Absolute Fully Resolved (e,3e) Cross Sections for the Double Ionization of Helium

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We have measured for the first time full sets of coplanar (e,3e) angular distributions for double ionization of He, at an impact energy of ~5 and ~1 keV. Ejected electrons are detected with equal energies, 10 and 4 eV. Comparison is made with analog (γ,2e) results, and deviations from the dipolar limit are pointed out. The data are also compared with two calculations, using either a four-body final-state wavefunction for the three electrons moving in the field of He^{2+}, or the convergent close coupling method.

WHY DOING THESE EXPERIMENTS?

Main objective is the investigation of the double ionization (DI) process under electron impact, in a kinematically complete experiment in which the energies and emission angles, and hence the momenta of all participating particles are determined in the final state, and all these particles are detected in a triple coincidence. For the purpose, the ideal target is He, the simplest two-electron system that yields a pure 4-body problem in the final state. This simplicity is essential since the N-body problem, with N=3 or larger, is one of the most fundamental problems not yet solved in atomic physics. Such experiments yield the most detailed insight into the fundamentals of the DI process.

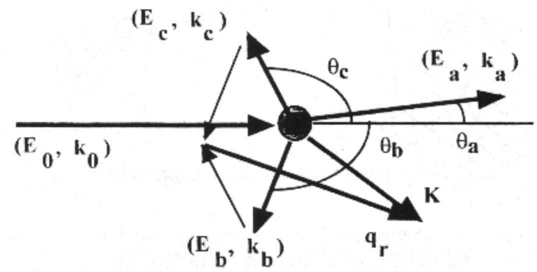

FIGURE 1. Schematic momentum diagram of a coplanar (e,3e) experiment.

CP500, *The Physics of Electronic and Atomic Collisions*, edited by Y. Itikawa, et al.

We briefly report here results of the first kinematically completely determined (e,3e) experiment for He. More details may be found in Refs. (1,2). Figure 1 shows an (e,3e) momentum diagram : the incident electron, denoted 0, with energy E_0 and momentum $\mathbf{k_0}$ is scattered under the angle θ_a, with energy E_a and momentum $\mathbf{k_a}$, while 2 electrons denoted b and c are ejected from the target, respectively in the directions θ_b and θ_c, with E_b, $\mathbf{k_b}$ and E_c, $\mathbf{k_c}$. To fully determine the kinematics, one needs to measure all three energies and angles and detect the 3 final electrons in a triple coincidence. Here, $\mathbf{K} = \mathbf{k_0}-\mathbf{k_a}$ is the momentum transfer to the target, and $\mathbf{q_r}$ is the ion recoil momentum, given by the difference "**K** minus the sum momentum for the pair of ejected electrons". $\mathbf{q_r}$ is of course known from the measurement of all other quantities.

The (e,3e) spectrometer has been extensively described in (3). Briefly, a 1 to 10 keV electron beam crosses at right angle the gas jet. The fast a electron is analysed in a cylindrical analyser, and detected on a scintillator-photomultiplier arrangement. The electron gun rotates about the gas jet axis, which allows to vary the scattering angle θ_a. The slow ejected b and c electrons are analysed in a double toroidal analyser. This system includes multiangle detection of the ejected electrons, the key point being that the angular information contained in the collision plane is preserved upon arrival on the two position sensitive detectors.

Before presenting the results, it should be stressed that the measurements are obtained on an absolute scale. This is very important in order to be able to disentangle between different theoretical models which might yield similar results as to the shape of the angular distributions, but might differ by large factors as to the magnitude. Our absolute scale determination is based on the relationship between the measured triple coincidence count rate and the (e,3e) cross section, via a number of experimental parameters. These parameters are not determined directly, which would be a tedious and quite inaccurate procedure. Rather, we relie first on the measuremt of DDCS and TDCS obtained under exactly the same kinematical parameters as in the (e,3e) experiments, and second on their comparison with well established theoretical DDCS and TDCS. The overall final accuracy reached with this method is roughly 30%.

