# 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).

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| >0.2 | BARROSO | 82 | ASTR | Standard Axion |
| >0.25 | [1] RAFFELT | 82 | ASTR | Standard Axion |
| >0.2 | [2] DICUS | 78C | ASTR | Standard Axion |
| | MIKAELIAN | 78 | ASTR | Stellar emission |
| >0.3 | [2] SATO | 78 | ASTR | Standard Axion |
| >0.2 | VYSOTSKII | 78 | ASTR | Standard Axion |

[1] Lower bound from 5.5 MeV $\gamma$-ray line from the sun.
[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

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

Limits are for branching ratios.

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $<1.1 \times 10^{-10}$ | 90 | | [3] ADLER | 00 | B787 | $K^+ \to \pi^+ A^0$ |
| $<3.3 \times 10^{-5}$ | 90 | | [4] ALTEGOER | 98 | NOMD | $\pi^0 \to \gamma X^0$, $m_{X^0} < 120$ MeV |
| $<5.0 \times 10^{-8}$ | 90 | | [5] KITCHING | 97 | B787 | $K^+ \to \pi^+ A^0$ ($A^0 \to \gamma\gamma$) |
| $<5.2 \times 10^{-10}$ | 90 | | [6] ADLER | 96 | B787 | $K^+ \to \pi^+ A^0$ |
| $<2.8 \times 10^{-4}$ | 90 | | [7] AMSLER | 96B | CBAR | $\pi^0 \to \gamma X^0$, $m_{X^0} < 65$ MeV |
| $<3 \times 10^{-4}$ | 90 | | [7] AMSLER | 96B | CBAR | $\eta \to \gamma X^0$, $m_{X^0}=$ 50–200 MeV |
| $<4 \times 10^{-5}$ | 90 | | [7] AMSLER | 96B | CBAR | $\eta' \to \gamma X^0$, $m_{X^0}=$ 50–925 MeV |
| $<6 \times 10^{-5}$ | 90 | | [7] AMSLER | 94B | CBAR | $\pi^0 \to \gamma X^0$, $m_{X^0}$=65–125 MeV |
| $<6 \times 10^{-5}$ | 90 | | [7] AMSLER | 94B | CBAR | $\eta \to \gamma X^0$, $m_{X^0}$=200–525 MeV |
| $<0.007$ | 90 | | [8] MEIJERDREES | 94 | CNTR | $\pi^0 \to \gamma X^0$, $m_{X^0}$=25 MeV |

| | | | | | | |
|---|---|---|---|---|---|---|
| $<0.002$ | 90 | | [8] MEIJERDREES | 94 | CNTR | $\pi^0 \rightarrow \gamma X^0$, $m_{X^0}$=100 MeV |
| $<2 \times 10^{-7}$ | 90 | | [9] ATIYA | 93B | B787 | $K^+ \rightarrow \pi^+ A^0$ |
| $<3 \times 10^{-13}$ | | | [10] NG | 93 | COSM | $\pi^0 \rightarrow \gamma X^0$ |
| $<1.1 \times 10^{-8}$ | 90 | | [11] ALLIEGRO | 92 | SPEC | $K^+ \rightarrow \pi^+ A^0$ ($A^0 \rightarrow e^+ e^-$) |
| $<5 \times 10^{-4}$ | 90 | | [12] ATIYA | 92 | B787 | $\pi^0 \rightarrow \gamma X^0$ |
| $<4 \times 10^{-6}$ | 90 | | [13] MEIJERDREES | 92 | SPEC | $\pi^0 \rightarrow \gamma X^0$, $X^0 \rightarrow e^+ e^-$, $m_{X^0}$= 100 MeV |
| $<1 \times 10^{-7}$ | 90 | | [14] ATIYA | 90B | B787 | Sup. by KITCHING 97 |
| $<1.3 \times 10^{-8}$ | 90 | | [15] KORENCHE... | 87 | SPEC | $\pi^+ \rightarrow e^+ \nu A^0$ ($A^0 \rightarrow e^+ e^-$) |
| $<1 \times 10^{-9}$ | 90 | 0 | [16] EICHLER | 86 | SPEC | Stopped $\pi^+ \rightarrow e^+ \nu A^0$ |
| $<2 \times 10^{-5}$ | 90 | | [17] YAMAZAKI | 84 | SPEC | For 160<$m$<260 MeV |
| $<(1.5–4) \times 10^{-6}$ | 90 | | [17] YAMAZAKI | 84 | SPEC | $K$ decay, $m_{A^0} \ll$ 100 MeV |
| | | 0 | [18] ASANO | 82 | CNTR | Stopped $K^+ \rightarrow \pi^+ A^0$ |
| | | 0 | [19] ASANO | 81B | CNTR | Stopped $K^+ \rightarrow \pi^+ A^0$ |
| | | | [20] ZHITNITSKII | 79 | | Heavy axion |

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

[4] 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.

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

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

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

[8] 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.

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

[10] 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 nucleosyntheis $\Delta N_\nu < 0.3$ (WALKER 91) is employed. It applies to $m_{X^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier $X^0$.

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

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

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

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

[15] 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.

[16] 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 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.

