New limits on light scalar and pseudoscalar particles produced in nuclear decay

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We present the results of a search for scalar and pseudoscalar particles produced in nuclear deexcitation. Measurements of the angular correlation of e^+e^- pairs emitted from excited states of ^{14}N, ^{16}O, and ^8Be provided sensitivity to particles with lifetimes $10^{-19} < \tau < 10^{-11}$ s within the mass range $2m_e < M_X < 5$ MeV. We find no evidence for such particles and set upper limits on the branching ratio to electromagnetic decay.

I. INTRODUCTION

Recently, searches for light, short-lived elementary particles X have been motivated by the observation of narrow-peak structures in the positron spectra from certain heavy-ion experiments.[1-3] Additional data from e^+ and e^- coincidences,[4] observed in these experiments, are consistent with the production and subsequent decay of a previously unobserved neutral particle of mass ~ 1.8 MeV. The surprising fact[5-8] that the existence of such a particle was not ruled out by previous experiments has stimulated considerable experimental and theoretical work.

Recent experimental searches for new light particles have included beam-dump,[9-12] nuclear-deexcitation,[13-16] pion-decay,[17] and e^+e^--scattering[18-20] experiments. However, most of the experiments are sensitive only to a narrow range of particle lifetimes (2–3 orders of magnitude) and masses. The most stringent limits on the existence of new particles come from the beam-dump results[9-11] when combined with constraints from the agreement of $(g-2)$ for the electron with QED predictions.[21] The $(g-2)$ constraint can be removed if both a scalar and a pseudoscalar particle exist with similar masses and lifetimes. It should also be noted that the beam-dump limits require that the interaction cross section of the particle with the nuclei in the dump be sufficiently small that the particles do not interact before reaching the detector. Thus it is important to constrain the X-nucleon coupling.

Nuclear transitions provide a useful laboratory to search for light particles which couple to quarks and/or gluons. The spin and parity of a particle emitted in nuclear decay can be constrained by an appropriate choice of the nuclear transition: for example, the emission of a pseudoscalar particle is constrained to obey the same selection rules as a magnetic γ-ray transition.[22] Thus 0^- X decay is expected to compete with the γ decay of excited nuclear states if the transition is predominantly magnetic. For a scalar particle, $0^+ \to 0^+$ transitions provide the best sensitivity.

In order to detect the e^+e^- pairs emitted from a particle produced in nuclear decay, they must be distinguished from the ordinary internal pairs produced in the electromagnetic decay of the nuclear state (a virtual photon converts internally to e^+e^-). It has been suggested previously[23] that pairs produced from the decay of a light particle can be distinguished from internal pairs by their angular correlation. For a transition energy significantly larger than M_X, the angular correlation between the electron and positron produced in the X decay is sharply peaked in the laboratory frame at a nonzero angle that varies inversely with the transition energy. In contrast, internal pair conversion (IPC) is known[24,25] to be peaked at 0°. Thus by measuring the angular correlation between the e^+e^- pairs, the relative branch of X particles to internal pairs (Γ_X/Γ_π) can be determined. This method has been used previously by several groups to set upper limits on the branching ratio to such particles[13-16,26] within certain limited mass and lifetime regions.

We can parametrize the interaction of a 0^- particle X with the nucleons in a nucleus by an effective Lagrangian following Donnelly *et al.*:[22]

$$\mathcal{L}_{\rm int} = \bar{\psi}\gamma_5 (g^{(0)} + \tau_3 g^{(1)})\psi X \ , \qquad (1)$$

where X and ψ are the particle and nucleon fields, respectively, and τ_3 is the Pauli matrix. $g^{(0)}, g^{(1)}$ are the isoscalar and isovector coupling constants analogous to the electromagnetic couplings μ_0, μ_1 and contain all the information about interactions between X or its constituents and the constituents of the nucleon. As in the electromagnetic case, it is necessary to make two independent measurements to extract the separate couplings $g^{(0)}$ and $g^{(1)}$.

In this work, we report on a search for scalar and pseudoscalar particles with masses in the range $2m_e < M_X < 5$ MeV and lifetimes in the range $10^{-19} < \tau_X < 10^{-11}$ s emitted from excited states of nuclei. We measure the angular correlation between e^+e^- pairs emitted in the ground-state decay of excited states in ^{16}O, ^{14}N, and ^8Be within the angular range from 0° to 35°. The ^{14}N and ^8Be transitions provide information on the isoscalar and isovector couplings of a pseudoscalar particle, while the ^{16}O transition is sensitive to scalar particles which couple to nucleons.

II. EXPERIMENTAL PROCEDURE

To measure the angular correlation of e^+e^- pairs from an excited nuclear state, a detector with reasonable angular and energy resolution is required. We constructed a 12-element, 3-layer hodoscope from NE-102 plastic scintillator (see Fig. 1). The first layer was composed of eight 10.2 cm$\times$2.5 cm$\times$0.32 cm parallel elements, the second layer (orthogonal to the first) consisted of three 25.4 cm$\times$ 2.5 cm$\times$0.32 cm parallel elements and the third layer was a single 10.2 cm$\times$7.6 cm$\times$25.4 cm scintillator. Each element was optically isolated and viewed by a 5.1-cm 14-stage photomultiplier tube (RCA 6810) via an adiabatic light pipe. Each detector was calibrated in energy from cosmic rays collected by forming a telescope with another scintillator mounted $\sim$1 m above the hodoscope.

