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Binary encounter electron emission in collisions of highly charged ions with helium gas targets

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Abstract

The energy and angular distribution of δ-electrons produced in collisions of bare argon projectiles with helium gas targets are reported. Double differential electron emission cross sections, $d^2\sigma/dE_e\,d\Omega_e$, have been measured as a function of the electron emission energy, E_e, and the polar electron emission angle, ϑ_e. The major interest was directed upon the angular dependence of the integrated single differential emission cross sections of the binary encounter (BE) electrons, $d\sigma(\Theta_e)/d\Omega_e$. The cross sections are compared with electron argon scattering data (calculated and tabulated in Phys. Rev. A 15 (1977) 2173 [1]) as well as experimental data derived from light ion impact on helium (ionic charge $q \leq 9+$). The theoretical results are calculated with the impulse approximation (IA) model developed by Lee et al. (Phys. Rev. A 41 (1990) 4816 [2]). Even for higher ionic charge states the measured BE electron emission cross sections are well described by the IA model and are found to scale quadratically with the ionic charge state, q^2, and the projectile energy, E_P^2.

1. Introduction

Double differential cross sections for the ejection of electrons from helium have been studied intensively for proton impact (see the references in Rudd et al. [3]). But up to now not much is known about the systematics of the electron production for heavy ion impact (projectile nuclear charge $Z_P \geq 2$). Only a few measurements have been reported for heavy ion impact at some selected emission angles ([4–6] and references quoted therein).

Typical energy spectra for electron emission resulting from fast heavy ion impact on atomic gas targets are shown in Fig. 1 for the collision system 5.7 MeV/u Ar^{18+} + He. The double differential electron emission cross sections, $d^2\sigma/dE_e\,d\Omega_e$, are determined for different emission angles, $\vartheta_e = 30°$ up to 70°. All spectra exhibit an exponentially decreasing shape, superimposed by a prominent broad peak, the so-called binary encounter peak.

Electrons contributing to the exponentially decreasing continuum are well known as resulting from collisions where more than two particles are involved. In these cases, the electrons are simultaneously attracted in the Coulomb potential of both the projectile and the target nucleus. This process has been termed "two-centre electron emission". For more details see Refs. [4,7–10].

The binary encounter (BE) peak is due to target electron emission through direct hard collisions with the charged projectile only. Thus, this electron emission process can be treated as a true two-body encounter process. Regarding the target electron as quasifree and initially at rest in the laboratory frame, the emission can be denoted in the projectile frame as an elastic electron scattering process in the point-like Coulomb potential of the ion (Rutherford scattering). The classical kinematics result in a maximum energy transfer to a target electron in the laboratory frame of

$$E_e = 4\left(\frac{m_e}{m_P}\right)E_P\cos^2\vartheta_e, \qquad (1)$$

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. The width of the BE peak reflects the Compton profile, i.e. the momentum distribution of the target electrons due to the orbital motion around the target nucleus. Therefore, in a first approximation the final emission energy of the ejected electrons should be corrected by their binding energy, E_{bind}.

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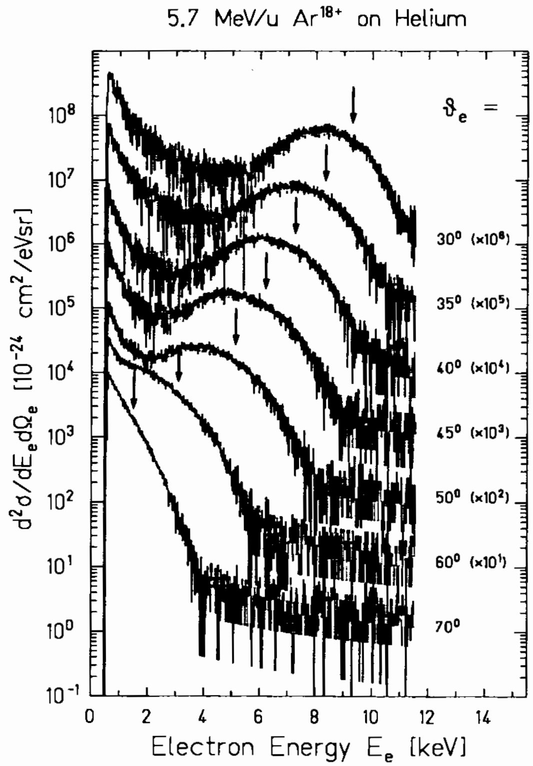

Fig. 1. Double differential cross sections for electron emission in collisions of 5.7 MeV/u Ar^{18+} with helium. For the observation angles $\vartheta_e = 30$ up to 70° the spectra are multiplied by the noted numbers. The locations of the BE peak maximum due to a classical two-body collision are denoted by the arrows.