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

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

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

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

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

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

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $<1.3 \times 10^{-5}$ | 90 | | [21] BALEST | 95 | CLEO | $\Upsilon(1S) \to A^0\gamma$ |
| $<4.0 \times 10^{-5}$ | 90 | | ANTREASYAN | 90C | CBAL | $\Upsilon(1S) \to A^0\gamma$ |
| | | | [22] ANTREASYAN | 90C | RVUE | |
| $<5 \times 10^{-5}$ | 90 | | [23] DRUZHININ | 87 | ND | $\phi \to A^0\gamma$ ($A^0 \to e^+e^-$) |
| $<2 \times 10^{-3}$ | 90 | | [24] DRUZHININ | 87 | ND | $\phi \to A^0\gamma$ ($A^0 \to \gamma\gamma$) |
| $<7 \times 10^{-6}$ | 90 | | [25] DRUZHININ | 87 | ND | $\phi \to A^0\gamma$ ($A^0 \to$ missing) |
| $<3.1 \times 10^{-4}$ | 90 | 0 | [26] ALBRECHT | 86D | ARG | $\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+e^-$) |
| $<4 \times 10^{-4}$ | 90 | 0 | [26] ALBRECHT | 86D | ARG | $\Upsilon(1S) \to A^0\gamma$ ($A^0 \to \mu^+\mu^-$, $\pi^+\pi^-$, $K^+K^-$) |
| $<8 \times 10^{-4}$ | 90 | 1 | [27] ALBRECHT | 86D | ARG | $\Upsilon(1S) \to A^0\gamma$ |
| $<1.3 \times 10^{-3}$ | 90 | 0 | [28] ALBRECHT | 86D | ARG | $\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+e^-$, $\gamma\gamma$) |
| $<2. \times 10^{-3}$ | 90 | | [29] BOWCOCK | 86 | CLEO | $\Upsilon(2S) \to \Upsilon(1S) \to A^0$ |
| $<5. \times 10^{-3}$ | 90 | | [30] MAGERAS | 86 | CUSB | $\Upsilon(1S) \to A^0\gamma$ |
| $<3. \times 10^{-4}$ | 90 | | [31] ALAM | 83 | CLEO | $\Upsilon(1S) \to A^0\gamma$ |
| $<9.1 \times 10^{-4}$ | 90 | | [32] NICZYPORUK | 83 | LENA | $\Upsilon(1S) \to A^0\gamma$ |
| $<1.4 \times 10^{-5}$ | 90 | | [33] EDWARDS | 82 | CBAL | $J/\psi \to A^0\gamma$ |
| $<3.5 \times 10^{-4}$ | 90 | | [34] SIVERTZ | 82 | CUSB | $\Upsilon(1S) \to A^0\gamma$ |
| $<1.2 \times 10^{-4}$ | 90 | | [34] SIVERTZ | 82 | CUSB | $\Upsilon(3S) \to A^0\gamma$ |

[21] 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 $\gamma X \overline{X}$ for $0 < m_X < 3.1$ GeV.

[22] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where $C_V$ ($V = \Upsilon$, $J/\psi$) is the reduction factor for $\Gamma(V \to A^0\gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. $x$ is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \to ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \to ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

[23] 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.

[24] 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.

[25] 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.

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

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

[28] Independent of $\tau_{A^0}$.

[29] BOWCOCK 86 looked for $A^0$ that decays into $e^+e^-$ in the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to A^0\gamma$. The limit for $B(\Upsilon(1S) \to A^0\gamma)B(A^0 \to e^+e^-)$ depends on $m_{A^0}$ and $\tau_{A^0}$. The quoted limit for $m_{A^0}$=1.8 MeV is at $\tau_{A^0} \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m_e < m_{A^0} < 2m_\mu$ when the results of this experiment are combined with the results of ALAM 83.

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

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

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

[33] EDWARDS 82 looked for $J/\psi \to \gamma A^0$ 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.

[34] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \to \gamma A^0$, $A^0$ undetected. Limit for 1$S$ (3$S$) is valid for $m_{A^0}$ <7 GeV (4 GeV).

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

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

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|

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

| | | | | | |
|---|---|---|---|---|---|
| $<2 \times 10^{-4}$ | 90 | MAENO | 95 | CNTR | o-Ps → $A^0\gamma$ $m_{A^0}$=850–1013 keV |
| $<3.0 \times 10^{-3}$ | 90 | [35] ASAI | 94 | CNTR | o-Ps → $A^0\gamma$ $m_{A^0}$=30–500 keV |
| $<2.8 \times 10^{-5}$ | 90 | [36] AKOPYAN | 91 | CNTR | o-Ps → $A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$), $m_{A^0} < 30$ keV |
| $<1.1 \times 10^{-6}$ | 90 | [37] ASAI | 91 | CNTR | o-Ps → $A^0\gamma$, $m_{A^0} < 800$ keV |
| $<3.8 \times 10^{-4}$ | 90 | GNINENKO | 90 | CNTR | o-Ps → $A^0\gamma$, $m_{A^0} <$ 30 keV |
| $<(1–5) \times 10^{-4}$ | 95 | [38] TSUCHIAKI | 90 | CNTR | o-Ps → $A^0\gamma$, $m_{A^0} =$ 300–900 keV |
| $<6.4 \times 10^{-5}$ | 90 | [39] ORITO | 89 | CNTR | o-Ps → $A^0\gamma$, $m_{A^0} < 30$ keV |
| | | [40] AMALDI | 85 | CNTR | Ortho-positronium |
| | | [41] CARBONI | 83 | CNTR | Ortho-positronium |

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

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

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

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

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

[40] 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.

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

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

| VALUE | DOCUMENT ID | COMMENT |
|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | |
| | [42] BASSOMPIE... 95 | $m_{A^0} = 1.8 \pm 0.2$ MeV |