The target chamber was an aluminum cylinder of length 45.7 cm and diameter 25.4 cm. Aluminum was chosen in order to reduce γ-ray interactions and electron scattering, which are potential sources of background in the experiment. A cryogenic vacuum pump was bolted directly to one end of the cylinder, while a 0.051-cm lexan sheet pressed against a Viton O ring at the other end served to isolate the detector from the vacuum system. Minimum-ionizing electrons exiting the system through the window were subject to energy losses on the order of 100 keV. Multiple scattering of the electrons in this window did not significantly change the measured angular correlations as the detector was only 2.5 cm from the window. The chamber was mounted with its symmetry axis perpendicular to the beam line and the detector was positioned at a distance of 35.6 cm from the targets, which were mounted on a linear drive perpendicular to the chamber axis and the beam line, at an angle of 45° to the beam. In this geometry, the angular resolution of the detector was approximately 8° and the maximum acceptance angle was 35°.

For the ^{14}N data, which were taken first, the detector was mounted in the vertical plane. In this configuration, cosmic-ray showers triggered the detector and produced events with a sum energy of approximately 16 MeV. Although these events did not interfere with the lower-energy ^{14}N pairs, it was clear that they would interfere with the observation of the higher-energy, lower-yield pairs from ^{8}Be. For this reason, the detector was repositioned to be in the horizontal plane, above the targets, for the later measurements. Cosmic-ray events were vetoed by a large scintillator mounted directly above the hodoscope.

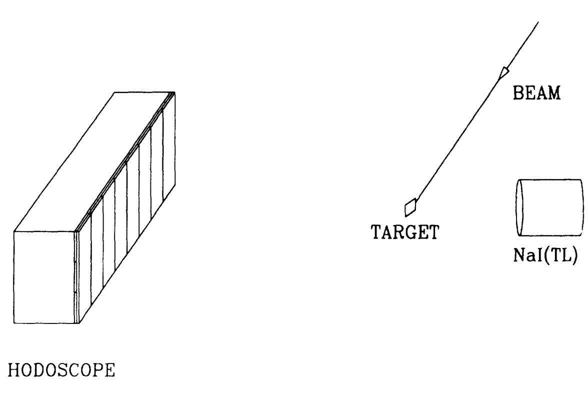

FIG. 1. Schematic diagram of the experimental apparatus. The plastic scintillator hodoscope used to detect pairs from the target is described in the text.

The γ-ray yield from the states of interest was monitored with a 7.6 cm$\times$7.6 cm NaI detector mounted at 90° to the beam and located 14 cm from the target.

For an event to be recorded, a signal of greater than 50 keV was required in any two elements of the first layer, any two of the second layer, and in the third layer within the 25-ns timing window of the system. At each such trigger, the signals from all 12 scintillators were digitized by a 12-channel integrating analog-to-digital converter and then stored event-by-event on computer disk for later analysis. At the end of each run, NaI spectra were stored on a disk and the total charge of protons incident on the target, measured with a beam current integrator, was recorded. Scalers monitored the rates in all of the detectors throughout the acquisition, with the average singles rate being of the order of 10 kHz. The trigger rate varied between 0.1 and 5 Hz, depending on the target under bombardment.

Monte Carlo simulations of the experiment were performed using the EGS3 code of Ford and Nelson[27] with the target chamber, target backing, window, and detector geometries included, in order to model the detector response. In these simulations, electrons and photons were tracked from the target continuously until their total energy fell below 590 and 80 keV, respectively. Minimum-ionizing particles deposited $\sim$500 keV in each of the front two layers of the detector and $\sim$15 MeV in the third. Low-energy electrons and positrons had a relatively high (10–20 %) probability of scattering between adjacent detectors, thereby mimicking a two-particle event. This effect was strongest in the low-energy ^{16}O transition; however, it could be substantially reduced by decreasing the width of the energy window around minimum ionizing in the software cuts on the first two layers of scintillators. After these cuts, the effect remained at the few-percent level (1–5 %) but did not significantly effect the sensitivity of our search. The energy spectra collected from ^{16}O and ^{14}N were reproduced well by the Monte Carlo simulation if the energy resolution of the detectors was taken into account.

The sensitivity of this experiment is based on the measured angular correlations of the e^+e^- pairs. If a particle decaying into e^+e^- were emitted from the level being studied, it would have two effects: to increase the total number of e^+e^- pairs produced and to perturb the angular correlation. In order to extract information on the opening angle of events which pass the energy cuts, we constructed a "correlation spectrum" consisting of 13 channels in ascending order of opening angle. Channel 1 was incremented if adjacent elements were triggered in both of the first two layers of the hodoscope, channel 2 if adjacent elements in one layer and elements separated by one were triggered in the other, and so on. Since there are many more combinations of elements (a total of 28 combinations) contributing to channel 1 than to channel

13 (only two combinations), the number of counts in each channel was scaled by the respective number of combinations. The correlation spectrum, constructed as described, completely specifies the angular correlation (albeit in variable-sized angular bins at an irregular array of angles) for a given target-detector geometry. The Monte Carlo simulations of the angular correlations are determined in the same manner.

All of the nuclear states studied in this experiment were produced by proton-induced reactions. Proton beams of 1–4 μA were supplied by the California Institute of Technology 3-MV Pelletron accelerator. The 6.05-MeV state in ^{16}O was produced as a resonance in the reaction ^{19}F$(p,\alpha)^{16}$O* at $E_p=842$ keV, using a 70-μg/cm^2 CaF_2 target on a 0.025-cm tantalum backing. The 9.17-MeV state in ^{14}N was produced as the 1.748-MeV resonance in $^{13}\mathrm{C}+p\rightarrow{}^{14}\mathrm{N}^*$, using 90%-enriched 30-$\mu$g/cm^2 ^{13}C target on a 0.05-cm copper backing. The 17.6- and 18.1-MeV states in ^{8}Be were populated by the 440- and 1030-keV resonances in $^7\mathrm{Li}+p\rightarrow{}^8\mathrm{Be}^*$. Metallic lithium targets with a thickness of 500-μg/cm^2 were prepared *in situ* by evaporation of lithium metal onto tantalum backings in an isolated section of the target chamber.