RESULTS

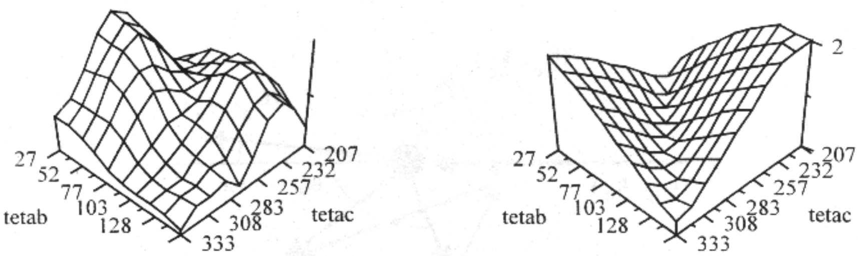

FIGURE 2. Left : 3-D plot of the measured (e,3e) cross section for He, versus the θ_b- and θ_c-angles. The incident direction is along the diagonal, from right to left. The scattered electron is detected at a fixed angle, 0.45° (K=0.24 au), with an energy of 5.5 keV. Right : Magnitude of the ion recoil momentum, versus θ_b and θ_c.

Figure 2 presents results for the DI of He in the so-called equal-energy sharing case, $E_b = E_c = 10$ eV. We can here make two important observations. First, there are mostly two structures in this surface, that is, the b and c electrons are preferentially emitted either *both simultaneously* forward, or *both simultaneously* backward with respect to the incident direction. Such forward or backward emission is not *a priori* an obvious expectation, as it corresponds to an ion recoil momentum which has to be rather large.

Indeed, one can see (Fig. 2) a striking similarity between the 3D surface for He and the one representing the magnitude of the ion recoil momentum, q_r : the cross section is minimum along the 'valley' where q_r is minimum, and the two intensity peaks strikingly correspond to the maximum ion momentum. The reason for this behaviour can be understood as follows : at our high incident energy and small momentum transfer, the optical limit is quite closely approached. However, the optical transition is forbidden for two free electrons, (which is the condition for the Bethe sphere), that is for photon absorption without participation of the nucleus. This is because a photon imparts to the system energy, but basically no momentum, therefore the electrons must recoil off the massive nucleus.

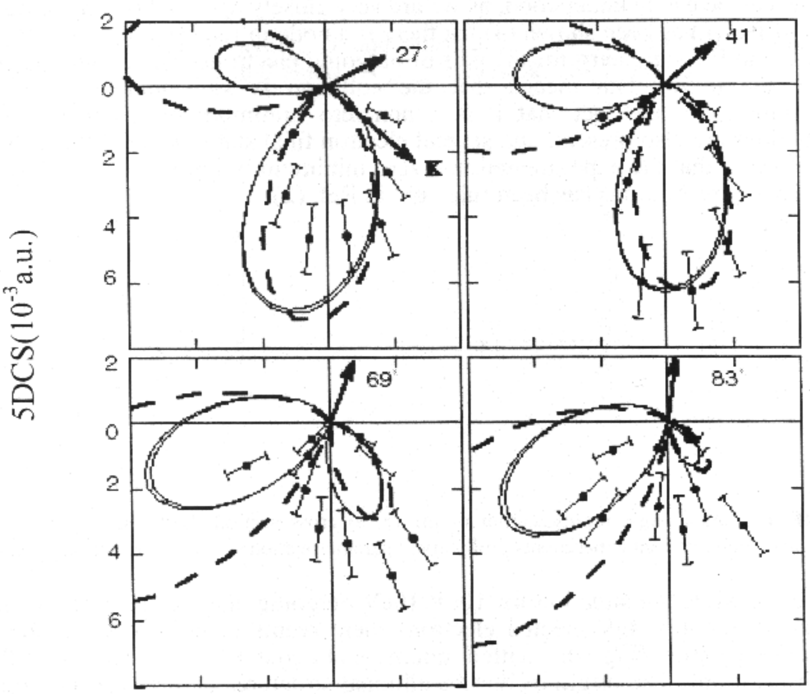

FIGURE 3. A selection of the measured angular distributions, with one ejection angle fixed (as shown by the arrow and the labeling), and the other one variable. The dots are the experimental data. The dashed curves are calculated results using the correlated 4-body final state (C4FS x 0.7) model, whereas the full curves are calculations using the Convergent Close Coupling (CCC x 3.2) method.

