Interference Effect in Electron Emission in Heavy Ion Collisions with H_2 Detected by Comparison with the Measured Electron Spectrum from Atomic Hydrogen

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Direct evidence of the interference effect in the electron emission spectra from ionization of molecular hydrogen in collisions with bare C and F ions at relatively low collision energies is presented. Oscillations due to the interference are deduced by comparing the measured double differential cross sections of the electrons emitted from molecular hydrogen to those emitted from atomic hydrogen, rather than using the calculated cross sections for H as in a previous report. We believe these experimental data provide stronger support for the evidence of the interference effect. We show that it is not only a feature of very high energy collisions, but also a feature to be observed in relatively lower energy collisions.

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Low energy electrons emitted in atomic collisions provide crucial information on the various ionization mechanisms. Especially, the electron spectrum emitted from H_2, under heavy ion impact, is very rich since it provides the evidence of the interference effect. Since the two H atoms in molecular hydrogen are indistinguishable, their contributions to the ionization add coherently and an interference effect might be expected (see [1] for details). Such electron emission from H_2 may be closely related to the well-known Young's two-slit experiment which provided the crucial input to the development of the quantum mechanics. How the indistinguishability of the two atoms plays a role in the particle induced ionization or other processes remains to be explored. Although this effect has been known, for many years, to exist in the case of photoionization [2–4] and electron capture [5,6], it is only very recently that the interference effect has been observed in the electron spectra in heavy ion induced ionization of H_2 using 60 MeV/u Kr^{34+} [7]. It was predicted that high velocity ions, for which the dipole term contributes largely to the double differential cross section (DDCS), were necessarily required in order to observe such an effect. The dependence of the interference pattern on the atomic number of the projectile has not been addressed.

The amplitude of oscillation (due to interference), being quite small, is difficult to be observed in such DDCS spectrum owing to its steep dependence on the electron energy. To enhance the visibility of the oscillatory structure in the DDCS spectrum of the H_2 target, it is necessary to divide it by twice the DDCS of atomic H. The oscillatory variation of the derived ratio R around 1.0 then signifies the interference effect. In the previous study [7] the DDCS data for atomic H were not measured rather taken from the theoretical calculations. It was then found that the ratio R increases with the energy and therefore it was necessary to normalize the derived ratios, R, to a straight line which was a fitted line in some cases [8] in order to compare with the theoretical predictions. It has now been realized that such an increase is due to the use of the incorrect value of the effective charge ($Z_T = 1.05$) of H and the use of a higher value of $Z_T (= 1.19)$ [9] makes the ratio decrease with energy [10].

Therefore, the shape of the oscillation and its interpretation in terms of theoretical models is subject to the choice of the parameters like Z_T and depends on the fitting procedure required for normalization. This, however, will not be necessary if experimental DDCS for an atomic H target were available. To have a direct observation of the interference pattern and for an unambiguous interpretation we report here the experimental e-DDCS for the atomic and molecular hydrogen target measured in the same experiment using relatively lower velocity (v_p) (between 1 and 6 MeV/u) and low atomic number (Z_p) (e.g., C and F) projectiles. It allows us to vary the Coulomb perturbation strength (Z_p/v_p) on a wide range between 0.4 and 1.2. The collision of bare ions with atomic hydrogen is one of the simplest atomic collision processes leading to pure three body ionization. A complete understanding of a pure three body system has certain applications in other branches of physics. However, the DDCS measurements for H have been carried out in the past mostly for low charged projectiles such as e^- [11], H^+ [12], and He^+ ions [13]. Only recently we have initiated such measurements using highly charged heavy ions such as C [14,15].

The bare C ions, of energy 6 MeV/u, were available from the BARC-TIFR 14 MV tandem Pelletron accelerator at the Tata Institute of Fundamental Research (TIFR). The experiments with lower energy C (1 MeV/u) and F (1.5 MeV/u) ions were carried out using the 7 MV tandem Van de Graaff accelerator at Kansas State University.

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An electron spectrometer equipped with a hemispherical electrostatic analyzer and a PC based data acquisition system was used for the experiments at TIFR. The energy and angular distributions of the electron-DDCS were studied for several forward and backward angles for electrons energies between 1 and 1000 eV for H_2 and 1–300 eV for H. The atomic H target was obtained using a commercially available Slevin-type radio frequency (rf) H-atom source [16]. The mixture of H and H_2 was allowed in the chamber through a capillary tube of diameter 1 mm. The spectrum of recoil ions produced in the collision of bare ions with H_2 contains a broad peak of protons having energy around 9 eV arising from Coulomb explosion or other mechanisms [17]. The dissociation fraction (D_f) was about 80% which was determined from the yields of the 9-eV protons with the rf power on and off, respectively. The DDCS ratio was then determined from the measured electron spectrum taken with the rf off and rf on and using the D_f and the absolute DDCS for H_2 using a static gas condition (see [12,14] for details).

