180°-Correlated Equal-Energy Photons From 5.9-MeV/Nucleon U+Th Collisions

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We have found a narrow line (intrinsic width ≤ 2.5 keV) at 1062 ± 1 keV in the summed-energy 180°-c.m.-correlated two-photon spectrum from 5.95-MeV/nucleon U+Th collisions. Including possible systematic uncertainties, the production cross section is found to be 50 ± 25 μb, averaged over the 1-mg/cm^2 Th target thickness. This line may belong to the decay of a neutral system which also produces correlated electron-positron pairs found by others in the same reaction.

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Recent results with the EPOS double-solenoid spectrometer at the Gesellschaft für Schwerionenforschung, Darmstadt, Germany (GSI), have revealed correlated, equal-energy positron-electron lines at summed energies of 624 ± 10, 760 ± 20, and 815 ± 10 keV in U+Th collisions between 5.8 and 5.9 MeV/nucleon.[1-4] The line structures are consistent with the hypothesis that a neutral system is formed in the center of mass (c.m.) of the collision,[1-7] with a velocity spread no larger than the c.m. velocity ($\beta_{\text{c.m.}} = 0.056$).[4] The implied masses of the neutral system would be 1646 ± 10, 1782 ± 20, and 1837 ± 10 keV. The ORANGE spectrometer group at GSI has found an additional positron line in 5.6–5.9-MeV/nucleon U+U collisions at a laboratory energy of 220 ± 10 keV.[8-10] Assuming that these positrons are also accompanied by equal-energy electrons emitted from a neutral system moving with the c.m. of the collision partners, one derives an additional mass for the neutral system of 1498 ± 20 keV.[9]

These results are consistent with the existence of a neutral system which has at least four different states of excitation. It was noted previously[10,11] that these states might decay into two or three photons, depending on their spins and parities, besides decaying into positrons and electrons. We have found a 180°-correlated two-photon line in $\simeq$6-MeV/nucleon U+Th collisions with a sum energy of 1062 ± 1 keV and an intrinsic width of less than 2.5 keV, which may represent yet another state of the neutral system.

In the present experimental arrangement, fourteen Ge detectors, each 5.0 cm diam by 5.0 cm long and surrounded by bismuth germinate (BGO) anti-Compton shields,[10] were arranged into seven detector pairs, each pair in a plane containing the U-beam axis. The forward detectors of each pair were located such that four had polar angles with respect to the beam of 65°, two had 43°, and one had 87°. The partner detectors for each pair were positioned at 174° with respect to the forward detectors, to take into account the expected aberration angle for photons emitted from a system moving with $\beta = 0.056$.

A 0.32-cm lead shield was placed in front of each detector and another 0.32-cm lead shield was placed over the faces of the target chamber to attenuate a background of low-energy photons. Also, each detector was provided with a 2.5-cm-long hollow conical lead plug which protected the BGO shield from direct target gamma rays and which insured an effective 8.6°-half-angle opening into the Ge detector.

Beam currents up to 50 nA U^{40+} from the Lawrence Berkeley Laboratory SuperHILAC impinged on 1-mg/cm^2 rolled Th targets. Total accumulation time for the data was approximately 150 h. Targets became translucent because of oxidization after 2 to 6 h, but otherwise did not deteriorate, as shown by weighing and by measuring the target thickness with alpha particles.[12] The typical duty cycle of the accelerator was (10–15)%, giving instantaneous counting rates in the forward BGO shields of $\simeq 10^5$/s and in the Ge detectors of $\simeq 2 \times 10^4$/s. Gains of the Ge detectors were kept constant to $\pm \frac{1}{2}$ keV at 1 MeV. All coincidences between any two detectors were recorded in event mode. A sorting program selected coincidences between any forward detector and its 174°-correlated partner, as well as the mirror partner of the latter, reflected in a plane containing the beam. The latter coincidences are called "uncorrelated" below; they satisfy the same first- and second-order Doppler shift conditions as the correlated coincidences.

