Search for Narrow Sum-Energy Lines in Electron-Positron Pair Emission from Heavy-Ion Collisions near the Coulomb Barrier

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The first results are presented from a new experiment, APEX, designed to study the previously reported sharp lines in sum-energy spectra of positrons and electrons produced in collisions of very heavy ions. Data were collected for $^{238}U + ^{181}Ta$ at 5.95, 6.10, and 6.30 MeV/u and $^{238}U + ^{232}Th$ at 5.95 MeV/u. In none of our analyses is any evidence found for sharp sum-energy lines. For the specific case of the isolated decay of a neutral particle of mass 1.4–2.1 MeV/c^2, the upper limits on cross sections obtained from the present data are significantly less than the previously reported cross sections.

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Line structures have been reported [1–8] in the energy spectra of positrons produced in collisions of very heavy ions. More remarkably, sharp lines have also been observed in the sum-energy spectra of coincident positrons and electrons [9–12]. In the experiments, carried out at the GSI UNILAC accelerator, lines were reported for a number of scattering systems over a range of bombarding energies near the Coulomb barrier. The features of these observations suggest the possible formation and decay of some hitherto unknown light neutral particle or composite object. In order to explain the sharp sum-energy lines, the objects must be produced with a relatively narrow velocity distribution in the heavy-ion center-of-mass frame, such that their free pair decay results, in the laboratory frame, in near back-to-back, equal energy, positron-electron pairs with consequent, almost exact, cancellation of the Doppler shifts. The existence of such low-mass neutral states is highly constrained by combinations of other experimental and theoretical results [13–20]. The only other known mechanism to produce sum-energy lines of the observed widths, without the use of lepton angles for Doppler correction, is internal pair conversion (IPC) of a discrete transition in a nucleus which, however, is required to be nearly at rest ($\beta \lesssim 0.01$). Some of the sharp sum-energy lines were found [9–11] to have features consistent with the particle scenario, but others did not [11,12]. Thus a rather uncertain picture of the phenomenon presently exists. In this Letter we present the first results from a new experiment designed to investigate these lines. Data were obtained for the $^{238}U + ^{181}Ta$ system at three bombarding energies and for the $^{238}U + ^{232}Th$ system at one energy, all nominally corresponding to situations where previous experiments have reported the observation of sharp sum-energy lines. No evidence is found for sharp peaks in the present data.

APEX—the ATLAS Positron Experiment—utilizes beams from the ATLAS superconducting linear accelerator at the Argonne National Laboratory, which has been upgraded recently to provide high intensity cw beams of the heaviest ions [21]. The apparatus and its components are described in detail in other publications [22]. APEX consists of a large uniform-field solenoid mounted transverse to the beam direction. A rotating target wheel assembly allows the use of higher beam intensities than would be possible with static targets. Scattered beam

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particles and recoiling targetlike fragments are detected in an array of position-sensitive gas counters covering the laboratory angle range $20° \leq \Theta \leq 68°$ around the beam axis. Angle and time-of-flight information from these detectors permit the reconstruction of the kinematics of the heavy-ion scattering. Positrons and electrons produced at the target are transported by the solenoidal field to two, 198 element, arrays of silicon detectors situated on the magnetic field axis of the solenoid. The average energy resolution of each array was typically 12 keV full width at half maximum (FWHM) at 363 keV. Detector elements with resolution worse than 20 keV were excluded from the analysis. Energy, position, and time-of-flight information from these arrays allow the determination of the lepton energies and the angles of emission. In the solenoid coordinate system, defined with the z direction along the magnetic field, the polar angle resolution is determined by the time resolution of the silicon detectors ($\Delta t \sim 6$ ns at 350 keV). The azimuthal angle is determined by the detector segmentation within $\pm 10°$. Positrons detected in the silicon arrays are identified and distinguished from an intense background of electrons by observation of their characteristic back-to-back annihilation radiation in assemblies of position sensitive NaI(Tl) detectors. These signals also provide the basic trigger for the experiment. The positrons thus identified contain a small ($< 5\%$) contribution of electrons, primarily below 200 keV in energy, which arise from random coincidences between gamma rays near 511 keV in energy and electrons in the silicon arrays. Additional detectors were used to monitor the target condition as well as the beam position, intensity, and timing. The apparatus has been tested with a number of different source measurements and scattering studies [22]. In particular, a measurement of IPC from a 1.84 MeV $E1$ transition in ^{206}Pb, excited in ^{206}Pb+^{206}Pb inelastic scattering, was used to verify the correct functioning of the apparatus.

