Probing Young-type interference effect on angular distributions of e-DDCS using fast electrons as projectile

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Abstract.
The energy and angular distributions of electron double differential cross sections (DDCS) of $H_2$ and He are measured for fast electron collision. The measured data are compared with recently developed theoretical calculations. The observed distributions of $H_2$ are explained in terms of interference effect by comparing with single center He and atomic hydrogen. We show experimentally by comparing with He, that partial constructive interference exists in soft and binary collision regions of $H_2$ spectra.

1. Introduction
Low energy electrons emitted from atoms and molecules in collision of heavy ions or electrons carry rich information regarding various ionization mechanisms such as soft-collision, binary encounter and two-center interactions. Since electrons are much lighter, dimensionless, negatively charged particles compared to heavy ions, therefore, electron impact dynamics is quite different in several aspects. For example, in contrary to highly charged heavy ions, electron projectiles show much less post-collisional two-center interaction with the emitted one [1, 2]. In case of binary encounter, for heavy ion collision, the emitted electrons suffer Rutherford back scattering from a huge mass. In contrast, in case of electron impact, it is a violent collision between the two identical particles. Therefore, the binary encounter effects in the energy spectrum of the emitted electrons are different for heavy ion and electron collisions. Hydrogen being a molecule with two identical atomic centers, carry additional rich information about wave nature of emitted electrons, which has been shown to be manifested by particular undulations in energy spectrum [3, 4, 5, 6, 7, 8]. In electron impact ionization studies, such undulation was first time observed in the energy spectrum of double differential cross section (DDCS)[9, 10] and later on in the angular spectrum of triple differential cross section (TDCS) [11, 12, 13] by investigating the relative change of binary and recoil peak intensities, caused by partial constructive or destructive interferences. Recently, effect of interference on angular spectrum for fixed emission energy has been shown in the DDCS measurements [1, 14].

Since the last three decades a number of measurements have been carried out to obtain differential cross sections of electron emission from $H_2$ and He, induced by electron collisions.
Several measurements exist on single and double differential cross sections [15, 16, 17] and on triple differential cross sections [18, 19, 20] of electron emission in $e^- + \text{He}$ collision for various electron impact energies. In this work, we present the energy and angular distributions of DDCS of electrons emitted in ionization of $\text{H}_2$ and $\text{He}$ in collision of 8 keV electrons and compared with recently developed theoretical calculations. Although we focus on ionization of $\text{H}_2$, the complementary measurement on $\text{He}$ atom is also reported. To investigate interference in the DDCS spectrum, it is necessary to employ atomic DDCS. We have used atomic $\text{H}$ DDCS from theory. Alternatively, we have also used DDCS of atomic He, which is measured.

2. Experimental details
The measurements were carried out for an 8 keV ($v_p \sim 24$ a.u.) electron beam colliding on $\text{H}_2$ [1, 14] and $\text{He}$ gaseous targets. Electron beam was generated from a commercial electron gun. In addition to the in-built focusing element in the e-gun, we have mounted another set of Einzel lens, deflector and collimator assembly at the entrance of the chamber to focus the beam at the center of the chamber. Electrons emitted from the target were detected using an electron spectrometer equipped with a hemispherical electrostatic energy analyzer and a channel electron multiplier. Care was taken regarding the spectrometer performance, stray fields, background electrons and projectile beam profile. The energy resolution of the spectrometer was about 6% of the electron energy, limited by the entrance and exit apertures. Experiments were done by flooding the chamber with target gas keeping pressure $0.15-0.2$ mTorr. The front and exit apertures of the spectrometer were biased to small voltages of $+6$V in order to help the lowest energy electrons to be detected. Background pressure was kept at $1 \times 10^{-7}$ Torr. For $\text{He}$, the $e$-DDCS is suitably normalized with respect to known absolute DDCS in our early measurements [1, 14]. The DDCSs were studied for different angles ranging from $30^0$ to $150^0$ and for electron energies between 1 and 500 eV. Further details of the experimental setup is described in [14].