The kinematics of the expected $\gamma\gamma$ decay of a system moving with a velocity $\boldsymbol{\beta} = \mathbf{v}/c$ is described in Fig. 1 of

Ref. 10. If E_1 and E_2 are the laboratory photon energies of any two 180°-correlated, equal-energy (E_0) γ rays emitted by the system, the expected counts lie in a wedge-shaped window in the E_1,E_2 plane centered on the parametrically expressed line

$$E_1 = E_0\gamma(1+\beta\cos\theta_0), \quad E_2 = E_0\gamma(1-\beta\cos\theta_0). \qquad (1)$$

Here, $\gamma=(1-\beta^2)^{1/2}$ and θ_0 is the forward photon-emission angle with respect to $\boldsymbol{\beta}$ in the reference frame of the emitting system. The slope of the line depends on the wedge parameter $\epsilon=\beta\cos\theta_0$ $[=(E_1-E_2)/(E_1+E_2)]$ and the width of the window can be expressed in terms of the range in ϵ.

At first, we used three sorting windows with ranges for ϵ equal to (−0.01,0.01), (0.02,0.07), and (0.10,0.13) for the 43° detectors, and similar windows for the other detectors. These ranges in $|\epsilon|$ correspond to $\beta=0$, $\beta_{\text{c.m.}}$, and $3\beta_{\text{c.m.}}$, respectively, where β represents a mean velocity of the emitter along the beam direction (the only symmetry axis in our experimental arrangement).

The corresponding correlated summed-energy spectra are shown in Figs. 1(a) to 1(c) and the uncorrelated spectra in Figs. 1(d) to 1(f). A prominent positron annihilation $\gamma\gamma$ line appears at 1022 keV in the correlated spectra, because the 87° Ge detector ($\theta_0=90°$) is insensitive to the velocity of the emitter. If coincidences from this detector pair are omitted, the 1022-keV line appears only in the $\beta=0$ window. A Gaussian fit to the 1022-keV line gives a linewidth of 2.8 keV which is slightly larger than the summed-energy resolution of our detector system of 2.1 keV (FWHM) as obtained with radioactive sources. In Fig. 1(b), corresponding to $\beta_e=\beta_{\text{c.m.}}$, a narrow line appears at 1062 ± 1 keV, which we believe to be a candidate for the two-γ decay of a neutral system. No other candidate could be found in our spectra, which extended to 2000 keV.

In order to interpret the event data in the E_1,E_2 plane in more detail, we made the assumption that the emitter laboratory velocity $\boldsymbol{\beta}$ consists of a component $\boldsymbol{\beta}_e$ along the beam direction and an additional component which is

