPRICE	79	Carbon
80 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.					
81 TSUNODA 95 looked for axion emission when $^{252}\text{Cf}$ undergoes a spontaneous fission, with the axion decaying into $e^+ e^-$ . The bound is for $m_{A^0} = 40$ MeV. It improves to $2.5 \times 10^{-5}$ for $m_{A^0} = 200$ MeV.					
82 MINOWA 93 studied chain process, $^{139}\text{Ce} \rightarrow ^{139}\text{La}^*$ by electron capture and M1 transition of $^{139}\text{La}^*$ to the ground state. It does not assume decay modes of $A^0$ . The bound applies for $m_{A^0} < 166$ keV.					
83 HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec.					
84 The ASANUMA 90 limit is for the branching fraction of $X^0$ emission per $^{241}\text{Am}$ decay and valid for $\tau_{X^0} < 3 \times 10^{-11}$ s.					
85 The DEBOER 90 limit is for the branching ratio $^8\text{Be}^*$ (18.15 MeV, $1^+$ ) $\rightarrow ^8\text{Be} A^0$ , $A^0 \rightarrow e^+ e^-$ for the mass range $m_{A^0} = 4$ – $15$ MeV.					
86 The BINI 89 limit is for the branching fraction of $^{16}\text{O}^*$ (6.05 MeV, $0^+$ ) $\rightarrow ^{16}\text{O} X^0$ , $X^0 \rightarrow e^+ e^-$ for $m_{X^0} = 1.5$ – $3.1$ 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

- 87 AVIGNONE 88 looked for the 1115 keV transition  $C^* \rightarrow Cu A^0$ , either from  $A^0 \rightarrow 2\gamma$  in-flight decay or from the secondary  $A^0$  interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for  $m_{A^0} < 1.1$  MeV.
- 88 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  $\tau$ - $m$  dependence of the limit.
- 89 The limit is for the branching fraction of  $^{16}O^*(6.05 \text{ MeV}, 0^+) \rightarrow ^{16}OX^0, X^0 \rightarrow e^+e^-$  against internal pair conversion for  $m_{X^0} = 1.7$  MeV and  $\tau_{X^0} < 10^{-11}$  s. Similar limits are obtained for  $m_{X^0} = 1.3$ – $3.2$  MeV. The spin parity of  $X^0$  must be either  $0^+$  or  $1^-$ . The limit at 1.7 MeV is translated into a limit for the  $X^0$ -nucleon coupling constant:  $g_{X^0 NN}^2/4\pi < 2.3 \times 10^{-9}$ .
- 90 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.
- 91 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  $^9Be$ . 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.
- 92 Limits are for  $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi^0)$ ; 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.
- 93 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.
- 94 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.
- 95 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).
- 96 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).
- 97 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.
- 98 ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check  $A^0$  production. No  $2\gamma$  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  $A^0$ .
- 99 ZEHNDER 81 looked for  $Ba^* \rightarrow A^0 Ba$  transition with  $A^0 \rightarrow 2\gamma$ . Obtained  $2\gamma$  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.
- 100 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 $4 \times 10^{-16}$ – $4.5 \times 10^{-12}$	90	101 BROSS	91 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )
		102 GUO	90 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )
		103 BJORKEN	88 CALO	$A \rightarrow e^+e^-$ or $2\gamma$
		104 BLINOV	88 MDI	$ee \rightarrow eeA^0$ ( $A^0 \rightarrow ee$ )
none $1 \times 10^{-14}$ – $1 \times 10^{-10}$	90	105 RIORDAN	87 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )
none $1 \times 10^{-14}$ – $1 \times 10^{-11}$	90	106 BROWN	86 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )
none $6 \times 10^{-14}$ – $9 \times 10^{-11}$	95	107 DAVIER	86 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )
none $3 \times 10^{-13}$ – $1 \times 10^{-7}$	90	108 KONAKA	86 BDMP	$eN \rightarrow eA^0 N$ ( $A^0 \rightarrow ee$ )

- 101 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  $\tau_{A^0}$ - $m_{A^0}$  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).
- 102 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).
- 103 BJORKEN 88 reports limits on axion parameters ( $f_A, m_A, \tau_A$ ) 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.
- 104 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%).
- 105 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.
- 106 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.

107  $m_{A^0} = 1.8$  MeV assumed. The excluded domain in the  $\tau_{A^0}$ - $m_{A^0}$  plane extends up to  $m_{A^0} \approx 14$  MeV, see their figure 4.

108 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	109 HALLIN	92 CNTR	$m_{A^0} = 1.75$ – $1.88$ MeV
none 0.0016–0.47	90	110 HENDERSON	92c CNTR	$m_{A^0} = 1.5$ – $1.86$ MeV
$< 2.0$	90	111 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	112 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	113 JUDGE	90 CNTR	$m_{A^0} = 1.832$ MeV, elastic
$< 1.9$	97	114 TSERTOS	89 CNTR	$m_{A^0} = 1.82$ MeV
$< (10-40)$	97	114 TSERTOS	89 CNTR	$m_{A^0} = 1.51$ – $1.65$ MeV
$< (1-2.5)$	97	114 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	115 TSERTOS	88 CNTR	$m_{A^0} = 1.832$ MeV
		116 VANKLINKEN	88 CNTR	
		117 MAIER	87 CNTR	
$< 2500$	90	MILLS	87 CNTR	$m_{A^0} = 1.8$ MeV
		118 VONWIMMER	87 CNTR	

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

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

111 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.

