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Observation of Positron Creation in Superheavy Ion-Atom Collision Systems

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(Received 16 February 1978)

We report the first observation of positron creation in high-energy $^{208}Pb + ^{208}Pb$ collisions and establish that a dominant fraction of the positron yield is from nonnuclear origins. The excess positron intensity observed over nuclear emission and its projectile energy dependence is consistent with recent predictions for pair-creation processes in the strong time-varying electric fields produced by the combined nuclear charges of the quasimolecular system formed in the collision.

There has been a long-standing interest in fundamental questions associated with the behavior of a Dirac electron in very strong electric fields originating from charges $Z > 1/\alpha$. In particular, as noted in theoretical studies,[1,2] a qualitatively new phenomenon is expected to occur when the binding energy of the electron exceeds the critical value of twice the electron mass. The filling of a vacancy in such an overcritically bound state without the expenditure of energy leads to a spontaneous emission of positrons with the creation of a charged lowest-energy state, a charged vacuum.[3,4] The observation of this positron-emission process would provide the crucial verification of the predicted transition from the neutral to a charged electron vacuum in overcritical fields.

Although the experimental conditions required to study this process cannot be realized in stable atoms presently, the formation of quasimolecular states in heavy-ion collisions, such as in U on U near the Coulomb barrier, may provide a suitable vehicle for creating overcritical potential binding.[5,6] However, in contrast to the stable-atom situation, in such dynamical systems positron creation also can reflect additional quantum electrodynamic (QED) processes associated with the time-varying electric field produced by the nuclear motion.[7,8] These dynamically induced positron-production processes are not only of considerable interest as background considerations associated with on-going experiments[9] to isolate spontaneous positron emission in heavy-ion collisions, but they are also inherently interesting since they reflect the salient features characterizing the interaction of electrons with very strong electromagnetic fields which, unlike pair creation by light charged particles,[10] cannot be treated in perturbation theory. These mechanisms can be studied independently of spontaneous positron emission by selecting collision systems in which the critical binding of $-2mc^2$ is not exceeded at any stage of the collision.[7] In this connection, the $^{208}Pb + ^{208}Pb$ system[11] is a particularly advantageous case to investigate experimentally, as is discussed below.

In this Letter we report the first observation of positron creation in ^{208}Pb + ^{208}Pb collisions as a function of laboratory energy and projectile scattering angle and show that a dominant contribution of positrons is from nonnuclear processes. The measurements were carried out at the Gesellschaft für Schwerionenforschung (GSI, Darmstadt) UNILAC employing ^{208}Pb beams with energies from 3.6 to 5.6 MeV/amu incident on ~ 1-mg/cm^2 ^{208}Pb self-supporting targets. The small cross sections expected—of less than a few hundred microbarns[7,8]—required that the detection sensitivity for positrons be large while maintaining an excellent discrimination against secondary, positron-background-producing processes such as external pair creation by γ rays and electrons. These characteristics were achieved with the detection system shown in Fig. 1. A combination of solenoidal focusing and a magnetic mirror arrangement at the ends of the solenoid is utilized to transport positrons emitted from the target with ~ 70% efficiency to a catcher device positioned 55 cm from the target location. The arrival and the annihilation of a positron at the aluminum catcher is signaled by collinear coincidences in two pairs of 3-in. by 3-in. NaI detectors. A measured differential response function for the total efficiency is also shown in Fig. 1. Including the selection of only the 511-keV photopeak in the coincident NaI counters, the total efficiency attains an approximately constant value of 2.8% over a range of positron energies below ~ 1 MeV.

Total cross sections for positron creation were measured using a Si surface-barrier detector at 45° to the beam direction for normalization to Rutherford scattering. Differential cross sections were measured with respect to the scattered ions at two scattering angles, (45 ± 10)° and (25.5 ± 4.5)°, by requiring a coincidence between a positron event, as defined above, and scattered projectiles or recoil target nuclei detected in a 50-μm NE-104 plastic scintillator arranged in an annular geometry about the beam axis. Elastic scattering and reactions with light particles such as O and C, which are the most likely target contaminants, were excluded from the positron events recorded.

The evaluation of the fractional contribution from positron production related to nuclear excitation in the target is of particular importance in these measurements and constitutes the primary source of systematic error in identifying the QED-related processes.[12] For the ^{208}Pb + ^{208}Pb system a determination of nuclear backgrounds becomes particularly straightforward. For bombarding energies below the Coulomb barrier, the principal source of nuclear positrons in this case is the pair-conversion decay of the Coulomb-excited 3^-(2.614 MeV) state of ^{208}Pb. This state is also populated in the decay of ^{212}Pb, and is again by far the dominant source of positrons from this radioactive source. Figure 2 compares the in-beam and source γ-ray spectra of a 3-in. × 3-in. NaI detector showing the similarity of the spectra above 1 MeV, except for the Doppler broadening and a small contribution from the Coulomb excitation of the 2^+ state of ^{208}Pb in the former case.