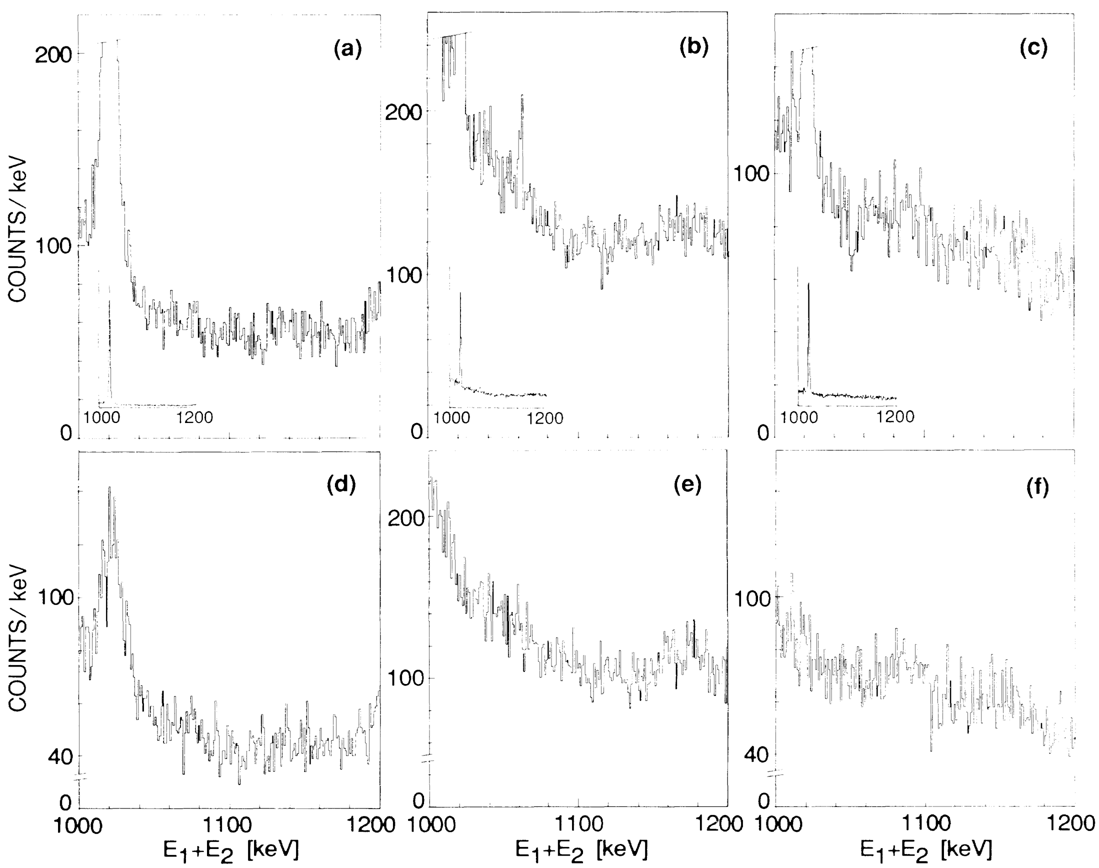

FIG. 1. Summed-energy photon spectra in all Ge detector pairs. (a)–(c) ≃174°-correlated spectra corresponding to sorting windows for mean emitter velocities $\beta=0$, $\beta_{\text{c.m.}}$, and $3\beta_{\text{c.m.}}$, respectively. Insets: Vertical scale is compressed by a factor of 10. The prominent 1022-keV line is due to positron annihilation. The 1062-keV line appearing in (b) meets all the criteria for correlated two-photon decay of a neutral system. (d)–(f) The uncorrelated spectra corresponding to (a)–(c), respectively.

isotropic in this moving frame of reference, corresponding to the (arbitrary) momentum ($|p|$) distribution assumed in Ref. 1:

$$N(|p|) \propto p^2 \exp(-|p|/p_0). \quad (2)$$

Here, p_0 characterizes the width of the momentum distribution, which is peaked at $|p|=2p_0$. We tried to extract values of β_e and p_0 by comparison of the event data with a relativistic Monte Carlo calculation.

The important criteria for a true $\gamma\gamma$ line are these:

(1) It must have a width close to the detector resolution since the laboratory photon sum energy $E_1+E_2=2\gamma E_0$ is broadened only by the second-order Doppler effect and is independent of the detector angle or opening. On the other hand, a cascade of accidentally nearly equal-energy γ rays from a source moving with $\beta_{\text{c.m.}}$ would give an average line width of $\simeq 7$ keV at 1000 keV, determined by the Ge detector opening angles. The 1062-keV line has a width of 3.4 keV; it is shown in Fig. 2. Superimposed on Fig. 2 is the line shape as given by the relativistic Monte Carlo calculation with $\boldsymbol{\beta}_e=\boldsymbol{\beta}_{\text{c.m.}}$, and $p_0=0.02mc$. Isotropic emission of photons in the rest frame of the emitting system was also assumed.

(2) A true $\gamma\gamma$ line must not appear in the uncorrelated spectra. The 1062-keV line does not appear in these spectra. The shape of the uncorrelated spectrum [Fig. 1(e)] was used as background in Fig. 2.

(3) A true $\gamma\gamma$ line must appear with exactly the same energy and width in each separate correlated detector pair. Unfortunately, the statistics of the data were insufficient to make this test fully meaningful. However, we were able to divide the detector pairs into two groups, one consisting of the four pairs with forward detectors at 65° and the other group composed of the three remaining detector pairs. The 1062-keV line appears in each group although with reduced statistical significance.

