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Interference and "Which Way" Information

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The well-known incompatibility of observing an interference pattern and at the same time gaining information on the photon's or particle's path is discussed in connection with atomic interference experiments. In particular, a feasible setup is proposed in which an almost negligible disturbance of the atom, via spontaneous emission, nevertheless completely destroys the interference pattern.

1. INTRODUCTION

Albert Einstein was the first to raise the question as to whether it might be possible to observe an interference pattern and in addition get information on the path of the particle that "interferes with itself." This issue was part of the famous Bohr–Einstein debate that took place at the fifth Solvay Conference in 1927 (Bohr, 1949). Einstein's basic idea was to measure, in a Young-type two-slit interference experiment with single electrons, the recoil that the screen with the entrance slit, assumed to be moveable, experiences as a result of the passage of the electron, and to infer from the measuring result which path the electron has actually taken. Clearly, this was in contradiction to quantum mechanics, which claims that interference is due to an intrinsic uncertainty of the particle's path. Soon Bohr refuted Einstein's argument, pointing out that, in fact, Heisenberg's uncertainty relation for position and momentum renders Einstein's *Gedanken*-experiment impracticable. The point is the following: In order to observe an interference pattern (by often repeating the single-electron experiment), the position of the entrance slit must be well defined; otherwise the interference pattern will be wiped out. On the other hand, what is needed in determining the electron's path is a rather precise measurement of the momentum *change* the screen with the entrance slit

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undergoes. This can be done only when the *initial* momentum is well defined. However, according to Heisenberg's uncertainty relation (assumed to be valid also for macroscopic bodies!) the screen's position and momentum, in the initial state, cannot both be sharp, and a simple quantitative estimate shows that the above two requirements actually contradict Heisenberg's uncertainty relation. Hence an observation of both an interference pattern and the electron's path is in conflict with the basic principles of quantum theory. It is interesting to note that it is not a disturbing effect of the momentum measurement that destroys interference—actually, this measurement can be done after the electron has already been detected on the interference screen—but the impossibility to prepare the initial state of the screen in the desired way, i.e., in contradiction to Heisenberg's uncertainty relation.

From this discussion one might guess that quite generally the incompatibility of interference and "which way" information can be traced back to Heisenberg's uncertainty relation. In the following, we will show that this is, in fact, not so.

2. INTERFERENCE OF EXCITED ATOMS

We study an atom-optical interference experiment which, for simplicity, is assumed to be also of Young's type. The new feature is that the atom is assumed to be initially excited. This provides us with an opportunity to infer the atom's path from observation of the spontaneously emitted photon. A pioneering experiment of this kind has already been carried out only recently by Pfau *et al.* (1994), and a general theoretical description of the atomic decoherence resulting from spontaneous emission was given by Steuernagel and Paul (1995).

Let us analyze a simple Young-type experimental setup (Fig. 1). An atom with sharp velocity $\mathbf{v}$ is supposed to be normally incident on a screen with two holes. Due to the wave–particle duality, it can be supposed to be a plane wave whose wavelength, named, after Louis de Broglie, is given by

$$\Lambda = \frac{h}{m\mathbf{v}} \tag{1}$$

(m is the atomic mass). Hence the plane wave in question is characterized by the wave vector

$$\mathbf{K} = \frac{m\mathbf{v}}{\hbar} \tag{2}$$

We suppose that the atom is initially excited and emits spontaneously a photon before reaching the interference screen. Since a photon with wave

