Search for a Short-Lived Neutral Particle Produced in Nuclear Decay

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We report on a search for a short-lived neutral particle ϕ produced in the decay of the 9.17-MeV $J^\pi = 2^+$ state in ^{14}N. The experiment is sensitive to decays into an e^+e^- pair with $\tau_\phi \lesssim 10^{-11}$ s. For $m_\phi = 1.7$ MeV we place a limit on the branching ratio of $\Gamma_\phi/\Gamma_\gamma \leq 4\times10^{-4}$ at the 90% confidence level.

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Anomalous narrow peaks have been observed in the spectra of positrons emitted in heavy-ion collisions in several recent experiments at Gesellschaft für Schwerionenforschung Darmstadt (GSI).[1-3] In addition, a new experiment[4] has revealed that the positrons associated with these peaks are correlated with electrons whose energy spectrum also contains a narrow peak at the same energy as the positron peaks. One explanation[4-6] for these peaks is the production and subsequent decay of a previously unobserved neutral particle ϕ of mass ~ 1.7 MeV. Monte Carlo simulations[4] of such a particle decay, assuming the particle to be produced at rest in the center-of-mass system and then to decay isotropically into an e^+e^- pair, have produced results in good agreement with the experimental spectra. Less exotic explanations[4,7,8] have also been considered, but none so far has succeeded in explaining all the features of the data.

Schäfer *et al.*[5] and Balantekin *et al.*[6] have considered the results of the GSI experiments and concluded that a neutral particle could have gone undetected in previous experiments only if it were pseudoscalar with a lifetime in the range 10^{-9} to 10^{-13} s. There have been many searches for light pseudoscalar particles ("axions") in nuclear[9] and particle[10] physics, at beam dumps,[11] and at reactors.[12] However, none of these is sensitive to a particle with a lifetime less than $\sim 10^{-11}$-10^{-12} s.[13] If the ϕ has a nonzero coupling to quarks and a mass less than the energy of a nuclear transition then it could be produced in nuclear decay. The spin and parity of such a particle constrain its emission to obey the same selection rules as a magnetic γ-ray transition,[14] and ϕ decay is thus expected to compete with the γ decay of excited nuclear states if the transition is predominantly magnetic. In this Letter we report on a search for a neutral particle with a mass between 1.02 and 2.2 MeV and a lifetime between $\sim 10^{-11}$ and $\sim 10^{-19}$ s emitted in a nuclear $M1$ transition.[15]

The observed positron peaks in the heavy-ion experiments, if attributed to this new neutral particle, indicate a large branching ratio for decay to e^+e^-. To observe these pairs emitted from a particle produced in nuclear decay we must separate them 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[16] that pairs produced from the decay of a pseudoscalar particle can be distinguished from internal pairs by their angular correlation. Previous detailed studies[17] of the angular correlation of nuclear pairs, which were used to extract transition multipolarities, indicate that $\Gamma_\phi/\Gamma_\gamma$ is likely to be small, although estimates are very sensitive to detection geometry.

For a transition energy significantly larger than m_ϕ, the angular correlation between the electron and positron produced in the ϕ decay will be sharply peaked in the laboratory frame at a nonzero angle that varies inversely with the transition energy. In the present measurement, we use this peaked angular correlation to separate the ϕ-decay pairs from the internal pairs, which have an angular correlation peaked at zero degrees.

We have chosen the decay of the 9.17-MeV $J^\pi = 2^+$, $T = 1$ state in ^{14}N for our search. This state is known to decay with an (85 ± 1)% branch to the $J^\pi = 1^+$, $T = 0$ ground state via an $M1$ γ-ray transition.[18,19] The internal-pair emission from this state has a calculated branching ratio of 2.2×10^{-3} and an angular correlation strongly peaked at zero degrees.[20] In contrast, approximately 80% of the pairs produced by the decay of a 1.7-MeV ϕ with a total energy of 9.17 MeV have an opening angle between 16° and 19°.

