**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>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tr>
<td>$&gt;0.2$</td>
<td>LOVE 08</td>
<td>CLEO</td>
<td>$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$, or $\tau^+\tau^-$</td>
</tr>
<tr>
<td>$&gt;0.25$</td>
<td>BARROSO 82</td>
<td>ASTR</td>
<td>Standard Axion</td>
</tr>
<tr>
<td>$&gt;0.2$</td>
<td>RAFFELT 82</td>
<td>ASTR</td>
<td>Standard Axion</td>
</tr>
<tr>
<td>$&gt;0.3$</td>
<td>DICUS 78c</td>
<td>ASTR</td>
<td>Standard Axion</td>
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<tr>
<td>$&gt;0.2$</td>
<td>MIKAELIAN 78</td>
<td>ASTR</td>
<td>Stellar emission</td>
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<td>$&gt;0.2$</td>
<td>SATO 78</td>
<td>ASTR</td>
<td>Standard Axion</td>
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<tr>
<td>$&gt;0.2$</td>
<td>VYSOTSKIY 78</td>
<td>ASTR</td>
<td>Standard Axion</td>
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</table>

1 LOVE 08 show mass-dependent limits on $B(\Upsilon \rightarrow \gamma A^0) B(A^0 \rightarrow \mu^+\mu^-)$ or $\tau^+\tau^-$ on their Fig. 3.

2 Lower bound from 5.5 MeV $\gamma$-ray line from the sun.

3 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.

<table>
<thead>
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<td>AMMAR 01b</td>
<td>CLEO</td>
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<td>$\pi^0 \rightarrow \gamma X^0, m X^0 &lt; 120$ MeV</td>
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<tr>
<td>$&lt;5.0 \times 10^{-8}$</td>
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<td>KITCHING 97</td>
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<td>$K^+ \rightarrow \pi^+ X^0 (X^0 \rightarrow \gamma\gamma)$</td>
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<td>CBAR</td>
<td>$\eta \rightarrow \gamma X^0, m X^0 = 50–200$ MeV</td>
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<td>CBAR</td>
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<td>$&lt;6 \times 10^{-5}$</td>
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<td>CBAR</td>
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<tr>
<td>$&lt;6 \times 10^{-5}$</td>
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<td>AMSLER 94b</td>
<td>CBAR</td>
<td>$\eta \rightarrow \gamma X^0, m X^0 = 200–525$ MeV</td>
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</table>
13 The MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of a new signal. It can be interpreted as an axion-like particle with $m_{A^0} = 214.3 \pm 0.5$ MeV and the branching fraction $B(S^+ \rightarrow \rho A^0) \times B(A^0 \rightarrow \mu^+ \mu^-) = (3.1 \pm 2.4 \pm 1.9) \times 10^{-8}$.

4 This limit applies for a mass near 180 MeV. For other masses in the range $m_{X^0} = 150$–250 MeV the limit is less restrictive, but still improves ADLER 02c and ATIYA 93b.

5 ADLER 02c bound is for $m_{X^0} = 60$ MeV. See Fig. 2 for limits at higher masses.

6 The quoted limit is for $m_{X^0} = 0$–80 MeV. See their Fig. 5 for the limit at higher mass.

7 The branching fraction limit applies purely due to a narrow spread in dimuon mass, they hypothesize the events as a possible signal of a new boson.

8 The quoted limit is for $m_{X^0} = 0$–80 MeV. See their Fig. 5 for the limit at higher mass.

9 This limit applies for $m_{X^0} = 0$–80 MeV. See their Fig. 5 for the limit at higher mass.

10 The branching fraction limit applies purely due to a narrow spread in dimuon mass, they hypothesize the events as a possible signal of a new boson.
17 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.

18 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 $m_{\chi^0} = 25$–120 MeV. Angular momentum conservation requires that $X^0$ has spin $\geq 1$.

19 ATIYA 90b limit is for $B(K^+ \to \pi^+ X^0) B(X^0 \to \gamma \gamma)$ and applies for $m_{\chi^0} = 50$ MeV. $\tau X^0 < 10^{-10}$ s. Limits are also provided for $0 < m_{\chi^0} < 100$ MeV, $\tau X^0 < 10^{-8}$ s.

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

21 EICHLER 86 looked for $\pi^+ \to e^+ \nu A^0$ followed by $A^0 \to e^+e^-$. Limits on the branching fraction depend on the mass and 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.

22 YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+ X$. Sensitive to wide mass range (5–500 MeV), independent of whether $X$ decays promptly or not.

23 ASANO 82 at KEK set limits for $B(K^+ \to \pi^+ X^0)$ for $m_{\chi^0} < 100$ MeV as BR $< 4. \times 10^{-8}$ for $\tau(X^0 \to n\gamma)$'s $> 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$ s, $\text{BR} < 4 \times 10^{-8}$ at CL = 90%.

