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Electron interference in fast ion collisions with H_2 and the frequency parameter

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Abstract
The Young-type interference effect has been investigated in electron emission from molecular hydrogen in collision of 5 MeV u^{-1} F^{9+} ions. The double differential cross section ratios of molecular-to-atomic hydrogen exhibits oscillatory structure, which is discussed in terms of the Young-type electron interference. We have obtained the frequencies of such oscillation for different angles. A comparative study of the frequency parameter is given with early measurements performed by other groups.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

Electrons emitted in the ionization of a homonuclear, diatomic molecule such as hydrogen carry rich information about its wave nature, which has been known to be manifested by Young-type interference in the last four decades [1, 2]. In such molecules, two identical centers act like two slits, and therefore coherent emission of electron radial waves may produce undulations in the electron spectrum associating the famous Young's double-slit experiment with light or electrons [3–7]. In ion–atom collision studies, this was observed only recently in the electron spectra resulting from the ionization of molecular hydrogen by heavy ion or electron impact [8–19] and in photoionization studies involving N_2 and H_2 molecules [20–23].

The present work was carried out for a collision system of 5 MeV u^{-1} $F^{9+} + H_2$. The electrons ejected from H_2 were measured in the energy range 1–300 eV and in a wide range of angles between 20° and 160°. Electron interference was investigated in the ratio spectra of molecular to effective-H-atom double differential cross sections (DDCSs), which are manifested by oscillations as a function of ejection velocity. The frequency parameters are obtained for several ejection angles in the range between 20° and 160° in the same experimental investigation by fitting the oscillations using the Cohen–Fano fitting function [2, 8, 24]. We make a comparative study of frequency parameters obtained by different groups for different collision systems.

2. Experimental details

The measurement was carried out for a 95 MeV F^{9+} beam (obtained from the BARC-TIFR Pelletron accelerator facility) colliding with H_2. The beam was well collimated by a series of four-jaw slits and a circular aperture before it entered the scattering chamber. The target gas was flooded inside the chamber through a 6 mm hole from one of the side ports. The gas pressure was constantly monitored and kept very low, i.e. 0.1 mTorr for electron energies up to 100 eV to minimize scattering of low-energy electrons from the gas and 0.3 mTorr for higher energy electrons to obtain sufficient counting rate. The electrons emitted in collisions were energy analyzed by a hemispherical electrostatic analyzer, with inner and outer radii of 25 and 35 mm, respectively. The resolution of the spectrometer was measured to be about 6% in energy ranging from 1 eV to a few keV. Further details about the performance of the spectrometer can be found in [25]. A stepper motor-driven, bellow-sealed, rotary vacuum feed-through was used to change the angular position of the spectrometer with respect to initial beam direction. Data acquisition, analyzer voltage scanning and stepper motor movement were

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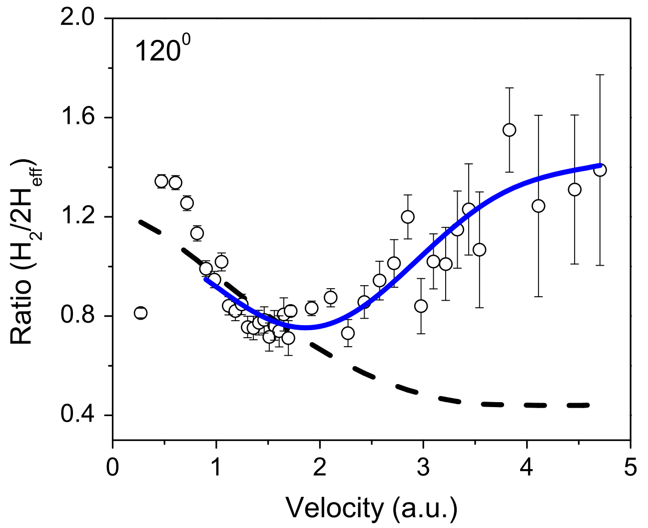

Figure 1. The DDCS ratio ($H_2/2H_{eff}$) for 120° is shown. The solid line represents the Cohen–Fano-type function fit and the dashed line represents the theoretical ratio.

controlled using the LabVIEW-based program. Further details regarding this experiment are described in [17].

