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

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

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

<table>
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<th>VALUE (MeV)</th>
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<td>&gt;0.2</td>
<td>BARROSO 82</td>
<td>ASTR</td>
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<tr>
<td>&gt;0.25</td>
<td>RAFFEL 82</td>
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<td>&gt;0.2</td>
<td>DICUS 78C</td>
<td>ASTR</td>
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<tr>
<td>&gt;0.3</td>
<td>MIKAELIAN 78</td>
<td>ASTR</td>
<td>Stellar emission</td>
</tr>
<tr>
<td>&gt;0.2</td>
<td>SATO 78</td>
<td>ASTR</td>
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<tr>
<td>&gt;0.2</td>
<td>VYSOTSKII 78</td>
<td>ASTR</td>
<td>Standard Axion</td>
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1. Lower bound from 5.5 MeV γ-ray line from the sun.
2. Lower bound from requiring the red giants’ stellar evolution not be disrupted by axion emission.

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

Limits are for branching ratios.

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<td>$K^+ \rightarrow \pi^+ X^0$</td>
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<td>NG 93</td>
<td>COSM</td>
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<1.1 \times 10^{-8} \quad 90 \quad 14 \text{ ALLIEGRO} \quad 92 \quad \text{SPEC} \quad K^+ \rightarrow \pi^+ \chi^0 (\chi^0 \rightarrow e^+ e^-) \\
<5 \times 10^{-4} \quad 90 \quad 15 \text{ ATIYA} \quad 92 \quad \text{B787} \quad \pi^0 \rightarrow \gamma \chi^0 \\
<4 \times 10^{-6} \quad 90 \quad 16 \text{ MEIJERDREES} \quad 92 \quad \text{SPEC} \quad \pi^0 \rightarrow \gamma \chi^0, \chi^0 \rightarrow e^+ e^-,
\quad m_{\chi^0} = 100 \text{ MeV} \\
<1 \times 10^{-7} \quad 90 \quad 17 \text{ ATIYA} \quad 90b \quad \text{B787 Sup. by KITCHING 97} \\
<1.3 \times 10^{-8} \quad 90 \quad 18 \text{ KORENCHENKO} \quad 87 \quad \text{SPEC} \quad \pi^+ \rightarrow e^+ \nu A^0 (A^0 \rightarrow e^+ e^-) \\
<1 \times 10^{-9} \quad 90 \quad 19 \text{ EICHLER} \quad 86 \quad \text{SPEC} \quad \text{Stopped } \pi^+ \rightarrow e^+ \nu A^0 \\
<2 \times 10^{-5} \quad 90 \quad 20 \text{ YAMAZAKI} \quad 84 \quad \text{SPEC} \quad \text{For } 160 < m < 260 \text{ MeV} \\
<(1.5–4) \times 10^{-6} \quad 90 \quad 21 \text{ ASANO} \quad 82 \quad \text{CNTR} \quad \text{Stopped } K^+ \rightarrow \pi^+ \chi^0 \\
\quad 22 \text{ ASANO} \quad 81b \quad \text{CNTR} \quad \text{Stopped } K^+ \rightarrow \pi^+ \chi^0 \\
\quad 23 \text{ ZHITNITSKII} \quad 79 \quad \text{Heavy axion} \\

3 This limit applies for a mass near 180 MeV. For other masses in the range $m_{\chi^0} =$ 150–250 MeV the limit is less restrictive, but still improves ADLER 02c and ATIYA 93b. 
4 ANISIMOVSKY 04 bound is for $m_{\chi^0} = 0$. 
5 ADLER 02c bound is for $m_{\chi^0} <$ 60 MeV. See Fig. 2 for limits at higher masses. 
6 The quoted limit is for $m_{\chi^0} = 0$–80 MeV. See their Fig. 5 for the limit at higher mass. 
    The branching fraction limit assumes pure phase space decay distributions. 
7 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. 
8 KITCHING 97 limit is for $B(K^+ \rightarrow \pi^+ X^0) \cdot B(X^0 \rightarrow \gamma \gamma)$ and applies for $m_{\chi^0} \approx 50$ MeV, $\tau_{\chi^0} < 10^{-10}$ s. Limits are provided for $0 < m_{\chi^0} < 100$ MeV, $\tau_{\chi^0} < 10^{-8}$ s. 
9 ADLER 96 looked for a peak in missing-mass distribution. This work is an update of ATIYA 93. The limit is for massless stable $X^0$ particles and extends to $m_{\chi^0} = 80$ MeV at the same level. See paper for dependence on finite lifetime. 
10 AMSER 94b and AMSER 96b looked for a peak in missing-mass distribution. 
11 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. 
12 ATIYA 93b looked for a peak in missing mass distribution. The bound applies for stable $X^0$ of $m_{\chi^0} =$ 150–250 MeV, and the limit becomes stronger ($10^{-8}$) for $m_{\chi^0} =$ 180–240 MeV. 
13 NG 93 studied the production of $X^0$ via $\gamma \gamma \rightarrow \pi^0 \rightarrow \gamma X^0$ in the early universe at $T \simeq$ 1 MeV. The bound on extra neutrinos from nucleosynthesis $\Delta N_{\nu} < 0.3$ (WALKER 91) is employed. It applies to $m_{\chi^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier $X^0$. 
14 ALLIEGRO 92 limit applies for $m_{\chi^0} =$ 150–340 MeV and is the branching ratio times the decay probability. Limit is $< 1.5 \times 10^{-8}$ at 99%CL. 
15 ATIYA 92 looked for a peak in missing mass distribution. The limit applies to $m_{\chi^0} = 0$–130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires $X^0$ to be a vector particle. 
16 MEIJERDREES 92 limit applies for $\tau_{\chi^0} = 10^{-23}$–$10^{-11}$ sec. Limits between $2 \times 10^{-4}$ and $4 \times 10^{-6}$ are obtained for $m_{\chi^0} = 25$–120 MeV. Angular momentum conservation requires that $X^0$ has spin $\geq 1$. 
17 ATIYA 90b limit is for $B(K^+ \rightarrow \pi^+ X^0) \cdot B(X^0 \rightarrow \gamma \gamma)$ and applies for $m_{\chi^0} = 50$ MeV, $\tau_{\chi^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{\chi^0} < 100$ MeV, $\tau_{\chi^0} < 10^{-8}$ s. 
18 KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and $B(A^0 \rightarrow e^+ e^-) = 1$. 

HTTP://PDG.LBL.GOV  Page 2  Created: 6/18/2012 15:09
19 EICHLER 86 looked for $\pi^+ \rightarrow e^+ \nu A^0$ followed by $A^0 \rightarrow e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of $A^0$. The quoted limits are valid when $\tau(A^0) \geq 3 \times 10^{-10}$s if the decays are kinematically allowed.

