Positrons from 1.4-GeV Uranium-Atom Collisions

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(Received 28 July 1978)

A large fraction of the number of positrons observed in collisions of $^{238}U + ^{238}U$, $^{238}U + ^{208}Pb$, and $^{208}Pb + ^{208}Pb$ at relative velocities $v/c = 0.11$ and for distance of closest approach $R_{min} < 40$ fm can be assigned to pair creation of nonnuclear origin, induced by the time-varying Coulomb fields of the projectile and target charges. An order-of-magnitude increase in the positron yield is observed by increasing the united-atom charge from 164 to 184.

A series of measurements have been carried out[1] at Darmstadt to investigate positron creation in heavy-ion collisions. Studies of Pb + Pb collisions, reported recently,[2] were extended to the heavier systems Pb + U and U + U for which at small distances of closest approach the superimposed Coulomb fields of the colliding nuclei become large enough that the binding energy of the lowest electron state may exceed $2mc^2$. In a heavy-ion collision, several sources of positron production are expected. The time-varying Coulomb field creates a $1s\sigma$ vacancy, which may decay spontaneously, if embedded in the Dirac sea, by emitting a positron and binding an electron.[3,4] But even more relevant to our present observation, this time-changing field can produce a pair by inducing a direct transition from the negative- to the positive-energy continuum, which does not involve intermediate bound states,[5] or by a two-step process, in which an inner-shell vacancy is first formed and then decays through the excitation of an electron from the Dirac sea into the vacant bound state. In the latter process the positron is emitted and an electron bound.[6,7] It should be noted that all three processes superimpose coherently because they have identical initial and final states. We report herein the first measurements of the dependence of the positron yield on the charge and on the ion scattering angle in collision systems with very large fields. A strong increase in the positron creation probability with the effective charge $Z_1 + Z_2$ was observed. The observed dependences on the charge $Z_1 + Z_2$ and on the scattering angle as well as the magnitude of the positron yield measured are, within their errors, in agreement with theoretical expectations for the coherent superposition of the positron production processes due to the time-dependent Coulomb field, without taking into account the spontaneous positron decay of a $1s\sigma$ vacancy.

Figure 1 shows a schematic view of the "orange"-type β spectrometer,[8] which uses a toroidal magnetic field produced by sixty current coils to focus positrons emitted from the target between 40° and 70° relative to the beam direction onto a 60-mm-diam × 100-mm-long, hollow cylin-

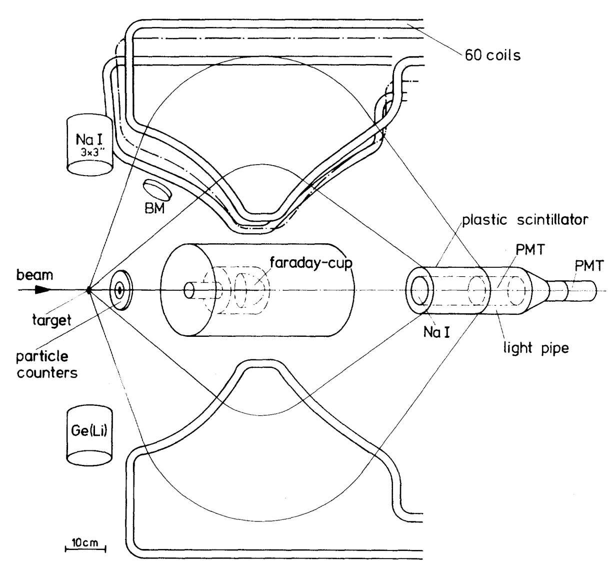

FIG. 1. Experimental setup in the "orange"-type β spectrometer. Positrons are focused by the toroidal magnetic field onto a cylindrical plastic scintillator containing a NaI crystal. Scattered particles are detected by an annular parallel-plate avalanche counter with four concentric anodes.

