Young Type Interference Effect on the Forward-Backward Asymmetry Parameter in Electron Emission from H$_2$ Under Fast Ion Impact

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Abstract. We have investigated the double differential distribution of electron emission from molecular hydrogen in collisions with fast bare carbon ions in order to investigate the effect of Young type interference on the forward-backward angular asymmetry. The asymmetry parameter, derived from the cross sections for complementary forward and backward angles, 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 the DDCS of H$_2$ only, can be used as a self normalizing way of obtaining the Young type interference in an inversion symmetric homo-nuclear diatomic molecule like H$_2$. 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 recent observation of Young type interference in ion-impact ionization of diatomic molecule H$_2$ [1,2] unfolds yet another important aspect of ion-atom ionization besides the well known mechanisms i.e. the soft collision, two center effect, binary encounter and electron capture in continuum [3-19]. Since the two indistinguishable H-atoms may be termed as a coherent source of electrons in a large impact parameter collision with a fast projectile, their contributions to the ionization add coherently and an interference effect may be expected and has been observed [1,2]. Several aspects of this process is a subject of interest of various recent theoretical and experimental investigations [20-40]. Since the double differential cross section (DDCS) varies over several orders of magnitudes in an energy range of few hundred eV, it becomes difficult to observe a small variation in the DDCS spectrum owing its steep variation. Therefore, to enhance the visibility of the structure, the molecular cross sections are divided by the corresponding atomic cross sections, which are either obtained theoretically [1] or in an experiment with atomic H [2]. We have now demonstrated [41] an independent way of obtaining the interference structure by using the forward backward asymmetry parameter of electron DDCS which is independent of the theoretical model calculations and does not require a complementary experiment with atomic H. The experiments with atomic H as a target become difficult owing to the involved procedure of production of atomic H from the dissociation of H$_2$. It is known that a large forward backward angular asymmetry is mainly caused by the two-center mechanism in heavy ion collisions [5-14]. The enhancement in the forward directions and depletion in the backward angles is caused by the long range post collisional interaction among the three particles.
in the continuum (electron-projectile ion-recoil ion) of the final states and qualitatively explained by the continuum distorted wave models such as CDW-EIS (eikonal initial state), at least for an atomic target like He [5-7] or H [8-10].

2. Experimental Details

The experimental set up and measurement techniques are standard. Bare C ions with energies 45, 72 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 to have an absolute normalization of the measured cross sections. 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 discuss the influence of the interference effect on the forward-backward angular asymmetry parameter, \( \alpha(\theta) \), by measuring the DDCS of energy distribution at two complementary angles, such as, 20° - 160° or 30° - 150°.

![Energy distribution of electrons emitted at two different angles in collision of 6 MeV/u bare C ions with H₂ (a), (b) (taken from [42]); 3.75 MeV/u bare C ions with H₂ (c), (d). Solid lines represent the CDW-EIS calculations.](image-url)
The long range Coulomb interactions between the electron-target and electron-projectile in the final state influence the evolution of electron wave function and hence the angular distribution. The two-center effect as well as non-Coulomb potential for two or multi electron targets are known to cause a large forward-backward angular asymmetry, which can be seen in the large difference in the DDCS-values ($\sigma$) for small forward and large backward angles.

The forward-backward asymmetry parameter, $\alpha(k)$, can be written as:

$$\alpha (k) = \frac{\sigma (k, \theta) - \sigma (k, \pi - \theta)}{\sigma (k, \theta) + \sigma (k, \pi - \theta)},$$

where electron energy $\varepsilon_e = k^2/2$ (in a.u.) and $\theta$ is chosen to be low forward angles, such as 20° and 30°. The measured $\alpha(k,\theta)$ approximately represents the angular asymmetry parameter [17] which is actually defined for 0° and 180°. However, this approximation is not a very stringent condition for the rest of the analysis below. Here we present a comparative study of $\alpha(k)$, using He and H$_2$ as targets.

In Fig. 1, we show such DDCS spectra for two different collision energies, namely 45 and 72 MeV bare C ions with H$_2$. The DDCSs below 5 - 10 eV are not used in some cases since they are very sensitive to instrumental errors. Qualitatively an overall good agreement with the molecular CDW-EIS model can be seen with small deviations at higher electron energies and low collision energies.

The derived values of $\alpha(k)$, (i.e. $\alpha(k,\theta)$) show a smooth monotonically increasing trend as a function of electron velocity, for an atomic target such as He ['□' in Fig. 2 (a)]. This behavior is expected based on the two center electron emission process which is qualitatively well represented by the CDW-EIS model [18]. On the contrary, for C$^{6+}$ colliding with H$_2$, the asymmetry parameter shows an oscillatory structure superimposed on a smoothly varying function ['○' in Fig. 2 (a)]. This difference in the behaviour between an atomic and molecular target at such high energy collision was unexpected based on the independent electron approximation and two-center effect alone.

