Search for Short-Lived Axions in an Electron-Beam-Dump Experiment

E. M. Riordan, M. W. Krasny, K. Lang, P. de Barbaro, A. Bodek, S. Dasu, N. Varelas, and X. Wang
University of Rochester, Rochester, New York 14627

R. Arnold, D. Benton, P. Bosted, L. Clogher, A. Lung, S. Rock, and Z. Szalata
The American University, Washington, D.C. 20016

B. W. Filippone and R. C. Walker
California Institute of Technology, Pasadena, California 91125

J. D. Bjorken, M. Crisler, and A. Para
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

J. Lambert
Georgetown University, Washington, D.C. 20007

J. Button-Shafer, B. Debebe, M. Frodyma, R. S. Hicks, and G. A. Peterson
University of Massachusetts, Amherst, Massachusetts 01003

and

R. Gearhart
Stanford Linear Accelerator Center, Stanford, California 94305
(Received 4 May 1987)

We report results of an electron-beam-dump search for neutral particles with masses in the range 1 to 15 MeV and lifetimes τ between 10^{-14} and 10^{-10} s. No evidence was found for such an object. We rule out the existence of any 1.8-MeV pseudoscalar boson with $\tau > 8.2\times10^{-15}$ s and an absorption cross section in matter less than 1 mb per nucleon, and exclude $\tau > 1\times10^{-14}$ s were its cross section to equal 50 mb per nucleon. In conjunction with measurements of the electron's anomalous magnetic moment, this experiment shows that the narrow positron peaks observed in heavy-ion collisions at the Gessellschaft für Schwerionenforschung are not due to an elementary pseudoscalar.

PACS numbers: 14.80.Gt, 13.60.Hb

The recent observation of monoenergetic positron peaks and apparent e^+e^- coincidences in heavy-ion collisions[1] at the Gesellschaft für Schwerionforschung (GSI) has stimulated theoretical speculation[2] that these phenomena 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/ψ and Υ 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; lifetimes $\tau > 10^{-14}$ s are permitted by comparison of theory and measurements of the electron's anomalous magnetic moment.[6]

An electron-beam-dump experiment is one of the cleanest ways to search for such neutral particles X^0. If one assumes that they couple predominantly to electrons, then the coupling constant α_X is uniquely determined[6] by the assumed mass m_X and lifetime τ: $\alpha_X = 2\tau^{-1}(m_X^2 - 4m_e^2)^{-1/2}$. Such a boson should be produced in a process analogous to bremsstrahlung:

$$e+Z \rightarrow e+Z+X^0.$$

The production cross section for pseudoscalar bosons would be very strongly peaked at forward angles and high secondary energies.[7] At sufficiently high electron energies, or in experiments with short dumps, a detectable fraction of these particles should exit the dump before decaying to e^+e^-.

In this experiment, high-energy electrons were stopped in several short beam dumps and a single-arm focusing spectrometer was used to detect high-energy positrons emerging at small angles. Electron beams with primary energies E_0 of 9.0, 10.7, 18.0, and 22.4 GeV struck copper and tungsten dumps ranging in length from 10 to 100 cm, providing sensitivity to masses between 1 and 15 MeV, and lifetimes between 10^{-14} and 10^{-10} s. A total of $\simeq 5\times10^{15}$ electrons were used in the entire experiment. The results reported here come from a subset of the $E_0 = 9.0$ GeV data in which $\simeq 2\times10^{15}$ electrons were stopped in 10- and 12-cm tungsten dumps, hereafter called "dump 10" and "dump 12," respectively.[8] These two dumps gave the best sensitivity to particles with the shortest lifetimes or large absorption cross sections in matter, while providing sufficient rejection of e^+ backgrounds from electromagnetic cascades.

Particles emerging from the back of the dumps continued drifting through a 32-m evacuated beam pipe surrounded for 15 m of its length with lead and concrete shielding. In the last five meters of this pipe was a cylindrical 7.5-cm-diam pipe that defined our angular acceptance to include only those positrons produced within 1.1 mrad of the nominal beam axis. This pipe was surrounded by lead to reduce the muon singles rate in the spectrometer. Because positrons from the decay of a light X^0 would be produced within 2 mrad of the beam axis, a substantial fraction of the anticipated signal should have fallen within this 4-μsr solid angle. Muons, pions, and kaons—as well as their decay products—were produced at much larger characteristic angles (10–20 mrad) and were mostly absorbed in the lead and concrete shielding.

