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Estimates of the Nuclear Time Delay in Dissipative U + U and U + Cm Collisions Derived from the Shape of Positron and δ-Ray Spectra

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Positron and δ-ray spectra have been measured in coincidence with quasielastic scattered particles and fission fragments from the bombardment of Pd, U, and Cm targets with U beams of energies between 5.9 and 8.4 MeV/u. For collisions leading to a fission reaction, the atomic positron and δ-ray spectra fall off more steeply at high energies than expected from calculations based on pure Rutherford trajectories. A quantitative analysis of this effect is in accord with a nuclear contact time of about 10^{-21} s.

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It is now well established that atomic positron emission in close Coulombic heavy-ion–atom collisions[1-3] (e.g., U+U) originates from the excitation of Dirac sea electrons caused by the monopole part of the time-changing Coulomb field of the collision partners. The nearly exponentially decreasing high-energy part of the positron spectra reflects the Fourier frequency spectrum of the pair-creation matrix element $\langle f|\partial/\partial t|i\rangle \propto \dot{R}(t)/R(t)$ [$\dot{R}(t)$ is the radial velocity and $R(t)$ the distance of the colliding nuclei]. In first-order time-dependent adiabatic perturbation theory, the Fourier spectrum can be characterized by a scattering time[4] which only depends on the kinematical variables of the Rutherford trajectory. If the colliding nuclei come close enough together that nuclear forces become important, the Rutherford trajectory will be perturbed. This results in a change of the Fourier frequency spectrum and, consequently, the energy distribution of emitted positrons will be altered. From a detailed analysis of deflection functions in deeply inelastic collisions,[5,6] nuclear interaction times of up to a few times 10^{-20} s have been deduced. For such long "sticking times" [time for which $\dot{R}(t)=0$] model calculations indicate intensity oscillations in the positron[4,7] and also δ-ray spectra[8] due to interference effects between the ingoing and outgoing channels. Additionally, at very long sticking times ($>1\times10^{-20}$ s) a K vacancy in a "supercritical" system (a dinuclear system for which the electronic 1*s* separation energy exceeds $2m_ec^2$) may decay spontaneously by emission of positrons with discrete energies[9] ($\simeq$ 300 keV). However, only small intimations of these effects are expected if the sticking time is only of the order of 10^{-21} s as calculated for the U+U system from various friction models.[10-12]

In this Letter, we report on the search for such effects of nuclear contact. The U+U ($Z_U=184$) system was chosen for a detailed study. In addition, the U+Cm system was investigated in one experiment to search for a narrow positron line. Although it is much more difficult to prepare and handle the radioactive ^{248}Cm targets, its use is advantageous in the study of this question since the spontaneous 1*s* decay width should be enhanced[7] by more than a factor of 4. For both systems, a nuclear attachment with energy dissipation can be recognized experimentally by the detection of fission fragments from the very fissile U or Cm nuclei.

^{238}U, ^{108}Pd, and ^{248}CmF$_3$ targets with thicknesses of 450, 1000, and 200 μg/cm^2, respectively, were irradiated by U beams from the UNILAC in Darmstadt with specific energies between 5.9 and 8.4 MeV/u (intensities < 1.5 particle nA). The U and Cm targets were sandwiched between 30- and 55-μg/cm^2 carbon layers; the Pd target was self-supporting. Positrons and electrons were detected with a solenoidal transport system with Si(Li) detectors for energy determination. The experimental setup is shown schematically in Fig. 1. To unambiguously detect the very few positron signals in the Si(Li) detector in the presence of a high δ-electron counting rate, the 511-keV annihilation radiation of the positron was measured coincidently by a fourfold-segmented NaI ring crystal surrounding the Si(Li) detectors.[3] The target electrons were detected by two Si(Li) diodes at the opposite end of the solenoid. The very intense low-energy background electrons below 250 keV travel in between the detectors and, in this way, are excluded from detection. Scattered particles or fission fragments from the target were detected with a 50-μm NE104 plastic-scintillator (PS) ring counter accepting laboratory scattering angles $35° < \theta < 55°$ with respect to the beam direction. The full energy sum peak of the quasielastic events has a relative width of about 25%, thereby allowing a separation from the broad distribution of fission events. At projectile energies of 5.9, 7.5, and 8.4 MeV/u, the quasielastic contribution (no sequential fission) in the U + U scattering system was about 100%, 30%, and 0%, respectively. The positron spectrum was recorded requiring the following coincidence conditions: $(\mathrm{Si}_1^{e+} \cup \mathrm{Si}_2^{e+}) \cap [(\mathrm{NaI}_1 \cap \mathrm{NaI}_2) \cup (\mathrm{NaI}_3 \cap \mathrm{NaI}_4)] \cap \mathrm{PS}$. Detector-response-function–unfolded and efficiency-corrected positron spectra are shown in Fig. 2.