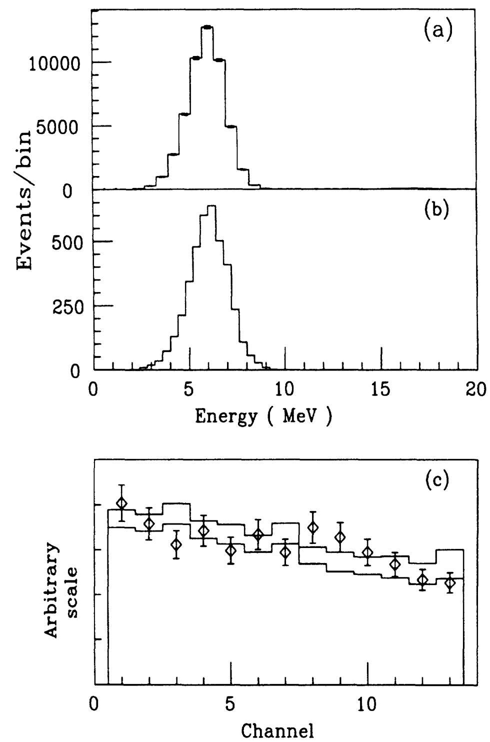

FIG. 2. (a) The total energy spectrum of pairs from proton bombardment of the CaF_2 target at $E_p=842$ keV shows a peak from pairs emitted from the 6.05-MeV level [populated by ^{19}F$(p,\alpha)^{16}$O]. (b) The Monte Carlo simulation of the total energy spectrum of pairs from the 6.05 MeV$\rightarrow$ground-state transition in ^{16}O. (c) The angular-correlation spectra obtained from ^{16}O ($\Diamond$) is compared with that expected from Monte Carlo simulations (the two histograms represent the 1σ statistical uncertainty in the Monte Carlo simulation). Channel 1 corresponds to an average angular separation of 4°, and channel 13 to 31°.

III. RESULTS

A. Scalar particles

The first excited state in ^{16}O ($J^\pi=0^+$, $T=0$) decays by an electric monopole transition ($E0$) to the ground state ($J^\pi=0^+$, $T=0$) by emitting a positron and an electron (IPC) with an angular correlation given by[25] $W(\theta)\propto(1+\cos\theta)$.

The reasons for examining this transition are threefold. Since the angular correlation of IPC pairs is essentially uniform over the face of the detector, the response of the detector can be checked against the Monte Carlo simulations for systematic problems. Second, because fluorine is a common contaminant it may be present in trace amounts in the other targets to be examined. Since the ^{19}F$(p,\alpha)^{16}$O reaction is capable of producing a large yield of internal pairs unaccompanied by γ rays, knowledge of the detector response is useful in identifying ^{19}F contamination. Last, the quantum numbers involved in this transition provide us with sensitivity to a short-lived, light scalar particle which couples to nucleons and decays to e^+e^-.

The energy and correlation spectra obtained for this transition are shown in Fig. 2, together with the results of the Monte Carlo simulation. The efficiency of the detector for $E0$ IPC pairs emitted from the state in ^{16}O passing the energy cuts was estimated from Monte Carlo simulations to be 5.8×10^{-5}.

To determine an upper limit on the branching ratio to particles, we first found the χ^2 per degree of freedom (χ^2_ν) for the angular correlation spectrum by comparing the data to a Monte Carlo simulation, normalized to the data, which included only IPC [$\chi^2_\nu(\Gamma_X/\Gamma_\pi=0.0)$]. A branch to X particles was then introduced and the $\chi^2_\nu(\Gamma_X/\Gamma_\pi>0)$ was again found after the Monte Carlo simulation was renormalized. The 95%-confidence-level upper limit on such a process is the branch that increases the χ^2_ν of the fit between the data and the Monte Carlo simulation by 2. This procedure for determining upper limits is based on the assumptions that the χ^2_ν is consistent with the null hypothesis and that the particle mass is unknown. With these assumptions and the discussion of Ref. 28 this procedure provides a consistent, unbiased procedure for determining upper limits. The χ^2_ν for the comparison of the data with the Monte Carlo simulation with $\Gamma_X/\Gamma_\pi=0.0$ is 1.4 with 11 degrees of freedom. The minimum χ^2_ν ($=1.1$) was achieved with $\Gamma_X/\Gamma_\pi=1.5\times10^{-2}$ for a particle mass of 1.7 MeV, but this change in χ^2_ν is not statistically significant and we therefore quote only upper limits on the branch.

B. Pseudoscalar particles

1. Isovector transition in ^{14}N

In order to investigate the coupling constant $g^{(1)}$ in Eq. (1), we have studied the isovector transition from the 9.173-MeV state ($J^\pi=2^+$, $T=1$) to the ground state

($J^{\pi}=1^{+}$, $T=0$) in ^{14}N. The 2^{+} state can deexcite by γ-ray emission (see Fig. 3) with a calculated[24] IPC branching ratio of $\Gamma_{\pi M1}/\Gamma_{\gamma}=2.2\times10^{-3}$ for the essentially pure $M1$, 85.1% branch to the ground state.[29] Although there was a large γ-ray flux incident upon the detector and chamber walls, the Monte Carlo simulations indicated that γ-ray-induced events would be between one and two orders of magnitude below the expected IPC pair yield, and degraded in energy. The summed energy spectra from data taken on, and just below, the 1.75-MeV resonance are shown in Fig. 4. The shoulder to the left of the main peak in the on-resonance spectrum [Fig. 4(a)] is attributed to pairs arising from ^{19}F contamination in the target. This conclusion is supported by the data taken below the resonance energy [Fig. 4(b)], which is con-

