Search for resonances in multiphoton final states from low-energy e^+e^- scattering

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We have performed a search for resonant states in low energy e^+e^- scattering through their decay to multiphoton final states using e^+ from ^{68}Ga sources and a Pb absorber. We obtained energy-sum and invariant mass spectra of coincident 2γ and 3γ events using the 20-element High Energy-Resolution Array (HERA) facility. No evidence for resonant states was found, and upper limits for the partial decay widths of such resonances were established in the energy range from 1.1 to 1.8 MeV.

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I. INTRODUCTION

Sharp peaks have been observed in coincident e^+e^- pair spectra obtained by the EPOS [1,2] and, independently, by the ORANGE [3] experimental groups, both at Gesellschaft für Schwerionenforschung (GSI). These peaks are observed when two heavy ions such as U and Th collide at center-of-mass (c.m.) energies near the Coulomb barrier and when a large-angle scattering of the two heavy ions is detected. Under such conditions, an effective charge of greater than 160 might be obtained for a short time period localized within a radius of about 20 fm from the c.m. These sharp peaks are suggestive of a long-lived neutral object (system or particle created in the collision process) that decays to an e^+e^- pair. Both experimental groups at GSI have reported that there is some evidence that the e^+e^- decays may occur from a neutral object interacting with a third body. The e^+e^- peaks observed at GSI have provided a major theoretical challenge [4].

Motivated by these results, numerous searches for resonance phenomena in e^+e^- (Bhabha) scattering, $e^+e^- \to X \to e^+e^-$, have been performed and the results are conflicting. Some experiments [5–7] claim to see a weak resonance, while other experiments [8–16] claim to exclude these signals. Since the observed signals are, at best, rather weak, present evidence for e^+e^- resonances produced directly in Bhabha scattering is inconclusive. It is interesting to note that the experiments claiming positive results generally used a thick high-Z target (which would provide a large electric field near the nucleus) and/or wide angular acceptance detectors (which would make them more sensitive to processes that deviate from strict two-body kinematics). We designed our experiment to include both of these characteristics, a high-Z target and wide angular acceptance detectors.

Additional searches have been conducted for evidence of resonances in the processes $e^+e^- \to X \to 2\gamma$ and $e^+e^- \to X \to 3\gamma$ by other investigators with little success. In these experiments, the e^- targets are bombarded with e^+ from a β^+ emitter or accelerator. The reported 2γ searches are negative [17–23]. However, a recent 3γ search by Skalsey and Kolata [24] found an energy-sum peak at 1455 keV whose area is 2.9σ above background, and a 2.2σ energy-sum peak at 1648 keV. (The quoted energy is the sum of the energies of three γ rays in triple coincidence and σ is the normal standard deviation.) In their experiment, a Be foil target is bombarded by a collimated beam of e^+ from a 100 μCi ^{68}Ge/^{68}Ga β^+ source. An array of five detectors coplanar with the source was used to detect the γ rays emitted from the Be target. Their total counting time was 222 hours. They concluded from a Dalitz analysis of the 1022-keV and 1455-keV peaks that momentum is conserved in the 3γ decay of the 1022-keV peak from orthopositronium (as expected), but not in the 3γ decay of the 1455-keV peak. This finding is consistent with an interpretation of the 1455-keV peak as either a random fluctuation in a widely distributed Dalitz plot or a decaying particle coupled to a massive partner such as the Be target [24]. Skalsey and Kolata thus conclude that there is no evidence for a new stopped

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unbound neutral particle in their data set.

This accumulated set of puzzling and seemingly conflicting experimental results motivated us to search for resonances in coincident multiphoton final states from e^+e^- scattering in the vicinity of strong fields. Our experiment was also motivated by recent calculations [25] of states in a proposed neutral e^+e^- compound called photonium. (For brevity, in the rest of this paper, the terms photonium and X will be used interchangeably.) The calculations were carried out in the $J^\pi=0^+$, $L=1$, $S=1$ channel using relativistic two-body wave equations that are based on QED. Some of these calculated states lie near the energies of peaks observed in the GSI experiments. The free-space widths of these states are zero in the present calculations, but neglected QED processes may be expected to add a finite contribution. Other experiments [8–16] indicate that if these states exist their free-space decay widths are exceedingly small. The current upper limits of the partial width for $e^+e^- \to X \to e^+e^-$ are 1.3×10^{-2} meV for spin-0 and 6.5×10^{-3} meV for spin-1 resonances at 1.83 MeV using the active-shadow technique [13], and 1.6×10^{-3} meV for spin-0 and 1.1×10^{-3} meV for spin-1 resonances in the mass range 1.5 MeV to 1.86 MeV using the active-target system [15]. For the process $e^+e^- \to X \to n\gamma$, the upper limits are 2.7 meV for spin-0 [22], and 5 meV for spin-1 resonances at 1.83 MeV [23]. A scenario that has not been excluded is that the e^+e^- peaks arise from the production and stimulated decay of photonium in high fields. Production rates for photonium from e^+e^- collisions in high-Z target materials have been studied [26,27] theoretically.

