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Electron Impact Double Ionization of Helium from [e, (3-1)e] Experiments

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Abstract

Electron impact double ionization of helium has been observed in an [e,(3-1)e] experiment at an incident electron energy of 200 eV. 110 eV scattered and 10 eV ejected electrons are observed in coincidence without detection of the second ejected electron (1 eV). Present and previous observations are discussed.

Key Words: Double Ionization, (e,2e), [e,(3-1)e], Coincidence Detection, Electron Impact

1. Introduction

Electron impact double ionization (DI) is a process which from even an elementary point of view, cannot be reduced to a two-body problem. This process is not a simple extension of single ionization. Electron impact ionization of atoms and molecules is one of the most basic processes in physics, fusion physics, surface physics, etc. Considerable knowledge of the single-ionization of atoms and molecules has been gained using a wide variety of projectiles. On the other hand, studies of double-ionization (also for excitation-ionization) processes are far less abundant in the literature, because of the smallness of the corresponding cross sections. Almost all investigators have measured integrated cross sections as a function of the incoming particle energy [1]. Such studies are not sensitive to finer details of the ionization dynamics. Differential cross sections (DCS) with respect to the energies and/or angles of emission of the final particles have seldom been reported.

A schematic diagram for a coplanar double ionization process is shown in Figure 1. The incident electron is indexed 0, whereas the three outgoing electrons, though indistinguishable, are indexed s for the scattered one, and $e1$ and $e2$ for the two slow ejected electrons.

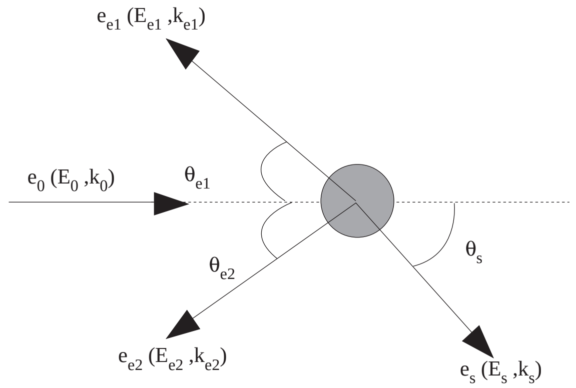

Figure 1 Schematic diagram for double-ionization processes.

The reaction under study in a DI experiment can schematically be written as

$$e_0 + A \rightarrow A^{++} + e_s + e_{e1} + e_{e2}. \tag{1.1}$$

Conservation of energy and momentum requires

$$E_0 = E_{th}^{++} + E_s + E_{e1} + E_{e2} \tag{1.2}$$

and

$$K = k_0 - k_s = k_{e1} + k_{e2} + q_r \tag{1.3}$$

where E_j and k_j are the electron energies and momenta and E_{th}^{++} is the DI threshold energy. The ion recoil momentum is denoted by q_r and K is the total momentum transfer to the target.

A complete description of the electron impact (e,3e) process in a coplanar geometry is given by the variables represented in the vector diagram in Figure 2. For coplanar kinematics, (k_o, k_s) define a plane and K lies in this plane; thus no momentum is transferred to the target out of plane.

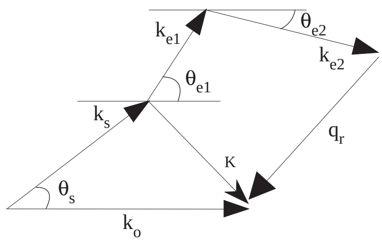

Figure 2 Schematic momentum vector diagram for a coplanar (e,3e) electron impact double ionization experiment.

The notation here is similar to that used in the (e,2e) case and the initial and final target states are assumed to be ground states. Measurement of the triple, four-fold or five-fold DCS using (e,2e) or (e,3e) techniques requires the determination of all energies and directions of all outgoing electrons. Coincidence techniques are needed to guarantee that these electrons originate from one interaction event. In an (e,3e) experiment, all three outgoing electrons are analyzed both in direction and in energy and are detected in coincidence, yielding the most detailed information about the double ionization process. The quantity that is measured in the (e,3e) experiments at a given impact energy is a fivefold-differential cross section (5DCS) [2-5]. The triple coincidence signal is very low, and is mostly limited by the high accidental coincidence rate generated by the dominant single ionization events (see [6] and reference therein). [e,(3-1)e] experiments constitute a promising method for studies of DI, without the difficulties of a triple coincidence experiment.

