Anomalous Positron Peaks from Supercritical Collision Systems

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Narrow positron peaks are observed in five supercritical collision systems with combined nuclear charge $180 \leq Z_u \leq 188$. The peaks do not originate from nuclear internal pair conversion and their production appears to occur in a narrow projectile-energy interval near the Coulomb barrier. The line shapes are consistent with emission by a source moving with the c.m. velocity. Particularly notable is an apparent independence of the peak energies on Z_u. These observations are discussed in the context of the spontaneous decay of the QED vacuum and other new potential sources of line positron spectra.

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Recently we reported the observation of a narrow positron peak at ~ 320 keV from U+Cm collisions at bombarding energies near the Coulomb barrier.[1] Line-shape studies as well as a search for related γ-ray and electron lines provide compelling arguments that the peak does not originate from nuclear transitions in the individual final-state nuclei.[1,2] Indeed, the mere occurrence of such a narrow, low-energy positron line is anomalous and speaks for an unorthodox explanation, possibly involving a previously undetected source.

One such source could be the spontaneous positron creation process originally sought in these experiments. It is predicted[3,4] to occur when the QED vacuum decays spontaneously in the presence of a supercritical charge ($Z_u \equiv Z_1 + Z_2$) assembled by the two nuclei. A short time scale for supercritical binding of $\sim 2\times 10^{-21}$ s precludes the appearance of such a narrow structure from this process during a Rutherford scattering. However, adopting the suggestion of Rafelski, Müller, and Greiner[5] to utilize nuclear reactions for prolonging supercritical binding, Reinhardt *et al.*[6] illustrated that the unexpected production of a narrow line could be explained in the context of spontaneous emission by invoking the formation of a long-lived ($\sim 10^{-19}$ s), giant, dinuclear complex at bombarding energies near the Coulomb barrier. This idea has been developed in more detail in recent papers.[7-9] As described in Ref. 1, a number of experimental features associated with the appearance of the peak in the U+Cm collision system conform to this interpretation, including the observation that the peak energy is consistent[6,8] with the energy of a supercritically bound $1s\sigma$ state for a system composed of the two nuclear charges ($Z_u = 188$) marginally touching.

In this paper we report on new measurements that pursue the question of the origin of this peak with particular emphasis on its possible association with spontaneous positron creation. Two distinctive signatures have been explored with should especially mark this process: (1) The peak energies and intensities are predicted[6] to scale with very unusual dependences, Z_u^{20} and Z_u^{70}, respectively, for constant configurations of nuclear charge and electron ionization, and (2) positron emission is expected to occur from the combined system and not from the individual nuclei. We have searched for peak structures in collision systems with Z_u between 180 and 188 where supercritical binding can be achieved with the beams and targets available. A prominent narrow positron peak has been observed in each case whose width is consistent with the Doppler broadening produced by a source moving with the center-of-mass (c.m.) velocity, $v_{\text{c.m.}}$. However, a near degeneracy in peak energies is observed for all systems, which contrasts with the strong Z_u dependence expected for spontaneous positron emission from systems with similar charge distributions and states of ionization. Other recent measurements[10] using a different positron detection technique have reported overlapping information.

The measurements were carried out with the EPOS spectrometer described in Ref. 1 upgraded by an increase of the overall positron detection efficiency by a factor of 2.5, by an extension of the relative sensitivity for detection of positrons with energies as low as ~ 100 keV to access the interesting low-energy part of the spectrum with high efficiency, and by an improvement of the angular resolution of the heavy-ion detectors to ~ 0.5° from the ~ 1° resolution employed in the earlier measurements.[1] The collision systems studied are $^{238}\text{U}+{}^{248}\text{Cm}$, $^{232}\text{Th}+{}^{248}\text{Cm}$, $^{238}\text{U}+{}^{238}\text{U}$, $^{238}\text{U}+{}^{232}\text{Th}$, and $^{232}\text{Th}+{}^{232}\text{Th}$. For this range in Z_u (180–188), scaling the peak energy by Z_u^{20} translates to a readily observable peak energy difference of greater than a factor of 3. The use of both ^{238}U and ^{232}Th as projectiles avoids the possibility that a common collision partner was responsible for a trivial nuclear source of structure in the positron spectra.