3. Interference effect in the DDCS ratio spectrum

The strong incoherent emission from individual atomic centers of H_2 may mask the tiny contribution of the interference effect. Therefore, to increase the visibility of the effect the experimental DDCS for H_2 is divided by twice the DDCS for the H atom calculation. A version of the CDW-EIS model modified by Galassi *et al* [26] to include the molecular wave function has been used in this work. In figure 1, we show the ratio of the experimentally measured DDCS of H_2 to twice the theoretically calculated DDCS of *effective* H for ejection angle 120°. Here, we have used the effective nuclear charge for H (Z_{eff}) = 1.19 [27], which yielded oscillatory structure around a horizontal line around 1.0, and no straight line fitting is needed to compare with the theory. However, almost no agreement is seen in the structure with the CDW-EIS calculation (dashed line). A fitting is done to the ratio spectra using a function $a + bk + f\sin(c\rho k)/c\rho k$ denoted by solid lines in figure 1, where a, b, f and c are adjustable parameters, k is ejection momentum and ρ is inter-nuclear separation (1.41 au for H_2). The expression $\sin(c\rho k)/c\rho k$ is referred to as the Cohen–Fano term [2, 8, 28], as mentioned before. The linear function $a + bk$ takes care of any slope present in the ratio spectrum. From the fitting using the above function, we derived the frequency of oscillation, i.e. parameter c in the fitting function for all ejection angles [17]. Here we tabulate the frequency parameters obtained from this experiment and compare with the early measurements and theoretical predictions. In earlier work, the angular dependence of the frequency parameter was reported for high-velocity (40 au), highly charged Kr ions [24] along with a few theoretical predictions [26, 28, 29]. The angular distribution of the frequency (shown in figure 2 of [24]) included the data from two independent investigations. In the present work, we have derived the frequency parameter for several ejection angles on a wide angular range (between 20° and 160°) in the same experimental investigation for a different collision system.

Table 1. Frequency parameters obtained from different experimental and theoretical studies.

Angle	Heavy ion impact data	Stolterfoht *et al* [27]	Tanis *et al* [24]	Electron impact data
20	1.04			
30	0.82	0.82	0.96	1.0
60	0.55	0.52		0.42
90	0.29	0.29	0.29	0.3
120	1.43		1.16	
135				1.28
150	1.7	1.46	1.55	1.27
160	2.19			

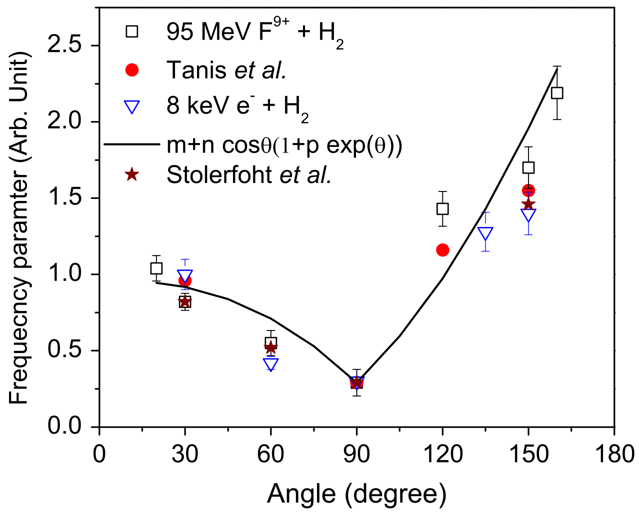

Figure 2. Frequency of oscillation is plotted as a function of angle. The squares represent data for 95 MeV $F^{9+} + H_2$, the asterisks from Stolterfoht *et al* [27], the circles from Tanis *et al* [24] and the triangles for 8 keV $e^- + H_2$. The solid line is a function to describe the experimental pattern [17].

The angular distribution of the frequency parameter *for heavy ion impact data (squares)* is shown in figure 2 along with the values found in early references for different measurement systems. The frequency parameters are also derived for an entirely different collision system such as 8 keV $e^- + H_2$ (triangles in figure 2). For electron impact measurement this is the first attempt to obtain frequency parameters. The detailed available values are also tabulated in table 1. The distribution exhibits higher frequencies of oscillation for the backward angles compared to the complementary forward angles, with a dip at 90°. In this work, we extended our study of the frequency distribution up to two more angles for heavy ion impact, namely 20° and 160°, respectively. For 30°, 60° and 90°, the present value of c has very good agreement with the previous measurements as well as our electron impact measurement. For 120°, however, the present data yield a larger value compared to the value reported by Tanis *et al* [24]. Note that the absolute uncertainty of the c values of the present data is about 15%, except for 60° and 90°, where there was a large fitting error of about 30–40%. The data for the forward angles may well be represented by a $\cos\theta$ function, which was predicted by Nagy *et al* [28], whereas for the backward angles the frequencies are much larger than the prediction of this function. A function (solid line) of the form $m + n \times \cos\theta(1 + p \times \exp(\theta))$ is used, which approximately describes the experimental behavior of figure 2, where $m = 0.29$, $n = 0.55$ and $p = 0.05$, respectively, in this case.

4. Conclusions

We have studied electron interference for the $5\,\mathrm{MeV\,u^{-1}}$ $F^{9+} + H_2$ collision system. The DDCS ratios (H_2-to-2H) were obtained using theoretical DDCSs for the atomic H target with an effective atomic number. The derived oscillations due to Young-type interference were reproduced by the Cohen–Fano-type fitting function for various angles. The frequency parameters for several forward and backward angles between 20° and 160° are tabulated along with previous experimental and theoretical studies. We have derived the frequency parameters for electron collision with H_2. In general, the results obtained from two entirely different projectile collisions, namely electron impact and heavy ion impact, are in good agreement and also in accordance with earlier works [24, 27] performed for completely different collision systems.

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