# Observation of a Peak Structure in Positron Spectra from U+Cm Collisions

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A narrow peak structure has been observed in positron spectra from U + Cm collisions at bombarding energies near the Coulomb barrier whose origin cannot be associated with established dynamic mechanisms of positron production involving Rutherford trajectories only. The peak's energy is centered at $316 \pm 10$ keV. Its width of $\sim 80$ keV, dominated by Doppler broadening, implies that the emitting system exists for longer than $\sim 10^{-20}$ sec.

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The strong electric field associated with a nucleus of charge $Z > 173$ is expected to produce supercritical binding of an electron exceeding $2mc^2$ and to lead to an unstable electron-positron vacuum state which decays spontaneously by positron emission.[1-3] The possibility of observing this rearrangement in the structure of the QED vacuum has motivated a search[4-6] for this unique phenomenon in superheavy collision systems where the required charge can be assembled transiently. However, in contrast to stable atoms, the dynamic aspect of the collision system introduces additional sources of positrons associated with the excitation of the antiparticle continuum by the rapid variation of the quasimolecular Coulomb potential.[7,8] Indeed, the first experiments[4-6] established that these dynamic mechanisms dominate the positron yield from systems such as U + U ($Z = Z_1 + Z_2 = 184$) at collision energies close to the Coulomb barrier, but they did not exhibit a signature for spontaneous positron creation within the limited range of projectile energies, positron energies, and scattering angles explored.

We have pursued this search with more comprehensive studies of the differential properties of positron spectra, including their dependence on scattering angle and projectile energy. Particularly, the measurements have been extended from U + U to U + Cm quasiatoms to exploit potential advantages. With the increase of $Z$ from 184 to 188, the spontaneous decay width is enhanced by a factor of >4[9] and, in addition, the kinetic energy of the spontaneous component approximately doubles.[9] Both effects alleviate some of the difficulties encountered detecting these low-energy positrons.

For U + Pb, U + U, and U + Cm collision systems near the Coulomb barrier, we find[10,11] that the gross features of positron spectra and their correlation with scattering angle are well reproduced by theory[7] employing Coulomb trajectories only. In addition to this anticipated behavior, we report here, primarily, on the observation of a well defined peak in the positron spectrum from U + Cm collisions at a bombarding energy of 6.05 MeV/u. It emerges prominently above the continuous dynamic and nuclear background spectra under selected kinematic conditions. Narrow structures have also been observed in positron spectra from U + U collisions in this[11] and other[12] experiments. It is not clear, presently, whether these share a common origin with the peak observed in U + Cm collisions.

The experiments were performed with beams of $^{238}$U from the UNILAC accelerator at Gesellschaft für Schwerionenforschung in Darmstadt. Targets consisted of ~0.5 mg/cm$^2$ $^{248}$Cm sandwiched between a thin carbon foil of 10–20 $\mu$g/cm$^2$ and a 0.7-mg/cm$^2$ Ti or a 120-$\mu$g/cm$^2$ carbon backing. The detection system, EPOS,[11] combines high efficiency, broad bandpass, and high resolution for positron detection. It possesses effective suppression of intense $\gamma$-ray and electron backgrounds, and unambiguous definition of scattered-ion kinematics. Scattered particles are detected in coincidence by two parallel-plate avalanche detectors arranged symmetrically about the beam axis. The overall resolution in the ion scattering angle, $\theta$, is less than 1°. The angle-angle correlations for two-body elastic-scattering events allow partial separation of c.m. backward and forward scattering even for the nearly symmetric U + Cm collision system. A solenoidal magnetic field, arranged perpendicular to the beam direction, transports the positrons to a cylindrical Si(Li) detector with an energy resolution of ~10 keV at 600 keV. Simulations transport of electrons to the Si(Li) detector is strongly suppressed by a spiral baffle arrangement, while the positrons are further identified by their annihilation radiation. The resulting positron detection efficiency, $\epsilon$, is a smooth function of energy with $\epsilon > 0.5\epsilon_{max}$ between 150 and 1000 keV. An appreciable Doppler broadening, closely centered on the intrinsic positron energy, is produced by the acceptance of a broad range in positron emission angle distributed symmetrically forward and backward relative to the direction of the rapidly moving sources. Because the broadening associated with emission from the center of mass and from the individual final-state nuclei differs significantly at some scattering angles, this feature can be exploited to provide information on the origin of the peak structure.