20 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.

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

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

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

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

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<td>&lt; 5 $\times 10^{-5}$</td>
<td>90</td>
<td>24 DRUZHININ 87</td>
<td>ND</td>
<td>$\phi \rightarrow A^0 \gamma (A^0 \rightarrow e^+ e^-)$</td>
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<td>&lt; 2 $\times 10^{-3}$</td>
<td>90</td>
<td>25 DRUZHININ 87</td>
<td>ND</td>
<td>$\phi \rightarrow A^0 \gamma (A^0 \rightarrow \gamma \gamma)$</td>
</tr>
<tr>
<td>&lt; 7 $\times 10^{-6}$</td>
<td>90</td>
<td>26 DRUZHININ 87</td>
<td>ND</td>
<td>$\phi \rightarrow A^0 \gamma (A^0 \rightarrow $ missing)</td>
</tr>
<tr>
<td>&lt; 1.4 $\times 10^{-5}$</td>
<td>90</td>
<td>27 EDWARDS 82</td>
<td>CBAL</td>
<td>$J/\psi \rightarrow A^0 \gamma$</td>
</tr>
</tbody>
</table>

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

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

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

27 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.

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

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<td>28 BADERT... 02</td>
<td>CNTR</td>
<td>$\text{o-Ps} \rightarrow \gamma X_1 X_2, m_{X_1} + m_{X_2} \leq 900 \text{ keV}$</td>
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<td>MAENO 95</td>
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<td>$\text{o-Ps} \rightarrow \gamma A^0 \gamma, m_{A^0} = 850–1013 \text{ keV}$</td>
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<td>&lt; 3.0 $\times 10^{-3}$</td>
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<td>29 ASAI 94</td>
<td>CNTR</td>
<td>$\text{o-Ps} \rightarrow \gamma A^0 \gamma, m_{A^0} = 30–500 \text{ keV}$</td>
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<td>&lt; 2.8 $\times 10^{-5}$</td>
<td>90</td>
<td>30 AKOPYAN 91</td>
<td>CNTR</td>
<td>$\text{o-Ps} \rightarrow \gamma A^0 \gamma (A^0 \rightarrow \gamma \gamma), m_{A^0} &lt; 30 \text{ keV}$</td>
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<td>31 ASAI 91</td>
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<td>&lt; (1–5) $\times 10^{-4}$</td>
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<td>32 TSUCHIAKI 90</td>
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<td>33 ORITO 89</td>
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<td>CARBONI 83</td>
<td>CNTR</td>
<td>Ortho-positronium</td>
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</table>
BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles.

The ASA1 94 limit is based on inclusive photon spectrum and is independent of $A^0$ decay modes.

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

ASA1 94 limit translates to $\frac{g^2_{A^0 e^+ e^-}}{4\pi} < 1.1 \times 10^{-11}$ (90% CL) for $m_{A^0} < 800$ keV.

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

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

AMALDI 85 set limits $B(A^0\gamma) / B(\gamma\gamma\gamma) < (1–5) \times 10^{-6}$ for $m_{A^0}$ from 150–900 keV which are about 1/10 of the CARBONI 83 limits.

CARBONI 83 looked for orthopositronium $\rightarrow A^0\gamma$. Set limit for $A^0$ electron coupling squared, $\frac{g(e e A^0)^2}{4\pi} < 6.2 \times 10^{-10}$. This is about 1/10 of the bound from $g^2$ experiments.

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

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<td>36 BASSOMPIERRE 95</td>
<td>$m_{A^0} = 1.8 \pm 0.2$ MeV</td>
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36 BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of $e^+e^-$ pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate $A^0$ for $\tau(A^0) = 10^{-18}$–$10^{-9}$ sec. They also found an excess of events in the range $m_{e^+e^-} = 2.1$–3.5 MeV.

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

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

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$<2. \times 10^{-11}$ 90 0
\begin{tabular}{lllll}
<1. \times 10^{-13} & 90 & 0 & BERGSMA & 85 CHRM CERN beam dump \\
& & & F AISNNER & 83 OSPK Beam dump, \( A^0 \rightarrow 2\gamma \) \\
& & & F AISNNER & 83b RVUE LAMPF beam dump \\
& & & FRANK & 83b RVUE LAMPF beam dump \\
& & & HOFFMAN & 83 CNTR \( \pi p \rightarrow n A^0 \) \\
& & & FETSCHER & 82 RVUE See FAISSNER 81 \\
<1. \times 10^{-12} & 90 & 1 & BECHIS & 79 CNTR \\
& & & COTEUS & 79 OSPK Beam dump \\
& & & DISHAW & 79 CALO 400 GeV \( p p \) \\
& & & ALIBRAN & 78 HYBR Beam dump \\
& & & ARATYAN & 78b CALO Beam dump \\
& & & BELLOTTI & 78 HLBC Beam dump \\
& & & BELLOTTI & 78 HLBC \( m_{A^0}=1.5 \) MeV \\
& & & BELLOTTI & 78 HLBC \( m_{A^0}=1 \) MeV \\
& & & BOSETTI & 78b HYBR Beam dump \\
<0.5 \times 10^{-8} & 90 & 2 & HANS & 80 HLBC Beam dump \\
& & & MICELMAC... & 78 \\
& & & VYSOTSKII & 78 \\
\end{tabular}

37 JAIN 07 claims evidence for \( A^0 \rightarrow e^+ e^- \) produced in \( ^{207}\text{Pb} \) collision on nuclear emulsion (Ag/Br) for \( m(A^0) = 7 \pm 1 \) or \( 19 \pm 1 \) MeV and \( \tau(A^0) \leq 10^{-13} \) s.

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

39 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.

40 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.

41 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 \( m_{e^-} > 2 \) MeV.

42 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 \( A^0 \).

43 MEIJERDREES 92 give \( \Gamma(\pi^- p \rightarrow n A^0) \cdot B(A^0 \rightarrow e^+ e^-) / \Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5} \) (90\% CL) for \( m_{A^0} = 100 \) MeV, \( \tau_{A^0} = 10^{-11} \) to \( 10^{-23} \) sec. Limits ranging from \( 2.5 \times 10^{-3} \) to \( 10^{-7} \) are given for \( m_{A^0} = 25 \) to 136 MeV.
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 $x < 1$.

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 $2m_e \sim 20$ MeV is excluded. Lower limit on $f_{A^0}$ of $\approx 10^4$ GeV is given for $m_{A^0} = 2m_e \sim 20$ MeV.

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.

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.

