ATOM INTERFEROMETRY WITH MECHANICAL STRUCTURES

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ABSTRACT

We present results on an interferometer for atoms based on Young's double-slit experiment. We also discuss proposed experiments in which the effect of spontaneous emission on the visibility of the atomic fringe pattern, as well as the effect of coherent atom-light interactions on the phase of the atomic wavefunction could be measured.

1. Introduction

Matter wave interferometry is a well established field in physics. Interferometers with de Broglie waves have been demonstrated for electrons[1] and neutrons,[2] and recently also for atoms.[3,4]

The main interest in interferometry with massive particles is due to the fact that, in contrast to light interferometry, gravitational effects can be studied and that the low particle velocity increases the interaction time in the interferometer, vastly increasing sensitivity. Therefore, neutron and electron interferometers have been extensively used for fundamental tests of quantum mechanics and general relativity.[5] Moreover, interferometers with atoms offer additional possibilities to study effects involving the atomic internal structure. Examples are the effect of electric fields on the atomic polarizability and the Casimir effect. Atoms can also be prepared in many different internal states, and effects due to resonant light-atom interactions and to spontaneous decay processes can be investigated.

The realization of an atom interferometer, however, has only been successful in the last year.[3] The construction of an atom interferometer is rendered difficult by the fact that atoms carry no charge and do not penetrate through condensed matter. Therefore, beam splitters different from those used in neutron or electron interferometry had to be developed and demonstrated.[6]

In Section 2 we present the experimental results obtained with our double slit interferometer. Section 3 discusses the effect of atom-light interactions on the interferometer behavior including the effects of spontaneous emission, and the potential uses of these interactions to improve the performance of the device.

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2. The Double-Slit Interferometer

Our atom interferometer, which is based on transmission structures, consists of an entrance slit, a double slit, and a detector slit. The double slit defines the two possible paths between entrance and detector slit. We have used metastable helium atoms as atomic species: helium is a light atom, which leads to a large de Broglie wavelength, and the production of a very bright atomic beam source by supersonic expansion is a standard technique. Moreover, metastable helium atoms can be detected very efficiently on almost zero background with a secondary electron multiplier.

The scheme of our experimental setup is shown in Fig. 1; details are presented elsewhere.[3] A supersonic gas expansion followed by a collinear electron beam excitation creates an intense and fairly monochromatic beam of metastable helium atoms in the two states 2^1S_0 and 2^3S_1. The variable temperature T of the gas reservoir and the nozzle system defines the mean velocity of the atoms in the beam and thus the de Broglie wavelength. The de Broglie wavelength for the results described in this paper was either $\lambda_{dB} = 56$ pm ($T = 300$K) or $\lambda_{dB} = 103$ pm ($T = 78$K).

After passing through the first slit following the beam source, the coherence length in the transverse direction is sufficiently large that the double slit is irradiated coherently. The double slit consists of two 1 μm wide slits separated by 8 μm. The atomic waves emerging from this double slit are superimposed coherently and create interference fringes in the atomic density distribution. This fringe pattern is monitored with either a single 2 μm wide slit or a grating whose periodicity of 8 μm is matched to the periodicity of the interference pattern. The complete detector system consists of a secondary electron multiplier (SEM) behind a gold foil with the two transmission structures described above. The system can be moved perpendicular to the atomic beam axis in steps of 1.9 μm. The pulses coming out of the SEM are preamplified and discriminated to eliminate unwanted detector noise. The microfabricated transmission structures imprinted in thin gold foils are approximately 2-4

