

## Search for narrow-peak structure in the three-photon spectrum from 6-MeV/nucleon U+Th, U+U, and Th+Th collisions

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We have searched for three-photon decays produced in 6-MeV/nucleon U+Th, Th+Th, and U+U collisions. We see no evidence for narrow lines corresponding to the electron-positron lines seen by others: in the summed-energy region between 1.2 and 2.0 MeV, we set an upper limit for the cross section of  $3 \times 10^{-28}$  cm<sup>2</sup> averaged over a target thickness of 1 mg/cm<sup>2</sup>.

Experimental studies of heavy-ion collisions at the Coulomb barrier at the UNILAC accelerator at GSI have revealed an unexpected line structure in positron spectra and in correlated electron-positron sum-energy spectra. The EPOS spectrometer group has found structures at kinetic sum energies of 608, 760, and 809 keV in the U+Th system, and at 625, 748, and 805 keV in the U+Ta system [1]. The ORANGE spectrometer group has seen significant structures at 630 and 805 keV in U+Ta and at 555 and 787 keV in U+U and U+Pb collisions [2]. There is evidence for 180° correlation for at least one of these lines [3].

It has been hypothesized that these results might be explained by the formation and decay of a new light neutral system which has two or three different states of excitation or a new family of neutral particles in the mass range 1.5–2 MeV [4–9]. Numerous attempts have been made to search for manifestations of these objects in other areas of physics: e.g., in Bhabha scattering [10], anomalous magnetic moment of the electron [6], positron annihilation in flight [11], beam-dump experiments [12], two-photon decay in heavy-ion collisions [13,14], level structure of positronium [15], but all to no avail. The GSI events remain an isolated phenomenon with no direct supporting evidence from other experiments, although some indirect evidence exists, e.g., a ten-standard-deviation discrepancy in the lifetime of the  $^3S_1$  positronium ground state [16].

The existence of new elementary bosons in this mass range has meanwhile been ruled out unambiguously.

This statement is based on new results from Bhabha scattering [10] and beam-dump experiments [12]. Extended particles with internal structure cannot completely be ruled out on this basis, because beam-dump experiments are not sensitive to particles much larger than 100 fm [17]. In this case, Bhabha scattering alone poses a lower limit on the lifetime of  $7.5 \times 10^{-12}$  s, leaving only a small gap to the upper limit of  $10^{-10}$  s, which the heavy-ion experiments can accommodate. In addition, theoretical studies have shown that, in principle, an entirely new sector of particle physics, involving new extended particles with new light fermions as constituents, could exist in the relevant range of energies [9], having escaped many years of research. Besides, the heavy-ion experiments provide a different scenario (e.g., large external fields) and can, therefore, not be replaced by the, in principle, much cleaner  $e^+e^-$  scattering system. The conclusion seems to be that the basis of existing evidence is not sufficient and that every lead should be followed which might show interactions of these hypothetical objects.

Although it has been noted that these objects might also decay into three photons [18], this potential interaction channel has not been investigated so far. We have decided to fill this gap and report here the results of our search for three-photon decay events in 6-MeV/nucleon U+Th, U+U, and Th+Th collisions. This search is especially meaningful in view of the above-mentioned discrepancy in the lifetime of the  $^3S_1$  positronium ground state.

Details of the experimental arrangement can be found

in Refs. [13] and [14]. Briefly, we used 18 Ge detectors, each 5 cm in diameter by 5 cm long and surrounded by bismuth-germanate (BGO) anti-Compton shields. The Lawrence Berkeley Laboratory SUPERHILAC delivered typical beam currents of 75 nA  $U^{42+}$  and  $Th^{37+}$ . In order to eliminate rapid target deterioration in these intense beams, five targets each were mounted on a rotating target wheel [19]. We used 1-mg/cm<sup>2</sup> targets of rolled thorium and evaporated metallic uranium [20].

During a total of seven weeks of beam time, we investigated the collision systems U on U at 5.95 MeV/nucleon (65 mC integrated beam charge), Th on Th at 5.75 MeV/nucleon (26 mC), Th on Th at 5.93 MeV/nucleon (30 mC), U on Th at 5.95 MeV/nucleon (63 mC), 5.85 MeV/nucleon (12 mC), and at 6.05 MeV/nucleon (26 mC). The beam energy was checked with a phase probe, and with a crystal detector placed both before and after the target. The typical beam energy spread was 1%.