112 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.

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

114 See also TSERTOS 88B in references.

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

116 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.

117 MAIER 87 obtained limits  $R\Gamma \lesssim 60$  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  $\Gamma = \Gamma_{e^+e^-}^2/\Gamma_{\text{total}}$ . For a discussion implying that  $\Delta E_{\text{cm}} \approx 10$  keV, see TSERTOS 89.

118 VONWIMMERSPERG 87 measured Bhabha scattering for  $E_{\text{cm}} = 1.37$ – $1.86$  MeV and found a possible peak at 1.73 with  $f\sigma\Delta E_{\text{cm}} = 14.5 \pm 6.8$  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  $\Gamma(A^0 \rightarrow e^+e^-)\Gamma(A^0 \rightarrow \gamma\gamma)/\Gamma_{\text{total}}$

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	119 TRZASKA	91 CNTR	$m_{A^0} = 1.8$ MeV
$< 4.4$	95	WIDMANN	91 CNTR	$m_{A^0} = 1.78$ – $1.92$ MeV
		120 FOX	89 CNTR	
$< 0.11$	95	121 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

119 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.

120 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).

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

See key on page 239

# Gauge & Higgs Boson Particle Listings

## Axions ( $A^0$ ) and Other Very Light Bosons

### Search 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	122 VO	94 CNTR	$m_{X^0}=1.1-1.9$ MeV
< 1.0	95	123 VO	94 CNTR	$m_{X^0}=1.1$ MeV
< 2.5	95	123 VO	94 CNTR	$m_{X^0}=1.4$ MeV
<120	95	123 VO	94 CNTR	$m_{X^0}=1.7$ MeV
< 3.8	95	124 SKALSEY	92 CNTR	$m_{X^0}=1.5$ MeV
122 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.				
123 VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.				
124 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	125 MITSUI	96 CNTR	$\gamma X^0$
< 4	68	126 SKALSEY	95 CNTR	$\gamma X^0$
<40	68	127 SKALSEY	95 RVUE	$\gamma X^0$
< 0.18	90	128 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.26	90	129 ADACHI	94 CNTR	$\gamma\gamma X^0, X^0 \rightarrow \gamma\gamma$
< 0.33	90	130 ADACHI	94 CNTR	$\gamma X^0, X^0 \rightarrow \gamma\gamma\gamma$
125 MITSUI 96 looked for a monochromatic $\gamma$ . The bound applies for a vector $X^0$ with $C=-1$ and $m_{X^0} < 200$ keV. They derive an upper bound on $e e X^0$ coupling and hence on the branching ratio $B(\sigma\text{-Ps} \rightarrow \gamma\gamma X^0) < 6.2 \times 10^{-6}$ . The bounds weaken for heavier $X^0$ .				
126 SKALSEY 95 looked for a monochromatic $\gamma$ without an accompanying $\gamma$ in $e^+e^-$ annihilation. The bound applies for scalar and vector $X^0$ with $C = -1$ and $m_{X^0} = 100-1000$ keV.				
127 SKALSEY 95 reinterpreted the bound on $\gamma A^0$ decay of $\sigma\text{-Ps}$ 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.				
128 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.				
129 ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+e^-$ annihilation. The bound applies for $m_{X^0} < 800$ keV.				
130 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. • • •					
			131 DIAZ	98 THEO	$H^0 \rightarrow X^0 X^0, A^0 \rightarrow X^0 X^0 X^0$ , Majoron
			132 BOBRAKOV	91	Electron quasi-magnetic interaction
$< 3.3 \times 10^{-2}$	95		133 ALBRECHT	90E ARG	$\tau \rightarrow \mu X^0$ , Familon
$< 1.8 \times 10^{-2}$	95		133 ALBRECHT	90E ARG	$\tau \rightarrow e X^0$ , Familon
$< 6.4 \times 10^{-9}$	90		134 ATIYA	90 B787	$K^+ \rightarrow \pi^+ X^0$ , Familon
$< 1.1 \times 10^{-9}$	90		135 BOLTON	88 CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$ , Familon
			136 CHANDA	88 ASTR	Sun, Majoron
			137 CHOI	88 ASTR	Majoron, SN 1987A
$< 5 \times 10^{-6}$	90		138 PICCIOTTO	88 CNTR	$\pi \rightarrow e\nu X^0$ , Majoron
$< 1.3 \times 10^{-9}$	90		139 GOLDMAN	87 CNTR	$\mu \rightarrow e\gamma X^0$ , Familon
$< 3 \times 10^{-4}$	90		140 BRYMAN	86B RVUE	$\mu \rightarrow e X^0$ , Familon
$< 1 \times 10^{-10}$	90	0	141 EICHLER	86 SPEC	$\mu^+ \rightarrow e^+ X^0$ , Familon
$< 2.6 \times 10^{-6}$	90		142 JODIDIO	86 SPEC	$\mu^+ \rightarrow e^+ X^0$ , Familon
			143 BALTRUSAIT.	85 MRK3	$\tau \rightarrow \ell X^0$ , Familon
			144 DICUS	83 COSM	$\nu(\text{light}) X^0$

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

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

133 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  $\mu$ ), 5.0% (for  $e$ ) for  $m_{X^0} = 500$  MeV.