Using the SLAC 8-GeV spectrometer, positioned at 0° relative to the incident beam and located 35 m downstream of the dump, we searched for high-energy positrons with secondary energies E' in the range $4.5 \le E' \le 8.1$ GeV, corresponding to an energy fraction $x = E'/E_0$ in the range $0.5 \le x \le 0.9$ at $E_0 = 9.0$ GeV. Positrons were cleanly separated from the residual 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 mrad in horizontal angle, ± 0.2 mrad in vertical angle, and $\pm 0.1\%$ in momentum.

The incident-beam direction was maintained to within 0.2 mrad of the nominal-beam axis by the use of collimators and by periodic insertion of ZnS screens. The integrated beam current was measured by a resonant toroid monitor with an accuracy of 5%. Two meters upstream of the spectrometer, a 0.6-radiation-length (3.8 g/cm^2) lead converter was regularly inserted into the beamline to determine the flux of high-energy photons emerging from the dumps; the data from these runs will be reported more extensively in a future communication. The equipment was periodically calibrated by removing the dumps, inserting an aluminum target in the electron beam at the spectrometer pivot, and measuring inelastic e-N cross sections at 11.5°.

In Fig. 1(a) we show the number of positrons detected in our (4 μsr) solid angle dN_{e^+}/dx, normalized to the number of electrons N_0 incident on dumps 10 and 12. These data were recorded with the photon converter *out* of the beamline. Errors due to counting statistics and systematic uncertainties have been added linearly; systematic errors are dominated by $\simeq 10\%$ uncertainties in the angular acceptance. The e^+ yield expected[7] behind dump 12 (corrected for our 16%–36% acceptance) from a 1.8-MeV axion with $\tau = 10^{-14}$ s is shown for comparison; for $x \gtrsim 0.7$ this yield is substantially higher than the measured data. Such an axion is easily ruled out by this experiment.

Figure 1(a) also shows the estimated e^+ yield behind dump 12 due to first-generation photon punchthrough.[9]

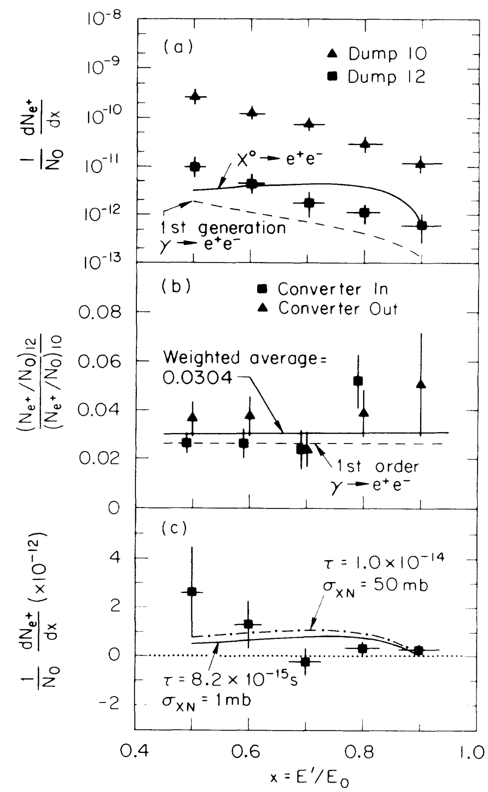

FIG. 1. (a) Number of positrons observed in our angular acceptance divided by the flux of electrons on dump, plotted vs x. Error bars represent statistical and systematic errors added linearly. The solid curve is the e^+ yield expected for dump 12 from a 1.8-MeV axion with $\tau = 1 \times 10^{-14}$ s; the dashed curve represents the corresponding e^+ background from first-generation γ punchthrough. (b) Measured ratio of e^+ yields from the two dumps, normalized by respective fluxes of incident electrons; errors shown are dominated by counting statistics. The dashed curve represents the ratio expected from γ punchthrough and pair conversion. (c) Residual e^+ yield behind dump 12 after subtraction of 1/27 of the dump-10 yield, compared with net yields expected for a 1.8-MeV axion with lifetimes and absorption cross sections listed.

