A Young-type experiment using a single-electron source and an independent atomic-size two-center interferometer: the realization of a thought experiment

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Abstract. Interferences caused by a single electron impacting on an independent double-center scatterer, which plays the role of an atomic-size double-slit system, are experimentally evidenced for the first time. The electron originates from the autoionization of doubly excited $2\ell n\ell'$ ($n \geq 2$) configurations of He following a double charge exchange process by He^{2+} ions impinging on H_2 molecules. Well-defined oscillations are visible in the angular distribution of the electrons emitted towards the receding H^+ protons. The presence of these oscillations demonstrates that a single electron interferes with itself. This is analogous to the famous "thought" experiment imagined and discussed by Feynman in 1963, in which the quantum nature of the electron was illustrated by making it traverse an atomic-size double-slit arrangement.

1. Introduction

In 1924, Louis de Broglie speculated that nature does not single out light as being the only particle which exhibits wave characteristics [1]. Since this hypothesis was stated, many experiments have been developed to demonstrate the wave nature of massive particles, by observing diffraction or interference patterns. The most famous example is given by the Davisson-Germer experiment [2], in which electrons, extracted from a heated filament, were accelerated and scattered on a nickel surface. Periodic structures in the intensity of the scattered electrons were observed when varying the acceleration voltage, showing the wave nature of the electrons. This behavior could also be observed for more massive particles, such as protons or neutrons [3], atoms [4], molecules [5], and clusters [6].

In particular, great efforts were devoted to trying to reproduce the well-known Young double-slit demonstration, but using electrons instead of light. For instance, already in 1961, C. Jönsson had performed for the first time an actual double-slit experiment with electrons [7]. The electron beam was

Journal of Physics: Conference Series **88** (2007) 012020 doi:10.1088/1742-6596/88/1/012020

produced by a 50-kV electron source of common variety. Jönsson succeeded in showing an electron interference pattern by using up to five very narrow slits in a copper foil, and large distances between the slits and the observation screen. However, the source intensity was not low enough to assure that there was only one electron in the apparatus at any single time. Two decades later, Merli *et al*. [8] and then Tonomura *et al*. [9] made the attempt to achieve this single-electron condition by using a source with extremely low electron-beam intensities. By using an electrostatic biprism instead of a two-slit scatterer, their experiment was not akin to the famous Young demonstration of 1807, but to the less-known slip-of-card set-up of 1805 [10].

In his famous lectures of 1963 [11], Feynman illustrated the quantum nature of the matter by means of a thought experiment where an electron traverses an atomic-size double-slit arrangement. However, he stressed that "we should say right away that you should not try to set up this experiment. This experiment has never been done in just this way. The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in". It is clear that none of the previously described experiments are of atomic dimensions. In 2005 Rolles et al [12] measured the spectra of the electrons emitted in the photoionization of N_2 molecules. A similar result had already been obtained four years earlier by Stolterfoht et al. [13], but where the ionization of the molecule was achieved by the impact of ions rather than photons. Both experiments were proposed as electronic atomic-size versions of Young's double-slit experiment. However, as stated in Ref. [15], in the latter experiments the electron is not coming from a distant source, but originates from the two-center scatterer itself. Therefore, it would be more accurate to relate these experiments to Young's original idea of 1801 regarding the interference of ''two undulations from different origins'', than to the two-slit demonstration of 1807 [10].

As the ones above, all the experiments proposed until now to demonstrate Feynman's electron version of the famous Young demonstration of 1807 share different parts of the puzzle. However –to our best knowledge-, none of them has fully grasped the complete scheme. We are referring to (a) an atomic-size experiment with (b) an independent source and (c) a two-center scatterer that exactly fulfills (d) the single-electron condition.