drical plastic scintillator detector. To further reduce background one of the positron annihilation quanta was detected by a 51-mm-diam× 100-mm-long NaI (Tl) counter placed inside of the plastic detector. Within the focused momentum band of 15% the positron detection efficiency was 2.6%. Scattered ions were detected in coincidence with positrons using an annular parallel-plate avalanche counter with four concentric anode rings subtending scattering angles between 13.5° and 15.7°, 16.1° and 20.2°, 20.6° and 26.5°, and 26.9° and 32.3°. The detector rings were capable of operating individually up to counting rates of 10^6 s^{-1}, thus permitting small positron yields to be measured. The energy resolution—20% of the energy loss—was sufficient to separate quasi-elastically scattered ions from fission fragments and light reaction products. Self-supporting, ~ 1-mg/cm^2, metallic foils of ^{238}U, ^{208}Pb, ^{197}Au, ^{181}Ta, and ^{139}La were bombarded with 5.9-MeV/amu ^{238}U ions. $^{208}Pb + ^{208}Pb$ collisions were also studied at the same relative velocities, i.e., at 5.9-MeV/amu bombarding energy. γ-ray spectra, related to positrons from the pair decay of nuclear excitations,[9] were measured in coincidence with scattered particles with a 76-mm-diam×76-mm-long NaI(Tl) detector positioned perpendicular to the beam direction.

A positron energy range between 0.44 and 0.55 MeV was selected for investigation where a maximum of the positron spectrum is expected to occur.[5-7] Accidental coincidences were small and were subtracted. γ-ray spectra in coincidence with scattered particles between 16.1° and 20.2° and 26.9° and 32.3° are shown in Fig. 2. All spectra exhibit an exponential falloff of similar slope up to energies of 6–7 MeV. They originate mainly from Coulomb excitation of the target and U projectile nuclei. The inset of Fig. 2 shows the ratios of positron to γ-ray yields above 1.44 MeV. For the lower-Z targets they are independent of nuclear species, scattering angle, and details of their associated γ-ray spectra. However, the higher-Z collision systems, U+Pb and U+U, exhibit a pronounced increase in their positron to γ-ray ratios. Moreover, detailed examination of the positron yields from the higher-Z systems shows a correlation to the number of scattered particles rather than to the number of γ rays. This suggests two sources of positrons coincident with the scattered particles. One is related to the number of scattered particles, N_p, and the other to the number of γ rays coincident with the scattered particles, $N_{\gamma p}$. With use of this pro-