Positron spectra accumulated in coincidence with binary scattering events are displayed in Fig. 1. The spectrum from U+Cm collisions reported in Ref. 1 is included for direct comparison. The general features of the spectra from all the collision systems are similar. A pronounced peak appears in each spectrum above the continuous dynamic and nuclear backgrounds for apparently narrow intervals of projectile energy which correspond in each system to a marginal overlap of nuclear surfaces in a head-on collision. As discussed in more detail in Ref. 1 with regard to the U+Cm studies, the peaks can be enhanced relative to the dynamic background from Rutherford scattering by the choice of kinematic cuts which take advantage of differences in the kinematic behavior exhibited by the peak events and elastic scattering. The spectra in Fig. 1 correspond to such kinematic selections. The enhancement, in fact, occurs for very similar kinematic regions in all the systems, but is most pronounced in the Th+Cm and U+Cm systems where there is sufficient mass asymmetry between the collision partners to allow nearly complete (Th+Cm) or at least partial (U+Cm) separation of forward and backward elastic scattering. With the angular resolution available, it becomes possible in these cases to select kinematic regions where the peak is particularly prominent relative to a reduced elastic-scattering contribution. The c.m. differential cross sections for the production of the peak are similar for all the systems, of order 10 μb/sr in the studied angular region of $25° < \theta_{\rm lab} < 65°$. In addition to these dominant reproducible peaks, some of the data may suggest the presence of other smaller structures in the positron spectra. However, the evidence for such structures presently lacks both adequate statistical significance and reproducibility.

The similarity in the widths of the peaks in Fig. 1 is of particular interest. Under the assumption that the emission is by either the detected ejectiles or the combined system, a peak shape analysis described in Refs. 1 and 2 leads to the same conclusions reached in the case of U+Cm.[1] Unless there is an exceptionally strong preference for the emission of positrons perpendicular to the scattering plane, it is found that the observed widths correspond to the minimum broadening expected from the Doppler effect, and that the line shapes are all consistent with the emission of a narrow positron line by a system moving with $v_{\rm c.m.}$. Moreover, for the U+Cm and Th+Cm systems, where the available data and the kinematics are both favorable for the observation of line shapes over a broad range

