Observation of Correlated Narrow-Peak Structures in Positron and Electron Spectra from Superheavy Collision Systems

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We have observed that the positrons associated with a narrow peak in the positron spectrum from U+Th collisions are correlated with the simultaneous emission of electrons whose energy spectrum also contains a narrow peak. The mean energies and widths of the two peaks are equal within measurement errors. Neither the coincidence-peak intensity nor the energy distributions of the positrons and electrons can be accounted for by known nuclear internal-conversion processes. Similar observations have also been made in the Th+Th and Th+Cm collision systems.

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The recent observation[1-3] of narrow peaks in the positron spectra emitted from superheavy collision systems has presented an interesting puzzle. Since a search for spontaneous positron emission originally motivated these experiments, the possibility that these peaks may be a signature for this process has been particularly pursued. Reinhardt *et al.* suggested[4] that the narrow peak widths of < 80 keV and the enhanced intensity beyond that expected from Coulomb scattering alone could be explained within the context of spontaneous positron emission by invoking the formation of a giant, dinuclear system whose lifetime exceeds $\sim 10^{-19}$ s. Applied to the structures reported in Refs. 1 and 2, this phenomenological framework was particularly successful in accounting for the observations in the U+Cm system,[1] where a consistent description could be made for the peak energy and its intensity.[5] With our followup systematic study[3] of supercritical collision systems with total charge Z_u between 180 and 188, however, it became clear that instead of exhibiting the unusually strong dependence of the peak energy on Z_u ($\sim Z_u^{20}$) expected for spontaneous positron emission,[4] the energies for the prominent peak appearing in all the systems were very similar. As has been pointed out,[3,6] to incorporate these results in an explanation involving spontaneous positron emission requires the use of radically different charge configurations and ionization states for the compound system. In addition, it has to be assumed that these shapes track fortuitously with Z_u from highly deformed to spherical configurations so as to keep the $1s\sigma$ binding energy constant. Without independent evidence to support these unusual conditions, this explanation for the peaks does not presently appear very plausible.

In this paper we present the results of an experiment which explores the suggestion made in Ref. 3, and discussed from a theoretical perspective in Ref. 6 and by Shäfer *et al.*, Balantekin *et al.*, and Wijewardhana and Chodos,[7] that the very similar peak energies may imply a common source such as, for example, a neutral particle which decays into an electron-positron pair. The signature for such a process, when viewed in the particle rest frame, would be the back-to-back, collinear emission of monoenergetic electrons and positrons. Viewed in the laboratory, the peak in the electron spectrum should reflect the kinematic broadening found in the related positron peak. Moreover, since the collinear emission produces a correlated canceling of Doppler shifts in the sum of the electron and positron energies, the distribution of this sum energy for the coincidence events is expected to be narrower than the individual peak widths. We have carried out an experiment which studied the emission of electrons in coincidence with positrons from several superheavy collision systems, and there appears to be evidence for such features in the measured spectra.

The measurements were performed at Gesellschaft für Schwerionenforschung, Darmstadt, with the electron-positron solenoid spectrometer EPOS[8] which was modified to detect electrons and positrons in coincidence. Two 32×65-mm^2 planar Si(Li) electron detectors were positioned on the opposite side of the target from the existing cylindrical positron detector[8] to permit high-efficiency detection of electron-positron pairs with opposing momentum components. With use of a geometrical arrangement similar to that of Backe *et al.*,[9] they were oriented with their sensitive faces parallel to the solenoid axis in order to suppress entrance of the oppositely spiraling positrons into the counters, and positioned symmetrically about the target–positron-detector axis to avoid the high flux of low-energy delta electrons. The resolutions of the positron and electron detectors were respectively ~ 12 and ~ 35 keV.

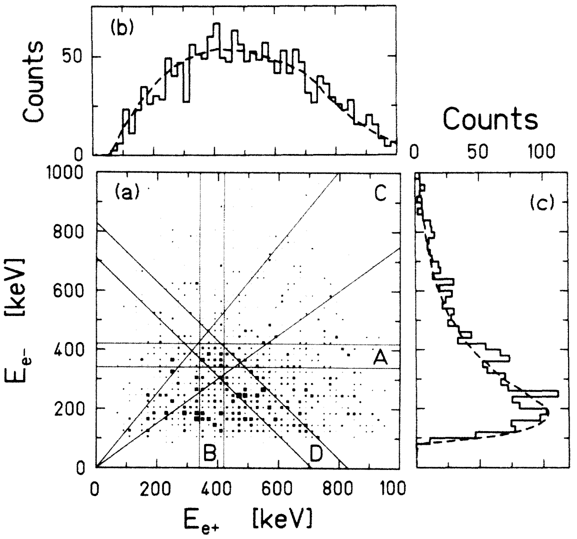

FIG. 1. (a) Intensity distribution of coincidence events as a function of E_{e^+} and E_{e^-} for 5.83-MeV/u U+Th collisions. (b),(c) Projections of this distribution onto the E_{e^+} and E_{e^-} axes, respectively. Cuts A through D are explained in the text.