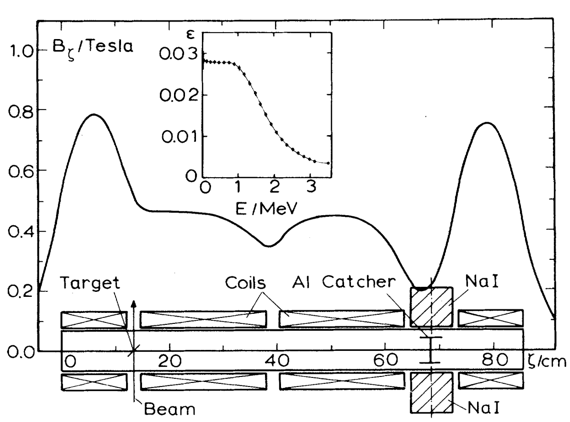

FIG. 1. Schematic and magnetic field distribution for the solenoid positron transport and detection system. The inset shows the positron detection efficiency as a function of positron energy.

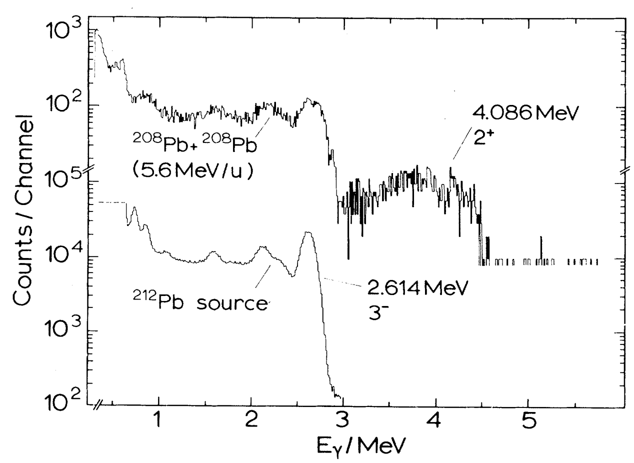

FIG. 2. γ-ray spectra from ^{208}Pb + ^{208}Pb collisions in coincidence with scattered projectile or target recoil at $\theta_{\rm ion}{}^{\rm lab} = 45° \pm 10°$ and from the ^{212}Pb source.

Obtaining the ratio of positrons to 2.614-MeV γ rays emitted by the ^{212}Pb source placed in the position of the target, and multiplying this ratio by the intensity of 2.614-MeV γ rays observed in-beam, directly yield the positron intensity from the Coulomb excitations of the 3^- state. The determination of the background positron intensity from such a direct comparison does not depend upon knowledge of the essential experimental parameters such as the γ-ray and positron detection efficiencies and the internal pair-conversion coefficient, and includes contributions from secondary processes such as external pair production.

Measured total and differential cross sections are plotted in Fig. 3 for a range of bombarding energies from 3.6 to 5.6 MeV/amu. The positron yields from the decay of the 3^- state, determined from the comparison with the ^{212}Pb-source decay, are also shown in Fig. 3 together with Coulomb-excitation calculations of these yields which utilize the measured value of $B(E3; 0\rightarrow 3^-) = 0.665 \pm 0.035\ e^2\cdot b^3$,[13] the quadrupole moment of the 3^- state, $Q_{3^-} = -0.42 \pm 0.32\ e\cdot b$,[13] and an internal pair-conversion coefficient of 0.37×10^{-3}.[14] With-

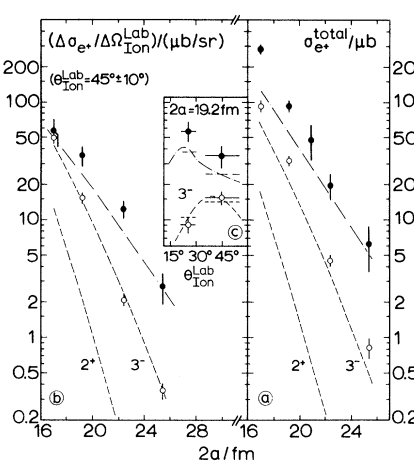

FIG. 3. Total and differential positron production cross sections for ^{208}Pb + ^{208}Pb as a function of distance of closest approach in a head-on collision, $2a = (19365\ \text{fm MeV})/E_{\text{lab}}$. The inset (c) shows the differential cross sections as a function of scattering angle with corresponding angle averages. The dashed lines are Coulomb-excitation calculations; the dot-dashed lines are theoretical calculations by J. Reinhardt *et al.* (Ref. 16); the open circles refer to measured positron yields from the decay of the 3^- state; the solid circles are positron yields *after* the subtraction of the measured backgrounds from Coulomb excitation and external pair creation by γ rays.

