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Young Double Slit Interference Effects at Quantum Level

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Abstract. The currently accepted model for quantum interference resulting from the emission of electron waves from two scattering centers induced by either light or charged particle impact is analogous to Young's emission of two light waves from two slits. In this work we show that this simple classical wave model is incomplete and that there is a more complicated quantum interference pattern for low energy ionization caused by electron impact.

1. Introduction

In the early 1800s, Thomas Young demonstrated the wave nature of light by observing the interference pattern resulting from two light waves emitted from two closely spaced slits. In 1966, Cohen and Fano [1] suggested that the same type of behavior should be observed on the quantum level for photo ionization of diatomic molecules by observing the interference pattern resulting from two photoelectron waves emitted from two nuclei. Theoretical studies of Stia et al. [2, 3] specified that interference effects should be observable in triply differential cross section measurements for electron impact ionization of H_2. Molecular hydrogen being the simplest molecule has gained attention for studying the collision mechanisms. Evidence of interference effect has been observed in previous works [4, 5] by changing the ejected electron energy (wavelength). In a recent study, we showed that there are three types of possible two-center interference effects and the most important one is the diffraction of the projectile from two scattering centers [6].

The most sophisticated theories for molecular ionization process are the Born approximation-two center continuum approximation with correct boundary conditions [3], the molecular three-body distorted wave approximation (M3DW) coupled with an orientation-averaged molecular orbital approximation [7], and the time dependent close coupling (TDCC) approximation [8]. Recent studies have shown that the M3DW [9] method yielded good agreement with experimental measurements for H_2, and this is the theoretical approach we will use in this work.

We report a study of the interference factor (I-factor) introduced by Cohen and Fano [1] for 250-eV electron-impact ionization for both an energy scan with a fixed projectile angle and a projectile angle scan with ejected electron energy. The experimental measurements are performed using a crossed-beam-type electron-electron coincidence spectrometer and theoretical calculations are obtained by using M3DW [9].

2.Experimental Apparatus

The apparatus used to perform the measurements including the data accusation system has been described in previous references [6, 10-12]. The electron beam that is produced by electron gun is placed in a vacuum chamber and it is guided to the interaction region by electrostatic fields. The electron beam crosses the target gas at the interaction region in the perpendicular plane. The scattered and ejected electrons are detected by electron energy analyzers after the collision. A schematic view of the experimental apparatus is given in figure 1a. This spectrometer operated at an electron current ~4 µA with a resolution of 0,6 eV. The (e,2e) technique is used to detect two outgoing electrons in coincidence after the ionization of the target. It is essential for the (e,2e) technique to obtain accurate knowledge of the energies of the incident, scattered and ejected electrons. The two electrons are analyzed by hemispherical electron energy analyzers and detected by Channel Electron Multipliers which are mounted on the analyzers. This technique has an advantage for identifying single ionization events for which the outgoing electrons are originated from the same ionization event. To do this, time correlation between the detected electrons are taken in consideration and time delay between the electrons are converted to a signal that is measured by computer and a narrow coincidence peak in the timing spectrum is observed. Coincidence electronics is shown in figure 1b.
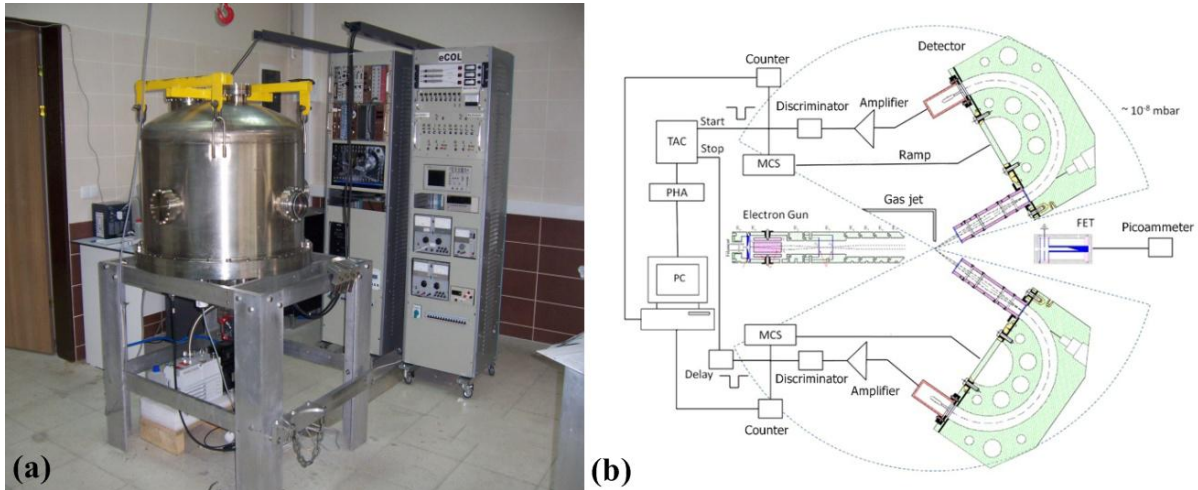