134 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.

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

136 CHANDA 88 find  $\nu\tau < 10$  MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and  $\nu_S > 5.8 \times 10^6$  GeV in the singlet Majoron model.

137 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  $L_{\text{int}} = \frac{1}{2} h \bar{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$ . For several families of neutrinos, the limit applies for  $(\Sigma h_i^2)^{1/4}$ .

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

139 GOLDMAN 87 limit corresponds to  $F > 2.9 \times 10^9$  GeV for the family symmetry breaking scale from the Lagrangian  $L_{\text{int}} = (1/F) \bar{\psi}_\mu \gamma^\mu (\partial + b\gamma_5) \psi_e \theta_\mu \phi_{X^0}$  with  $a^2 + b^2 = 1$ . This is not as sensitive as the limit  $F > 9.9 \times 10^9$  GeV derived from the search for  $\mu^+ \rightarrow e^+ X^0$  by JODIDIO 86, but does not depend on the chirality property of the coupling.

140 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.

141 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 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.

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

143 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.

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

### Majoron Searches in Neutrinoless Double $\beta$ 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. Also see the recent reviews ZUBER 98 and FAESSLER 98B.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID
>7200	90	<sup>128</sup> Te		CNTR	145 BERNATOW... 92
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.35	90	<sup>96</sup> Zr	$0\nu\chi$	NEMO-2	146 ARNOLD 99
> 1.2	90	<sup>116</sup> Cd	$0\nu\chi$	SCIN	147 DANEVICH 98
> 0.26	90	<sup>116</sup> Cd	$0\nu 2\chi$	SCIN	148 DANEVICH 98
> 7.2	90	<sup>136</sup> Xe	$0\nu 2\chi$	TPC	149 LUESCHER 98
> 7.91	90	<sup>76</sup> Ge		SPEC	150 GUENTHER 96
> 17	90	<sup>76</sup> Ge		CNTR	BECK 93
> 0.79	68	<sup>100</sup> Mo		SPEC	151 TANAKA 93
> 0.19	68	<sup>136</sup> Xe		CNTR	BARABASH 89
> 1.0	90	<sup>76</sup> Ge		CNTR	FISHER 89
> 0.33	90	<sup>100</sup> Mo		CNTR	ALSTON... 88
> 0.6 $\pm$ 0.1	90	<sup>76</sup> Ge		CNTR	AVIGNONE 87
> 1.4	90	<sup>76</sup> Ge		CNTR	CALDWELL 87
> 0.44	90	<sup>82</sup> Se		SPEC	ELLIOTT 87
> 1.2	90	<sup>76</sup> Ge		CNTR	FISHER 87
				CNTR	152 VERGADOS 82

145 BERNATOWICZ 92 studied double- $\beta$  decays of <sup>128</sup>Te and <sup>130</sup>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 <sup>128</sup>Te of  $(7.7 \pm 0.4) \times 10^{24}$  year. We calculated 90% CL limit as  $(7.7-1.28 \times 0.4=7.2) \times 10^{24}$ .

146 ARNOLD 99 use enriched <sup>96</sup>Zr and give a limit based on the matrix elements of STAUDT 90.

147 DANEVICH 98 use cadmium tungstate crystals, enriched to 83% in <sup>116</sup>Cd. The spectrum was analysed in the region of expected majoron emission. Using a variety of nuclear matrix elements, they obtain a limit  $\langle g_{\nu\chi} \rangle < (1-3) \times 10^{-4}$ .

148 DANEVICH 98 obtain a limit on the  $0\nu$  decay with emission of 2 majorons.

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

150 See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.

151 TANAKA 93 also quote limit  $5.3 \times 10^{19}$  years on two Majoron emission.

152 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  $\beta$  decay of <sup>48</sup>Ca.

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

$\nu_1 = \nu_2$  is usually assumed ( $\nu_i$  = vacuum expectation values). For a review of these limits, see RAFFELT 90C and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3 to 20	153 MOROI	98 COSM	K, hot dark matter
< 0.007	154 BORISOV	97 ASTR	D, neutron star
< 4	155 KACHELRIESS	97 ASTR	D, neutron star cooling
$< (0.5-6) \times 10^{-3}$	156 KEIL	97 ASTR	SN 1987A