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

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

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

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

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<td>ANTreASYAN 90C CBAL</td>
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<td>$&lt;2 \times 10^{-3}$</td>
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<tr>
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<tr>
<td>$&lt;3.1 \times 10^{-4}$</td>
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<td>$\gamma(1S) \to A^0 \gamma \ (A^0 \to e^+e^-)$</td>
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<tr>
<td>$&lt;4 \times 10^{-4}$</td>
<td>90</td>
<td>ALBRECHT 860 ARG</td>
<td>$\gamma(1S) \to A^0 \gamma \ (A^0 \to \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$</td>
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<td>$\gamma(1S) \to A^0 \gamma \ (A^0 \to e^+e-, \gamma \gamma)$</td>
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<tr>
<td>$&lt;1.3 \times 10^{-3}$</td>
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<td>$&lt;2 \times 10^{-3}$</td>
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<td>BOWCOCK 86 CLEO</td>
<td>$\gamma(2S) \to \gamma(1S) \to A^0$</td>
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<tr>
<td>$&lt;5 \times 10^{-3}$</td>
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<td>MAGERAS 86 CUSB</td>
<td>$\gamma(1S) \to A^0 \gamma$</td>
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<td>$&lt;3 \times 10^{-4}$</td>
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<tr>
<td>$&lt;9.1 \times 10^{-4}$</td>
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<tr>
<td>$&lt;1.4 \times 10^{-5}$</td>
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<td>EDWARDS 82 CBAL</td>
<td>$J/\psi \to A^0 \gamma$</td>
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<tr>
<td>$&lt;3.5 \times 10^{-4}$</td>
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<td>SIVERTZ 82 CUSB</td>
<td>$\gamma(1S) \to A^0 \gamma$</td>
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<tr>
<td>$&lt;1.2 \times 10^{-4}$</td>
<td>90</td>
<td>SIVERTZ 82 CUSB</td>
<td>$\gamma(3S) \to A^0 \gamma$</td>
</tr>
</tbody>
</table>
26 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.

27 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 86 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 $\Gamma(A^0 \rightarrow e e) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \rightarrow e e) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

28 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.

29 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.

30 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.

31 $\tau_{A^0} < 1 \times 10^{-13}$s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma \gamma$ when $m_{A^0} < 100$ MeV.

32 $\tau_{A^0} > 1 \times 10^{-7}$s.

33 Independent of $\tau_{A^0}$.

34 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 $2 \times 10^{-13}$s 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.

35 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.

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

37 NICZYPOURUK 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 $B(J/\psi(1S) \rightarrow A^0 \gamma)$ (EDWARDS 82) excludes standard axion.

38 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.

39 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).

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

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

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</table>

- We do not use the following data for averages, fits, limits, etc.
BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles.

The ASAI 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.

ASAI 91 limit translates to $b_{A^0, e^+e^-/4\pi} < 1.1 \times 10^{-11}$ (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 $b_{A^0, e^+e^-/4\pi} < 6.2 \times 10^{-10}$. 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 $m_{A^0} = 900-100$ 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, $g(ee/A^0)^2/(4\pi) < 6 \times 10^{-10}-7 \times 10^{-9}$ for $m_{A^0}$ from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from $g-2$ experiments.

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

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</tr>
<tr>
<td>40</td>
<td>90</td>
<td>BADERTSCHER 02</td>
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BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of $e^+e^-$ pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate $A^0$ for $\tau(A^0) = 10^{-18}$–$10^{-9}$ sec. They also found an excess of events in the range $m_{e^+e^-} = 2.1-3.5$ MeV.

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

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

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<td>BASSOMPIERRE 95</td>
<td>$m_{A^0} = 1.8 \pm 0.2$ MeV</td>
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We do not use the following data for averages, fits, limits, etc. |
49 JAIN 07 CNTR $A^0 \rightarrow e^+ e^-$
50 AHMAD 97 SPEC $e^+ e^-$ production
51 LEINBERGER 97 SPEC $A^0 \rightarrow e^+ e^-$
52 GANZ 96 SPEC $A^0 \rightarrow e^+ e^-$
53 KAMEL 96 EMUL $32S$ emulsion, $A^0 \rightarrow$
54 BLUEMLEIN 92 BDMP $A^0 N_Z \rightarrow e^+ e^-$
55 MEIJERDREES 92 SPEC $\pi^- p \rightarrow n A^0$, $A^0 \rightarrow$
56 BLUEMLEIN 91 BDMP $A^0 \rightarrow e^+ e^-$, $2\gamma$
57 FAISSNER 89 OSPK Beam dump,
58 DEBOER 88 RVUE $A^0 \rightarrow e^+ e^-$
59 EL-NADI 88 EMUL $A^0 \rightarrow e^+ e^-$
60 FAISSNER 88 OSPK Beam dump, $A^0 \rightarrow 2\gamma$
61 BADIER 86 BDMP $A^0 \rightarrow e^+ e^-$
62 BERGMA 85 CHRM CERN beam dump
63 FAISSNER 83 OSPK Beam dump, $A^0 \rightarrow 2\gamma$
64 FAISSNER 83b RVUE LAMPF beam dump
65 FRANK 83b RVUE LAMPF beam dump
66 HOFFMA 83 CNTR $\pi p \rightarrow n A^0$
67 FETSCHER 82 RVUE See FAISSNER 81b
68 FAISSNER 81 OSPK CERN PS $\nu$ wideband
69 FAISSNER 81b OSPK Beam dump, $A^0 \rightarrow 2\gamma$
70 KIM 81 OSPK 26 GeV $p N \rightarrow A^0 X$
71 FAISSNER 80 OSPK Beam dump,
72 JACQUES 80 HLBC $A^0 \rightarrow e^+ e^-$
73 SOUKAS 80 CALO $A^0 \rightarrow e^+ e^-$
74 BECHIS 79 CNTR
75 COTEUS 79 OSPK Beam dump
76 DISHAW 79 CALO 400 GeV $p p$
77 BELLOTTI 78 HLBC Beam dump
78 BELLOTTI 78 HLBC $m_{A^0}=1.5$ MeV
79 DONNELLY 78
80 MICELMAC... 78 WIRE Beam dump
81 VYSOTSKII 78