2. The Previous Studies

The difference in the information content between the 5DCS and the 4DCS can be illustrated by comparing with analogous single ionization quantities. The 4DCS measured via an integration over Ω_s are analogous to the doubly DCS extracted from angular distributions of the ejected electron, while the 4DCS with integration over Ω_{e1} (or Ω_{e2}) are analogous to the DDCS extracted, for instance, from energy-loss spectra of high energy electrons. Duguet et al. [7] used the [e,(3-1)e] technique to measure the energy partitioning between the two slow ejected electrons, at given momentum transfer and energy transfer values to the argon target. From this experiment, a striking similarity is observed between the 4DCS and the DDCS distributions for single ionization (Figure 3a). Lahmam-Bennani et al. [8] also used this technique to measure angular distributions for the pairs of scattered-ejected electrons from argon atoms and compared them with 3DCS for single ionization (Figure 3b).

The only previous 4DCS measurements for helium have been reported by El Marji et al. [9]. The coincidence angular distribution of the two slow ejected electrons has been measured for different energy sharing of the available excess energy among the two electrons and compared with a theoretical calculation of Lamy et al. [10] (Figure 4).

3. The Present Study

We report a set of measurements for helium, standing halfway between (e,2e) and (e,3e) experiments, [e,(3-1)e], in which the fast electron is detected for the first time in coincidence with only one of the two ‘atomic’ electrons, irrespective of the direction of the third unobserved one [11]. Therefore, integration is performed over the solid angle of emission of one undetected electron, say Ω_{e2}, yielding a four-fold DCS, i.e. we could not measure the momentum vector k_{e2} in Figure 2.

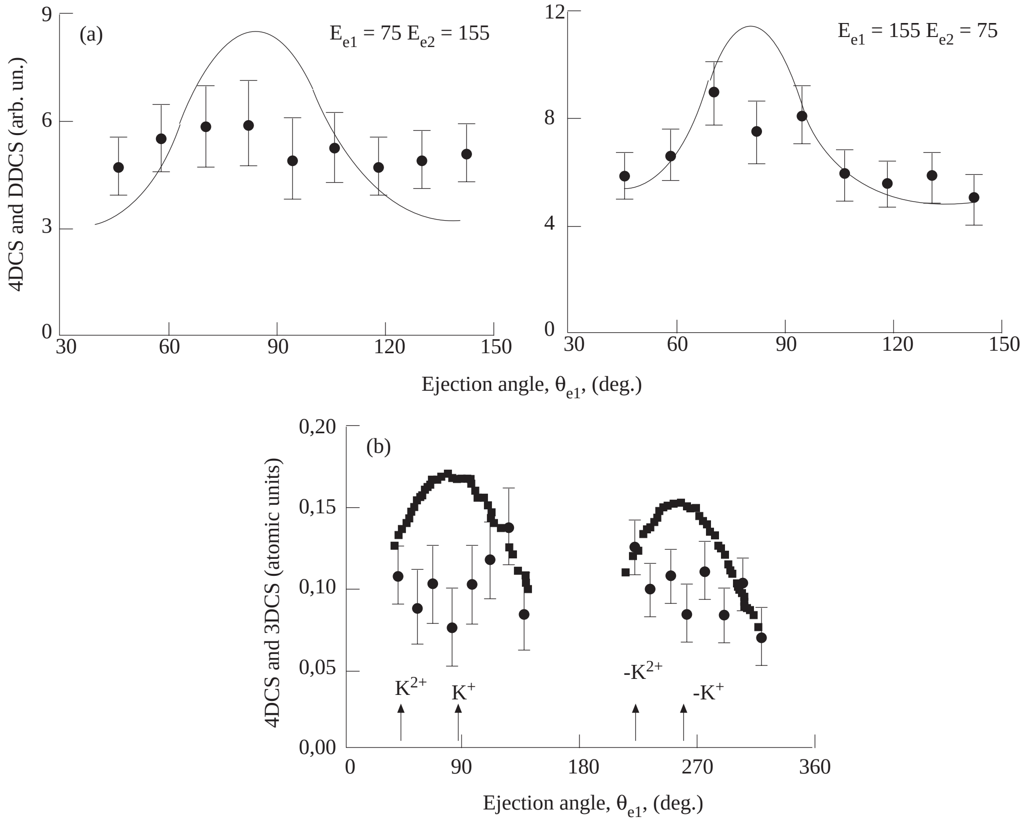

Figure 3. (a) [e,(3-1)e] 4DCSs (full circles) and DDCS (full curves) for double ionization of Ar in coplanar geometry at E_0=5.5 keV. The two atomic electrons are detected in coincidence with one angle fixed to $\theta_{e1}=255^0$, while θ_{e2} is varied. The full curves are corresponding DDCSs simultaneously measured during the same experiment. (b) Absolute 4DCS (circles) and TDCS (squares) for the coincidence detection of the pair (e_s-e_{e2}) from double and single ionization of Ar respectively, E_o=5.5 keV, $\theta_s=0.55^o$. Observed ejected electron energy is 5 eV and unobserved ejected electron energy is 75 eV. Single ionization cross sections (TDCS) are divided by 1500 (from ref. 8).

