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Energy Dependence of Binary Encounter Electron Emission in Collisions of Screened Heavy Bi^{26+} ions with He Gas Targets

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Abstract

Double differential emission cross sections $d^2\sigma/dE_e d\Omega_e$ (DDCS) of electron emission in collisions of highly charged and partially stripped ions with gas targets deviate dramatically from the predictions of simple theories like the First Born and Binary Encounter (BE) Approximation [C. Kelbch *et al.*, Z. Phys. D **22**, 713 (1992) and P. Richard *et al.*, J. Phys. B **23**, L213 (1990)] ([1],[2]). In our experiment the electron emission cross sections were investigated in collisions of partially stripped Bismuth ions with Helium gas targets at projectile energies in the range $1.4 \leq E_P \leq 6.0$ MeV/u. DDCS of electron emission have been measured as a function of the electron emission energy E_e and the observation angle ϑ_e. The data show systematic enhancement of the BE electron emission for all projectile energies. For the lowest projectile energy the predicted diffraction structures in the Binary Encounter peak were observed at angles between 35° and 45°.

1. Introduction

In collisions of highly charged heavy ions with gas targets double differential cross sections $d^2\sigma/dE_e\, d\Omega_e$ (DDCS) of electron emission exhibit an exponentially decreasing shape, superimposed by the prominent broad Binary Encounter (BE) peak. Electrons contributing to the exponentially decreasing continuum are well known as resulting from collisions where the electrons are simultaneously attracted in the Coulomb potential of both the projectile and the target nucleus (two-centre electron emission) [3]–[6]. The Binary Encounter peak is due to target electron emission through direct hard collisions with the charged projectile. Thus, this electron emission process can be treated as a true two-body, i.e. binary encounter process. Regarding the target electron as quasifree and initially at rest in the laboratory frame, the emission can be denoted in the centre of mass system (CM), i.e. in a first approximation in the projectile frame, as an elastic electron scattering process in the point-like Coulomb potential of the ion (Rutherford-scattering). The classical kinematics results in a maximum energy transfer to a target electron in the laboratory frame of

$$E_e = 4\left(\frac{m_e}{m_p}\right) E_P \cos^2 \vartheta_e \tag{1}$$

where E_e is the final energy of the target electron, E_P the projectile energy, m_e, m_P the electron, and the projectile masses, and ϑ_e the electron emission angle with respect to the incident beam. The width of the Binary Encounter peak reflects the Compton profile, i.e the momentum distribution of the target electrons due to the orbital motion around the target nucleus. The collision of a point–like charge with a quasi–free electron is theoretically described by the First Born and Binary Encounter Approximation (BEA). Here, electron production scales quadratically with the ratio of the projectile charge state and the energy $(q/E_P)^2$. Extended experiments on bare heavy ion of Lee *et al.* [7] and Ramm *et al.* [8] verified these simple theories.

Contrary to these results, Richard *et al.* [2] observed an anomaly of electron production using partially stripped Fluorine ions at different charged states $q = 3 - 9$. In contradiction to the predicted q^2-scaling for 0^0 the BE electron emission increased with decreasing projectile charge. Furthermore, for heavy U^{32+} ions Kelbch *et al.* [9] found at certain emission angles unexpected structures in the centre of the Binary Encounter peak. Quantum-mechanical calculations on Binary Encounter electron emission cross sections were performed by Reinhold *et al.* [10] by a partial-wave expansion in the field of non-bare projectiles. Using a model potential non-Coulomb interaction during the electron scattering in the potential of partially stripped heavy ions were taken into account. It was found, that the double peak structure and the enhancement of Binary Encounter electron emission are due to a quantum-mechanical interference phenomenon in the elastic scattering cross section. Extended theoretically approaches on Binary Encounter electron emission were performed by Schultz *et al.* [11]. The calculations has been applied to numerous ions ($Z = 6$, 9, 26, 53, 92) at various charge states for impact energies between $E_P = 0.1$ and 100 MeV/u. Further experiments on Binary Encounter electron productions for partially stripped heavy ions (Cu up to U) at small projectile energies around $E_P = 0.6$ MeV/u were well described by the theory [12]–[14]. The dependence on projectile energies up to $E_P = 3.6$ MeV/u was investigated for highly stripped Iodine ions only [15].