Very recently, we successfully realized such atomic-size Young-type experiment for the first time [14]. This experiment had been proposed and theoretically studied by Barrachina and Zitnik in 2004 [15]. An incident He^{2+} ion captures both electrons from a H_2 molecular target. After the collision, the He projectile is in a doubly excited $2\ell n\ell'$ ($n \geq 2$) state, while the residual H_2^{2+} target dissociates, giving rise to two protons. The collision may be written as follows:

$$He^{2+} + H_2(1\sigma_2) \rightarrow He^{**}(2\ell n\ell') + H^+ + H^+$$

Then, the excited projectile deexcites mainly by means of an Auger effect, emitting an electron of well-defined energy in any direction

$$He^{**}(2\ell n\ell') \rightarrow He^+(1s) + e_A^-$$

When emission takes place at backward angles with respect to the incident beam direction, the emitted electron scatters on the two H^+ centers which play the role of an atomic-size double-slit apparatus. Here, the autoionizing projectile emits only *one* electron, while the H^+-H^+ interferometer is systematically destroyed after this *single* electron has passed through. This collision process consists in an elementary *single-electron* Young-like interference experiment. As shown in detail in Ref. [14], the He-beam intensity and the H_2-target density were sufficiently low to ensure that the elementary single-electron experiments were well separated from each other both in time and space.

2. Theoretical description :

The He outgoing atom of velocity v_P decays by emitting an electron with energy E in the presence of the two protons. In a first order perturbation treatment [16] the autoionization amplitude is distorted by a factor (in atomic units)

$$F \approx -i\Gamma/2\int_0^\infty D(\boldsymbol{v_P},t)e^{i(E-E_o+i\Gamma/2)t}\, t^{2i/v_P}\, dt \tag{1}$$

where E_o and $1/\Gamma$ are the resonant energy and characteristic lifetime of the autoionizing state, respectively. $D(\boldsymbol{r}) = D(\boldsymbol{v_P},t)$ incorporates into the electron continuum state the distortion due to the interaction with the two protons. We write $D \approx D_+ \times D_-$, where $D_\pm$ are the distortions by each proton at a distance $\pm d/2$ from the center of mass. We approximate it by the standard asymptotic limit of a Coulomb continuum scattering state, $D_\pm \approx \chi_\pm^{-i\nu_\pm}\left\{1 + i\, g(\nu_\pm,\chi_\pm)\, e^{i\chi_\pm}\right\}$, where $g(\nu,\chi) = -i\nu\chi^{2i\nu-1}\ \Gamma(1-i\nu)/\Gamma(1+i\nu)$ is the Coulomb Scattering amplitude. Here we have defined $\chi_\pm = v_\pm r_\pm - \boldsymbol{v}_\pm \cdot \boldsymbol{r}_\pm$ and $\nu_\pm = 1/v_\pm$, where $\boldsymbol{r}_\pm = \boldsymbol{r} \mp \boldsymbol{d}/\boldsymbol{2}$ and $\boldsymbol{v}_\pm = d\boldsymbol{r}_\pm/dt$ are the relative electron-proton position and velocity, respectively. This distortion factor is dominated by two terms, one showing an eikonal-type distortion and another one proportional to the electron proton scattering amplitude. In this sense, Kunikeev and Senashenko [17] interpret them as representative of those parts of the wave function that has and has not been scattered by the ion.

As it is explained in Ref. [15], we assume that each proton moves so slowly that the approximation $\boldsymbol{v}_\pm \approx \boldsymbol{v}$. Furthermore, we assume that $\chi_\pm$ is so large that we can approximate $\chi_\pm \approx \chi = v\,r - \boldsymbol{v}\cdot\boldsymbol{r}$, except in the phase that would give rise to the foreseeable interference, where we take $\chi_\pm \approx \chi \pm (\boldsymbol{v} - v\,\boldsymbol{r}/r)\cdot\boldsymbol{d}/2$.

Thus, we obtain $D_\pm \approx \chi^{-i\nu_\pm}\left\{1 + i\, g(\nu,\chi)\, e^{i\chi} e^{i(\boldsymbol{v}-v\,\boldsymbol{r}/r)\cdot\boldsymbol{d}/2}\right\}$, with $\nu = 1/v$. Our basic assumption here is that, while the non-scattered term only sees the cluster as a whole, the other senses its structure, giving rise to a phase shift that takes into account the different optical paths from each proton. Finally, replacing $D \approx D_+ \times D_-$ in Eq. 1 we obtain $F = A + B\cos(\boldsymbol{s}\cdot\boldsymbol{d}/2)$, where $\boldsymbol{s} = \boldsymbol{v} - v\,\boldsymbol{v_P}/v_P$ is the momentum transfer. Since in the present experiment, the molecule is not oriented in any particular direction, we have to average the square modulus of this distortion factor over the orientation of ***d***, in order to obtain