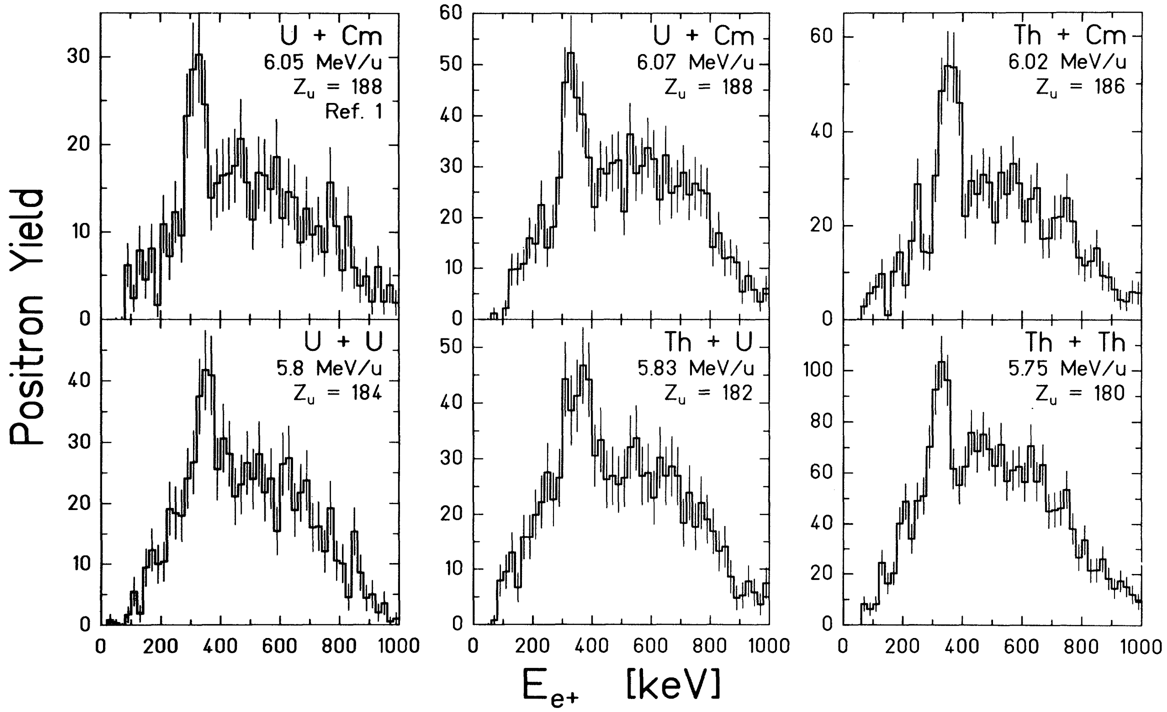

FIG. 1. Positron energy spectra for the five collision systems and bombarding energies indicated. The top-left panel repeats data from Schweppe *et al.* (Ref. 1); the other spectra are from this work. Kinematic constraints were chosen as discussed in text.

in scattering angle, the line shapes distinguish convincingly between emission from a source moving with $v_{\rm c.m.}$ and from a source with velocities associated with the individual nuclei. Figure 2 illustrates this point. At $\theta_{\rm lab}$ near 45°, it is clear that even a crude measurement suffices to differentiate between ejectile and c.m. emission. We find that the measured widths for both systems appear to be independent of the scattering angle, as expected for c.m. emission, and that their magnitudes also overlap with the Doppler widths expected for a source moving with $v_{\rm c.m.}$.

However, it bears emphasis that the identification of the source and its velocity from the peak shape and width is confined in this analysis to the assumption that the source is either the detected ejectiles or the c.m. source. Generalizing to the possibility that the emission can be by other sources created in the collision obviates such direct conclusions. For example, at the present level of data acquisition it is not possible to distinguish between the line shapes associated with c.m. emission and emission by a positron line source created isotropically in the c.m. system with a broad and constant distribution of velocities, starting from rest, relative to the c.m. The peak widths at half maximum differ only by ~10% and the different distributions of tail structure are difficult to identify in the measurement. Moreover, the distinction is further diminished if the velocity distribution of the source relative to the c.m. is weighted more towards lower velocities, or if a sufficiently long lifetime can carry the positron emitters with the larger velocities beyond the 0.5 cm from the target where the positron detection efficiency begins to diminish.

The most notable observation is the near degeneracy found for the main peak energies. These are summarized in Fig. 3 as a function of Z_u. Also shown are calculations[6] of peak energies expected for spontaneous positron emission from a long-lived nuclear complex for two very different nuclear charge configurations. They illustrate the limiting scenarios represented by elongated charge distributions formed by the two deformed nuclei touching in a head-on collision (line *a*) or a spherical assimilation of the colliding partners (line *b*). The effect of screening is demonstrated by comparison of ionization states of +50 with bare nuclei for the case of the spherical charge distribution (line *c*).

It becomes apparent that any accommodation of the measured peak energies within the context of spontaneous positron emission involving the formation of giant, metastable nuclear systems must necessarily invoke both very radically different nuclear charge configurations and ionization states for the compound systems. Moreover, the excursion from the highly deformed to spherically compressed nuclear shapes must track with the change in Z_u so as to maintain the $1s\sigma$ binding energy substantially constant. An alternative mechanism could assume the formation of a similar, particularly stable, spherical nuclear complex in all the

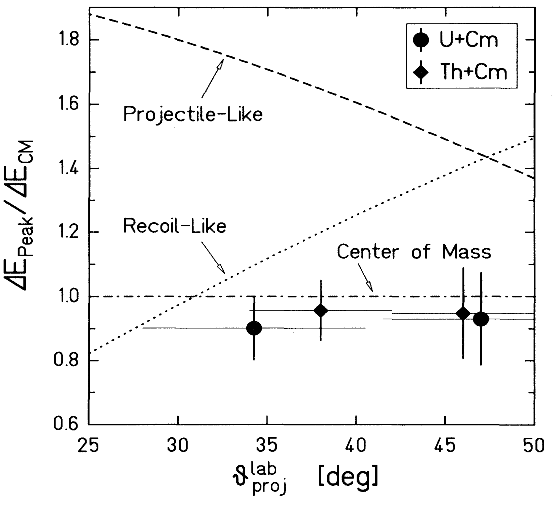

FIG. 2. Doppler broadening expected from projectile, target, and center-of-mass emission of the positron line spectra in binary scattering events from 6.05-MeV/u U+Cm and 6.02-MeV/u Th+Cm collisions plotted as a function of the laboratory projectile scattering angle. Broadening is expressed as a fraction of the calculated width for c.m. emission.