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 substantial additional contributions to this e^+ background,[9] and may account for the observed difference between our data and the first-generation estimates. For *all* such punchthrough processes, including higher-generation photons, the e^+ yield measured behind dump 12 should be attenuated by a factor of 37^{+2}_{-3} relative to that measured behind dump 10, because of additional photon absorption in the extra $\Delta t = 4.8$ radiation lengths. By contrast, the e^+ yields from a 1.8-MeV axion would be expected to decrease by factors of at most 5 for $10^{-14} < \tau < 10^{-10}$ s. The measured e^+ yield actually dropped by a factor of 33 ± 3, as shown in Fig. 1(b), where we have included ratios measured in both converter-out and converter-in configurations to improve the statistical accuracy of this average. The measured average ratio is therefore consistent with the value predicted by interpreting these yields as due solely to photon punchthrough and pair conversion processes.

To remove this background, and improve our lifetime limits slightly, we divided the dump-10 yield by 37 and subtracted the result from the dump-12 yield, obtaining the data presented in Fig. 1(c). This procedure subtracted the punchthrough background plus a small fraction ($\leq 15\%$) of any possible axion signal. The residual e^+ yield was then compared with the predicted net yields from $X^0 \to e^+e^-$ decays as a function of m_X and τ. In obtaining this anticipated net signal, we also divided the predicted dump-10 yield by 37 and subtracted the result from the predicted dump-12 yield. Our results are therefore insensitive to any *a priori* assumptions made about the background contribution.

The solid curve in Fig. 1(c) is the acceptance-corrected e^+ yield expected from the decay of a 1.8-MeV axion with $\tau = 8.2 \times 10^{-15}$ s and absorption cross section $\sigma_{XN} \leftarrow 1$ mb per nucleon. Comparing this prediction with experiment for $x \geq 0.7$, where the expected signal/background ratio is largest, 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 $\tau = 8.2 \times 10^{-15}$ s is excluded with 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 $A^{0.7}$) for $\tau = 1.0 \times 10^{-14}$ s, we get the second curve in Fig. 1(c), which is excluded with better than 90% confidence. Thus, the lifetime limits reported here are relatively insensitive to the assumed absorption cross sections.

Proceeding similarly for other assumed axion masses, we have established the 90% confidence limits on τ shown in Fig. 2 assuming both $\sigma_{XN} = 1$ and 50 mb per nucleon. The dashed curve is close to the limits we obtained earlier (assuming $\sigma_{XN} = 1$ mb) using an analysis[10] that did not require the subtraction of any backgrounds. Both limits are substantially better than the lifetime limits reported in two recent electron-beam-dump searches.[11] We also improve upon the limits established by a recent proton-beam-dump experiment,[12] which was unable to exclude axions with $\sigma_{XN} > 1$ mb.

The above analysis assumes that axion coupling to e^+e^- is much stronger than its coupling to $\gamma\gamma$ for $m_X > 1$ MeV, consistent with most reasonable axion models; in this case bremsstrahlung production of X^0 dominates.[7] One could conceivably formulate axion models for which these couplings are about equal, but in this case Primakoff production of X^0 would dominate, leading to substantial increases in the e^+ yield when the photon converter was inserted before the spectrometer. Such increased yields are not observed.

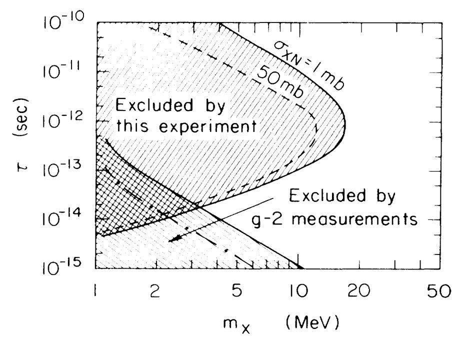

FIG. 2. Regions of m_X and τ, for a light pseudoscalar boson X^0 decaying predominantly to e^+e^-, that are excluded by this experiment, assuming an absorption cross section of $\sigma_{XN} = 1$ and 50 mb per nucleon. Also shown are regions excluded by electron $g-2$ measurements by use of two assumptions (see Refs. 14 and 15) for the possible discrepancy between theory and experiment.

