Search for Correlated Narrow-Peak Structure in the Two-Photon Spectrum from 6-MeV/ Nucleon U + Th Collisions

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(Received 25 August 1986)

We have searched for 180° (c.m.) correlated equal-energy two-photon decays produced in 6-MeV/nucleon U + Th collisions. In the summed-energy region between 1.5 and 1.8 MeV, we set an upper limit of 3×10^{-10} decay per projectile for the yield integrated over a target thickness of 3.6 mg/cm^2, which corresponds to a cross section of 3×10^{-29} cm^2 averaged over the target. This can be compared to a production cross section of $(1-2)\times10^{-28}$ cm^2, averaged over a target thickness of 0.3–0.6 mg/cm^2 found by others for correlated electron-positron pairs in the same reaction.

PACS numbers: 25.70.Ef, 14.80.Pb

Cowan *et al.* have recently observed a narrow peak structure at 760 ± 20 keV in the summed-energy spectrum of equal-energy electrons and positrons, correlated at 180° (c.m.), in the 5.87-MeV/nucleon U + Th collisions.[1] (A recalibration of the UNILAC accelerator has changed the originally quoted energy of 5.83 to 5.87 MeV/nucleon.[2]) The peak structure is consistent with the hypothesis that a neutral particle is formed in this reaction[3–6] with a c.m. velocity spread not greater than the c.m. velocity of the system ($\beta_{c.m.}\approx0.056$).[1] The mass of the neutral particle would be near 1.78 MeV. If one assumes that all narrow positron-peak structures found in similar heavy-ion reactions[3,7,8] are also correlated with equal-energy electrons, one obtains from the quoted range of positron-peak energies values for the mass of the neutral particle lying between 1.5 and 1.8 MeV. It is also possible that there is a fine structure in the positron peak energies and, hence, in the implied particle masses.[1,2]

If the hypothetical neutral particle is spinless, it is expected to have a decay branch into two photons of equal energy, which are correlated by 180° in the rest system of the particle. (A spin-1 particle would decay into three photons, but this possibility is less attractive because it would imply the existence of new gauge structures which are difficult to accommodate.) Since coupling of the particle to electrons implies the existence of an electromagnetically induced coupling to photons, and vice versa, we find absolute limits for the $\gamma\gamma/e^+e^-$ branching ratio R, $1\times10^{-6}\leq R\leq6\times10^5$ for a scalar particle and $1.6\times10^{-5}\leq R\leq7\times10^4$ for a pseudoscalar particle (the bounds are of order α^2 and $1/\alpha^2$, respectively). Any experiment that sets a limit within these numbers helps to restrict the range of acceptance particle models. We also note that the lowest lifetime of a hypothetical pseudoscalar particle of mass 1.7 MeV against two-gamma decay allowed by analysis of Delbrück scattering[9] is 4×10^{-13} s. This is similar to the limit against e^+e^- decay obtained from the anomalous magnetic moment of the electron.[4,5] The branching ratio is, therefore, not restricted by such bounds, which makes an experimental investigation worthwhile.

We have searched for correlated, equal-energy, two-photon events (henceforth abbreviated $\gamma\gamma$) in 6.02-MeV/nucleon U + Th collisions using the experimental arrangement schematically shown in Fig. 1(a). Although in principle the gamma-ray background might be reduced in a coincidence experiment with the scattered particles, the low detection efficiency for gamma rays made the expected $\gamma\gamma$ rate so small that a coincidence experiment would have impaired the statistics too much in the available running time. Hence, we decided to forego any scattered particle selection similar to that used in the positron experiments.[1–3,7,8] Two pairs of Ge detectors, each 5.0 cm diam by 5.0 cm long, were placed at 57° and 117° with respect to the U beam produced by the Lawrence Berkeley Laboratory SUPERHILAC. (These angles correspond to 60° and 120° c.m. angles for the $\gamma\gamma$ decay of the presumed particle moving with $\beta=\beta_{c.m.}$.) Each Ge detector was surrounded by a bismuth germanate (BGO) anti-Compton shield which had the effect of raising the peak-to-total ratio to 50% for monoenergetic gamma rays near 1 MeV.[10] A 0.64-cm lead shield was placed in front of each Ge detector to

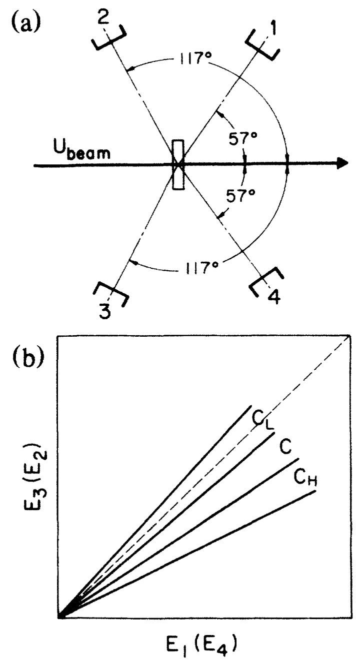

FIG. 1. (a) Experimental arrangement. The Th target is placed at 90° to the U beam. The Ge detectors (1–4) were placed 13 cm from the target at the angles shown. (b) Schematic sketch of the windows chosen to select the particular Doppler velocities: for C, $\beta=\beta_{c.m.}$, for C_L, $\beta=0$, and for C_H, $\beta=2\beta_{c.m.}$ The photon energies are denoted by E_i where i is the detector number in (a).