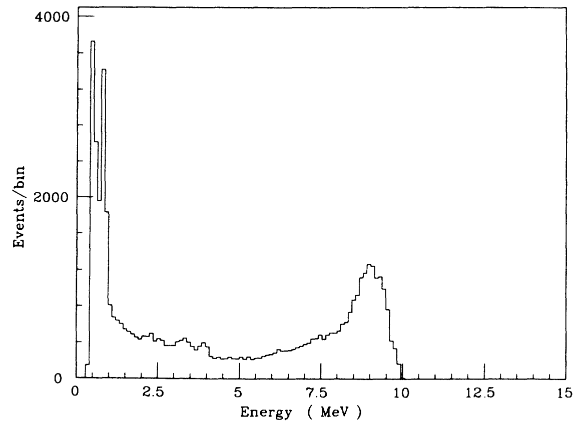

FIG. 3. γ-ray spectrum recorded during proton bombardment of the ^{13}C target at $E_p=1.75$ MeV.

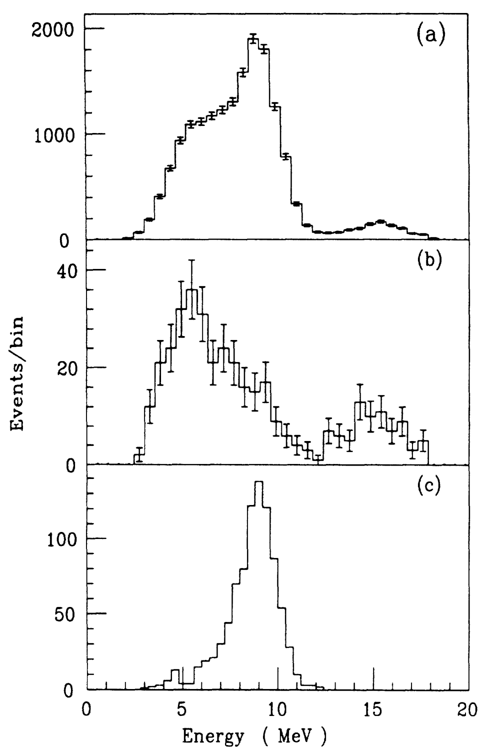

FIG. 4. The total energy spectrum of pairs from proton bombardment of the ^{13}C target at $E_p=1.75$ MeV. The main peak at $\sim$9 MeV corresponds to the pairs from the 9.17-MeV level in ^{14}N populated via resonant proton capture on ^{13}C. The shoulder at $\sim$6 MeV is due to pairs from the ^{19}F$(p,\alpha)^{16}$O reaction caused by ^{19}F contamination of the target, and the peak at $\sim$15 MeV is from cosmic rays. (b) The total energy spectrum at proton energy 5 keV below the $E_p=1.75$-MeV resonance. Events from the ^{19}F$(p,\alpha)^{16}$O reaction and cosmic rays are present. (c) A Monte Carlo simulation of the total energy spectrum of pairs from ^{14}N*.

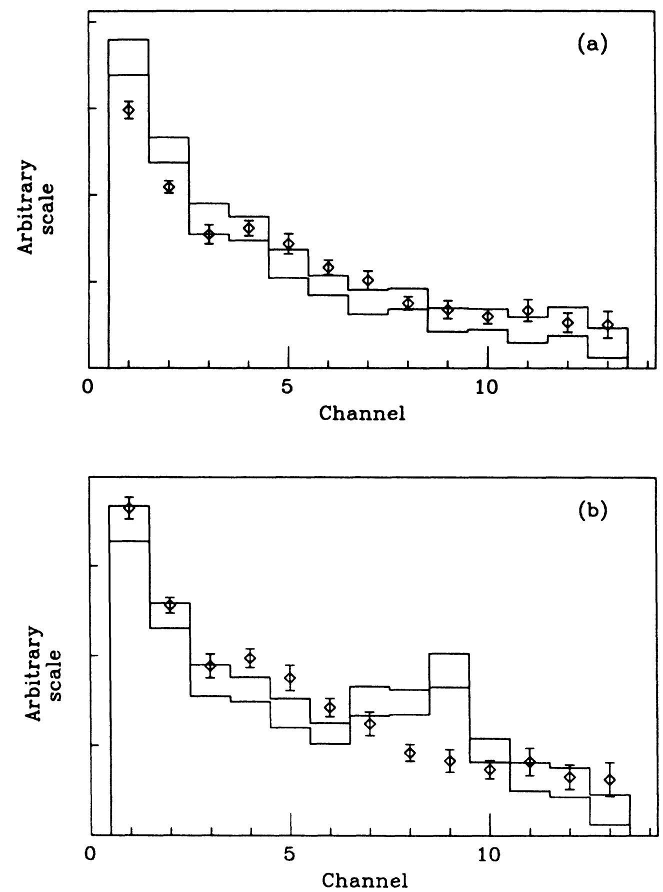

FIG. 5. (a) The angular-correlation spectra obtained from ^{14}N ($\Diamond$) is compared with that expected from Monte Carlo simulations (the two histograms represent the 1σ statistical uncertainty in the Monte Carlo simulation). Only events with energy in the upper-half of the ^{14}N peak in Fig. 4 were used to generate this spectrum. (b) The same data as in (a) are compared with that expected from Monte Carlo simulations when a 1.8-MeV particle branch is present at the limit quoted as the upper-limit (histograms represent 1σ limits). The particle appears in channels 7–10, but is most obvious in channel 9. There is no such enhancement for any group of channels in the measured angular-correlation spectrum.