$$\begin{aligned}\left\langle |F|^2 \right\rangle &= \frac{1}{2}\int_{-1}^{+1} \left|A + B\cos(s\gamma\, d/2)\right|^2 d\gamma \\ &= |A+B|^2 + (AB^* + A^*B)\left(\frac{\sin sd/2}{sd/2} - 1\right) + \frac{|B|^2}{2}\left(\frac{\sin sd}{sd} - 1\right)\end{aligned} \tag{2}$$

The terms $\sin\delta/\delta$ were first derived by Debye and Ehrenfest in 1915 [18,19], but applied to the diffraction of X-rays by molecules. These terms would produce an oscillatory pattern in the electron angular distribution that is directly and solely associated with the spatial structure of the two-proton scatterer.

3. Experimental set-up

The present experiment was conducted at the 14-GHz electron cyclotron resonance (ECR) ion source of the LIMBE facility, at the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen. The He^{2+} ions, extracted at an energy of 30 keV, were magnetically analyzed and focused to a diameter of ~2 mm. Typical ion currents of 100 nA were collected in a Faraday cup and these were used to normalize the spectra. In the center of the scattering chamber, the He^{2+} beam was colliding with a gas-beam target of H_2 that was created by an effusive gas jet. The average H_2 target pressure was determined to be ~10^{-4} mbar, corresponding to a residual pressure of ~2 10^{-6} mbar in the chamber. These pressures were sufficiently low to ensure the regime of single collisions.

The electrons produced after the collision were detected at angles ranging from 20^o to 160^o with respect to the incident beam direction, using a single-stage spectrometer which consists of an electrostatic parallel-plate analyzer. The intrinsic energy resolution of the exit analyzer was 5% full width at half maximum. The acceptance angle was ~2^o. The length ℓ_o of the ion beam, as seen by the spectrometer at 90^o, was ~4 mm. This length, increasing according to $\ell_f = \ell_o / \sin \theta$ as the observation angle θ decreases, was taken into account in the determination of the differential cross sections.

4. Spectra analysis and discussion

Figure 1 shows two typical electron spectra obtained at observation angles of 120^o (left side) and 160^o (right side). Two distinct contributions are seen : *(i)* a monotonically decreasing part originating from direct ionization of the molecular target and *(ii)* several peaks attributed to the deexcitation of the projectile by autoionization, after the capture of both electrons from H_2 into $2\ell n\ell'$ (n ≥ 2) configurations. The structures labeled (a), (b) and (c) correspond to the Auger decay of $2s^2\ {}^1S$, $2\ell 2\ell'$ ($2p^2\ {}^1D$ and $2s2p\ {}^1P$) and $2\ell n\ell'$ (n ≥ 3) states, respectively.

