Search for Neutral Particles in Electron-Beam-Dump Experiment

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An experiment to search for the production of neutral penetrating particles decaying into electron-positron pairs was performed with a 2.5-GeV electron beam. A total of 0.027 C was injected into a tungsten target. No such particle is found. Constraints on coupling constants α_e and α_γ are given.

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The recent observations[1] of narrow peaks in positron and electron spectra in heavy-ion collisions have attracted much attention in high-energy physics. One of the most interesting interpretations of these results is production of a new neutral boson with mass around 1.8 MeV decaying into an electron-positron pair. There are extensive investigations[2-5] as to whether the particle can be interpreted as the axion, a light neutral pseudoscalar particle introduced to suppress P and CP nonconservation in gauge theories of the strong interactions.[6,7] The conclusion of these theoretical studies is that there are many difficulties in identifying this "particle" with the standard axion originally proposed.[7] In particular, it is pointed out[3] that the parameter $X = \tan\lambda$, the ratio of the vacuum expectation values for the two Higgs doublets in the standard axion model, is estimated to be either ~ 24 or $\sim \frac{1}{24}$ for the axion mass of 1.8 MeV, which is suggested by the heavy-ion experiments. A large value of X, implying a long axion lifetime, is ruled out by many experiments in the past. A small value of X, on the other hand, leads to a short lifetime. In this case, the measurement of the axion production in the radiative Υ decay is the only experiment to date that can exclude the existence of such an axion. The expected branching ratio of the radiative decay of $\Upsilon(1S)$ into an axion relative to the decay into $\mu^+\mu^-$ is inconsistent with the experimental observation.[8] To avoid this difficulty, several variants of the standard model have been proposed.[4,5] In these new theoretical models, axions are postulated to couple preferentially to electrons and light quarks, and to have a short lifetime to accommodate the negative results of earlier search experiments. It is, therefore, highly desirable to search for such new particles with a high-energy electron beam because it relies only upon the coupling to the electron-positron and/or photon-photon pairs.

This Letter reports the results of an experimental search for neutral penetrating particles (referred to as "axions" for simplicity) with a 2.5-GeV electron linear accelerator at National Laboratory for High Energy Physics (KEK) in Japan. Figure 1 shows the experimental layout. The machine was operated with an average peak current of 13 mA and ~ 1 μsec spill at the repetition rate of 10 pulses per second. A total of 0.027 C was injected into a 3.5-cm-thick tungsten target. The dump was formed with a combination of iron, lead, and plastic blocks. It attenuated the intensity of neutrons, the major background particles, to a tolerable level. In order to veto charged particles, the dump was followed by two identical scintillation counters, each of which was 25 cm wide and 8 cm high. It turned out that these two counters were the weakest against the background, and thus the electron beam intensity was so adjusted that their counting rates were about one per a single machine spill. Axions were supposed to decay in a 220-cm-long decay volume filled with helium gas. The distance between the target and the entrance of the decay volume was about 240 cm. The detector system for e^+e^- pairs consists of multiwire proportional chambers

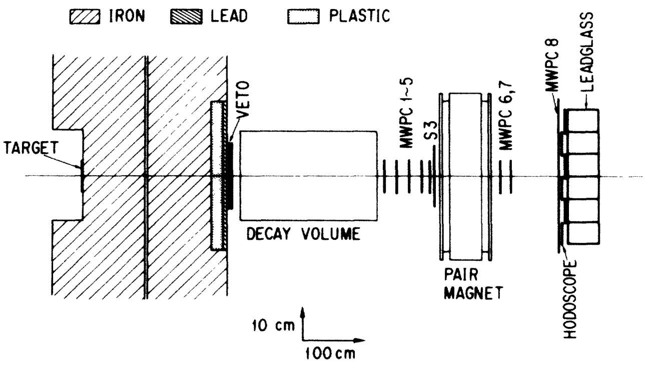

FIG. 1. Schematic of the experimental apparatus.

(MWPC's), scintillation counters, a pair magnet, and a lead-glass Cherenkov counter. The sensitive regions of the chambers are 64 mm in height and 112 mm in width for MWPC 1 through 7, and 256 mm in height and 512 mm in width for MWPC 8. The anode wire spacings are 1 mm for MWPC 1 through 7, and 2 mm for MWPC 8. There is a scintillation counter (S3) in front of the pair magnet, and a scintillation hodoscope (H1–H6) in front of the lead-glass counter. The magnetic field provided a horizontal momentum kick of 13.5 MeV for ~70% of the total running time and 40.5 MeV for the rest of the time. The last element in the detector system is the lead-glass Cherenkov counter. It is composed of eighteen identical modules, 7.5×7.5 cm^2 in cross section and 26 cm in depth (13.9 radiation-lengths thick), and is placed in the form of a 3×6 matrix. All the detector elements are aligned with their centers on the beam line.