attenuate low-energy gamma rays from Coulomb excitation and other nuclear processes. The BGO suppressors were surrounded by 0.32-cm lead shields to reduce an intense background from diffusely scattered gamma rays. Beam currents of 20–30 nA of $U^{\sim 60+}$ could be tolerated by the detection electronics without introducing unreasonable dead time or resolution deterioration. The typical duty cycle of the accelerator was 10–15%, giving peak counting rates in the forward BGO shields of $\sim 80\times 10^3$/s and in the Ge detectors of $\sim 20\times 10^3$/s. The detectors were calibrated at these counting rates by use of radioactive sources, and the gains were equalized within 0.2 keV at 1700 keV. By means of suitable multiplexing, all coincident events between any two of the four detectors shown in Fig. 1(a) were measured. The total accumulation time was approximately 35 h.

The kinematics of the expected $\gamma\gamma$ decay is similar to that of the e^+e^- decay of the presumed particle (Fig. 1 of Ref. 1). Plotting the gamma-ray energies E_1 and E_3 for one pair (1,3) of opposite detectors shown in Fig. 1(a) on a two-dimensional plot [Fig. 1(b)], we set the various windows shown to look for the measured $\gamma\gamma$ events. Window C was set to select those events where E_1 and E_3 would be Doppler shifted by the c.m. velocity ($\beta=\beta_{c.m.}$) and Doppler broadened by the opening angle of each detector ($\pm 11°$). Window C_L selected those events where equal-energy gamma rays would be produced in the laboratory system ($\beta=0$). Window C_H selected events which might be due to particles moving with the projectile velocity ($\beta=2\beta_{c.m.}$).

Gated summed-energy photon spectra are shown in Fig. 2. Since the gains of all the four detectors were carefully set to be equal, spectra from pairs (1,3) and (2,4) were added together. For Figs. 2(a)–2(c) the gates are C, C_H, and C_L, respectively.

Coincident events were also determined for pairs of detectors not correlated at 180° (c.m.) [(1,2) and (3,4)], but preserving the Doppler shift and broaden-

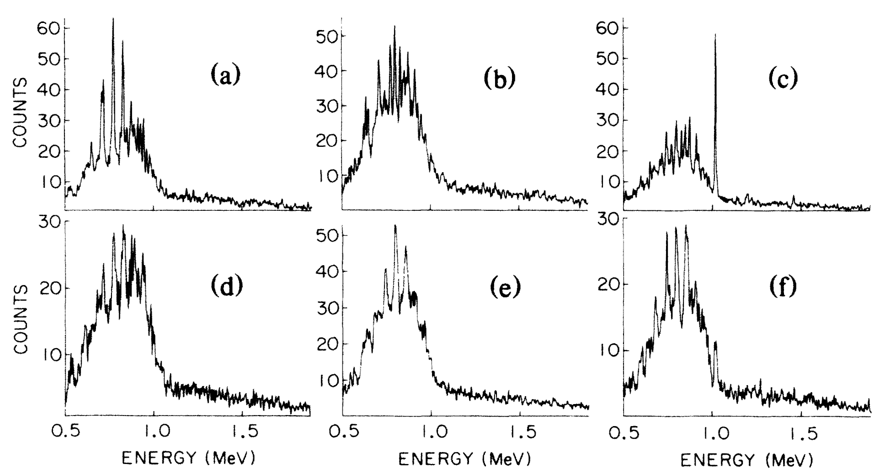

FIG. 2. Summed-energy photon spectra in the Ge detectors shown in Fig. 1(a). Spectra (a), (b), and (c) correspond to 180° (c.m.) correlated detector pairs (1,3) and (2,4), and to windows C, C_H, and C_L, respectively. Spectra (d), (e), and (f) correspond to 60° correlated detector pairs (1,2) and (3,4), and to windows C, C_H, and C_L, respectively. The origin of the line structures is discussed in the text.