II. EXPERIMENTAL PROCEDURE

A search was carried out for 2γ and 3γ decay channels of a resonant e^+e^- composite system, which we refer to as photonium. An e^+ source made of ^{68}Ga, in secular equilibrium with its 288-day half-life parent ^{68}Ge, was enclosed inside the cavity of a lead spherical shell. The HERA facility at the Lawrence Berkeley Laboratory was used to detect the γ rays. The HERA array consisted of 20 Compton-suppressed Ge detectors and a 4π, 40-element bismuth germanate (BGO) inner ball. The solid angle of each Ge detector is 82 msr. The angle between any pair of Ge detectors ranged from 37° to 157°. The lead shell had an inner radius of 0.238 cm and an outer radius of 0.476 cm. The positrons of interest for the experiment are emitted in the decay of ^{68}Ga to the ground state of ^{68}Zn. The ground-state decay branch is 97%, with 88% by positron emission, and the positron kinetic end-point energy is 1.899 keV [28]. The upper limit on the mass of the composites that can be produced in this experiment ranges from 1728 keV to 2921 keV depending on the assumed reaction mechanism, i.e., whether it is a simple two-body process or a more complicated many-body process. In the case of the higher limit, one assumes an infinitely massive partner recoiling to conserve energy and momentum, leaving the produced particle at rest in the lab frame.

Even for a pure two-body process, the end-point energy is sufficient to produce the lowest energy GSI resonance (1660 keV) and the three lowest predicted resonances (1351, 1498, and 1659 keV) in photonium [25]. The target-source assembly was positioned at the focal center of HERA so each of the 20 Ge detectors subtended the same solid angle. The source strength at the beginning of the experiment was 67 μCi. The counting took place whenever HERA was available for off-line experiments (i.e., not used for in-beam experiments). The total counting time on HERA using the lead sphere was 94 days (2260 hrs) over a period of 5 months. The experiment was terminated by the permanent shut down of HERA in preparation for the construction of Gammasphere.

During the experiments, the energies of the coincident γ rays from the Ge detectors, the time relationship between the first and second γ rays, plus the total energy and multiplicity from the BGO ball were recorded on magnetic tape. The average singles rate in each Ge detector was 12 kHz and the average total coincidence rates were 610 Hz and 12 Hz for 2γ and 3γ coincidences, respectively. A total of 4.9×10^9 double and 9.8×10^7 triple coincidence events were recorded from the 94-d total counting time with the lead sphere. For analysis, the only accepted events were those with no energy deposited in the BGO ball and a multiplicity of two (for 2γ coincidences) or three (for 3γ coincidences) in order to ensure that most of the events came from the annihilation of positrons or the decay of photonium. This condition reduced the total number of accepted events to 1.1×10^9 and 1.3×10^7 for the double and triple coincidences, respectively. Also, the events were selected within the timing window of 35 ns. Random coincidence events were selected by setting a chance timing gate about 60 ns from the true timing gate.

III. EXPERIMENTAL RESULTS

A prime motivation of this experiment was to measure the invariant mass for photonium decaying into two or three γ rays. An additional motivation was to search for the peaks at 1455 and 1648 keV that were observed by Skalsey and Kolata [24]. It is interesting to note that all previous experiments used an "energy-sum" formula to search for the resonances rather than an "invariant mass" formula. In our experiments, we analyzed the data using both methods. The restrictions, advantages, and disadvantages of each method are described in the following subsections.

A. 3γ decay at rest

The search for 2γ decay of photonium at rest was not possible due to the geometry of HERA since it had no pair of detectors separated by 180°. Therefore, we only performed the search for 3γ decay at rest. In constructing our 3γ energy-sum plots, a sort was first made on all triple-coincidence events. Conditions were imposed on the sorted data such that the three γ rays were coplanar with the source and that their measured total momentum was in the interval $[p, p + \delta p]$, where p is the total momentum and δp is the deviation from the true value due to the finite solid angles of the Ge detectors such that about 75% of the true decay would be accepted. For decay at rest, p equals zero and the average δp was about 66 keV/c for an 1100 keV resonance and 108 keV/c at 1800 keV. Also, random coincidences were subtracted and any coincident event with a single 511-keV γ ray or with any known γ ray from the ^{68}Ga source was rejected. A number of new, very low intensity γ rays were identified as being emitted in the ^{68}Ga decay. These new results on the level scheme will be published elsewhere.