3. Energy and angular distributions
Figures 1 (a)-(d) show the measured energy distribution of DDCS at four emission angles $45^0$, $75^0$, $90^0$ and $135^0$ respectively, for electron emission in collision of 8 keV electrons with $\text{H}_2$ (open circles) [14] and $\text{He}$ (solid squares), respectively. Good agreement can be found between theoretical predictions and experimental data throughout the energy range. Dashed curves are representing theoretical $e$-DDCSs of $\text{H}_2$ calculated with two-effective center approximation (TEC), where the ionization of one of the target electrons may be considered as produced preferably from the vicinity of either molecular center, whereas the other electron screens completely the nucleus from which ionization is not produced. The molecular DDCS contains an interference term which appears due to coherent electron emission from two identical centers. A detailed discussion on this theory is given in Ref. [1, 14, 9, 10]. Also in the same figures, the dotted lines represent calculations corresponding to two $-\text{effective}$ $\text{H}$ atomic centers, where an $\text{effective}$ hydrogen with an $\text{effective}$ nuclear charge equal to the one used in the Heitler-London wave function and an $\text{effective}$ energy equal to the molecular bound energy have been used [1, 14, 9, 10]. For calculation of $e$-DDCS of $\text{He}$, a first-order Born approximation is employed to compute differential cross sections for the single ionization of helium atoms by impact of high velocity electrons. Within the framework of this approximation, both fast electrons, i.e., the incident and the scattered one are described by plane waves, whereas the final continuum state for the ionized electron is chosen as an effective Coulomb wavefunction, taking into the account the interaction between the emitted electron and the residual target. It has been shown that this first-order model gives a good description of the measured triply differential cross sections for ionization of $\text{He}$ atoms at an incident-electron energy of around 8 keV [18].

The angular distributions for fixed emission energies of 60 eV and 90 eV are plotted in figure 2(a) and (b), respectively. In this case also the experimental data for $\text{H}_2$ and $\text{He}$ are well
Figure 1. The DDCSs of electrons emitted from H$_2$ (open circle) [14] and He (solid square) as a function of emission energy in collision of 8 keV electrons for emission angles of (a) 45°, (c) 75°, (b) 90° and (d) 135°. The theory for molecular H$_2$ and twice the theoretical cross sections for effective H atoms are shown in dashed and dotted lines, respectively. Solid lines are theoretical predictions for He.

reproduced by theoretical predictions in almost all angles. The symmetric behaviour observed in angular distributions is an indication that post-collisional two-center effects are less relevant than for multicharged ion impact.

4. Interference effect in DDCS spectrum

Since H$_2$ is inversion symmetric, homonuclear diatomic molecule with two electrons, the contributions from each atomic center to the ionization probability add coherently and this may lead to constructive and destructive interference in emission spectrum. In contrary, He is one center with two electrons and hence no two-center interference effect is expected. The apparent cross over of the DDCSs of H$_2$ and He in Figure 1 might be due to combined effect of Compton profiles and constructive interference. In all four spectra, below 30 eV emission energy, the DDCSs of He underestimate the DDCSs for molecular H$_2$ beyond their experimental uncertainties, indicating presence of partial constructive interference in the low energy (or soft collision) region, where momentum transfer from projectile is very small. The theoretical cross sections of twice the atomic hydrogen also support the above observation [1].

For electron impact studies, it can be shown classically that the binary encounter (BE) peak energy for electron impact scales with $\cos^2 \theta$, where $\theta$ is emission angle. At angles 75° and 90°, the BE peaks shift and merge with low energy electrons. It was already shown that the partial constructive interference is prevailed in BE electrons [1, 14]. In sharp contrast to 45° and 135° of Fig. 1, the DDCSs of H$_2$ for 75° and 90°, are considerably larger than that of He between emission energies of 30 eV and 500 eV. Such a change in slope can be attributed to presence of constructive interference in H$_2$ and different Compton profiles of H$_2$ and He. However, individual
Figures 2. (a) and (b): DDCSs of electrons emitted from H$_2$ (circles) and He (square) in collision of 8 keV electrons, at various angles between 30° and 150° for two different emission energies of 60 eV and 90 eV, respectively. The theory for He are shown in solid lines, molecular H$_2$ in dashed lines and twice the theoretical cross sections for effective H atoms are shown in dotted lines, respectively. In (c) and (d) the experimental (H$_2$-to-He) ratios are represented in open circles; solid lines: theoretical (H$_2$-to-He) ratios. The solid lines in (e) and (f) are complete theoretical (H$_2$-to-2H) ratios and circles are for experimental(H$_2$)-to-theoretical(2H) ratios.