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

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

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

| VALUE | CL% | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | | | [43] AHMAD | 97 SPEC | $e^+$ production |
| | | | [44] LEINBERGER | 97 SPEC | $A^0 \to e^+e^-$ |
| | | | [45] GANZ | 96 SPEC | $A^0 \to e^+e^-$ |
| | | | [46] KAMEL | 96 EMUL | $^{32}$S emulsion, $A^0 \to e^+e^-$ |
| | | | [47] BLUEMLEIN | 92 BDMP | $A^0 N_Z \to \ell^+\ell^- N_Z$ |
| | | | [48] MEIJERDREES | 92 SPEC | $\pi^- p \to n A^0$, $A^0 \to e^+e^-$ |
| | | | [49] BLUEMLEIN | 91 BDMP | $A^0 \to e^+e^-$, $2\gamma$ |
| | | | [50] FAISSNER | 89 OSPK | Beam dump, $A^0 \to e^+e^-$ |
| | | | [51] DEBOER | 88 RVUE | $A^0 \to e^+e^-$ |
| | | | [52] EL-NADI | 88 EMUL | $A^0 \to e^+e^-$ |
| | | | [53] FAISSNER | 88 OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | | [54] BADIER | 86 BDMP | $A^0 \to e^+e^-$ |
| $<2. \times 10^{-11}$ | 90 | 0 | [55] BERGSMA | 85 CHRM | CERN beam dump |
| $<1. \times 10^{-13}$ | 90 | 0 | [55] BERGSMA | 85 CHRM | CERN beam dump |
| | | 24 | [56] FAISSNER | 83 OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | | [57] FAISSNER | 83B RVUE | LAMPF beam dump |
| | | | [58] FRANK | 83B RVUE | LAMPF beam dump |
| | | | [59] HOFFMAN | 83 CNTR | $\pi p \to n A^0$ ($A^0 \to e^+e^-$) |
| | | | [60] FETSCHER | 82 RVUE | See FAISSNER 81B |
| | | 12 | [61] FAISSNER | 81 OSPK | CERN PS $\nu$ wideband |
| | | 15 | [62] FAISSNER | 81B OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | 8 | [63] KIM | 81 OSPK | 26 GeV $pN \to A^0 X$ |
| | | 0 | [64] FAISSNER | 80 OSPK | Beam dump, $A^0 \to e^+e^-$ |
| $<1. \times 10^{-8}$ | 90 | | [65] JACQUES | 80 HLBC | 28 GeV protons |
| $<1. \times 10^{-14}$ | 90 | | [65] JACQUES | 80 HLBC | Beam dump |
| | | | [66] SOUKAS | 80 CALO | 28 GeV $p$ beam dump |
| | | | [67] BECHIS | 79 CNTR | |
| $<1. \times 10^{-8}$ | 90 | | [68] COTEUS | 79 OSPK | Beam dump |
| $<1. \times 10^{-3}$ | 95 | | [69] DISHAW | 79 CALO | 400 GeV $pp$ |
| $<1. \times 10^{-8}$ | 90 | | ALIBRAN | 78 HYBR | Beam dump |
| $<6. \times 10^{-9}$ | 95 | | ASRATYAN | 78B CALO | Beam dump |
| $<1.5 \times 10^{-8}$ | 90 | | [70] BELLOTTI | 78 HLBC | Beam dump |
| $<5.4 \times 10^{-14}$ | 90 | | [70] BELLOTTI | 78 HLBC | $m_{A^0}$=1.5 MeV |
| $<4.1 \times 10^{-9}$ | 90 | | [70] BELLOTTI | 78 HLBC | $m_{A^0}$=1 MeV |
| $<1. \times 10^{-8}$ | 90 | | [71] BOSETTI | 78B HYBR | Beam dump |
| | | | [72] DONNELLY | 78 | |
| $<0.5 \times 10^{-8}$ | 90 | | HANSL | 78D WIRE | Beam dump |
| | | | [73] MICELMAC... | 78 | |
| | | | [74] VYSOTSKII | 78 | |

[43] 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.

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

[45] GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of $e^+e^-$ pairs from $^{238}$U+$^{181}$Ta and $^{238}$U+$^{232}$Th collisions at GSI. See Table 2 for limits both for back-to-back and isotropic configurations of $e^+e^-$ pairs. These limits rule out the existence of peaks in the $e^+e^-$ sum-energy distribution, reported by an earlier version of this experiment.

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

[47] 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.

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

[49] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \to e^+e^-$, $2\gamma$ are found. Fig. 6 gives the excluded region in $m_{A^0}$-$x$ plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m_{A^0} < 3.2$ MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$.

[50] FAISSNER 89 searched for $A^0 \to e^+e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m_e$–20 MeV is excluded. Lower limit on $f_{A^0}$ of $\simeq 10^4$ GeV is given for $m_{A^0} = 2m_e$–20 MeV.

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

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

[53] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \to \gamma\gamma$. A standard axion decaying to $2\gamma$ is excluded except for a region $x \simeq 1$. Lower limit on $f_{A^0}$ of $10^2$–$10^3$ GeV is given for $m_{A^0} =$ 0.1–1 MeV.

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

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

[56] 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.

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

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

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

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

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

[62] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 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 ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[63] KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86\sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[64] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+ e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/($A^0$ mass) MeV/s (CL = 90%), which is about $10^{-7}$ below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

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

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

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

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

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

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

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

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

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

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

## $A^0$ (Axion) Searches in Reactor Experiments

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|

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

| | | | | |
|---|---|---|---|---|
| [75] ALTMANN | 95 | CNTR | Reactor; $A^0 \rightarrow e^+ e^-$ |
| [76] KETOV | 86 | SPEC | Reactor, $A^0 \rightarrow \gamma\gamma$ |
| [77] KOCH | 86 | SPEC | Reactor; $A^0 \rightarrow \gamma\gamma$ |
| [78] DATAR | 82 | CNTR | Light water reactor |
| [79] VUILLEUMIER | 81 | CNTR | Reactor, $A^0 \rightarrow 2\gamma$ |

[75] ALTMANN 95 looked for $A^0$ decaying into $e^+ e^-$ from the Bugey 5 nuclear reactor. They obtain an upper limit on the $A^0$ production rate of $\omega(A^0)/\omega(\gamma) \times$B($A^0 \rightarrow e^+ e^-$)$< 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier $A^0$. In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances $Z^0$ in the ($m_{X^0}$,$f_{X^0}$) plane.

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

[77] KOCH 86 searched for $A^0 \rightarrow \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the $A^0$ production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m_{A^0} = 250$ keV gives $10^{-5}$ for the ratio. Not valid for $m_{A^0}$ >1022 keV.