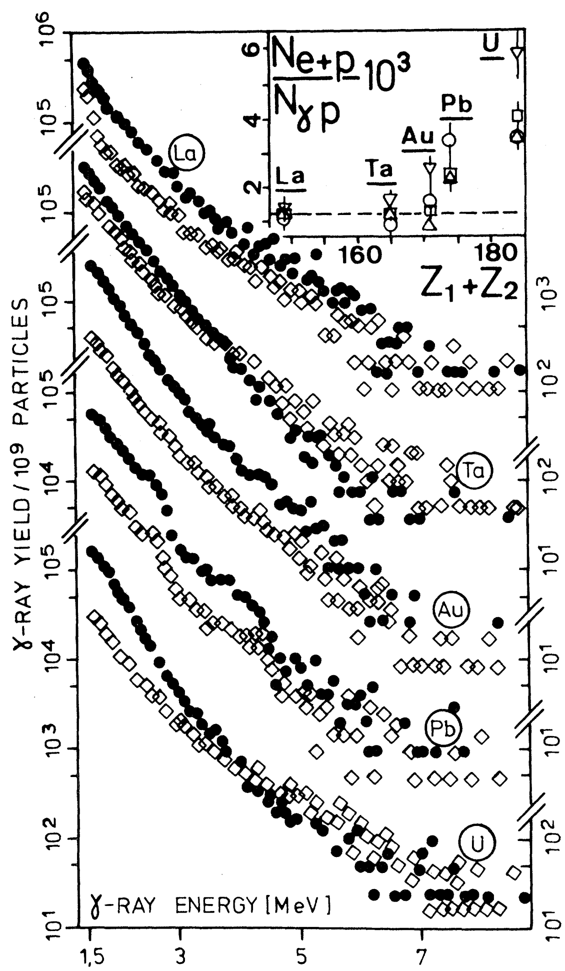

FIG. 2. γ-ray spectra in coincidence with particles scattered under angles (◇) between 16.1 and 20.2° and (●) between 26.9 and 32.3° from collisions of 1.4-GeV U ions with U, Pb, Au, Ta, and La targets. The inset shows the ratio of the observed positron yield to the observed γ-ray yield above 1.44 MeV, both in coincidence with the particles scattered under angles between (▽) 13.5 and 15.7°, (○) 16.1 and 20.2°, (□) 20.6 and 26.5°, and (△) 26.9 and 32.3° as a function of the sum of the projectile and target charges (Z_1+Z_2).

portionality, the number of observed positrons, N_{e^+p}, becomes $N_{e^+p}=PN_p+CN_{\gamma p}$, with P being the positron creation probability not associated with nuclear excitations and with C representing an empirical internal-pair-conversion factor, which is, considering the data for the lower-Z targets, apparently independent of Z and details of the continuous γ-ray spectra. These characteristics exhibited by C were confirmed by a calculation of the positron spectrum from the unfolded γ-ray yields using theoretical internal-pair-conversion factors and positron spectral distributions for $E2$ multipolarities. The value of C was determined from all measurements of U + La and U + Ta collisions and confirmed by a least-squares fit to all data, assuming a power law for the dependence of P on Z_1+Z_2. The inset in Fig. 3 displays the total yield of coincident positrons per scattered particle from U + U collisions, together with the nuclear-positron contribution calculated by multiplying the empirical conversion factor C by the number of observed coincident γ rays, $N_{\gamma p}$. For U + Pb collisions the background is dominated by the U excitations, except for a small contribution from the excitation of the 2.615-MeV, 3^- state of ^{208}Pb. The latter is the main source of background for the Pb + Pb collisions and was determined by using a ^{212}Pb source, as described previously.[2] The nuclear background for Pb + Pb collisions is roughly a factor of 8 lower than for U + Au collisions where it essentially dominated the total positron yield.

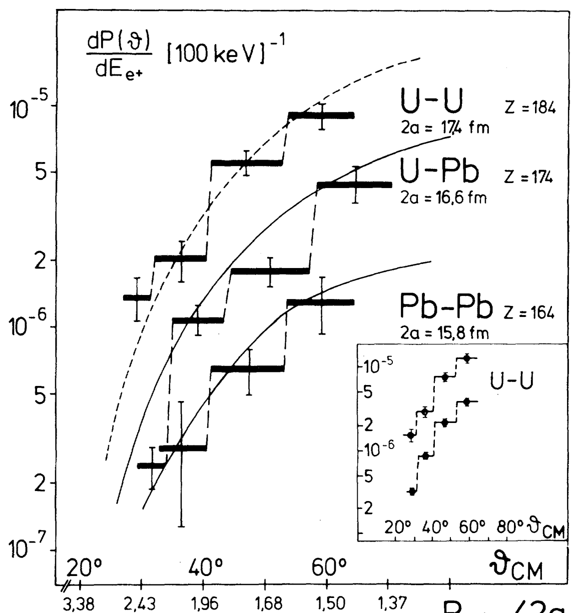

FIG. 3. Differential positron production probabilities per scattered particle within a positron energy interval of 100 keV centered around 490 keV as a function of the c.m. scattering angle $\vartheta_{\text{c.m.}}$ of the projectile and of the distances of closest approach for forward scattering R_{min} in units of the minimum distance for a head-on collision, $2a$. Positron background from nuclear excitation is subtracted. The solid lines present the results of calculations performed by Reinhardt *et al.* (Ref. 13); the dashed line shows the extrapolation to the U-U system. The inset shows the total number of observed positrons per scattered particle (upper curve) together with the calculated background from nuclear processes (lower curve) for U-U collisions.