$<2 \cdot 10^{-11}$ 90 0
$<1 \cdot 10^{-13}$ 90 0

$<1 \cdot 10^{-8}$ 90 0
$<1 \cdot 10^{-14}$ 90 0

$<1 \cdot 10^{-8}$ 90 0
$<1 \cdot 10^{-3}$ 95 0
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$<1 \cdot 10^{-8}$ 90 0
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$<1 \cdot 10^{-8}$ 90 0
$<1 \cdot 10^{-3}$ 95 0
$<1 \cdot 10^{-8}$ 90 0
$<6 \cdot 10^{-9}$ 95 0
$<1.5 \cdot 10^{-8}$ 90 0
$<5.4 \cdot 10^{-14}$ 90 0
$<4.1 \cdot 10^{-9}$ 90 0
$<1 \cdot 10^{-8}$ 90 0
$<0.5 \cdot 10^{-8}$ 90 0

49 JAIN 07 claims evidence for $A^0 \rightarrow e^+ e^-$ produced in $^{207}$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.
50 AHMAD 97 reports a result of APEX Collaboration which studied positron production in $^{238}$U+$^{232}$Ta and $^{238}$U+$^{181}$Ta collisions, without requiring a coincident electron. No narrow lines were found for $250 < E_{e^+} < 750$ keV.
51 LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy \( e^+ e^- \) line at \( \sim 635 \text{ keV} \) 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.

52 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.

53 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 \( m_{ee} > 2 \text{ MeV} \).

54 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.

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

56 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 \( 0.2 < m_{A^0} < 3.2 \text{ MeV} \) for most \( x > 1 \), 0.2-11 MeV for most \( x < 1 \).

57 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 \( 2m_{ee} < 20 \text{ MeV} \) is excluded. Lower limit on \( f_{A^0} \) of \( \sim 10^4 \text{ GeV} \) is given for \( m_{A^0} = 2m_{ee} - 20 \text{ MeV} \).

58 DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass \( \sim 1.1 \text{,} \sim 2.1 \text{, and} \sim 9 \text{ MeV} \), lifetimes \( 10^{-16} - 10^{-15} \text{ s} \) 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 89 is a reply which contests the criticism.

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

60 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 \( x \simeq 1 \). Lower limit on \( f_{A^0} \) of \( 10^2 - 10^3 \text{ GeV} \) is given for \( m_{A^0} = 0.1 - 1 \text{ MeV} \).

61 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 \( m_{A^0} = (20 - 200) \text{ MeV} \), 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.

62 BERGSMA 85 look for \( A^0 \rightarrow 2 \gamma \), \( e^+ e^- \), \( \mu^+ \mu^- \). First limit above is for \( m_{A^0} = 1 \text{ MeV} \); 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 \( A^0 \), \( m_{A^0} < 180 \text{ keV} \) and \( \tau > 0.037 \text{ s} \) (CL = 90%). For the axion of FAISSNER 818 at 250 keV, BERGSMA 85 expect 15 events but observe zero.

63 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.

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

65 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.

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

67 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.

68 FAISSNER 81 see excess \( \mu e \) events. Suggest axion interactions.

69 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 BERGMSA 85. Also see in the next subsection ALEK-SEEV 82b, CAVAIGNAC 83, and ANANEV 85.

70 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 \((0.86 \pm 5.6) \times 10^{-3} \) s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

71 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/(\( A^0 \) mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to \( m_{A^0} < 2m_{e^-} \).

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

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

74 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.

75 COTEUS 79 is a beam dump experiment at BNL.

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

77 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 <2\( m_{e^-} \). For any mass satisfying this, limit is above value (mass^{-4}). Third value uses data of PL 60B 401 and quotes \( \sigma(\text{production})\sigma(\text{interaction}) < 10^{-67} \text{ cm}^4 \).