In Fig. 1 the angular dependence of the location of the binary encounter peaks calculated from the classic two-body kinematics is indicated by the arrows. As denoted in Eq. (1) the BE peak shifts to lower electron energies, E_e, with increasing emission angle, ϑ_e. But the experimental peak maxima are found to be located at lower energies then predicted from Eq. (1). Besides the energy shift due to the binding energy, the peak position is affected by the other ionized electrons ejected in the collision and the exponentially decreasing continuum yields a displaced and asymmetric energy distribution of the binary encounter electrons [8].

Recently Lee et al. [2] and Pedersen et al. [8] performed a joint experimental and theoretical study of the double and single differential electron emission for collisions of bare projectiles with H_2 and He at intermediate energies up to $E_P = 2$ MeV/u. The ion charge state ranged up to $q = 9+$ (bare fluorine projectiles). Among other theories (e.g. plane wave Born approximation (PWBA)) they proved the reliability of the impulse approximation (IA) model to calculate the double and single differential cross section of ion-induced electron emission from gas targets. The measured binary encounter electron production cross sections for bare ions were well described by the IA model and were found to scale quadratically with the projectile charge state, q^2.

In this paper the electron emission cross sections are reported for the collision system 5.7 MeV/u Ar^{18+} on helium. This extends the above systematics on electron emission cross sections to a higher ionic charge state and a higher projectile energy. The results presented here are focussed on the cross sections of the binary encounter electron emission process. Since the BE electron emission process can be treated as the reverse of elastic scattering of free electrons in an ionic potential, the experimental data are compared with the electron scattering cross sections calculated and tabulated by McCarthy et al. [1] and with the electron emission cross sections calculated from the impulse approximation model developed by Lee et al. [2].

2. Experiment

The experiments for evaluating the double differential electron emission cross sections (DDCS) were performed at the UNILAC accelerator at the GSI in Darmstadt. The heavy ion beam is collimated to a spot size of 0.2 mm × 0.2 mm within 3 m before entering the scattering chamber and intersects a differentially pumped static gas target. The ejected electrons emerge from the gas cell through a slit of 1 mm height. In order to maintain single collision conditions the target gas is kept at low pressure, typically below 5 mTorr. Electrons ejected from the target region are measured at various angles using a 90° electrostatic hemispherical sector analyzer. The analyzer was mounted rotatable with respect to the center of the gas cell and covers an observation angle range between $\vartheta_e = 30$ and 90° with respect to the beam axis. The electrons are detected by a single channel electron multiplier (channeltron) mounted at the focal point of the analyzer. The beam current is monitored in a shielded Faraday cup and digitized for normalization of the electron counting rate to a constant number of particles. The voltage at the electron analyzer is controlled by a programmable power supply, which is driven by the digitized beam current. The channeltron signals are electronically processed and recorded by a multichannel analyzer. A personal computer system stores the electron data for further analysis. Contributions due to rest-gas ionization are determined from measurements without a gas target and subtracted from the electron spectra.

The pressure in the gas cell, the transmission rate of the analyzer and the efficiency of the channeltron are not known precisely. Measuring also the relative cross sections of the collision system 3.6 MeV/u Ni^{22+} on helium and normalizing them to the absolute data taken from a related collision system of Schneider et al. (3.5 MeV/u Fe^{22+} on helium) [9], absolute cross sections for 5.7 MeV/u Ar^{18+} on He could be derived. Due to the accuracy of the iron data the normalization procedure yields an absolute uncertainty of the cross sections of about 40% [9]. The deduced relative uncertainties in the cross sections are estimated to be around 10% resulting from statistical error and slight experimental drifts, e.g. in the zero-point of the target pressure control setup.

