Intra-atomic Double Scattering of Binary Encounter Electrons in Collisions of Fast Heavy Ions with Atoms and Molecules

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We present first experimental evidence for intra-atomic double scattering of binary encounter electrons produced in collisions of 5.9 MeV/u U^{29+} with neon, xenon, and molecular gases. A broad distribution of electrons is observed at a velocity twice the velocity of the moving ion (v_P) at angles ϑ_e up to 135°. We attribute this emission pattern to well-known target binary encounter electrons around $2v_P$ at extreme forward laboratory angles that are subsequently elastically scattered in the target nuclear potential to the large angles observed. [S0031-9007(97)03987-2]

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Observation of double differential electron emission spectra after ion-atom collisions has proven to be a major tool in the understanding of complex as well as fundamental ionization processes. Aside from the possibility to improve theories of ion-atom interactions in comparison of predictions and experimental data, interest for electron emission cross sections is especially widespread in applied particle physics such as radiobiology and condensed matter physics. About 2/3 of the energy loss of the ion is transferred into kinetic energy of the δ electrons [1] (electronic stopping). The maximum possible momentum transfer is received by the so-called binary encounter electrons (BEe), which are produced in hard, knock-on collisions between the ion and the target. They are therefore responsible for radiation effects in biological or other material in regions far from the primary ionization events [2] leading to induction of latent tracks. In this context, our observation of high energy electrons emerging under large angles from single-ion atom or molecule collisions described in this Letter are not only of significant importance for basic scattering theory. Moreover, the treatment planning for the hadron cancer therapy at GSI and elsewhere relies on the calculation of relative biological efficiencies [3] on the basis of track structure models.

In the classical impulse approximation (IA) [4], the BE electrons are described as being elastically scattered by the projectile potential in the center-of-mass (CM) system, thus being a simple two-body interaction [5]. The target nucleus determines only the properties of the electron initial state, i.e., their binding energy and momentum distribution (Compton profile). Theoretical treatment in this framework has shown excellent agreement between theory and experiment for specific collision systems. To a good approximation, the CM system can be considered to be the projectile rest frame, due to the large mass difference. In the rest frame, the target electrons travel at the speed of v_P before and after the collision and are scattered into an angle θ_e between 0° and 180° as a function of the impact parameter. For comparison with experimental cross sections, the results of IA calculations have to be transformed to the laboratory system. For bare ion impact on light targets like H_2 and He, only slight deviations have been found between experimental data and predicted cross sections [6]. According to the Rutherford scattering formula, the BE production cross section for fast, light ion impact was found to scale with $\frac{Z_P^2}{E_P^2 \sin^4(\theta_e/2)}$, with Z_P being the projectile nuclear charge, E_P the projectile energy, and θ_e being the emission angle in the CM system.

Within the last ten years, many experiments using heavy ions with low charge states were performed and displayed strong deviations from the scaling laws predicted by IA. The simple approximations being highly accurate for fast, bare projectiles experience a dramatic failure for heavy, partially stripped ions; in the CM system the cross section of electron scattering in backward direction is strongly enhanced compared to bare projectiles, and prominent diffraction minima and maxima are observed for smaller angles [7,8]. These results, along with the findings in this work, underline that knowledge about even fundamental ionization processes is still not yet complete.

The experiments reported here have been performed at GSI, Darmstadt, Germany. An ECR source delivered an U^{29+} ion beam that was accelerated by the UNILAC to 5.88 MeV/u. A newly developed toroidal electron spectrometer with two-dimensional position sensitive detection of electrons was employed to obtain the double differential spectra [9]. The apparatus enables a simultaneous detection of electrons in the angular range from 0° to 360° with respect to the beam axis with an energy resolution $\frac{\Delta E}{E}$ of $\approx 5\%$. Electron energies between 20 eV and 20 keV are

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accessible by scanning the plate voltage in this electrostatic analyzer. Scanning speed is controlled by a beam current driven ramp generator. Rest gas pressures were in the range of $P = 5 \times 10^{-7}$ mbar, and target gas pressures in the range of $P = 5 \times 10^{-5}$ mbar; thus single collision conditions are established at a very low background electron rate from the rest gas. For each target a run without gas was performed, normalized to beam current, and subtracted from the distribution obtained with the gas target in operation.

In Fig. 1, the complete momentum distribution of final state continuum electrons is presented as a "scatter plot" for 5.88 MeV/u U^{29+} ions colliding with C_3F_8 molecules.