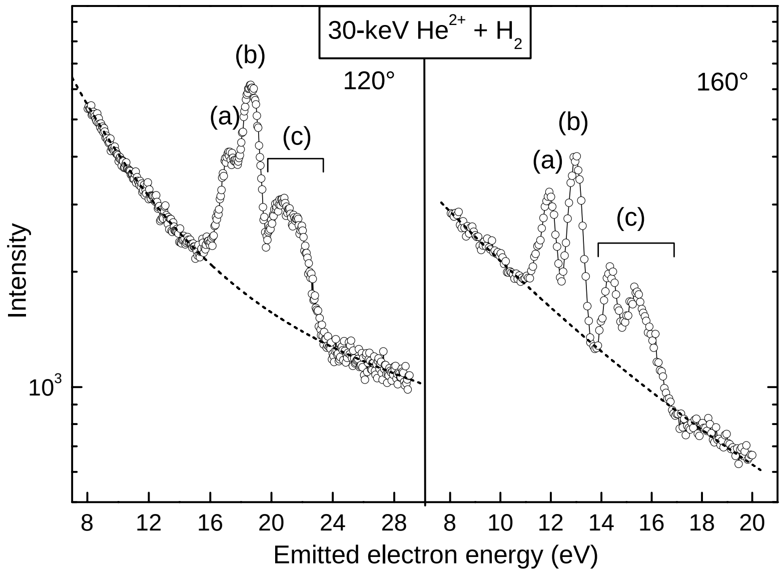

Figure 1. Energy distribution for electron emission in 30 keV He^{2+} + H_2 collisions, at detection angles of 120° and 160°, with respect to the incident beam direction. The continuously decreasing contribution, which is fitted using a polynomial function in the lin-log scale, originates from the direct ionization of H_2. The superimposed structures (a), (b) and (c) are related to autoionization of He following the production of doubly excited states. Due to kinematics effects, the width of the individual structures is larger at 120° than that at 160°.

To separate both contributions, a polynomial function was chosen to fit the direct ionization part in a lin-log scale as shown in Figure 1. Since the Auger electrons originate from moving emitters, they are influenced by kinematic effects which were accounted for by transforming the spectra from the laboratory frame to the projectile rest frame. Furthermore, the spectra are affected by line broadening effects due to the finite acceptance angle (~2^o) of the spectrometer. Hence, the width of individual structures increases when decreasing the detection angle from 160^o down to 90^o.

The angular dependence of autoionization, obtained by integration of the spectra over the emitted electron energy, is presented in Figure 2 as a function of the observation angle θ_d in the range 20^o – 160^o. The intensity is found to be minimum at ~ 90^o, and maximum when the electron is ejected along the beam direction. A careful inspection of the data shows differences between forward and backward distributions. At forward angles, the intensity decreases monotonically when θ_d increases. In contrast, at backward angles, at least three oscillations are superimposed on the main dependency.

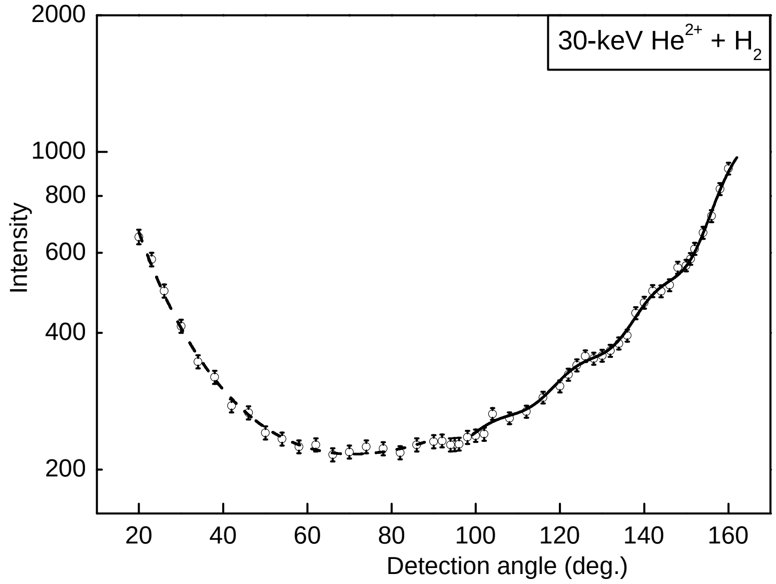

Figure 2. Total intensity for autoionization following double electron capture in 30 keV He^{2+} + H_2 collisions, as a function of the detection angle (solid circles). The autoionization intensity is given in the frame of the autoionizing He** doubly excited atom. At backward angles, superimposed to a main increase of the intensity, at least three oscillations are visible.

To increase the visibility of the oscillations, the autoionization cross section was obtained by multiplying the total intensity by $\sin\theta$ in order to take into account the collision length ℓ_f, as mentioned in section 3. The result for the cross section is presented in Figure 3, as a function of the observation angle. Well defined oscillations are visible at backward angles, providing clear evidence for the electron-interference pattern. The period of the oscillations is ~17°, in agreement with the predictions of the model developed recently [14,15].