Figure 1(a) presents an intensity distribution of coincidence events as a function of the positron and electron kinetic energies, E_{e^+} and E_{e^-}, for 5.83-MeV/u U+Th collisions. As a result of especially rapid deterioration of $\sim\frac{1}{3}$ of the targets in the beam, we have used here $\sim\frac{2}{3}$ of the total U+Th data accumulated.[10] In order to use the maximum data base available, this plot contains all the events for measured laboratory ion-scattering angles between 20° and 70°, and is not restricted to the subset of events in kinematic cuts where the positron peak intensity has been found to be particularly enhanced over the background.[1,3] Figures 1(b) and 1(c) show the coincidence events projected onto the E_{e^+} and E_{e^-} axes, respectively. The lines through the spectra represent Monte Carlo calculations using the shapes of individual contributions from nuclear and atomic dynamic processes, normalized to the total event yield.

Figure 2(a) presents a projection of the coincidence events onto the E_{e^+} axis of Fig. 1(a), with the specification that the electron energy is in the interval $340 < E_{e^-} < 420$ keV. Having started with the spectrum in Fig. 1(b) which shows little structure, it is very striking to find the peak structure in this positron spectrum at an energy of 380 ± 15 keV and with a width of 80 ± 15 keV, similar to the peak found in our previous study of this system.[3] Making the complementary projection onto the E_{e^-} axis, with the gate $340 < E_{e^+} < 420$ keV, produces the spectrum shown

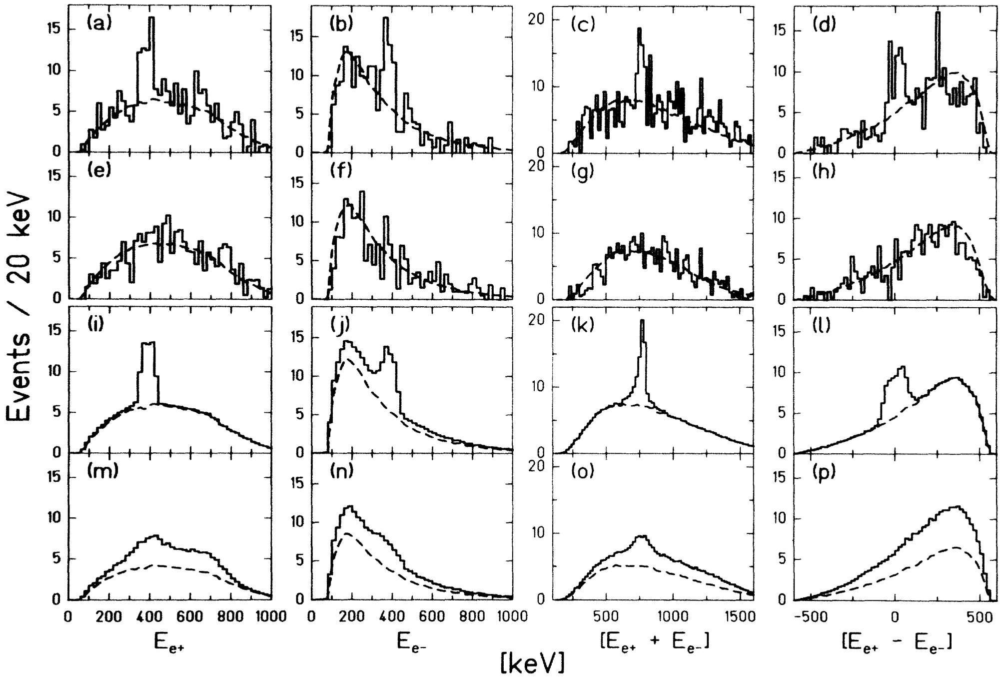

FIG. 2. (a)–(h) Projections of the measured intensity distribution of Fig. 1(a). (i)–(p) Results of Monte Carlo calculations: (i)–(l) for the two-body decay of a neutral particle (scaled by 6×10^{-4}), and (m)–(p) for internal pair conversion of a nuclear state (scaled by 6×10^{-3}). The columns correspond to projections onto the E_{e^+}, E_{e^-}, $E_{e^+}+E_{e^-}$, and $E_{e^+}-E_{e^-}$ axes, respectively. Parts (a)–(d), as well as (i)–(l) and (m)–(p), correspond to the gates labeled A–D in Fig. 1(a), respectively. Parts (e)–(h) are the average of similar gates adjacent to either side of gates A–D respectively.