Beam-dump experiments establish upper limits on τ, while lower limits can be obtained from the agreement between theory and measurements of the anomalous magnetic moment of the electron[13]; taken together, they exclude entire ranges of axion mass m_X. Shown in Fig. 2 are lower limits on τ using the most recent results of Kinoshita,[14] which excluded $\tau < 6 \times 10^{-14}$ s at $m_X = 1.8$ MeV (solid curve). Using these limits in conjunction with our own, we rule out any possible pseudoscalar boson with $m_X < 3.2$ MeV (90% confidence); if we instead use the recent analysis of Samuel[15] (dash-dotted curve in Fig. 2), we can rule out $m_X < 2.2$ MeV. With either analysis, we conclude that the GSI phenomena are *not* due to an elementary axion, or any other elementary pseudoscalar decaying to e^+e^-, even if it were strongly absorbed in matter. These phenomena might still be due to an extended object, which could be produced with a reduced cross section or absorbed in the dump, and therefore not be seen in this experiment.

We thank G. Davis, R. Eisele, C. Hudspeth, L. Keller, and D. Walz for their aid in the setup and running of this experiment. The support of B. Richter and the SLAC staff were crucial to its success. We also acknowledge valuable discussions with S. Brodsky, M. Karliner, L. Krauss, B. Lu, and Y. S. Tsai. This research was supported by Department of Energy Contracts No. ER13065-453, No. DE-AC02-76ER02853, and No. DE-AC03-76SF00515; and National Science Foundation Contracts No. PHY84-10549 and No. PHY85-05682.

[1]J. Schweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983); M. Clemente *et al.*, Phys. Lett. **B137**, 41 (1984); T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985); T. Cowan *et al.*, Phys. Rev. Lett. **56**, 444 (1986).

[2]A. Schäfer *et al.*, J. Phys. G **11**, L69 (1985); A. B. Balantekin *et al.*, Phys. Rev. Lett. **55**, 461 (1985); M. C. Mukhopadhyay and Z. Zehnder, Phys. Rev. Lett. **56**, 206 (1986).

[3]R. D. Peccei and Helen R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[4]L. M. Krauss and F. Wilczek, Phys. Lett. B **173**, 189 (1986); R. D. Peccei, T. T. Wu, and T. Yanagida, Phys. Lett. B **172**, 435 (1986).

[5]Such "generic" axions have been suggested by J. D. Bjorken, SLAC Report No. SLAC-312, 1987 (to be published).

[6]J. Reinhardt *et al.*, Phys. Rev. C **33**, 194 (1986); A. Zee, Phys. Lett. B **172**, 377 (1986); L. Krauss and M. Zeller, Phys. Rev. D **34**, 3385 (1986).

[7]Y. S. Tsai, Phys. Rev. D **34**, 1326 (1986).

[8]The shorter dump was a 10.16-cm-thick [27.5 radiation lengths] 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 32.2 radiation lengths. Both estimates of the dump thickness in radiation lengths are based on the calculations of Tsai, which agree with other calculations to better than 1%. See Y. S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); O. I. Dovzhenko and A. A. Pomanski, Zh. Eksp. Teor. Fiz. **45**, 268 (1963) [Sov. Phys. JETP **18**, 187 (1963)].

[9]Y. S. Tsai and Van Whitis, Phys. Rev. **149**, 1248 (1966); Y. S. Tsai, private communication.

[10]E. M. Riordan *et al.*, in *Proceedings of the Twenty-Third International Conference on High-Energy Physics, Berkeley, California, 1986*, edited by S. Loken (World Scientific, Singapore, 1987), p. 635.

[11]A. Konaka *et al.*, Phys. Rev. Lett. **57**, 659 (1986); M. Davier *et al.*, Phys. Lett. B **180**, 295 (1986).

[12]C. Brown *et al.*, Phys. Rev. Lett. **57**, 2101 (1986).

[13]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 on τ by $g-2$ measurements. See Reinhardt *et al.* (Ref. 6) for further discussion.

[14]The contribution of an elementary pseudoscalar X^0 to the electron anomalous magnetic moment is

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

where $a=\frac{1}{2}(g-2)$ and α_X is the electron-pseudoscalar coupling strength. Using $|\Delta a| < 2\times 10^{-10}$ we obtain the (90% confidence) upper limits on τ shown in Fig. 2. See T. Kinoshita, in *Proceedings of the 1986 Conference on Precision Electromagnetic Measurements, Gaithersburg, Maryland, 1986*, edited by R. F. Dziuba (IEEE, New York, 1986), for a recent review of the status of theory and experiment on the electron $g-2$ measurements.

[15]M. Samuel, Phys. Rev. Lett. **57**, 3133 (1986). Here we have used $\Delta a = 7.5\times 10^{-10}$ consistent with his results; these conclusions are, however, controversial (T. Kinoshita, private communication).