3. Theory of the impulse approximation (IA)

An impulse approximation (IA) model has been applied by Lee et al. [2] to describe the electron emission process in energetic collisions of bare projectiles with H_2 and He gas targets at forward observation angle, $\vartheta_e = 0°$. This model allows the calculation of single and double differential electron emission cross sections of binary encounter electron emission from the impact of fast ions on atomic targets. Within the IA, the BE electron emission process is treated in the projectile frame, where it is considered as a 180° Rutherford scattering of "quasifree" target electrons in the potential of the projectile nucleus at rest. Single differential cross sections of the BE process are evaluated by integrating the Rutherford cross section times the square of the momentum wave function of the target electrons (i.e. two electrons in the molecular hydrogen target) over all electron momenta in the projectile frame.

To apply the IA model on the BE process the experimental double differential cross sections, $d^2\sigma/dE_e\,d\Omega_e$, at forward observation angle, $\vartheta_e = 0°$, are transformed from the laboratory (LS) into the projectile frame. The transformation of the double differential cross sections, and the observation angles, ϑ_e, is given by simple relations (in this case the projectile frame is approximately the same as the centre of mass system (CM)):

$$\left[\frac{d^2\sigma}{dE_e^{CM}\,d\Omega_e}\right]_{BE}^{CM} = \left[\frac{d^2\sigma}{dE_e\,d\Omega_e}\right]_{BE}^{LS}\sqrt{E_e^{CM}/E_e} \qquad (2)$$

$$\Theta_e = 180° - 2\vartheta_e. \qquad (3)$$

The electron energy in the projectile frame, E_e^{CM}, is in a first approximation related to the projectile energy E_P and the mass ratio of the electron and the projectile only, with:

$$E_e^{CM} = \left(\frac{m_e}{m_p}\right)E_P. \qquad (4)$$

From Eq. (4) for the Ar^{18+} + He collision system with $E_P = 5.7$ MeV/u an electron energy in the projectile frame of $E_e^{CM} = 3105$ eV is calculated.

The absolute single differential cross sections, $d\sigma/d\Omega_e$, at backward scattering angle $\Theta_e = 180°$ are calculated by integrating over the BE peak. Taking the binding energy of the target electrons into account, Lee et al. found an excellent agreement of the double differential cross sections with the data for light bare ions up to $q = 9+$. In the considered q-range a scaling of the binary encounter single differential emission cross section with the square of the projectile charge, q^2, was found [2].

4. Results and discussion

Treating the binary encounter electron emission as a Rutherford scattering, the electron scattering cross section of the Ar^{18+} + He collision system can be obtained from the experimental double differential cross sections given in Fig. 1. The double differential electron emission cross sections are transformed from the laboratory into the projectile frame as described above (see Eqs. (2)–(4)). For each scattering angle, Θ_e, in the projectile frame (i.e. observation angle, ϑ_e, in the laboratory frame) the BE peak is separated from other components by a fit procedure to the two-centre electrons. The decreasing continuum is described by an exponential function and subtracted from the energy spectra, leaving the BE peak only. The data are integrated over the binary encounter peak, yielding the single differential cross sections, $d\sigma/d\Omega_e(\Theta_e)$. Fig. 2 shows the angular dependence of the measured emission cross sections (solid line to guide the eyes), where the BE cross section decreases with increasing scattering angle, Θ_e. In the figure, the dotted line represents electron scattering data obtained from elastic scattering of fast electrons in a screened potential of a neutral target atom [1], representing the reverse of the BE emission process in the laboratory frame. Using an optical model McCarthy et al. [1] calculated and tabulated the angular dependence of the scattering cross sections for fast electrons by neutral argon atoms ($E_e^{CM} = 3000$ eV). The broken line is due to elastic Rutherford scattering of fast free electrons in the Coulomb potential of a point-like charge (also $E_e^{CM} \approx 3000$ eV in the projectile frame; $q = 18+$). Both the single differen-

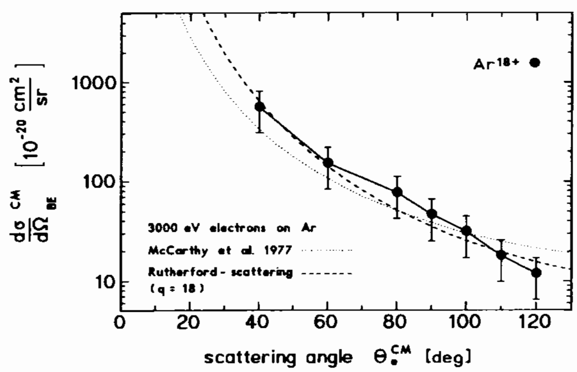

Fig. 2. Angular dependence of single differential cross sections for binary encounter electron emission from helium induced by fast Ar^{18+} projectiles. The solid line is drawn to guide the eyes. Broken line: scattering of free electrons with $E_e^{CM} \approx 3000$ eV in the potential of an unscreened point-like charge, $q = 18+$; dotted line: scattering of fast electrons by a neutral argon atom, taken from McCarthy et al. [1].