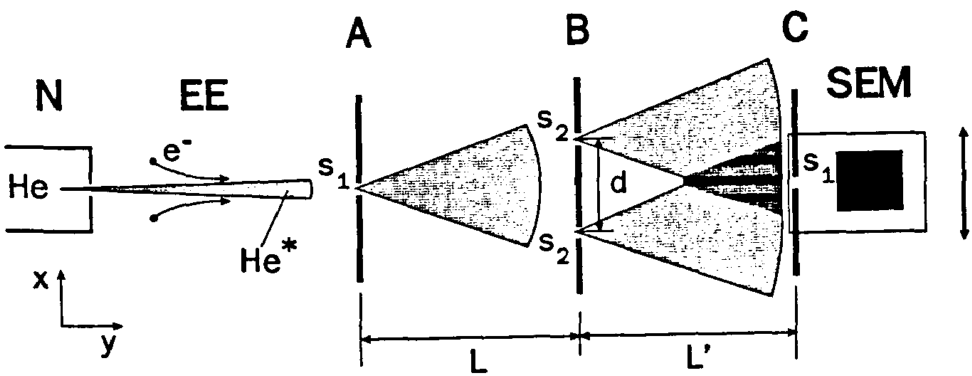

Figure 1: Schematic representation of the experimental setup: Nozzle system and gas reservoir, N; electron impact excitation, EE; entrance slit A, double slit B, and detector screen C; secondary electron multiplier, SEM. Dimensions $d = 8$ μm, $L = L' = 64$ cm; slit widths: $s_1 = 2$ μm, $s_2 = 1$ μm.

mm high and have been manufactured by Heidenhain Inc., Traunreut, Germany.

The interference pattern obtained at the de Broglie wavelengths $\lambda_{dB} = 56$ pm and $\lambda_{dB} = 103$ pm were first scanned with the single 2 μm detector slit. The measured fringe spacings of 4.5 ± 0.6 μm ($\lambda_{dB} = 56$ pm) and 8.4 ± 0.8 μm ($\lambda_{dB} = 103$ pm) are in good agreement with the predictions given by the Fraunhofer diffraction theory.[3] The extremely low signal at the detector (approximately 5-15 counts/minute) has the disadvantage of requiring long integration times, leading to a high sensitivity to slow thermal drifts in the beam machine.

This problem can be overcome by using a grating with a period matched to the fringe spacing instead of a single slit to monitor the intensity distribution. The simultaneous integration over many interference maxima or minima increased the count rate by a factor of 10 and therefore allowed us to decrease the integration time. The 8 μm grating periodicity is matched to the interference pattern at $\lambda_{dB} =$ 103 pm. Scanning the interference fringes with the grating is of interest in experiments where only the phase change between the two paths and not the exact shape of the interference pattern is of importance. A scan over the atomic interference structure is shown in Fig. 2. The visibility is 30%, whereas 50% can be expected under ideal conditions. The mean relative error at each detector position is less than 10% when integrating 5 minutes per point, and is due to the stochastic nature of the atom arrivals at the detector. This error corresponds to an accuracy of our device on phase changes of 0.3 radian in less than 10 minutes.

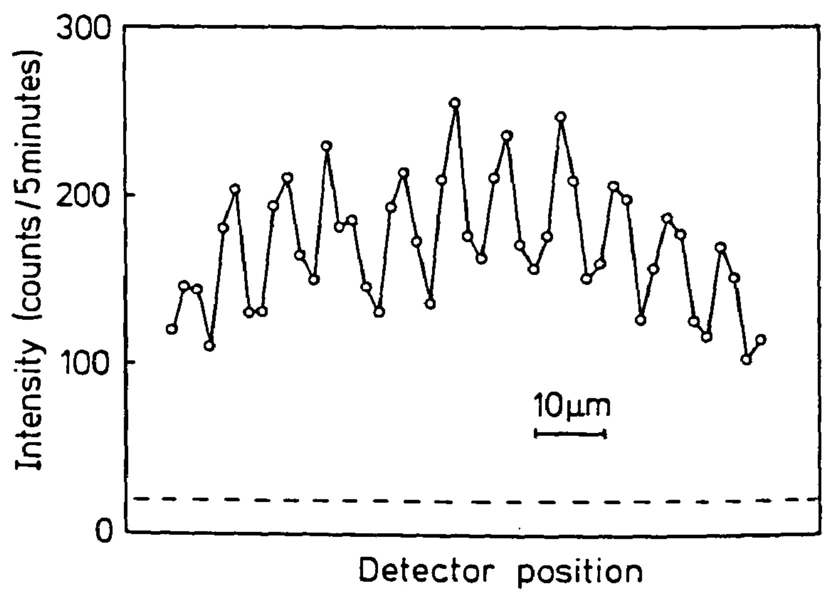

Figure 2: Atomic density profile monitored with the 8 μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line connecting the experimental points is a guide to the eye.