Figure 1 displays positron energy spectra which are correlated with two regions of ion scattering angles. The kinematic region associated with

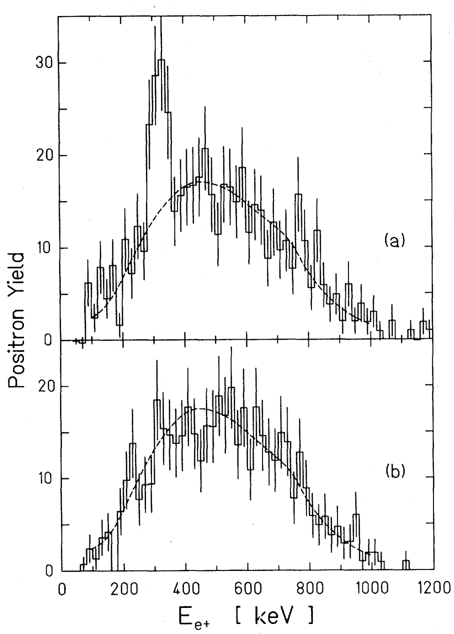


FIG. 1. Positron energy spectra observed for $^{238}U + ^{248}Cm$ collisions at a projectile energy of 6.05 Mev/u. Kinematic selections overlap preferentially with elastic scattering angles of (a) $100° < \theta_{c.m.} < 130°$ and (b) $50° < \theta_{c.m.} < 80°$. The dashed lines represent the theoretical distributions for dynamic positron production based on Rutherford trajectories together with the nuclear background deduced from $\gamma$-ray spectra, folded with the positron detection efficiency and normalized to the region outside the peak.

Fig. 1(a) preferentially overlaps with backward elastic scattering ($100° < \theta_{c.m.} < 130°$), while in Fig. 1(b) the kinematic selection favors overlap with forward elastic scattering ($50° < \theta_{c.m.} < 80°$). Although the partial separation between elastic forward and backward scattering in the U+Cm system precludes an absolute comparison with theoretical yields, it is found that the shape of the positron spectrum in Fig. 1(b) is reproduced by dynamic theory based on Rutherford trajectories[7] superimposed on a nuclear background deduced from simultaneous $\gamma$ measurements.[4,5,10,11,13,14]

On the other hand, a peak structure emerges with the choice of scattering angles represented by Fig. 1(a) at a mean energy of $E_{e^+} = 316 \pm 10$ keV with a width of ~80 keV. The strong dependence of the peak intensity on particle kinematics dissociates the peak from instrumental effects. The statistical significance of the peak is demonstrated in that the probability of fitting the whole spectrum with dynamic theory together with nuclear background is at a confidence level of $< 0.1\%$. It is also clear that the intrinsic width of the Doppler-broadened peak is surely less than 80 keV, implying that the emitting system exists for times longer than $\sim 10^{-20}$ sec. In an excitation-function measurement we observed that the structure is connected with a narrow interval in projectile energy confined between 6.0 and 6.2 MeV/u. At least part of this interval can be accounted for by the mean energy loss in the target.

The correlated distributions of the two reaction products provide additional information on the peak production mechanism. The effect of the solenoid's magnetic field on the scattered ion trajectories influences the kinematic angle-angle correlations of the scattered ions. The ensuing pattern of events indicates that the ionic charge states associated with the positrons in the peak differ from the mean equilibrium charge states which we found to be characteristic of Rutherford scattering leading to the underlying dynamic spectra. This anomalous behavior singles out these events and again suggests that the positron peak does not originate from Rutherford scattering. It also bears emphasis that the contrasting peak to dynamic background ratios exhibited in the spectra of Figs. 1(a) and 1(b) in large part reflect the magnetic field redistribution of the kinematic correlations and, therefore, do not directly represent the angular distribution of the peak events. The peak in Fig. 1(a) is particularly prominent above background because it overlaps a kinematic region of backward elastic scattering with relatively small dynamic positron intensity.

It is apparent that an explanation for the peak production process cannot be based on a mechanism involving Rutherford scattering alone since, in addition to the observations cited above, positron production based on Rutherford trajectories does not allow for narrow peak structure.[7] An obvious source of positrons is the pair decay of a strongly excited nuclear state in the separated reaction products. However, no evidence was found for an isolated $\gamma$-ray line which would be consistent with the intensity of the positron peak. For the most strongly converted $E1$ multipolarity, the peak intensity at the required energy of ~1350 keV is calculated[14] to be more than a factor of 10 larger than the sensitivity with which a line can be observed in the appropriate $\gamma$-ray spectra. Therefore, if plausible, such an explanation must be sought in the pair conversion of an intense $E0$ transition not detectable in the $\gamma$-ray spectra.

Two observations argue against this possibility. Figure 2(a) illustrates that the broad triangular-shaped spectrum with a half-width > 120 keV calculated[15] here for the pair conversion of an $E0$ transition, but also characteristic of any higher multipolarity, is a very unlikely match to the data at a confidence level of better than 98%. Moreover, although the ratio of internal electron and pair conversion coefficients[14] implies that a corresponding $K$-conversion line should be readily observable above background if the $K$ electrons are present, no evidence was found for such a line in the electron spectrum measured with the kinematics associated with the positron peak.