The contribution of interference effect and Compton profile mismatch is difficult to estimate. The effect of two-center Young type interference on angular spectrum of H$_2$ has been shown in Ref. [1, 14]. Here we further show complete experimentally the evidence of modulations due to presence of partial constructive interference in the angular distributions of H$_2$ in figure 2. The relative overestimation of e-DDCSs of H$_2$ compared to that of He in the binary collision region around 90° for two emission energies of 60 eV and 90eV (figure 2(a) and (b)), can be attributed to the presence of partial constructive interference in case of H$_2$. The effect is quantified in the ratio spectra shown in figure 2(c) and (d). The complete experimental ratios of H$_2$/He show very good agreements with corresponding complete theoretical predictions (solid lines). However, in this case too the contribution of Compton profile mismatch is difficult to estimate. The experimental(H$_2$)-to-theoretical(2H) ratios are plotted in figure 2(e) and (f) respectively, which also independently show similar oscillating structures supported by complete theoretical (H$_2$-to-2H) ratios, implying a significant contribution of partial constructive interference to the structures of e-DDCSs of H$_2$. 
5. Conclusion
We have studied energy and angular distributions of electron DDCSs for He and H$_2$ in collision of 8 keV electrons and compared with theoretical predictions. An overall good agreements are seen between experimental data and theoretical predictions. A comparison is made for energy and angular DDCS spectra between H$_2$ and He and demonstrated that the presence of partial constructive interference modulates the cross section of H$_2$. DDCS ratio (H$_2$/He) as a function of angle shows signature of interference, which is agreement with theoretical prediction. Furthermore, the presence of constructive interference is shown in soft and binary collision regions of H$_2$ spectrum.

References
[1] Chatterjee S et al 2008 Phys. Rev. A 78 052701
[2] Fainstein P D, Ponce V H, and Rivarola R D 1996 J. Phys. B 24 3091
[3] Cohen H D and Fano U 1966 Phys. Rev 150 30
[4] Stolterfoht N et al 2001 Phys. Rev. Lett. 87 023201
[5] Misra D et al 2004 Phys. Rev. Lett. 92 153201
[6] Hossain S et al 2003 Nucl. Instr. Meth. Phys. Res. B 205 484
[7] Misra D, Kelkar A, Kadhane U, Kumar A, Tribedi LC, and Fainstein PD 2006 Phys. Rev. A 74 060701(R)
[8] Misra D, Kelkar A, Kadhane U, Kumar A, Singh YP, Tribedi LC, and Fainstein PD 2007 Phys. Rev. A 75 052712
[9] Stia C R, Fojón O A, Weck P F, Hanssen J and Rivarola R D 2003 J. Phys. B: At. Mol. Opt. Phys. 36 L257
[10] Kamalou O, Chesnel J Y, Martina D, Hanssen J, Stia C R, Fojón O A, Rivarola R D, and Frémont F 2005 Phys. Rev. A 71 010702(R)
[11] Milne-Brownlie D S, Foster M, Gao J, Lohmann B, and Madison D H 2006 Phys. Rev. Lett. 96 233201
[12] Staicu Casagrande E M et al 2008 J. Phys. B: At. Mol. Opt. Phys. 41 025204
[13] Fojón O A, Stia C R, and Rivarola R D 2006 AIP Conference Proceedings 811 42
[14] Chatterjee S et al 2009 J. Phys. B: Atom. Opt. Mol.Phys. 41 065201
[15] Opal C B et al 1972 At. Data 4 209
[16] Oda N 1975 Radiat. Res. 64 80
[17] Rudd M E and DuBois R D 1977 Phys. Rev. A 16 26
[18] Lahmann-Bennani et al 1983 J. Phys. B 16 2219
[19] Bellm S et al 2008 Phys. Rev. A 78 032710
[20] Casagrande E M Staicu et al 2008 Journal of Physics: Conference Series 141 012016 and references therein