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 $\sim 1$. Lower limit on $f_{A^0}$ of $10^2$–$10^3$ GeV is given for $m_{A^0} = 0.1$–1 MeV.

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.

BERGSMA 85 look for $A^0 \rightarrow 2\gamma$, $e^+e^-$, $\mu^+\mu^-$. First limit above is for $m_{A^0} = 1$ MeV; second for 200 MeV. See their figure 4 for excluded region on $f_{A^0}$-$m_{A^0}$ plane, where $f_{A^0}$ is $A^0$ decay constant. For Peccei-Quinn PECCEI 77 $A^0$, $m_{A^0} < 180$ keV and $\tau > 0.037$ s. (CL = 90%). For the axion of FAISSNER 81b at 250 keV, BERGSMA 85 expect 15 events but observe zero.

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

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 $[d\sigma(A^0)/d\omega]$ at $90^\circ$ for $A^0$ is $14 \times 10^{-35}$ cm$^2$ sr$^{-1}$ MeV ms$^{-1}$. See comment on FRANK 83b.

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.

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

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

FAISSNER 81 see excess $\mu e$ events. Suggest axion interactions.

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 BERGSMA 85. Also see in the next subsection ALEK-SEEV 82b, CAVAIGNAC 83, and ANANEV 85.
KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86 \sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

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 $m_{A^0} < 2m_e^-$. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

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

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

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.

COTEUS 79 is a beam dump experiment at BNL.

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

BELLOTTI 78 first value comes from search for $A^0 \rightarrow e^+e^-$. Second value comes from search for $A^0 \rightarrow 2\gamma$, assuming mass $<2m_e^-$. For any mass satisfying this, limit is above value $\times (\text{mass}^{-4})$. Third value uses data of PL 60B 401 and quotes $\sigma(\text{production})/\sigma(\text{interaction}) < 10^{-67} \text{ cm}^4$.

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

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

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

VYSOTSKI 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.
MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances $Z^0$ in the $(m_{\chi^0}, f_{\chi^0})$ plane.

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

73 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 $\omega(A^0)/\omega(M1) < 1.5 \times 10^{-10} (\text{CL}=95\%)$. Standard axion with $m_{A^0} = 250 \text{ keV}$ gives $10^{-5}$ for the ratio. Not valid for $m_{A^0} \gtrsim 1022 \text{ keV}$.  

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

75 VUILLEUMIER 81 is at Grenoble reactor. Set limit $m_{A^0} < 280 \text{ keV}$.

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

Limits are for branching ratio.

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<td>$125m^1\text{Te decay}$</td>
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<tr>
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<td>77 DEBOER</td>
<td>RVUE</td>
<td>M1 transitions</td>
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<td>78 TSUNODA</td>
<td>CNTR</td>
<td>$252\text{Cf fission, } A^0 \rightarrow e^+e^-$</td>
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<td>80 HICKS</td>
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<td>$35\text{S decay, } A^0 \rightarrow \gamma \gamma$</td>
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<tr>
<td>$&lt; (0.4–10) \times 10^{-3}$</td>
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<td>81 ASANUMA</td>
<td>CNTR</td>
<td>$241\text{Am decay}$</td>
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<td>85 DATAR</td>
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<td>$12\text{C}^* \rightarrow 12\text{C}A^0$, $A^0 \rightarrow \gamma e, A^0 \rightarrow \gamma Z$</td>
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<td>89 HALLIN</td>
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<td>92 CAVAINAC</td>
<td>CNTR</td>
<td>$97\text{Nb}^<em>, deut^</em> \rightarrow 2\gamma$</td>
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<tr>
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<td>93 ALEKSEEV</td>
<td>CNTR</td>
<td>$Li^<em>, deut^</em> \rightarrow 2\gamma$</td>
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<tr>
<td>$&lt; 94 \times 10^{-4}$</td>
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<td>94 LEHMANN</td>
<td>CNTR</td>
<td>$Cu^* \rightarrow CuA^0 (A^0 \rightarrow 2\gamma)$</td>
</tr>
</tbody>
</table>
88 SA V AGE 88 looked for the axion emission when $^{252}$Cf undergoes a spontaneous fission, with the axion decaying into $e^+ e^-$. The bound is for $m_{A^0} = 40$ MeV. It improves to $2.5 \times 10^{-5}$ for $m_{A^0} = 200$ MeV.

90 TSUNODA 90 studied the chain process, $^{139}$Ce → $^{139}$La$^*$ by electron capture and M1 transition of $^{139}$La$^*$ to the ground state. It does not assume decay modes of $A^0$. The bound applies for $m_{A^0} < 166$ keV.

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

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

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

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

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

85 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.

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

87 The DOEHNPER 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.

88 SAVAGE 88 looked for $A^0$ that decays into $e^+e^-$ in the decay of the 9.17 MeV $J^P = 2^+$ state in $^{14}$N, 17.64 MeV state $J^P = 1^+$ in $^{8}$Be, and the 18.15 MeV state $J^P = 1^+$ in $^{8}$Be. This experiment constrains the isovector coupling of $A^0$ to hadrons, if $m_{A^0} = (1.1 \rightarrow 2.2)$ MeV and the isoscalar coupling of $A^0$ to hadrons, if $m_{A^0} = (1.1 \rightarrow 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

89 Limits are for $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of $e^+ e^-$ pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$ s. $^6$Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the $^{10}$B and $^{14}$N isoscalar decay data strongly reject PECCEI 86 model II and III.
Savage 86 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 isovector coupling of $A^0$ to hadrons.

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

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

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

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

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

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

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

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<td>$eN \to eA^0N$ $(A^0 \to ee)$</td>
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<td>$eN \to eA^0N$ $(A^0 \to ee)$</td>
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<td>CAILO</td>
<td>$A \to e^+e^-$ or $2\gamma$</td>
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98 The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. $B(A^0 \to e^+e^-) = 1$ assumed. Excluded domain in the $\tau_{A^0} - m_{A^0}$ 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).