The second observation is the following : there are at present a few theoretical calculations dealing with these results. This short presentation does not allow to discuss them here. We will only briefly refer to Fig. 1 of Ref. (1) to illustrate the point that all of them reasonably agree with the experiments as far as a global picture like the one in Fig. 2 is concerned : we see the two peaks, forward and backward, and the valley in between. But noticeable differences do appear when one examines detailed cuts of these surfaces. A sample of such cuts is shown in Figure 3. We note here that first, as to the magnitude, one theory (CCC) is a factor of 3.2 too small with respect to the experiment, whereas the other theory (C4FS) is about a factor of 1.5 too large. Second, as to the shape, the agreement between theory and experiment is good for some fixed angles, whereas for some others it is less satisfactory, if not bad.

Another observation is the following : at our high incident energy and small momentum transfer, it is well known that the electron impact ionization is approaching the photoionization. Therefore, it is certainly of interest to compare the (e,3e) results with photo-double ionization (PDI) results. This is done in Figure 4. We first note that the two electrons do not fly out in the same direction with the same velocity : this is trivial, due to the Coulomb repulsion in the final state. Moreover, the back to back emission corresponding to a mutual emission angle of π is clearly not the most likely one.This can be easily understood, as we are very closely approaching the optical limit. In PDI of He, it has been shown (4) hat there is a node in intensity at a mutual angle of π, due to the $^1P^o$ symmetry for the pair of outgoing electrons. The minimum observed here in the (e,3e) data means that the collision is still dominated by dipolar contributions, but the fact that it is a non-zero minimum means that non dipole contributions are also present, and several electron final states are accessible. Note that the possibility that the experimental non-zero minimum might be due to finite angular and/or energy resolutions has been ruled out in Ref. (2).

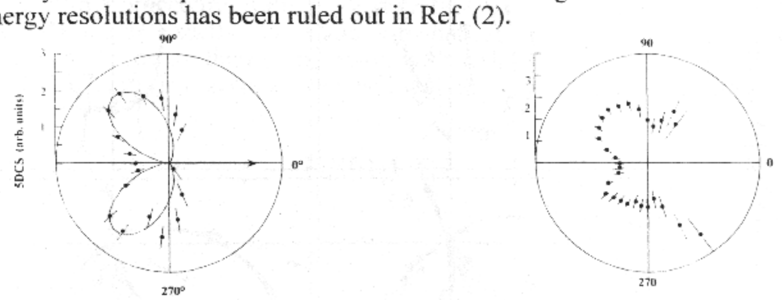

FIGURE 4. Mutual angle representation of the (e,3e) cross section. Left : $E_b=E_c=10eV$. Right : $E_b=E_c=4eV$. Dots: Present experiments. Full curve : parametrization of the PDI results according to (5).

However, while the situation for 10eV/10eV outgoing energies (Fig.4a) seems to be understood, for 4eV/4eV ejected electrons there seems to be 4 lobes in the mutual angle representation (Fig. 4b), with a minimum at about ±90°, quite different from the PDI observations. The origin of these additional structures is not clear. Of course, we have checked and counter-checked the experimental results, and we think this is not an experimental artefact. What else? May be a strong non-first Born contribution?· The question remains open, and more theoretical as well as experimental investigations are needed to confirm or not this observation.

CONCLUSION

We have presented a sample of results from the first kinematically complete (e,3e) experiments on He, at ~5 keV impact energy, and 10+10 and 4+4 eV outgoing energies. Reasonable global agreement is obtained with available theories, but more work is still to be done on the detailed comparison. The (e,3e) data resemble the PDI ones, however significant differences are observed, showing that the optical limit is not fully reached.

The measurements are presently being extended to a wider range of kinematical variables (lower E_0, larger K, unequal E-sharing, larger E_{ej}, etc ...).

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