The spectrum for the 3γ energy sum measured in this work is shown in Fig. 1(a). The broad bump around 900 keV is due to the scattering of two 511-keV back-to-back γ rays: one γ ray hits a detector, deposits part of its energy, and then scatters into a second detector; the second 511-keV γ ray forward scatters from the lead sphere surrounding the source into the third detector. Figure 1(b) includes an additional condition: rejection of any event in which the sum of any two γ rays falls into the window 511$\pm$5 keV. The difference between the two spectra in Fig. 1(a) and Fig. 1(b) is the absence of the broad bump around 900 keV. Figure 1(a) is similar to the 3γ energy-sum spectrum shown in Ref. [24]. The lack of rejection of the scattering of two 511-keV back-to-back γ rays may explain the broad bump below the 1022-keV peak and the sharp drop of the background above the 1022-keV peak shown in Ref. [24].

The large peak at 1022 keV in Fig. 1(b) is due to the 3γ decay of orthopositronium in the nonmetallic material within the hollow metal sphere. It has an energy resolution of 3.7 keV (FWHM). The energy resolution of any photonium peak is assumed to be similar to that of the orthopositronium peak and varies linearly with the resonant energy. The values of the energy resolutions used in the calculations of the linear behavior were 3.7 keV at 1022 keV, and 4.8 keV at 2044 keV. The background events can mostly be attributed to coincidences between Compton-scattered γ rays from positron annihilation and the Compton scattering of the 1077-keV γ ray from ^{68}Ga decay. The decay branch to the 1077-keV level in ^{68}Zn is 1.3% abundant. There will also be some events from Compton scattering between detectors since the BGO Compton suppression system is not 100% efficient.

Figure 1(b) shows no evidence for peaks above 1100 keV in the energy-sum spectrum for the 3γ decay of photonium. The region between 1100 keV and 1800 keV is shown in the inset using a linear scale for counts. In particular, we see no evidence for small peaks at 1455 and 1648 keV reported by Skalsey and Kolata [24].

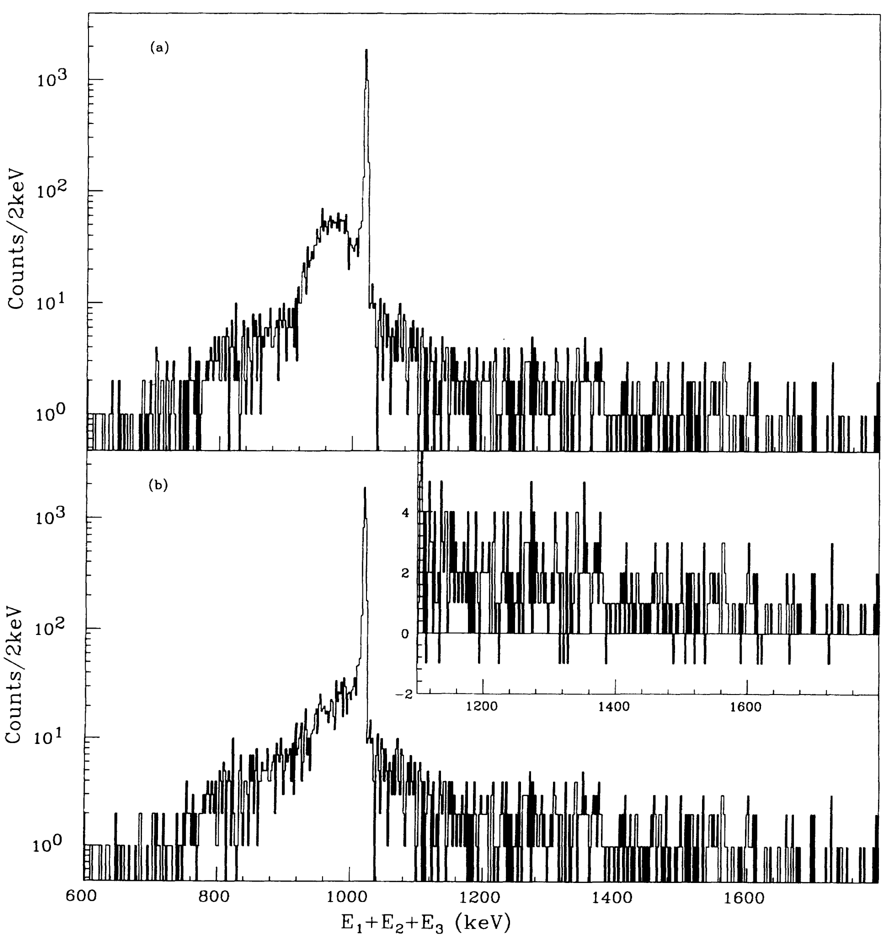

FIG. 1. (a) Energy-sum spectrum for three coincident γ rays. (b) Energy-sum spectrum for three coincident γ rays with the rejection of events in which the sum of any two γ rays falls into the window 511$\pm$5 keV. The inset shows the detail of the region above 1.1 MeV on a linear scale.

