Forward backward asymmetry in electron emission from H$_2$ by fast carbon ions and Young type interference effect

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Abstract. We have investigated the effect of Young type interference on the forward backward angular asymmetry in electron emission from molecular hydrogen in collisions with fast bare carbon ions. The asymmetry parameter shows an oscillatory behaviour as a function of electron velocity which is absent in atomic target such as He. It is shown that the asymmetry parameter which is based on DDCS from H$_2$ only can be a tool to investigate the Young type interference. The measured energy and angular distributions as well as the asymmetry parameter are compared with a molecular CDW-EIS (continuum distorted wave-eikonal initial state) model.

1. Introduction

The spectrum of low energy electron emission in fast ion-atom collisions is very rich containing crucial information about various mechanisms responsible for the Coulomb ionization process. The ionized electron moves in the presence of two moving sources of Coulomb potentials, which due to their long range nature, can distort the initial and final state wave functions even when the two centres are far away. Such two centre effect leaves its signature in the strong forward focussing of the electrons emitted in fast ion atom collisions [1-10]. In order to account for the two center effects, the CDW-EIS (the continuum distorted wave eikonal initial state) model has been developed by Crothers et al [8], extended and fine tuned by Fainstein and coworkers [9,10] over the period of time and has been tested by experimental data [3-6]. Low energy electron emission spectrum from the simplest diatomic molecule H$_2$ in fast ion collisions manifests yet another important aspect of ion-atom ionization with a fast projectile. Since the two indistinguishable H-atoms may be considered as coherent sources of electrons, their contributions to electron emission add coherently thereby giving an interference effect. Although it was predicted by Cohen and Fano [11] for photoionization many years back it is only very recently, that the interference effect has been observed in the electron spectrum in heavy ion induced ionization of H$_2$ [12,13]. Following these observations various aspects of the interference effect are being investigated experimentally [14-18] and theoretically [19-21].

In all these investigations, the interference effect manifests itself as oscillations in the ratio of the doubly differential cross sections (DDCS) for H$_2$ and atomic H targets. Following our initial work [13] we show here that one can use the electron DDCS from H$_2$ only to get information on the interference oscillation i.e. without using DDCS for H. It is shown that the forward-backward angular distribution gets substantially influenced due to the interference effect and therefore one gets an oscillatory behaviour in the asymmetry parameter. We provide new measurements on the angular and energy distributions of the DDCS and show examples of interference effect by deriving the DDCS ratios (H$_2$/2H) using theoretical values of atomic H for 72 and 80 MeV C$^{6+}$ ions colliding with H$_2$. Finally we
derive the forward-backward asymmetry parameter from the measured DDCS as a function of emission angles. The measured DDCS, their angular distributions and the asymmetry parameter are compared with the state-of-the art model calculation based on the molecular CDW-EIS approximation [20, 21].

2. Experimental Details
The experimental set up and measurement techniques are standard. Bare C ions with energy 72 MeV (and 80 MeV) 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 μ-metal shield 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° and 160° and the electrons were detected at 10 to 12 different angles at an interval of about 15°. The data was collected in fine energy steps between 1 to 500 eV and in some cases up to a few keV. Hydrogen gas was flooded inside the chamber. 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.

2.1. Energy distribution
The figure 1(a) shows the measured DDCS at two complementary angles 30° and 150°. For the forward angle the data was collected between 1 and 1000 eV whereas for the backward angles the highest energy was about 300 eV, after which the cross section falls rapidly. The DDCS varies over five orders of magnitude in an energy interval of 300 eV and reaches a maximum value for very low energy electrons. The overall agreement with the CDW-EIS model can be termed as excellent for 30° considering the wide variation of the cross sections in the given energy range. For the backward angle, the CDW-EIS shows some deviations and crosses the data-spectrum around 50-60 eV indicating the limitation of the model in explaining the mechanism of the backward emission process. The angular distributions of the low energy (5 eV and 40 eV) electrons are shown in figure 1(c,d). The difference between the CDW-EIS and the B1 model is now obvious. For example, the B1 predicts almost no difference between the DDCS for 30° and 150° angles. But the measured data show a large forward-backward asymmetry caused by the two centre effect and is quite well reproduced by the CDW-EIS.

