[36] 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.

[37] 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 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25$–136 MeV.

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

[39] 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.

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

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

[42] 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 2γ 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.

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

[44] 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.

[45] FAISSNER 83 observed 19 1-γ and 12 2-γ 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.

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

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

[48] 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.

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

[50] FAISSNER 81 see excess μe events. Suggest axion interactions.

[51] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with η-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.

[52] KIM 81 analyzed 8 candidates for $A^0 \to 2\gamma$ 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.

[53] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \to e^+e^-$ 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 $m_{A^0} < 2m_{e^-}$.

[54] 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 2γ's or e^+e^-, and for axion mass a few MeV.

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

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

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

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

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

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

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

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

[63] 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. • • •				
	[64] KETOV	86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[65] KOCH	86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[66] DATAR	82	CNTR	Light water reactor
	[67] VUILLEUMIER	81	CNTR	Reactor, $A^0 \to 2\gamma$

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

[65] KOCH 86 searched for $A^0 \to \gamma\gamma$ 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.

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

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

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

Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.2 \times 10^{-6}$	95		[68] MINOWA	93	CNTR	^{139}La$^* \to {}^{139}$LaA^0
$< 2 \times 10^{-4}$	90		[69] HICKS	92	CNTR	^{35}S decay, $A^0 \to \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[70] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4$–$10) \times 10^{-3}$	95		[71] DEBOER	90	CNTR	^{8}Be$^* \to {}^8$BeA^0, $A^0 \to e^+e^-$
$<(0.2$–$1) \times 10^{-3}$	90		[72] BINI	89	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+e^-$
			[73] AVIGNONE	88	CNTR	Cu$^* \to$ CuA^0 ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[74] DATAR	88	CNTR	^{12}C$^* \to {}^{12}$CA^0, $A^0 \to e^+e^-$
$< 5 \times 10^{-3}$	90		[75] DEBOER	88C	CNTR	^{16}O$^* \to {}^{16}$OX^0, $X^0 \to e^+e^-$
$< 3.4 \times 10^{-5}$	95		[76] DOEHNER	88	SPEC	^{2}H*, $A^0 \to e^+e^-$
$< 4 \times 10^{-4}$	95		[77] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[77] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[78] HALLIN	86	SPEC	^{6}Li isovector decay
< 10.8	90		[78] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[78] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[79] SAVAGE	86B	CNTR	^{14}N*
			[80] ANANEV	85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[81] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \to 2\gamma$
			[82] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[83] LEHMANN	82	CNTR	Cu$^* \to$ CuA^0 ($A^0 \to 2\gamma$)
		0	[84] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.
		0	[85] ZEHNDER	81	CNTR	Ba$^* \to$ BaA^0 ($A^0 \to 2\gamma$)
			[86] CALAPRICE	79		Carbon

[68] MINOWA 93 studied chain process, ^{139}Ce $\to {}^{139}$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.

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

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

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

[72] The BINI 89 limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\to {}^{16}$OX^0, $X^0 \to e^+e^-$ 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^-.

[73] AVIGNONE 88 looked for the 1115 keV transition C$^* \to$ CuA^0, either from $A^0 \to 2\gamma$ 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.

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