sistent in yield, energy, and angular correlation with ~ 100 ppm of ^{19}F contamination in the target and the 95-keV-wide resonance in $^{19}F(p,\alpha)^{16}O^*$ at 1.720 MeV (Ref. 30). The broad peak appearing on the high-energy side of the ^{14}N peak is present with the beam off and is due to cosmic-ray interactions. To produce the angular-correlation spectrum shown in Fig. 5(a), an energy requirement was imposed on the total energy spectrum such that only events in the upper-half of the full energy peak were accepted. With this cut, the contribution from ^{19}F pairs and cosmic rays was negligible. The efficiency of the detector to $M1$ pairs,[24,31] passing the energy cuts, from the 9.17-MeV state was calculated to be 3.7×10^{-4}, and hence, from the γ-ray yield observed during the data acquisition, the expected number of IPC pairs was $(6.6\pm0.6)\times10^3$, in good agreement with the $(6.0\pm0.6)\times10^3$ actually seen. The uncertainty quoted includes the uncertainty in the NaI efficiency and in the efficiency of the software cuts.

As for the scalar-particle case, we define the upper limit on particle decay to be the branch which increases χ_ν^2 of the fit between the data and the Monte Carlo simulation by 2. The χ_ν^2 for a Monte Carlo simulation without particle emission [shown in Fig. 5(a)] is 1.5. Figure 5(b) shows the correlation spectrum that would be produced if this state had a 4×10^{-4} branch to a 1.8-MeV particle that decayed to e^+e^-, which is our quoted limit.

2. *Isoscalar transition in ^{8}Be*

The third transition studied was the decay of the 18.15-MeV ($J^\pi=1^+$, $T=0$) level in ^{8}Be. The level scheme[32] for the relevent states in ^{8}Be is shown in Fig. 6. The 18.1-MeV state, which is apparently the isospin-singlet partner of the triplet state at 17.4 MeV (Ref. 33),

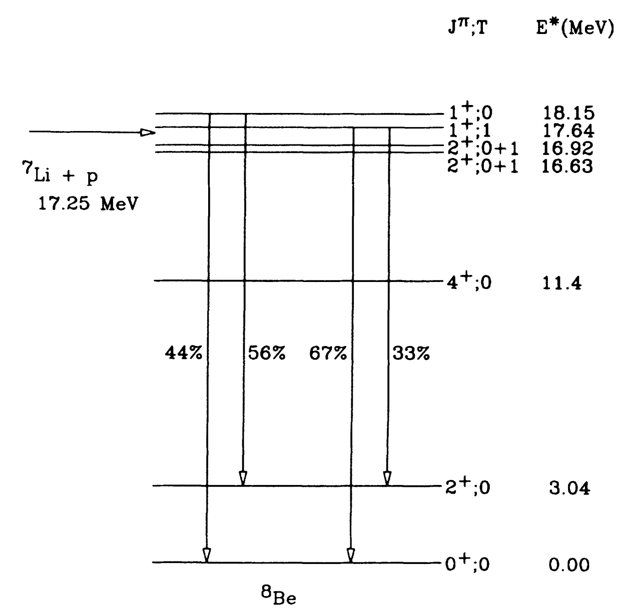

FIG. 6. Level scheme of ^{8}Be showing the branches of interest from the two $J^\pi=1^+$ states at $\sim$18-MeV excitation.

decays with a 44% branch to the ($J^\pi=0^+$, $T=0$) ground state and a 56% branch to the ($J^\pi=2^+$, $T=0$) first excited state at 3.04 MeV, both of which promptly decay to two α particles.[32] There are also small branches to the isospin mixed levels at 16.6 and 16.9 MeV which also α decay.[34] The α particles are stopped in the lexan window at the end of the target chamber, and are not seen by the detector. The transition to the ground state is pure $M1$ but has a $\Delta T=1$ isospin admixture of the order of 10%;[33,34] however, the ratio of the $E2$ to $M1$ components of the transition to the first excited state has not been experimentally determined. The isospin-triplet state at 17.4 MeV, for which the decay to the first excited state has an $E2$ component two orders of magnitude lower than the $M1$ component,[32] has similar nuclear structure to the 18.1-MeV state; however, $\Delta T=0$, $M1$ transitions are inhibited in self-conjugate nuclei by 1 to 2 orders of magnitude.[35] The inhibition is due to the near cancellation of the isoscalar and isovector magnetic moments in the sum $\mu^{(0)}=\mu^p+\mu^n$, where $\mu^{(0)}$ is the isoscalar magnetic moment of the nucleon and μ^p and μ^n are the proton and neutron magnetic moments, respectively. It is therefore not easy to estimate the amount of $E2$ in this transition to the first excited state; however, the uncertainty does not significantly effect the expected number of pairs because the branching ratio of internal pairs for $E2$ and $M1$ transitions is comparable.[24] Transitions involving pseudoscalar particles are not inhibited *a priori*, and so are included in the Monte Carlo simulations of the experiment. It is important to note that the uncertainty in the $M1$ component of the decay to the broad ($\Gamma\simeq1.5$ MeV) first excited state has little effect ($\lesssim 15\%$) on our sensitivity to particle emission because particle decay to this state would produce a broad feature, rather than a peak, in the correlation spectrum. The bulk of our sensitivity comes from the ground-state transition which is pure $M1$, and so for the purpose of deriving limits on particle emission we assume that the first-excited-state transition is pure $E2$ (i.e., no particle emission).