The APEX spectrometer [22] accepts positrons and electrons in the range $20° < \theta_s < 70°$, $110° < \theta_s < 160°$, and $0° < \phi_s < 360°$ in the solenoid coordinate system over a broad range of energies (150–750 keV). This has a large overlap with the range covered by the spectrometer used in the measurements of Refs. [9,11] ($20° < \theta_s^{e+} < 90°$, $110° < \theta_s^{e-} < 160°$, and $0° < \phi_s < 360°$), and is particularly so in the case of back-to-back pairs, for which APEX is optimized. In the case of the other apparatus [10,12], which is symmetric around the beam axis, APEX covers the same range of polar angles defined with respect to the beam axis, but is limited to the azimuthal range $20° < \phi_B < 160°$ and $200° < \phi_B < 340°$. The absolute peak detection efficiencies for 363 keV electrons and positrons are 20% and 5%, respectively, with all silicon detectors operational. A measurement of IPC pairs from the 1.761 MeV 0^+ state in ^{90}Zr—populated in ^{90}Y β decay—gave an efficiency of 0.29(1)%; simulations yield a value of 0.32(2)%. The efficiency for detection of a single quasielastically scattered heavy ion in the laboratory angular range 20°–68° was typically 90%. The dead time of the data acquisition system was approximately 20%.

The data presented here were obtained during three separate measurements. The beam was ^{238}U with intensity as high as 4 particle nA with average values of 1–2 particle nA. For both the ^{181}Ta and ^{232}Th measurements the targets were rolled metal foils. The average effective target thicknesses and the energy loss of the beam in the targets, the total integrated luminosity, and the total numbers of positrons and pairs detected in coincidence with two scattered heavy ions are summarized in Table I for each measurement. The absolute beam energy was obtained from the accelerator time-of-flight system and is thought to be accurate to 1 part in 10^3. The total sum-energy spectra of positron-electron pairs, produced in coincidence with two quasielastically scattered heavy ions, are shown in Fig. 1 for ^{238}U+^{181}Ta at 5.95, 6.10, and 6.30 MeV/u, and ^{238}U+^{232}Th at 5.95 MeV/u. The overall yields of positrons [5] and positron-electron pairs [11] in the present experiment are in good agreement with previous results.

A variety of analyses have been carried out on the present data sets. These have not resulted in any statistically significant evidence for sharp sum-energy lines. The analyses ranged from systematic searches for peak structures by gating on parameters such as heavy-ion scattering angle, positron and electron difference energy, positron-electron opening angle, and positron emission angle with respect to the beam direction to searches based on proposed physics scenarios and, to the extent possible, dupli-

Table I. Experimental parameters and efficiencies.

System	Beam energy range (MeV/u)	Average target thickness (μg/cm^2)	Integrated luminosity (μb^{-1})	N_{e+} [a]	$N_{\rm pair}$ [a]	Detection efficiency (%)[b] Particle	IPC
^{238}U+^{232}Th	5.78–5.95	760	7000	246 000	126 000	1.30	0.44
^{238}U+^{181}Ta	5.79–5.95	660	5800	59 000	17 000	0.88	0.30
^{238}U+^{181}Ta	5.94–6.10	650	11 000	84 000	25 000	0.84	0.27
^{238}U+^{181}Ta	6.13–6.30	700	8600	70 000	16 000	0.55	0.18

[a]Number of positrons (N_{e+}) and positron-electron pairs ($N_{\rm pair}$) detected in coincidence with two heavy ions scattered in the angle range $20° \leq \Theta \leq 68°$.
[b]Simulated detection efficiency for a particle of mass 1.8 MeV/c^2, and for an IPC transition of 1.8 MeV in a $Z = 92$ nucleus at rest.

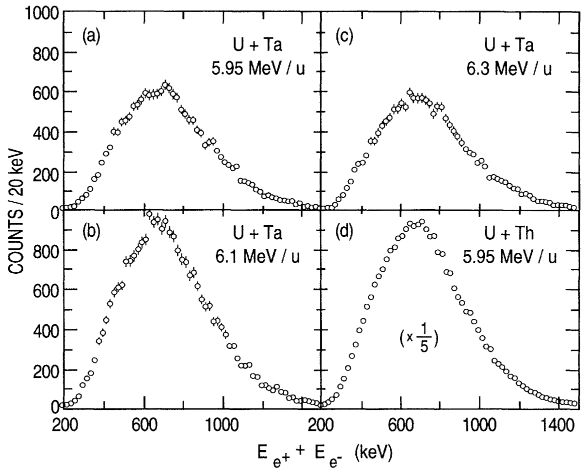

FIG. 1. Sum-energy spectra for positrons and electrons measured in coincidence with two quasielastically scattered ions detected in the laboratory angle range 20°–68° for ^{238}U+ ^{181}Ta at (a) 5.95 MeV/u, (b) 6.10 MeV/u, (c) 6.30 MeV/u, and (d) ^{238}U+ ^{232}Th at 5.95 MeV/u.