Figure 3 shows the differential positron production probabilities per scattered particle corrected for positron background from nuclear excitation as a function of the c.m. scattering angle of the projectile for U + U, U + Pb, and Pb + Pb collisions. Also indicated in this figure is the distance of closest approach R_{min} in units of the minimum distance for a central collisions, $2a$. We have chosen to compare the data under the same dynamic conditions, i.e., the same relative velocities and c.m. scattering angles. For such a presentation we have to assume that the observed positrons, coincident with particles scattered between 13.5° and 32.3°, originate mainly from collisions in which the projectile is scattered forward through an angle ϑ. Collisions in which the projectile is scattered backward through an angle $\pi-\vartheta$, while the recoiling target nucleus is detected, are expected[10] to contribute a minor fraction to the positron yield observed, because the strong decrease of the Rutherford cross section when going from ϑ to $\pi-\vartheta$ overcompensates the expected increase in the positron yield per scattered particle, within the angular range considered. The data of Fig. 3 suggest that the positrons are created with nearly exponentially increasing probability when the distance of closest approach decreases from $5a$ to $3a$, i.e., from 40 to 25 fm for U + U collisions.

The most striking feature of the data is the increase in the positron yield by a factor 2.6 when Z_1+Z_2 changes from 164 to 174, and by about the same factor for a variation between 174 and 184. It should be noted in interpreting this result that the $1s\sigma$-vacancy production probability is, under similar conditions, expected to decrease by about a factor of 2 when Z_1+Z_2 increases from 164 to 184 in accordance with the first experimental results.[11,12] Thus the strong increase of the positron production with Z is characteristic for the production process itself. It reflects the fact that while the energy transfer required to create a pair remains essentially constant, the binding energy of the $1s\sigma$ state as well as the enhancement of the electron continuum wave functions at the origin and the delocalization of the positron wave functions all become very strongly dependent on Z in the region were the binding energy of the lowest electron state approaches $2mc^2$. These characteristics of very strong fields are corroborated quantitatively in calculations performed by Reinhardt *et al.*,[13] which take into account coherently the direct as well as the two-step excitation mechanism via inner-shell vacancies for the Pb + Pb and Pb + U systems. These calculations and the extrapolation for the U + U system, which does not include effects from the spreading of the $1s\sigma$ state in the negative-energy continuum, reproduce the absolute positron yield as well as its dependence on Z and on the distances of closest approach within the limits of error.

We would like to acknowledge the achievements of the UNILAC crew in making excellent U beams, P. Maier-Komor and E. Kellner for fabricating the delicate U targets, M. Richter, R. Hadsell, and F. Weik for their computational assistance, and H. Stettmeier and L. Richter for helping us during the initial phase of the work. We thank W. Greiner, D. H. Jakubassa, M. Kleber, V. Oberacker, J. Reinhardt, H. Schmidt, G. Soff, and G. Süssmann for theoretical discussions and encouragement. This work was supported by grants of the Bundesministerium für Forschung and Technologie and in part by the Alexander von Humboldt–Stiftung. One of us (J.S.G.) acknowledges receipt of a Senior U. S. Scientist Award from the Alexander von Humboldt–Stiftung.

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Observation of Scattering of Ion-Acoustic Cylindrical Solitons

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A large-amplitude ion-acoustic cylindrical soliton launched in an axisymetric cylindrical system collapses at the center of the cylinder. The highly nonlinear nature of the interaction is observed after the collapse, showing that many isolated pulses are emitted abruptly and propagate out without clear evolution of their wave forms.

The solitary wave is one of the most interesting phenomenon in nonlinear physics.[1,2] They are known to relate not only to large-amplitude dispersive waves[2,3] in plasmas, including laser- and/or microwave-plasma–interaction phenomena, but also to the waves of hydrodynamics or even to the oscillations in a lattice of solids.[4] Here we focus our attention on the ion-acoustic solitons. It has been clarified that the solitons do not interact strongly, i.e., elasticity has been observed in the collision process. On this point, rather small-amplitude, one-dimensional solitons

