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Atom Wave Interferometry with Diffraction Gratings of Light

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We have developed a novel interferometer for atom de Broglie waves, where amplitude division and recombination is achieved by diffraction at standing light waves operating as phase gratings. Our new atom interferometer is the exact mirror image of interferometers for light, with the roles of atoms and photons interchanged, and it directly demonstrates coherence of the diffraction of atomic waves at standing light waves. Easy manipulation of the phase, intensity, and polarization of the standing light wave permits novel studies of atomic coherence properties.

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Interferometry has always had a significant impact on the development of physics, both on the fundamental and on the applied level. Fundamental experiments with photon interferometers have, mainly in the last century, contributed to the development of relativity theory. Beginning in the middle of our century, these experiments were supplemented by fundamental experiments with matter-wave interferometers. So far, experiments with electrons [1] and neutrons [2] have provided both demonstrations of many fundamental aspects of quantum theory and precision tests against alternative theories [3]. Most recently, interferometry with matter waves has been greatly expanded by the technique of coherently splitting and recombining atomic beams [4,5]. All experimentally realized atom interferometers may be divided into two classes.

In one class [6], called atomic state interferometers by Sokolov and Yakovlev [7], the beam splitter produces a superposition of internal states, and this is the mechanism for coherently splitting the beams.

In the other class of interferometers the beam splitter does not change the internal state of the atom. Here diffraction produces a superposition of external states and thus directly creates distinctly different paths in real space. Such interferometers, where the beam splitting process is directly linked to the wave nature of the external motion, we call de Broglie wave interferometers. In the experiments performed so far, the diffraction of de Broglie waves at a material double slit [8] or at a material absorption grating [9] serves as the beam splitter mechanism.

In the present Letter we report the successful development of a de Broglie atom interferometer where diffraction at standing light waves, acting as phase gratings for the atomic de Broglie waves, is the beam splitter mechanism. This interferometer is then the exact mirror image of a three grating Mach-Zehnder interferometer for light, with the roles of atoms and photons interchanged. While diffraction at standing light waves has already been shown experimentally [10], it is important to realize that the operation of the interferometer depends crucially on whether or not the beam splitting process results in mutually coherent atomic beams. That this question is not obvious may be seen if one pictures the standing light wave as a coherent superposition of two counterpropagating waves with photon momenta $\hbar\vec{k}$ and $-\hbar\vec{k}$, respectively. An atom can then be viewed as absorbing a photon out of one these waves and reemitting it via stimulated emission into the other one, thus acquiring a momentum change of $2\hbar\vec{k}$. One could argue that measurement of the number of photons in these waves results in the determination of whether or not the atom has been diffracted and thus in path information destroying interference. Operation of our interferometer proves that this is not the case. One might expect that this is due to the fact that our light beams can be described as coherent stated where the photon number is not well defined. This is misleading, and we will show

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the following in a forthcoming paper: The beam splitter mechanism is coherent even for a number state when its coherence length greatly surpasses the distance between the atomic beam and the retroreflection mirror. This condition erases the *"welcher Weg"* information and is necessary and sufficient for any state.

In our interferometer (Fig. 1) incident atoms are diffracted at the first standing light wave which produces a coherent superposition of mainly zeroth and first order beams. These beams impinge on the second standing light wave, where each beam is coherently split. Finally, at the third standing light wave, each one of the incident beams is once more coherently split and a number of emerging beams result, some of which are coherent superpositions of different paths through the interferometer with different relative phase. We use either one of the two skew symmetric interferometers formed by the zeroth and first diffraction orders at the first grating, the first diffraction orders at the second grating, and finally again the zeroth and first diffraction orders at the third grating. The interferences are detected by translating the third grating and observing the intensity alternatively in one of the two outgoing beams of the selected interferometer in the far field. The two output ports of the Mach-Zehnder interferometer show complementary intensity oscillations (Fig. 2).