99 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).
Search for $A^0$ (Axion) Resonance in Bhabha Scattering

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

<table>
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<td>92c</td>
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<td>89</td>
<td>CNTR $m_{A^0} = 1.80$–$1.86$ MeV</td>
</tr>
<tr>
<td>&lt; 31</td>
<td>95</td>
<td>LORENZ</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.646$ MeV</td>
</tr>
<tr>
<td>&lt; 94</td>
<td>95</td>
<td>LORENZ</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.726$ MeV</td>
</tr>
<tr>
<td>&lt; 23</td>
<td>95</td>
<td>LORENZ</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.782$ MeV</td>
</tr>
<tr>
<td>&lt; 19</td>
<td>95</td>
<td>LORENZ</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.837$ MeV</td>
</tr>
<tr>
<td>&lt; 3.8</td>
<td>97</td>
<td>TSERTOS</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.832$ MeV</td>
</tr>
<tr>
<td>113 VANKLINKEN</td>
<td>88</td>
<td>CNTR</td>
<td></td>
<td></td>
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<tr>
<td>114 MAIER</td>
<td>87</td>
<td>CNTR</td>
<td></td>
<td></td>
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<tr>
<td>&lt;2500</td>
<td>90</td>
<td>MILLS</td>
<td>87</td>
<td>CNTR $m_{A^0} = 1.8$ MeV</td>
</tr>
<tr>
<td>115 VONWIMMER.B7</td>
<td>CNTR</td>
<td></td>
<td></td>
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</tr>
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</table>

106 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.

107 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.
108 WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming $B(A^0 \to e^+ e^-) = 100\%$. They say that TSERTOS 89 overestimate the limit by a factor of $\pi/2$. WU 92 also quote a bound for vector boson, $\tau > 8.2 \times 10^{-13}$ s.

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

110 JUDGE 90 excludes an elastic pseudoscalar $e^+ e^- \to e^+ e^-$ 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 $m_{A^0} = 1.786$–1.856 MeV.

111 See also TSERTOS 88 in references.112 The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88, footnote 3.

113 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.

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

115 VONWIMMERSPERG 87 measured Bhabha scattering for $E_{\text{cm}} = 1.37$–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}} = 14.5 \pm 6.8$ keV-b. For a comment and a reply, see VANKLINKEN 88 and VONWIMMERSPERG 88. Also see CONNELL 88.

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

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

<table>
<thead>
<tr>
<th>VALUE ($10^{-3}$ eV)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<td>0.18</td>
<td>95</td>
<td>VO</td>
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<tr>
<td>1.5</td>
<td>95</td>
<td>VO</td>
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<td>CNTR $m_{A^0} = 1.4$ MeV</td>
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<tr>
<td>12</td>
<td>95</td>
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<tr>
<td>6.6</td>
<td>95</td>
<td>TRZASKA</td>
<td>91</td>
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<td>4.4</td>
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<tr>
<td>0.11</td>
<td>95</td>
<td>FOX</td>
<td>89</td>
<td>CNTR</td>
</tr>
<tr>
<td>33</td>
<td>97</td>
<td>CONNELL</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.062$ MeV</td>
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<tr>
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<td>97</td>
<td>CONNELL</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.580$ MeV</td>
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<td>79</td>
<td>97</td>
<td>CONNELL</td>
<td>88</td>
<td>CNTR $m_{A^0} = 1.782$ MeV</td>
</tr>
<tr>
<td>1.045–1.085 MeV</td>
<td></td>
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</tr>
</tbody>
</table>

116 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.

117 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).

118 Similar limits are obtained for $m_{A^0} = 1.045$–1.085 MeV.
Search for $X^0$ (Light Boson) Resonance in $e^+e^- \to \gamma\gamma$

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

### Table

<table>
<thead>
<tr>
<th>VALUE ($10^{-3}$ eV)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<td>$&lt; 0.2$</td>
<td>95</td>
<td>119 VO 94</td>
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<td>$m_{X^0} = 1.1–1.9$ MeV</td>
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<tr>
<td>$&lt; 1.0$</td>
<td>95</td>
<td>120 VO 94</td>
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<td>$m_{X^0} = 1.1$ MeV</td>
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<tr>
<td>$&lt; 2.5$</td>
<td>95</td>
<td>120 VO 94</td>
<td>CNTR</td>
<td>$m_{X^0} = 1.4$ MeV</td>
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<tr>
<td>$&lt; 120$</td>
<td>95</td>
<td>121 SKALSEY</td>
<td>CNTR</td>
<td>$m_{X^0} = 1.5$ MeV</td>
</tr>
</tbody>
</table>

119 VO 94 looked for $X^0 \to \gamma\gamma\gamma$ decaying at rest. The precise limits depend on $m_{X^0}$. See Fig. 2(b) in paper.

120 VO 94 looked for $X^0 \to \gamma\gamma\gamma$ decaying in flight.

121 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 $\gamma\gamma$.

### Table

<table>
<thead>
<tr>
<th>VALUE ($10^{-6}$)</th>
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<tbody>
<tr>
<td>$&lt; 4.2$</td>
<td>90</td>
<td>122 MITSUI</td>
<td>96</td>
<td>CNTR $\gamma X^0$</td>
</tr>
<tr>
<td>$&lt; 4$</td>
<td>68</td>
<td>123 SKALSEY</td>
<td>95</td>
<td>CNTR $\gamma X^0$</td>
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<tr>
<td>$&lt; 40$</td>
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<td>124 SKALSEY</td>
<td>95</td>
<td>RVUE $\gamma X^0$</td>
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<tr>
<td>$&lt; 0.18$</td>
<td>125</td>
<td>ADACHI 91</td>
<td>94</td>
<td>CNTR $\gamma\gamma X^0, X^0 \to \gamma\gamma$</td>
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<tr>
<td>$&lt; 0.26$</td>
<td>126</td>
<td>ADACHI 91</td>
<td>94</td>
<td>CNTR $\gamma\gamma X^0, X^0 \to \gamma\gamma$</td>
</tr>
<tr>
<td>$&lt; 0.33$</td>
<td>127</td>
<td>ADACHI 91</td>
<td>94</td>
<td>CNTR $\gamma\gamma X^0, X^0 \to \gamma\gamma$</td>
</tr>
</tbody>
</table>

122 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 $e^+e^0$ coupling and hence on the branching ratio $B(o-Ps \to \gamma\gamma X^0) < 6.2 \times 10^{-6}$. The bounds weaken for heavier $X^0$.

123 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.

124 SKALSEY 95 reinterpreted the bound on $\gamma A^0$ decay of o-Ps by ASAI 91 where 3% of delayed annihilations are not from $3S_1$ states. The bound applies for scalar and vector $X^0$ with $C = -1$ and $m_{X^0} = 0–800$ keV.

125 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.

126 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.