# Gauge & Higgs Boson Particle Listings

## Axions ( $A^0$ ) and Other Very Light Bosons

< 0.018	157 RAFFELT	95 ASTR	D, red giant
< 0.010	158 ALTHERR	94 ASTR	D, red giants, white dwarfs
< 0.01	159 CHANG	93 ASTR	K, SN 1987A
< 0.03	WANG	92 ASTR	D, white dwarf
< 0.03	WANG	92C ASTR	D, C-O burning
none 3-8	160 BERSHADY	91 ASTR	D, K, intergalactic light
< 10	161 KIM	91C COSM	D, K, mass density of the universe, super-symmetry
< 1	162 RAFFELT	91B ASTR	D,K, SN 1987A
none $10^{-3-3}$	163 RESSELL	91 ASTR	K, intergalactic light
< 0.02	BURROWS	90 ASTR	D,K, SN 1987A
< 1	164 ENGEL	90 ASTR	D,K, SN 1987A
< $1 \times 10^{-3}$	165 RAFFELT	90D ASTR	D, red giant
< $(1.4-10) \times 10^{-3}$	166 BURROWS	89 ASTR	D,K, SN 1987A
< $3.6 \times 10^{-4}$	167 ERICSON	89 ASTR	D,K, SN 1987A
< 12	168 MAYLE	89 ASTR	D,K, SN 1987A
< 1	CHANDA	88 ASTR	D, Sun
< $1 \times 10^{-3}$	RAFFELT	88 ASTR	D,K, SN 1987A
< 0.07	169 RAFFELT	88B ASTR	red giant
< 0.7	FRIEMAN	87 ASTR	D, red giant
< 2-5	170 RAFFELT	87 ASTR	K, red giant
< 0.01	TURNER	87 COSM	K, thermal production
< 0.06	171 DEARBORN	86 ASTR	D, red giant
< 0.7	RAFFELT	86 ASTR	D, red giant
< 0.03	172 RAFFELT	86 ASTR	K, red giant
< 1	RAFFELT	86B ASTR	D, white dwarf
< 0.003-0.02	173 KAPLAN	85 ASTR	K, red giant
> 1	IWAMOTO	84 ASTR	D, K, neutron star
> $1 \times 10^{-5}$	ABBOTT	83 COSM	D,K, mass density of the universe
< 0.04	DINE	83 COSM	D,K, mass density of the universe
> $1 \times 10^{-5}$	ELLIS	83B ASTR	D, red giant
< 0.1	174 BARROSO	82 ASTR	D, red giant
< 0.07	FUKUGITA	82 ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B ASTR	D, red giant

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

154 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.

155 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.

156 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.

157 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).

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

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

160 BERSHADY 91 searched for a line at wave length from 3100-8300 Å expected from  $2\gamma$  decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.

161 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.

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

163 RESSELL 91 uses absence of any intracuster line emission to set limit.

164 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  $g_{AN} \sim 10^{-6}$ .

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

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

167 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.

168 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.

169 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.

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

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

172 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.

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

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

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 5.5 \times 10^{-43}$	95	175 HAGMANN	98 CNTR	$m_{A^0} = 2.9-3.3 \times 10^{-6} \text{ eV}$
		176 KIM	98 THEO	
$< 2 \times 10^{-41}$		177 HAGMANN	90 CNTR	$m_{A^0} = (5.4-5.9)10^{-6} \text{ eV}$
$< 1.3 \times 10^{-42}$	95	178 WUENSCH	89 CNTR	$m_{A^0} = (4.5-10.2)10^{-6} \text{ eV}$
$< 2 \times 10^{-41}$	95	178 WUENSCH	89 CNTR	$m_{A^0} = (11.3-16.3)10^{-6} \text{ eV}$

175 Based on the conversion of halo axions to microwave photons. Limit assumes  $\rho_A = 0.45 \text{ GeV cm}^{-3}$ . At 90%CL this result excludes a version of KSVZ axions as dark matter in the halo of our Galaxy, for the quoted axion mass range.

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

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

178 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  $\rho_A = 300 \text{ MeV/cm}^3$  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 ( $\text{GeV}^{-1}$ )	CL%	DOCUMENT ID	TECN	COMMENT
$< 2.7 \times 10^{-9}$		179 MASSO	00 THEO	induced photon coupling
		180 AVIGNONE	98	$m_{A^0} < 1 \text{ keV}$
$< 6.0 \times 10^{-10}$	95	181 MORIYAMA	98	$m_{A^0} < 0.03 \text{ eV}$
$< 3.6 \times 10^{-7}$	95	182 CAMERON	93	$m_{A^0} < 10^{-3} \text{ eV}$ , optical rotation
		183 CAMERON	93	$m_{A^0} < 10^{-3} \text{ eV}$ , photon regeneration
$< 3.6 \times 10^{-9}$	99.7	184 LAZARUS	92	$m_{A^0} < 0.03 \text{ eV}$
$< 7.7 \times 10^{-9}$	99.7	184 LAZARUS	92	$m_{A^0} = 0.03-0.11 \text{ eV}$
$< 7.7 \times 10^{-7}$	99	185 RUOSO	92	$m_{A^0} < 10^{-3} \text{ eV}$
$< 2.5 \times 10^{-6}$		186 SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4} \text{ eV}$

179 MASSO 00 studied limits on axion-photon coupling using the induced axion-photon coupling through the proton loop and CAMERON 93 bound on the axion-photon coupling using optical rotation. They obtained the bound  $g_{p\bar{p}}^2/4\pi < 1.7 \times 10^{-9}$  for the coupling  $g_{p\bar{p}} = 15\rho\phi_A$ .

