# THE SLAC BEAM DUMP SEARCH FOR SHORT-LIVED AXIONS*

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We report results of an electron beam dump search for neutral, penetrating particles $X^o$ with masses in the range $1 < m_X < 15$ MeV and lifetimes $\tau_X$ between $10^{-14}$ and $10^{-11}$ sec. The existence of any possible 1.8 MeV pseudoscalar boson with $\tau_X > 8.2 \times 10^{-15}$ sec and an absorption cross-section in matter less than 1 mb per nucleon is ruled out by our data. If such an object had instead a strong interaction cross-section, typically 50 mb per nucleon, this experiment still excludes lifetimes greater than $1 \times 10^{-14}$ sec. Inasmuch as measurements of the electron's anomalous magnetic moment exclude $\tau_X < 2 \times 10^{-14}$ sec for a neutral 1.8 MeV pseudoscalar boson, this experiment proves that the recent GSI phenomenon cannot be due to an elementary axion.

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The recent observation of monochromatic positron peaks and apparent $e^+e^-$ coincidences in heavy ion collisions at the Gesellschaft fur Schwerionenforschung (GSI) [1] has stimulated a round of theoretical speculation [2] that this phenomenon might be induced by an elementary 1.8 MeV axion decaying into $e^+e^-$ pairs. Such an object could not be the "standard" Peccei-Quinn-Weinberg-Wilczek axion [3], which has already been ruled out by J/psi and upsilon decays. However, axion variants coupling preferentially to light fermions [4], and a neutral, elementary pseudoscalar boson coupling only to electrons or photons [5] are not ruled out by these heavy quarkonium decays.

An electron beam dump experiment is one of the cleanest ways to search for such particles. Here one only assumes that they couple predominantly to electrons, with a coupling constant uniquely determined by the assumed mass $m_X$ and lifetime $\tau_X$: $\alpha_X = 2\tau_X^{-1}(m_X^2 - 4m_e^2)^{-1/2}$. For masses between 1 and 15 MeV and lifetimes $\tau_X \sim 10^{-13}$ sec, as suggested by various non-standard axion models and allowed by measurements of the electron's anomalous magnetic moment [6], any such boson should be produced copiously in a process analogous to bremsstrahlung:

$$e + Z \rightarrow e + Z + X^{\circ}$$

The production cross-section for pseudoscalar bosons would be very strongly peaked at forward angles ($\leq 2mr$) and high secondary energies [7]. At sufficiently high electron energies, or in experiments with very short dumps, a detectable fraction of these particles should penetrate the dump and decay to $e^+e^-$.

In this experiment we stopped high-energy electrons in short beam dumps and used a single-arm focussing spectrometer to search for high-energy positrons emerging from the dump at small angles. Electron beams with primary energies $E_o$ of 9.0, 10.7, 18.0 and 22.4 GeV struck copper and tungsten dumps ranging in length from 10 to 100 cm. The results reported here come from a subset of the 9.0 GeV runs in which $\sim 2 \times 10^{15}$ electrons were stopped in 10 and 12 cm tungsten dumps, hereafter called "dump 10" and "dump 12" respectively [8]. These two dumps provided our best sensitivity to penetrating particles with the shortest lifetimes or large absorption cross-sections in matter, while providing sufficient attenuation of the electromagnetic cascades within the dump.

Using the SLAC 8 GeV focussing spectrometer, positioned at 0° w.r.t. the incident beam and located ~35m downstream of the dump, we searched for high-energy positrons produced at small angles with secondary energies $E'$ in the range $4.5 \leq E\prime \leq 8.1$ GeV. This corresponds to an energy fraction $x = E'/E_0$ within the range $0.5 \leq x \leq 0.9$ at $E_o = 9.0$ GeV. Positrons were separated from a background of muons and pions by a hydrogen-filled Cherenkov counter and a segmented lead-glass shower counter. Track information supplied by a set of ten proportional wire chambers allowed event reconstruction to an accuracy of 0.1 mr in horizontal angle, 0.2 mr in vertical angle, and 0.1% in momentum.

The energy spread of the incident electron beam was typically 0.5%, and the beam direction was maintained within 0.2 mr of the central spectrometer angle. The instantaneous beam current was measured by a resonant toroid monitor whose accuracy is better that 5%. A cylindrical 3-inch diameter pipe ~ 5 meters upstream of the spectrometer entrance window limited our angular acceptance to only those positrons produced within 1.1 mr of the beam axis. This pipe was surrounded by lead to reduce the muon singles rate in the spectrometer. Two meters upstream of the spectrometer, a 0.6 r.l. (3.8 g/cm$^2$) lead converter was regularly inserted into the beamline to determine the flux of high-energy photons emerging behind either dump. The equipment was periodically calibrated by inserting an aluminum target in the electron beam and measuring inelastic e - N cross sections at 11.5°; these agreed with previous data to better than 10%.