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

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

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

81 VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.
A\(^0\) (Axion) Searches in Reactor Experiments

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<td>86 DATAR 82</td>
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<td>Reactor, A(^0) → 2γ</td>
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82 CHANG 07 looked for monochromatic photons from Primakoff or Compton conversion of axions from the Kuo-Sheng reactor due to axion coupling to photon or electron, respectively. The search places model-independent limits on the products G\(_{A\gamma\gamma}\)G\(_{AN/N}\) and G\(_{Ae\gamma}\) for m(A\(^0\)) less than the MeV range.

83 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\(^0\) → e\(^+\)e\(^-)\) < 10\(^{-16}\) for m\(^A\) \(=\) 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\(^A\) \(<\) 4.8 MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances Z\(^0\) in the \((m\chi, f\chi)\) plane.

84 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 \(\times 10^{-6}\) per fission. In the standard axion model, this corresponds to m\(^A\) \(>\) 150 keV. Not valid for m\(^A\) \(\approx\) 1 MeV.

85 KOCH 86 searched for A\(^0\) → γγ 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\(^A\) = 250 keV gives 10\(^{-5}\) for the ratio. Not valid for m\(^A\) \(>\) 1022 keV.

86 DATAR 82 looked for A\(^0\) → 2γ in neutron capture \((n p \rightarrow d A\(^0\))\) at Tarapur 500 MW reactor. Sensitive to sum of \(I = 0\) and \(I = 1\) amplitudes. With ZEHNDER 81 \([I = 0]\) result, assert nonexistence of standard A\(^0\).

87 VUILLEUMIER 81 is at Grenoble reactor. Set limit m\(^A\) \(<\) 280 keV.

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

Limits are for branching ratio.

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<td>88 DERBIN 02</td>
<td>CNTR</td>
<td>125(^m)Te decay</td>
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<td>90 TSUNODA 95</td>
<td>CNTR</td>
<td>252(^m)Cf fission, A(^0) → ee</td>
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<td>93 MINOWA 93</td>
<td>CNTR</td>
<td>139(^La) → 139(^La)A(^0)</td>
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<td></td>
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<tr>
<td>92 HICKS 92</td>
<td>CNTR</td>
<td>35(^S) decay, A(^0) → γγ</td>
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<tr>
<td>93 ASANUMA 90</td>
<td>CNTR</td>
<td>241(^Am) decay</td>
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<td>&lt; 5.5 \times 10^{-10}</td>
<td>95</td>
<td>90 DEBOER 97C</td>
<td>RVUE</td>
<td>M1 transitions</td>
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<td>&lt; 1.2 \times 10^{-6}</td>
<td>95</td>
<td>91 MINOWA 93</td>
<td>CNTR</td>
<td>125(^m)Te decay</td>
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<td>&lt; 2 \times 10^{-4}</td>
<td>90</td>
<td>95 KETOV 86</td>
<td>SPEC</td>
<td>Reactor, A(^0) → γγ</td>
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<tr>
<td>&lt; 1.5 \times 10^{-9}</td>
<td>95</td>
<td>88 AVIGNONE 88</td>
<td>CNTR</td>
<td>Cu(^+) → CuA(^0) (A(^0) → 2γ, A(^0) e → γe, A(^0) Z → γZ)</td>
</tr>
</tbody>
</table>

< 1.5 \times 10^{-4} & 90 & 97 DATAR & CNTR & 12C* \rightarrow 12CA^0, & 12CA^0 \rightarrow e^+e^- \\
< 5 \times 10^{-3} & 90 & 98 DEBOER & CNTR & 16O* \rightarrow 16OX^0, & 2H^*, A^0 \rightarrow e^+e^- \\
< 3.4 \times 10^{-5} & 95 & 99 DOEHNER & SPEC & 99 SPEC 14N isoscalar decay \\
< 4 \times 10^{-4} & 95 & 100 SAVAGE & CNTR & Nuclear decay (isovector) \\
< 3 \times 10^{-3} & 95 & 100 SAVAGE & CNTR & Nuclear decay (isoscalar) \\
< 10.6 \times 10^{-2} & 90 & 101 HALLIN & SPEC & 139La isovector decay \\
< 10.8 & 90 & 101 HALLIN & SPEC & 139La isovector decay \\
< 2.2 & 90 & 102 SAVAGE & CNTR & 14N isoscalar decays \\
< 4 \times 10^{-4} & 90 & 102 SAVAGE & CNTR & 14N* \\
103 ANANEV & 85 & 103 ANANEV & CNTR & Li^*, deut* A^0 \rightarrow 2\gamma \\
104 CAVAIGNAC & 83 & 104 CAVAIGNAC & CNTR & 97Nb*, deut* transition \\
& & & & A^0 \rightarrow 2\gamma \\
105 ALEKSEEV & 82b & 105 ALEKSEEV & CNTR & Li^*, deut* transition \\
& & & & A^0 \rightarrow 2\gamma \\
106 LEHMANN & 82 & 106 LEHMANN & CNTR & Cu* \rightarrow CuA^0 (A^0 \rightarrow 2\gamma) \\
107 ZEHNDER & 82 & 107 ZEHNDER & CNTR & Li^*, Nb* decay, n-capt. \\
108 ZEHNDER & 81 & 108 ZEHNDER & CNTR & Ba* \rightarrow BaA^0 (A^0 \rightarrow 2\gamma) \\
109 CALAPRICE & 79 & 109 CALAPRICE & Carbon \\

88 DERBIN 02 looked for the axion emission in an M1 transition in 125mTe decay. They looked for a possible presence of a shifted energy spectrum in gamma rays due to the undetected axion. 