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

[79] VUILLEUMIER 81 is at Grenoble reactor. Set limit $m_{A^0}$ <280 keV.

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

Limits are for branching ratio.

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | | [80] DEBOER | 97C | RVUE | M1 transitions |
| $< 5.5 \times 10^{-10}$ | 95 | | [81] TSUNODA | 95 | CNTR | $^{252}$Cf fission, $A^0 \rightarrow ee$ |
| $< 1.2 \times 10^{-6}$ | 95 | | [82] MINOWA | 93 | CNTR | $^{139}\text{La}^* \rightarrow {}^{139}\text{La}\, A^0$ |
| $< 2 \times 10^{-4}$ | 90 | | [83] HICKS | 92 | CNTR | $^{35}$S decay, $A^0 \rightarrow \gamma\gamma$ |
| $< 1.5 \times 10^{-9}$ | 95 | | [84] ASANUMA | 90 | CNTR | $^{241}$Am decay |
| $<(0.4–10) \times 10^{-3}$ | 95 | | [85] DEBOER | 90 | CNTR | $^8\text{Be}^* \rightarrow {}^8\text{Be}\, A^0$, $A^0 \rightarrow e^+ e^-$ |
| $<(0.2–1) \times 10^{-3}$ | 90 | | [86] BINI | 89 | CNTR | $^{16}\text{O}^* \rightarrow {}^{16}\text{O}\, X^0$, $X^0 \rightarrow e^+ e^-$ |
| | | | [87] AVIGNONE | 88 | CNTR | $\text{Cu}^* \rightarrow \text{Cu}\, A^0$ ($A^0 \rightarrow 2\gamma$, $A^0 e \rightarrow \gamma e$, $A^0 Z \rightarrow \gamma Z$) |
| $< 1.5 \times 10^{-4}$ | 90 | | [88] DATAR | 88 | CNTR | $^{12}\text{C}^* \rightarrow {}^{12}\text{C}\, A^0$, $A^0 \rightarrow e^+ e^-$ |
| $< 5 \times 10^{-3}$ | 90 | | [89] DEBOER | 88C | CNTR | $^{16}\text{O}^* \rightarrow {}^{16}\text{O}\, X^0$, $X^0 \rightarrow e^+ e^-$ |
| $< 3.4 \times 10^{-5}$ | 95 | | [90] DOEHNER | 88 | SPEC | $^2\text{H}^*$, $A^0 \rightarrow e^+ e^-$ |
| $< 4 \times 10^{-4}$ | 95 | | [91] SAVAGE | 88 | CNTR | Nuclear decay (isovector) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $<3$ | $\times 10^{-3}$ | 95 | | [91] SAVAGE | 88 | CNTR | Nuclear decay (isoscalar) |
| $<0.106$ | | 90 | | [92] HALLIN | 86 | SPEC | $^{6}$Li isovector decay |
| $<10.8$ | | 90 | | [92] HALLIN | 86 | SPEC | $^{10}$B isoscalar decays |
| $<2.2$ | | 90 | | [92] HALLIN | 86 | SPEC | $^{14}$N isoscalar decays |
| $<4$ | $\times 10^{-4}$ | 90 | 0 | [93] SAVAGE | 86B | CNTR | $^{14}$N* |
| | | | | [94] ANANEV | 85 | CNTR | Li*, deut* $A^0 \rightarrow 2\gamma$ |
| | | | | [95] CAVAIGNAC | 83 | CNTR | $^{97}$Nb*, deut* transition $A^0 \rightarrow 2\gamma$ |
| | | | | [96] ALEKSEEV | 82B | CNTR | Li*, deut* transition $A^0 \rightarrow 2\gamma$ |
| | | | | [97] LEHMANN | 82 | CNTR | Cu* $\rightarrow$ Cu $A^0$ ($A^0 \rightarrow 2\gamma$) |
| | | | 0 | [98] ZEHNDER | 82 | CNTR | Li*, Nb* decay, $n$-capt. |
| | | | 0 | [99] ZEHNDER | 81 | CNTR | Ba* $\rightarrow$ Ba $A^0$ ($A^0 \rightarrow 2\gamma$) |
| | | | | [100] CALAPRICE | 79 | | Carbon |

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

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

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

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

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

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

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

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

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

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

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

[91] SAVAGE 88 looked for $A^0$ that decays into $e^+ e^-$ in the decay of the 9.17 MeV $J^P = 2^+$ state in $^{14}$N, 17.64 MeV state $J^P = 1^+$ in $^8$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.

[92] 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.

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

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

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

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

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

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

[99] ZEHNDER 81 looked for Ba* $\rightarrow A^0$ Ba transition with $A^0 \rightarrow 2\gamma$. Obtained $2\gamma$ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding $m_{A^0}$ >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

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

## $A^0$ (Axion) Limits from Its Electron Coupling

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

| VALUE (s) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| none $4 \times 10^{-16}$–$4.5 \times 10^{-12}$ | 90 | [101] BROSS | 91 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |
| | | [102] GUO | 90 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |
| | | [103] BJORKEN | 88 | CALO | $A \rightarrow e^+ e^-$ or $2\gamma$ |
| | | [104] BLINOV | 88 | MD1 | $ee \rightarrow eeA^0$ $(A^0 \rightarrow ee)$ |
| none $1 \times 10^{-14}$–$1 \times 10^{-10}$ | 90 | [105] RIORDAN | 87 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |
| none $1 \times 10^{-14}$–$1 \times 10^{-11}$ | 90 | [106] BROWN | 86 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |
| none $6 \times 10^{-14}$–$9 \times 10^{-11}$ | 95 | [107] DAVIER | 86 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |
| none $3 \times 10^{-13}$–$1 \times 10^{-7}$ | 90 | [108] KONAKA | 86 | BDMP | $eN \rightarrow eA^0 N$ $(A^0 \rightarrow ee)$ |