127 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.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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</thead>
<tbody>
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<td>$&lt;3.3 \times 10^{-2}$</td>
<td>95</td>
<td>131</td>
<td>ALBRECHT</td>
<td>ARG $\tau \rightarrow e_X^0$. Familon</td>
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<tr>
<td>$&lt;1.8 \times 10^{-2}$</td>
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<td>131</td>
<td>ALBRECHT</td>
<td>ARG $\tau \rightarrow e_X^0$. Familon</td>
</tr>
<tr>
<td>$&lt;6.4 \times 10^{-9}$</td>
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<td>132</td>
<td>ATIYA</td>
<td>B787 $K^+ \rightarrow \pi^+ X^0$. Familon</td>
</tr>
<tr>
<td>$&lt;1.1 \times 10^{-9}$</td>
<td>90</td>
<td>133</td>
<td>BOLTON</td>
<td>CBOX $\mu^+ \rightarrow e^+ \gamma X^0$. Familon</td>
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<tr>
<td>$&lt;5 \times 10^{-6}$</td>
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<td>136</td>
<td>PICCIOTTO</td>
<td>CNTR $\pi \rightarrow e \nu X^0$. Majoron</td>
</tr>
<tr>
<td>$&lt;1.3 \times 10^{-9}$</td>
<td>90</td>
<td>137</td>
<td>GOLDMAN</td>
<td>CNTR $\mu \rightarrow e \gamma X^0$. Familon</td>
</tr>
<tr>
<td>$&lt;3 \times 10^{-4}$</td>
<td>90</td>
<td>138</td>
<td>BRYMAN</td>
<td>RVUE $e \rightarrow e X^0$. Familon</td>
</tr>
<tr>
<td>$&lt;1 \times 10^{-10}$</td>
<td>90</td>
<td>139</td>
<td>EICHLER</td>
<td>SPEC $\mu^+ \rightarrow e^+ X^0$. Familon</td>
</tr>
<tr>
<td>$&lt;2.6 \times 10^{-6}$</td>
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<td>140</td>
<td>JODIDIO</td>
<td>SPEC $\mu^+ \rightarrow e^+ X^0$. Familon</td>
</tr>
<tr>
<td>128</td>
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<td>LESSA</td>
<td>O7</td>
<td>07</td>
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<td>129</td>
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<td>DIAZ</td>
<td>98</td>
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<td>130</td>
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<td>BOBRAKOV</td>
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<td>DIAZ</td>
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<td>130</td>
<td></td>
<td>BOBRAKOV</td>
<td>91</td>
<td></td>
</tr>
</tbody>
</table>

128 LESSA 07 consider decays of the form Meson $\rightarrow \ell \nu X^0$ and $\ell \rightarrow e \nu \nu X^0$ Majoron and use existing data to derive limits on the neutrino-Majoron Yukawa couplings $g_{\alpha \beta}$ ($\alpha, \beta = e, \mu, \tau$). Their best limits are $|g_{e \alpha}|^2 < 5.5 \times 10^{-6}$, $|g_{\mu \alpha}|^2 < 4.5 \times 10^{-5}$, $|g_{\tau \alpha}|^2 < 5.5 \times 10^{-2}$ at CL = 90%.

129 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 $H^0 \rightarrow X^0 X^0$.

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

131 ALBRECHT 90 limits are for $B(\tau \rightarrow e_X^0)/B(\tau \rightarrow e \nu \nu)$ for $m_{X^0} < 100$ MeV. The limits rise to 7.1% (for $\mu$), 5.0% (for $e$) for $m_{X^0} = 500$ MeV.

132 ATIYA 90 limit is for $m_{X^0} = 0$. The limit $B < 1 \times 10^{-8}$ holds for $m_{X^0} < 95$ MeV.

133 For the reduction of the limit due to finite lifetime of $X^0$, see their Fig. 3.

134 BOLTON 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.
Limits are for $\Gamma(\mu \rightarrow e X^0)/\Gamma(\mu \rightarrow e \nu \tau)$. Valid when $m_{X^0} = 0$–93.4, 98.1–103.5 MeV.

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.

JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F) \bar{\psi} H \gamma^\mu (a + b \gamma_5) \psi \phi \partial_\mu \phi / 2$ 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.

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

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.

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BERNATOWICZ 92 studied double-$\beta$ decays of $^{128}$Te and $^{130}$Te, and found the ratio $\tau(130^{\text{Te}})/\tau(128^{\text{Te}}) = (3.52 \pm 0.11) \times 10^{-4}$ in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of $^{128}$Te of $(7.7 \pm 0.4) \times 10^{24}$ year.

We calculated 90% CL limit as $(7.7 - 1.28 \times 0.4 = 7.2) \times 10^{24}$.

ARNOLD 11 use the NEMO-3 detector to obtain the reported limit on Majoron emission. It implies that the coupling constant $g_{\nu \chi} < 0.6 - 1.6 \times 10^{-4}$ depending on the nuclear matrix element used. Supercedes ARNABOLDI 03.

ARGYRIADES 10 use the NEMO-3 tracking detector and $^{96}$Zr to derive the reported limit. No limit for the Majoron electron coupling is given.

ARGYRIADES 09 use $^{150}$Nd data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu \chi} \rangle < 1.7 - 3.0 \times 10^{-4}$ using a range of nuclear matrix elements that include the effect of nuclear deformation.

ARNOLD 06 use $^{100}$Mo data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu \chi} \rangle < (0.4 - 1.8) \times 10^{-4}$ using a range of matrix element calculations. Supersedes ARNOLD 04.

NEMO-3 tracking calorimeter is used in ARNOLD 06. Reported half-life limit for $^{82}$Se corresponds to $\langle g_{\nu \chi} \rangle < (0.66 - 1.9) \times 10^{-4}$ using a range of matrix element calculations. Supersedes ARNOLD 04.

ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu \chi} \rangle < (0.5 - 0.9) \times 10^{-4}$ using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.

ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu \chi} \rangle < (0.7 - 1.6) \times 10^{-4}$ using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.

Supersedes ALESSANDRELLI 00. Array of TeO$_2$ crystals in high resolution cryogenic calorimeter. Some enriched in $^{130}$Te. Derive $\langle g_{\nu \chi} \rangle < 17 - 33 \times 10^{-5}$ depending on matrix element.

Supersedes ALESSANDRELLI 00. Cryogenic calorimeter search.

Limit for the $0\nu \chi$ decay with Majoron emission of $^{116}$Cd using enriched CdWO$_4$ scintillators. $\langle g_{\nu \chi} \rangle < 4.6 - 8.1 \times 10^{-5}$ depending on the matrix element. Supersedes DANEVICH 00.

Limit for the $0\nu 2\chi$ decay of $^{116}$Cd. Supersedes DANEVICH 00.

BERNABEI 020 obtain limit for $0\nu \chi$ decay with Majoron emission of $^{136}$Xe using liquid Xe scintillation detector. They derive $\langle g_{\nu \chi} \rangle < 2.0 - 3.0 \times 10^{-5}$ with several nuclear matrix elements.