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

90 TSUNODA 95 looked for axion emission when 252Cf undergoes a spontaneous fission, with the axion decaying into e^+e^- . The bound is for \( m_{A^0} = 40 \text{ MeV} \). It improves to \( 2.5 \times 10^{-5} \) for \( m_{A^0} = 200 \text{ MeV} \). 

91 MINOWA 93 studied chain process, 139Ce \rightarrow 139La^* by electron capture and M1 transition of 139La^* to the ground state. It does not assume decay modes of A^0 . The bound applies for \( m_{A^0} < 166 \text{ keV} \). 

92 HICKS 92 bound is applicable for \( \tau_{X^0} < 4 \times 10^{-11} \text{ sec} \). 

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

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

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

96 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 \( m_{A^0} < 1.1 \text{ MeV} \). 

97 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 \( 10^{-13}-10^{-8} \text{ s} \). The above limit is for \( \tau = 5 \times 10^{-13} \text{ s} \) and \( m = 1.7 \text{ MeV} \), see the paper for the \( \tau-m \) dependence of the limit. 

98 The limit is for the branching fraction of 16O* (6.05 MeV, 0^+) \rightarrow 16OX^0, X^0 \rightarrow e^+e^- against internal pair conversion for \( m_{X^0} = 1.7 \text{ MeV} \) and \( \tau_{X^0} < 10^{-11} \text{ s} \).
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: $g_{X^0 N}^2 / 4\pi < 2.3 \times 10^{-9}$.

99 The DOEHNNER 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.

100 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.

101 Limits are for $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi M_1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of $e^+ e^-$ pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$ s. 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.

102 SAVAGE 868 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.

103 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.

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

105 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).

106 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.

107 ZEHNDER 82 used Gosgen 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 $A^0$.

108 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.

109 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>CALO</td>
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The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. 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 $e^+e^-$ are ruled out for $m_{A^0} < 4.8$ MeV (90% CL).

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).

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.

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%).

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.

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.

$m_{A^0} = 1.8$ 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.

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

<table>
<thead>
<tr>
<th>VALUE ($10^{-3}$ eV)</th>
<th>VALUE (%)</th>
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<th>COMMENT</th>
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<td>95</td>
<td>WIDMANN</td>
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Search for $A^0$ (Axion) Resonance in $e^+ e^- \to \gamma \gamma$

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

<table>
<thead>
<tr>
<th>VALUE ($10^{-3}$ eV)</th>
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<th>COMMENT</th>
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<tr>
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<td>&lt; 4.4</td>
<td>95</td>
<td>WIDMANN</td>
<td>129</td>
<td>FOX</td>
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</table>

See also TSERTOS 88B in references.

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

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.

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

VONWIMMERSPERG 87 measured Bhabha scattering for $E_{cm} = 1.37$–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{cm} = 14.5 \pm 6.8$ keV b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.
128 TRZASKA 91 also give limits in the range (6.6-30) \times 10^{-3} \text{ eV} (95\% \text{ CL}) for \( m_{A^0} = 1.6-2.0 \text{ MeV} \).

129 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).

130 Similar limits are obtained for \( m_{A^0} = 1.045-1.085 \text{ MeV} \).

---

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

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

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<td>CONNELL</td>
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</table>

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

132 VO 94 looked for \( X^0 \rightarrow \gamma\gamma \) decaying in flight.

133 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>
<thead>
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<th>VALUE (units 10^{-6})</th>
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<td>MITSUI</td>
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<td>&lt; 0.33</td>
<td>90</td>
<td>139</td>
<td>ADACHI</td>
<td>94</td>
</tr>
</tbody>
</table>
134 MITSUI 96 looked for a monochromatic $\gamma$. The bound applies for a vector $X^0$ with $C = -1$ and $m_X < 200$ keV. They derive an upper bound on $eeX^0$ coupling and hence on the branching ratio $B(\alpha - \gamma \gamma X^0) < 6.2 \times 10^{-6}$. The bounds weaken for heavier $X^0$.

135 SKALSEY 95 looked for a monochromatic $\gamma$ without an accompanying $\gamma$ in $ee$ annihilation. The bound applies for scalar and vector $X^0$ with $C = -1$ and $m_X = 100\sim 1000$ keV.

136 SKALSEY 95 reinterpreted the bound on $\gamma A^0$ decay of $\alpha$-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 $m_X = 0\sim 800$ keV.