From the data shown in Fig. 1(b), we attempt to extract upper limits for photonium decaying at rest into 3γ. We assume a Breit-Wigner line shape and total angular momentum of $\hbar$ for a resonant state of mass M. Then the integrated cross section is given by (for c = speed of light = 1):

$$\int \sigma_{3\gamma}(E)dE = \frac{6\pi^2\hbar^2}{[M^2 - 4m_e^2]}\frac{\Gamma_{3\gamma}\Gamma_{e^+e^-}}{\Gamma}, \qquad (3.1)$$

where Γ, $\Gamma_{3\gamma}$, and $\Gamma_{e^+e^-}$ are the total width of the resonance and partial widths for decay into 3γ and e^+e^-, respectively. Furthermore, $\int \sigma_{3\gamma}(E)dE$ can be determined from the data using

$$\frac{1}{\Gamma}\int \sigma_{3\gamma}(E)dE = \frac{N_{3\gamma}}{C_{3\gamma} \times n_p(e^+) \times n_t(e^-)}, \qquad (3.2)$$

where $N_{3\gamma}$ = counts in the hypothetical peak of the resonance at mass M, $C_{3\gamma}$ = (opening angle factor) $\times$ (γ-ray attenuation factor in lead) $\times$ (detector efficiency), $n_p(e^+)$ = number of e^+ above the resonance, and $n_t(e^-)$ = number of e^- in the target (82 e^- per atom), in units of barns^{-1}.

The "opening angle factor" is the probability of all three coincident γ rays getting into three detectors. It was calculated using Monte Carlo simulation techniques and the HERA detector geometry. It is interesting to note that out of all 1140 possible combinations of 3 detectors, 62 were coplanar with the source. Of these 62 triplets, we retained events from only those 26 triplets sensitive to the decay of photonium at rest in or near the Pb sphere.

The number of e^- in the target is calculated using an effective thickness in the Pb target. This is approximately the average distance an e^+ with kinetic energy $E_{\rm res} + \Gamma/2$ will travel before its energy decreases to $E_{\rm res} - \Gamma/2$. The e^+ can excite the resonance at $E_{\rm res}$ only within this thickness. Thus

$$n_t(e^-) = \frac{Z}{A}N_A\Gamma\left(\frac{dE_{\rm loss}}{dx}\right)^{-1}, \qquad (3.3)$$

where $dE_{\rm loss}/dx$ = energy loss per unit thickness, and N_A = Avogadro's constant.

To obtain an upper limit for $N_{3\gamma}$, we used the following analysis: Assume that all the events (after subtracting the chance background) with total energy greater than 1022 keV in the spectrum are from the decay of an isolated state of photonium. This portion of the spectrum is then fitted to a Gaussian, with the centroid held fixed at a certain energy and the FWHM = [2.6 keV + $1.1\times10^{-3}E_{\rm centroid}$]. From the fit, the area N_0, and its rms uncertainty σ_0, are obtained. The 95% upper limit on N_0 is then calculated assuming the distribution of N_0 to be Gaussian and σ_0 to be its standard deviation. From the Gaussian, the 95% confidence level upper limit of $N_{3\gamma}$ is taken to be the point in the distribution dividing the physical region (positive N_0 values) into two subareas—one with the lower 95% area and the other with the higher 5% area [29]. The process is then repeated in 1 keV steps of the hypothetical resonance across the energy range.

The resulting upper limits of the "strength," $\int \sigma_{3\gamma}(E)dE$, and the partial width, $\Gamma_{3\gamma}\Gamma_{e^+e^-}/\Gamma$, of the resonance decaying at rest into 3γ are shown in Fig. 2. These limits were deduced from the data in Fig. 1(b). Our results can be compared with those of Skalsey and Kolata [24], who gave results of 95% confidence level upper limits for $\Gamma_{3\gamma}\Gamma_{e^+e^-}/\Gamma$ at three energies: 1500, 1540, and 1640 keV. At these energies, our upper limits are lower by factors of about 20, 20, and 70, respectively. Thus, overall, our results in Fig. 2 decrease the upper limits by more than an order of magnitude.

B. 2γ and 3γ energy-sum masses

We made a search for photonium decaying in flight into 2γ and 3γ. This was possible since there are many combinations of two detectors in HERA with angles between them less than 180° and three detectors not lying in a plane containing the source.