in Fig. 2(b). A peak structure again appears in this case at a mean energy of 375 ± 15 keV with a width of 75 ± 15 keV, superimposed on a continuous background. The lines through the smooth part of the spectra in Figs. 2(a)–2(h) again are obtained with Monte Carlo calculations by using the shapes of the total electron-positron coincidence spectra to represent the dynamic background, and making the appropriate projections after normalization to the total number of coincidence events in Fig. 1(a). We note that enhancing the positron peak with kinematic cuts also enhances the electron peak with respect to the continuous background. The correlated yields of positron and electron peak events above the continuous backgrounds are 26.7 ± 7.7 counts and 31.7 ± 7.6 counts, respectively. The possibility that only a statistical fluctuation of the background produces the excess structure in the electron spectrum [Fig. 2(b)] at the specified energy of the positron peak is precluded at a statistical confidence level corresponding to 6σ.

Two particularly informative projections of the distribution plotted in Fig. 1(a) are displayed in Figs. 2(c) and (d). In the first [Fig. 2(c)], the intensity of coincidences is displayed as a function of the energy sum $(E_{e^+} + E_{e^-})$ for $E_{e^+} \simeq E_{e^-}$. To allow for kinematic broadening, the width of the projection window has been scaled proportionally to $E_{e^+} + E_{e^-}$ from the measured widths of the electron and positron peaks. This corresponds to making the wedge-shaped cut C shown in Fig. 1(a) centered on $E_{e^+} \simeq E_{e^-}$ with a slight offset from equal energy to take into account the different responses of the electron and positron counters. The resulting sum-energy spectrum contains a narrow peak, at a mean energy of 760 ± 20 keV, with 35.3 ± 9.4 counts in excess of the fitted continuous background. It bears emphasis that the width of this structure does not increase as the width of the wedge cut is increased. Complementary information is obtained from cut D of Fig. 1(a). In this case, the coincidence intensity is plotted [Fig. 2(d)] as a function of the energy difference $(E_{e^+} - E_{e^-})$ keeping $E_{e^+} + E_{e^-}$ constant. A peak structure again appears in this projection, near $E_{e^+} - E_{e^-} \simeq 0$, with 38.5 ± 9.7 counts, superimposed on a sloping background which primarily reflects the shape of the coincidence-electron spectrum. Of course, all four projections [Figs. 2(a)–2(d)] are correlated, and differences in the number of events in the respective peaks reflect settings of gates and differences in backgrounds.

We found, moreover, that none of these structures appear in projections that exclude the energy regions spanned by the electron and positron peaks. Figures 2(e)–2(h) show such projections, averaging cuts from the intensity distribution of Fig. 1(a) adjacent to both sides of cuts A through D, respectively. The frames in each column represent projections onto the corresponding axes used in Figs. 2(a)–2(d).

For comparison to the data, Fig. 2 also shows Monte Carlo simulations of two possible scenarios: (1) the decay of a neutral particle of mass 1.80 MeV [Figs. 2(i)–2(l)], and (2) the internal pair conversion of a nuclear transition ($Z = 92$) of 1.80 MeV, twice the total energy of the positron peak [Figs. 2(m)–2(p)], both superimposed on atomic and nuclear backgrounds.

Internal pair conversion is an obvious source of correlated positrons and electrons. We note, however, that in order to produce visible structures in any of the spectra, it is necessary to assume that internal conversion from this one nuclear transition alone contributes on the order of 30% to the total detected positron yield. The need for such an unreasonably strong transition readily excludes the internal-conversion process on grounds of intensity considerations alone, in agreement with the conclusions of Refs. 1–3. Moreover, it is apparent from making the comparison between the data and the Monte Carlo simulation that, taken together, the spectra also present clear evidence that the narrow, correlated electron and positron lines do not represent the internal-conversion process. In this respect the presence of the peak in the difference-energy spectrum [Fig. 2(d)] and its absence in Fig. 2(p) is especially relevant. Comparison of the data to Monte Carlo simulations also excludes several other production processes. Among those considered are internal pair conversion followed by electron internal conversion in cascade (excluded by intensity and sum-energy distribution), internal pair conversion with the electron captured into empty inner electronic shells (excluded by the correlated electron peak), internal pair conversion in a light nuclear fragment emitted in the collision (excluded by intensity and sum- and difference-energy distributions), accidental correlation of unrelated electron and positron structures (excluded by sum-energy distribution and adjacent cuts), and coincident emission of more than one monoenergetic positron (excluded by the small efficiency for detection of positrons in the electron counter).