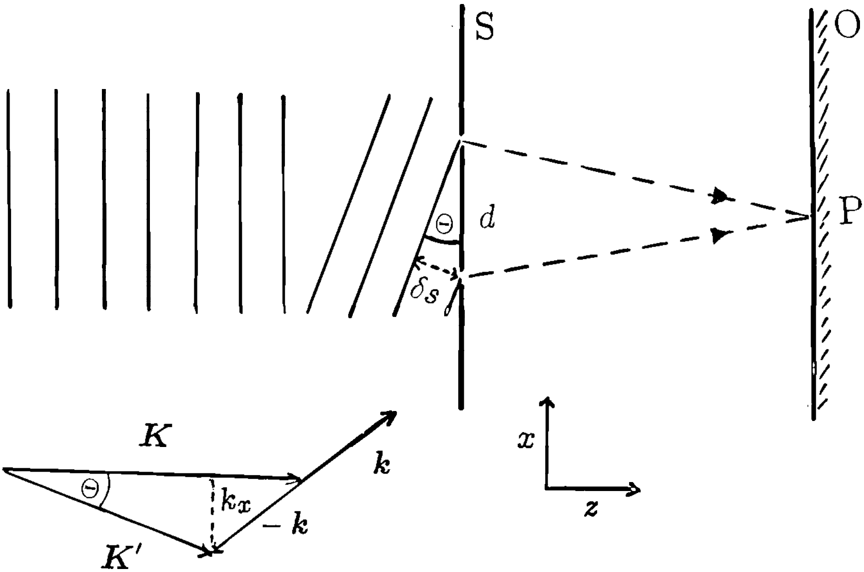

Fig. 1. Young-type interference experiment in atom optics. An atom with a plane wave center-of-mass wave function (wavefronts indicated by straight lines) is incident on a screen S with two small holes. O is the observation screen, P the observation point, $\mathbf{K}$ and $\mathbf{K}'$ are wave vectors of the plane wave before and after spontaneous emission of a photon with wave vector $\mathbf{k}$, respectively, and δs is the path difference.

vector $\mathbf{k}$ has a momentum $\hbar\mathbf{k}$, momentum conservation requires that the atom suffers a recoil that changes its wave vector by just $\mathbf{k}$. As a result, the plane wave will fall obliquely on the screen. Assuming, for simplicity, that $\mathbf{k}$ lies in the x,z plane (the drawing plane in Fig. 1) and noticing that $|\mathbf{K}| = K_z >> |\mathbf{k}|$, we learn from Fig. 1 that the angle of incidence undergoes a change Θ which, to a very good approximation, is determined by the relation

$$\tan \Theta = \frac{k_x}{K_z} \approx \Theta \tag{3}$$

Due to the oblique incidence, there is now a phase difference at the two holes

$$\delta\varphi = \frac{2\pi\delta s}{\Lambda} = \frac{2\pi d \sin \Theta}{\Lambda} \tag{4}$$

where d is the separation of the holes. Making use of equations (1)–(4), we thus obtain

$$\delta\varphi \approx \frac{2\pi k_x d}{K_z \Lambda} = k_x d \tag{5}$$

From this result it follows that for a fixed value of k_x the interference pattern will be shifted, provided, of course, that the corresponding phase shift $\delta\varphi$ is noticeable. In order to observe such a pattern, a conditional measurement has to be performed: The locations of the atoms in the observation plane have to be registered on condition that a detector being placed far away and thus selecting a definite propagation direction responds.

On the other hand, when no observation is made on the emitted light, the atomic interference pattern, being now a superposition of differently shifted single patterns, will become more or less wiped out, depending on the uncertainty of the photonic wave vector in the x direction, Δk_x. Since photons are emitted into all directions, Δk_x roughly equals the wave number k. We learn from (5) that the interference pattern will become less and less visible when Δk_x grows from values $\Delta k_x << 2\pi/d$, and it will practically vanish when the critical value Δk_x^{crit} satisfying

$$d\Delta k_x^{\text{crit}} \approx 2\pi \tag{6}$$

is reached or exceeded. Clearly, (6) can be interpreted as Heisenberg's uncertainty relation when the distance between the two holes is identified with the position uncertainty. Hence we have shown that Heisenberg's uncertainty relation governs also the interference behavior of an atomic beam.

3. "WHICH WAY" INFORMATION WITHOUT NOTICEABLE DISTURBANCE

Now, the question arises whether this is always so. To give an answer, the Garching group (Scully *et al.*, 1991) analysed an ingenious modification of the atomic interference experiment. They placed, in a *Gedanken*-experiment, a separate microwave cavity before each slit (see Fig. 2). Assuming the experimental parameters to be chosen such that the atom leaves the cavity almost with certainty in its lower state, one knows that a photon must have been deposited in either the one or the other cavity. We thus get full "which way" information, and accordingly the interference must disappear. The point is that this happens, in principle, without any restriction on the photonic wavelength, in contrast to the free-space situation, i.e., in the absence of the cavities, as was shown above. Correspondingly, the center-of-mass motion will be disturbed only slightly as a result of spontaneous emission (Morawitz, 1969), so that the uncertainty principle does not apply.