If it is assumed that photonium is formed from a moving e^+ and a stationary, free e^- which decays spontaneously into $n\gamma$, then an "energy-sum" plot could be generated. This type of plot is motivated by the fact that the directions and energies of the two (or three) decay γ rays are not fixed, but the sum of the two (or three) energies is uniquely related to the total momen-

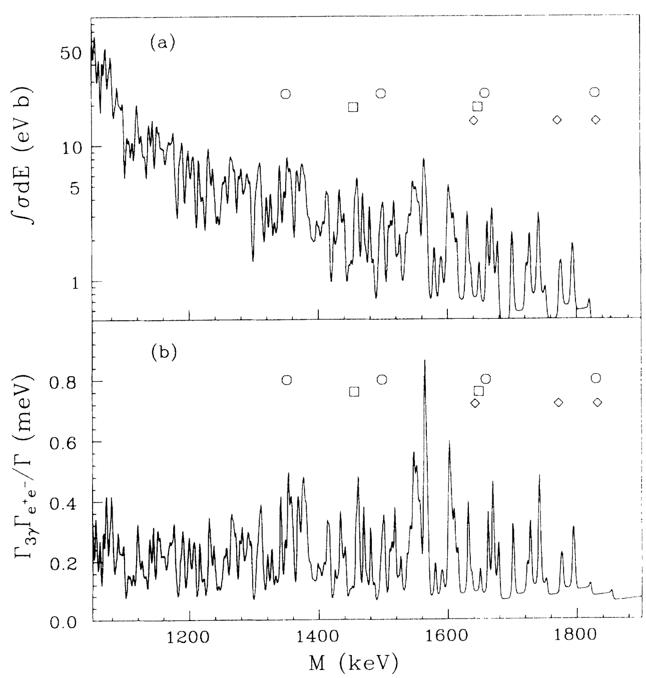

FIG. 2. (a) Upper limits (95%) of the total strength $\int \sigma_{3\gamma}(E)dE$ for a resonance of mass M decaying at rest in the range 1050–1900 keV. Diamonds: energies of peaks seen by EPOS and ORANGE [1–3]; squares: energies of peaks seen in the data reported by Skalsey and Kolata [24]; circles: predicted energies of photonium peaks [25]. (b) Upper limits (95%) of the partial width $\Gamma_{3\gamma}\Gamma_{e^+e^-}/\Gamma$. Comparison of our upper limits with those of Ref. [24] is made in the text.

tum and mass M. Therefore, a narrow resonance would occur at the position $M = \sqrt{2m_e \sum_j^n E_j}$ as a sharp peak above a positron-annihilation-in-flight background in the $(\sum_j^n E_j)$ spectrum. Such a sharp peak would have a width of about 4 keV FWHM due to the intrinsic detector resolution. The expected widths were obtained by measuring the widths of the energy sum of the known γ rays from the source. The FWHM values used in the calculations of the upper limits were FWHM = [2.5 keV + $6.8\times10^{-4}E_{\text{centroid}}$] for 2γ energy-sum mass and FWHM = [2.6 keV + $1.1\times10^{-3}E_{\text{centroid}}$] for 3γ energy-sum mass. The upper limits are calculated using the Breit-Wigner formula:

$$\int \sigma_{n\gamma}(E)dE = \frac{2\pi^2\hbar^2(2J_n+1)}{[M^2-4m_e^2]}\frac{\Gamma_{n\gamma}\Gamma_{e^+e^-}}{\Gamma}, \tag{3.4}$$

where J_n is the total angular momentum of the resonant state, and other values are the same as in Eq. (3.1). The value $\sigma_{n\gamma}$ can be calculated using

$$\frac{1}{\Gamma}\int \sigma_{n\gamma}(E)dE = \frac{N_{n\gamma}}{C_{n\gamma}\times n_p(e^+)\times n_t(e^-)}, \tag{3.5}$$

which is similar to Eq. (3.2).

In the calculations of $n_t(e^-)$, we excluded all the K, L, and M shell electrons. For such tightly bound electrons, their Fermi motion would smear out the resonant peak. Use of less than the full electron number was also done in Ref. [21], where 75% of the total electrons were used. Our cutoff leads to the use of only 54 of the 82 electrons in lead (66% of the total number of electrons). This makes our upper limit larger by a factor of 82/54, which we regard as a conservative choice.

The energy-sum spectra, unlike the case for 3γ decay at rest, contain a large background due to the annihilation-in-flight of positrons. The upper limits of $N_{2\gamma}$ and $N_{3\gamma}$ are calculated by assuming the peak's area to be zero and the standard deviation to be the statistical uncertainty of the background. The 3σ upper limits for $N_{2\gamma}$ and $N_{3\gamma}$ are then just three times the standard deviation.

