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Research Article

Periodic Variations in the Wavelength Distributions following Photon Interferences: Analogy with Electron Interferences

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A new interference phenomenon is reported, which has so far not been observed with either matter or light. In a nanometer-sized version of Feynman's famous two-slit "thought" experiment with single electrons, the width of a quasi-monochromatic line has been found to oscillate with the detection angle. Since this experiment resembles the original double-slit experiment by Young with light (1807), photon interferences were investigated in order to determine the wavelength distribution as a function of the position in the interference field. In addition to the well-known oscillating dependence of the intensity with a succession of dark and bright fringes, a periodic dependence with respect to the detection position has also been observed for the width of the wavelength distribution, revealing a larger analogy between electron and photon interferences.

1. Introduction

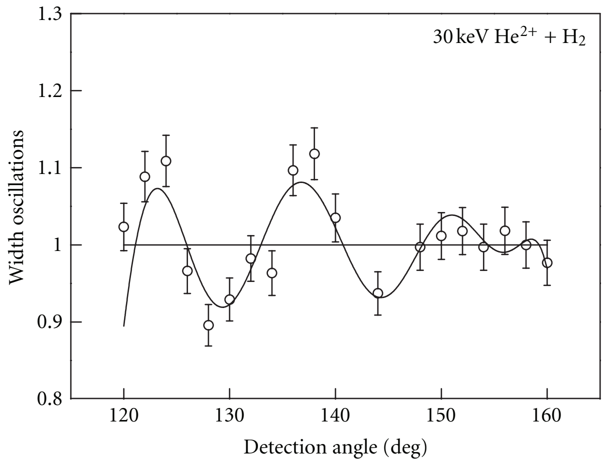
In 1923, de Broglie advanced the idea of the wave-like nature of a moving matter particle [1]. Since this hypothesis, the wave nature of the electron has been demonstrated in numerous experiments, by observing diffraction or interference patterns resulting in electron scattering on matter, for example, [2–10]. During the last years, electron interference effects have been widely investigated in electron- and ion-induced ionization [7–18], as well as in photoionization [19–27] of isolated atoms and molecules. In the electron interference experiments [5–15, 19–23], each single electron hits the position-sensitive detector like a particle but traverses the interferometer slits (or scatters on atomic centers) like a wave. Thus, over many repetitions, an interference pattern builds up as oscillations of the intensity $I(\theta_d) = \int (dI/d\lambda)d\lambda$ with the observation angle θ_d [5–10]. In experiments for which the actual wavelength distribution $dI/d\lambda$ can be characterized by a well-defined width at half maximum $\Delta\lambda$, the question arises whether it would be possible to observe similar oscillations in quantities other than $I(\theta_d)$, as for instance the linewidth $\Delta\lambda$ itself.

Recently, we studied the process:

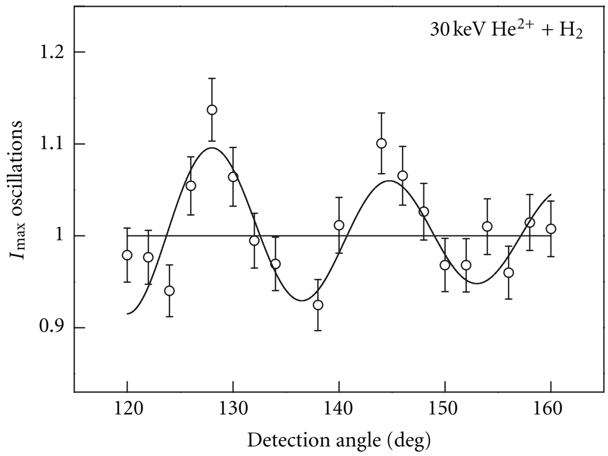
$$\mathrm{He}^{2+} + \mathrm{H}_2\left(1\sigma_g\right) \longrightarrow \mathrm{He}^{**}(2\ell n\ell', n \geq 2) + \mathrm{H}^+ + \mathrm{H}^+ \quad (1)$$

where the outgoing autoionizing helium atom plays the role of the source of a single electron emitted with a wavelength λ of the order of a few Angstroms, while the two residual protons provide the double-center interferometer [7–10]. First, investigation of the total intensity of undiscerned $2\ell n\ell'$ ($n \geq 2$) autoionization configurations revealed oscillations in the angular distribution of the scattered electrons, showing that each electron interferes with itself [7].

More recently, instead of following the standard procedure of seeking for oscillations on the line intensity, we concentrated on studying the linewidth [10]. This approach seems to have never been tried before either with electrons or photons. We focused on the single $2s^2\ {}^1S$ line and determined its maximum $I_{\max}$ and linewidth $\Delta\lambda$ as a function of the detection angle. Figure 1 shows the oscillating terms of $I_{\max}$ and $\Delta\lambda$ obtained in both cases by dividing the experimental data by a monotonic background. The maximum $I_{\max}$ of $dI/d\lambda$ oscillates in phase with the intensity $I(\theta_d)$ [10]. On



(a)



(b)

Figure 1: Oscillating term in the experimental width and maximum intensity of the $2s^2\,{}^1S$ line in 30-keV ${}^3He^{2+} + H_2$ collisions as a function of the detection angle. The full curves fit the experimental results, using the Bessel function of zero and first order.

the other hand, the $2s^2\,{}^1S$ linewidth was found to strongly oscillate in counter phase with the maximum (Figure 1), a fact that can be explained by means of simple theoretical arguments [10]. These results provided a new demonstration of the Young-type interference of single electrons.