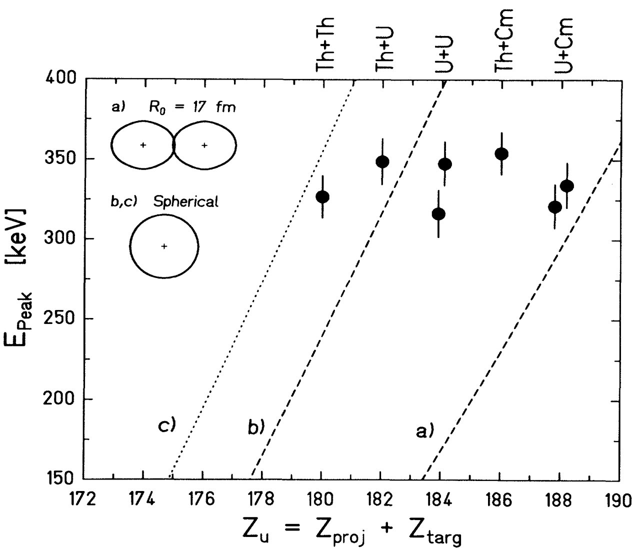

FIG. 3. Mean energies of positron peaks in Fig. 1 as a function of Z_u. Calculations (Ref. 6) (lines) are peak energies for spontaneous positron emission from static nuclear complexes with either (line *a*) deformed shapes consisting of the two nuclear centers separated by 17 fm in a head-on collision of major axes or (line *b*) spherical nuclear shapes and normal density, both with fiftyfold ionization. Bare nuclei are presented for the spherical shape in line *c*.

collision systems with a nuclear charge ≤ 180. Since for the heaviest collision systems this possibility involves the evaporation of many nucleons, it can be readily excluded by the kinematic constraints imposed to obtain the spectra in Fig. 1 unless very extreme angular distributions are attributed to the evaporated products. A narrow positron peak from a fast ($\tau \sim 10^{-19}$ s) internal pair conversion of a nuclear transition in the composite nuclear complex has also been considered[11] as a possibility. The shortcoming of the latter explanation is again the need for a state with nearly common energy in all the systems.

In summary, therefore, these data have developed the following experimental situation. Narrow peaks, with similar observed widths of ~ 75 keV, appear in superheavy collision systems with $180 \leq Z_u \leq 188$ where supercritical binding can occur. The peaks are produced in a narrow interval of bombarding energies at the Coulomb barrier, they cannot be assigned to any trivial source involving electromagnetic transitions in excited final-state nuclei,[1,2,10] and their line shapes are compatible with emission by a composite system moving with $v_{\text{c.m.}}$ although other sources created under circumstances noted above can also reproduce the line shapes. The possibility of attributing the peaks to spontaneous positron emission is challenged by the need to develop an understanding of the formation of giant nuclear complexes with long lifetimes and with the grossly different shapes required to explain the apparent independence of peak energy on Z_u. Particularly, an understanding is required of the entrance into a spherical state together with the exit from the state into binary systems with kinematics that closely resemble elastic scattering.

Indeed, the salient feature of our observations is this nearly common, or perhaps common, mean energy for all the peaks. (A simple average of the data gives 336 ± 10 keV.) This suggests a common source. An obvious speculation is that the source of the monoenergetic positrons is the two-body decay of a previously undetected particle which may be produced directly in the collision or in competition with the electromagnetic decay of an excited nuclear state. A clear signal for a neutral particle could be provided by the detection of a monoenergetic electron in coincidence with the peak positrons. Creation of charged pairs[12] of such particles could lead to similar consequences. The detection of the monoenergetic electron among the large delta-electron background is difficult, but appears feasible, presently, if its kinetic energy is not appreciably distorted by the proximity of a nuclear charge.

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