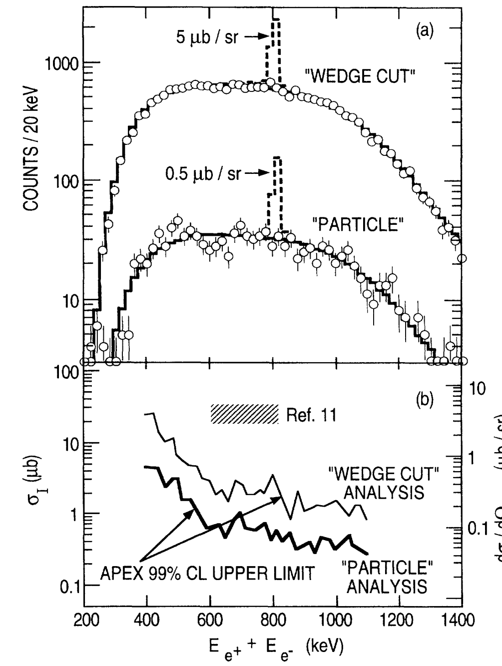

FIG. 2. (a) Sum-energy spectra for ^{238}U+ ^{232}Th at 5.95 MeV/u analyzed according to the expectations for the isotropic decay of a particle produced at rest in the center of mass ($\beta = 0.06$), selected on positron and electron energies (wedge cut), and further selected on correlated energies and azimuthal angles (particle). The superimposed curves correspond to event-mixed spectra. The expected additional yields for a 1.8 MeV/c^2 particle, produced with cross sections of 5 and 0.5 μb/sr, respectively, are shown dashed. (b) Upper limits (99% C.L.) for the cross section derived from the wedge cut and particle analyses as a function of sum energy. The shaded area indicates the energy range of peaks and the level of cross section given in Ref. [11].

cation of published analyses. In the following paragraphs we present two examples.

Of the previously observed lines, those observed at 760 [9] and 809 keV [11] in the ^{238}U+ ^{232}Th system were reported to have the characteristics associated with the two-body decay of an isolated neutral object. A sum-energy spectrum for ^{238}U+ ^{232}Th, selected on lepton energies determined from simulations of the isotropic decay of a particle produced at rest in the center of mass ($\beta = 0.06$), is shown in Fig. 2(a) (upper curve). This selection is the same as the "wedge cut" analysis of Ref. [9]. The histogram superimposed on the data corresponds to a spectrum of uncorrelated pairs generated by summing the energies of positrons and electrons from different events (event mixing). The dashed peak, superimposed on the event-mixed spectrum, corresponds to the signal expected from the decay of an isolated neutral object of mass 1.8 MeV/c^2, produced with the cross section given in Ref. [11] ($d\sigma/d\Omega_{\rm HI} \sim 5\mu$b/sr—the pair production cross section averaged over the heavy-ion detector acceptance). These data, further selected on solenoid azimuthal angle–energy correlations expected for two-body decay, are also shown in Fig. 2(a) (lower curve). The superimposed histogram, in this case, corresponds to the appropriate event-mixed spectrum plus a signal 1/10, that of Ref. [11] ($d\sigma/d\Omega_{\rm HI} \sim 0.5\mu$b/sr). Figure 2(b) shows the upper limits (99% C.L.) on the cross sections derived from these analyses using Poisson statistics, shown as a function of sum-energy, assuming uniform production through the target. These upper limits are approximately one and two orders of magnitude smaller, respectively, than the values inferred from the earlier observations [9,11] which are indicated by the shaded area in Fig. 2(b). Similar upper limits—within a factor of 2—were also obtained from analysis of our ^{238}U+ ^{181}Ta data.

The efficiencies for the "particle" scenario used in the above analysis are listed in Table I for the case of $M = 1.8$ MeV/c^2. We also list the efficiency for IPC pairs from a 1.8 MeV transition in a $Z = 92$ nucleus at rest. This latter situation does not apply to the actual experiments, as the detected heavy ions are moving with appreciable velocities ($\beta > 0.04$) which would result in a significantly broadened (> 75 keV) sum-energy line. This efficiency is therefore included here as a yardstick by which the previous and present results may be judged. The variations in efficiencies between the measurements result from the different fractions of silicon detectors retained in the analysis in each case.