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

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

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

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

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

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

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

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

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

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

| VALUE ($10^{-3}$ eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 1.3 | 97 | [109] HALLIN | 92 | CNTR | $m_{A^0} = 1.75$–$1.88$ MeV |
| none 0.0016–0.47 | 90 | [110] HENDERSON | 92C | CNTR | $m_{A^0} = 1.5$–$1.86$ MeV |
| < 2.0 | 90 | [111] WU | 92 | CNTR | $m_{A^0} = 1.56$–$1.86$ MeV |
| < 0.013 | 95 | TSERTOS | 91 | CNTR | $m_{A^0} = 1.832$ MeV |
| none 0.19–3.3 | 95 | [112] WIDMANN | 91 | CNTR | $m_{A^0} = 1.78$–$1.92$ MeV |
| < 5 | 97 | BAUER | 90 | CNTR | $m_{A^0} = 1.832$ MeV |
| none 0.09–1.5 | 95 | [113] JUDGE | 90 | CNTR | $m_{A^0} = 1.832$ MeV, elastic |
| < 1.9 | 97 | [114] TSERTOS | 89 | CNTR | $m_{A^0} = 1.82$ MeV |
| <(10–40) | 97 | [114] TSERTOS | 89 | CNTR | $m_{A^0} = 1.51$–$1.65$ MeV |
| <(1–2.5) | 97 | [114] TSERTOS | 89 | CNTR | $m_{A^0} = 1.80$–$1.86$ MeV |
| < 31 | 95 | LORENZ | 88 | CNTR | $m_{A^0} = 1.646$ MeV |
| < 94 | 95 | LORENZ | 88 | CNTR | $m_{A^0} = 1.726$ MeV |
| < 23 | 95 | LORENZ | 88 | CNTR | $m_{A^0} = 1.782$ MeV |
| < 19 | 95 | LORENZ | 88 | CNTR | $m_{A^0} = 1.837$ MeV |
| < 3.8 | 97 | [115] TSERTOS | 88 | CNTR | $m_{A^0} = 1.832$ MeV |
| | | [116] VANKLINKEN | 88 | CNTR | |
| | | [117] MAIER | 87 | CNTR | |
| <2500 | 90 | MILLS | 87 | CNTR | $m_{A^0} = 1.8$ MeV |
| | | [118] VONWIMMER... | 87 | CNTR | |

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

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

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

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

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

[114] See also TSERTOS 88B in references.

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

[116] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}$–$10^{-12}$ s). The sensitivity is not sufficient to exclude such a narrow resonance.

[117] MAIER 87 obtained limits $R\Gamma \lesssim$ 60 eV (100 eV) at $m_{A^0} \simeq$ 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 $\Gamma = \Gamma^2_{ee}/\Gamma_{total}$. For a discussion implying that $\Delta E_{cm} \simeq$ 10 keV, see TSERTOS 89.

[118] 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.

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

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

| VALUE ($10^{-3}$ eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.18 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.1 MeV |
| < 1.5 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.4 MeV |
| <12 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.7 MeV |
| < 6.6 | 95 | [119] TRZASKA | 91 | CNTR | $m_{A^0}$ = 1.8 MeV |
| < 4.4 | 95 | WIDMANN | 91 | CNTR | $m_{A^0}$= 1.78–1.92 MeV |
| | | [120] FOX | 89 | CNTR | |
| < 0.11 | 95 | [121] MINOWA | 89 | CNTR | $m_{A^0}$ = 1.062 MeV |
| <33 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.580 MeV |
| <42 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.642 MeV |
| <73 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.782 MeV |
| <79 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.832 MeV |

[119] TRZASKA 91 also give limits in the range (6.6–30) $\times 10^{-3}$ eV (95%CL) for $m_{A^0}$ = 1.6–2.0 MeV.

[120] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($< 9 \times 10^{-5}$ of two-photon annihilation at rest).

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

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

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

| VALUE ($10^{-3}$ eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.2 | 95 | [122] VO | 94 | CNTR | $m_{X^0}$=1.1–1.9 MeV |
| < 1.0 | 95 | [123] VO | 94 | CNTR | $m_{X^0}$=1.1 MeV |
| < 2.5 | 95 | [123] VO | 94 | CNTR | $m_{X^0}$=1.4 MeV |
| <120 | 95 | [123] VO | 94 | CNTR | $m_{X^0}$=1.7 MeV |
| < 3.8 | 95 | [124] SKALSEY | 92 | CNTR | $m_{X^0}$= 1.5 MeV |

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

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

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

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

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

| VALUE (units $10^{-6}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 4.2 | 90 | [125] MITSUI | 96 | CNTR | $\gamma X^0$ |
| < 4 | 68 | [126] SKALSEY | 95 | CNTR | $\gamma X^0$ |
| <40 | 68 | [127] SKALSEY | 95 | RVUE | $\gamma X^0$ |
| < 0.18 | 90 | [128] ADACHI | 94 | CNTR | $\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$ |
| < 0.26 | 90 | [129] ADACHI | 94 | CNTR | $\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$ |
| < 0.33 | 90 | [130] ADACHI | 94 | CNTR | $\gamma X^0$, $X^0 \rightarrow \gamma\gamma\gamma$ |

[125] MITSUI 96 looked for a monochromatic $\gamma$. The bound applies for a vector $X^0$ with $C$=−1 and $m_{X^0}$ <200 keV. They derive an upper bound on $eeX^0$ coupling and hence on the branching ratio B($o$-Ps $\rightarrow \gamma\gamma X^0$)$< 6.2 \times 10^{-6}$. The bounds weaken for heavier $X^0$.

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

[127] SKALSEY 95 reinterpreted the bound on $\gamma A^0$ decay of $o$-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.