Stimulated by the *Gedanken*-experiment (Scully *et al.*, 1991), we will consider a simpler, maybe even feasible, experimental setup. Specifically, we will replace the two microwave cavities by one perfectly reflecting mirror (see Fig. 3a). Let the experimental conditions be such that the emission process has finished before the atom reaches the interference screen. Similarly

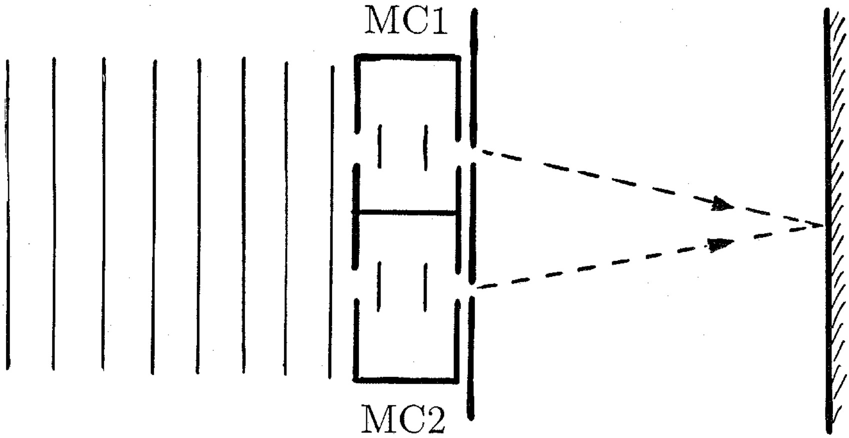

Fig. 2. Modification of the interference experiment depicted in Fig. 1. In any individual case spontaneous emission takes place in one of the microwave cavities *MC*1, *MC*2, thus indicating the atom's path.

to the previous case, we then get full 'which way' information from the spontaneously emitted photon. The perturbation of the center-of-mass motion due to the atomic recoil is certainly tiny when the photonic wavelength is large. However, one might object that a multiple transfer of transverse momentum takes place, resulting from virtual processes in which the photon is emitted, reflected from the mirror, and reabsorbed. Anyway, this picture offers itself when the photonic wavelength is large compared to the distance of the atom from the mirror, which is about $d/2$. In fact, the mean lifetime of the excited atom becomes then drastically enhanced (Morawitz, 1969), and intuitively this effect suggests an explanation in terms of the aforementioned virtual processes. It should be noted, however, that this slowing down of the emission process in the presence of the mirror actually takes place only when the atomic dipole moment is oriented parallel to the mirror. In case of orthogonal orientation, the mean lifetime is, on the contrary, diminished (Morawitz, 1969). So, at least in this case, our assumption will be justified that the atom experiences only a slight kick when a large-wavelength photon is emitted. We thus arrive, in full agreement with the argument of the Garching group (Scully *et al.*, 1991; Englert *et al.*, 1995), at the result that 'which way' information can, in fact, be gained, under suitably chosen experimental conditions, at the cost of a very small backreaction on the atom or, equivalently, interference can be destroyed without noticeably disturbing the atom.

This might be felt as a surprise. However, we will show that it is easily understood from the viewpoint of classical optics. Let us first have a look at the interference experiment sketched in Fig. 1. The rotation of the wavefronts resulting from the kick the atom experiences is obviously analogous to the