The present experiment was performed at the California Institute of Technology 3-MV Pelletron accelerator. We produce the 9.17-MeV state in ^{14}N as a resonance in the reaction ^{13}C$(p,\gamma)^{14}$N at $E_p = 1.75$ MeV. A 90%-enriched 30-μg/cm^2 ^{13}C target on a 0.05-cm copper backing was used for the ^{14}N measurements. A 70-μg CaF$_2$ target on a 0.025-cm tantalum

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backing was also used for studies of detector response with the reaction $^{20}F(p,\alpha)^{16}O$. Targets were mounted at 45° to the beam axis and proton beam currents were kept below $\sim 4\ \mu A$ to minimize their deterioration. A 7.6-cm × 7.6-cm NaI detector mounted at 90° to the beam axis provided a measure of the number of 9.17-MeV γ rays produced in the reaction. The e^+e^- detector, described below, was also placed at 90° to the beam axis and directly viewed the target face.

The pair detector consisted of a 6×2-element plastic-scintillator hodoscope, to provide angular and energy information, followed by two additional scintillators, each 18 cm long, 15 cm wide, and 3.8 cm thick, to give total-energy information. A schematic diagram of the detector is shown in Fig. 1. The scintillators H were 0.5 cm thick and ranged in width from 2 to 4 cm (H1=3.8 cm, H2=2.6 cm, H3=3.9 cm, H4=3.8 cm, H5=2.6 cm, H6=3.8 cm), while the two scintillators DE were 0.3 cm thick, 3.8 cm wide, and 20 cm long. A 35-cm vacuum drift region between the target and the hodoscope allowed the pairs to have a measurable separation upon entering the detector, which was isolated from the vacuum system by an $18\times5\times0.025\text{-cm}^3$ Mylar window. This window defined the acceptance of the detector. The angular resolution of the hodoscope was approximately 7° and the maximum detectable angle between two charged particles was 29°. The energy resolution of the detector was measured to be 30% FWHM for the pairs emitted from the 6.06-MeV state in ^{16}O. An energy calibration for each scintillator was obtained by use of cosmic rays.

The trigger for recording an event was a signal above threshold in two of the six detectors H, both of the detectors DE, and one of the detectors E, all within a resolving time of 20 ns. The threshold for each element of the hodoscope array corresponded to an energy of ~ 100 keV and the minimum energy required for a particle to trigger the rear scintillator was approximately 1.1 MeV. Upon receipt of a trigger, all of the detector signals were read by a twelve-channel integrating analog-to-digital converter and the digitized signals were stored event by event on computer disks for later analysis. NaI spectra were collected independently in singles. Off-line analysis consisted of constructing the total energy for each event and then compiling fifteen spectra, one for each of the possible combinations of two out of six of the H detectors. The number of counts in the total energy peak of each spectrum was used to generate correlation spectra of the type displayed in Fig. 2.

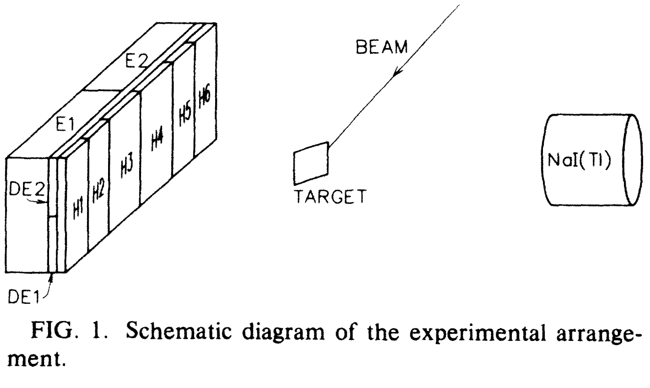

FIG. 1. Schematic diagram of the experimental arrangement.