In the Monte Carlo simulation of the particle-decay scenario, the particles are assumed to be produced at rest in the center-of-mass frame and then decay isotropically into an electron-positron pair. Use of a velocity distribution for the particles does not substantially alter the main features of the spectra provided that there is an appreciable contribution of low-velocity components to maintain effectively narrow lines in the individual positron and electron spectra.[3] The particle production rate has been chosen to contribute 3% to the total positron spectrum in order to reproduce the measured peak intensities. The background spectral shapes are derived from the measurements, as previously, and the sum is normalized to the total events.

It is apparent that these simulated spectra in Figs. 2(i)–2(l) very much resemble the measured spectra, including the efficiency for detection of the coincidence-electron peak relative to the positron peak and the shift of the peak centroids due to the detector responses. As illustrated by the Monte Carlo simulation in Fig. 2(k), the correlated cancellation of Doppler shifts associated with collinear, back-to-back emission produces the *minimum* possible sum-energy peak width of 50 keV which primarily reflects detector resolution. This appears to be consistent with the width of 80 ± 20 keV observed for the sum-energy peak shown in Fig. 2(c). The absence of structure in the spectra of Figs. 2(e)–2(h) is also consistent with the particle-decay scenario, but not with the internal-conversion processes.

Data have also been obtained on the Th+Th and Th+Cm systems. They exhibit features very similar to those discussed above but with lower statistical significance. There is one additional feature of note appearing in these data: In the Th+Th system, peaks in the positron spectra were observed both at ~ 310 and ~ 370 keV corresponding to projectile energies of 5.70 and 5.75 MeV/u, respectively. There is evidence that, in both cases, an electron peak also accompanies the positron peaks with $E_{e^-} \simeq E_{e^+}$. This observation may be related to possible positron-peak energy differences present in the data of Ref. 3, which may also reflect more than one structure.

In summary, we have found evidence, in the cases studied, that the positron peaks observed in superheavy collision systems are correlated with an electron peak of similar width and energy. A narrow peak is also observed in the distribution of the sum of the positron and electron energies. It has been found that the coincidence intensity and the shape of the spectra cannot be reproduced by known internal-conversion processes. The presence of the coincidence-electron peak clearly excludes spontaneous positron emission as a source of the positron peak, and it is improbable that the measured correlations in electron and positron energies can be accommodated within dynamic production of pairs in heavy-ion collisions.[4] Features associated with the electron-positron decay of a slowly moving neutral particle appear to be reflected in the observations involving electron-positron coincidences.

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[1] J. Schweppe, A. Gruppe, K. Bethge, H. Bokemeyer, T. Cowan, H. Folger, J. S. Greenberg, H. Grein, S. Ito, R. Schule, D. Schwalm, K. E. Stiebing, N. Trautmann, P. Vincent, and M. Waldschmidt, Phys. Rev. Lett. **51**, 2261 (1983).

[2] M. Clemente, E. Berdermann, P. Kienle, H. Tsertos, W. Wagner, C. Kozhuharov, F. Bosch, and W. Koening, Phys. Lett. **137B**, 41 (1984).

[3] T. Cowan, H. Backe, M. Begemann, K. Bethge, H. Bokemeyer, H. Folger, J. S. Greenberg, H. Grein, A. Gruppe, Y. Kido, M. Kluver, D. Schwalm, J. Schweppe, K. E. Stiebing, N. Trautmann, and P. Vincent, Phys. Rev. Lett. **54**, 1761 (1985).

[4] J. Reinhardt, U. Müller, and W. Greiner, Z. Phys. A **303**, 173 (1981).

[5] U. Müller *et al.*, Z. Phys. A **313**, 263 (1983).

[6] A. Schäfer *et al.*, J. Phys. G **11**, L69 (1985).

[7] A. Schäfer *et al.*, Phys. Lett. **149B**, 455 (1984); A. B. Balantekin *et al.*, Phys. Rev. Lett. **55**, 461 (1985); A. Chodos and L. C. R. Wijewardhana, Phys. Rev. Lett. **56**, 302 (1986).

[8] H. Bokemeyer *et al.*, in *Quantum Electrodynamics of Strong Fields*, edited by W. Greiner (Plenum, New York, 1983), pp. 273–292; J. S. Greenberg and P. Vincent, in *Treatise on Heavy-Ion Science*, edited by D. A. Bromley (Plenum, New York, 1985), pp. 139–421.

[9] H. Backe *et al.*, Phys. Rev. Lett. **50**, 1838 (1983).

[10] Target deterioration is particularly relevant if the positron peaks are associated with a resonancelike dependence on beam energy. This question of resonant formation of a compound system can be uniquely addressed also by electron-positron coincidence measurements; for sticking times $\geq 10^{-20}$ s, destructive interference could significantly alter the delta-electron yield coincident with the positron peak events.