The present investigation was undertaken in order to examine the theoretical predictions of interference phenomena in Binary Encounter electron emission of ion atom collisions with heavy non-bare projectiles. Our experiments were extended to collisions of fast, partially stripped Bi^{26+} ions with He gas targets. For systematics the cross sections were investigated for different projectile energies in the range $E_P = 1.4$ MeV/u up to 6.0 MeV/u. DDCS of electron emission

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have been measured as a function of the electron emission energy E_e and the observation angle ϑ_e. Deviations from Rutherford-scattering cross sections for all projectile energies were quantified.

2. Experiment

The experiment for evaluating the double differential emission cross sections $d^2\sigma/dE_e\, d\Omega_e$ of electron emission in collisions of highly charged and partially stripped Bi^{26+} ions was performed at the UNILAC-accelerator at the GSI (Darmstadt, FRG). The ion beams were well collimated and hit a thin Helium gas target. The energy spectra of the electrons ejected in the heavy ion atom collisions were collected with a electrostatic hemispherical sector analyzer at observation angles $30^\circ \leq \vartheta_e \leq 90^\circ$ with respect to the beam axis. The measured energy range was $300 \leq E_e \leq 12000$ eV with a resolution of about 5%. The data were taken in multiscaling mode with the steps normalized to the beam current in a shielded Faraday-Cup behind the gas target. The measured spectra were corrected to the effective solid angle at each emission angle ϑ_e. For a more detailed description of the experimental setup and data analysis see Ref. [8].

3. Results and discussion

In Fig. 1 energy spectra for electron emission resulting from fast heavy ion impact on atomic gas targets are shown for the collision system 1.4 and 3.6 MeV/u Bi^{26+} + He. The double differential electron emission cross sections $d^2\sigma/dE_e\, d\Omega_e$ are determined for different emission angles $\vartheta_e = 30^\circ$ up to 70°. All electron spectra exhibit the exponentially decreasing shape, superimposed by one or two prominent broad peaks. For the high energetic Bismuth projectiles ($E_P = 3.6$ MeV/u and 6.0 MeV/u) the emission cross sections show the expected contribution of "two-centre" and Binary Encounter electrons. According to Eq. (1) the BE–peak shifts to lower electron energy with increasing observation angle ϑ_e. For $E_P = 1.4$ MeV/u, however, a splitting of the Binary Encounter peak can be seen at emission angles $35^\circ \leq \vartheta_e \leq 45^\circ$. Within that angular interval a minimum appears at the electron energy where the maximum of the BE-peak is expected.

For comparison with the Rutherford–scattering the experimental double differential cross sections $d^2\sigma/dE_e\, d\Omega_e$ and the observation angles ϑ_e were transformed into the projectile frame. Considering the Binary Encounter electron emission process as an elastic scattering of quasi-free target electrons in the potential of a charged projectile in rest, the electron energy in the projectile frame E_e^{CM} is given by the projectile energy E_P and the mass ratio of the electron and the projectile only: $E_e^{CM} = (m_e/m_P)E_P$. From the simple relation $\Theta_e = 180^\circ - 2\,\vartheta_e$ BE electron emission into forward angle $\vartheta = 0^\circ$ relates to backward scattering $\Theta_e = 180^\circ$ in the CM-system. For each scattering angle Θ_e the Binary Encounter electrons are separated by a fit procedure to the exponentially decreasing continum of the two-centre electrons, leaving the BE-peak only. The data are integrated over the peak, yielding the single differential cross section $d\sigma/d\Omega_{eBE}^{CM}$. Fig. 2 shows the single differential cross section $d\sigma/d\Omega_{eBE}^{CM}$ versus the emission angle Θ_e in the centre of mass system for the different projectile energies. The broken lines indicate the elastic scattering cross section of a quasi–free electron in the Coulomb–like projectile potential with the point–like charge $q = 26+$ and the electron energies $E_e^{CM} = 763$ eV, 1580 eV, 1961 eV and 3268 eV. To account for the two electrons of the Helium target the Rutherford-scattering cross sections are multiplied by 2.