To check the performance of the detector, we stud-

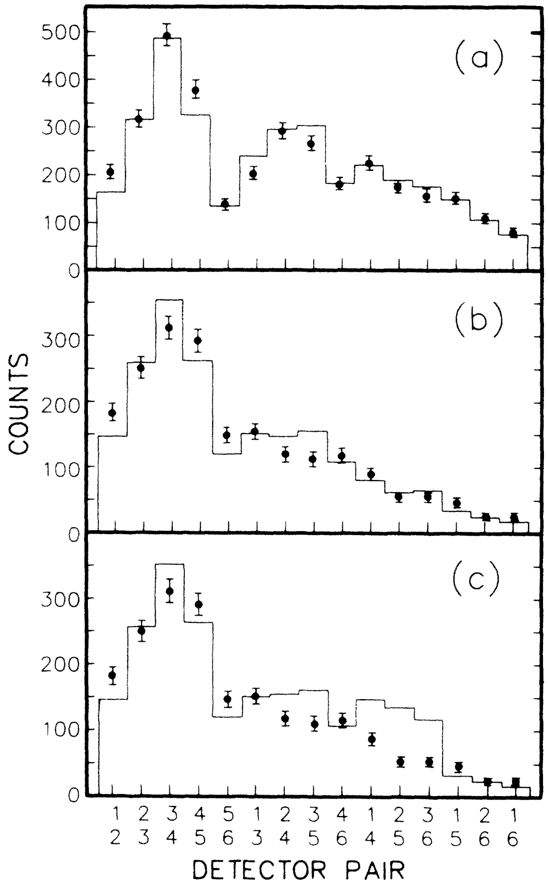

FIG. 2. Pair-correlation spectra. The abscissa is the pair of H detectors that fired (see Fig. 1). Pairs (1,2), (2,3), (3,4), (4,5), and (5,6) have average opening angle $\bar{\theta} \sim 7°$; (1,3), (2,4), (3,5), and (4,6) have $\bar{\theta} \sim 12°$; (1,4), (2,5), and (3,6) have $\bar{\theta} \sim 17°$; (1,5) and (2,6) have $\bar{\theta} \sim 21°$; and (1,6) has $\bar{\theta} \sim 25°$. The spectrum shape reflects a combination of pair angular correlation and detector geometry effects. Error bars represent statistical uncertainties only. (a) Pairs from the decay of the 6.06-MeV 0^+ state in ^{16}O. The solid line is a Monte Carlo simulation of the nuclear pair decay of the state. (b) Pairs from the decay of the 9.17-MeV 2^+ state in ^{14}N. The solid line is a Monte Carlo simulation of nuclear pair decay according to the prescription of Rose (Ref. 20). (c) The same as in (b), but here the Monte Carlo simulation includes nuclear decay both by internal pair and by pseudoscalar ϕ emission with $m_\phi = 1.7$ MeV, $\tau_\phi \lesssim 10^{-11}$ s, and $\Gamma_\phi/\Gamma_\gamma = 5\times10^{-4}$.

ied the well-known pair transition from the 6.06-MeV 0^+ state to the 0^+ ground state in ^{16}O. The state was produced as the $E_p = 842$ keV resonance in the reaction $^{20}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$. The pair correlation spectrum, corresponding to ~ 6 mC of incident protons, is shown in Fig. 2(a). The solid line in Fig. 2(a) is the result of a 50 000-event Monte Carlo simulation of the pair decay, using the known angular correlation,[21] normalized to the total number of observed events. We allowed one free parameter in the Monte Carlo simulation: the horizontal position of the detector relative to the exit window. Best agreement was found when the detector was shifted 0.3 cm from its nominal position, which is within the alignment uncertainty of the experimental setup. This geometry was then used in subsequent Monte Carlo calculations.

The results of the $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ measurements, for ~ 60 mC of protons, are shown in Fig. 2(b). A Monte Carlo simulation of the internal pair decay, normalized to the total number of observed events, is represented by the solid line. The ratio of the observed pair yield to that expected based on the γ-ray yield in the NaI detector and the calculated branching ratio[20] was 1.3 ± 0.5. The uncertainty in this number is chiefly due to the estimate of the NaI photopeak efficiency. Because of the strict five-level coincidence requirement imposed, the major yield in our detector is expected to be from processes which generate e^+e^- pairs in the vicinity of the target: internal pair decay, pair conversion of 9.17-MeV γ rays, and ϕ decay. However, although the ^{13}C target was mounted on a thick copper backing, the estimated yield from 9.17-MeV γ-ray conversion in the backing is small compared with the yield from the internal pairs, as is the yield from pair production in the aluminum chamber walls. Another potential source of background in the experiment is random coincidences resulting from the high γ-ray flux, but the probability of such events surviving our timing and energy cuts is insignificant. The yield from non-beam-induced events, such as cosmic rays, was measured with the beam off and found to be negligible.

