Young type interference in electron emission from H$_2$ and forward-backward asymmetry: a new approach

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Abstract. The energy and angular distribution of electron double differential cross sections (DDCS) in collision of 95 MeV F$^{9+}$ ions with molecular hydrogen have been measured. We explain the observed distributions in terms of the two-center effect and the Young-type interference effect. The asymmetry parameter, derived from the cross sections for complementary forward (30$^\circ$) and backward (150$^\circ$) angles, shows an oscillatory behavior as a function of electron velocity. 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) theory.

1. Introduction

The low energy electron emission spectrum from molecular hydrogen induced by heavy ion collision contains rich information about various ionization mechanisms. Since the two atoms in molecular hydrogen are indistinguishable, their contributions to the ionization probability add coherently and an interference effect might be expected in the single ionization of H$_2$. Such electron emission from H$_2$ may be closely related to the well-known Youngs double-slit experiment. It was predicted nearly forty years ago by Cohen and Fano in photoionization [1] and was first observed only recently in the electron spectra resulting from the ionization of molecular hydrogen by GeV energy heavy-ions in a pioneering investigation by Stolterfoht $et$ $al.$ [2] and by MeV energy heavy-ions [3, 4, 5]. The oscillations observed in the ratio of DDCS of H$_2$ and 2H, as a function of electron velocity i.e. de Broglie wavelength of electrons was termed as the signature of Young type interference. Such ratios were fully measured by Misra $et$ $al.$ [3] and Tribedi $et$ $al.$ [6, 7] by measuring the DDCS of H$_2$ as well as atomic H. Recently, the interference effect has been shown in the DDCS spectrum and in the ratio (H$_2$-to-H) spectrum as function of emission angle [8], which is an analogous situation of original Young’s double-slit experiments with light or with single electrons, where the interference fringes are observed as a function of observation angle.

The two-center effect as well as non-Coulomb potential for two or multielectron targets are known to cause a large forward-backward angular asymmetry, which can be seen in the large difference in the DDCS values for small forward and large backward angles [9, 10, 11, 12, 13, 14, 15]. Apart from the methods of deriving interference pattern from the ratio of molecular DDCS to
that of atomic one, another way to look into it comes from the analysis of the angular asymmetry of molecular DDCS, which is derived “only” from molecular DDCS and is free from any normalization. This procedure, which was introduced by Misra et al. [17] can be used self-consistently to study the interference.

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 95 MeV $F^{9+}$ ions colliding with $H_2$. Finally we derive the forward-backward asymmetry parameter from the measured DDCS as a function of emission velocity. 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.

2. The experiment
The measurement was carried out for a 95 MeV ($v_p \sim 14$ a.u.) $F^{9+}$ beam (obtained from BARC-TIFR Pelletron accelerator facility) colliding with $H_2$. The emitted electrons were detected using an electron spectrometer equipped with a hemispherical electrostatic energy analyzer and a channel electron multiplier. The energy resolution of the spectrometer was about 6% of the electron energy. Experiments were done by flooding the chamber with target gas keeping pressure of 0.15 mTorr for ejected electron energies 1-40 eV. For higher energy electrons the gas pressure was 0.2 mTorr. The front and exit apertures of the spectrometer were biased to a small voltages of +6V in order to help the lowest energy electrons to be detected. Background pressure was kept at 1x10$^{-7}$ Torr. The DDCSs were studied for different angles ranging from $20^\circ$ to $160^\circ$ (in steps of $15^\circ$) and for electron energies between 1 and 300 eV. The further details of the experimental setup are described in [16].

3. Energy and angular distributions
Figures 1. (a) and (b) show the measured energy distribution of DDCS at two complementary angles $30^\circ$ and $150^\circ$ respectively for electron emission in 5 MeV/u $F^{9+}$+$H_2$ collision along with the CDW-EIS predictions. 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 angular distributions, one for low energy (15 eV) and one for high energy electrons (120 eV) are shown in figure 1(c,d). The measured data show a large forward-backward asymmetry caused by the two centre effect and is quite well reproduced by the CDW-EIS.