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

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

182 Experiment based on proposal by MAIANI 86.

183 Experiment based on proposal by VANBIBBER 87.

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

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

186 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  $m_{A^0} = 4 \times 10^{-3} \text{ eV}$  where  $G_{A\gamma\gamma} < 1 \times 10^{-4} \text{ GeV}^{-1}$ .

### Limit on Invisible $A^0$ (Axion) Electron Coupling

The limit is for  $G_{Aee} \delta_{\mu\nu} \phi_A \tilde{e}^{\mu} \tilde{e}^{\nu} \gamma_5 e$  in  $\text{GeV}^{-1}$ , 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 ( $\text{GeV}^{-1}$ )	CL%	DOCUMENT ID	TECN	COMMENT
$< 5.3 \times 10^{-5}$	66	187 NI	94	Induced magnetism
$< 6.7 \times 10^{-5}$	66	187 CHUI	93	Induced magnetism
$< 3.6 \times 10^{-4}$	66	188 PAN	92	Torsion pendulum
$< 2.7 \times 10^{-5}$	95	187 BOBRAKOV	91	Induced magnetism
$< 1.9 \times 10^{-3}$	66	189 WINELAND	91	NMR
$< 8.9 \times 10^{-4}$	66	188 RITTER	90	Torsion pendulum
$< 6.6 \times 10^{-5}$	95	187 VOROBYOV	88	Induced magnetism

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

See key on page 239

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

- 187 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.
- 188 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.
- 189 WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

## Invisible $A^0$ (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • •	• • •	• • •	• • •	• • •
<745	90	<sup>190</sup> KRCMAR	98 CNTR	Solar axion
<sup>190</sup> KRCMAR	98			looked for solar axions emitted by the M1 transition of thermally excited <sup>57</sup> Fe nuclei in the Sun, using their possible resonant capture on <sup>57</sup> Fe in the laboratory, following MORIYAMA 95b. The mass bound assumes $m_u/m_d=0.56$ and the flavor-singlet axial-vector matrix element $S=3F-D \approx 0.5$ .

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

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

VALUE	DOCUMENT ID	TECN	COMMENT
• • •	• • •	• • •	• • •
<sup>191</sup> NI	99		paramagnetic Tb F <sub>3</sub>
<sup>192</sup> POPELOV	98	THEO	neutron EDM
<sup>193</sup> YODIN	96		
<sup>194</sup> RITTER	93		torsion pendulum
<sup>195</sup> VENEMA	92		nuclear spin-precession frequencies
<sup>196</sup> WINELAND	91	NMR	

- <sup>191</sup>NI 99 searched for a T-violating medium-range force acting on paramagnetic Tb F<sub>3</sub> salt. See their Fig. 1 for the result.
- <sup>192</sup>POPELOV 98 studied the possible contribution of T-violating Medium-Range Force to the neutron electric dipole moment, which is possible when axion interactions violate CP. The size of the force among nucleons must be smaller than gravity by a factor of  $2 \times 10^{-10}$  ( $1 \text{ cm}/\lambda_A$ ), where  $\lambda_A = \hbar/m_A c$ .
- <sup>193</sup>YODIN 96 compared the precession frequencies of atomic <sup>199</sup>Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.
- <sup>194</sup>RITTER 93 used a torsion pendulum to study the influence of bulk mass with polarized electrons on the pendulum.
- <sup>195</sup>VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of <sup>199</sup>Hg and <sup>201</sup>Hg atoms.
- <sup>196</sup>WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored <sup>9</sup>Be<sup>+</sup> ions using nuclear magnetic resonance.