Replaces TANAKA 93. FUSHIMI 02 derive half-life limit for the $0\nu \chi$ decay by means of tracking calorimeter ELEGANT V. Considering various matrix element calculations, a range of limits for the Majoron-neutrino coupling is given: $\langle g_{\nu \chi} \rangle < (6.3 - 360) \times 10^{-5}$.

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

DANEVICH 01 obtain limit for the $0\nu \chi$ decay with Majoron emission of $^{160}$Gd using Gd$_2$SiO$_5$:Ce crystal scintillators.

DANEVICH 01 obtain limit for the $0\nu 2\chi$ decay with 2 Majoron emission of $^{160}$Gd.
ARNOLD 00 reports limit for the $0\nu \chi$ decay with Majoron emission derived from tracking calorimeter NEMO 2. Using $^{82}\text{Se}$ source: $\langle g_{\nu \chi} \rangle < 1.6 \times 10^{-4}$. Matrix element from GUENTHER 96.

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

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

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

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

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

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

$v_1 = v_2$ is usually assumed ($v_i$ = vacuum expectation values). For a review of these limits, see RAFFELT 91 and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

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<td>COSM D</td>
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<td>CNTR D</td>
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<tr>
<td>&lt; 1.02</td>
<td>171 DERBIN 09A</td>
<td>CNTR K</td>
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<td>&lt; 0.42</td>
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<tr>
<td>3 to 20</td>
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<td>&lt; 0.007</td>
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<td>&lt; 4</td>
<td>177 MOROI 98</td>
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<tr>
<td>&lt;(0.5–6) × 10$^{-3}$</td>
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<td>ASTR D</td>
<td>neutron star</td>
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<td>180 KEIL 97</td>
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<td>ASTR D</td>
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<tr>
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<td>ASTR D</td>
<td>red giants, white dwarfs</td>
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<tr>
<td>none 3–8</td>
<td>183 CHANG 93</td>
<td>ASTR K</td>
<td>SN 1987A</td>
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<tr>
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<td>WANG 92C</td>
<td>ASTR D</td>
<td>C-O burning</td>
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<tr>
<td>none 3–8</td>
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<td>ASTR D</td>
<td>K, intergalactic light</td>
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<tr>
<td>&lt; 10</td>
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<td>COSM D</td>
<td>K, mass density of the universe, supersymmetry</td>
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<tr>
<td>&lt; 1 × 10$^{-3}$</td>
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<td>SN 1987A</td>
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<tr>
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<td>187 RESSELL 91</td>
<td>ASTR K</td>
<td>intergalactic light</td>
<td></td>
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<tr>
<td>none 10$^{-3}$–3</td>
<td>188 BURROWS 90</td>
<td>ASTR D,K</td>
<td>SN 1987A</td>
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< 0.02
< 1 × 10⁻³
< (1.4–10) × 10⁻³
< 3.6 × 10⁻⁴
< 12
< 1 × 10⁻³
< 0.07
< 0.7
< 2–5
< 0.01
< 0.06
< 0.7
< 0.03
< 1
< 0.003–0.02
> 1 × 10⁻⁵
< 1 × 10⁻⁵
< 0.04
> 1 × 10⁻⁵
< 0.1
< 1
< 0.07

166 CADAMURO 11 use the deuterium abundance to show that the $m_A^0$ range 0.7 eV – 300 keV is excluded for axions, complementing HANNESTAD 10.

167 DERBIN 11A look for solar axions produced by Compton and bremsstrahlung processes, in the resonant excitation of $^{169}$Tm, constraining the axion-electron × axion nucleon couplings.

168 ANDRIAMONJE 10 search for solar axions produced from $^7$Li (478 keV) and D(p,γ)$^3$He (5.5 MeV) nuclear transitions. They show limits on the axion-photon coupling for two reference values of the axion-nucleon coupling for $m_A < 100$ eV.

169 This is an update of HANNESTAD 08 including 7 years of WMAP data.

170 ANDRIAMONJE 09 look for solar axions produced from the thermally excited 14.4 keV level of $^{57}$Fe. They show limits on the axion-nucleon × axion-photon coupling assuming $m_A < 0.03$ eV.

171 DERBIN 09A look for Primakoff-produced solar axions in the resonant excitation of $^{169}$Tm, constraining the axion-photon × axion-nucleon couplings.

172 KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used.

173 This is an update of HANNESTAD 07 including 5 years of WMAP data.

174 This is an update of HANNESTAD 05A with new cosmological data, notably WMAP (3 years) and baryon acoustic oscillations (BAO). Lyman-α data are left out, in contrast to HANNESTAD 05A and MELCHIORRI 07A, because it is argued that systematic errors are large. It uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component.

175 MELCHIORRI 07A is analogous to HANNESTAD 05A, with updated cosmological data, notably WMAP (3 years). Uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component. Leaving out Lyman-α data, a conservative limit is 1.4 eV.
HANNESTAD 05A puts an upper limit on the mass of hadronic axion because in this mass range it would have been thermalized and contribute to the hot dark matter component of the universe. The limit is based on the CMB anisotropy from WMAP, SDSS large scale structure, Lyman $\alpha$, and the prior Hubble parameter from HST Key Project. A $\chi^2$ statistic is used. Neutrinos are assumed not to contribute to hot dark matter.

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.

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

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.

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.

RAFFLET 85 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).

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

CHANG 93 updates ENGEL 90 bound with the Kaplan-Manohar ambiguity in $z=m_\gamma/m_\pi$ (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.

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.

KIM 91 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.

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

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

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 $2.5 \times 10^{-3}$ eV $\lesssim m_{A0} \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

RAFFLET 90D is a re-analysis of DEARBORN 86.

The region $m_{A0} \gtrsim 2$ eV is also allowed.

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.

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.

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

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

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

RAFFLET 86 gives a limit $g_{A\gamma} < 1.1 \times 10^{-10}$ GeV$^{-1}$ from red giants and $< 2.4 \times 10^{-9}$ GeV$^{-1}$ from the sun.
Search for Relic Invisible Axions

Limits are for \([G_{A\gamma\gamma}/mA_0]^2/\rho_A\) where \(G_{A\gamma\gamma}\) denotes the axion-two-photon coupling.