137 ADACHI 94 looked for a peak in the $\gamma \gamma$ invariant mass distribution in $\gamma \gamma \gamma \gamma$ production from $ee$ annihilation. The bound applies for $m_X = 70\sim 800$ keV.

138 ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma \gamma$ channel, using $\gamma \gamma \gamma \gamma$ production from $ee$ annihilation. The bound applies for $m_X < 800$ keV.

139 ADACHI 94 looked for a peak in the missing mass distribution in $\gamma \gamma \gamma \gamma$ channel, using $\gamma \gamma \gamma \gamma$ production from $ee$ annihilation. The bound applies for $m_X = 200\sim 900$ keV.

### Searches for Goldstone Bosons ($X^0$)

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

<table>
<thead>
<tr>
<th>VALUE</th>
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<th>TECN</th>
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<td>$&lt;3.3 \times 10^{-2}$</td>
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<td>$H^0 \rightarrow X^0 X^0, A^0 \rightarrow X^0 X^0 X^0$, Majoron</td>
<td></td>
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<tr>
<td>$&lt;1.8 \times 10^{-2}$</td>
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<td>$&lt;6.4 \times 10^{-9}$</td>
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<td>DICUS 83 COSM</td>
<td>$\nu(hv) \rightarrow \nu(light) X^0$</td>
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</tbody>
</table>

140 LESSA 07 consider decays of the form Meson $\rightarrow \ell \nu$ Majoron and $\ell \rightarrow \ell \nu \pi$ 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%.

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

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

ALbrecht 90\% limits are for \( B(\tau \rightarrow e X^0)/B(\tau \rightarrow \ell \nu \bar{\nu}) \). 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.

ATiya 90 limit is for \( m_\nu \). 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.

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

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 \( L_{\text{int}} = (1/2) \bar{\psi} \gamma^\mu (a+b\gamma_5) \psi \phi X_0 \) 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.

Limits for \( \Gamma(\mu \rightarrow e X^0)/\Gamma(\mu \rightarrow e \nu \bar{\nu}) \). Valid when \( m_{X^0} = 0 \sim 93.4, 98.1 \sim 103.5 \) 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 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 \( L_{\text{int}} = (1/F) \bar{\psi} \gamma^\mu (a+b\gamma_5) \psi \phi X^0 \).

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

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 \( m_{\text{heavy}} \) between \( 5 \times 10^{-5} \) and \( 5 \times 10^{-4} \) MeV (\( \mu \) decay) and \( m_{\text{heavy}} \) 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.

No experiment currently claims any such evidence. Only the best or comparable limits for each isotope are reported. Also see the reviews ZUBER 98 and FAESSLER 98b.
We do not use the following data for averages, fits, limits, etc.

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<td>CNTR</td>
<td>BECK 93</td>
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</tbody>
</table>

155 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 $(7.7 \pm 0.4) \times 10^{24}$.

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

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

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

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

160 Supersedes ALESSANDRELLO 00. Array of TeO$_2$ crystals in high resolution cryogenic calorimeter. Some enriched in $^{130}$Te. Derive $g_{\beta\beta} < 17\,\text{–}\,33 \times 10^{-5}$ depending on matrix element.

161 Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search.

162 Limit for the 0ν$\beta$β decay with Majoron emission of $^{116}$Cd using enriched CdWO$_4$ scintillators. $g_{\beta\beta} < 4.6\,\text{–}\,8.1 \times 10^{-5}$ depending on the matrix element. Supersedes DANEVICH 00.

163 Limit for the 0ν2$\beta$β decay of $^{116}$Cd. Supersedes DANEVICH 00.
164 BERNABEI 02 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.

165 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: $\langle g_{\nu\chi} \rangle < (6.3 - 360) \times 10^{-5}$.

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

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

168 DANEVICH 01 obtain limit for the $0\nu2\chi$ decay with 2 Majoron emission of $^{160}$Gd.

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

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

171 ARNOLD 00 reports limit for the $0\nu2\chi$ decay with two Majoron emission derived from tracking calorimeter NEMO 2.

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

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

174 See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.
KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used.

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

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.

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-α, and the prior Hubble parameter from HST Key Project. A χ² 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_Aγ 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.

183 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.

184 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).

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

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

187 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.

188 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.

189 RAFFELT 91 argues that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

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

191 ENGEL 90 rule out $10^{-10} < g_{AN} < 10^{-3}$, 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 $g_{AN} \sim 10^{-6}$.

192 RAFFELT 90 is a re-analysis of DEARBORN 86.

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

194 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.

195 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 88.

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

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

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

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

200 KAPLAN 85 says $m_{A0} < 23$ eV is allowed for a special choice of model parameters.

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

### Search for Relic Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m_{A0}]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{int} = \frac{G_{A\gamma\gamma}}{4} \phi_A F_{\mu\nu} \tilde{F}^{\mu\nu} = G_{A\gamma\gamma} \phi_A E \cdot B$, and $\rho_A$ is the axion energy density near the earth.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
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<tbody>
<tr>
<td>• • •</td>
<td>We do not use the following data for averages, fits, limits, etc.</td>
<td>• • •</td>
<td></td>
</tr>
</tbody>
</table>

HTTP://PDG.LBL.GOV Page 20 Created: 6/1/2009 14:18
202 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.