The momentum restriction set on these spectra was the same as that in Sec. III A, i.e., the measured total momentum was in the interval $[p-\delta p,\ p+\delta p]$. For these energy-sum spectra, $p = \sqrt{E_{\text{tot}}^2 - M^2} = \sqrt{E_{\text{tot}}^2 - 2mE_{\text{tot}}}$, and δp was chosen so that 95% of true decay events would satisfy the imposed condition. For 2γ decay, this δp corresponds to a deviation of about 9.5° in the separation angle of detector pairs. For 3γ decay, δp varies greatly for different energies and different detector combinations. On the average, δp was about 200 keV/c for a hypothetical resonance at 1100 keV and about 800 keV/c for a hypothetical resonance at 1700 keV.

The spectrum and the upper limits of 2γ decay are shown in Figs. 3 and 4. From the positron kinetic endpoint energy of 1.9 MeV, the smallest angle between a pair of detectors possible for two coincident γ rays is 73°. However, the probability of two coincident γ rays (decay from photonium) getting into pairs of detectors with small angles between them is small. Most of the events recorded in those pairs of detectors were from coincidences between Compton scattered γ rays from ^{68}Ga decay and not from photonium decay. Therefore, we only used the data from detector pairs whose separations ranged from 103° to 157°. This reduced the combinations of detector pairs from a total of 190 (out of 20 detectors) to 88. Because of HERA's geometry, which did not have a smooth distribution of detector combinations, the 2γ and 3γ spectra are somewhat "bumpy." The two broad bumps at about 1100 keV and 1300 keV in Fig. 3 are caused by annihilation-in-flight in two sets of angles, 152° − 157° and 103° − 123°, respectively. There were no pairs of detectors with angles between 123° and 152°. Again, there is no photonium peak seen above the annihilation-in-flight background. In the energy range of 1100−1600 keV, these limits in Fig. 4 are slightly better than the previous best upper limits, which were reported in Ref. [23] using sources of ^{22}Na and ^{27}Si.

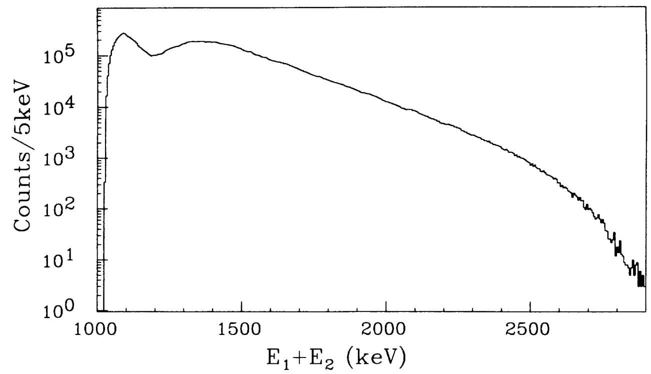

FIG. 3. Energy-sum spectrum for two coincident γ rays.

The spectra for 3γ decay and its limits are shown in Figs. 5 and 6. The conditions for these are the same as for the 3γ coplanar data in Sec. III A, but without the coplanarity requirement. There has been no previously reported search for resonances with mass in the range 1100−1350 keV decaying in flight into 3γ. Thus our results provide for the first time the upper limits for resonances decaying in flight to 3γ in the range 1100−1350 keV.

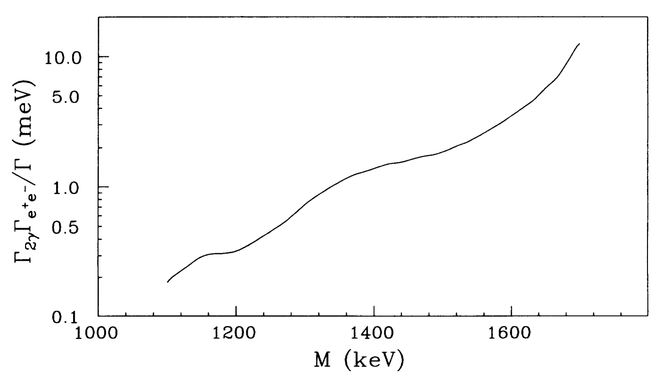

FIG. 4. Upper limits (3σ) of the partial width for a resonance of mass M decaying into 2γ using the energy-sum formula in the range 1100−1700 keV.