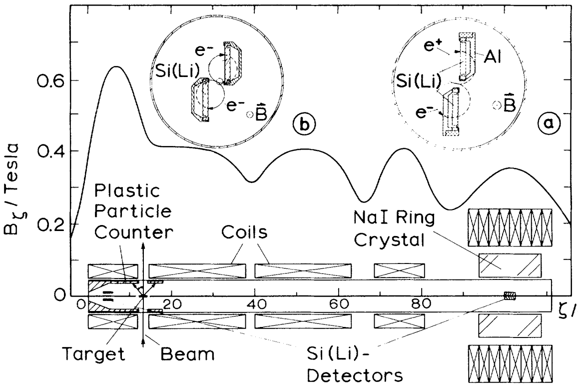

FIG. 1. Experimental setup with the calculated magnetic mirror field configuration on an axis of the solenoid providing a large collection efficiency for positrons. Insets (a) and (b) show cuts perpendicular to the solenoid axis at $\zeta = 102$ and 5 cm, respectively. The geometrical suppression of δ rays in (a) and of low-energy electrons in (b) is indicated by the projected electron orbits. Dimensions of the Si(Li) detectors: diameter 19.5 mm, thickness 3 mm; of the NaI ring crystal: inner diameter 90 mm, outer diameter 204 mm, length 150 mm.

It is well known that the separation of atomic and nuclear positrons is a major problem.[1-3,13] The technique we applied was to measure the target γ rays of the U + U and U + Cm scattering system with a 7.5× 7.5-cm NaI(Tl) detector in coincidence with reaction products and then convert

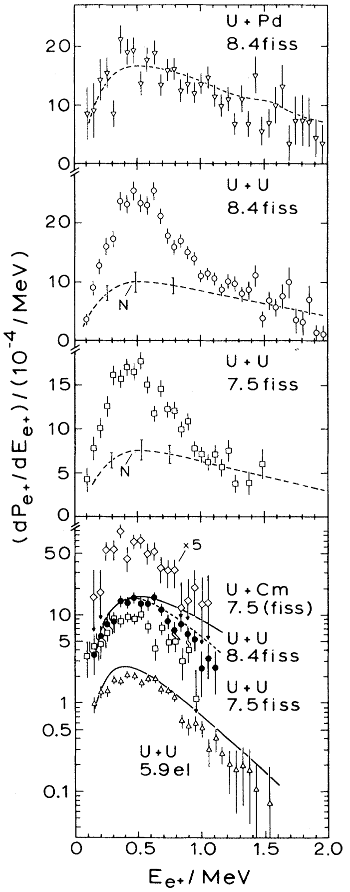

FIG. 2. Number of positrons per detected plastic-scintillator fission event and positron energy interval dP_{e^+}/dE_{e^+} for the U + Pd system at 8.4 MeV/u, and the U + U system at 8.4 MeV/u and at 7.5 MeV/u. The dashed curves N indicate nuclear positrons as derived from target γ-ray spectra. The bottom part of the figure shows the spectra of atomic positrons in a semilogarithmic representation. Included also is the U + Cm system scaled by a factor of 5. The heavy lines are calculations based on the assumption of Rutherford trajectories. The dashed line includes effects of a nuclear contact time (Ref. 7) of about 10^{-21} s.