The [e,(3-1)e] spectrometer used in this study will be described in full detail in a subsequent publication [12]. We measured 4DCS for the (e_s-e_{e1}) pair. The overall energy resolution was set to 1.3 eV. A sample 4DCS preliminary result for the pair (e_s-e_{e1}) is shown in Figure 5. The incident electron energy (E_o =200 eV) is chosen in such a way that the unobserved ejected electron has an energy E_{e2}=1 eV, while the observed ejected electron is detected for E_{e1}=10 eV. Also shown in Figure 5 are the ±K momentum transfer directions, corresponding to double ionization of the target.

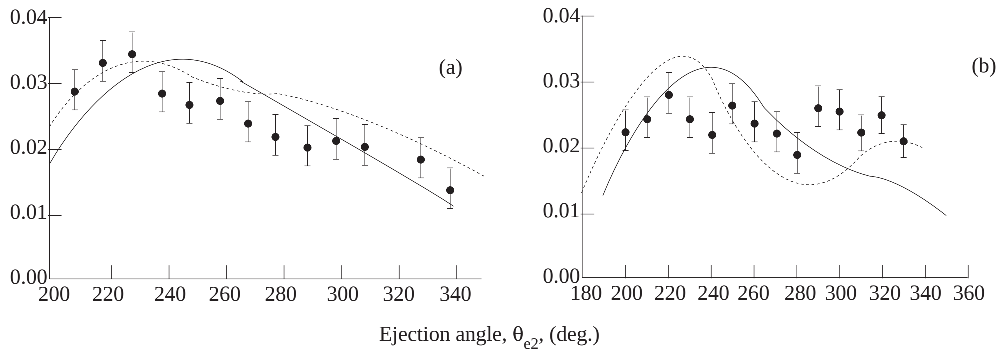

Figure 4. The 4DCS for the double ionization of helium. θ_{e1}= -90^o, E$_s$=5525 eV for; (a) E$_{e1}$=7 eV and E$_{e2}$=28 eV; (b) E$_{e1}$=E$_{e2}$=17.5 eV (from ref. 10).

The forward and the backward peaks of the single ionisation distribution are found to peak in the corresponding $\theta_{\pm K}$ directions, whereas the Double Ionisation (DI) distribution shows a very different angular behaviour. Moreover, the momentum transfer direction has lost its significance as a symmetry axis. It has a relatively simple form with a single well-defined forward peak away from the θ_K direction and a rapidly increasing backward cross section as the angle is increased away from θ-$_K$. No previous experimental or theoretical data are available for comparison under similar kinematics.

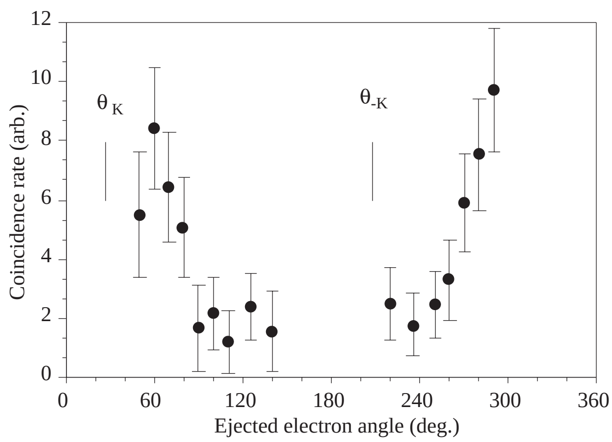

Figure 5. The relative 4DCS for double ionization of helium for E$_o$=200 eV. The observed ejected electron has an energy of 10 eV and the scattered electron an energy of 110 eV. θ_K is momentum transfer direction.

It is clear that electron impact double ionisation is not a simple extension of single ionisation [13]. DI may involve a large momentum transfer to the atomic core, implies that there are fundamental differences between the mechanisms of single and double ionisation by electron impact.

In many areas of physics, the many-body problems play a central role. The fully differential investigation of the ionisation processes is fundamental to the understanding of the dynamical electron-electron correlation during collision. Such dynamical correlation in two- or multiple-electron transitions is one of the basic unsolved problems of modern atomic physics. In this, the Coulomb force plays a paramount role. The measurement of angular distributions of the DI products should provide an essential insight into the understanding of this problem in complete detail.

When the mechanism of DI is understood, the process can be used to probe an even more fundamental manifestation of the three and four-body problem, that of electron correlation in atoms. Double ionization of atoms is currently the subject of an increasing number of experimental and theoretical investigations. All of these studies open exciting new avenues in atomic physics.

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