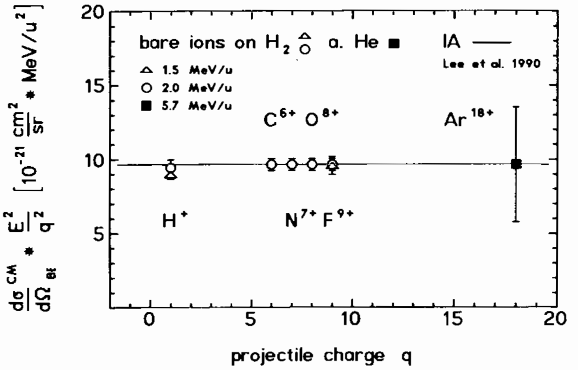

Fig. 3. Projectile charge (q) dependence of the scaled single differential binary encounter electron emission cross section in the projectile frame. Solid symbol: 5.7 MeV/u Ar^{18+} on He (this work); open symbols: light ion data $q \leq 9+$; and solid line: impulse approximation, both taken from Lee et al. [2].

tial cross sections of McCarthy et al. and of the Rutherford scattering calculation are multiplied by 2 to account for the two electrons of the helium target. Within the error bars, the single differential cross sections agree best with the elastic Rutherford scattering data (broken line), since for the bare Ar^{18+} ion no screening by bound electrons can occur. The discrepancy of the experimental data and of those calculated for electron scattering by a neutral atom [1] shows the importance of the screening effect of electrons bound to the scattering centre (in the case of BE electron emission of bound projectile electrons). Thus the data are very useful in the case of partially stripped (e.g. Ar^{10+}) or even neutral projectiles. Using the Rutherford scattering cross section, the experimental data of the Ar^{18+} + He collision system are extrapolated to the backscattering angle in the projectile frame, $\Theta_e = 180°$ (i.e. forward emission angle in the LS, $\vartheta_e = 0°$) yielding

$$\frac{d\sigma^{CM}}{d\Omega_{e\,BE}}(\Theta_e = 180°,\ \vartheta_e = 0°) = 9.72 \times 10^{-20}\ \mathrm{cm^2/sr}.$$

In Fig. 3 the experimental results and the theoretical data calculated by means of the impulse approximation model are compared for various bare projectiles investigated in Ref. [2] and the present work. As expected from the IA model and Rutherford scattering, the single differential cross sections scale quadratically with the projectile energy, E_P, divided by the charge state, q, of the corresponding ion. The horizontal line is evaluated from the impulse approximation due to Lee et al. [2] by integrating the Rutherford cross section times the square of the momentum wave function of both target electrons (two electrons in the molecular hydrogen target) over all electron momenta. The open symbols are the experimental data obtained from Lee et al. [2] for bare ions (from proton to fluorine) colliding on hydrogen molecules at two different projectile energies, $E_P = 1.5$ and 2 MeV/u, respectively. The single differential cross section for the Ar^{18+} impact on helium, as obtained from the extrapolation, is indicated by the full square. All data concerning the binary encounter electron emission for ion helium collisions show excellent agreement for projectiles ranging from protons up to bare argon ions. The experimental cross sections are well described by the IA model. It is noted too that the electron production cross sections obtained from a bombarded hydrogen molecule and a helium atom are comparable [2] since the number of bound electrons are identical in both cases.

5. Conclusion

In summary, electron emission cross sections are reported for bare ion helium atom collisions. The systematics of binary encounter electron emission cross section [2] are extended to a higher projectile charge state ($q = 18+$) and to an intermediate energy ($E_P = 5.7$ MeV/u). In accordance with light ion data ($q \leq 9+$) at low projectile energies ($E_P \leq 2$ MeV/u), for a highly ionized argon projectile the measured binary encounter electron emission cross sections are well described by the impulse approximation model and are confirmed to scale with E_P^2/q^2.

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