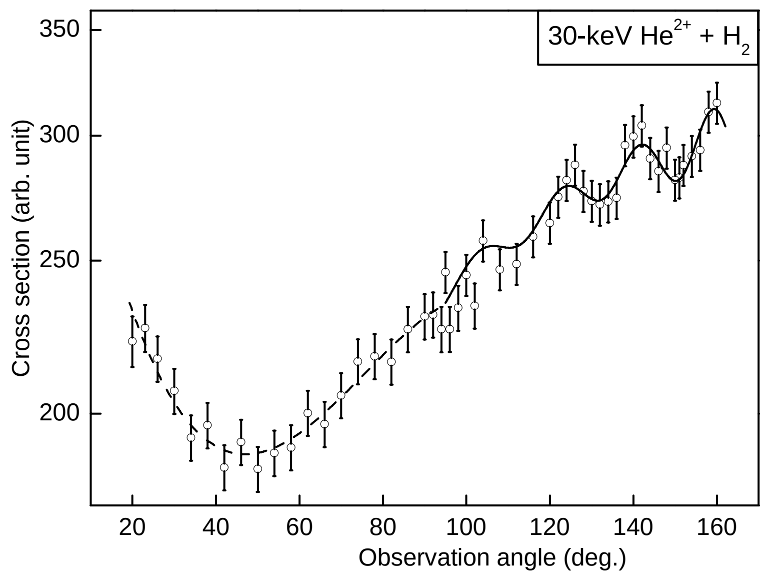

Figure 3. Differential cross section for autoionization, as a function of the observation angle, derived from the intensity by taking into account the length of the collision as viewed by the spectrometer. The oscillations due to interferences are clearly visible, within the uncertainties, at backward angles.

5. Conclusion and future experiments

This work is the first complete realization of Feynman's thought experiment, in which a single electron emitted from a source well separated from an atomic size two-slit system, interferes with itself. In addition to the fact that the two-slit system has to be of an extremely small size, the most challenging condition for realizing Feynman's experiment was to prevent any chance of finding two or more electrons in the two-slit apparatus at the same time (single-electron condition). Here, since each H^+-H^+ two-center interferometer is destroyed after one electron at maximum has passed through, we attained the ideal situation in which the single-electron condition is fulfilled in an unquestionable manner [14]. Thus, the electron-interference pattern shown in Fig. 3 is an unprecedented experimental demonstration that a single electron interferes with itself while passing through a Young-like apparatus.

As mentioned in section 4, the interference pattern is described by the Debye-Ehrenfest term $\sin\delta/\delta$, with $\delta = 2v_e d\cos(\theta_d/2)$, where v_e is the electron velocity in the laboratory frame, and θ_d is the observation angle. Since v_e depends on θ_d and on the projectile velocity v_p, it is expected that the period T of the oscillations strongly depends on v_p. However, this expectation is in disagreement with our more recent experiments: At a projectile energy of 8 keV, the period T is found to be practically the same as that found at 30 keV, within the uncertainties. Thus, in future work, we propose to go further in the analysis of the interference pattern by decreasing the velocity of the projectile down to ~0.03 a.u., which corresponds to a projectile energy of ~100 eV. This experiment will be a crucial test for the theory.

Moreover, as the projectile energy decreases, two additional effects may be taken into account. First, at the limit where $v_p = 0$, the electron is emitted in the field of a pseudo-molecule which consists of three interacting particles (H^+-H^+-He^+). Thus, the interference pattern can be affected by the presence of the projectile. Second, as shown previously for the collision systems $N^{7+} + H_2$ and $O^{5+} + H_2$ [20], at low projectile energies (< 100 eV), the double capture may occur in "the way in" of the collision. In the case of the collision $He^{2+} + H_2$, the consequence would be the appearance of an interference pattern at forward angles. For these different reasons, the projectile velocity dependence of the interference effect will be investigated in details for the collision system $He^{2+} + H_2$.

Acknowledgements
This work was partially supported by the Agencia Nacional de Promoción Científica y Tecnológica (Grants 03-12567 and 03-20548) and the Consejo Nacional de 2 Investigaciones Cientificas y Técnicas (Grant PIP 5595), Argentina. ROB is also amember of the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

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