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Raffelt (MPIM)	RAFFELT 90D PR D41 1324 G.G. Raffelt (MPIM)	RITTER 90 PR D42 977 R.C. Ritter et al. (VIRG)	SEMERITZIDIS 90 PRL 64 2988 Y.K. Semertzidis et al. (ROCH, BNL, FNAL+)	STAUDT 90 EPL 13 31 A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus	TSUCHIAKI 90 PL B236 81 M. Tsuchiaki et al. (ICEPP)	TURNER 90 PRL 63 67 M.S. Turner (FNAL)	BARABASH 89 PL B223 275 A.S. Barabash et al. (ITER, INRM)	BINI 89 PL B221 99 M. Bini et al. (FIRZ, CERN, AARH)	BURROWS 89 PR D39 1020 A. Burrows, M.S. Turner, R.P. Brinkmann (ARIZ+)	DEBOER 89B PRL 60 1797 M.S. Turner (FNAL, EFI)	ERICSON 89 PR B219 507 F.W.N. de Boer, R. van Dantzig (CERN, IPN)	FAISSNER 89 ZPHY C44 557 H. Faissner et al. (AACH3, BERL, PSI)	FISHER 89 PL B218 257 P.H. Fisher et al. (CIT, NEUC, PSI)	FOX 89 PR L69 2280 J.D. Fox et al.	MAYLE 89 PL B219 515 R. Mayle et al. (LLL, CERN, MINN, FNAL+)	Also 88 PL B203 188 R. Mayle et al. (LLL, CERN, MINN, FNAL+)	MINOWA 89 PRL 62 1091 H. Minowa et al. (ICEPP)	ORITO 89 PRL 63 597 S. Orito et al. (ICEPP)	PERKINS 89 PRL 62 2638 D.H. Perkins (OXF)	TSERTOS 89 PR D40 1397 H. Tsertos et al. (GSI, ILLG)	VANBIBBER 89 PR D39 2089 K. van Bibber et al. (LLL, TAMU, LBL)	WUENSCH 89 PR D40 3153 W.U. Wuensch et al. (ROCH, BNL, FNAL)	Also 88 PR L69 2280 S. de Panfilis et al. (ROCH, BNL, FNAL)	ALSTON... 88 PRL 60 1928 M. Alston-Garnjost et al. (LBL, MTHO+)	AVIGNONE 88 PR D37 618 F.T. Avignone et al. (PRIN, SCUC, ORNL+)	BJORKEN 88 PR D38 3375 J.D. Bjorken et al. (FNAL, SLAC, VPI)	BLINOV 88 SJNP 47 563 A.E. Blinov et al. (NOVO)	Translated from YAF 47 889	BOLTON 88 PR D38 2077 R.D. Bolton et al. (LANL, STAN, CHIC+)	Also 88 PRL 60 1241 R.D. Bolton et al. (LANL, STAN, CHIC+)	Also 86 PRL 57 3241 D. Grosnick et al. (CHIC, LANL, STAN+)	CHANDA 88 PR D37 2714 R. Chanda, J.F. Nieves, P.B. Pal (UMD, UPR+)	CHOI 88 PR D37 3225 K. Choi et al. (JHU)	CONNELL 88 PRL 60 2242 S.H. Connell et al. (WITW)	DATAR 88 PR C37 250 V.M. Datar et al. (IPN)	DEBOER 88 PRL 61 1274 F.W.N. de Boer, R. van Dantzig (ANIK)	Also 89 PRL 62 2644 erratum F.W.N. de Boer, R. van Dantzig (ANIK)	Also 89 PRL 62 2538 D.H. Perkins (OXF)	DEBOER 89C JGP 14 L131 F.W.N. de Boer, R. van Dantzig (LOUV)	DOEHNER 88 PR D38 2722 J. Doehner et al. (HEIDP, ANL, ILLG)	EL-NADI 88 PRL 61 1271 M. el Nadi, O.E. Badawy (CAIR)	ENGEL 88 PR C37 731 J. Engel, P. Vogel, M.R. Zirnbauer	FAISSNER 88 ZPHY C37 231 H. Faissner et al. (AACH3, BERL, SIN)	HATSUDA 88B PL B203 469 T. Hatsuda, M. Yoshimura (KEK)	LORENZ 88 PL B214 10 E. Lorenz et al. (MPIM, PSI)	MAYLE 88 PL B203 188 R. Mayle et al. (LLL, CERN, MINN, FNAL+)	PICCIOTTO 88 PR D37 1131 C.E. Picciotto et al. (TRIU, CNRC)	RAFFELT 88 PRL 60 1793 G. Raffelt, D. Seckel (UCB, LLL, USCSC)	RAFFELT 88B PR D37 349 G.G. Raffelt, D.S.P. Dearborn (UCB, LLL)	SAVAGE 88 PR D37 1134 M.J. Savage, B.W. Filippone, L.W. Mitchell (CIT)	TSERTOS 88 PL B207 273 A. Tsertos et al. (GSI, ILLG)	TSERTOS 88B ZPHY A331 103 A. Tsertos et al. (GSI, ILLG)	VANKLINKEN 88 PL B205 223 J. van Kiinen et al. (GRON, GSI)	VANKLINKEN 88B PRL 60 2442 J. van Kiinen (GRON)	VONWIMMER... 88 PRL 60 2443 U. von Wimmersberg (BNL)	VOROBYOV 88 PR D37 140 P.V. Vorobiev, V.I. Gitars (NOVO)	AVIGNONE 87 AIP Conf. 1987 F.T. Avignone et al. (SCUC, PNLO)	AIP Conf. Proc. Salt Lake City, UT	CALDWELL 87 PRL 59 419 D.O. Caldwell et al. (UCSB, LBL)	DRUZHININ 87 ZPHY C37 1 V.P. Druzhinin et al. (NOVO)	ELLIOTT 87 PRL 59 1649 S.R. Elliott, A.A. Hahn, M.K. Moe (UCI)	FISHER 87 PL B192 460 P.H. Fisher et al. (CIT, NEUC, SIN)	FRIEMAN 87 PR D36 2201 I.A. Frieman, S. Dimopoulos, M.S. Turner (SLAC+)	GOLDMAN 87 PR D36 1543 T. Goldman et al. (LANL, CHIC, STAN)	KORENCHENKO... 87 SJNP 46 192 S.M. Korenchenko et al. (JINR)	Translated from YAF 46 313
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# Gauge & Higgs Boson Particle Listings

