Two center Electron Emission in fast Collisions of Bare C and F Ions with He and H₂ and CDW-EIS Model

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Abstract. We report the energy and angular distributions of the electron double differential cross sections (DDCS) for two collision systems: 6 MeV/u C⁺⁶ on H₂ and 4 MeV/u F⁺⁹ ions on He. The electrons having energies between 1 and 500 eV are detected at about ten different emission angles between 30° and 150°. The measured data is compared with the state-of-the art continuum distorted wave-eikonal initial state (CDW-EIS) and the first Born (B1) models. In case of molecular H₂ target a molecular wave function as been used for the calculations of the cross section of H₂. A comparative study has been presented for the spectral shape for the atomic (He) and molecular (H₂) target.

1. Introduction

Electron spectroscopy is a powerful tool to explore the dynamics of ion-atom and ion-molecule collisions. The detection of low energy electrons emitted in atomic collisions provides crucial information on the various ionization-mechanisms. The double differential cross section (DDCS) for electron emission spectrum clearly identifies the different processes such as soft collisions (SC), electron capture in continuum (ECC) cusp and the binary encounter (BE) electron emission as well as the two center effect (TCE) [1-13]. In addition, the measurements with the H₂ molecule as a target, it has been shown very recently that the Young type interference also influences the electron DDCS spectrum. Here we present the energy and angular distributions of DDCS of low energy electrons emitted in collisions of bare C and F ions with H₂ and He. Unlike the case of low charged projectile ions, such as, e⁻, H⁺ and He⁺⁺ etc., the motion of the ionized electron is considerably affected by the two moving sources of Coulomb potentials, namely, the receding highly charged heavy projectile ion and the residual recoil ion. Although, the projectile velocities considered here are much larger than the velocity of the electron in the atom (v_p/v_e ~ 10-15), it is seen [4,6,7] that the first Born calculation (B1) fails to explain the energy and angular distributions of the ionized electrons. This is a consequence of the fact that, B1 accounts only for the target center effect and doesn't consider the effect of the receding projectile after the electron has been emitted. The angular distribution of electron emission is known to be affected by the two center effect. The long range Coulomb interaction between the electron-target and electron-projectile in the final state influences the evolution of electron wave function and thereby the angular distribution. A large forward-backward asymmetry is caused due to
such two-center effect which is included in the state-of-the-art theoretical calculations like continuum distorted wave-eikonal initial state (CDW-EIS) approximation [8-10]. The two center effect depends on the projectile atomic number (Z) and velocity (v). There have been some previous measurements, although not too many, with fast ions of atomic number about 1 to 10 for which these models are tested. We extend these studies for two such projectiles in this range of atomic numbers i.e. for Z=6 and 9 with velocity between 12 and 14 a. u. We show that although this model gives an overall very good agreement there are still some deviations from the measured data especially for the small forward and large backward angles.

2. Experimental Details
The experimental set up and measurement techniques are standard. Bare C and F ions, with energies 72 and 76 MeV respectively, were obtained from the BARC-TIFR Pelletron accelerator at TIFR, Mumbai. The energy and charge state selected fast ion beam was collimated by three sets of four-jaw-slits arrangements and was made to pass through another aperture of diameter 4 mm before it collides with the target gas. Two layers of thin μ-metal plates of thickness 0.3 mm inside the chamber were enough to reduce the stray magnetic field below 10 mG in the region where the electrons travel before entering the analyzer. The electrons emitted in ionization of target were energy analyzed with the help of a hemispherical electrostatic analyzer before they were detected by a channel electron multiplier (CEM). The spectrometer could be rotated between 20\(^\circ\) and 160\(^\circ\) and the electrons were detected at ten or twelve different angles at an interval of about 10\(^\circ\) or 15\(^\circ\). The data was collected in fine energy steps between 1 to 500 eV and in some cases up to a one keV. Target gas was static inside the flooded chamber. The gas pressure was about 0.1 mT for electrons with energies below 40 eV and about 0.3 mT above 40 eV. The pressure for the low energy electron detection was kept low in order to reduce the re-scattering of the electrons before it reaches the analyzer. Extreme care was taken as far as the cleanliness of the chamber was concerned particularly to avoid any unwanted oil vapour. All insulating surfaces were carefully covered to avoid any space charge development which would otherwise deflect the low energy electrons. The chamber base pressure was typically ~ 10\(^{-8}\) mTorr. A PC based data acquisition system was used for data collection which was equipped with the automation and control system.

3. Results and Discussions
In this paper, we report the energy distributions of the low energy electron DDCS for the helium and molecular hydrogen targets in collisions with bare ions of C and F ions. Although the data was taken for many angles, we concentrate here only for emissions at three different angles: one extreme forward (20\(^\circ\) and 30\(^\circ\)), transverse direction and one extreme backward (150\(^\circ\) and 160\(^\circ\)). We focus our discussions towards a comparative study of electron emissions from two-electron targets : H\(_2\) and He. In a typical electron spectrum there are contributions of the three body ionization as well as a two body process known as binary encounter in which the target electrons are emitted in elastic scattering with the projectile nucleus and the width of the binary peak depends on the Compton profile of the target. Hydrogen molecule has a narrower Compton profile compared to He and hence the binary peak for H\(_2\) has less width than that for He. Therefore for H\(_2\) target the low energy electron spectrum of small forward angles (<60\(^\circ\)) will have relatively less contribution from the low energy tail of the binary peak and therefore mostly affected by the TCE process, for the present collision energies. On the other hand, apart from the TCE, the recently observed [14-20] Young type interference effect will also influence the DDCS spectrum for H\(_2\) which is missing for the He target. The large asymmetry in the forward-backward electron emission is a signature the two-center effect and a large deviation from the prediction of the B1 approximation which is essentially a one centre model is generally taken as a measure of the TCE. An oscillation in the forward backward asymmetry has also been observed for H\(_2\) and has been shown due to the interference effect [13,18,20,21].
We show, in Fig. 1, the examples of the measured electron DDCS for 76 MeV bare F ions on He for three different angles i.e., 20°, 90° and 160°. The electron energies of 1 to 400 eV is covered for all the three angles. One can, however, see that the cross sections fall about three orders of magnitude going from 1 eV to 400 eV for the forward angles. In contrast, for the backward angle the fall of cross

