Abstract. Using a multi-particle momentum spectrometer (reaction microscope), three-dimensional and fully differential cross sections (FDCS) for electron impact ionization are obtained, providing benchmark data for comprehensive tests of theoretical calculations. Since all final-state particles, including the scattered projectile were detected, a good momentum transfer resolution was obtained also for heavy targets like Ar. Results for ionization of the Ar $3p$- and He $1s$-orbitals by 200 eV electron impact are presented. The cross section patterns display rich structure, which is partially reproduced by theory, although differences persist out-of-the scattering plane. Kinematically complete experiments for electron impact ionization of simple diatomic molecules have attracted increased attention concerning molecular structure effects. (e, 2e) on He and H$_2$ is studied at equivalent collision kinematics to explore the differences of atomic and molecular ionization. Here FDCS were obtained covering the whole solid angle.

1. Introduction
Electron impact single ionization, the so-called (e, 2e) reaction, on atoms or molecules represents one of the fundamental dynamical few-body problems in quantum mechanics, and plays a key role in many naturally occurring and technical plasma phenomena. Since the first pioneering work on single ionization of He [1] a large amount of cross sections has been measured over a wide range of kinematics and geometries, on the other hand most of the dynamic studies were performed in the scattering plane, where the ejected, the incoming and the scattered projectile were in a common plane. The agreement between state-of-the-art theories and experimental data has been significantly improved especially for simple targets such as atomic hydrogen and He [2–4]. For heavier or more
complex many-electron atoms, the agreement is not as good particularly at low and intermediate collision energies [5–8].

Recently three-dimensional images of the complete electron emission pattern have been obtained for the single ionization of He by the impact of ions [9] and electrons [10] due to the development of many-particle imaging techniques, the so called “reaction microscope”. An unexpected structure in the fully differential cross sections (FDCS) out of the scattering plane was observed for the single ionization of He [9, 10], and has so far not been fully understood, (for more details see [11, 12]). Full three-dimensional (3D) studies of ionization from the heavier targets, such as the case of Ar, would be interesting because of the rich structures that they can display. Furthermore, it would be important to explore the experimental images of p-orbital ionization (e.g. Ar 3p) into not only the scattering plane but also the full solid angle. This work is to reveal the features of single ionization on He 1s and Ar 3p orbitals at 200 eV impact energy by using the three-dimensional images. In addition, experiments for electron impact ionization of simple diatomic molecules have attracted increased attention recently, since strong molecular structure effects were observed for electron emission in the plane perpendicular to the incoming beam direction [13, 14]. In order to study these effects more comprehensively we have performed comparative (e, 2e) experiments on the two-electron targets He and H₂ at low impact energies (16 eV excess energy) covering the full solid angle of electron emission.

2. Experimental Setup
The experiments were performed by using a highly efficient reaction microscope which was especially designed for electron impact experiments. The experimental setup of the reaction microscope and experimental procedure have been described in detail elsewhere [15, 16] (Figure 1).

![Figure 1. Schematic view of the experimental setup.](image)

Briefly, a well focused (1 mm), pulsed electron beam (pulse length:1–2 ns, repetition rate: 180 kHz), produced by a standard thermo cathode gun, crosses and ionizes on atomic or molecular gas target (1mm diameter, 10¹² atoms/cm³), which is produced in a two-stage supersonic gas jet. All three final-state particles, i.e., the scattered projectile electron, the emitted target electron, and the recoiling ion, were extracted into the opposite directions, respectively, along the projectile beam axis (the longitudinal direction defines the z-axis) by a homogeneous electric field over 11 cm and projected onto two-dimensional position-sensitive multi-hit detectors. A uniform longitudinal magnetic field was applied to confine the transverse motion of the electrons, such that all electrons with energies below 25 eV were collected with the full solid angle. While the ion-detector is equipped with a wedge and strip anode, the electron detector employs a delay-line anode for position read-out with increased
multihit capability. From the hitting positions and the time-of-flight the vector momenta of the particles can be reconstructed. It is noted that, since the projectile beam axis is adjusted exactly parallel to the electric and magnetic extraction fields, there is a central bore in the forward electron detector to avoid the complete saturation of the electron detector by the unscattered projectiles (~10^8 s^{-1}) and allow for the passage of the non-deflected electrons (see Figure 1). In this way a large part of the full solid angle is covered, 100% for the detection of recoil-ion and 80% for electrons below 25 eV. For the present measurements, the scattered projectile electrons were detected together with ejected electrons, as well as the residual ion, such that the triple coincidence of all final-state continuum particles delivered superior background suppression. Furthermore, the experimental electron momentum resolution is independent of the recoil ion momentum resolution (and therefore independent of the target temperature). That makes it feasible to measure heavier targets with the reaction microscope. The electron momentum resolution depends on how well the time and position of the ionizing collision can be determined from the pulse width and the focus diameter of the projectile beam in the target. Note that for our present (e, 2e) measurements on the light targets He and H_{2} at low impact energies (16 eV excess energy). One of the outgoing electrons and the recoil ion are detected in coincidence, and the momentum of the second outgoing electron is recalculated by using the momentum conservation.