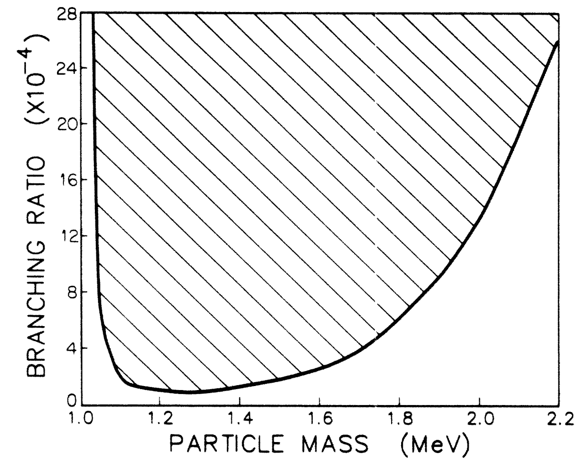

FIG. 3. Sensitivity limits for the branching ratio $\Gamma_\phi/\Gamma_\gamma$ as a function of m_ϕ for ϕ a pseudoscalar and $\tau_\phi \lesssim 10^{-11}$ s. The shaded region is excluded by the present experiment.

To determine our sensitivity to ϕ emission, Monte Carlo simulations of $\sim 10\,000$ detected events were generated for a range of particle masses and branching ratios. Included were corrections for the angular distributions of both the nuclear e^+e^- pairs[22] and the ϕ's as calculated from the nuclear alignment parameters according to the prescription of Rose and Brink.[23] The sensitivity of our detector to e^+e^- pairs produced in ϕ decay depends upon both the mass and lifetime of the particle, as these affect the separation of the pair measured at the detector. However, for lifetimes $\lesssim 10^{-11}$ s the sensitivity becomes a function of only mass, as the decays take place very close to the target. The lower limit to our sensitivity, $\sim 10^{-19}$ s, is due to the constraint that the ϕ's natural width be somewhat less than its mass. As previous experiments with a sensitivity comparable to ours have searched for pseudoscalar particles with lifetimes greater than 10^{-11} s, here we concentrate on investigating lifetimes $\lesssim 10^{-11}$ s.

Because of their angular correlation, the pairs produced in ϕ decays appear in only a few channels in the correlation spectrum. For example, Fig. 2(c) shows a comparison with the data of a Monte Carlo simulation for a 1.7-MeV particle with a 5×10^{-4} branching ratio. The sensitivity of the detector to m_ϕ and the branching ratio $\Gamma_\phi/\Gamma_\gamma$ was determined from the difference between the observed yields in the relevant angle bins (see Fig. 2) of the correlation spectra and the prediction of the Monte Carlo simulations for those bins. We define our sensitivity as the branching ratio $\Gamma_\phi/\Gamma_\gamma$ that produces a yield 2σ above the maximum deviation between the data and the Monte Carlo calculation for $\Gamma_\phi/\Gamma_\gamma = 0$. Figure 3 shows the branching ratios and masses ruled out (at the 2σ level) by this experiment for the decay of the 9.17-MeV state in ^{14}N to the ground state by emission of a short-lived pseudoscalar ϕ. In particular, for a particle of mass 1.7 MeV decaying into an e^+e^- pair with a lifetime less than 10^{-11} s, we obtain a limit[24] of less than 4×10^{-4} (at 90% confidence level) for $\Gamma_\phi/\Gamma_\gamma$.