4. Interference effect in DDCS ratio spectrum
Since $H_2$ is inversion symmetric homonuclear diatomic molecule, the contributions from each atomic center to the ionization probability add coherently and this may lead to oscillatory structure in the electron emission spectrum representing the interference effect. In order to amplify the visibility of the oscillatory structure, the experimental DDCS for $H_2$ is divided by twice the DDCS corresponding to the two-effective H atom calculations. In figure 2(a) we show the ratio of the experimentally measured DDCS of $H_2$ to the twice the theoretically calculated DDCS of H for $30^\circ$ 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 [3, 4]. To compare the oscillations with theory i.e., to produce the oscillations around a horizontal line the ratio is divided by D1. The normalized ratio is plotted in Fig. 2(b), which is in good agreement with the molecular CDW-EIS prediction. The normalized ratio is fitted with Cohen-Fano model function, which can be in found in ref. [2, 18].
Figure 1. Electron energy distribution of DDCS for emission angle 30° (a) and 150° (b); angular distributions of DDCS for electrons with energy 15 eV (c) and 120 eV (d). Solid lines are CDW-EIS predictions for 95 MeV F\(^{9+}\) + H\(_2\) collision.

Figure 2. (a) DDCS ratio (H\(_2\)/2H) for 95 MeV F\(^{9+}\) + H\(_2\) collision. Solid line: linear fit to the data. (b) Symbols: the normalized ratio, Solid line: CDW-EIS and dashed line for Cohen-Fano model fit.
Figure 3. The asymmetry parameter for 95 MeV F\(^{9+}\) collisions with H\(_2\) including a model fit in solid line and dashed line for CDW-EIS theory [to be published elsewhere in details]. Two complementary forward-backward angles 30\(^0\) and 150\(^0\) are considered.

5. Forward-backward asymmetry and interference effect

Besides first-order effects derived from the molecular to atomic cross-section ratios, the interference mechanism has been investigated in asymmetry parameter of the electrons emitted from H\(_2\) targets in collision with 95 MeV F\(^{9+}\). The asymmetry parameter can be defined as \[ \alpha(k) = (\sigma(\theta, k) - \sigma(\pi - \theta, k))/\sigma(\theta, k) + \sigma(\pi - \theta, k)), \]

where \(\sigma\) refers to the DDCS, \(\theta\) is any small forward angle and \(k\) is the ejection velocity. The asymmetry parameter \(\alpha(k)\) derived from the molecular DDCSs for emission angles 30\(^0\) and 150\(^0\) is plotted as a function of ejection velocity in Fig. 3. It can be seen that the molecular CDW-EIS (dashed line) predicts a similar oscillation in \(\alpha\) with a slightly different phase. Such oscillation may stem from difference of frequencies of first-order oscillations of the two complementary angles as explained earlier in ref. [17] i.e., the frequencies of oscillation for backward angles are more than complementary forward angles, causing the oscillatory structure in \(\alpha\). Fig. 3 also shows an oscillation starting at a value \(\alpha\) of about 0.4 and the oscillation is seen to be around a straight line with a steep slope. The steep slope for heavy-ion collision on H\(_2\) could be attributed to the post-collisional two-center effect [14, 15, 17] where influence of the field of the highly-charged positive ions on the final state of the ejected electron contributes towards a continuous increment of the yield in the forward direction compared to the backward angles. The effect increases with increasing ejection velocity in the velocity range considered. Therefore, the asymmetry parameter for H\(_2\) reveals the combined effect of two-center post-collision and interference effect. Using Cohen-Fano type model for interference and considering the observed frequency difference in forward-backward angles a good fitting is obtained (solid line in Fig. 3). The details about the model fitting has been discussed in ref. [17].
6. Conclusion

We have studied energy and angular distribution of electron emission and derived the first-order interference as well as the forward-backward asymmetry parameter from the DDCS spectrum at 30° and 150°. The CDW-EIS prediction is in good agreement with the experimental observations. It is shown that the asymmetry parameter which is based on the DDCS of H₂ only, can be used as self normalizing way of the obtaining the Young type interference. The simple model fitting based on Bessel function type term for DDCS and the frequency difference between forward and backward angles reproduces the oscillation quite well.

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