For the highest projectile energy $E_P = 6.0$ MeV/u the single differential cross sections of BE electron emission shows the expected dependence on the scattering angle Θ_e. The cross sections decrease monotonously with increasing scattering angle. In contradiction to the expected q^2-scaling the cross sections are exceeding the Rutherford-scattering by a factor of 1.5 to 2.5. With decreasing projectile energy the cross sections exhibit structures at certain scattering angles. The most pronounced deviation from Rutherford-scattering cross sections appears at the lowest projectile energy $E_P = 1.4$ MeV/u and backward scattering angles $\Theta_e \approx 100^\circ$. The location of the maximum relates to forward electron emission in the laboratory frame around $\vartheta_e \approx 40^\circ$. Within that angular interval the electron production is enhanced by a factor of 2 to 4.

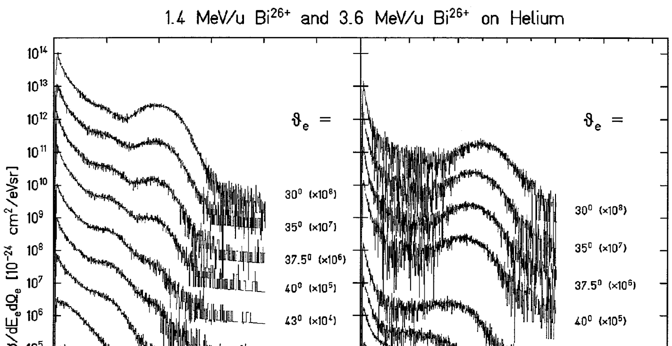

Fig. 1. Double differential cross section of electron emission from collisions of 1.4 MeV/u Bi^{26+} and 3.6 MeV/u Bi^{26+} with Helium. For the observation angle $\vartheta_e = 30^\circ$ up to 90° the spectra are multiplied by the noted numbers.

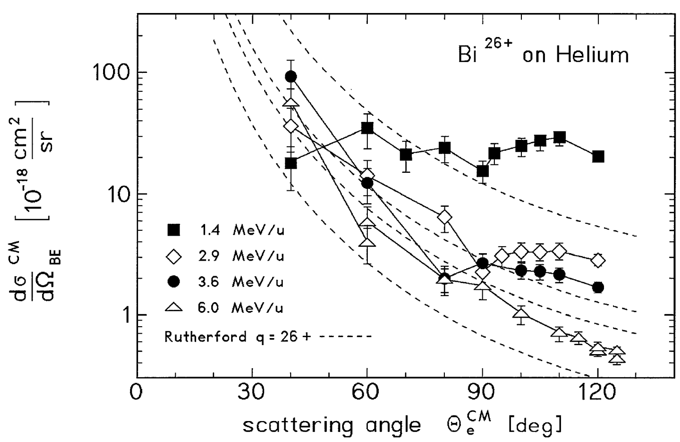

Fig. 2. Single differential cross sections for the emission of Binary Encounter electron emission from Helium induced by various projectile energies of Bi^{26+}. Broken lines: Rutherford-scattering cross section of free electrons with $E_e^{CM} = 763$ eV up to 3268 eV.

The scattering of the target electrons in the non-Coulomb potential of the screened heavy Bismuth ions leads to the predicted phenomena in BE electron emission. Quantum-mechanical interference processes give rise to enhancement of the BE electron emission at forward observation angle and diffraction structures in the BE emission cross sections.

4. Conclusions

In this presentation the Binary Encounter electron emission cross sections are reported for fast and partially stripped Bismuth ions in an extended energy range up to $E_P = 6.0$ MeV/u. The BE electron emission cross section depends strongly on the projectile energy E_P and the emission angle ϑ_e. The electron emission shows deviations from Rutherford-scattering cross sections and double peak structures in the energy spectra at low projectile energies and forward emission angles. Our investgations confirm theoretical predictions of interference phenomena in Binary Encounter electron emission in collisions of heavy non–bare projectiles with rare gas targets.

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