There are sum-energy lines reported in the literature [11,12] which do not exhibit all the expected properties of two-body decay. Theses include lines at 608 keV [11] in ^{238}U+ ^{232}Th and 625 [11], 634 [12], 748 [11], and 805 keV [11] in ^{238}U+ ^{181}Ta. We have analyzed our data according to the selection of the lepton energies given in the literature. Examples of sum-energy spectra thus obtained for the case of the 748 keV line in ^{238}U+ ^{181}Ta are shown in Fig. 3. No evidence is seen for a line near 748 keV or elsewhere in these spectra. In the absence of a model for the lepton energy distributions, their angular correlations, and for the emitter velocity distributions of the reported lines, extraction of upper limits for the cross sections from the data is not possible. Using, however, the efficiency of our apparatus for IPC from a nucleus at rest, given in Table I, and assuming uniform production through the target and isotropic decay, we arrive at upper limits for the cross sections of $<7\ \mu$b (99% C.L.) for ^{238}U+ ^{181}Ta at all three energies. Similar values are also obtained from the analyses carried out for the other lines. Based on the published information [9,11], the previously reported yields correspond to production cross sections of approximately 100 μb. A value of 7 μb was reported for the line at 634 keV [12] under more limited acceptance of lepton energies and selection of heavy-ion scattering angles. In this case, the analysis assumed approximately equal energy, uncorrelated lepton pairs in the derivation of the cross section which, therefore, is not readily comparable with our limit.

The absence of the reported sum-energy lines in our data is puzzling. The origin of this apparent discrepancy may lie in so far unknown characteristics of the phenomenon. The overlap between the acceptance of APEX and that of the previous experiments is large. Nevertheless, it is conceivable that the energy and angle correlations of the lepton pairs are such that they escape detection in our apparatus, although rather extreme situations are required for this to occur. There is some evidence [11] that the line phenomenon is dependent on beam energy. Our measurements have covered a wide range of energies encompassing the region of previous line observations, and it is unlikely that the absolute energy calibrations of the two accelerators are so far in error that there is no overlap between the current and previous sets of measurements. If indeed the line production cross section does have a strong, resonancelike, energy dependence, the upper limits derived from the current data would have to be scaled by the ratio of target thicknesses used in the two cases. This would amount to no more than a factor of 2 to 3 increases in our quoted upper limits. The lack of specific models for many of the lines, and the conditions under which they are produced, makes definitive conclusions hard to draw. Nevertheless, we believe that the results of the present experiment represent a real disagreement with the previous observations. In the specific case of the particle scenario, we have established upper limits to cross sections which are far below those implied by previous results.

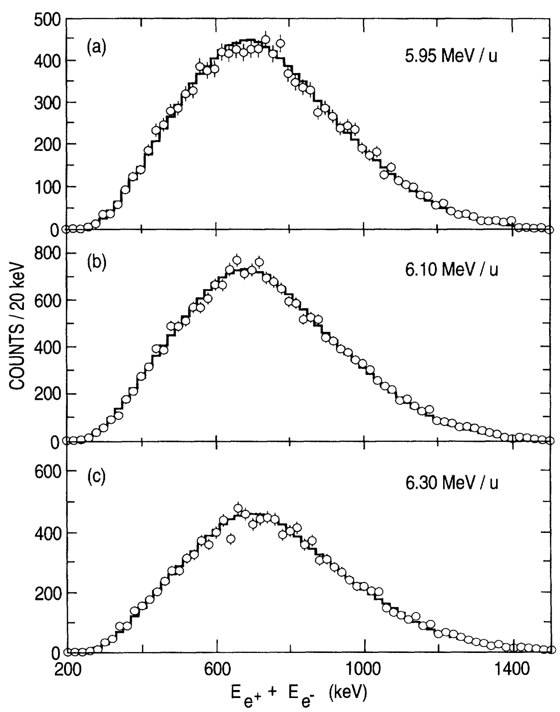

FIG. 3. Sum-energy spectra for ^{238}U+ ^{181}Ta at (a) 5.95, (b) 6.10, and (c) 6.30 MeV/u, analyzed according to the selection on lepton energies for the 748 keV line reported in Ref. [11]. The superimposed histograms represent spectra obtained by event mixing.

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