The momenta are given in atomic units a.u., for the momentum components parallel ($p_\parallel$) and perpendicular ($p_\perp$) to the beam direction (0°). Low-energy ("soft") electrons from the target are centered around $\vec{p}_e = (p_\parallel, p_\perp) = (0,0)$, the origin in the laboratory frame. A further emission centered in the target system is the fluorine KLL Auger electron emission, visible as a circle with the radius of about 6.5 a.u. It is discernible from background electrons only in backward direction and smeared out in energy, due to the different charge states of the emitting fluorine ions. Soft electron emission from the projectile is centered around $(p_\parallel, p_\perp) = (15,0)$, with 15 a.u. being the projectile velocity. Because $q = 29+$ is far below the equilibrium charge state of uranium at this velocity, we attribute this peak mainly to "electron-loss to the continuum" (ELC), caused by projectile electrons ionized in the target nuclear potential [10].

The circular structure with a radius of 15 a.u. around the projectile emission system (15,0) represents the well-known binary encounter ridge. In the target frame the momentum varies with laboratory emission angle ϑ_e according to $v_e = 2v_p \cos(\vartheta_e)$. Minima occur at $\vartheta_e = 25^\circ$ and 60°. This behavior has been found before and has been explained in a quantum-mechanical picture as diffraction of impinging electron waves in the non-Coulomb potential of the screened ion [11,12].

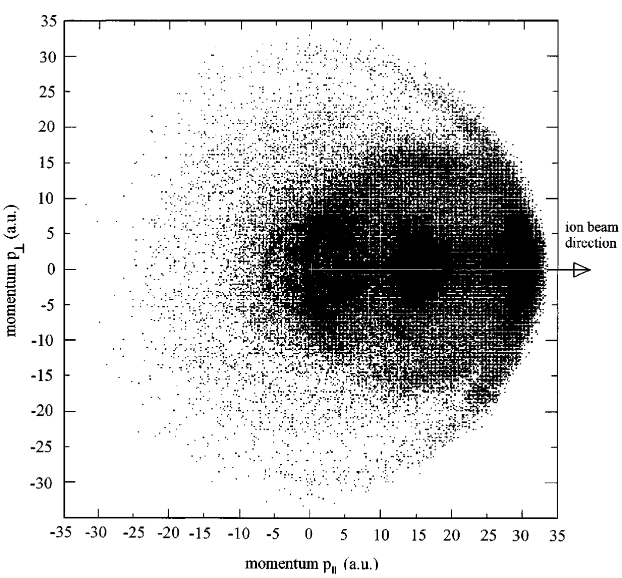

FIG. 1. Complete two-dimensional final state momentum space for electrons emitted in collisions of 5.88 MeV/u U^{29+} with C_3F_8.

In this Letter we report on a novel, prominent feature of the electron emission in collisions of heavy, nonbare ions with complex atomic and molecular targets. A ridge of high-energy electrons at velocities around $2v_P$ ($\approx$12.5 keV) is observed at large laboratory scattering angles ϑ_e up to 135°. For angles ϑ_e from 0° to 20° it is of course not discernible from the "normal" BE emission. At larger angles the ridge is clearly separated from BE electrons and displays approximately the shape and centroid energy of the 10° binary encounter peak. It should be noted that the structure observed at the outer edge of this plot has nothing to do with the actual location on the microchannel plate detector, where enhanced count rates at the edges are well known. A more conventional representation, a sequence of double differential spectra for 10 different laboratory angles ϑ_e, is shown in Fig. 2. The distribution of electrons around 12.5 keV is clearly visible at all angles.

At intermediate observation angles, this structure appears to be similar to the "binary peak splitting" that has already been observed in other experiments [13]. In these cases, however, the impact velocity was much smaller (4.9–7.5 a.u. $\approx$ 0.6–1.4 MeV/u), and the peak splitting that was detected for a much smaller range of observation angles was attributed to diffraction of the electron emission in the screened potential of the projectile [14,15]. At high collision energies, as used in this experiment, the amplitude coefficients of the higher order Legendre polynomials, which contain the quantum-mechanical phase shifts (and thus the potentials involved), strongly decrease as described by Shinpaugh *et al.* [16].

For this novel electron emission in single ion-atom collisions we propose the following interpretation: a binary encounter electron produced at extreme forward angles in a close collision with the projectile is subsequently scattered by the target nuclear potential of its parent atom. In a simple picture the electron is first hit on a position between the projectile and the target, travels in forward direction, and is deflected by its own nucleus.