203 ASZTALOS 04 looked for a conversion of halo axions to microwave photons in magnetic field. At 90% CL, the KSVZ axion cannot have a local halo density more than 0.45 GeV/cm³ in the quoted mass range. See Fig. 7 of their paper on the axion mass dependence of the limit.

204 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.

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

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

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**Invisible $A^0$ (Axion) Limits from Photon Coupling**

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

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

<table>
<thead>
<tr>
<th>VALUE (GeV$^{-1}$)</th>
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<th>DOCUMENT ID</th>
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<tbody>
<tr>
<td>&lt; 1.2–2.8 $\times 10^{-10}$</td>
<td>95</td>
<td>207 ARIK</td>
<td>CAST</td>
<td>$m_{A^0} = 0.02–0.39 \text{ eV}$</td>
</tr>
<tr>
<td>&lt; 3.5 $\times 10^{-7}$</td>
<td>99.7</td>
<td>208 CHOU</td>
<td></td>
<td>$m_{A^0} &lt; 0.5 \text{ meV}$</td>
</tr>
<tr>
<td>&lt; 1.1 $\times 10^{-6}$</td>
<td>99.7</td>
<td>209 FOUCHE</td>
<td></td>
<td>$m_{A^0} &lt; 1 \text{ meV}$</td>
</tr>
<tr>
<td>&lt; 5.6–13.4 $\times 10^{-10}$</td>
<td>95</td>
<td>210 INOUE</td>
<td></td>
<td>$m_{A^0} = 0.84–1.00 \text{ eV}$</td>
</tr>
<tr>
<td>&lt; 5 $\times 10^{-7}$</td>
<td>95</td>
<td>211 ZAVATTINI</td>
<td></td>
<td>$m_{A^0} &lt; 1 \text{ meV}$</td>
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<td>&lt; 8.8 $\times 10^{-11}$</td>
<td>95</td>
<td>212 ANDRIAMONO..07</td>
<td>CAST</td>
<td>$m_{A^0} &lt; 0.02 \text{ eV}$</td>
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<tr>
<td>&lt; 1.25 $\times 10^{-6}$</td>
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<td>213 ROBILLIARD</td>
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<td>$m_{A^0} &lt; 1 \text{ meV}$</td>
</tr>
<tr>
<td>&lt; 2.5 $\times 10^{-6}$</td>
<td>95</td>
<td>214 ZAVATTINI</td>
<td></td>
<td>$m_{A^0} = 1–1.5 \text{ MeV}$</td>
</tr>
<tr>
<td>&lt; 1.1 $\times 10^{-9}$</td>
<td>95</td>
<td>215 INOUE</td>
<td></td>
<td>$m_{A^0} = 0.05–0.27 \text{ eV}$</td>
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<tr>
<td>&lt; 2.78 $\times 10^{-9}$</td>
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<td>216 MORALES</td>
<td>02B</td>
<td>$m_{A^0} &lt; 1 \text{ keV}$</td>
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<tr>
<td>&lt; 1.7 $\times 10^{-9}$</td>
<td>90</td>
<td>217 BERNABEI</td>
<td>01B</td>
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<tr>
<td>&lt; 1.5 $\times 10^{-4}$</td>
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<td>218 ASTIER</td>
<td>00B</td>
<td>NOMD $m_{A^0} &lt; 40 \text{ eV}$</td>
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<td></td>
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<td>219 MASSO</td>
<td>THEO</td>
<td>induced $\gamma$ coupling</td>
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<tr>
<td>Mass Limit</td>
<td>Experiment</td>
<td>Mass Limit</td>
<td>Experiment</td>
<td>Mass Limit</td>
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<td>------------</td>
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<td>&lt;2.7 \times 10^{-9}</td>
<td>220 AVIGNONE</td>
<td>98 SLAX</td>
<td>$m_A^0 &lt; 1$ keV</td>
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<td>&lt;6.0 \times 10^{-10}</td>
<td>221 MORIYAMA</td>
<td>98</td>
<td>$m_A^0 &lt; 0.03$ eV</td>
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<td>&lt;3.6 \times 10^{-7}</td>
<td>222 CAMERON</td>
<td>93</td>
<td>$m_A^0 &lt; 10^{-3}$ eV</td>
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<tr>
<td>&lt;6.7 \times 10^{-7}</td>
<td>223 CAMERON</td>
<td>93</td>
<td>$m_A^0 &lt; 10^{-3}$ eV</td>
<td></td>
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<tr>
<td>&lt;3.6 \times 10^{-9}</td>
<td>99.7</td>
<td>224 LAZARUS</td>
<td>92</td>
<td>$m_A^0 &lt; 0.03$ eV</td>
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<tr>
<td>&lt;7.7 \times 10^{-9}</td>
<td>99.7</td>
<td>224 LAZARUS</td>
<td>92</td>
<td>$m_A^0 = 0.03-0.11$ eV</td>
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<tr>
<td>&lt;7.7 \times 10^{-7}</td>
<td>99</td>
<td>225 RUOSO</td>
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<td>$m_A^0 &lt; 10^{-3}$ eV</td>
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<tr>
<td>&lt;2.5 \times 10^{-6}</td>
<td>226 SEMERTZIDIS</td>
<td>90</td>
<td>$m_A^0 &lt; 7 \times 10^{-4}$ eV</td>
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</tr>
</tbody>
</table>

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

208 CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 7 for mass-dependent limits.

209 FOUCHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits.

210 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.