The excitation function of the $^7Li(p,\gamma)^8Be$ reaction indicated a large direct capture yield to the first excited state which reduced the sensitivity of the measurement since the direct capture proceeds via an $E1$ (Ref. 36) transition for which 0^- particles cannot be emitted. For an $E1$ transition the IPC to γ-ray ratio is somewhat greater than that of an $M1$: $\Gamma_{\pi E1}/\Gamma_\gamma=4.3\times10^{-3}$ compared with $\Gamma_{\pi M1}/\Gamma_\gamma=3.5\times10^{-3}$ for the 18.15-MeV transition.[24] The ratio of the yield of high-energy γ rays on resonance to that off resonance was used to estimate the direct capture contribution to the pairs and was used as input for the Monte Carlo simulation. Even with the uncertainty in the nature of the multipolarity of the radiation to the first excited state, the number of pairs expected was 464 ± 50, which is significantly less than the 1001 events recorded. The summed-energy spectrum [Fig. 7(a)] is broad and shows little structure (except for a possible small contribution from ^{19}F contamination) in contrast with the expected spectrum [Fig. 7(b)] that is skewed toward the high-energy end. The maximum of the Monte Carlo spectrum occurs at 14 MeV and not 18 MeV as naively expected for an 18-MeV transition, since

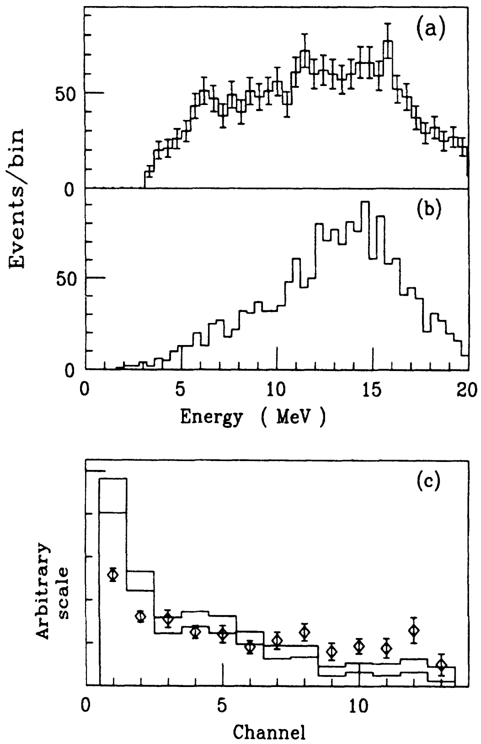

FIG. 7. (a) Total-energy spectrum of pairs obtained from proton bombardment of the ^{7}Li target at $E_p = 1.03$ MeV. (b) Monte Carlo energy spectrum including the pair decay of the 18.15-MeV level in ^{8}Be and direct capture to the first excited state. (c) The angular-correlation spectrum generated from the events in (a). Data are indicated by $\Diamond$ and the histograms are the Monte Carlo 1σ limits.

at these electron/positron energies it becomes likely that a bremsstrahlung γ ray is emitted and escapes the detector giving rise to a spread of energies instead of a sharp line. By generating the energy spectra for different angular bins, it appears that there is an uncorrelated background present which we attribute to pairs scattering in the chamber and entering the detector. Even though we were not able to reproduce this effect with sufficient strength in the Monte Carlo simulations, the simulation does produce a background which is relatively flat with maximum energy equal to the highest energy of an e^+e^- pair from the transition. It is important to note that the background appears to be uncorrelated, from which we conclude that it is not associated with the decay of a particle.

The correlation spectrum used in extracting the particle decay limits was generated from all recorded twofold events [Fig. 7(c)]. Since the origin of $\sim 50\%$ of the observed events is not fully understood, we cannot, with confidence, employ the perturbation of the angular-correlation technique (used for the ^{16}O and ^{14}N data) to extract limits for the branching ratio of isoscalar pseudoscalar particles relative to the IPC pairs. Instead, we derived our limits by assuming all of the observed yield is due to particle decay. For a given particle mass, the ratio for particle decay which produced a yield 2σ above the measured yield in the relevant correlation bins was deduced. In this analysis the only assumption is that a pair hitting the detector is recorded in the appropriate channel, and the background events serve only to weaken the limit we can set.

3. *Isovector transition in ^{8}Be*

In order to broaden the energy range of our particle search, we also examined the 17.6-MeV ($J^\pi = 1^+$, $T = 1$) to ground-state ($J^\pi = 0^+$, $T = 0$) isovector transition in ^{8}Be. The 17.6-MeV state decays via a 67% branch to the ground state and a 33% branch to the first excited state at 3.04 MeV (Ref. 32).

The experimental procedure and data analysis for this transition followed very closely that employed for the 18.1-MeV isoscalar transition. As for the isoscalar transition, the energy spectrum shows little structure when all the correlation channels are combined. However, when the energy spectrum associated with events firing adjacent elements of the hodoscope (i.e., channel 1 of the correlation spectrum) is constructed, it shows the shape expected from Monte Carlo simulations but with a uniform background. The best signal-to-noise ratio is expected in this channel if the background is uncorrelated. The γ-ray spectra, a typical example of which is shown in Fig. 8, showed no evidence of contaminant reactions.

Because of the presence of additional background attributed to pairs scattering in the chamber walls, the limits on the particle branching ratio are derived from the data by the same method as used for the isoscalar ^{8}Be transition. These limits extend over a wider range of particle masses than those from ^{14}N but are slightly less sensitive in the region of 1.5 to 2.5 MeV.