The typical duty cycle of the accelerator was 15%, giving instantaneous counting rates in the individual Ge detectors of  $3 \times 10^4$  s<sup>-1</sup>. All coincidences between any two or more detectors were recorded in event mode. A sorting program selected coincidences between any three detectors.

In searching for three-photon decay events, it would be ideal to perform an invariant mass determination. This is, unfortunately, impossible in our setup. But we can, instead, exploit the kinematics of a three-photon decay to impose sorting cuts that pass only a small number of remaining background events: (1) The hypothetical object is expected to move with roughly the center-of-mass (c.m.) velocity of the collision partners  $v_{c.m.}/c = 0.056$ . The first-order Doppler shifts cancel event by event for a three-photon decay. So the laboratory photon sum energy  $E_1 + E_2 + E_3 = \gamma E_0$  is broadened only by the small second-order Doppler effect and is independent of the detector opening or angle. Hence, the sum-energy line must have a width close to the detector resolution (4 keV for three-photon sum energies). (2) For such slowly moving objects the laboratory photon emission angles will essentially lie in a plane and momentum conservation gives simple relations between the permissible photon energies.

These considerations leave only two possible triples out of our 18 detectors. Their arrangement is shown in Fig. 1. Spectra from detectors 1-7-13 and 4-10-16 were added together to form the "correlated" sum-energy spectrum. In addition, we also created an "uncorrelated" spectrum from triples 1-4-7 and 10-13-16, which should be identical, except that it cannot contain real three-photon decay events. This is because, with all three photons going into the same hemisphere, momentum conservation would be violated for slowly moving objects undergoing a three-photon decay.

The total detection efficiency for three-photon decays is not simply determined by the efficiency of the single detectors, but it is a function of solid angle, quantum efficiency, and the geometry-dependent phase-space acceptance. Solid angle and quantum efficiency were determined by the combination of singles and coincidence calibrations using the 511-keV annihilation radiation from a

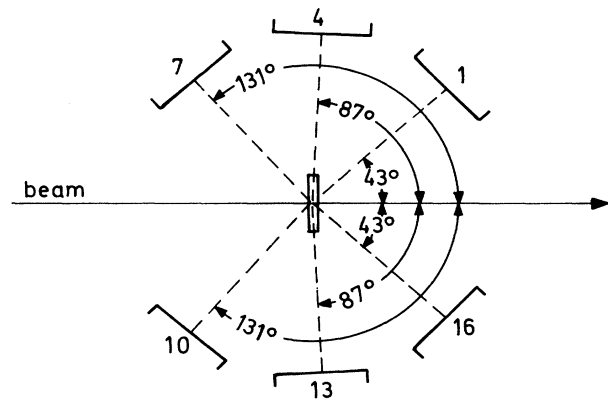


FIG. 1. Experimental arrangement. The target is placed at 90° to the beam. The Ge detectors are placed 11 cm from the target at the angles shown. Detector triples 1, 7, 13 and 4, 10, 16 give correlated spectra, detector triples 1, 4, 7 and 10, 13, 16 uncorrelated spectra. All the detectors lie in one plane.

$^{22}Na$  source. After considering the geometry of our arrangement, we calculated the phase-space acceptance depicted as a Dalitz plot in Fig. 2(a). In the sorting program we approximated this acceptance window by the simpler linear cuts depicted in Fig. 2(b). With a singles efficiency of one count per 2800 photons at 500 keV, an effective solid angle of 0.07 sr per detector, and the phase-space acceptance of Fig. 2(a), we estimate the total detection efficiency for three-photon decays of slowly moving objects at one count per  $10^7$  decays for two detector triples.

The correlated summed-energy spectra for the collision systems U+Th, U+U, and Th+Th were added to improve statistics and the total spectrum is shown in Fig. 3(a). Figure 3(b) shows the corresponding uncorrelated spectrum.