![Figure 1](image.png)

**Figure 1.** Energy distribution of electron DDCS emitted at three different angles 20°, 90° and 160° in collision of 4 MeV/u bare F ions with He; the solid and dotted lines represent, respectively, the CDW-EIS and B1 calculations in (a), (b) and (c), (d): the DDCS ratios obtained by dividing the experimental (symbols) DDCS by the B1 predictions. The lines in (d) are the similar ratios i.e., CDW-EIS divided by B1 predictions.
section between 1 eV to 400 eV is even faster i.e. by about four orders of magnitude. The figure also shows the comparison with the first Born (dotted lines) and the CDW-EIS (solid lines) calculations. The CDW-EIS provides an excellent agreement with the data. The B1 calculations although reproduces the qualitative behaviour quite well the absolute values are not so well represented by the model, except for 90°. For example in case of 30° the B1 underestimates the measured data whereas for the backward angle the data is lower than the model. The deviations from the B1 calculations are explored with more resolution, in Fig. 1(d), in which we plot the ratio of the measured DDCS to the B1 prediction as well as that for the CDW-EIS to the B1 prediction. For extreme forward and backward angles the ratios deviate from the expected value 1.0 and the deviations are large above 100 eV. One may note that for 30° the ratios are typically more than 1.0 whereas for 90° and 150°. This is reflected in the ratios plotted in (d) as one can see that for 30° the ratios grow from 1.0 to about 2.5. In case of 160° the ratio is less than 1.0 i.e. about 0.5 and for 90° the deviation from 1.0 is, however, lower. This behaviour of enhancement in the forward angles and depletion in the backward angles is typically expected due to the two-center effect. Overall shapes of these distributions are well reproduced by the CDW-EIS calculations whereas some deviations can now be observed while plotted on a linear scale. The peak observed around 35 eV is due to the population of the doubly excited state of He. The details of these measurements, results and interpretation can be found in [13].

We show, in Fig. 2, the examples of the electron DDCS for 72 MeV bare C ions on H₂ (details can be found in [13]) for three different angles i.e., 30°, 90° and 150°. One can see that the cross sections fall about five orders of magnitude going from 1 eV to 1000 eV for the forward angles whereas it falls for three orders of magnitude at 300 eV. In contrast, for the backward angle the fall of cross section between 1 eV to 300 eV is even faster i.e. by about four orders of magnitude which is similar to that observed for He target. This explains why the spectrum was not taken beyond 300 eV for this angle i.e. due to highly reduced cross section as well as for the comparable background contributions at these electron energies. The shape change in the spectrum between 20° and 90° is obvious especially in the region of 200-1000 eV which is expected based on the kinematical relation for the binary encounter peak position which dominates the lowest energy part of the spectrum in case of 90°. The similar BE peak for 30° is expected at much higher energy than 1000 eV and hence do not contribute to the lowest energy part of the spectrum. Therefore, the low energy part of the spectrum for 90 degree emission angle is contributed by the binary encounter process as well as and the three body ionization which is again affected by the two center mechanism. Similarly the kinematics do not allow the elastic peak for the backward angles. The deviations from the B1 calculations are explored in the three insets in which we plot the ratio of the measured DDCS to the B1 prediction as well as that for the CDW-EIS to the B1 prediction. For extreme forward and backward directions the ratios deviate from the expected value 1.0 and the deviations are large above 100 eV. One may note that for 30° the ratios are typically more than 1.0 and grows up to about 3.0 whereas for 90° the ratios are slightly lower than (and fairly closer to) 1.0 (i.e. about 0.75-80) and then at higher energy it crosses 1.0. For 150° it is almost same as 0.5 and then it crosses the 1.0 at about 50 eV and then with the increase of the electron energy it shows a structure. A closer look shows that these behaviours are different than those observed in case of He target (i.e. in Fig. 1(d)). The possible reasons could be the mixing of two effects i.e. the two center mechanism and the Young type interference which is known to introduce oscillatory structure in the DDCS spectrum [see the paper in this volume and references therein].
Figure 2. Same as in Fig. 1, except for 72 MeV C^6+ + He collision system and for angles 30°, 90° and 150°, respectively (from Ref. [13]). The insets show the DDCS ratios obtained by dividing the experimental (symbols) DDCS by the B1 prediction and the CDW-EIS (lines) divided by the B1.

4. Conclusions
We have discussed the energy distribution of the electron DDCS measured for the bare C and F ions colliding with He and H_2 targets. The measured cross sections for three different angles were compared with the B1 and CDW-EIS calculations. The deviation from the B1 was found to be substantial and energy dependent. The CDW-EIS model, which includes the two center influences on the emitted electrons, agrees quite well with the experimental results for He, whereas, deviations are seen in case of H_2. It was indicated that the additional mechanism of Young type interference in case of H_2 may be responsible for the additional deviations and the approximate molecular wave function incorporated in the model calculations may not be adequate enough for the proper description of the molecular character of H_2.

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