## Axions ( $A^0$ ) and Other Very Light Bosons

MAIER	87	ZPHY A326 527	K. Maier <i>et al.</i>	(STUT, GSI)	ASANO	82	PL 113B 195	Y. Asano <i>et al.</i>	(KEK, TOKY, INUS, OSAK)
MILLS	87	PR D36 707	A.P. Mills, J. Levy	(BELL)	BARROSO	82	PL 116B 247	A. Barroso, G.C. Branco	(LISB)
RAFFELT	87	PR D36 2211	G.G. Raffelt, D.S.P. Dearborn	(LL, UCBS)	DATAR	82	PL 114B 63	V.M. Datar <i>et al.</i>	(BHAB)
RIORDAN	87	PRL 59 755	E.M. Riordan <i>et al.</i>	(ROCH, CIT+)	EDWARDS	82	PRL 48 903	C. Edwards <i>et al.</i>	(Crystal Ball Collab.)
TURNER	87	PRL 59 2489	M.S. Turner	(FNAL, EFI)	FETSCHER	82	JPG 8 L147	W. Fetscher	(ETH)
VANBIBBER	87	PRL 59 759	K. van Bibber <i>et al.</i>	(LLL, CIT, MIT+)	FUKUGITA	82	PRL 48 1522	M. Fukugita, S. Watamura, M. Yoshimura	(KEK)
VONWIMMER	87	PRL 59 266	U. von Wimmersperg <i>et al.</i>	(WITW)	FUKUGITA	82B	PR D26 1840	M. Fukugita, S. Watamura, M. Yoshimura	(KEK)
ALBRECHT	86D	PL B179 403	H. Albrecht <i>et al.</i>	(ARGUS Collab.)	LEHMANN	82	PL 115B 270	P. Lehmann <i>et al.</i>	(SACL)
BADIER	86	ZPHY C31 21	J. Badier <i>et al.</i>	(NA3 Collab.)	RAFFELT	82	PL 119B 323	G. Raffelt, L. Stodolsky	(MPIM)
BOWCOCK	86	PRL 56 2676	T.J.V. Bowcock <i>et al.</i>	(CLEO Collab.)	SIVERTZ	82	PR D26 717	J.M. Sivertz <i>et al.</i>	(CUSB Collab.)
BROWN	86	PRL 57 2101	C.N. Brown <i>et al.</i>	(FNAL, WASH, KYOT+)	VERGADOS	82	PL 109B 96	J.D. Vergados	(CERN)
BRYMAN	86B	PRL 57 2787	D.A. Bryman, E.T.H. Clifford	(TRIU)	ZEHNDER	82	PL 110B 419	A. Zehnder, K. Gabathuler, J.L. Vuilleumier	(ETH+)
DAVIER	86	PL B180 295	M. Davier, J. Jeanjean, H. Nguyen Ngoc	(LALO)	ASANO	81B	PL 107B 159	Y. Asano <i>et al.</i>	(KEK, TOKY, INUS, OSAK)
DEARBORN	86	PRL 56 26	D.S.P. Dearborn, D.N. Schramm, G. Steigman	(LLI+)	BARROSO	81	PL 106B 91	A. Barroso, N.C. Mukhopadhyay	(SIN)
EICHLER	86	PL B175 101	R.A. Eichler <i>et al.</i>	(SINDRUM Collab.)	FAISSNER	81	ZPHY C10 95	H. Faissner <i>et al.</i>	(AACH3)
HALLIN	86	PRL 57 2105	A.L. Hallin <i>et al.</i>	(PRIN)	FAISSNER	81B	PL 103B 234	H. Faissner <i>et al.</i>	(AACH3)
JODIDIO	86	PR D34 1967	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)	KIM	81	PL 105B 55	B.R. Kim, C. Stamm	(AACH3)
Also	86	PR D37 237 erratum	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)	VUILLEUMIER	81	PL 101B 341	J.L. Vuilleumier <i>et al.</i>	(CIT, MUNI)
KETOV	86	JETPL 44 146	S.N. Ketov <i>et al.</i>	(KIAE)	A. Zehnder	81	PL 104B 494	A. Zehnder	(ETH)
Also	86	JETPL 44 146	S.N. Ketov <i>et al.</i>	(KIAE)	FAISSNER	80	PL 96B 201	H. Faissner <i>et al.</i>	(AACH3)
Translated from ZETFP	86	NC 96A 182	H.R. Koch, O.W.B. Schult	(JULI)	JACQUES	80	PR D21 1206	F.F. Jacques <i>et al.</i>	(RUTG, STEV, COLU)
KOCH	86	PRL 57 659	A. Konaka <i>et al.</i>	(KYOT, KEK)	SOUKAS	80	PRL 44 564	A. Soukas <i>et al.</i>	(BNL, HARV, ORNL, PENN)
KONAKA	86	PRL 57 659	A. Konaka <i>et al.</i>	(KYOT, KEK)	BECHIS	79	PRL 42 1511	D.J. Bechis <i>et al.</i>	(UMD, COLL, AFRR)
MAGERAS	86	PRL 56 2672	G. Mageras <i>et al.</i>	(MPIM, COLU, STON)	CALAPRICE	79	PR D20 2708	F.P. Calaprice <i>et al.</i>	(PRIN)