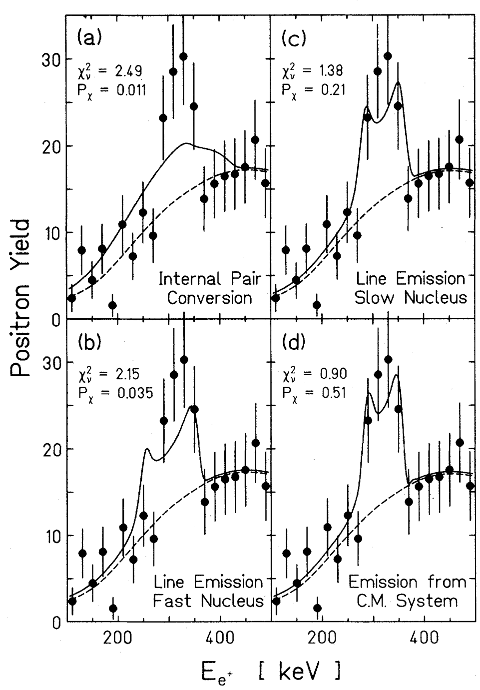


FIG. 2. Maximum-likelihood fits to the energy spectrum in Fig. 1(a) assuming origins for the peak structure as indicated. The fit involves varying the peak intensity, its position, and the continuous distributions of Fig. 1(a). The fit is made for the entire spectrum of Fig. 1(a), and the $\chi^2$ is quoted for the 200-keV region around the peak.

However, the possibility of having highly ionized inner shells does introduce a mechanism which can both inhibit electron conversion and produce the narrow positron structure observed. The latter occurs if the electron from the pair conversion process is captured into a vacant shell.[14,16] Capture into the $K$ shell is most probable. Figures 2(b) and 2(c) show the best fits to the data obtained for the two possibilities where it is assumed that monoenergetic positrons are emitted from either the fast or the slow collision product corresponding to the kinematics imposed in Fig. 1(a). Because of the Doppler effect, the spectrum emitted by the fast fragment again produces a poor fit to the data, while the emission from the slow fragment leads to a fit which cannot be rejected on statistical grounds only. However, any such explanation must consider that this nuclear monoenergetic positron emission is a very improbable process which can occur only under the exceptional circumstance that the lifetime of the $K$-shell vacancy of $\sim 10^{-17}$ sec is prolonged by several orders of magnitude so that it becomes competitive with the $E0$ lifetime of typically $10^{-12}$ sec. Furthermore, to account both for the positron peak's intensity and for the structureless electron spectrum requires that almost two such vacancies be present at the time of the $E0$ transition.

The unlikely suitability of any of these nuclear processes to account for the observations suggests that spontaneous positron emission should also be considered as the source of the peak. As demonstrated in Fig. 2(d), an excellent fit to the data is achieved with the assumption that a narrow positron line spectrum is emitted by the combined U + Cm system moving with the center-of-mass velocity. The Doppler broadening of ~70 keV accounts for most of the measured linewidth, and the intrinsic width emerging from this analysis is < 40 keV. Furthermore, the mean peak energy of 316 ± 10 keV coincides with the kinetic energy calculated[9] for positrons spontaneously emitted from the composite U + Cm nuclear system at the internuclear separation of ~17 fm encountered in head-on collisions at the bombarding energies used.

In fact, spontaneous positron emission from a collision-formed system with a lifetime as long as the $\sim 10^{-20}$ sec noted above can produce a spectrum such as in Fig. 1(a).[9] It has been pointed out[17] that prolonging the time of supercritical binding by a nuclear reaction, beyond the $2\times 10^{-21}$ sec dictated by Rutherford scattering, leads to a strong enhancement of the spontaneous positron emission and, thereby, to the production of a distinct peak which grows above the dynamic background as the collision time approaches the spontaneous $1s\sigma$ lifetime of $\sim 10^{-19}$ sec. The pronounced resonancelike excitation we observed for the positron peak may be reflecting the formation of a metastable nuclear complex which can provide such a time delay.[9,10,17] Within a schematic model of a fixed time delay,[9] a width of <40 keV and the observed intensity of the peak correspond to a time delay of $\geqslant 10^{-19}$ sec and to an event rate of approximately one in a thousand scatterings. Although there is no previous evidence for the formation of very long-lived, superheavy systems with little mass exchange and energy loss, such rare events could have escaped detection. Spontaneous positron emission may be the singularly effective probe for isolating the few events associated with the long time delays.

In summary, a well defined, narrow positron peak has been detected in the U + Cm system at an energy commensurate with a supercritically bound state for the combined system. Internal pair conversion of nuclear transitions does not seem to yield a plausible explanation of the peak structure. A consistent interpretation of the peak, however, can be provided by spontaneous positron emission enhanced by the formation of a metastable, giant dinuclear system.

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