Experiments with H_2.—In Figs. 1(a)–1(c) we display the absolute DDCS for 6 MeV/u, C^{6+} + H_2, measured at 45°, 75°, and 105° along with the predictions of the recent extension of the continuum distorted wave-eikonal initial state (CDW-EIS) model [9]. The main feature of this model is to represent the initial bound state by a two-center molecular wave function. Within the impact parameter approximation the transition amplitude reduces to a coherent sum of atomic transition amplitudes for each molecular center. For both forward angles, the theory agrees very well with the data over a wide energy range, i.e., between 1 and 1000 eV, over which the DDCS falls by more than 5 orders of magnitude. In the case of 105° again a good agreement is found with the calculations except at the lowest energies for which a slight deviation can be seen. An increased deviation may be noticed for even larger backward angle, i.e., for 150° (see later).

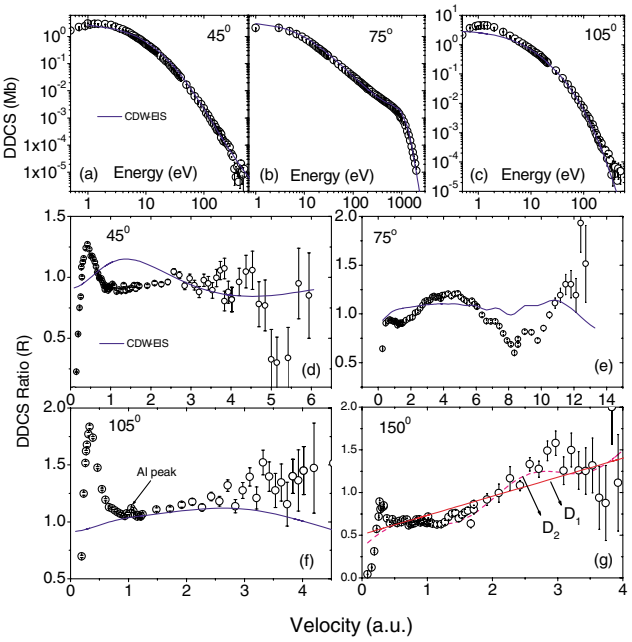

FIG. 1 (color online). (a) The measured *e*-DDCS for 6 MeV/u C^{6+} + H_2: (a) 45°, (b) 75°, (c) 105°, along with the CDW-EIS predictions (solid lines). (d)–(g) Experimental-to-theoretical DDCS ratios for 45°, 75°, 105°, and 150°, respectively. The line D_1 in (g) is the linear fit to the data points and the dotted line (D_2) is to guide the eye and also indicate an oscillatory structure. The solid lines in (d)–(f) represent the fully calculated ratios, i.e., those derived using theoretical values for the DDCS for H_2 and H. The peak indicated by "AI"in (f) is due to autoionization [10].

Now we derive the DDCS ratios (R) by using the CDW-EIS predictions for the DDCS of H (with $Z_T = 1.0$). These ratios, for all three angles [Figs. 1(d)–1(f)], were found to oscillate about an approximate horizontal line near 1.0 (with a slight decreasing trend for 45° with negligible slope), and therefore there is no need to normalize the ratios by any fitted line in order to enhance the visibility of the oscillations. This behavior is quite different from the earlier studies in which the R was a steeply increasing or decreasing function of energy depending on the choice of Z_T. We feel that the present observation is due to a good agreement of the DDCS data with theory over a wide energy range. In addition, the structure in the case of 75° is different from that for 45° due to the binary encounter (BE) peak which influences the low energy part of spectrum for 75°. However, the situation is different for a large backward angle, 150°, for which the ratio increases with the electron energies and there is an oscillation (D_2, dotted line) overriding the increasing trend [Fig. 1(g)]. The increasing trend can be represented by a fitted straight line, D_1, and can be due to deviation of the calculations from the actual cross sections for H [or H_2 target, as shown in Fig. 2(a)]. In Fig. 2(b) we display the normalized ratios R_N i.e., R divided by D_1, for 150°. The R_N clearly shows the oscillatory structure around an approximate horizontal line (i.e., $R_N = 1.0$), as expected. Therefore (i) there is a signature of oscillation in the ratios measured in all the angles; (ii) the procedure to deduce the oscillatory structure in the ratios is not unique but rather angle dependent; and (iii) the frequency of oscillation is *higher* in the case of backward angles compared to the forward angles, which is qualitatively in agreement with the theoretical prediction (for 45° and 150°). However, the agreement with the calculation is not impressive as far as the phase and amplitudes are concerned. Especially the deviations in the low energy part are very large as observed also in the high energy collisions earlier [7].