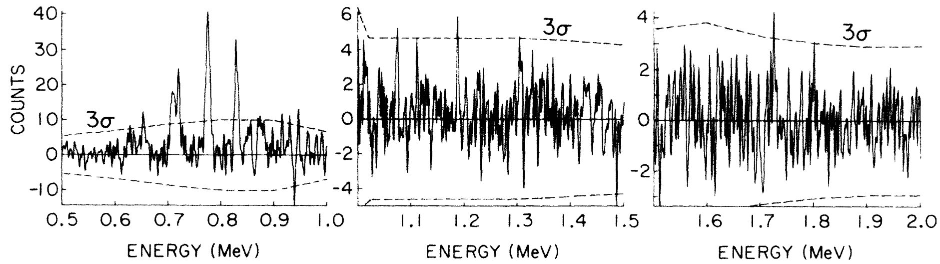

FIG. 3. Difference spectrum between Figs. 2(a) and 2(d). The dashed lines correspond to statistical 97% confidence limits (3 times the standard deviation) for a 4-keV-wide photon line. The expected $\gamma\gamma$ line(s) should lie in the 1.5–1.8-MeV energy interval.

ing for a source moving along the beam axis. Again, the spectra were added and are shown in Figs. 2(d)–2(f) for the gates C, C_H, and C_L, respectively. These spectra should give the background under the expected $\gamma\gamma$ spectrum. By subtracting the counts in the spectrum of Fig. 2(d) from those in Fig. 2(a) we obtained the spectrum in Fig. 3. In the absence of correlated γ rays emitted in the c.m. frame, the counts in this difference spectrum should scatter around zero. In Fig. 3 we show the statistical 97% confidence limits (3 times the standard deviation σ).

Interesting line features appear in the spectra of Figs. 2 and 3, but unfortunately not in the range of summed energies of interest here (1.5–1.8 MeV). In Fig. 2(c), one sees a sharp line at 1.02 MeV due to annihilation radiation. The width of the line is 3.5 keV. This should also be the width of the expected $\gamma\gamma$ line if all the particles emitting it move with the same velocity. No Doppler broadening due to the detector opening is expected for the line, since the first-order Doppler shifts cancel exactly in the sum spectrum for two equal-energy γ rays emitted back-to-back in the source system. The $\gamma\gamma$ line is affected only by the second-order Doppler shift which does not depend on angle. If the presumed particles were emitted in the laboratory system with a range of velocities corresponding to $\beta_{\text{c.m.}} \pm \beta_{\text{c.m.}}$, a $\sim$5-keV second-order Doppler broadening of the $\gamma\gamma$ peak would be expected.

In the spectra of Fig. 2, a line structure appears below 1 MeV. These features are accidentally produced by photons from Coulomb excitation of high-spin states (around $J=18$) of ^{238}U and ^{232}Th from which nearly equal-energy coincident gamma transitions can occur.[11,12] If pairs of these gamma rays enter two of our detectors, the Doppler broadening is determined by the detector opening and relatively sharp lines are obtained (width $\sim$16 keV). For 60°-correlated detector pairs gated by the C window, the angular correlation between the gamma rays happens to decrease the intensity compared to 180° correlation and so the lines also appear in the difference spectrum in Fig. 3. For the windows C_L and C_H, this trend is reversed and strong line features appear in the summed-energy spectra produced by the 60°-correlated detector pairs [Figs. 2(e) and 2(f)].

In Fig. 3, the 97% confidence limits correspond to the sum of the counts in a 4-keV-wide line. (For the purpose of display in Fig. 3, a 4-keV-wide running average is presented, which does not degrade the intrinsic resolution of the spectrum.) We do not see any statistically significant excursion above this limit in the range of interest for the expected $\gamma\gamma$ line (1.5–1.8 MeV). The feature in Fig. 3 near 1.72 MeV extends to 4 times the standard deviation above the zero line.

From the difference spectrum of Fig. 3 we can estimate an upper limit for the number of counts in an expected 4-keV-wide $\gamma\gamma$ line. Correcting for absorption in the Pb shield, solid angle, and efficiency of the detectors, we arrive at an upper limit for the yield of the $\gamma\gamma$ line of 3×10^{-10} $\gamma\gamma$ decay per incident 6.02-MeV/nucleon U in a 3.6-mg/cm^2-thick target, or an average cross section of 3×10^{-29} cm^2. It is desirable to compare this limit with the yield of the e^+e^- line[1] in the same reaction. The latter has been estimated by comparison with the Rutherford scattering cross section to be approximately $(1\text{–}2)\times10^{-28}$ cm^2, averaged over typical target thicknesses of 0.3–0.6 mg/cm^2, and with the assumption of isotropic e^+e^- emission.[2,3] It is believed that the e^+e^- line is produced only in a narrow energy window near 5.87 MeV/amu, with a width corresponding to the target thicknesses used. Possibly, several such energy windows exist.[1,2] Our targets were chosen to be thick enough to integrate over these energy regions. If we assume that the presumed particle is produced only within a target thickness of 0.6 mg/cm^2, our upper limit to the $\gamma\gamma$ cross section becomes 2×10^{-28} cm^2. Hence, we conclude that most likely the $\gamma\gamma$ decay branch of the presumed particle is not larger than the e^+e^- decay branch. This would eliminate all theoretical models predicting a $\gamma\gamma/e^+e^-$ branching ratio exceeding unity.

We thank the SUPERHILAC operators for producing an exceptionally stable uranium beam. This work was supported in part by the National Science Foundation Grants No. PHY-83-13676 and No. INT-84-14671, and by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High-Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF 00098.

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