3. Atom Interferometry and Atom-Light Interactions

A significant difference between atom interferometers and other matter interferometers is that atoms can interact with the radiation field at optical frequencies. This gives rise to the possibility of studying new aspects of atom-light interactions. The first part of this section discusses the effect of spontaneous emission on the behavior of an atom interferometer, while proposed experiments involving coherent atom-light interactions are treated in the second and third parts.

3.1. Spontaneous emission in an atom interferometer

We present a problem relating to the effect of spontaneous emission on atomic coherence. Imagine that by some means, perhaps by the coherent excitation by a laser beam, the atoms in both paths of a two slit interferometer are put into the excited state and shortly afterwards spontaneously decay to the ground state by emitting a photon, as shown in the inset of Fig. 3. We assume that both excitation and spontaneous emission occur in the vicinity of the slits, which are spaced a distance d apart. In addition, we assume that the width of the slits is much smaller than an optical wavelength λ_{opt}. The question is, will interference fringes be observed.

To answer this question, we consider the effect of spontaneous emission on

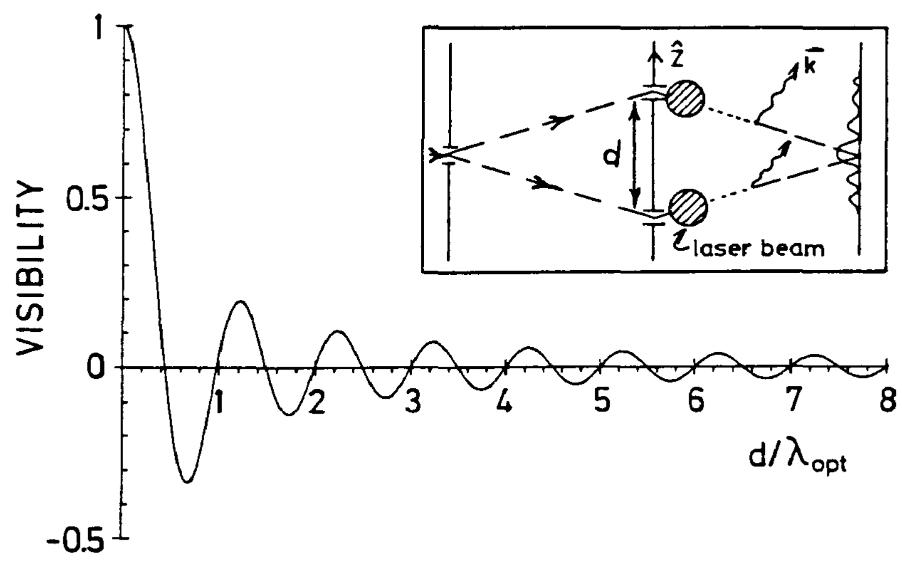

Figure 3: Calculated visibility after spontaneous emission of the atomic fringe pattern vs. d/λ_{opt}. The result is shown for a $\Delta m = \pm 1$ transition with quantization axis along $\hat{z}$. The probability of emitting a photon an angle θ from the z-axis is proportional to $1 + \cos^2 \theta$. Inset: Diagram of the experimental configuration. The hatched circles are laser beams. The dashed (dotted) line is the path of the atom in the ground (excited) state. The momentum of the emitted photon is $\hbar$k

the atomic wave packet. If the photon is emitted at an angle θ with respect to the direction $\hat{\mathbf{z}}$ from one slit to the other (see the inset of Fig. 3), the fringe pattern will be shifted an amount proportional to $k\cos\theta$, where $k = 2\pi/\lambda_{opt}$ is the magnitude of the photon wave vector. The solution to the problem is obtained in effect, by integrating the atomic intensity pattern obtained for a given direction of the emitted photon over all directions of the emitted photon, weighted by the probability of emitting a photon in a given direction. A further discussion of the calculation can be found in Reference 7.