3. Results and discussion

3.1. ionization of He and Ar at intermediate energy

Figure 2 exhibits the experimental and theoretical three-dimensional electron emission patterns for the (e, 2e) cross section of He by 200 eV electron impact at a scattering angle of \theta = 10^\circ. The energy of the emitted electron is fixed at \( E_2 = 15 \) eV.

![Figure 2. 3D cross sections of the ejected electron (15 eV) for single ionization of He by 200 eV electrons. (a) experiment, (b) CCC calculation](image.png)

In such a 3D plot, the FDCS for a particular direction is given as the distance from the origin of the plot (also the collision point) to the point on the surface which is intersected by the ionized electron’s trajectory. The cross section patterns are governed by the well-known double-lobe structure: the binary lobe in the direction of momentum transfer \( q \) corresponding to electrons emitted in a single binary collision with the projectile and the recoil lobe in the direction of \(-q\), where the target electron initially going along the \( q \) direction backscatters in the ionic potential. Due to the long-range nature of the Coulomb-force, the emitted electron is repelled by the outgoing projectile. For this reason, the binary and recoil lobes do not point exactly along the directions of \( q \) and \(-q\), respectively. Instead they are
tilted away from the outgoing projectile direction. The importance of such post-collision interaction (PCI) effect increases with decreasing relative velocity of the two outgoing electrons.

For the present asymmetric kinematics, the angular electron emission pattern has been well studied only in coplanar experiments. The three-dimensional representation in figure 2 allows for a more complete investigation. Also shown in Figure 2 is the corresponding cross sections predicted by the convergent close coupling (CCC) method. In a global view, good agreement between experimental data and CCC calculation is visible. The magnitudes and the angular position of the binary and recoil lobes are nicely reproduced. More detailed comparisons show discrepancies in the region bridging the angular range between the binary and recoil lobes, which is the plane perpendicular to the scattering plane including the incoming projectile. In this perpendicular plane higher intensity is observed in experiment than the calculation. Such phenomenon was also clearly visible in the (e, 2e) data on He at 1keV impact energy [17].

![Figure 2](image.png)

**Figure 2.** Three-dimensional representation of electron emission pattern for single ionization of Ar (3p) by 200 eV electrons. The magnitudes and the angular position of the binary and recoil lobes are nicely reproduced.

For the heavier target of Ar, the (e 2e) differential cross section behaviour is more complex than He, because of its many-electron property. As an example, Figure 3 presents the 3D FDCS for Ar at a projectile scattering angle of $\theta_1 = 10^\circ$ in comparison with predictions from a hybrid second-order DWBA + R-matrix model [5]. The energy of the emitted electron is fixed at $E_2 = 10$ eV. From the global view of the 3D plots, we see the qualitative agreements between the experiment and the theory. The patterns are again governed by the binary lobe and the recoil lobe. In both experimental and theoretical plots the binary lobe shows a minimum in the momentum transfer direction. This minimum is due to the momentum profile of the Ar 3p-orbital. Which is in contrast to the He 1s-orbital momentum profile showing a maximum. The experimental data also highlight some discrepancies compared with the calculations, especially in the region, between the binary and the recoil lobes. The experiment shows a double-peak structure similar to the binary peak feature in the scattering plane, instead the calculation only shows one peak. This might be a signature of the importance of projectile-nucleus scattering interaction.