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

<table>
<thead>
<tr>
<th>VALUE/CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tbody>
<tr>
<td>&lt;3.5 × 10^{-43}</td>
<td>199 HOSKINS 11</td>
<td>ADMX</td>
<td>(m_{A_0} = 3.3-3.69 \times 10^{-6}) eV</td>
</tr>
<tr>
<td>&lt;2.9 × 10^{-43}</td>
<td>200 ASZTALOS 10</td>
<td>ADMX</td>
<td>(m_{A_0} = 3.34-3.53 \times 10^{-6}) eV</td>
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<tr>
<td>&lt;1.9 × 10^{-43}</td>
<td>201 DUFFY 97.7</td>
<td>ADMX</td>
<td>(m_{A_0} = 1.98-2.17 \times 10^{-6}) eV</td>
</tr>
<tr>
<td>&lt;5.5 × 10^{-43}</td>
<td>202 ASZTALOS 90</td>
<td>ADMX</td>
<td>(m_{A_0} = 1.9-3.3 \times 10^{-6}) eV</td>
</tr>
<tr>
<td>&lt;2 × 10^{-41}</td>
<td>203 KIM 98</td>
<td>THEO</td>
<td></td>
</tr>
<tr>
<td>&lt;2 × 10^{-41}</td>
<td>204 HAGMANN 90</td>
<td>CNTR</td>
<td>(m_{A_0} = (5.4-5.9) \times 10^{-6}) eV</td>
</tr>
<tr>
<td>&lt;1.3 × 10^{-42}</td>
<td>205 WUENSCH 95</td>
<td>CNTR</td>
<td>(m_{A_0} = (4.5-10.2) \times 10^{-6}) eV</td>
</tr>
<tr>
<td>&lt;2 × 10^{-41}</td>
<td>205 WUENSCH 95</td>
<td>CNTR</td>
<td>(m_{A_0} = (11.3-16.3) \times 10^{-6}) eV</td>
</tr>
</tbody>
</table>

199 HOSKINS 11 is analogous to DUFFY 06. See Fig. 4 for the mass-dependent limit in terms of the local density.

200 ASZTALOS 10 used the upgraded detector of ASZTALOS 04 to search for halo axions. See their Fig. 5 for the \(m_{A_0}\) dependence of the limit.

201 DUFFY 06 used the upgraded detector of ASZTALOS 04, while assuming a smaller velocity dispersion than the isothermal model as in Eq. (8) of their paper. See Fig. 10 of their paper on the axion mass dependence of the limit.

202 ASZTALOS 04 looked for a conversion of halo axions to microwaves photons in magnetic field. At 90% CL, the KSVZ axion cannot have a local halo density more than 0.45 GeV/cm\(^3\) in the quoted mass range. See Fig. 7 of their paper on the axion mass dependence of the limit.

203 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.

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

205 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 \([G_{A\gamma\gamma}/mA_0]^2 = 2 \times 10^{-14}\) MeV\(^{-4}\) (the three generation DFSZ model) and \(\rho_A = 300\) MeV/cm\(^3\) that makes up galactic halos \(G_{A\gamma\gamma}/mA_0 \rho_A = 4 \times 10^{-44}\). 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 \(L = G_{A\gamma\gamma} \phi_A E \cdot B\).

For scalars \(S_0\) the limit is on the constant in \(L = G_{S\gamma\gamma} \phi_S (E^2 - B^2)\).

<table>
<thead>
<tr>
<th>VALUE (GeV(^{-1}))</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
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<tbody>
<tr>
<td>&lt;2.3 × 10^{-10}</td>
<td>95</td>
<td>206 ARIK 11</td>
<td>CAST</td>
<td>(m_{A_0} = 0.39-0.64) eV</td>
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</table>

HTTP://PDG.LBL.GOV Page 20 Created: 6/18/2012 15:09
210 CHOU 09 use the GammeV apparatus in the afterglow mode to search for chameleons, (pseudo)scalar bosons with a mass depending on the environment. For pseudoscalars they exclude at 3σ the range $2.6 \times 10^{-7} \text{ GeV}^{-1} < G_{A\gamma\gamma} < 4.2 \times 10^{-6} \text{ GeV}^{-1}$ for vacuum $m_A^0$ roughly below 6 meV for density scaling index exceeding 0.8.

211 GONDOLO 09 use the all-flavor measured solar neutrino flux to constrain solar interior temperature and thus energy losses.

212 LIPSS photon regeneration experiment, assuming scalar particle $S^0$. See Fig. 4 for mass-dependent limits.

213 CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 3 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06.

214 FOUCHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits.
INOUE 08 is an extension of INOUE 02 to larger axion masses, using the Tokyo axion helioscope. See their Fig. 4 for mass-dependent limits.

ZA VATTINI 08 is an upgrade of ZA VATTINI 06, see their Fig. 8 for mass-dependent limits. They now exclude the parameter range where ZA VATTINI 06 had seen a positive signature.

ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. See their Fig. 4 for mass-dependent limits.

ZA VATTINI 06 propagate a laser beam in a magnetic field and observe dichroism and birefringence effects that could be attributed to an axion-like particle. This result is now excluded by ROBILLIARD 07, ZA VATTINI 08, and CHOU 08.

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

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

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

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

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

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

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

Experiment based on proposal by MAIANI 86.

Experiment based on proposal by VANBIBBER 87.

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

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

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

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

The limit is for $G_{Ae}^\gamma \gamma e^\mu \phi A^\gamma e_{\gamma}$ in GeV$^{-1}$, or equivalently, the dipole-dipole potential $G_{Ae}^\gamma \gamma e^\mu \phi A^\gamma e_{\gamma}^\mu \phi A^\gamma e_{\gamma}$. The limit is $G_{Ae}^\gamma \gamma e^\mu \phi A^\gamma e_{\gamma} < 1 \times 10^{-4}$ GeV$^{-1}$.

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<td>234 DAVIDIASSI</td>
<td>ASTR</td>
<td>Earth cooling</td>
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<td>$&lt; 5.3 \times 10^{-5}$</td>
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<td>235 NI</td>
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<td>$&lt; 6.7 \times 10^{-5}$</td>
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<td>235 CHUI</td>
<td>93</td>
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<3.6 × 10^{-4} 66 236 PAN 92 Torsion pendulum
<2.7 × 10^{-5} 95 235 BOBRAKOV 91 Induced magnetism
<1.9 × 10^{-3} 66 237 WINELAND 91 NMR
<8.9 × 10^{-4} 66 236 RITTER 90 Torsion pendulum
<6.6 × 10^{-5} 95 235 VOROBYOV 88 Induced magnetism

AALSETH 11 assume keV-mass pseudoscalars are the local dark matter and constrain the axio-electric effect in the CoGeNT detector. See their Fig. 4 for mass-dependent limits.

AHMED 09A is analogous to AALSETH 08, using the CDMS detector. See their Fig. 5 for mass-dependent limits.

DAVOUDIASL 09 use geophysical constraints on Earth cooling by axion emission.

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.

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.

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.