Figure 1. a) General view of electron spectrometer and b) coincidence electronics used to accumulating a coincidence timing spectrum at each kinematics.

3.Theory

The molecular 3-body distorted wave (M3DW) approximation has been presented in previous publications [9,13,14] so only a brief outline of the theory will be presented. The triple differential cross section (TDCS) for the M3DW is giving by:

$$\frac{d\sigma}{d\Omega_a d\Omega_b dE_b} = \frac{1}{(2\pi)^5}\frac{k_a k_b}{k_i}\left(\left|T_{dir}\right|^2 + \left|T_{exc}\right|^2 + \left|T_{dir} - T_{exc}\right|^2\right) \qquad (1)$$

Where $\vec{k}_i$, $\vec{k}_a$, and $\vec{k}_b$ are the wave vectors for the initial, scattered and ejected electrons, T_{dir} is the direct scattering amplitude, and T_{exc} is the exchange amplitude. The direct scattering amplitude is given by:

$$T_{dir} = \left\langle \chi_a^-(\vec{k}_a, \mathbf{r}_1)\chi_b^-(\vec{k}_b, \mathbf{r}_2)C_{scat-eject}(r_{12}^{ave}) \,|\, V - U_i \,|\, \phi_{DY}^{OA}(\mathbf{r}_2)\chi_i^+(\vec{k}_i, \mathbf{r}_1)\right\rangle \quad (2)$$

Where r_1 and r_2 are the coordinates of the incident and the bound electrons, χ_i, χ_a, and χ_b are the distorted waves for the incident, scattered, and ejected electrons respectively, and $\phi_{DY}^{OA}(r_2)$ is the initial bound-state Dyson molecular orbital averaged over all orientations. The factor $C_{scat-eject}(r_{12}^{ave})$ is the Ward-Macek average Coulomb-distortion factor between the two final state electrons [14], V is the initial state interaction potential between the incident electron and the neutral molecule, and U_i is a spherically symmetric distorting potential which is used to calculate the initial-state distorted wave for the incident electron $\chi_i^+(\vec{k}_i, \mathbf{r}_1)$. Details about the calculation of initial and final state distorted waves can be found in Madison and Al-Hagan [9]. For the exchange amplitude T_{exc}, particles 1 and 2 are interchanged in the final state wavefunction in Eq. (2).

4.Results and Discussion

Previous theoretical and experimental works showed that traces of the interference effects can be identified by changing the energy of the ejected electron for electron impact ionization of H_2. In addition to examining the effects of changing the ejected electron energy for a fixed scattered projectile angle, we have examined the effect of keeping the ejected electron energy fixed while varying the projectile scattering angle.

The I-factor introduced by Cohen Fano model [1] is defined to be the molecular cross section divided by the corresponding atomic cross section

$$I = \frac{\sigma_{H_2}}{2\sigma_H} \approx \frac{\sigma_{H_2}}{\sigma_{He}} \tag{3}$$

Where we make the same approximation that has been used earlier that the double hydrogen cross section can be replaced by the cross section for helium. For the approximations made by Cohen and Fano [1]

$$I^{CF} = 1 + \frac{\sin(QD)}{QD} \tag{4}$$

Where D is the separation between the two nuclei (1.4 a_0 for H_2) and Q is the momentum transferred to the final ion. The idea behind the I-factor is that, in any quantum mechanical calculation, there will probably be multiple interference effects even for scattering from a single center atom. Consequently, if the molecular cross sections are divided by the atomic cross sections, the single center interference effects will cancel and one will be left with the two center interference effects.