The result of the above procedure can be expressed in terms of the fringe visibility V, which depends on the slit spacing d, the magnitude of the photon wave vector k, and the angular momentum of the transition. If θ_d is the angle between the atomic quantization axis and the $\hat{\mathbf{z}}$, we find for an electric dipole transition,

$$V = \frac{3}{4}\sin^2\theta_d\left[\frac{\sin kd}{kd} - \frac{\cos kd}{(kd)^2} + \frac{\sin kd}{(kd)^3}\right] + \frac{3}{2}\cos^2\theta_d\left[\frac{\sin kd}{kd} + \frac{\cos kd}{(kd)^2} - \frac{\sin kd}{(kd)^3}\right] \quad (1)$$

for $\Delta m = \pm 1$, and

$$V = \frac{3}{2}\sin^2\theta_d\left[\frac{\sin kd}{kd} + \frac{\cos kd}{(kd)^2} - \frac{\sin kd}{(kd)^3}\right] + 3\cos^2\theta_d\left[-\frac{\cos kd}{(kd)^2} + \frac{\sin kd}{(kd)^3}\right] \quad (2)$$

for $\Delta m = 0$. Here, we have made a generalization of the concept of visibility. If the positions of the maxima and minima in the fringe pattern are unchanged by the spontaneous emission process, then we take the usual definition: $V = V_{usual} \equiv (I_{max} - I_{min})/(I_{max} + I_{min})$. If the positions of the maxima and minima are exchanged, we define $V = -V_{usual}$.

As an example, Fig. 3 shows the visibility of the fringes V *vs.* d/λ_{opt} for the case of a $\Delta m = \pm 1$ transition and a quantization axis along the z-axis ($\theta_d = 0$ in Eq. 1) Such a transition could be achieved with metastable He atoms, for example with the 1.083 μm transition between the $^3P_2$ excited state and the $^3S_1$ metastable state in the triplet system.

The calculation shows that when $d << \lambda$, the visibility is 100%. In this case, the recoil momentum of the atom is too small to deflect the atomic trajectory a significant fraction of an interference fringe. In contrast, when the slit spacing becomes much larger than the wavelength ($d >> \lambda$), the fringe pattern tends to disappear. This we expect, because by looking at the emitted photon, one could in principle determine from where it was emitted (to a precision of roughly λ), and therefore, which slit the atom passed through. It is very interesting, however, to notice that even for slit spacings several times the wavelength there is still significant visibility, and for some values, this visibility is negative.

An example of an experiment that could be done to test the above ideas would be to construct a pair of slits, each with about 0.2μm width, and a 0.7μm spacing between them (for metastable He, the transition wavelength is about 1μm). Then, by putting the atoms into the excited state with a π pulse from a laser beam, one should be able to see an inversion of the fringe pattern (see Fig. 3).

Another possible experiment would be to measure the correlation of the direction of the emitted photon with the fringe pattern of the atoms. One would find for large slit spacings that spontaneous emission would wipe out the fringe pattern. However, if one looked only at those atomic events in which a photon was emitted in a certain direction, then one should recover the fringe pattern.[8] Correspondingly, if one looked only at those events in which the atom strikes the detector at a particular position, then one would expect to see a fringe pattern in the angular distribution of the emitted photons.

3.2. Standing wave as a phase shifter

Here, we discuss some potential experiments in which a phase shift in the atomic wave function is introduced as a result of the coherent interaction of a laser beam with the atoms in one path of the interferometer. This phase shift leads to a displacement of the atomic fringe pattern on the screen. One interesting aspect of this experimental configuration is that it represents a way of probing the properties of a light field in which no energy is exchanged with a given photon mode. This has the possibility of leading to "quantum non demolition" measurements of the photon number similar to those proposed by Brune *et al.*[9]

To investigate atom-light-interactions using the atom-interferometer we are planning to add a standing light wave perpendicular to the atomic beam axis. In this and the next subsection we briefly discuss two possible experiments using either absolute light intensity differences between the two paths or a constant intensity gradient across each of the two slits.

To introduce a phase shift in our atom-interferometer we plan to use a standing wave with a period of twice the slit separation of our double slits, as shown in Fig. 4a.

