Recoil-ion momentum distribution for He(e,2e)He$^+$- and He(e,3e)He$^{++}$-reactions

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Abstract. Using Recoil-Ion Momentum Spectroscopy (RIMS) we have measured the momenta of recoiling target ions in He(e,2e)He$^+$- and He(e,3e)He$^{++}$-reactions at impact energies between 270 ev and 3200 eV. The recoil-ion momentum reflecting the sum momentum of all outgoing electrons was determined for the first time in all three spatial dimensions separately for single and double ionization by electron impact. The data are compared to results of a nCTMC-calculation.

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The investigation of the helium double ionization has attracted considerable interest in atomic physics since it represents the simplest many-particle reaction for a multiply ionizing collision. From a detailed analysis of the momentum balance for doubly ionizing collisions induced by various projectiles, detailed information about the dynamical correlation between the initial and final state of the electrons can be obtained. Although the cross sections are rather small, helium is one of the most favourable targets for probing electron–electron correlation since the electron–electron interaction strength is of the same order as the electron–nucleus force. In this paper we present the first momentum distributions of He$^{++}$ recoil ions resulting from the (e,3e)-collision i.e.

\[ e^- + He \rightarrow e^- + He^{++} + e^- + e^- \]  

The recoil-ion momentum is a direct measure of the sum momentum of the outgoing electron(s) and the momentum transfer to the projectile electron. Thus, the recoil momenta reflect the properties of the correlated motion and should therefore provide a crucial test of many-body collision theory.

So far, the common experimental approach for a complete momentum analysis of doubly ionizing reactions is the coincident detection of all outgoing electrons using electrostatic electron spectrometers. Remarkable results have recently been reported by Schwarzkopf et al. for (γ,2e) reactions [1] and Lahman-Bennani et al. for (e,3e)-experiments [2]. These double and triple coincidence techniques generally lack high detection efficiency, e.g. the solid angle of the electron momentum analysers is of the order of milli-sterad. Thus, the coincidence rate is extremely low and no results on the (e,3e)-reaction with the fundamental helium target have been reported so far. Furthermore, since the cross sections strongly decrease with impact energy, (e,3e)- and (γ,2e)-experiments in the high velocity regime are beyond the range of these conventional techniques. However, such experiments are important especially in the high energy limit to diminish post collision interaction effects on the momentum balance.

In this paper we present a new experimental approach to this problem. We measure all three momentum components of the recoiling target ion in the (e,ne)-reaction. The technique of Cold Target Recoil-Ion Momentum Spectroscopy (COLTRIMS) has been developed to study the ionization dynamics in swift ion–atom collisions [3]. It has been demonstrated that recoil-ion momentum spectroscopy (RIMS) is a powerful tool to measure highly differential ionization cross sections [4–8]. The recoil-ion momentum reflects not only the dynamical properties of the pure Rutherford scattering in these collisions, but also comprises the sum momentum of all emitted electrons. Since a 4π solid angle combined with a good momentum resolution is obtained for the determination of the recoil-ion momentum, our technique in combination with a large efficiency electron spectrometer [8] can be the key for kinematically complete experiments on (e,3e) or (γ,2e) reactions in the near future.

For reactions of the type He(e,ne)He$^\pm$ with \( n = q + 1 \), it follows from momentum conservation

\[ p e_0^q + p_{He}^q = \sum_{0}^{q} p e_q^q, \]  

where \( p e_0^q \) is the momentum of the projectile electron, \( p e_q^q \) are the outgoing continuum electron momenta and \( p_{He}^q \) is the momentum of the recoiling target ion.
\( \mathbf{p}_{\text{He}^+} = - \sum_i \mathbf{p}_{e_i} - \mathbf{k}, \) (3)

where \( \mathbf{k} \) is the momentum transfer vector in the collision, i.e. the momentum change of the primary electron. The determination of the recoil-ion momentum \( \mathbf{p}_{\text{He}^+} \) yields 3 of the 5, respectively 8 independent momentum components in the collision. The spectroscopy of one electron would principally yield the same information, but since the final recoil-ion charge state is recorded simultaneously additional and complementary information about the ionization process is obtained. Even in the present stage of the experiment without any additional electron detection devices, we obtain informations about the ionization mechanisms which are not yet accessible by double or triple electron coincidence techniques.

Using a very cold jet target we are able to measure all three components of the recoil ion momentum and to identify its charge state \( q \). The effective solid angle is about 4\( \pi \) and a momentum resolution of less than \( +/−0.2 \) a.u. for each momentum component is obtained. This is comparable to an electron energy resolution of about 1 eV. A pulsed electron beam intersects a supersonic helium gas jet with a target density of a few \( 10^{12}/\text{cm}^2 \). Due to the properties of the supersonic expansion the atoms in the jet have an offset momentum of 5.9 a.u. and a very low internal temperature in the moving frame of the target atoms \( (\approx 0.15 \text{ K}) \). Thus, the momentum resolution limit caused by the initial Maxwellian momentum spread is well below 0.1 a.u. in each direction. The ions produced in the collisions are extracted by a well-defined weak homogeneous electrostatic field perpendicular to the jet axis and the electron beam. The ions then traverse a field free drift zone and their trajectories are projected onto a position sensitive multi-channel plate detector (MCP) with a position resolution of better than \( 140 \) pm. The time-of-flight of each ion can be derived from a standard coincidence technique triggered by the pulsed electron gun. A more detailed description of the experimental setup is given elsewhere [9, 10].

Figure 1 shows how the recoil-ion charge state and momentum components can be deduced from its trajectory (\( Ay, Az \) on the detector) and time-of-flight difference \( At \).

\( q = \text{recoil-ion charge state}, \ m = \text{recoil-ion mass}, \ t_f = \text{recoil-ion TOF}, \ E = \text{electric field strength}, \ At, Ay, Az \) see Fig. 1. The offset gas jet momentum is disregarded here.

This way it is possible to detect practically the whole momentum spectrum simultaneously, single- and double-ionization events can be distinguished and the offset velocity of the gas jet atoms yields a significant suppression of background from residual gas. Special care was taken to ensure proper field conditions in the spectrometer by coating the inside walls with carbon and shielding the spectrometer from external fields.

The impact energy of the electrons was varied between 270 eV and 3200 eV corresponding to initial velocities (momenta) of 4.5 to 15.3 a.u. Data for neon and argon targets have also been recorded [10]. In this paper we report mainly on collisions of 500 eV electrons on helium since single ionization in this system has been extensively investigated by means of the (e,2e)-technique. Also, our experimental findings are very similar for all collision energies investigated here and yield the same interpretations.

The dots in Fig. 2 show such differential cross sections \( d\sigma/dp_z \) for electrons emitted in collisions of 500 eV (2000 eV) \( e^- \) on He for single ionization. These data are derived from absolute \( d\sigma/dE \) cross sections obtained from (e,2e)-experiments [11, 12]. Note that the shape of the cross section as a function of the momentum is not symmetric as it would be on an energy scale and that the momentum distribution of the fast electrons is remarkably narrow. The fast electron can be considered as the