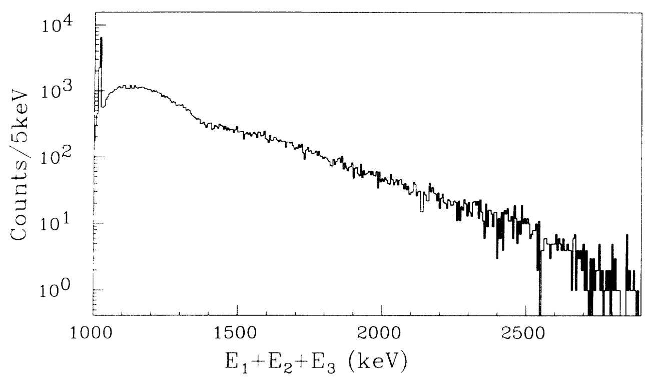

FIG. 5. Energy-sum spectrum for three coincident γ rays.

C. 2γ and 3γ invariant masses

We also searched for photonium decaying in flight into 2γ and 3γ using the invariant mass formula. From energy and momentum conservation, the invariant mass formula for photonium decaying into $n\gamma$ is given by

$$M = 2\sqrt{\sum_{j>i}^{n} E_i E_j \sin^2 \frac{\Theta_{ij}}{2}}, \qquad (3.6)$$

where Θ_{ij} is the angle between detectors i and j, and E_i is the energy of the ith γ ray.

In principle, the invariant-mass formula has an advantage over the energy-sum formula, that the motion of the target electrons does not affect the resolution of the peak. Therefore we need not assume that the momentum of photonium is fixed. In addition, all of the electrons in the target can be used to calculate the cross section of the resonant state. However, the measured line shape will have a large FWHM in mass due to the finite solid angle subtended by each detector because of the relatively large half-cone angle (8.25°). From the geometry of HERA, Monte Carlo techniques were used to simulate the distributions of FWHM(M) for each angle Θ_{ij} for 2γ decay. These results can be written as

$$\frac{\mathrm{FWHM}(M)}{M} \approx \frac{\frac{1}{2}\mathrm{FWHM}(\Theta_{ij})}{\tan(\Theta_{ij}/2)} \approx \frac{\sin 6.5^\circ}{\tan(\Theta_{ij}/2)}. \qquad (3.7)$$

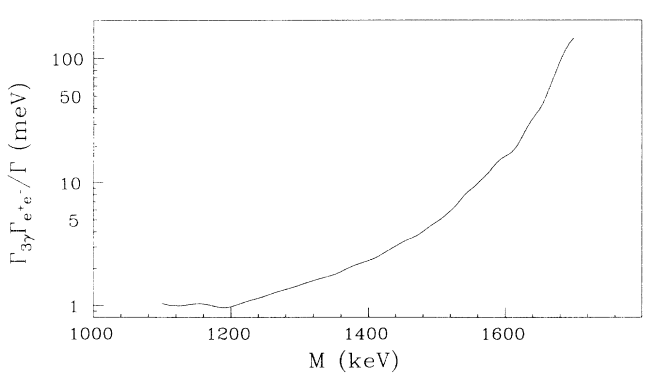

FIG. 6. Upper limits (3σ) of the partial width for a resonance of mass M decaying into 3γ using the energy-sum formula in the range 1100−1700 keV.

The Monte Carlo distributions show that the values of FWHM(Θ_{ij}) are almost independent of Θ_{ij} and have an average value of about $2\sin 6.5°$. The value of FWHM(M)/M is about 2–9 % for Θ_{ij} between 160° and 100° for the 2γ decay case.

The spectrum of the 2γ invariant mass is shown in Fig. 7(a). This spectrum is the sum of the data of all pairs of detectors with angles from 103° to 157° (88 out of 190 possible combinations of two detectors). For each set of data at each angle, we searched for photonium peaks assuming the FWHM of the peaks to have the values corresponding to Eq. (3.7). No photonium peak was found. The data sets were also summed into two subgroups with angles from $103° - 123°$ and $152° - 157°$. The search for photonium from these subgroups was also carried out (with width of about 2.5% of the hypothetical resonance energy for the $152° - 157°$ subgroup and 7.5% for the $103° - 123°$ subgroup) and no peak was found. All the data from all the angles from 103° to 157° were also summed [Fig. 7(a)]. This would give a width of about 5% of the resonance energy. We did not find any peak that could be attributed to the decay of photonium. The results of the upper limits of the partial width are shown in Fig. 7(b). Upper limits were calculated for each angle. In no case were the limits significantly lower than those shown in Fig. 7(b) and, in most cases, were significantly higher.