We can use these results to set limits on the pseudoscalar-nucleon coupling constant by considering an effective interaction Lagrangean[14] of the form

$$L = i\bar{\psi}\gamma_5(g^{(0)} + g^{(1)}\tau_3)\psi\phi,$$

where ψ is the nucleon field, ϕ is the pseudoscalar field, and $g^{(0)}$ and $g^{(1)}$ are the isoscalar and isovector coupling constants. For the 9.17-MeV transition in ^{14}N, which is isovector, we can use the estimates of

Donnelly *et al.*[14] to relate the branching ratio to the isovector coupling constant:

$$\frac{\Gamma_\phi}{\Gamma_\gamma} \approx \frac{1}{2}\left(\frac{k_\phi}{k_\gamma}\right)^3\left(\frac{2g^{(1)}}{e\mu^{(1)}}\right)^2,$$

where k_ϕ and k_γ are the momenta of the ϕ and the photon, and $\mu^{(1)} \approx \mu_p - \mu_n$ is the isovector nucleon magnetic moment.[25] Thus the present limit for $\Gamma_\phi/\Gamma_\gamma$ of 4×10^{-4} yields an upper limit of $\sim 1.4\times10^{-2}$ for $g^{(1)}$. These results provide a useful constraint on models that attempt to explain the narrow e^+e^- peaks seen at GSI in terms of the production of a new neutral particle.

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[1] J. Schweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983).

[2] M. Clemente *et al.*, Phys. Lett. **137B**, 41 (1984).

[3] T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985).

[4] T. Cowan *et al.*, Phys. Rev. Lett. **56**, 444 (1986).

[5] A. Schäfer, *et al.*, J. Phys. G **11**, L69 (1985).

[6] A. B. Balantekin *et al.*, Phys. Rev. Lett. **55**, 461 (1985).

[7] J. Reinhardt *et al.*, Z. Phys. A **303**, 173 (1981).

[8] C.-Y. Wong, Phys. Rev. Lett. **56**, 1047 (1986).

[9] F. P. Calaprice *et al.*, Phys. Rev. D **20**, 2706 (1979).

[10] See, e.g., C. Edwards *et al.*, Phys. Rev. Lett. **48**, 903 (1982); M. Sivertz *et al.*, Phys. Rev. D **26**, 717 (1982).

[11] See, e.g., P. F. Jacques *et al.*, Phys. Rev. D **21**, 1206 (1980); H. Faissner *et al.*, Phys. Lett. **96B**, 201 (1980); F. Bergsma *et al.*, Phys. Lett. **157B**, 458 (1985).

[12] See, e.g., A. Zehnder *et al.*, Phys. Lett. **110B**, 419 (1982); J. F. Cavaignac *et al.*, Phys. Lett. **121B**, 193 (1983); V. D. Anan'ev *et al.*, Sov. J. Nucl. Phys. **41**, 585 (1985); H. R. Koch and O. W. B. Schultz, Z. Phys. A **321**, 361 (1985).

[13] N. C. Mukhopadhyay and A. Zehnder, Phys. Rev. Lett. **56**, 206 (1986).

[14] T. W. Donnelly *et al.*, Phys. Rev. D **18**, 1607 (1978).

[15] Although we confine our discussion here to the relevant case of ϕ pseudoscalar, we note that the present experiment is also sensitive to vector particles.

[16] A. Hallin and F. P. Calaprice, Bull. Am. Phys. Soc. **24**, 63 (1979).

[17] E. K. Warburton *et al.*, Phys. Rev. **133**, B42 (1964), and references therein.

[18] F. Ajzenberg-Selove, Nucl. Phys. **A360**, 1 (1981).

[19] F. W. Prosser, Jr., R. W. Krone, and J. J. Singh, Phys. Rev. **129**, 1716 (1963).

[20] M. E. Rose, Phys. Rev. **76**, 678 (1949).

[21] S. Devons, G. Goldring, and G. R. Lindsey, Proc. Phys. Soc. London, Sect. A **67**, 134 (1954).

[22] S. Devons and L. J. B. Goldfarb, *Encyclopedia of Physics*, edited by S. Flügge (Springer, New York, 1957), p. 362.

[23] H. F. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967).

[24] If ϕ is a vector particle, we get $\Gamma_\phi/\Gamma_\gamma < 2\times10^{-4}$ at 90% confidence level.

[25] This relation assumes that the convection-current contribution to the electromagnetic matrix elements is negligible. This approximation is supported by a shell-model calculation (M.-C. Chu and V. Pönisch, private communication) using the wave functions of Lee and Kurath [T.-S. H. Lee and D. Kurath, Phys. Rev. C **21**, 293 (1980)].