IV. DISCUSSION

Our limits on the branching ratio for particle decay in the transitions studied are presented in Fig. 9. The

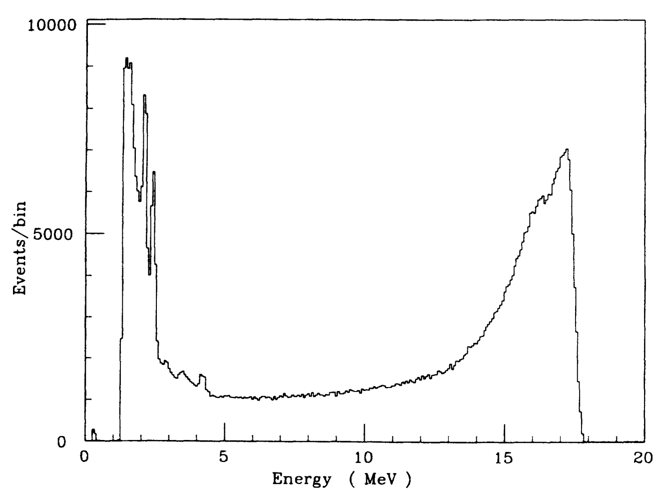

FIG. 8. γ-ray spectrum recorded during proton bombardment of the ^{7}Li target at $E_p = 440$ keV.

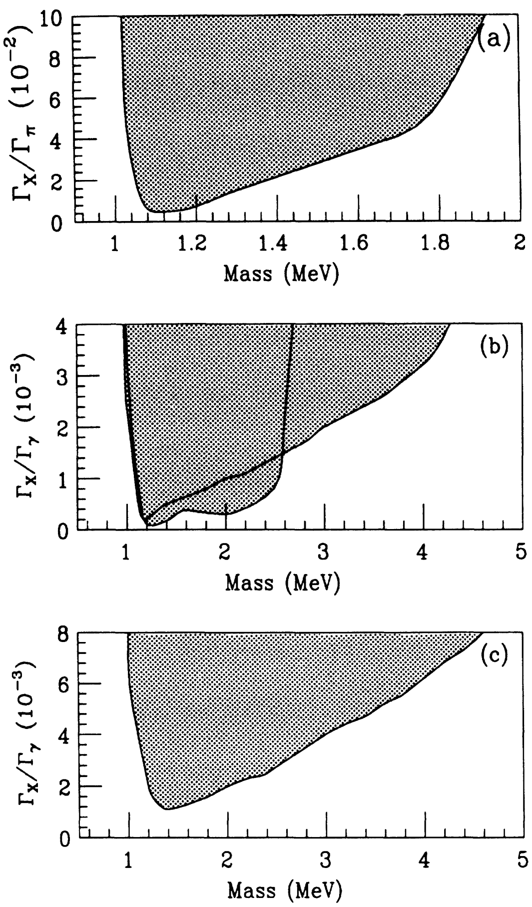

FIG. 9. (a) Sensitivity limits for the branching ratio Γ_X/Γ_π as a function of M_X for scalar particles emitted from $^{16}O^*$. The shaded region is excluded by the present experiment. (b) Limits on Γ_X/Γ_γ for isovector coupling of pseudoscalar particles emitted from $^{14}N^*$ and $^8Be^*$. The shaded region beyond $M_X=2.5$ MeV is due to the ^8Be data. (c) Limits on Γ_X/Γ_γ for isoscalar coupling of pseudoscalar particles emitted from $^8Be^*$.

branching ratio Γ_X/Γ_γ for pseudoscalar particles is less than 1% for masses between 1.02 and 4.5 MeV for both isoscalar and isovector transitions, while for scalar particles with masses from 1.02 to 1.8 MeV, Γ_X/Γ_π is less than 10%. Both limits apply within the lifetime interval of $10^{-19}<\tau<10^{-11}$ s, since for lifetimes longer than 10^{-11} s the particle decay no longer occurs near the target, and for lifetimes shorter than 10^{-19} s the particle width distorts the angular correlation.

Searches for light scalar particles emitted in nuclear transitions have been made previously by Freedman, Napolitano, Camp, and Kroupa[37] studying the $(J^\pi=0^+,\ T=0)\rightarrow(J^\pi=0^+,\ T=0)$ 20.1-MeV transition in ^4He and by Kohler, Watson, and Becker[38] studying the $(J^\pi=0^+,\ T=0)\rightarrow(J^\pi=0^+,\ T=0)$ 6.03-MeV transition in ^{16}O as examined in this work. These experiments were not sensitive to particles with lifetimes less 10^{-11} s because of shielding placed between the target and the detector in order to reduce the γ-ray flux.

The branching ratio for pseudoscalar particles is related to the couplings $g^{(0)}$ and $g^{(1)}$ by the relation

$$\frac{\Gamma_X}{\Gamma_\gamma}=\frac{137}{2\pi}\left[\frac{k_X}{k_\gamma}\right]^3\left[\frac{\left[\sum_T a_T g^{(T)}\right]^2}{\left[\sum_T a_T[\mu^{(T)}+\eta^{(T)}]\right]^2}\right], \qquad (2)$$

which is found by extending the relation given by Donnelly *et al.*[22] to include mixed isospin transitions. The a_T are the probability amplitudes for different isospin components, $\eta^{(0)}=\frac{1}{2}$, $\eta^{(1)}=0$, $\mu^{(T)}$ is the magnetic moment in units of μ_N the nucleon Dirac magnetic moment, and k is the particle momentum. For a 1.8-MeV pseudoscalar particle, the limits on the coupling constants from the present work are

$$g^{(0)}<1.6\times10^{-2}\ ,$$

$$g^{(1)}<2.0\times10^{-2}\ .$$

These limits assume that the 9.17-MeV level in ^{14}N is pure $T=1$ and the 18.15-MeV level in ^8Be has a 10% $T=1$ component.[33,34]