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

212 ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. Supersedes ZIOUTAS 05.

213 ROBILLIARD 07 perform a photon regeneration experiment with a pulsed laser and pulsed magnetic field. See their Fig. 4 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06.

214 ZAVATTINI 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, ZAVATTINI 08, and CHOU 08.

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

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

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

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

219 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 $g_{\gamma A}^2 / 4\pi < 1.7 \times 10^{-9}$ for the coupling $g_{\gamma A}^2$. 

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

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

222 Experiment based on proposal by MAIANI 86.

223 Experiment based on proposal by VANBIBBER 87.

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

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

226 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$^{-1}$. 

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

The limit is for $G_{Ae} e \phi A^0 A^+ e \in GeV^{-1}$, or equivalently, the dipole-dipole potential $\frac{G_{Ae}^2}{4\pi} (\sigma_1 \cdot \sigma_2 - 3(\sigma_1 \cdot n)(\sigma_2 \cdot n))/r^3$ where $n = r/r$.

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

<table>
<thead>
<tr>
<th>VALUE ($GeV^{-1}$)</th>
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<td>&lt;6.7 x 10^-5</td>
<td>66</td>
<td>227 CHUI</td>
<td>93</td>
<td>Induced magnetism</td>
</tr>
<tr>
<td>&lt;3.6 x 10^-4</td>
<td>66</td>
<td>228 PAN</td>
<td>92</td>
<td>Torsion pendulum</td>
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<td>&lt;2.7 x 10^-5</td>
<td>66</td>
<td>227 BOBRAKOV</td>
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<td>Induced magnetism</td>
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<tr>
<td>&lt;1.9 x 10^-3</td>
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<td>229 WINELAND</td>
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<td>&lt;8.9 x 10^-4</td>
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<td>228 RITTER</td>
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<td>&lt;6.6 x 10^-5</td>
<td>95</td>
<td>227 VOROBYOV</td>
<td>88</td>
<td>Induced magnetism</td>
</tr>
</tbody>
</table>

227 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.

228 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.

229 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>
<thead>
<tr>
<th>VALUE (eV)</th>
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<td>&lt; 1.6 x 10^4</td>
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<tr>
<td>&lt; 1.6 x 10^4</td>
<td>90</td>
<td>232 ADELBERGER 07</td>
<td>Test of Newton’s law</td>
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<td>&lt; 360</td>
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<td>CNTR</td>
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<tr>
<td>&lt; 216</td>
<td>95</td>
<td>234 NAMBA 07</td>
<td>CNTR</td>
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<td>&lt; 400</td>
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<td>235 DERBIN 05</td>
<td>CNTR</td>
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<tr>
<td>&lt; 3.2 x 10^4</td>
<td>95</td>
<td>236 LJUBICIC 04</td>
<td>CNTR</td>
<td>Solar axion</td>
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<tr>
<td>&lt; 745</td>
<td>95</td>
<td>237 KRCMAR 01</td>
<td>CNTR</td>
<td>Solar axion</td>
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<tr>
<td>&lt; 230 BELLi 08A is analogous to KRCMAR 01 and DERBIN 05.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>231 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 $m_{A^0} &lt; 450$ keV they find mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.</td>
<td></td>
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</tr>
<tr>
<td>232 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.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>233 DERBIN 07 is analogous to KRCMAR 98.</td>
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<tr>
<td>234 NAMBA 07 is analogous to KRCMAR 98.</td>
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<tr>
<td>235 DERBIN 05 bound is based on the same principle as KRCMAR 01.</td>
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</table>
236 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.

237 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 $S=0.4$.

238 KRCMAR 98 looked for solar axions emitted by the M1 transition of thermally excited $^{57}$Fe nuclei in the Sun, using their possible resonant capture on $^{57}$Fe in the laboratory, following MORIYAMA 95b. The mass bound assumes $m_u/m_d=0.56$ and the flavor-singlet axial-vector matrix element $S=3F−D=0.5$.

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 $V = \frac{g^2}{8\pi m_p} (\alpha \cdot \gamma) \left( \frac{1}{r^2} + \frac{m_A c}{\hbar r} \right) e^{-m_A c r/\hbar}$.

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239 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 μm—a few mm. See their Fig. 3 for results.

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

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

242 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 $\lambda_A = \hbar/m_A c$.

243 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.

244 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.

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

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