![Figure 1](image-url)

Figure 1. (a) Electron energy distribution of DDCS for emission angle 300 (a) and 1500 (b); angular distributions of DDCS for electrons with energy 5 eV (c) and 40 eV (d). Solid (dashed) lines are CDW-EIS (B1) predictions for 72 MeV C^6+ on H₂.
2.1. Oscillations in DDCS ratio and interference effect
To increase the visibility of the effect the molecular DDCS are divided by the corresponding atomic DDCS. In figure 2(a) we show the ratio of the experimentally measured DDCS of H\textsubscript{2} to the theoretically calculated DDCS of H for 135\textdegree emission angle. The ratio goes through an oscillation around the fitted straight line (D1). This oscillation can be attributed to the Young type interference effect\textsuperscript{[12,13]}. To compare the oscillations with theory i.e. to produce the oscillations around a horizontal line one has to divide the ratios by D1. The normalized ratio (R\textsubscript{N}) then shows an oscillation, about a horizontal line, in good agreement with the molecular CDW-EIS prediction.

2.2. Forward backward asymmetry and oscillation
We derive the forward-backward asymmetry parameter which is defined as $\alpha = \frac{\sigma(30) - \sigma(150)}{\sigma(30) + \sigma(150)}$ where $\sigma$ is the DDCS for H\textsubscript{2}. The asymmetry parameter for atomic target (such as He) has shown to be sensitive to the two centre effect (and the non-Coulomb potential of the atom)\textsuperscript{[10]} and the CDW-EIS reproduces it quite well. We have plotted $\alpha$ for He in figure 3(a) which shows a monotonically increasing behaviour with electron velocity as expected based on the two centre effect. On the contrary, for C\textsuperscript{6+} colliding with H\textsubscript{2} the asymmetry parameter shows an oscillatory structure superimposed on a smoothly varying function. This difference in the behavior between an atomic and molecular target at such high energy collision was unexpected in the framework of independent electron approximation and two centre effect alone. It can be seen (figure 3(b)) that the molecular CDW-EIS predicts a similar oscillation in $\alpha$ with a slightly different phase. For example, the CDW-EIS gives a full oscillation within 5.5 a.u whereas the data shows a full oscillation within 4 a.u for both the spectra i.e. for 30\textdegree-150\textdegree (figure 3(a)) and for 20\textdegree-160\textdegree (figure 3(c)). For completeness, we have added our recently observed similar data for emission angles 20\textdegree-160\textdegree\textsuperscript{[22]}. On the contrary, the atomic type CDW-EIS calculation based on the independent electron approximation i.e. using an effective atomic number does not reproduce (dashed-dotted line in figure 3(b)) any oscillation and behaves like a single centre target such as He-atom (figure 3(a)). This implies that the interference process built-in CDW-EIS model using molecular wave function gives rise to the oscillations in asymmetry parameter for H\textsubscript{2}. It can be understood physically: the molecular CDW-EIS automatically reproduces the Young type interference effect and predicts a higher number of oscillation for backward angles than forward. The difference in the frequency causes the oscillatory structure in $\alpha$.

![Figure 2](image-url)

Figure 2. (a) DDCS ratio ($R$) i.e. H\textsubscript{2}/2H for 72 MeV C\textsuperscript{6+}. Dashed line (D1) is a straight line fitted through the data. (b) The normalized ratio i.e. $R$ divided by $D1$. The data correspond to 135\textdegree.

3. Conclusions
We have studied energy and angular distribution of electron emission and in particular derived the forward backward asymmetry parameter from the DDCS spectrum at 30\textdegree and 150\textdegree. The asymmetry parameter increases smoothly with the electron velocity for He whereas
it goes through a full oscillation for $H_2$. The molecular CDW-EIS calculation including interference effect reproduces the oscillations qualitatively very well. The exploration of oscillatory structure does no need complementary theoretical or experimental study for atomic-H target and hence is self-normalized. The simple model fitting based on Bessel function type term for DDCS according to [7,8,11] and the frequency difference between forward and backward angles reproduces the oscillation quite well.

**Figure 3.** (a) Forward backward asymmetry parameter for 80 MeV C$^{6+}$ on He ($\square$) and $H_2$ (o) measured at 30$^\circ$-150$^\circ$; (b) Model predictions: molecular CDW-EIS (solid) and effective atomic CDW-EIS (dash-dot). (c) Similar result on oscillation for emission angles 20$^\circ$-160$^\circ$ (taken from [22]).

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