It has already been discussed in literature [17,18], that for simple kinematic reasons, only multiple scattering processes can produce electrons with a velocity greater than twice the projectile velocity. In 1996, Suarez *et al.* [17] showed an electron peak at $3v_P$ in forward direction in comparison of 20–50 keV H^+ and H^0 on He collisions. It was attributed to a projectile electron, which is first scattered in the target nuclear potential and then again in the projectile potential. Since a double scattering event is necessary to produce the emission patterns observed in both experiments, one could speak of these electrons as

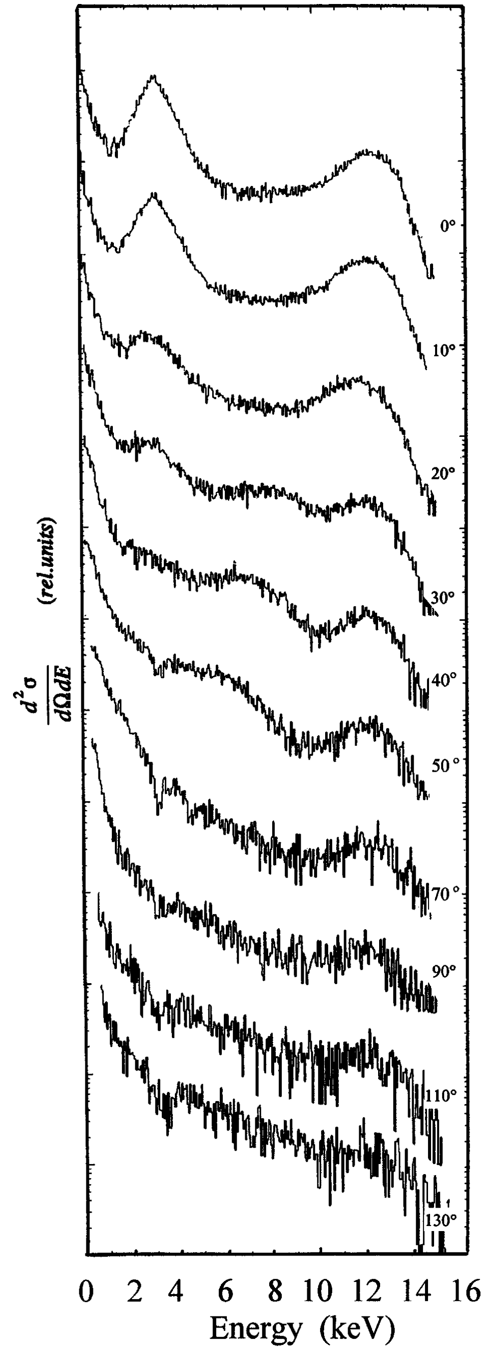

FIG. 2. Relative double differential electron emission cross sections in the collision system 5.88 MeV/u U^{29+} on C_3F_8 for 0° to 50° ($\Delta\vartheta_e = 10^\circ$) and 70° to 130° ($\Delta\vartheta_e = 20^\circ$).

"ternary encounter electrons." In the Suarez experiment the projectile electron ternary encounter leads thus to a distribution with $2v_P$ in the projectile rest frame at v_P. In our case, the target electron ternary encounter leads to a distribution at $2v_P$ around the target rest frame.

Several conditions are required for the target electron ternary encounter to occur at a detectable level: (a) cross sections for production of fast electrons that are enhanced over Rutherford in forward direction leading to a jet-like emission toward the target nucleus and (b) a target nucleus with a high atomic number, because the scattering cross sections strongly depend on Z^2. Experiments employing fast, screened heavy ions colliding with high Z ($Z > 6$) targets are scarce, and the energy range of the measured spectra is often limited to the high energy "end" of the BE peak. This might explain why these structures have never been observed before. Investigations with 3.6 MeV/u Ne^{10+} and Xe^{40+} ion beams performed with the same experimental setup did not display these features.

The angular dependence of the elastic scattering cross section in the target potential is complicated. First, the electrons are scattered by a highly screened potential, where the actual charge state at the time of the collision is unknown. Second, the impact parameter distribution for the scattering in the target potential is weighted because the electrons in their atomic shells are anisotropically distributed in space according to $|\psi_i(r)|^2$ at the time of the projectile-electron collision. Therefore, a scattering cross section according to simple Rutherford law is not expected. Measured single differential cross section for ternary encounter electron emission integrated from 10 to 15 keV as a function of laboratory emission angle is plotted in Fig. 3 for a variety of target gases.