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

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

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

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

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

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | | [131] DIAZ | 98 | THEO | $H^0 \rightarrow X^0 X^0$, $A^0 \rightarrow X^0 X^0 X^0$, Majoron |
| | | | [132] BOBRAKOV | 91 | | Electron quasi-magnetic interaction |
| $<3.3 \times 10^{-2}$ | 95 | | [133] ALBRECHT | 90E | ARG | $\tau \rightarrow \mu X^0$. Familon |
| $<1.8 \times 10^{-2}$ | 95 | | [133] ALBRECHT | 90E | ARG | $\tau \rightarrow e X^0$. Familon |
| $<6.4 \times 10^{-9}$ | 90 | | [134] ATIYA | 90 | B787 | $K^+ \rightarrow \pi^+ X^0$. Familon |
| $<1.1 \times 10^{-9}$ | 90 | | [135] BOLTON | 88 | CBOX | $\mu^+ \rightarrow e^+ \gamma X^0$. Familon |
| | | | [136] CHANDA | 88 | ASTR | Sun, Majoron |
| | | | [137] CHOI | 88 | ASTR | Majoron, SN 1987A |
| $<5 \times 10^{-6}$ | 90 | | [138] PICCIOTTO | 88 | CNTR | $\pi \rightarrow e \nu X^0$, Majoron |
| $<1.3 \times 10^{-9}$ | 90 | | [139] GOLDMAN | 87 | CNTR | $\mu \rightarrow e \gamma X^0$. Familon |
| $<3 \times 10^{-4}$ | 90 | | [140] BRYMAN | 86B | RVUE | $\mu \rightarrow e X^0$. Familon |
| $<1. \times 10^{-10}$ | 90 | 0 | [141] EICHLER | 86 | SPEC | $\mu^+ \rightarrow e^+ X^0$. Familon |
| $<2.6 \times 10^{-6}$ | 90 | | [142] JODIDIO | 86 | SPEC | $\mu^+ \rightarrow e^+ X^0$. Familon |
| | | | [143] BALTRUSAIT... | 85 | MRK3 | $\tau \rightarrow \ell X^0$. Familon |
| | | | [144] DICUS | 83 | COSM | $\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$ |

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

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

[133] ALBRECHT 90E limits are for $B(\tau \rightarrow \ell X^0)/B(\tau \rightarrow \ell \nu \overline{\nu})$. Valid for $m_{X^0} < 100$ MeV. The limits rise to 7.1% (for $\mu$), 5.0% (for $e$) for $m_{X^0} = 500$ MeV.

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

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

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

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

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

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

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

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

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

[143] BALTRUSAITIS 85 search for light Goldstone boson($X^0$) of broken U(1). CL = 95% limits are $B(\tau \rightarrow \mu^+ X^0)/B(\tau \rightarrow \mu^+ \nu\nu) < 0.125$ 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.

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

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## Majoron Searches in Neutrinoless Double $\beta$ Decay

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

Previous indications for neutrinoless double beta decay with majoron emission have been superseded. No experiment currently claims any such evidence. Also see the recent rviews ZUBER 98 and FAESSLER 98B.

| $t_{1/2}(10^{21}$ yr) | CL% | ISOTOPE | TRANSITION | METHOD | DOCUMENT ID | |
|---|---|---|---|---|---|---|
| **>7200** | **90** | **$^{128}$Te** | | **CNTR** | [145] BERNATOW... | 92 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| > 0.0035 | 90 | $^{160}$Gd | $0\nu$ | $^{160}Gd_2SiO_5$:Ce | [146] DANEVICH | 01 |
| > 0.013 | 90 | $^{160}$Gd | $0\nu 2\chi$ | $^{160}Gd_2SiO_5$:Ce | [147] DANEVICH | 01 |
| > 1.4 | 90 | $^{130}$Te | $0\nu\chi$ | Cryog. det. | [148] ALESSAND... | 00 |
| > 0.7 | 90 | $^{130}$Te | $0\nu 2\chi$ | Cryog. det. | [149] ALESSAND... | 00 |
| > 2.3 | 90 | $^{82}$Se | $0\nu\chi$ | NEMO 2 | [150] ARNOLD | 00 |
| > 0.31 | 90 | $^{96}$Zr | $0\nu\chi$ | NEMO 2 | [151] ARNOLD | 00 |
| > 0.6 | 90 | $^{100}$Mo | $0\nu\chi$ | NEMO 2 | [152] ARNOLD | 00 |
| > 0.92 | 90 | $^{116}$Cd | $0\nu\chi$ | NEMO 2 | [153] ARNOLD | 00 |
| > 0.63 | 90 | $^{82}$Se | $0\nu 2\chi$ | NEMO 2 | [154] ARNOLD | 00 |
| > 0.063 | 90 | $^{96}$Zr | $0\nu 2\chi$ | NEMO 2 | [154] ARNOLD | 00 |
| > 0.16 | 90 | $^{100}$Mo | $0\nu 2\chi$ | NEMO 2 | [154] ARNOLD | 00 |
| > 0.35 | 90 | $^{116}$Cd | $0\nu 2\chi$ | NEMO 2 | [154] ARNOLD | 00 |
| > 3.7 | 90 | $^{116}$Cd | $0\nu\chi$ | $^{116}CdWO_4$ scint. | [155] DANEVICH | 00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| > | 0.59 | 90 | $^{116}$Cd | $0\nu 2\chi$ | $^{116}$CdWO$_4$ scint. | [156] DANEVICH | 00 |
| > | 0.35 | 90 | $^{96}$Zr | $0\nu\chi$ | NEMO-2 | [157] ARNOLD | 99 |
| > | 1.2 | 90 | $^{116}$Cd | $0\nu\chi$ | SCIN | [158] DANEVICH | 98 |
| > | 0.26 | 90 | $^{116}$Cd | $0\nu 2\chi$ | SCIN | [159] DANEVICH | 98 |
| > | 7.2 | 90 | $^{136}$Xe | $0\nu 2\chi$ | TPC | [160] LUESCHER | 98 |
| > | 7.91 | 90 | $^{76}$Ge | | SPEC | [161] GUENTHER | 96 |
| > | 17 | 90 | $^{76}$Ge | | CNTR | BECK | 93 |
| > | 0.79 | 68 | $^{100}$Mo | | SPEC | [162] TANAKA | 93 |
| > | 0.19 | 68 | $^{136}$Xe | | CNTR | BARABASH | 89 |
| > | 1.0 | 90 | $^{76}$Ge | | CNTR | FISHER | 89 |
| > | 0.33 | 90 | $^{100}$Mo | | CNTR | ALSTON-... | 88 |
| > | 1.4 | 90 | $^{76}$Ge | | CNTR | CALDWELL | 87 |
| > | 0.44 | 90 | $^{82}$Se | | SPEC | ELLIOTT | 87 |
| > | 1.2 | 90 | $^{76}$Ge | | CNTR | FISHER | 87 |
| | | | | | CNTR | [163] VERGADOS | 82 |