The linewidth oscillations reported in our previous work [10] might be prone to be found in similar configurations with matter particles and photons. The question arises whether the analogy between photon and electron interferences can be extended to quantities such as the linewidth. Thus, in the present work, we revisited the photon interference experiment in order to determine the wavelength distribution as a function of the detection position in the interference pattern.

2. Experimental Setup

The optical setup is based on the classical Lloyd mirror experiment, first described by Lloyd in 1834. For alignment simplicity and robustness, the current system is an all-fiberized transposition to the original experiment. The light source is a superluminescent erbium-doped silica fiber (Figure 2).

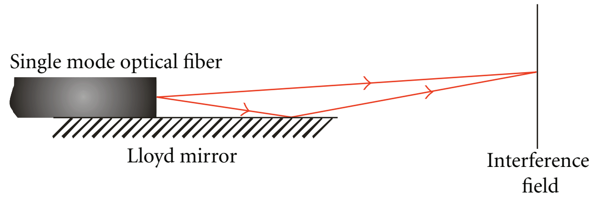


Figure 2: Schematic view of the experimental setup. Light originating from the optical fiber can reach the detector either directly or after reflection on the mirror.

The output power of the light source is typically of a few mW with a broadband optical emission spectrum between 1.53 and 1.56 μm. A peak centered at ~1532 nm with a width of ~0.93 nm is well separated from the rest of the emission spectrum. This emission peak is selected for the present optical experiment. The output facet of the optical fiber (9 μm fiber core diameter) acts as a high-brightness spatially coherent light source. A metal-coated plane mirror is precisely positioned at razing angle close to the optical fiber for creating a virtual light source. Moving the fiber allows adjusting the distance between the real and virtual light sources from 125 μm up to 500 μm. The reflected light interferes with the direct light. The resulting interference fringes are detected point by point using a multimode fiber mounted on a step-motorized translation stage.

The entrance facet of the multimode fiber is located 30 to 50 mm away from the light source position. For each transverse position (moving step down to 20 μm), the collected light is analyzed using an optical spectrum analyzer (OSA) for simultaneous recording of the spectral and intensity distributions versus the detection position in the interference field.

3. Results and Discussion

The upper part of Figure 3 shows a typical experimental interference pattern, consisting in well-defined oscillations in the photon intensity distribution versus the position along a transverse direction with respect to the mirror.

The width of the fringes was found to be about 0.2 mm. The middle part of the figure exhibits the spectral width of the interfering light as a function of the detection position. The average value of the width is ~0.93 nm. Whereas quasi-sinusoidal oscillations were observed for electrons, a nonsinusoidal but periodic dependency is visible for the width in case of photons. A significant change in $\Delta\lambda$—typically larger than 0.01 nm—occurs at the position of dark fringes, while a smooth variation is observed for $\Delta\lambda$ when varying the detection position from a dark fringe to the next one. The same period is obtained for the intensity and the width. Lastly, the position λ_{max} of the maximum of $dI/d\lambda$ is presented in the bottom part of Figure 3. The dependency of λ_{max} versus the detection position is found to be similar to