(4) The line should not appear in the $\beta_e=0$ window; otherwise it could be due to a strongly correlated cascade from a radioactive or slowly moving nucleus. A 0^+-0^+ transition from a nucleus at rest would appear as a 2.1-keV-wide line in all β_e windows; if the nucleus were moving with $\beta_e \gtrsim \beta_{\text{c.m.}}$, this line would be at least 7 keV broad.

(5) In sorting the data on E_1-E_2, it is necessary to shift the origin of E_1-E_2 so that, for each detector group, $E_1-E_2=0$ corresponds to an emitter moving with the velocity β_e along the beam direction. By choosing various sorting wedges, we found that the area of the 1062-keV peak maximizes for wedge parameters ϵ that correspond to $\beta_e=(1.1\pm0.3)\beta_{\text{c.m.}}$. Hence, we assumed $\beta_e=\beta_{\text{c.m.}}$. A difference-energy distribution can then be obtained by the variation of the width of the sorting wedge and the differentiation of the line area. The final $|E_1-E_2|$ distribution is shown in Fig. 3. Data for positive and negative values of E_1-E_2 were averaged to obtain meaningful statistics. Superimposed we show results of the above-mentioned Monte Carlo calculations with $p_0=0.02mc$ and $0.05mc$. If $p_0<0.01mc$ or $p_0>0.04mc$ a fit can no longer be obtained with the experimental data. The Monte Carlo calculation takes into account that the 174° mean angle between detector pairs and 19° total opening of the detector favors emitters with $\beta_e=0.056$. The relative detection efficiency remains larger than 50% for emitters moving with $\beta<0.2$; it drops to 1% for $\beta>0.5$.

(6) The line must be statistically significant. Figure 3 indicates that the number of counts in the 1062-keV line increases as the $|E_1-E_2|$ window is opened. The maximum number of counts is 200, but the optimum peak-

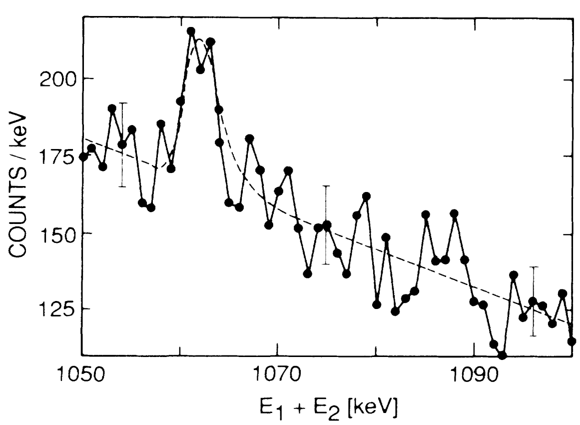

FIG. 2. Summed-energy photon spectrum corresponding to the sorting window for $\beta_e=\beta_{\text{c.m.}}$. Superimposed dashed line is a relativistic Monte Carlo calculation with $p_0=0.02mc$ [Eq. (2)].

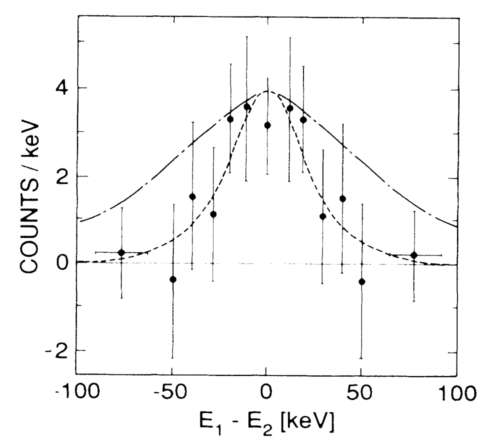

FIG. 3. Yield per kiloelectronvolt of photons within the 1062-keV peak shown in Fig. 2 as a function of the energy difference E_1-E_2. $E_1-E_2=0$ corresponds to the energy difference expected for an emitting system moving with $\boldsymbol{\beta}_e-\boldsymbol{\beta}_{\text{c.m.}}$. Superimposed are Monte Carlo calculations with $p_0=0.02mc$ (dashed line) and $p_0=0.05mc$ (dash-dotted line).