Now turning to the question of the effective atomic number for H, we show examples of the DDCS ratios determined for another effective charge, i.e., $Z_T = 1.19$ in Figs. 3(a) and 3(b). These plots emphasize the dependence of the interference structure on the choice of Z_T. It

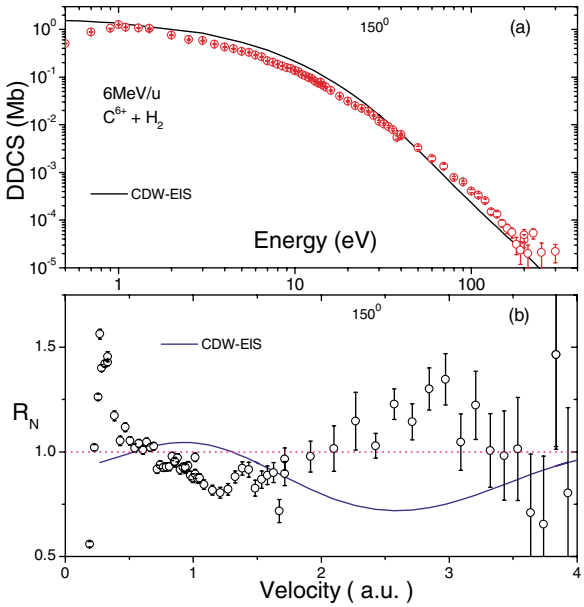

FIG. 2 (color online). (a) The DDCS measured at 150° along with the CDW-EIS calculations (solid line) and (b) the normalized DDCS ratio (R_N) showing oscillation around 1, i.e., the dashed line (see text). The solid lines represent the fully calculated DDCS ratios.

may be mentioned that no fitted straight line was used to derive the ratios since a higher value of Z_T was used. It is obvious that the shapes of the structures are quite different. Especially for 45° the oscillation is hardly visible and the theory does not reproduce the shapes either, although the agreement is slightly better at least for 75°. Therefore, the use of any arbitrary Z_T may not necessarily be required to derive the oscillations.

Experiments with H and H_2.—We display the fully measured (i.e., experimental-to-experimental) ratios R, derived by using the measured DDCS for both H and H_2 in collisions with 1.5 MeV/u F^{9+} (Fig. 4) and 1 MeV/u C^{6+} (Fig. 5) [15]. The absolute DDCS for 60° is shown in the inset of Fig. 4(b). The oscillatory structures in the ratios are visible for the lower energy part of the spectrum which are dominated by the soft collisions. The agreement between theory and data seems to be better in the case of 60° [Figs. 4(b) and 5(b)] compared to that for 45° [Figs. 4(a) and 5(a)]. The presence of the BE peak causes additional structures between 10 and 12 a.u. [see the inset in Fig. 4(a)] for 45° and between 8 and 10 a.u. for 60°, owing to the difference in the Compton profiles of H and H_2 [9].

Interestingly, the ratios do not show any increasing or decreasing trends with the electron energies, unlike the previous case (and also the cases in Ref. [10]), and the oscillations are around approximately a horizontal line close to 1, as expected. Therefore, now there is no need for the normalization by dividing the data points by any straight line. Although there is some deviation from the CDW-EIS calculations in the phase and the peak values, the overall agreement is good.

In Fig. 4(b) we also display the DDCS ratios (dash-dotted line) derived using experimental values for H_2 and theoretical values for H. Also the structures observed in the experimental-to-theoretical ratios deviate largely from the experimental-to-experimental ratios.

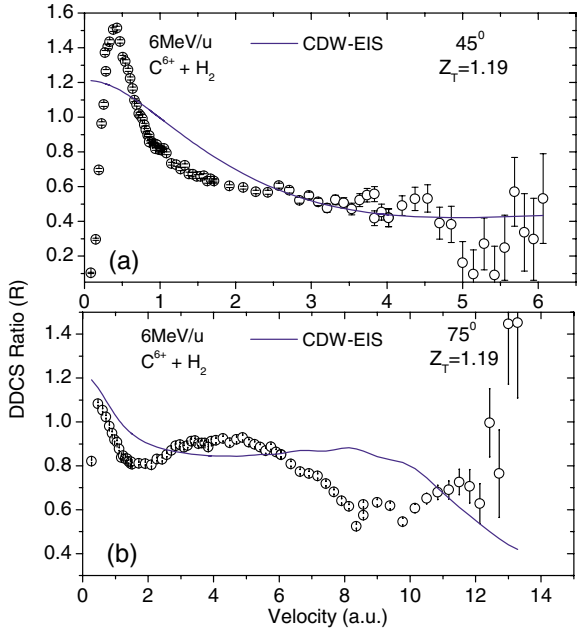

FIG. 3 (color online). Experimental-to-theoretical DDCS ratio (R) derived using $Z_T = 1.19$: (a) 45° and (b) 75° along with the theoretical-to-theoretical DDCS ratios (solid lines).