Because the novel observed emission features are measured for monoatomic rare gases as well, the electrons have to be scattered by the field of their own nuclei and

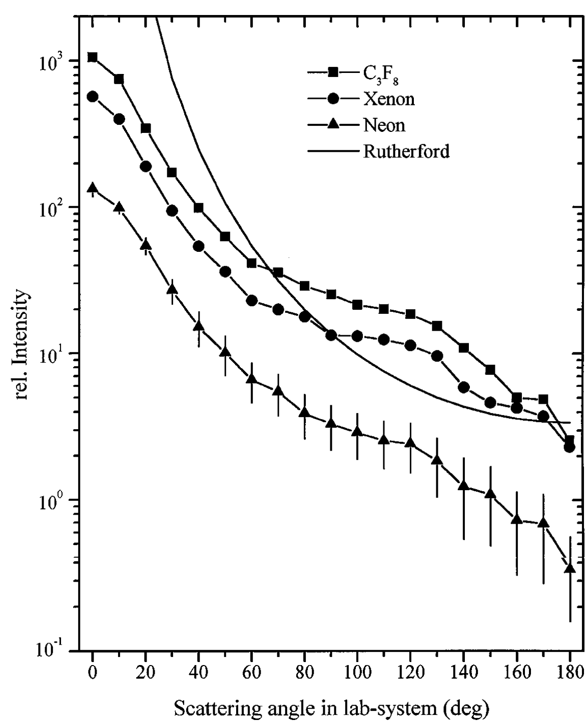

FIG. 3. Single differential cross section of ternary encounter electron emission in 5.88 MeV/u U^{29+} collisions with neon, xenon, and C_3F_8. The electron energies are integrated from 10 to 15 keV.

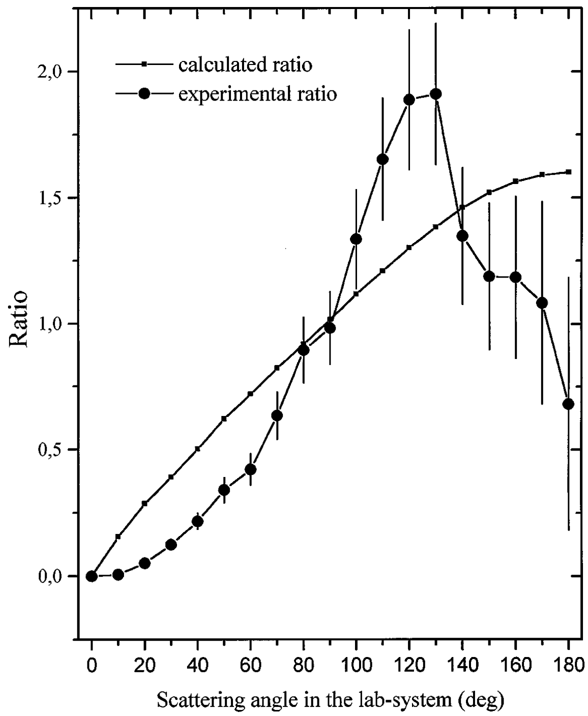

FIG. 4. Ratio of calculated cross sections for elastic electron scattering on Xe^{0+} and Rutherford scattering on Xe^{54+} $R = \frac{d\sigma/d\Omega_{Xe^{0+}}}{d\sigma/d\Omega_{Ruth}}$ (full line) as calculated by Bhalla and measured data from Fig. 3 (full circles) $R = \frac{d\sigma/d\Omega_{exp}}{d\sigma/d\Omega_{Ruth}}$.

not by the other atoms in the molecule. For comparison, a curve according to the $\sin^{-4}(\vartheta_e)$ dependence of Rutherford scattering is plotted as a full line for the xenon target in Fig. 3. In order to investigate the process in more detail, a calculation of elastic scattering cross sections for electrons in a screened Xe potential was performed. The ratio of elastic scattering cross sections for 12.5 keV electron impact on neutral Xe and bare Xe^{54+} is plotted in Fig. 4 as well as the ratio of the measured data in Fig. 3 and data of bare xenon.

Overall agreement between the two curves is not very well; only the general trend of the calculated ratio is to a large extent mirrored in the experimental ratio. We believe the deviations to originate from the reasons described above.

In other experiments high energy electrons of $2v_P$ at large emission angles have been observed in collisions of fast projectiles with thick solid state targets [19], in agreement with predictions of Monte Carlo simulations [20]. These electrons have been shown to result from scattering of primary electrons by other target nuclei while traveling through the solid. In these investigations, not a distinct peak, but a broad shoulder extending to $2v_P$ for angles up to 150° was visible. The novel structure observed here under single collision conditions in diluted gaseous targets is an additional example of a series of recent exciting observations in the electron emission for heavy-ion atom collisions in the strongly nonperturbative regime. As a conclusion, the consequence of our measurements is that the belief in negligible cross sections of multiple scattering processes in collisions of fast ions with gaseous targets has to be revised.

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