[145] 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 $(7.7–1.28 \times 0.4=7.2) \times 10^{24}$.

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

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

[148] ALESSANDRELLO 00 obtain limit for the $0\nu\chi$ decay with Majoron emission of $^{130}$Te using cryogenic calorimeter. Derive $\langle g_{\nu\chi}\rangle < 2.6–6.7 \times 10^{-4}$ with several nuclear matrix elements.

[149] ALESSANDRELLO 00 obtain limit for the $0\nu 2\chi$ decay with two Majoron emission of $^{130}$Te using cryogenic calorimeter.

[150] 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.

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

[152] Using $^{100}$Mo source: $\langle g_{\nu\chi}\rangle < 2.0 \times 10^{-4}$. Matrix element from GUENTHER 96.

[153] Using $^{116}$Cd source: $\langle g_{\nu\chi}\rangle < 2.1 \times 10^{-4}$. Matrix element from GUENTHER 96.

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

[155] DANEVICH 00 obtain limit for the $0\nu\chi$ decay with Majoron emission of $^{116}$Cd using enriched $CdWO_4$ scinlattors. Derive $\langle g_{\nu\chi}\rangle < 6.5\times10^{-5}$ (matrix elements of ARNOLD 96) and $12 \times 10^{-5}$ (matrix elements of HIRSCH 96). Replaces DANEVICH 98.

[156] DANEVICH 00 obtain limit for the $0\nu 2\chi$ decay with two Majoron emission of $^{116}$Cd using enriched $CdWO_4$ scinlattors. Replaces DANEVICH 98.

[157] ARNOLD 99 use enriched $^{96}$Zr and give a limit based on the matrix elements of STAUDT 90.

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

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

[160] LUESCHER 98 report a limit for the $0\nu$ 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 $2.0 \times 10^{-4}$.

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

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

[163] VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, $g_H$, of scalar boson (Majoron) to neutrinos, from analysis of data on double $\beta$ decay of $^{48}$Ca.

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

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

| *VALUE* (eV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 3 to 20 | [164] MOROI | 98 | COSM | K, hot dark matter |
| $<$ 0.007 | [165] BORISOV | 97 | ASTR | D, neutron star |
| $<$ 4 | [166] KACHELRIESS | 97 | ASTR | D, neutron star cooling |
| $<(0.5\text{–}6) \times 10^{-3}$ | [167] KEIL | 97 | ASTR | SN 1987A |
| $<$ 0.018 | [168] RAFFELT | 95 | ASTR | D, red giant |
| $<$ 0.010 | [169] ALTHERR | 94 | ASTR | D, red giants, white dwarfs |
| | [170] CHANG | 93 | ASTR | K, SN 1987A |
| $<$ 0.01 | WANG | 92 | ASTR | D, white dwarf |
| $<$ 0.03 | WANG | 92C | ASTR | D, C-O burning |
| none 3–8 | [171] BERSHADY | 91 | ASTR | D, K, intergalactic light |
| $<$10 | [172] KIM | 91C | COSM | D, K, mass density of the universe, supersymmetry |
| | [173] RAFFELT | 91B | ASTR | D,K, SN 1987A |
| $< 1 \times 10^{-3}$ | [174] RESSELL | 91 | ASTR | K, intergalactic light |
| none $10^{-3}$–3 | BURROWS | 90 | ASTR | D,K, SN 1987A |
| | [175] ENGEL | 90 | ASTR | D,K, SN 1987A |
| $<$ 0.02 | [176] RAFFELT | 90D | ASTR | D, red giant |
| $< 1 \times 10^{-3}$ | [177] BURROWS | 89 | ASTR | D,K, SN 1987A |
| $<(1.4\text{–}10) \times 10^{-3}$ | [178] ERICSON | 89 | ASTR | D,K, SN 1987A |
| $< 3.6 \times 10^{-4}$ | [179] MAYLE | 89 | ASTR | D,K, SN 1987A |
| $<$12 | CHANDA | 88 | ASTR | D, Sun |
| $< 1 \times 10^{-3}$ | RAFFELT | 88 | ASTR | D,K, SN 1987A |
| | [180] RAFFELT | 88B | ASTR | red giant |
| $<$ 0.07 | FRIEMAN | 87 | ASTR | D, red giant |
| $<$ 0.7 | [181] RAFFELT | 87 | ASTR | K, red giant |
| $<$ 2–5 | TURNER | 87 | COSM | K, thermal production |
| $<$ 0.01 | [182] DEARBORN | 86 | ASTR | D, red giant |
| $<$ 0.06 | RAFFELT | 86 | ASTR | D, red giant |