Present work represents the experimental and theoretical interference factor results for 250 eV electron impact ionization of H_2.
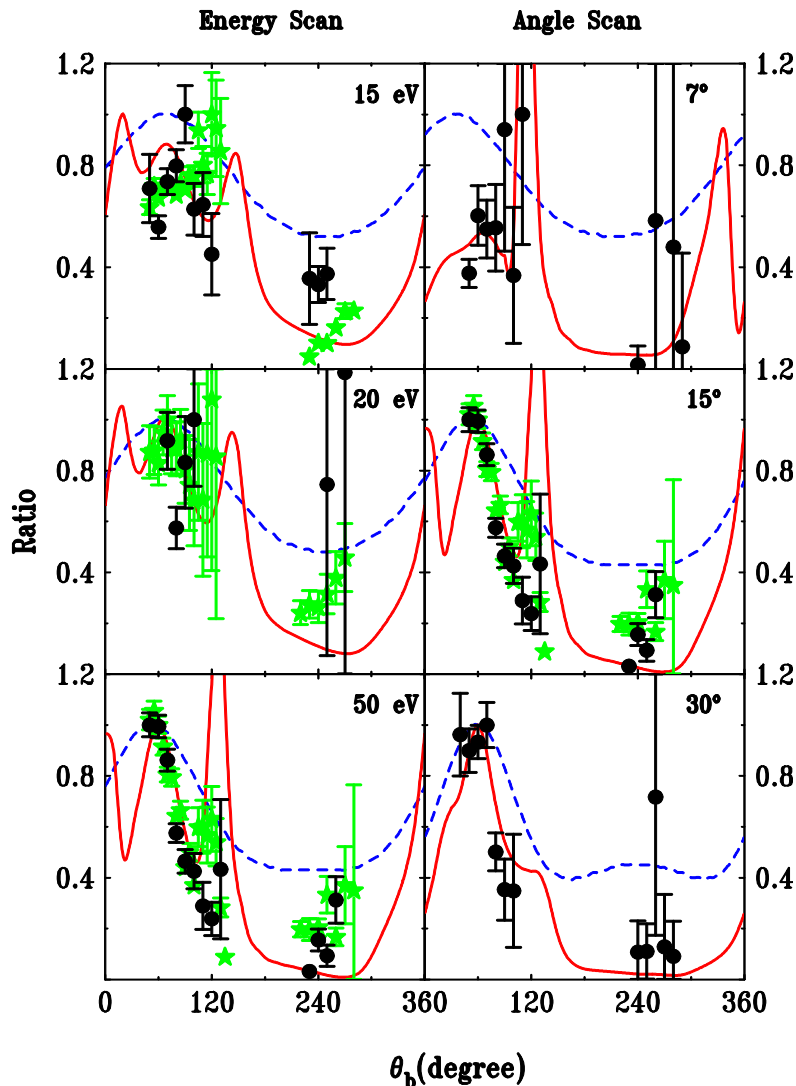
Figure 2. Interference factor for 250 eV electron impact ionization of H_2 and He as a function of the ejected electron angle θ_b. The results of the interference factor for an ejected electron energy scan of 15, 20 and 50 eV for a fixed projectile scattering angle of 15^0 (left hand column); and for a projectile angular scan of 7^0, 15^0, and 30^0 for fixed ejected electron energy of 50 eV (right hand column) are shown. Solid circles - present data, stars - data of Milne-Brownlie et al. [4], solid curve - M3DW, and dashed curve – I^{CF} [2].

We have reported that there is an overall good agreement with both experiment and theory in our previous work [6]. We see that the results of both experiment and theory predict a much more complicated interference pattern particularly in the binary peak region than is given by the elementary I^{CF} factor. We also see that the I-factor is more sensitive to projectile angular scans than to ejected electron energy scans which indicates that the diffraction of the projectile from two scattering centers is more important than the interference between electron waves emitted from two different centers for the present set of kinematics as seen in Fig. 2. Consequently, we see that there is significant interference at the quantum level that it is not amenable to a simple classical interpretation for lower energy incident electrons.

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