Output pulses from eighteen lead-glass modules were added together to generate a trigger signal. The hardware threshold was set to about 100 MeV. Digitized information on pulse heights from individual lead-glass modules, pulse heights and timing information from all scintillation counters, and hit positions of MWPC's were fed into a computer and recorded onto magnetic tapes for further off-line analysis. All electronics were gated on during a 1.5-μsec-long beam gate pulse. They were also gated on for a 15-msec-long period between beam gate pulses in order to study the cosmic-ray background. According to these gates, the events were classified into two categories: beam events and cosmic-ray events. The trigger rate of the beam events was about one per 1000 machine spills. It was found that the contribution to the beam events from the cosmic-ray background was completely negligible. The performances of the detector elements were periodically tested by a β source, cosmic-ray events, and beam events.

Axions are supposed to penetrate the dump and to decay into e^+e^- pairs in the decay volume. In the off-line analysis, therefore, axion candidates were required to have the following properties: (i) no signal in the veto counters, (ii) a hit in S3, (iii) two charged tracks in MWPC 's 6 through 8, (iv) a hit or hits in the hodoscope, and (v) energy deposits in the lead-glass counter, matching the momentum measured by the MWPC system. In addition, the reconstructed momentum vector of such neutral particles should point back to the target. In actual analysis, however, no candidate event is left when the requirements (i) through (iv) are imposed.

Now it is necessary to assume production mechanisms for axions to interpret this result. To this end, two processes are considered: the Primakoff process by virtual and/or real photons and the bremsstrahlung from electrons. It is assumed that the effective couplings of axions to photons and electrons are given, respectively, by

$$(g_\gamma/m_e)F_{\mu\nu}\tilde{F}^{\mu\nu}\phi,$$

and

$$g_e\bar{e}\gamma_5 e\phi.$$

Here m_e is the electron mass, and g_e and g_γ denote the dimensionless coupling constants. In the following, the two production processes are considered separately to simplify the analysis.

For the Primakoff process, it is assumed that the axion mass is 1.8 MeV, and that the coupling constants g_e and g_γ are independent of each other. In order to estimate expected event rates, Monte Carlo simulation studies were performed. These included energy degradation of electron beam in the target,[9] detection efficiency, and the angular and energy dependence of the axion production cross section.[10] It turned out that the contribution from the real photon is bigger than that from the virtual photon for the tungsten target of our thickness. In Fig. 2, the region excluded at the 90% confidence level (C.L.) in the two-dimensional parameter space of $\alpha_e = g_e^2/4\pi$ and $\alpha_\gamma = g_\gamma^2/4\pi$ is shown by the hatched area. The dash-dotted lines in the figure show the axion lifetime, and the dashed line indicates

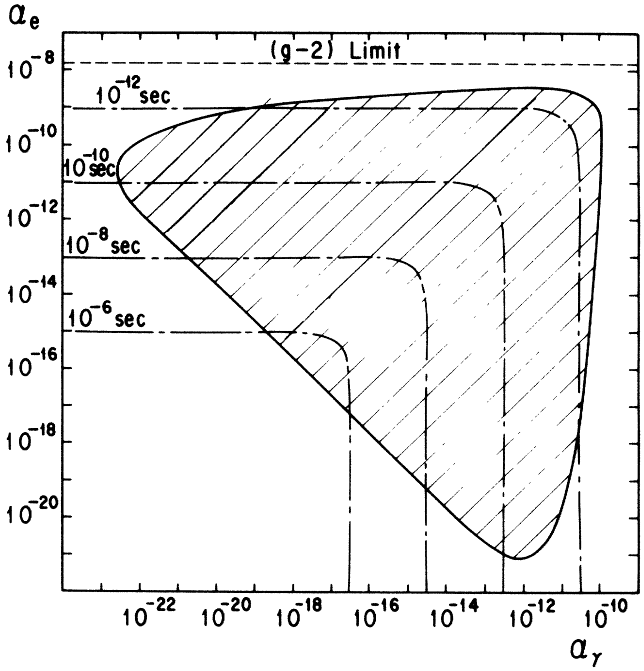

FIG. 2. Constraints on α_e and α_γ. The hatched region is excluded (90% C.L.) by the present experiment if we assume the Primakoff process for the production process. The dashed line shows the upper bound allowed by the measurement of the electron anomalous magnetic moment. The dash-dotted lines indicate the axion lifetime. The axion mass is assumed to be 1.8 MeV.

