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Gouy phase and visibility in the double-slit experiment

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ABSTRACT

We study a matter wave double-slit experiment with unequal aperture widths in order to evaluate the effect of the Gouy phase on the visibility/predictability. While the predictability changes as one increases the width of one of the slits, the visibility receives a contribution from the Gouy phase at a specific point in the detection screen. Consequently such apparatus constitutes a simple device for measuring the Gouy phase of matter waves. We illustrate it numerically for neutrons.

1. Introduction

Over a hundred years ago, L.G. Gouy described an anomalous behavior of the phase of a converging diffracted spherical light wave as it passed through a focus [1,2]. An electromagnetic beam subjected to confinement experiences an additional π phase shift with respect to a plane wave traveling the

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same distance. He also performed the experiment which confirmed his theoretical analysis. Several authors consider the Gouy phase as a not fully exploited quantity [3], and several simple explanations have been offered in terms of Berry geometrical phase [4], the uncertainty principle [5], and so on [6–9]. Although it is often presented as a property of Gaussian light beams [10], the Gouy phase shift appears in any kind of wave that is submitted to some sort of transverse spatial confinement, either by focusing or by diffraction through small apertures, for instance. As discussed in [5], when a wave is focused, the Gouy phase shift is associated to the propagation from $-\infty$ to $+\infty$ and is equal to $\pi/2$ for cylindrical waves (line focus), and π for spherical waves (point focus). The Gouy phase shift has been observed in water waves [11], acoustic [12], surface plasmon-polariton [13], and phonon-polariton [14] pulses. Recently the Gouy phase was theoretically treated in some works [15]. It was shown that the vector nature of the electric field must be taken into account in order to characterize the Gouy phase of a high-aperture optical system. The Gouy phase for idealized infinite-energy Airy beams was defined and analytical expressions for its behavior were derived. The Gouy phase for partially coherent fields were examined and it was demonstrated in terms of their correlation functions. It was shown that the radially polarized fields vary rapidly the state of polarization through the focus as a consequence of the Gouy phase. It was analyzed how the primary spherical aberration of a lens influences on the Gouy phase [15].

In optics, important consequences of the Gouy phase shift have been studied. Just to mention a few applications, the Gouy phase is important to determine the resonant frequencies in laser cavities [10] or the phase matching in high-order harmonic generation (HHG) [16] and to describe the spatial variation of the carrier envelope phase of ultrashort pulses in a laser focus [17]. Moreover, the Gouy phase plays an important role in the evolution of optical vortex beams [18] as well as electron beams which acquire an additional Gouy phase dependent on the absolute value of the orbital angular momentum [19]. Gravity wave detection antennas are based on precision measurements using laser interferometry in which the Gouy phase is crucial [20].

The Bohr's complementarity principle is a fundamental subject in quantum mechanics and it is still a matter of debate [21,22]. At first it was believed that under different experimental conditions a quantum object exhibited either wave or particle character alone [23]. Young's slit-type experiments are practical arrangements to experimentally observe the wave–particle duality in quantum mechanics having been realized for electrons [24], neutrons [25], atoms [26], small molecules and noble gas clusters [27]. By controlling the transmission of electrons through the individual slits of a double-slit arrangement it was possible to observe the diffraction patterns from each slit [28]. Recently it was performed, at the molecular level, the Einstein–Bohr recoiling double-slit gedanken experiment [29]. The study of light scattering from two localized atoms has enabled to experimentally exhibit the wave or particle properties of the photon by changing its state of polarization [30]. Greenberger and Yasin have given a quantitative formulation of Bohr's complementarity principle which includes in the same experiment simultaneous wave and particle properties expressed by the duality relation $\mathcal{P}^2 + \mathcal{V}^2 \leq 1$, where $\mathcal{P}$ stands for predictability and $\mathcal{V}$ for visibility. The equality holds in the case of pure quantum mechanical states and the inequality for mixed states [31]. Based on this quantitative formulation the simultaneous wave and particle behavior were studied in double-slit experiments, neutral-kaon system and in Mott scattering of identical nuclei [32]. Recently novel experiments with photons and massive particles were realized and exhibited simultaneously wave and particle behavior for a quantum object [33–38].

The existence of a particle wave analogy to the Gouy phase has been first pointed out in Ref. [39] followed by an experimental proposal using Ramsey interferometry with cylindrical focusing of Rydberg atoms [40]. Recently, this proposal has stimulated the search for the matter wave Gouy phase in different systems: Bose–Einstein condensates [41,42], electron vortex beams [43] and astigmatic electron matter waves using in-line holography [44,45]. Moreover, it was claimed that in order to improve the accuracy in imaging the dynamics of free-electron Landau states, the diffractive Gouy phase rotation has to be reduced [46]. In this letter we return to the double-slit experiment and propose a novel investigation related to the role of the Gouy phase of matter waves in the interference phenomena and in the complementarity principle via the duality relation. The model developed here can be useful to experimentally observe the Gouy phase in a simpler way in comparison with the systems cited above.