<table>
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<td>CNTR</td>
<td>Solar axion</td>
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<tr>
<td>&lt; 1.39 × 10^4</td>
<td>90</td>
<td>239 BELLl</td>
<td>CNTR</td>
<td>Solar axion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>240 BELLINI</td>
<td>CNTR</td>
<td>Solar axion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>241 ADELBERGER 07</td>
<td>CNTR</td>
<td>Test of Newton’s law</td>
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<td>CNTR</td>
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<tr>
<td>&lt;400</td>
<td>95</td>
<td>243 LJUBICIC</td>
<td>CNTR</td>
<td>Solar axion</td>
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<tr>
<td>&lt; 3.2 × 10^4</td>
<td>95</td>
<td>244 KRCMAR 01</td>
<td>CNTR</td>
<td>Solar axion</td>
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</tbody>
</table>

238 DERBIN 11 looked for solar axions emitted by the M1 transition of thermally excited $^{57}$Fe nuclei in the Sun, using their possible resonant capture on $^{57}$Fe in the laboratory. The mass bound assumes $m_u/m_d = 0.56$ and the flavor-singlet axial vector matrix element $S = 3F - D \simeq 0.5$.

239 BELLl 08A is analogous to KRCMAR 01 and DERBIN 05.

240 BELLINI 08 consider solar axions emitted in the M1 transition of $^7$Li* (478 keV) and look for a peak at 478 keV in the energy spectra of the Counting Test Facility (CTF), a Borexino prototype. For $m_{A^0} < 450$ keV they find mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.

241 ADELBERGER 07 use precision tests of Newton’s law to constrain a force contribution from the exchange of two pseudoscalars. See their Fig. 5 for limits on the pseudoscalar coupling to nucleons, relevant for $m_{A^0}$ below about 1 meV.

242 DERBIN 05 bound is based on the same principle as KRCMAR 01.

243 LJUBICIC 04 looked for ejection of K-shell electrons by the axioelectric effect of 14.4 keV solar axions in a Germanium detector. The limit assumes the hadronic axion model and the same solar axion flux as in KRCMAR 98 and KRCMAR 01.

244 KRCMAR 01 looked for solar axions emitted by the M1 transition of $^7$Li after the electron capture by $^7$Be and the emission of 384 keV line neutrino, using their resonant capture on $^7$Li in the laboratory. The mass bound assumes $m_u/m_d = 0.56$ and the flavor-singlet axial-vector matrix element $S=0.4$.
Axion Limits from T-violating Medium-Range Forces

The limit is for the coupling \( g = g_p g_s \) in a T-violating potential between nucleons or nucleon and electron of the form

\[
V = \frac{g \hbar^2}{8 \pi m_p} \left( \sigma \cdot \mathbf{F} \right) \left( \frac{1}{r^2} + \frac{1}{\lambda_A^2} \right) e^{-r/\lambda},
\]

where \( g_p \) and \( g_s \) are dimensionless scalar and pseudoscalar coupling constants and \( \lambda = \hbar/(m_A c) \) is the range of the force.

<table>
<thead>
<tr>
<th>VALUE</th>
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<td>245 HOEDL 11</td>
<td>torsion pendulum</td>
<td></td>
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<td>246 PETUKHOV 10</td>
<td>polarized ( ^3 )He</td>
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<td>247 SEREBROV 10</td>
<td>ultracold neutrons</td>
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<td>248 IGNA TOVICH 09</td>
<td>RVUE ultracold neutrons</td>
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<td>251 HECKEL 06</td>
<td>torsion pendulum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>252 NI 99</td>
<td>paramagnetic ( \text{TB F}_3 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>253 POSPELOV 98</td>
<td>THEO neutron EDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>254 YOUDIN 96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>255 RITTER 93</td>
<td>torsion pendulum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>256 VENEMA 92</td>
<td>nuclear spin-precession frequencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>257 WINELAND 91</td>
<td>NMR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

245 HOEDL 11 use a novel torsion pendulum to study the force by the polarized electrons of an external magnet. In their Fig. 3 they show restrictive limits on \( g \) in the approximate \( m_A^0 \) range 0.03–10 meV.

246 PETUKHOV 10 use spin relaxation of polarized \( ^3 \)He and find \( g < 3 \times 10^{-23} \, (\text{cm}/\lambda)^2 \) at 95% CL for the force range \( \lambda = 10^{-4}–1 \) cm.

247 SEREBROV 10 use spin precession of ultracold neutrons close to bulk matter and find \( g < 2 \times 10^{-21} \, (\text{cm}/\lambda)^2 \) at 95% CL for the force range \( \lambda = 10^{-4}–1 \) cm.

248 IGNA TOVICH 09 use data on depolarization of ultracold neutrons in material traps. They show \( \lambda \)-dependent limits in their Fig. 1.

249 SEREBROV 09 uses data on depolarization of ultracold neutrons stored in material traps and finds \( g < 2.96 \times 10^{-21} \, (\text{cm}/\lambda)^2 \) for the force range \( \lambda = 10^{-3}–1 \) cm and \( g < 3.9 \times 10^{-22} \, (\text{cm}/\lambda)^2 \) for \( \lambda = 10^{-4}–10^{-3} \) cm, each time at 95% CL, significantly improving on BAESSLER 07.

250 BAESSLER 07 use the observation of quantum states of ultracold neutrons in the Earth’s gravitational field to constrain \( g \) for an interaction range 1 \( \mu \)m–a few mm. See their Fig. 3 for results.

251 HECKEL 06 studied the influence of unpolarized bulk matter, including the laboratory’s surroundings or the Sun, on a torsion pendulum containing about \( 9 \times 10^{22} \) polarized electrons. See their Fig. 4 for limits on \( g \) as a function of interaction range.

252 NI 99 searched for a T-violating medium-range force acting on paramagnetic \( \text{TB F}_3 \) salt. See their Fig. 1 for the result.

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

254 YOUDIN 96 compared the precession frequencies of atomic \( ^{199} \)Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.

255 RITTER 93 studied the influence of bulk mass with polarized electrons on an unpolarized torsion pendulum, providing limits in the interaction range from 1 to 100 cm.
256. VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of $^{199}\text{Hg}$ and $^{201}\text{Hg}$ atoms.

257. WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored $^{9}\text{Be}^+$ ions using nuclear magnetic resonance.

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

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References for searches for axions ($A^0$) and other very light bosons.
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<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Journal</th>
<th>Volume</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SREDNICKI</td>
<td>85</td>
<td>NP</td>
<td>B260</td>
<td>689</td>
</tr>
<tr>
<td>BARDEEN</td>
<td>78</td>
<td>PL</td>
<td>74B</td>
<td>229</td>
</tr>
</tbody>
</table>

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Citation: J. Beringer et al. (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)