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11 OCT. 1982

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Talk presented at the International Advanced Course on "Fundamental Processes in Energetic Atomic Collisions", Maratea, Italy

SEPTEMBER 1982

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ELECTRON EXCITATION AND POSITRON EMISSION IN QUASI-MOLECULAR COLLISIONS OF VERY HEAVY IONS*

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In collisions of very heavy ions superheavy quasiatomic systems are created, where the electrons experience for a period $T \sim 10^{-20}$ s the combined nuclear charge $Z = Z_p + Z_t$ of the projectile and the target. This offers us the possibility to extend our knowledge on atomic physics by about a factor of two concerning the nuclear charge number and by an order of magnitude concerning the binding energy of the strongest bound electron⁽¹⁾. For $Z > 173$ the binding energy of the 1s-electron exceeds the pair production threshold of $2 mc^2 \sim 1$ MeV, which allows for a spontaneous emission of positrons. In heavy-ion collisions close to or slightly above the nuclear Coulomb barrier superheavy nuclear compound systems may be formed. The spectroscopy of the emitted δ -electrons and positrons in such scattering experiments is a sensitive tool for the investigation of the nuclear reaction mechanism and for the determination of the reaction time.

*This work was supported by the Bundesministerium für Forschung und Technologie (BMFT) and the Deutsche Forschungsgemeinschaft (DFG). One of us (G.S.) acknowledges the support of the DFG-Heisenberg Programm.

For nonrelativistic bombarding energies inner-shell electrons move quasi adiabatically in the Coulomb field of the projectile and target nuclei. The enormous binding energies and the high-momentum components in the wavefunctions necessitate a relativistic treatment of the dynamical behaviour of the electrons. In our calculations the total electron wavefunction is expanded into adiabatic basis states¹⁾ including the bound states as well as the positive and negative energy continuum. These basis states are determined by the stationary solutions of the Dirac equation, where we restricted ourselves to the monopole part of the two-centre potential. Electron screening effects are taken into account within the Hartree-Fock-Slater model^{5,6)}. The fate of a single electron during the collision is then determined by the occupation amplitudes which are the solutions of the coupled channel equations. It remains to solve the many-electron problem in the dynamical situation, which is easily achieved by the reduction to single electron occupation amplitudes¹⁾.

We have calculated for the colliding system $Pb - Cm$ with $Z_p + Z_t = 82 + 96 = 178$ the number of created vacancies per collision in the innermost 1so-state as a function of the classical impact parameter b ($E_{lab} = 5.9$ MeV/u). The nuclear motion is described by Rutherford trajectories. In our evaluations it is assumed that initially ($t \rightarrow -\infty$) all states up to the 4so level are occupied. If we neglect the Coulomb interaction with the other present electrons, i.e. only the attractive interaction with the nuclear charge centres is considered, we obtain as result⁵⁾ the dashed line in fig. 1. The inclusion of electron screening corrections within the Hartree-Fock-Slater (HFS) model⁶⁾ leads to the solid line which agrees with the experimental data of Liesen et al⁷⁾. Typical features are the rather high ionization probability for almost central collisions ($b \sim 0$) and the exponential decline of $P(b)$ for increasing collision parameter. The high value of $P_{1so}(b \sim 0)$ is predominantly caused by relativistic effects in the electron wavefunction, which allows for the transfer of rather high momenta to the bound state electron. The shape of $P(b)$ is determined by the binding energy of the initial electron state at the distance of closest approach. Employing this fact $P(b)$ measurements enable us to deduce spectroscopic informations about electrons in superheavy quasiatomic systems¹⁻³⁾. Even more detailed informations can be gained in measurements of the emitted δ -electrons in coincidence with created K-vacancies⁴⁾

Perhaps the most exciting process in atomic physics of superheavy systems is the intrusion of the 1s-electron into the negative energy continuum. A long standing question was, whether the repulsive electron self energy may prevent this critical behaviour. We evaluated the influence of this field-theoretical contribution to the K-shell binding energy (see Fig. 2). In our

Fig. 1: Number of created iso-vacancies $P(b)$ per Pb-Cm collision versus the classical impact parameter b . The dashed line represent the result where only the monopole part of the two-centre nuclear potential was taken into account. The inclusion of electron screening corrections within the Hartree-Fock-Slater (HFS) model leads to the solid line5) which agrees with the experimental data of Liesen et al7).

calculations of the self-energy we employed the methods developed by Johnson and collaborators8). Our calculations, which contain all orders in the coupling constant $Z\alpha$ of the external field, are performed for hydrogen-like systems taking into account the finite nuclear size. For the elements of the known periodic table the obtained results agree well with those of Mohr9) and Johnson8). As the most important result we found for $Z = 170$ an energy shift of +10.99 keV, which represents only a 1% correction to the total K-electron binding energy10). Therefore it may safely be neglected in investigations of ionization probabilities in superheavy quasmolecular systems7). If one adds to this the vacuum-polarization calculations for critical external potentials, the total energy shift due to radiative corrections of order α amounts only to 300 eV. This tiny effect is at present far outside of any measurable consequences. We conclude that radiative corrections as vacuum-polarization or self-energy may not prevent the K-shell binding energy from exceeding $2mc^2$ in superheavy systems with $Z > Z_{cr} \sim 170$. Positron creation has been observed in collisions of very heavy ions such as Pb - Pb and U - U (see eq. refs. 11-14). In contrast to high-energy collisions of elementary particles positron production in superheavy quasmolecular systems is not determined by the kinematics alone. It is strongly influenced by the Coulomb distortion of the initial and final state wavefunction. A typical value for the production probability is 10^{-4} per collision. The theoretical calculation of the e^+ -