To understand this effect we use the molecular CDW-EIS calculation [19]. The main feature of this model is to represent the initial bound state of the active electron by a two-center molecular wave function. Within the impact parameter approximation, the transition amplitude reduces to a coherent sum of atomic transition amplitudes corresponding to individual molecular centers. This model, however, automatically reproduces the Young type interference effect in the electron emission from H$_2$ and its dependence on the emission angle such that the frequency of oscillation is higher for backward angles compared to the complementary forward ones. This difference in the frequency, for forward and backward angles, causes the oscillatory structure in the $\alpha(k)$.

It can be seen [Fig.2 (b)] that molecular CDW-EIS predicts the oscillation in the $\alpha(k)$ values between 1 and 5 a.u. On the contrary, the atomic type CDW-EIS calculation [18] based on independent electron approximation, i.e. using an effective atomic number ($Z_{\text{eff}}$) for atomic H does not produce [dashed-dotted line in Fig. 2 (b)] any oscillation and behaves like a single center target such as He-atom. This again implies that the interference process built-in molecular CDW-EIS model using molecular wave function gives rise to the oscillations in the asymmetry parameter for H$_2$.

However, for completeness and to get a deeper insight into the problem, we have developed a new model [41, 42] using the Cohen-Fano type [43] oscillatory behaviour for the DDCSs, which is basically represented by a Bessel function of order zero, $j_0(x)$. The argument of $j_0$, $x = kc(\theta)d$, is taken to be dependent on the angle of emission, $\theta$. The ratio between the two frequencies is given by
\[ \beta = \frac{c(\theta)}{c(\pi - \theta)}. \]
The dotted line in Fig. 2 (c) is the proposed model fit to the data points. A good fitting indicates that the simple expression of interference-influenced DDCS using peaking approximation can generally explain the phenomenon. This may imply that the interference plays a major role in the asymmetry parameter such that this parameter itself will be a sensitive tool to explore the interference effect. In addition, a deviation of \( \beta \) from 1.0 (i.e. about 1.3) implies that for backward angle the frequency of oscillation can not be governed by only the longitudinal component of the momentum transfer i.e., the simple \( \cos \theta \) dependence [20] which seems to explain the forward angle data only. In addition, this provides an important tool to study the interference phenomena for molecular target without making a comparison with the similar data with corresponding atomic target.

**Figure 2.** The Asymmetry parameter: symbols represent the experimental data for collision of 6 MeV/u C\(^{6+}\) with H\(_2\) (○) [42] and He (□). Solid line represents the molecular CDW-EIS calculation for H\(_2\), the dashed line is an effective atomic CDW-EIS calculation (\( Z_{eff}=1.19 \)) for H\(_2\); dash-dotted line corresponds to the atomic CDW-EIS calculation for He and the dotted line is model fit to the H\(_2\) data.

Similar measurements were also carried out at two other collisions energies, namely for 80 and 45 MeV bare C ions colliding with H\(_2\). In Fig. 3 (a) we show the \( \alpha(k) \) value for 80 MeV bare C ions on
H₂ [41] along with the CDW-EIS and first Born (B1) predictions. It can be noted that both the theoretical calculations predict the oscillation in the asymmetry parameter, whereas B1 predicts much less asymmetry compared to the experimental results. This is due to the fact that B1 doesn’t consider the so called two center effect (TCE) in ion-atom ionization process. In Fig. 3 (b) and (c) we show the α(k) values for 45 MeV bare C ions at two different sets of complimentary angles. It is observed that the frequency parameter β, remains almost similar (close to 1.3) for the two different complimentary angles in case of 45 MeV C ions. However, the asymmetry is larger for 80 MeV energy (close to 1.7). Also the structure is quite prominent for the higher energy data but less prominent for the lower energy collision.

![Figure 3](image.png)

Figure 3. The Asymmetry parameter: (a) symbols in represent the experimental data for collision of 6.66 MeV/u C⁶⁺ with H₂ (○) (taken from [41]); solid line represents the Molecular CDW-EIS calculation for H₂; dash-dotted line is an effective atomic CDW-EIS calculation (Z_{eff}=1.19) for H₂; the dotted line is the B1 prediction and dashed line is the proposed model fit in [41]; (b), (c) symbols represent experimental data for 3.75 MeV/u C⁶⁺ with H₂ (○); dashed line is the proposed model fit in [41], based on Cohen-Fano type model [43].
4. Conclusion
We have demonstrated the evidence of interference effect in the ionization of H₂. A novel technique of extracting interference effect has been proposed by us [41] invoking the effect of interference on the forward backward angular asymmetry parameter, which simplifies the experimental procedure a lot. We have discussed the influence of interference effect on the asymmetry parameter by doing a comparative study at three different collision energies. In addition, it is demonstrated that the asymmetry in electron emission is influenced by this new mechanism i.e. the interference effect other than the known mechanisms such as two center effect. It is also found that the frequency ratio β tends to decreasing with the beam energy and the reason for this is not understood. One needs more investigations towards this. The present technique may be unique for the study of interference effect in case of diatomic molecules, such as, N₂, O₂ etc, since for these multi-electronic atoms (e.g. O, N etc.) the experimental and even theoretical investigations are challenging tasks.

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