to-background ratio is 167/680. Using a statistical reasoning similar to that of Ref. 1, we see that the $\gamma\gamma$ line has a statistical significance of 5.7 σ (σ=standard deviation), if we assume that the linear background under the line is taken over a sufficiently large interval. Equivalently, one can say that a 167-count excursion of a 680-count background would be a 6.4σ excursion, which has a likelihood of 1 part in 10^{10} at any given location or approximately 1 part in 10^7 in the full spectrum.

Including possible systematic uncertainties in the detection efficiency, we find the total production cross section of the 1062-keV $\gamma\gamma$ line to be 50 ± 25 μb averaged over the 1-mg/cm^2 target thickness or, equivalently, over the projectile energy interval from 5.75 to 5.95 MeV/nucleon. We also find that any higher-energy 2.8-keV-wide $\gamma\gamma$ line has a production cross section of less than 3 μb. Possible $\gamma\gamma$ lines below 1022 keV would be masked by the large background of nuclear cascades.[10]

The question now arises as to whether the 1062 ± 1 ($\Gamma \leq 2.5$ keV), 1498 ± 20, 1646 ± 10 ($\Gamma \leq 25$ keV), 1782 ± 20, and 1837 ± 10 ($\Gamma \leq 40$ keV) keV masses and intrinsic widths Γ of the proposed neutral system show any systematic features. First, on general phase-space considerations, one can argue that a $\gamma\gamma$-decay mode of any states might be enhanced, relative to the e^+e^- width, close to the 1022-keV e^+e^- breakup threshold. As soon as sufficient e^+e^- kinetic energy is available, the e^+e^- width $\Gamma_{e^+e^-}$ will overwhelm the $\gamma\gamma$ width $\Gamma_{\gamma\gamma}$. Second, if the decaying system is pseudoscalar, one expects the production cross section of lower-energy states to be strongly enhanced,[11] but present e^+e^- spectrometers would not detect states below $\simeq 1400$ keV. Third, it is possible that the 1062-keV state is the ground state (with spin zero) of the proposed neutral system. If there were states below 1022 keV, they could be reached by positronium decay, but such a decay mode has not been found.[13] On the other hand, given the correct spin and parity, the 1062-keV state might influence the half-life of parapositronium.[14] In summary, the narrow 1062-keV line found in this experiment supports the suggestion[1,8,9] that the neutral system giving rise to the e^+ and e^+e^- lines in heavy-ion collisions has a complex structure.

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1. T. E. Cowan *et al.*, Yale University Report No. 3074-927, 1986 (to be published).

2. H. Bokemeyer, Gesellschaft für Schwerionenforschung Report No. GSI-87-1, 1987 (to be published).

3. T. Cowan *et al.*, Phys. Rev. Lett. **56**, 444 (1986).

4. T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985).

5. A. Schäfer *et al.*, J. Phys. G **11**, L69 (1985); J. Reinhardt *et al.*, Phys. Rev. C **33**, 194 (1986).

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

7. B. Müller *et al.*, J. Phys. G **12**, L109, L477 (1986).

8. P. Kienle, Gesellschaft für Schwerionenforschung Report No. GSI-86-33, 1986 (to be published).

9. H. Tsertos *et al.*, Z. Phys. A **326**, 235 (1987).

10. W. E. Meyerhof *et al.*, Phys. Rev. Lett. **57**, 2139 (1986).

11. B. Müller and J. Rafelski, Phys. Rev. D **34**, 2896 (1986).

12. We are very grateful to A. Ghiorso for these measurements.

13. W. Wahl, Ph.D. thesis, University of Heidelberg, 1987 (unpublished).

14. C. I. Westbrook *et al.*, Phys. Rev. Lett. **58**, 1328 (1987), have found a theoretically significant discrepancy in the lifetime of orthopositronium.

15. F. T. Avignone *et al.*, Phys. Rev. A **32**, 2622 (1985).