in the errors of the calculation parameters used, the agreement between the Coulomb-excitation calculations and the direct measurements is excellent. A number of corrections have been applied to the data. They include the energy loss in the target, the deflection of the scattered beam in the magnetic field of the solenoid, the Doppler shift of the γ rays, dead-time corrections, and small positron contributions from the ^{212}Pb source[15] in addition to those from the dominant internal conversion of the 3^- ^{208}Pb level. The positron energy window accepted in the measurement reflects the differential energy response function illustrated in Fig. 1, which includes, with high efficiency, the major portion of the positron spectrum expected for the processes being sought.[7,8] Figure 3 also illustrates that the positron yield from the Coulomb excitation of the 2^+ state is negligible over the range of projectile energies used. The absolute normalization error is estimated to be ± 30% and is not included in Fig. 3.

For all these measurements the contribution from nuclear Coulomb excitation alone is only a fraction of the total positron yield and this fraction is particularly small at the lowest bombarding energies. Figure 3(c) illsutrates that the differential cross section, with respect to $\theta_{\text{ion}}^{\text{lab}}$, for the excess positron intensity over the Coulomb-excitation contribution possesses a more forward-peaked angular distribution than that for positrons from the deexcitation of the 3^- state. The possibility that this excess positron intensity in the differential cross sections is due to nuclear reactions is largely excluded by limiting the minimum internuclear separation between Pb nuclei beyond the nuclear interaction radius of 17 fm, and by rejecting reactions with light target contaminants (O and C) by the coincidence requirement with scattered ions. The essential absence of γ rays in the spectrum of Fig. 2, other than from ^{208}Pb, further emphasizes this point. In the total-cross-section measurements nuclear reactions from close collisions with Pb target nuclei and light contaminants would be reflected by a rapid onset of the cross section for $2a \sim 19$ fm. Indeed, for the highest-energy point a nuclear-reaction contribution to the positron yield cannot be excluded. For the data of lower projectile energy the growing difference between the total and the Coulomb-excitation positron yields with decreasing energy again largely obviates the possibility that there is a significant contribution from nuclear reactions to the total cross section.

Calculations by Reinhardt *et al.*[16] for positron production from the QED processes cited above are shown in Fig. 3. The general agreement of the calculated intensities and projectile energy dependences with the measured excess yields above Coulomb-excitation backgrounds suggests that the observed positrons are associated with these processes involving positron emission by the very strong time-varying electric fields present in the quasimolecular collision system, and with electrons of the pair-filling, pre-ionized, quasimolecular states and the continuum, with relative amplitudes which are presently not fully determined.

We thank Professor W. Greiner, Professor B. Müller, Dr. G. Soff, J. Reinhardt, and Dr. V. Oberacker for valuable discussions. We are very grateful to the technical staff of GSI for their invaluable assistance in carrying out the experiment. One of us (J.S.G.) acknowledges the support of an Alexander von Humboldt–Stiftung Senior U. S. Scientist Award; another (Y.N.) acknowledges the support of the Humboldt-Stiftung. This work was supported by the Bundesministerium für Forschung und Technologie.

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State-Resolved Differential Cross Sections for Rotational Transitions in Na_2+Ne (He) Collisions

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(Received 19 April 1978)

We demonstrate a new technique for the measurement of state-resolved differential cross sections for elastic and inelastic collision processes involving molecules with small level spacing. Lasers are used to label a specific rovibronic level by modulation of its population via optical pumping and to probe the population of neighboring levels by laser-induced fluorescence. First results on Na_2 + Ne (He) collisions show that beyond the center-of-mass scattering angle $\theta_{c.m.} = 50°$ nearly all collision events are inelastic.

The exchange of rotational energy is an important and efficient energy transfer mechanism. Attempts to investigate these processes in molecular beams date back as far as 1964.[1] A major progress towards the ultimate goal, namely, the determination of fully state-resolved differential cross sections, has been achieved only very recently. Transitions between specified rotational quantum states have first been studied in ionic-atom–neutral-molecule collisions.[2] Mean-