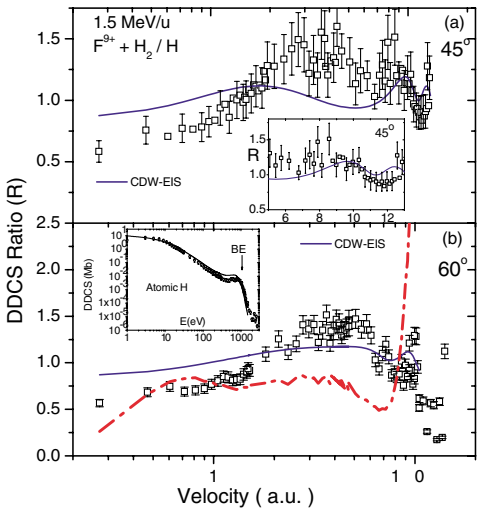

FIG. 4 (color online). Fully measured DDCS ratio for F^{9+}: (a) 45° and (b) 60° along with the fully calculated DDCS ratios (solid lines). The inset in (a) shows the ratios near the BE peak and that in (b) shows the DDCS for H with calculations (line). The experimental-to-theoretical ratios (dash-dotted line) are also shown for comparison.

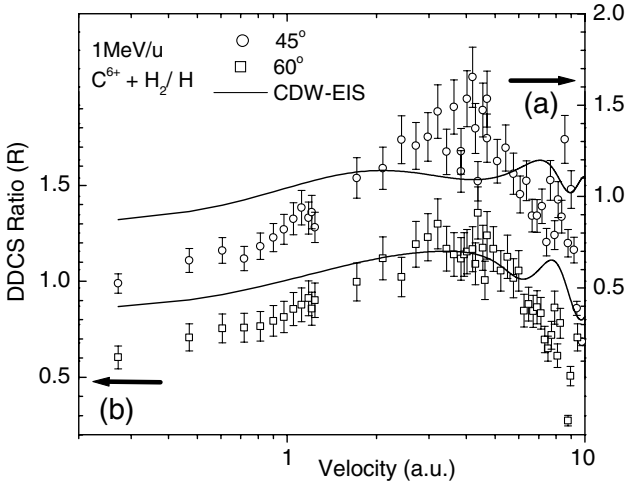

FIG. 5. The experimental-to-experimental ratios of DDCS for $C^{6+} + H_2/H$: (a) 45°, (b) 60°. The arrows indicate the respective scales. The solid lines are for the fully calculated DDCS ratios.

The former ratio not only *deviates from the experimental* data but also shows additional oscillatory structure, showing the inadequacy of the method adopted. Any small systematic error in the measured data may give rise to such spurious structures, which will be otherwise absent if one fully measures the ratio directly [14], as shown by the data points (squares) in Fig. 4. It is obvious that the fully measured ratios are in much better agreement with the fully calculated values (solid line). It may be noted that the agreement with theory, both in phase and amplitude, is relatively better than that for the earlier collision system (Figs. 1–3) in which the atomic H was not used. This clearly demonstrates the need to use the experimental quantities for direct observation of the oscillatory structure which is free from any systematic experimental errors. Also the observed structure is now independent of theoretical parameters. Additionally, comparing Figs. 1–5 we find that the dependence of the oscillation pattern, i.e., the amplitude and the frequency, on the projectile atomic number and velocity is very weak, confirming the theoretical predictions of Galassi *et al.* [9].

In conclusion, we have demonstrated that the measurements of the electron-DDCS for atomic and molecular hydrogen in the same experiment allow us to have an unambiguous observation of the interference pattern which is free from the normalization procedure and the choice of effective Z_T, as well as systematic experimental errors. The striking feature is that dependence of the ratios on the fitting function could be avoided and the ratios using experimental DDCS data for H show the oscillations approximately around 1.0. The frequency of oscillation is *higher* for large backward angles. The interference process is an important mechanism influencing the electron-DDCS spectra even for relatively lower energy collisions. The dependence of the oscillation on the projectile atomic number is very weak. The agreement between theory and data is in better shape in the case of atomic H experiments, where the interference pattern is measured fully, i.e., by comparing the measured data for H_2 and H.

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