this γ-ray spectrum to a positron spectrum using theoretical pair conversion coefficients.[14] The unknown γ-ray multipolarity was adjusted with the U + Pd system for which only nuclear positrons are expected. A γ-energy–independent mixing ratio of 45% $E1$ + 55% $E2$ at 7.5 MeV/u and 30% $E1$ + 70% $E2$ at 8.4 MeV/u was found to reproduce the measured positron spectrum; see Fig. 2. (The assumption that the γ-ray spectrum below 1.5 MeV is dominantly of $E2$ multipolarity yields within 10% the same shape of the positron spectrum.) This mixing ratio was kept constant in the conversion procedure of the U + U and U + Cm γ-ray spectra. The correctness of this procedure can be tested with electron spectra recorded in coincidence with positrons $\{(\mathrm{Si}_1^{e^-} \cup \mathrm{Si}_2^{e^-}) \cap [(\mathrm{NaI}_1 \cap \mathrm{NaI}_2) \cup (\mathrm{NaI}_3 \cap \mathrm{NaI}_4)] \cap \mathrm{PS}\}$. We observe from Fig. 3 (upper part) that even in the heaviest systems, the high-energy tail is still dominated by electrons from nuclear pair decay. The coincident-electron spectra $dP_{e\pm}/dE_{e^-}$ can be well reproduced by the sum of pair-decay electrons $dP_{e^-\gamma}/dE_{e^-}$, calculated from the target γ-ray spectrum in complete analogy as for pair-decay positrons, and uncorrelated coincidences of positrons with the δ- and conversion-electron spectrum dP_{e^-}/dE_{e^-}:

$$dP_{e\pm}/dE_{e^-} = (N_{e^+}{}^{\mathrm{exp}}/N_p)(dP_{e^-}/dE_{e^-}) + \epsilon_{e^+\gamma}(dP_{e^-\gamma}/dE_{e^-}). \qquad (1)$$

Here, $N_{e^+}{}^{\mathrm{exp}}$ is the number of experimentally detected positrons in the NaI ring counter, and N_p in the plastic-scintillator particle counter. $\epsilon_{e^+\gamma}$ is the mean detection efficiency for nuclear positrons.

Nuclear-background- and efficiency-corrected positron spectra are shown in the bottom part of Fig. 2. The error bars include, besides statistics, a 10% uncertainty due to background subtraction. An additional error of about ± 20% has to be assumed, originating from normalization. The spectra exhibit the typical exponential drop-off at high energies indicating the importance of collision dynamics in the positron-production process. No statistically significant structures have been observed in this experiment in which particles are accepted over the full angular range between 35° and 55°. For the U + U system at 5.9 MeV/u taken in coincidence with elastic scattered particles, calculations on the basis of pure Rutherford trajectories reproduce the shape of the spectrum. This, however, is not the case for the spectra taken in coincidence with fission products (i.e., after nuclear contact) which drop off much steeper. Such an effect can be caused by a time delay during the nuclear contact and, therefore, should also be present in the δ-ray spectra.