In Figure 1a are shown the differential number of positrons detected in our (~ 4 $\mu$sr) solid angle $dN_{e^+}/dx$, normalized by the number of electrons $N_0$ incident on

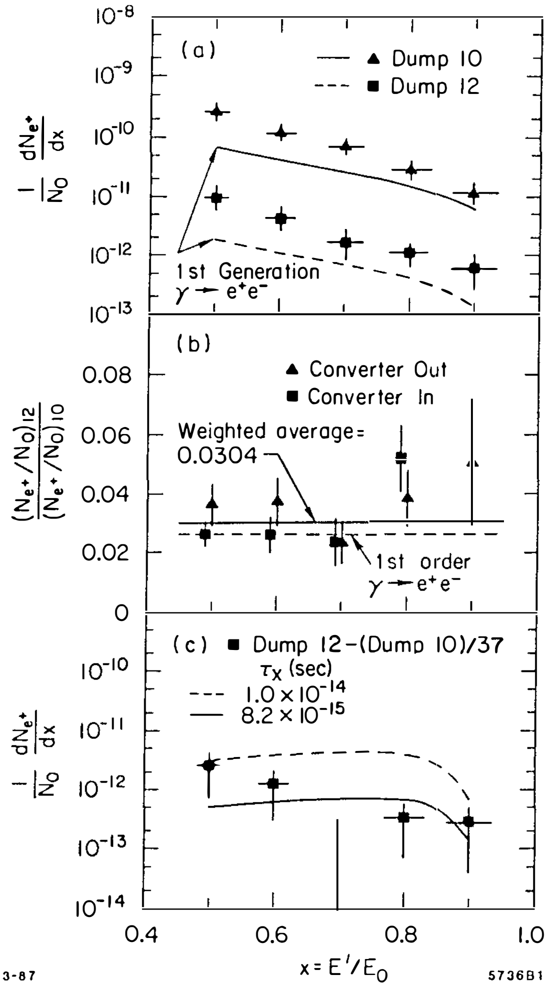


**Figure 1.** a) The differential fraction of positrons observed in our angular acceptance plotted versus x. Error bars represent statistical and 15% systematic errors added linearly. The two curves are the expected $e^+$ backgrounds from first-generation $\gamma$ punchthrough. b) Ratio of $e^+$ yields from the two dumps, normalized by respective fluxes of incident electrons. Errors shown are dominated by counting statistics. c) Net yield of $e^+$ behind dump 12 after subtracting estimated background from $\gamma$ punchthrough, compared with net yields expected for a 1.8 MeV axion with lifetimes listed and $\sigma_{XN} = 1$ mb per nucleon.

the dumps. These data were recorded with the photon converter *out* of the beamline. Errors due to counting statistics and systematic uncertainties have been added linearly. The $\sim$ 15% systematic errors (as presently estimated) are dominated by uncertainties in the angular acceptance and momentum acceptance, each about 10%.

For comparison, we also show the estimated $e^+$ spectra due to first-generation photon punchthrough [9]. In this process a hard bremsstrahlung photon created in the first few radiation lengths penetrates the dump and converts in the last radiation length, yielding a high-energy positron. Higher generation photons would make additional contributions to this $e^+$ background, especially at lower values of $x$ where they become dominant. For all such punchthrough photons, however, the $e^+$ yield measured behind dump 12 should be attenuated by a factor of 37, relative to that measured behind dump 10, because of photon absorption in the additional $\Delta t$ = 4.8 r.l. By contrast, the $e^+$ yields from a 1.8 MeV axion would be expected to drop by factors of only 1 to 5 for $10^{-14} < \tau_X < 10^{-12}$ sec. Figure 1b indicates that the measured $e^+$ yield actually dropped by a uniform factor of 33 $\pm$ 3, for both converter-in and converter-out configurations, consistent with the interpretation of these yields as due solely to photon punchthrough and pair conversion processes.

In Figure 1c we have subtracted 1/37 times the $e^+$ yield behind dump 10 from that measured behind dump 12. This procedure subtracts the punchthrough background plus a small fraction ($\leq$ 15%) of any possible axion signal. The residual yield is then compared with the predicted net yields from $X^0 \rightarrow e^+e^-$ decays as a function of $m_X$ and $\tau_X$.

Figure 1c also shows curves for the acceptance-corrected $e^+$ yields from the decay of a 1.8 MeV axion with $\tau_X = 1.0 \times 10^{-14}$ sec and $\tau_X = 8.2 \times 10^{-15}$ sec, assuming an absorption cross-section for these axions in matter $\sigma_{XN} \leq 1$ mb per nucleon. We compare these predictions with experiment for $x \geq 0.7$, where the expected signal/background ratio is largest. A lifetime of $\tau_X = 1.0 \times 10^{-14}$ sec is clearly ruled out in this range of

$x$, and for $\tau_X = 8.2 \times 10^{-15}$ sec, we get $\chi^2 = 5.1$ for two degrees of freedom. Thus a 1.8 MeV axion decaying into $e^+e^-$ with a lifetime of $\tau_X = 8.2 \times 10^{-15}$ sec is excluded at better than 90% confidence by these data, assuming $\sigma_{XN} \leq 1$ mb. If we instead assume $\sigma_{XN} = 50$ mb per nucleon (and an A-dependence of $A^{0.7}$) we can exclude $\tau_X = 1.0 \times 10^{-14}$ sec at better than 90% confidence. Proceeding similarly for other assumed axion masses, we have established the limits on $\tau_X$ shown in Figure 2 assuming both $\sigma_{XN} = 1$ mb and 50 mb per nucleon. The dashed curve is close to the limits we reported at Berkeley [10], using an analysis that did not require the subtraction of backgrounds reported here. Both limits are substantially better than the lifetime limits reported in two recent electron beam dump searches [11]. Fermilab Experiment 605 set limits similar to our own but less restrictive [12]; that experiment is unable to exclude any axion with $\sigma_{XN} > 1$ mb.