MAIANI	86	PL B175 359	L. Maiani, R. Petronzio, E. Zavattini	(CERN)	COEUS	79	PRL 42 1438	P. Coeus <i>et al.</i>	(COLU, ILL, BNL)
PECCIE	86	PL B172 435	R.D. Peccie, T.T. Wu, T. Yanagida	(DESY)	DISHAW	79	PL 85B 142	J.P. Dishaw <i>et al.</i>	(SLAC, CIT)
RAFFELT	86	PR D33 897	G.G. Raffelt	(MPIM)	ZHITNITSKII	79	SJNP 29 517	A.R. Zhitenitsky, Y.I. Skovpen	(NOVO)
RAFFELT	86B	PL 166B 402	G.G. Raffelt	(MPIM)	Translated from YAF 29	1001.			
SAVAGE	86B	PRL 57 178	M.J. Savage <i>et al.</i>	(CIT)	ALIBRAN	78	PL 74B 134	P. Alibrant <i>et al.</i>	(Gargamelle Collab.)
AMALDI	85	PL 153B 444	U. Amaldi <i>et al.</i>	(CERN)	ASRATYAN	78B	PL 79B 497	A.E. Asratyan <i>et al.</i>	(ITEP, SERP)
ANANEV	85	SJNP 41 585	V.D. Ananev <i>et al.</i>	(JINR)	BELLOTTI	78	PL 76B 223	E. Bellotti, E. Fiorini, L. Zanotti	(MILA)
Translated from YAF 41	85	PRL 55 1842	R.M. Baltrusaitis <i>et al.</i>	(Mark III Collab.)	BOSETTI	78B	PL 74B 143	P.C. Bosetti <i>et al.</i>	(BEBC Collab.)
BALTRUSAITIS...	85	PL 157B 458	F. Bergsma <i>et al.</i>	(CHARM Collab.)	DICUS	78C	PR D18 1829	D.A. Dicus <i>et al.</i>	(TEXA, VPI, STAN)
BERGSMAN	85	NP B260 215	D.B. Kaplan	(HARV)	DONNELLY	78	PR D18 1607	T.W. Donnelly <i>et al.</i>	(STAN)
KAPLAN	85	NP B260 215	D.B. Kaplan	(HARV)	Also	76	PRL 37 315	F. Reines, H.S. Gurr, H.W. Sobel	(UCI)
IWAMOTO	84	PRL 53 1198	N. Iwamoto	(UCSB, WJSL)	HANSL	78D	PL 74B 139	T. Hansl <i>et al.</i>	(UCI)
YAMAZAKI	84	PRL 52 1089	T. Yamazaki <i>et al.</i>	(INUS, KEK)	MICELMAC...	78	LNC 21 441	G.V. Mitselmakher, B. Pontecorvo	(CDHS Collab.)
ABBOTT	83	PL 120B 133	L.F. Abbott, P. Sikivie	(BRAN, FLOR)	MIKAEKIAN	78	PR D18 3505	K.O. Mikaelian	(JINR)
ALAM	83	PR D27 1665	M.S. Alam <i>et al.</i>	(VAND, CORN, ITHA, HARV+)	SATO	78	PTP 60 1942	K. Sato	(FNAL, NWES)
CARBONI	83	PL 123B 349	G. Carboni, W. Dahme	(CERN, MUNI)	VYSOTSKII	78	JETPL 27 502	M.I. Vysotsky <i>et al.</i>	(KYOT)
CAVAIGNAC	83	PL 121B 193	J.F. Cavaignac <i>et al.</i>	(ISNG, LAPP)	Translated from ZETFP	27 533.			(ASCI)
DICUS	83	PR D28 1778	D.A. Dicus, V.L. Tepilitz	(TEXA, UMD)	YANG	78	PRL 41 523	T.C. Yang	(MASA)
DINE	83	PL 120B 137	M. Dine, W. Fischler	(IAS, PENN)	PECCIE	77	PR D16 1791	R.D. Peccie, H.R. Quinn	(STAN, SLAC)
ELLIS	83B	NP B223 252	J. Ellis, K.A. Olive	(CERN)	Also	77B	PR 38 1440	R.D. Peccie, H.R. Quinn	(STAN, SLAC)
FAISSNER	83	PR D28 1190	H. Faissner <i>et al.</i>	(AACH)	REINES	76	PRL 37 315	F. Reines, H.S. Gurr, H.W. Sobel	(UCI)
FAISSNER	83B	PR D28 1787	H. Faissner <i>et al.</i>	(AACH3)	GURR	74	PR 33 179	H.S. Gurr, F. Reines, H.W. Sobel	(UCI)
FRANK	83B	PR D28 1790	J.S. Frank <i>et al.</i>	(LANL, YALE, LBL+)	ANAND	53	PRSL A22 183	Anand	
HOFFMAN	83	PR D28 660	C.M. Hoffman <i>et al.</i>	(LANL, ARZ5)					
NICZYPORUK	83	ZPHY C17 197	B. Niczyporuk <i>et al.</i>	(LENA Collab.)					
PRESKILL	83	PL 120B 127	J. Preskill, M.B. Wise, F. Wilczek	(HARV, UCSBT)					
SIKIVIE	83	PRL 51 1415	P. Sikivie	(FLOR)					
Also	84	PR 52 695 erratum	P. Sikivie	(FLOR)					
ALEKSEEV	82	JETP 55 591	E.A. Alekseeva <i>et al.</i>	(KIAE)					
Translated from ZETF	82	B2 1007.							
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