Fig. 2: The self-energy shift ΔE of K-shell electrons as a function of the nuclear charge Z . The calculations are performed to first order in α but to all orders in the coupling constant $(Z\alpha)$ of the external field. The dots denote the numerical results of P. Mohr9) for 1s-electrons in the Coulomb field of point-like nuclei. The open circles represent the values obtained by Cheng and Johnson8) for a Hartree-Fock potential and extended nuclei. The results of the present calculations for extended nuclei are indicated by triangles10).

creation is quite analogous to the evaluations of ionization processes except for the treatment of the resonance state in the negative energy continuum. Using a projection formalism¹⁵ the resonance state is split off in a pure bound state and a pure continuum part. Besides the ordinary dynamical coupling this gives rise to a spontaneous coupling, which does not vanish in a stationary situation. However, this splitting is not unique. The dynamical contribution to the positron creation exhibits several typical features. It was predicted theoretically¹⁶ that the production probability increases approximately like $(Z_p + Z_t)^{17}$ for fixed impact parameters b . The corresponding experimental finding was reported by Backe et al.¹¹. $P_{e^+}(b)$ decreases nearly exponentially as a function of b . The spectrum of the emitted positrons displays a broad maximum at about $E_{e^+} = 500$ keV. The production of low energy positrons is strongly suppressed due to the Coulomb repulsion. The available Fourier frequencies in the collision determine the exponential decline of the high energy part of the spectrum. For a detailed discussion we refer to refs. 15 and 17. As one specific example of considerable interest we will discuss in the following the positron emission in collisions with nuclear contact, especially in deep inelastic nuclear collisions. To analyse a given experiment the employed nuclear trajectories should be consistent with the elastic and inelastic heavy-ion scattering data. Many reaction models with different degrees of refinement have been discussed in the literature. We have calculated trajectories with the macroscopic friction model of Schmidt et al.¹⁸, which includes nuclear neck formation. Strong deviations from Coulomb trajectories are found and an energy loss up to ~30% (for $b \sim 0$) can be obtained. The corresponding positron spectra show a gradual enhancement at $E_{e^+} = 500$ keV due to the occurrence of the spontaneous positron production in the s-channel. On the other hand the change in kinematics causes a drift to lower kinetic energies in the p1/2-partial wave spectra due to destructive interference. Both effects taken together lead to an enhancement of the maximum and a drift towards lower energies also in the total spectrum.

Measurements by Backe et al.¹⁴ seem to indicate such tendencies: In U+U and U+Gm collisions at energies above the Coulomb barrier positron spectra have been measured in coincidence with fission fragments in order to get a signature for close nuclear contact. The analysis shows an enhancement of dP/dE_{e^+} at lower kinetic energies. For a quantitative comparison one has to integrate the impact parameter-dependent positron spectra over all values of b which lead to a nuclear reaction, weighted by the corresponding probability $w(b)$ to induce nuclear fission. Performing the integration with a weight factor $w(b) = 1$ for $b < b_{gr}$ and $w(b) = 0$ elsewhere, there remains an energy shift of ~50 keV in the experimental data in comparison with the theoretical

curves, which might be due to electron screening effects⁵). Furthermore, the theoretical values have to be reduced by an overall factor ~2/3. Fig. 3a shows the experimental data for U+U collisions at $E_{lab} = 5.9$ MeV/u, 7.5 MeV/u, and 8.4 MeV/u, in comparison with theoretical results¹⁹ excluding electron screening, but reduced by the factor mentioned above. Dashed lines indicate pure Rutherford scattering trajectories, whereas the solid lines display spectra calculated with the modified trajectories. For an even better agreement longer delay times Δt (~2.10⁻²¹ sec) may be needed. For the same collisions the δ -electron distribution (Fig. 3b) has been calculated¹⁹. Compared with calculations for the elastic Rutherford trajectory it is most striking that due to the destructive interference between the two branches of the trajectory in deep inelastic nuclear collisions the spectrum decreases considerably and falls off steeper. Further investigations along these lines seem to be very promising, both to establish the mechanism of positron production and to deduce the nuclear reaction time scale.

Fig. 3a) Comparison of theoretical calculations¹⁹ for the positron spectra in U+U collisions at $E_{lab} = 5.9, 7.5$ and 8.4 MeV/u with experimental data of Backe et al.¹⁴), as described in the text.

Fig. 3b) The calculated δ -electron spectrum for the same collisions. Most striking is the steeper decline for deep inelastic nuclear collisions.

We are grateful to H. Backe, H. Bokemeyer, F. Bosch, W. Koenig, Ch. Kozhuharov, D. Liesen, P. Mokler, J. Schweppe, P. Senger for making their experimental results available to us prior to publication.

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