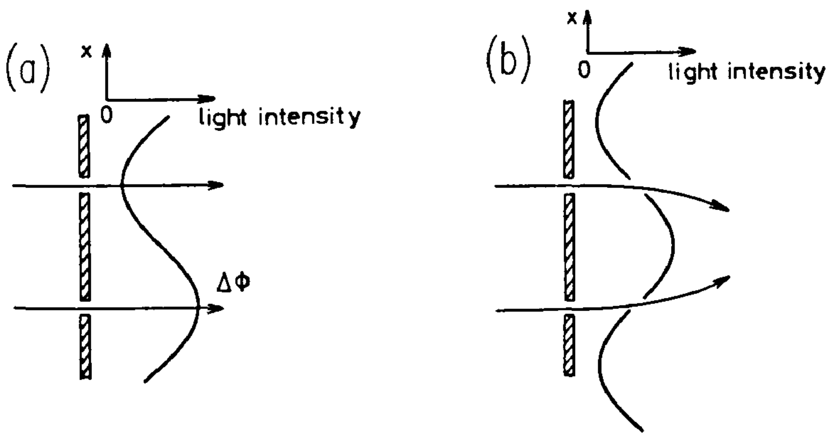

Figure 4: a) Phase shift by a standing light wave; the intensity is zero at one slit and a maximum at the other slit. b) Atomic biprism by a standing light wave; the two slits see opposite intensity gradients.

A standing wave with period much larger than the optical wavelength can be produced by crossing two laser beams at a small angle. Due to coherent off-resonance atom-light-interaction the center of mass of the atom sees an effective potential:[10]

$$U(x) = \frac{\hbar}{2}\Delta\sqrt{1 + \frac{\Omega_R^2(x)}{\Delta^2}} \quad , \tag{3}$$

where Δ is the laser detuning from resonance and $\Omega_R(x)$ is the position dependent Rabi frequency. The phase shift can be directly calculated from this potential[7] and may be measured by observing the displacement of the fringe pattern. To keep the visibility high, one has to minimize the possibility of spontaneous emission. Using the 1.083 μm transition of the metastable 2 $^3S_1$ state of helium we find that we should need less than 0.3 mW of power to get a 2π phase shift with a 400 μm beam waist and a detuning $\Delta/2\pi$ of 160 MHz.

3.3. Atomic biprism by gradient-force

By slightly changing the setup one could also make use of the opposite linear field-gradients in front of the two slits, thereby constructing an atomic biprism as shown in Fig. 4b. Biprisms have been demonstrated in matter wave optics for electrons [11] and neutrons.[2] Using the gradient-force would allow us to increase the slit separation in the two slit interferometer by a factor of 5 to 40 μm with the same atomic beam parameters as those used in our already existing interferometer. An atom interferometer with a larger separation between the paths would have a higher sensitivity to accelerations and rotations, and make other experiments that measure a differential phase shift (such as electric polarizability measurements) easier to perform.

To recombine the two wave packets after the double slit the required deflection angle of the paths is 33 μrad. Avoiding spontaneous emission requires a laser power of 5 mW with 700 MHz detuning and 250 μm beam waist. Under ideal conditions (e.g.

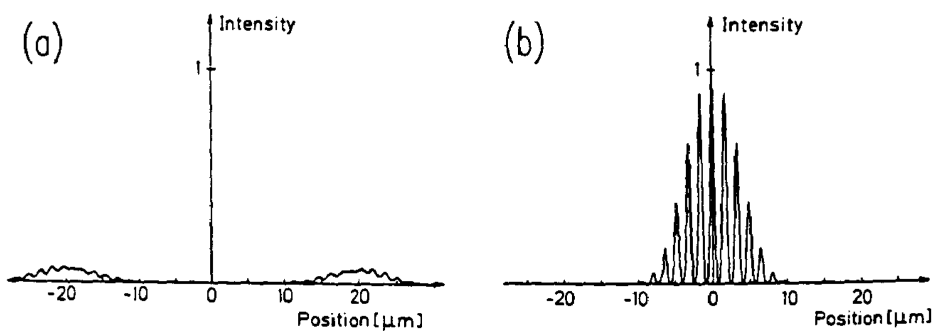

Figure 5: a) Calculated intensity pattern of a 40 μm double slit without light field. b) Interference pattern of a 40μm double slit with each beam path being deflected by 33 μrad; the geometry corresponds to Fig. 4b.

point source, monochromatic beam, narrow slit width compared to slit separation) we find the result shown in Fig. 5a without the light field and in Fig. 5b with light field. This result shows that it is possible to increase the separation between the paths in our interferometer without loss of intensity.

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