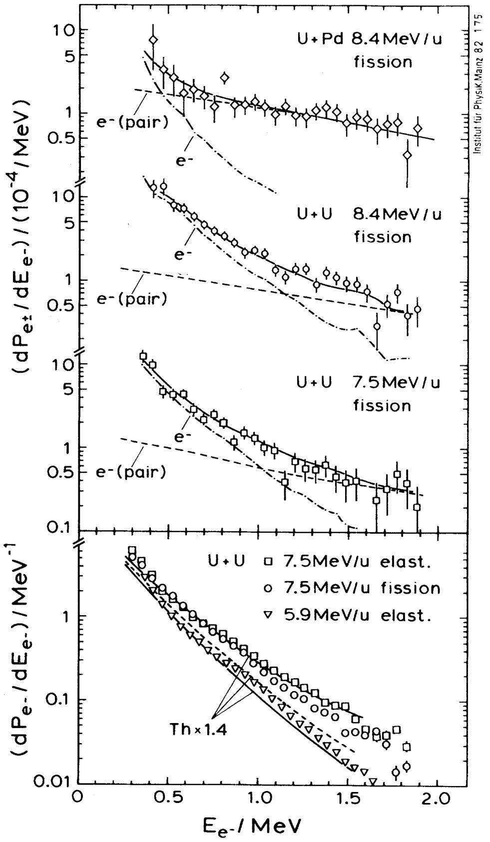

FIG. 3. Upper part: Number of electrons coincident with positrons per detected plastic-scintillator event and electron energy interval $dP_{e\pm}/dE_{e^-}$ as a function of the electron energy E_{e^-}. The dashed line indicates the calculated nuclear-pair-decay electrons; the dashed-dotted line, the uncorrelasted contribution of δ- and conversion electrons. The heavy line is the sum of both. Lower part: δ-electron spectra for the U + U scattering system at 5.9 and 7.5 MeV/u in coincidence with quasielastic scattered particles and at 7.5 MeV/u also in coincidence with fission fragments. The heavy lines are calculations (Ref. 7) assuming Rutherford trajectories; the dashed line includes effects of a nuclear contact time of about 10^{-21} s for a collision at 7.5 MeV/u.

To check this, electron spectra have been recorded in the same experiment under the identical coincidence condition with respect to the plastic-scintillator particle counter as for the positron spectra. Various efficiency-corrected spectra are shown in Fig. 3 (lower part). The conversion electrons can be calculated again from the target γ-ray distribution. An upper limit for this contribution was estimated to be 7% of the yield, having nearly the same slope above 0.8 MeV as the observed electron spectra. Possible $E0$ contributions which obviously appear around 1 MeV in the spectrum taken at 5.9 MeV/u seem to be negligible at 7.5 MeV/u. Therefore, no correction was applied to the data. The contribution of electron-electron sum coincidences was also found to be negligible. Of particular interest are the electron spectra taken for U+U at 7.5 MeV/u in coincidence with quasielastic and fission events. It can clearly be seen in Fig. 3 that, for the latter, the intensity between 1 and 1.7 MeV is reduced, even though the impact-parameter dependence (for Rutherford trajectories) would imply just the opposite effect. Again, this is consistent with the idea of a time delay during the nuclear contact. To estimate its order of magnitude, we have made the simple model assumption of a linear delay-time distribution ranging from 0 at the grazing impact parameter $b_{\rm gr} = 7$ fm to an adjustable value ΔT for central collisions. Furthermore, we assume that the δ-ray spectra are dominated by electrons originating from the excitation of the $2p_{1/2\sigma}$ shell. With these assumptions we obtain from the experiment, using first-order time-dependent adiabatic perturbation theory, a delay time ΔT between 1 and 1.5×10^{-21} s. A detailed coupled-channel calculation of the positron and δ-ray spectra, in the presence of a nuclear time delay on the basis of the friction model of Ref. 10, has recently been performed by Reinhard *et al.*[7] (see Figs. 2 and 3). When compared with these calculations, the nuclear-time-delay effect was found experimentally to be larger in the positron and smaller in the δ-ray spectra. The reasons for these discrepancies are not presently understood. Possible causes include experimental uncertainties, especially in the nuclear-background subtraction procedure, and possibly approximations made in the calculations. However, these calculations again indicate quantitatively a nuclear time delay $\Delta T = 10^{-21}$ s. Such small contact times in deep-inelastic collisions rule out an observable contribution of spontaneous positrons. This agrees with the experimental finding that the positron spectrum for the U+Cm system differs from that for the U+U system only by a constant factor but not in shape (see Fig. 2).

We conclude that strong evidence for a nuclear contact time of about 10^{-21} s was found in U+U collisions with fission fragments in the exit channel from both the positron and δ-ray spectra. Such effects may provide an atomic clock for the measurement of time scales in nuclear reactions, supplementing the techniques which have so far been used: analysis of deflection functions in deeply inelastic collisions[5,6] and proximity effects in the fission of medium heavy nuclei.[15]

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