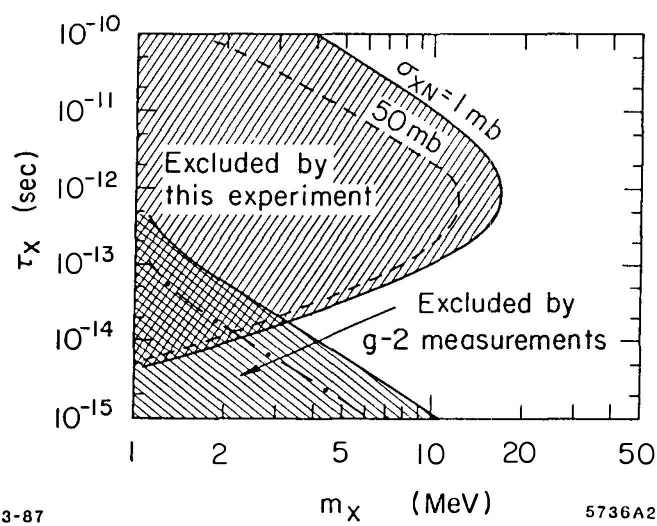


**Figure 2.** Regions of $m_X$ and $\tau_X$, for a light pseudoscalar boson $X^\circ$ decaying predominantly to $e^+e^-$, that are excluded (at 90% confidence) by this experiment, assuming an absorption cross section of $\sigma_{XN} = 1$ mb and 50 mb per nucleon. Also shown are the regions excluded by electron $g$-2 measurements using two assumptions for the discrepancy in $a = \frac{1}{2}(g-2)$ : $\Delta a = 2 \times 10^{-10}$ (solid curve) and $\Delta a = 7.5 \times 10^{-10}$ (dash-dot curve).

Beam dump experiments establish upper limits on $\tau_X$, while lower limits come from the agreement between theory and measurements of the anomalous magnetic moment of the electron [14]; taken together, they exclude entire ranges of axion mass $m_X$. Shown in Figure 2 are lower limits on $\tau_X$ using the most recent results of Kinoshita [13], which restricts $\tau_X > 6 \times 10^{-14}$ sec at $m_X = 1.8$ MeV. Using these limits in conjunction with our own, we exclude any possible pseudoscalar boson with $m_X < 3.2$ MeV (90% c.l.). If we instead use the recent analysis of M. Samuel [15], we can exclude $m_X$ <2.2 MeV at 90% confidence. Either way, however, we conclude that the 1.8 MeV GSI phenomenon is *not* due to an elementary axion, or any other pseudoscalar boson, decaying to $e^+e^-$ even if it is strongly absorbed in matter.

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8. The shorter dump was fabricated from a 10.16 cm thick (27.4 r.l.) block of Kennertium W-2, an alloy composed of 97.4% tungsten plus 2.6% nickel, copper and iron. To the back of a portion of this block was added another 2.00 cm block of Kennertium W-10, a different alloy composed of 90% tungsten plus 10% nickel, copper and iron. The 12.16 cm combination contained 32.4 r.l. Both estimates of the dump thickness in radiation lengths are based on the calculations of Tsai, which agree with other calculations to better that 1% [8]. See Y. S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); O. I. Dovzhenko and A. A. Pomanski, Soviet Physics JETP **18**, 187 (1963).

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13. The contribution of an elementary pseudoscalar X° to the electron anomalous magnetic moment is

$$\Delta a = -\frac{\alpha_X}{2\pi}\int_0^1 dz \frac{z^3}{z^2 + (1-z)\frac{m_X^2}{m_e^2}}$$

where $\alpha_X$ is the electron-pseudoscalar coupling strength. Using $|\Delta a| < 2 \times 10^{-10}$ we obtain the (90% confidence) upper limits on $\tau_X$ shown in Figure 2. See T. Kinoshita, Proceedings of the 1986 Conference on Precision Electromagnetic Measurements for a recent review of the status of theory and experiment on the electron $g$-2 measurements.

14. A possible loophole in this argument occurs, however, if there exists a neutral scalar boson with mass and coupling strength similar to the hypothetical pseudoscalar. In such a case their contributions to the electron magnetic moment would *cancel*, invalidating the limits placed by $g$-2 measurements on $\tau_X$. See J. Reinhardt *et al.*, (Ref. 6) for further discussion of this possibility.

15. M. Samuel, Phys. Rev. Lett. **57**, 3133 (1986). In this case, we have used $\Delta a = 7.5 \times 10^{-10}$ consistent with his results; these are however still controversial.