A search for neutral-particle emission from excited nuclear states has recently been made by Hallin, Calaprice, Dunford, and McDonald[14] who reanalyzed an earlier experiment by Warburton *et al.*[39] A magnetic pair spectrometer, with a removable baffle that excluded pairs with $\theta<50°$, was employed to search for an enhancement in the ratio of e^+e^- pairs with an opening angle $\theta<90°$ to those with $50°<\theta<90°$ over theoretical predictions. Three nuclei were studied: ^6Li (isovector; 3.562 MeV, 0^+, $1\rightarrow$ground state (g.s.), 1^+,0), ^{14}N (isoscalar; 7.028 MeV, 2^+, $0\rightarrow$g.s., 1^+,0), and ^{10}B (isoscalar; 3.587 MeV, 2^+,$0\rightarrow$g.s. 3^+,0). They had no angular distribution information except integrated yields and so were not sensitive to any local structure in the angular correlation between the electron and the positron. Their 90% confidence limits, presented only for a particle of mass 1.7 MeV, are $\Gamma_X/\Gamma_\pi<0.104$ for isovector particles (^6Li) and $\Gamma_X/\Gamma_\pi<2.2$ for isoscalar particles (^{14}N and ^{10}B). Our 95% confidence limits are $\Gamma_X/\Gamma_\pi<0.18$ for isovector particles (^{14}N) and $\Gamma_X/\Gamma_\pi<0.50$ for isoscalar particles (^8Be). Baba, Indumathi, Roy, and Vaidya[16] searched for particle emission from the 3.68-MeV $\frac{3}{2}^-$; $\frac{1}{2}$ state in ^{13}C and were able to set limits $\Gamma_X/\Gamma_\pi<0.1$ for particles with masses near 1.8 MeV and $\tau<10^{-11}$ s at 95% confidence. This is a mixed isospin transition and so must be used in conjunction with other data to extract the isovector and isoscalar couplings. Another search using this technique was carried out by de Boer *et al.*[15] studying the same ^{10}B transition as Hallin, Calaprice, Dunford, and McDonald[14] using four miniorange spectrometers with relative angular separations of 60°. They constrained $\Gamma_X/\Gamma_\pi<1.0$, for a limited mass range around 1.7 MeV and again for $\tau<10^{-11}$.

Two comprehensive reviews of experimental results and theoretical models for pseudoscalar particles have recently appeared in the literature.[21,40] These analyses indicate that stringent limits have been placed on a short-lived pseudoscalar particle with mass less than 2.5 MeV coupling to e^+e^-. However the strongest limits, which come from beam-dump experiments, are valid only if the X-nucleon cross section σ_{XN} is sufficiently small so that X interaction in the dump is negligible. While it is difficult to estimate the X-nucleon cross section from $\alpha = g^2/4\pi$, an order-of-magnitude estimate is possible by comparing α_{XN} to $\alpha_{\pi N}$, the pion-nucleon coupling. This comparison yields a X-nucleon cross section (σ_{XN}) of ~ 1 μb (assuming a π-nucleon cross section of 50 mb) which is significantly below the cross section that begins to limit the sensitivity of the beam-dump experiments due to X absorption in the dump. The results of the present experiment, combined with previous results, thus place stringent limits on the properties of new light scalar and pseudoscalar particles.

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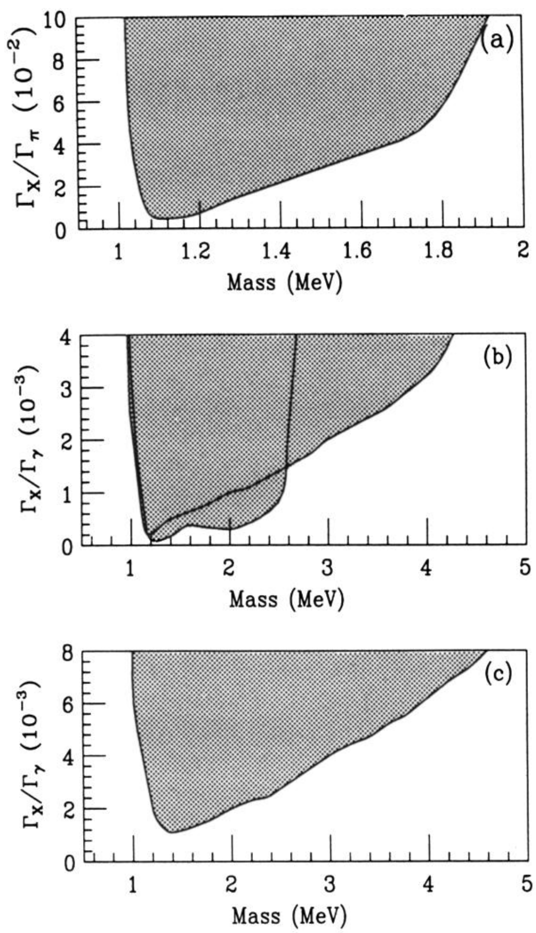

FIG. 9. (a) Sensitivity limits for the branching ratio Γ_X/Γ_π as a function of M_X for scalar particles emitted from $^{16}O^*$. The shaded region is excluded by the present experiment. (b) Limits on Γ_X/Γ_γ for isovector coupling of pseudoscalar particles emitted from $^{14}N^*$ and $^{8}Be^*$. The shaded region beyond $M_X=2.5$ MeV is due to the ^{8}Be data. (c) Limits on Γ_X/Γ_γ for isoscalar coupling of pseudoscalar particles emitted from $^{8}Be^*$.