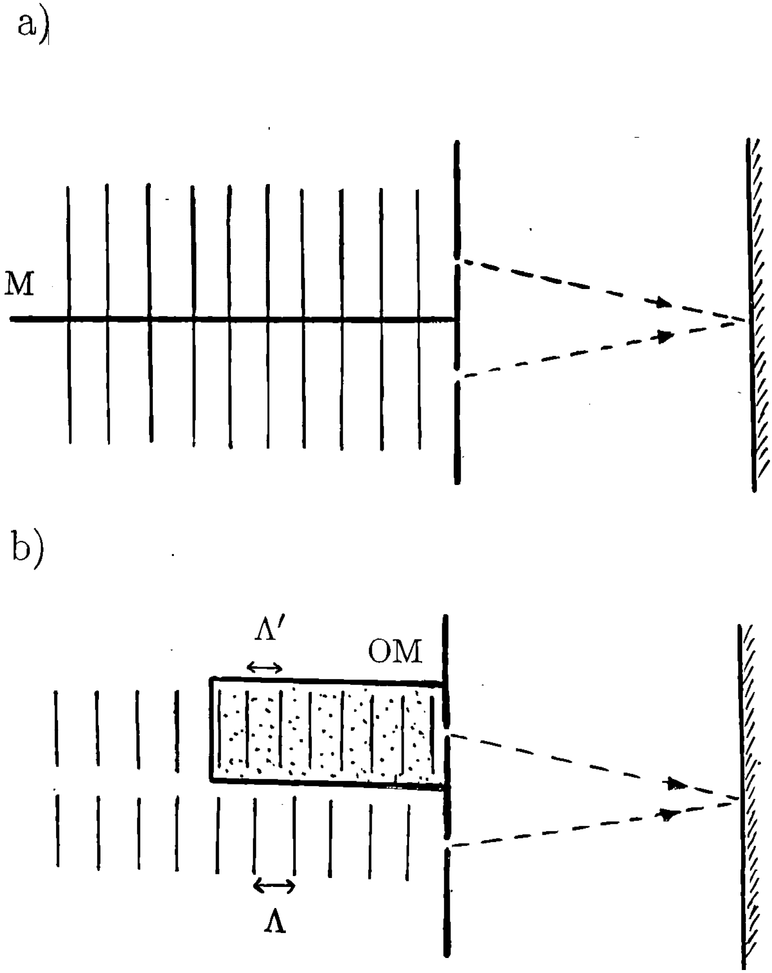

Fig. 3. (a) New version of the interference experiment shown in Fig. 2. The two microwave cavities are replaced by a perfectly reflecting mirror *M*. (b) Optical analog of the experiment. The effect of spontaneous emission is modeled by an optical medium *OM* with a refractive index $n \neq 1$ (Λ, Λ' are the wavelengths).

action of a prism. Of course, our analysis applies also to the optical case, and according to (5), in which k_x refers now to the optical beam leaving the prism, an appreciable deflection of the original beam is required to produce a phase shift comparable with 2π. It should be noticed that in the present case the total beam is affected. However, this is not so in the optical analog of the experimental setup depicted in Fig. 3a. Here, only one of the two partial beams that are made to interfere is disturbed in any individual case, and the main effect of the perturbation will be to change the *longitudinal* component of the wave vector and hence the wavelength (see Fig. 3b). In fact, this effect, which is brought about in optics by letting the beam pass through a medium with an appropriately chosen refractive index, is cumulative: If only the total path length is large enough, a tiny deviation of the index of refraction from unity will give rise to an appreciable phase shift (with respect to the unaffected partial beam). Specifically, in the atom-optical interference experiment according to Fig. 3a, the z component of the photonic wave vector, k_z, gives rise to a relative change of the de Broglie wavelength

$$\frac{\Delta\Lambda}{\Lambda} = -\frac{\Delta K_z}{K_z} = \frac{k_z}{K_z} = \frac{\Lambda}{\lambda}\cos\alpha, \tag{7}$$

where α is the angle between the photonic propagation direction and the atomic one (z). Hence, when the experimental conditions are such that the atom travels after spontaneous emission has taken place, a distance greater than the photonic wavelength λ until it reaches the interference screen, a phase shift of the order of 2π, or even greater, will occur. In view of the fact that (i) the angle α varies between 0 and π and (ii) the location of the atom is uncertain over the whole wavepacket (from observation of the emitted photon with the help of a microscope, with its axis oriented perpendicularly to the atomic propagation direction, it could be determined just with an accuracy given by λ) there is actually a large uncertainty in the phase shift that will make the interference pattern disappear. This reasoning gives us, in fact, an explanation of why tiny perturbations suffice to destroy phase relations, provided only one partial beam is affected in any individual case.

In summary, we have shown that Heisenberg's uncertainty relation, which was successfully invoked already by Bohr to refute Einstein's claim to be able to observe both interference and the particle's path, does not give us a universal clue to an understanding of the incompatibility of interference with "which way" information. Specifically, we have analyzed a feasible atom-optical interference experiment in which spontaneous emission provides an interference-destroying mechanism. Our main result is that, in fact, Heisenberg's uncertainty relation applies to the free-space situation, whereas in the presence of a mirror it does not come into play. Instead it turns out that almost negligible perturbations of the atomic center-of-mass motion suffice to make the interference pattern disappear.

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