| | | | | |
|---|---|---|---|---|
| $< 0.7$ | [183] RAFFELT | 86 | ASTR | K, red giant |
| $< 0.03$ | RAFFELT | 86B | ASTR | D, white dwarf |
| $< 1$ | [184] KAPLAN | 85 | ASTR | K, red giant |
| $< 0.003$–$0.02$ | IWAMOTO | 84 | ASTR | D, K, neutron star |
| $> 1 \times 10^{-5}$ | ABBOTT | 83 | COSM | D,K, mass density of the universe |
| $> 1 \times 10^{-5}$ | DINE | 83 | COSM | D,K, mass density of the universe |
| $< 0.04$ | ELLIS | 83B | ASTR | D, red giant |
| $> 1 \times 10^{-5}$ | PRESKILL | 83 | COSM | D,K, mass density of the universe |
| $< 0.1$ | BARROSO | 82 | ASTR | D, red giant |
| $< 1$ | [185] FUKUGITA | 82 | ASTR | D, stellar cooling |
| $< 0.07$ | FUKUGITA | 82B | ASTR | D, red giant |

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

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

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

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

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

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

[170] CHANG 93 updates ENGEL 90 bound with the Kaplan-Mahohar ambiguity in $z=m_u/m_d$ (see the Note on the Quark Masses in the Quark Particle Listings). It leaves the window $f_A=3\times10^5$–$3\times10^6$ GeV open. The constraint from Big-Bang Nucleosynthesis is satisfied in this window as well.

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

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

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

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

[175] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to $2.5 \times 10^{-3}$ eV $\lesssim m_{A^0} \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

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

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

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

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

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

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

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

183 RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}$ GeV$^{-1}$ from red giants and $< 2.4\times10^{-9}$ GeV$^{-1}$ from the sun.

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

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

## Search for Relic Invisible Axions

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

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

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

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

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

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

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

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

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

| VALUE (GeV$^{-1}$) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |

| | | | | | |
|---|---|---|---|---|---|
| $<1.5 \times 10^{-4}$ | 90 | [190] ASTIER | 00B | NOMD | $m_{A^0} <40$ eV |
| | | [191] MASSO | 00 | THEO | induced photon coupling |
| $<2.7 \times 10^{-9}$ | 95 | [192] AVIGNONE | 98 | | $m_{A^0} < 1$ keV |
| $<6.0 \times 10^{-10}$ | 95 | [193] MORIYAMA | 98 | | $m_{A^0} < 0.03$ eV |
| $<3.6 \times 10^{-7}$ | 95 | [194] CAMERON | 93 | | $m_{A^0} < 10^{-3}$ eV, optical rotation |
| $<6.7 \times 10^{-7}$ | 95 | [195] CAMERON | 93 | | $m_{A^0} < 10^{-3}$ eV, photon regeneration |
| $<3.6 \times 10^{-9}$ | 99.7 | [196] LAZARUS | 92 | | $m_{A^0} < 0.03$ eV |
| $<7.7 \times 10^{-9}$ | 99.7 | [196] LAZARUS | 92 | | $m_{A^0} = 0.03$–$0.11$ eV |
| $<7.7 \times 10^{-7}$ | 99 | [197] RUOSO | 92 | | $m_{A^0} < 10^{-3}$ eV |
| $<2.5 \times 10^{-6}$ | | [198] SEMERTZIDIS | 90 | | $m_{A^0} < 7 \times 10^{-4}$ eV |

[190] 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.

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

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

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

[194] Experiment based on proposal by MAIANI 86.

[195] Experiment based on proposal by VANBIBBER 87.

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

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

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

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

The limit is for $G_{Aee} \partial_\mu \phi_A \overline{e} \gamma^\mu \gamma_5 e$ in GeV$^{-1}$, or equivalenty, the dipole-dipole potential $\frac{G_{Aee}^2}{4\pi} ((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})\ (\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ where $\boldsymbol{n}=\boldsymbol{r}/r$.

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

| *VALUE* (GeV$^{-1}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<5.3 \times 10^{-5}$ | 66 | [199] NI | 94 | | Induced magnetism |
| $<6.7 \times 10^{-5}$ | 66 | [199] CHUI | 93 | | Induced magnetism |
| $<3.6 \times 10^{-4}$ | 66 | [200] PAN | 92 | | Torsion pendulum |
| $<2.7 \times 10^{-5}$ | 95 | [199] BOBRAKOV | 91 | | Induced magnetism |
| $<1.9 \times 10^{-3}$ | 66 | [201] WINELAND | 91 | NMR | |
| $<8.9 \times 10^{-4}$ | 66 | [200] RITTER | 90 | | Torsion pendulum |
| $<6.6 \times 10^{-5}$ | 95 | [199] VOROBYOV | 88 | | Induced magnetism |

[199] 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.
[200] 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.
[201] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

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

Limits are for the axion mass in eV.

| VALUE (eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <745 | 90 | [202] KRCMAR | 98 | CNTR | Solar axion |

[202] 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 $S$=3$F$−$D\simeq$ 0.5.

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

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

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [203] NI | 99 | | paramagnetic Tb $F_3$ |
| | [204] POSPELOV | 98 | THEO | neutron EDM |
| | [205] YOUDIN | 96 | | |
| | [206] RITTER | 93 | | torsion pendulum |
| | [207] VENEMA | 92 | | nuclear spin-precession frequencies |
| | [208] WINELAND | 91 | NMR | |

[203] NI 99 searched for a $T$-violating medium-range force acting on paramagnetic Tb $F_3$ salt. See their Fig. 1 for the result.
[204] 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 $2 \times 10^{-10}$ $(1\,\mathrm{cm}/\lambda_A)$, where $\lambda_A$=$\hbar/m_A c$.
[205] 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.
[206] RITTER 93 used a torsion pendulum to study the influence of bulk mass with polarized electrons on the pendulum.
[207] VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of $^{199}$Hg and $^{201}$Hg atoms.
[208] 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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