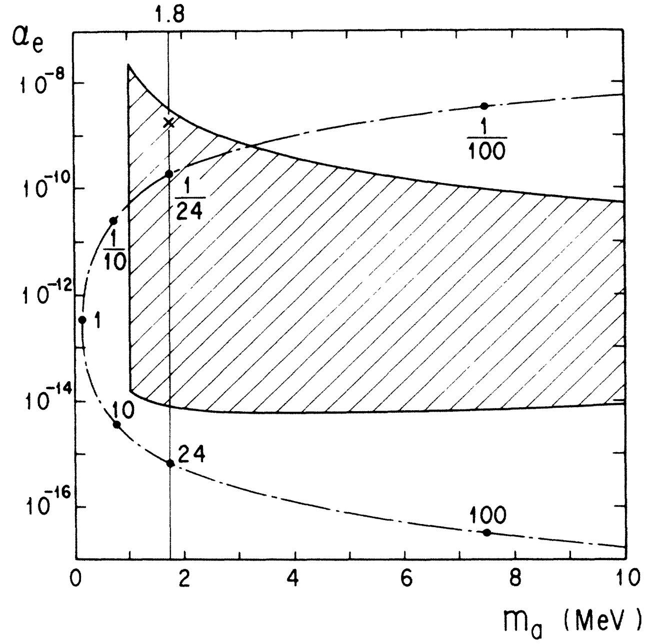

FIG. 3. Constraints on α_e as a function of the axion mass m_a. The hatched region is excluded (90% C.L.) by the present experiment if we assume axion bremsstrahlung. The dash-dotted line indicates the prediction of the standard axion model. The values of the parameter X are also shown by numbers at several points. The point indicated by a cross is the prediction by Ref. 4.

the upper limit allowed by the measurement of the electron anomalous magnetic moment.[4] The sensitivity of the experiment is determined by the following facts. If one or both of the coupling constants are very large, then axions have a lifetime too short to penetrate through the dump. The present experiment is sensitive up to several times 10^{-13} sec, which is essentially determined by the dump length and the electron beam energy. For the region with small coupling constants, on the other hand, the sensitivity is limited by the production cross section of the Primakoff process ($\propto \alpha_\gamma$) and the rate of subsequent decay into e^+e^- pairs ($\propto \alpha_e$). Therefore, the limit is roughly given by the product of α_γ and α_e.[11]

In many theoretical models including the standard axion model, the coupling constant g_γ is expected to be very small. Thus it is appropriate to consider the bremsstrahlung of axions from electrons. If we assume $g_\gamma = 0$ in this case, not only the production cross section but also the lifetime of the axion are determined by the coupling constant g_e alone. Again similar Monte Carlo simulations were performed to evaluate the expected event rates using the axion bremsstrahlung cross section.[12] The excluded region (90% C.L.) is shown in Fig. 3 by the hatched area as a function of the axion mass m_a. The dash-dotted line in the figure indicates the prediction by the standard axion model with three generations as a function of the parameter X. The interval $0.022 < X < 0.074$, overlapping with the hatched area, is excluded. In particular, the value $X \sim \frac{1}{24}$ is ruled out by the present experiment besides the Υ-decay experiments. This fact reinforces the statement that the 1.8-MeV "particle" suggested by the heavy-ion experiments cannot be interpreted as the standard axion. The point indicated by a cross in Fig. 3 is the predicted value for a 1.8-MeV axion in the model by Krauss and Wilczek.[4] The models by Peccei *et al.* also predict similar values for α_e.[5] In conclusion, it is unlikely that the 1.8-MeV "particle" is one of the variants of the axion models postulated by Ref. 4 and Ref. 5.

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[11] The sensitive region may further be expanded especially for small-coupling regions by consideration of the bremsstrahlung process at the same time and/or by measurement of the two-photon decay mode. Such a detailed analysis will be described in the next paper including our measurement for the two-photon mode.

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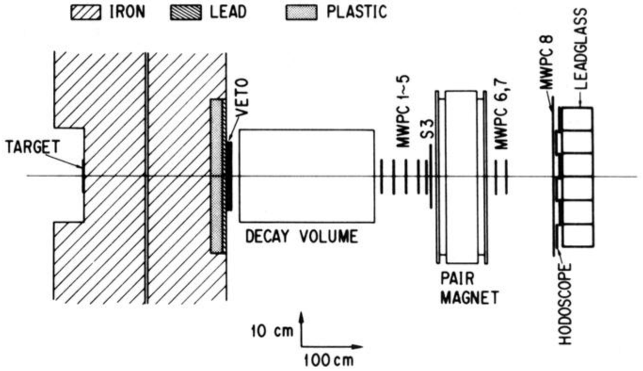

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