![Figure 3](image.png)

**Figure 3.** 3D images of the ionized electron (10 eV) emission pattern for single ionization of Ar (3p) by 200 eV electrons. (a) experiment, (b) DW2−RM calculation.

For the heavier target of Ar, the (e 2e) differential cross section behaviour is more complex than He, because of its many-electron property. As an example, Figure 3 presents the 3D FDCS for Ar at a projectile scattering angle of $\theta_1 = 10^\circ$ in comparison with predictions from a hybrid second-order DWBA + R-matrix model [5]. The energy of the emitted electron is fixed at $E_2 = 10$ eV. From the global view of the 3D plots, we see the qualitative agreements between the experiment and the theory. The patterns are again governed by the binary lobe and the recoil lobe. In both experimental and theoretical plots the binary lobe shows a minimum in the momentum transfer direction. This minimum is due to the momentum profile of the Ar 3p-orbital. Which is in contrast to the He 1s-orbital momentum profile showing a maximum. The experimental data also highlight some discrepancies compared with the calculations, especially in the region, between the binary and the recoil lobes. The experiment shows a double-peak structure similar to the binary peak feature in the scattering plane, instead the calculation only shows one peak. This might be a signature of the importance of projectile-nucleus scattering interaction.

3.2. ionization of He and H$_2$ at low energy

(e, 2e) on simple diatomic molecules has attracted increased attention recently since strong molecular structure effects were observed for electron emission in the plane perpendicular to the incoming beam direction [13, 14]. In order to study these effects more comprehensively we have performed comparative (e, 2e) experiment on the two-electron targets He and H$_2$ covering the full solid angle of electron emission at 16 eV excess energy.

In Figure 4, we compare our experimental results on He with previous experiments and CCC calculations, where one slow electron ($E_1 = 4$eV) is fixed to $\theta_1 = 80^\circ$ in Figure 4(a) and $\theta_1 = 147^\circ$ in Figure 4(b) and the cross section is plotted as a function of the second electron emission angle $\theta_2$ in the scattering plane. The agreement is perfect between the two experiments and the CCC calculations. One of the advantages of our new experiments is that the full angular range is reached not only for the angular distributions in the scattering plane but also for the full 4$\pi$ solid angle.
Figure 4. (e, 2e) on He at 16 eV excess energy, one of the outgoing electrons ($E_1 = 4$ eV) is fixed to $\theta_1 = 80^\circ$ for (a) and $\theta_1 = 147^\circ$ for (b), and the second outgoing electron angle ($E_2 = 12$ eV) is plotted in the scattering plane. Also included are the previous experimental and theoretical results in [18].

The full 3D image of the second electron emissions is shown in Figure 5. The (e, 2e) cross sections for $H_2$ and He are plotted as three-dimensional polar plots representing the emission pattern for the fast electron ($E_2 = 12$ eV). The slow electron ($E_1 = 4$ eV) is fixed to $\theta_1 = 70^\circ$.

Figure 5. (e, 2e) cross sections as a 3D polar plot for the electron emission (12 eV) from $H_2$ (a) $E_0=31.5$ eV and He (b) $E_0=40.5$ eV.

It can be seen from the 3D images that the cross sections are governed by the well-known double lobe structure: the binary lobe and the recoil lobe. Distinct differences with a much stronger recoil intensity (bottom lobe) for He can be seen which can be attributed to the stronger nuclear potential in comparison with $H_2$ where the two positive charges are 1.4 a.u. apart from each other. The 3D images also show richer structure in the cross section of $H_2$ target than He in the range perpendicular to the incident beam direction [13, 14]. More detailed comparisons will be discussed in [19].
4. Summary
Kinematically complete experiments of (e, 2e) on He and Ar at intermediate impact energy of 200 eV and single ionization of He and H\textsubscript{2} by lower energy electrons (16 eV excess energy) have been performed. Full 3D images of the electron emission are obtained. For the intermediate projectile energy and heavier atomic collisions, strong out-of-plane intensity is observed. The discrepancies between experiments and theories are possibly due to approximations in the description of the projectile-target and projectile-ejected electron interactions. For low energy collisions, distinct differences between atomic and molecular ionization are visible, where much stronger recoil intensity for He is observed in comparison with H\textsubscript{2}. Furthermore H\textsubscript{2} shows richer structures outside the scattering plane than He.

5. References
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