Both spectra are essentially identical and we do not see any statistically significant narrow structure in any of our

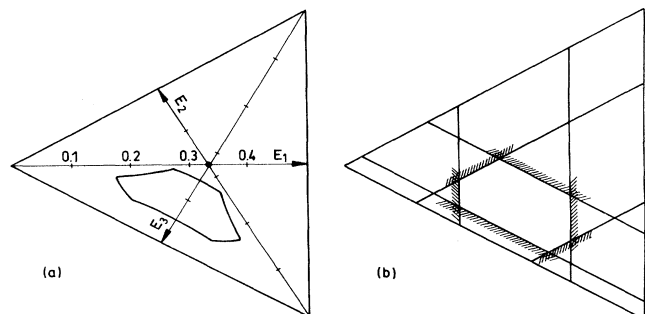


FIG. 2. Dalitz plot of phase space for three-photon decay.  $E_1$ ,  $E_2$ , and  $E_3$  are the individual photon energies normalized by the sum energy. (a) Accepted phase space due to geometry of detectors. (b) Approximation by linear cuts for sorting program.

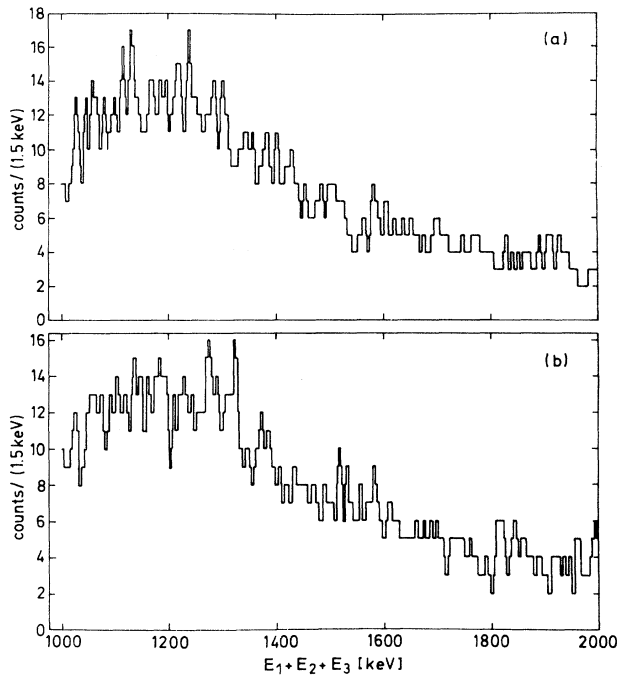


FIG. 3. Three-photon sum energy spectra obtained by summing data for all collision systems. For display purpose, a 7-keV-wide running average has been applied. (a) Correlated sum-energy spectrum. (b) Uncorrelated sum-energy spectrum.

collision systems. Correcting for absorption in the Pb absorber, for the solid angle, for the phase-space acceptance, and for the efficiency of the detectors, we arrive at an upper limit (one standard deviation) for the yield of any 4-keV-wide correlated three-photon line of  $1 \times 10^{-9}$  three-photon decays per incident nucleus in a 1-mg/cm<sup>2</sup>-thick target, or an average cross section of 300  $\mu\text{b}$ . This has to be compared with the yield of the  $e^+e^-$  lines in similar reactions. But a serious difficulty arises, because

the  $e^+e^-$  cross sections are normalized to the solid angle of the heavy ions detected in coincidence, and they have been obtained for a restricted range of scattering angles. The emission probability depends strongly on the scattering angle and is unknown outside the range investigated. For the single positron lines the EPOS group quotes a cross section of 10  $\mu\text{b}/\text{sr}$  [1]. They also state that the coincidence  $e^+e^-$  lines account for a cross section of about 5  $\mu\text{b}/\text{sr}$ . The ORANGE group obtains a value of 14  $\mu\text{b}/\text{sr}$  for the single positron lines in U+U [2], but their coincidence yield seems to be smaller by more than a factor of 10 [3]. Assuming isotropic  $e^+e^-$  emission and integrating over the heavy-ion solid angle, we derive from these numbers typical production cross sections for the  $e^+e^-$  lines of approximately 50 and 5  $\mu\text{b}$ , respectively.

If there is only one three-photon branch and if the full target thickness contributes, we can set upper limits for the ratio  $R$  of the three-photon decay branch to the  $e^+e^-$  decay branch of the presumed neutral particle of  $R < 6$  and  $R < 60$ , respectively. We conclude that the three-photon decay branch of a presumed object cannot be much larger than the  $e^+e^-$  decay branch. This would eliminate all theoretical models predicting a  $3\text{-}\gamma/e^+e^-$  branching ratio appreciably exceeding unity, i.e., any model that couples the unknown object directly to photon decay. The theoretical implications remain to be explored.

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