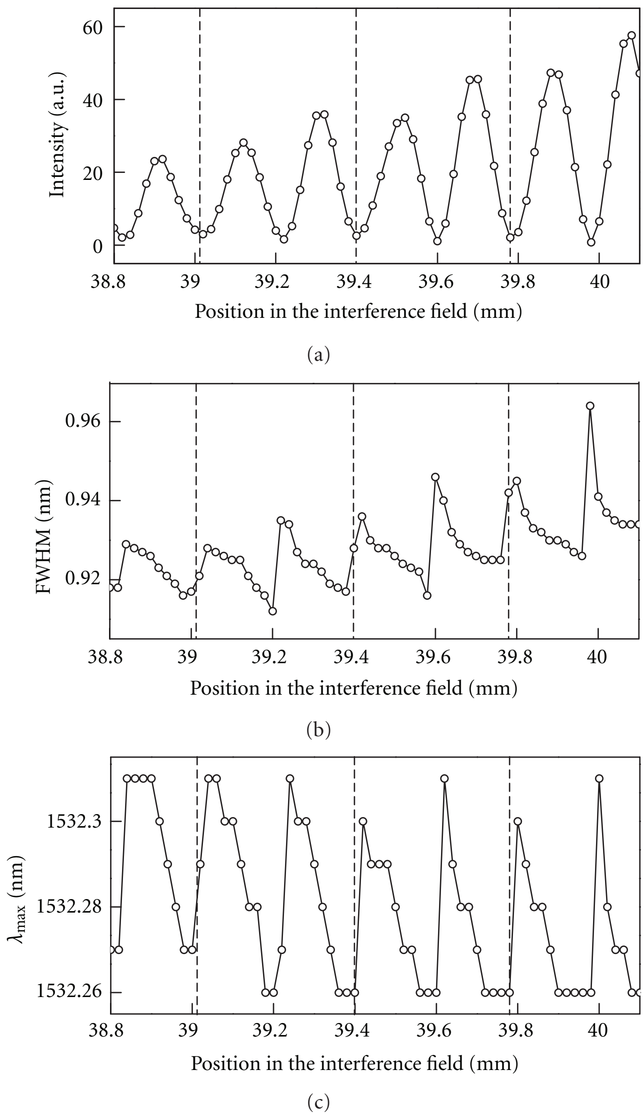


Figure 3: Experimental results: total light intensity $I(\theta_d)$ (top), full width at half maximum $\Delta\lambda$ (middle), and position λ_{max} (bottom) of the spectral distribution $dI/d\lambda$ as a function of the position along a direction perpendicular to the Lloyd mirror. The error bars (not shown) are of about 0.01 nm for λ_{max}, while they are smaller than 0.01 nm for $\Delta\lambda$.

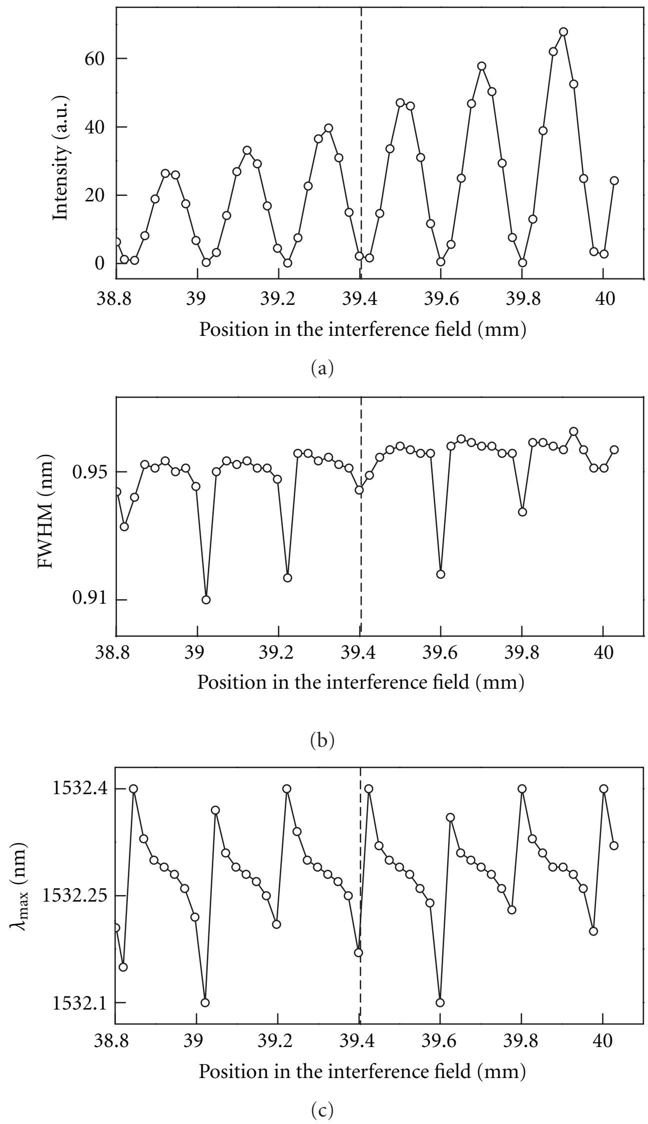


Figure 4: Calculation results: total light intensity $I(\theta_d)$ (top), full width at half maximum $\Delta\lambda$ (middle), and position λ_{max} (bottom) of the spectral distribution $dI/d\lambda$ as a function of the position along a direction perpendicular to the Lloyd mirror.

that of $\Delta\lambda$. When determining λ_{max}, we considerably reduced the time of analysis by scanning the spectra in a restricted range of wavelengths. Nevertheless, although truncated, the obtained results (bottom of Figure 3) were accurate enough to reveal the periodic variation of λ_{max} with respect to the detection position in the interference field.

The present experiment shows that interference phenomena with photons manifest themselves not only as a sinusoidal variation of the light intensity versus the position in the interference pattern but also as a periodic position dependency of both λ_{max} and $\Delta\lambda$. A simple theoretical approach based on classical optics reproduces fairly well the main experimental features (Figure 4). Our present findings with photons provide a qualitative support to our previous interpretation of the oscillating behavior of the autoionization linewidth as a signature of a Young-type electron interference effect.

4. Conclusion

Photon experiments have been conducted using a Lloyd mirror and a 1.5 μm source. In addition to well-defined oscillations in the intensity distribution, the width and the maximum position of the wavelength distribution present a periodic nonsinusoidal dependency versus the detection position in the interference field.

The present results extend the qualitative analogy between photon and electron interference experiments. The observed differences between photon and electron interferences can be attributed to the different nature of the interaction involved in each case, since the interaction between the photon and the interferometer is well localized, whereas the Coulombic interaction between the electron and the protons has a long-range character.

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