For the 3γ decay case, a corresponding Monte Carlo study shows that the FWHM(M) are found to be $\approx$ 34 keV for a hypothetical resonance at 1100 keV, and $\approx$ 130 keV at 1700 keV. The 3γ invariant-mass spectrum is shown in Fig. 8(a). The conditions for this are

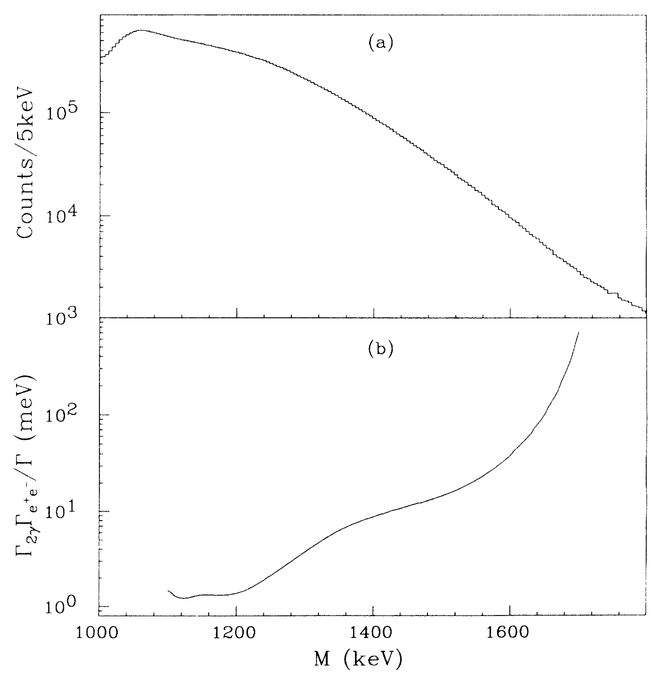

FIG. 7. (a) Invariant mass spectrum for two coincident γ rays. (b) Upper limits (3σ) of the partial width for a resonance of mass M decaying into 2γ using the invariant mass formula in the range 1100−1700 keV.

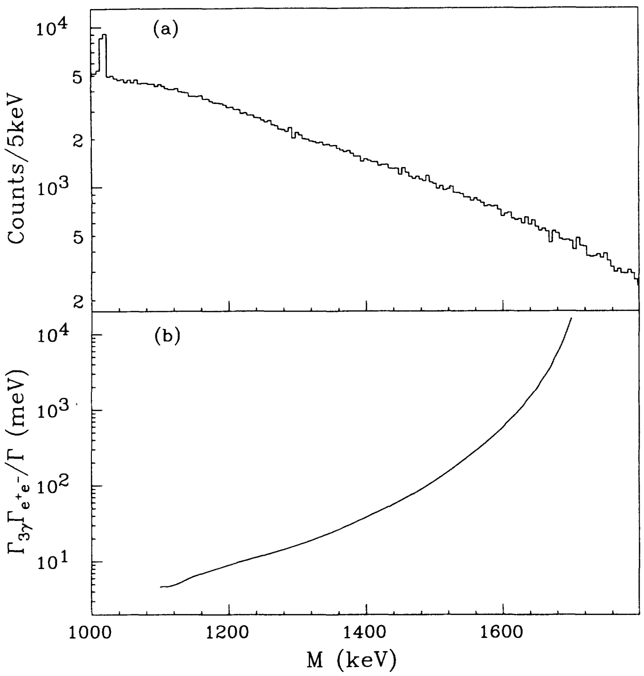

FIG. 8. (a) Invariant-mass spectrum for three coincident γ rays. (b) Upper limits (3σ) of the partial width for a resonance of mass M decaying into 3γ using the invariant-mass formula in the range 1100–1700 keV.

the same as for the energy-sum spectrum (Fig. 1), but without the momentum restriction and coplanarity requirement. This means that all 1140 3γ combinations were used. The width limits are shown in Fig. 8(b).

As the preceding discussion shows, the broad width of a fast moving resonance indicates that invariant-mass spectra are not well suited for searches for weak resonances unless the background is suitably suppressed. With our resolution we have not observed any resonance above the positron annihilation-in-flight background. We have presented our results in this invariant-mass form, as well as the energy-sum form, since it is important to know the upper limits for any potential phenomena related to the GSI experiments under as wide a set of conditions as possible.

IV. SUMMARY

In summary, we have used the large-acceptance angle feature of the multi-γ-ray detector HERA to search for evidence for photonium decay (at rest and in flight) produced from e^+e^- scattering using a Pb target, namely, $e^+e^- \to X \to n\gamma$, where $n = 2$ or 3.

We see no evidence for photonium (X) decay into 2γ or 3γ from our experiments. The upper limits for both stopped and moving photonium are given here. For stopped photonium, we have lowered the upper limits for the 3γ decay mode by more than an order of magnitude. Also, for the case of photonium in motion, we have improved the upper limits for 2γ decay in the energy range 1100–1600 keV and provided for the first time upper limit results for 3γ decay in the energy range 1100–1350 keV.

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