Now we describe our experiment in more detail. We used metastable $^{40}\mathrm{Ar}^*$ for our experiments, which has the advantage that it has zero nuclear spin and hence no hyperfine structure. Its relatively simple level structure affords both a closed two-level system at 811 nm transition frequency and pumping transitions at 801 and 795 nm, respectively. All three frequencies are accessible by diode laser technology.

In the source, a cold cathode discharge burning through the nozzle to the skimmer did provide the electronic collisions for excitation of atoms into a mixture of highly excited states of which some decay into the $^{40}\mathrm{Ar}^*$ metastable states, $[3p^54_s]1s_5$ and $[3p^54_s]1s_3$, with relative weights of about 85:15. The $1s_3$ state can be pumped away using the transition at 795 nm. The emerging beam had a most probable velocity of 850 m/s corresponding to a de Broglie wavelength of 0.12 Å. The velocity spread and hence width of the wavelength distribution in the beam was 60% FWHM.

In order to resolve the diffraction angle from a 405 nm ($\lambda/2$) period standing wave ($\vartheta_{\mathrm{diff}} \approx 32\ \mu$rad), the beam was collimated by two 3 mm $\times$ 5 μm slits at a distance of 0.85 m. The metastable Ar* atoms were detected by deexcitation and subsequent detection of the emitted Auger electrons using a Galileo type 4860 channeltron. A 10 μm wide slit was scanned in front of the channeltron to obtain the desired spatial resolution.

The standing light waves were realized by retroflecting a ribbon shaped laser beam at precision mirrors with $\lambda/30$ surface flatness. The mirrors were mounted with a separation of 25 cm between each other on a vibration isolated optical bench inside the vacuum chamber. Thus an interferometer with an overall length of 50 cm (Fig. 1) results. With a diffraction angle of 32 μrad the beam separation at the second grating is about 8 μm, more than the width of the collimated beam. This results in spatial separation of the two interfering beams.

The ribbon shaped laser beams for the three standing light waves were created by using three separate telescopes, each consisting of a cylindrical lens (f = 30 mm) and a spherical lens (f = 300 mm). The incident laser beam is focused to a focal waste of 90 μm in the direction along the atomic beam and expanded to a more than 30 mm high sheet in the direction perpendicular to the atomic beam. The mirrors are placed in the focus of the ribbon. The atomic beam passes less than 5 mm away from the mirror surfaces. This is closer than the Rayleigh range of the Gaussian focus $\sim$8 mm. The

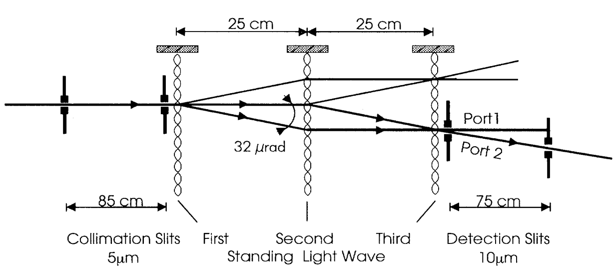

FIG. 1. Schematic arrangement of our interferometer setup (not to scale). The collimation slits for the incoming beam, the three standing light waves created by retroflection at the mirrors, and the two final slits, one selecting a specific interferometer (thick lines) and the other selecting a specific output port are shown. For reasons of presentation, the wavelength of the light beams is greatly exagerated. In the experiment the atomic beam was wide enough to cover more than 12 light wave antinodes.

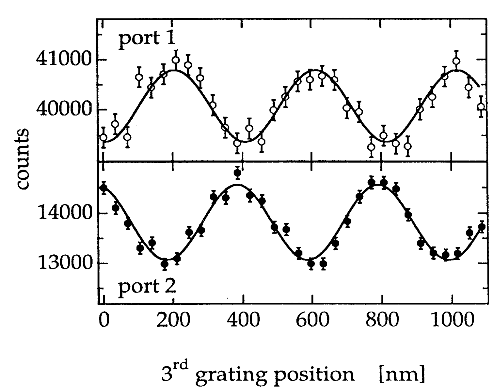

FIG. 2. Measured atom interference pattern for both output ports of the interferometer. The complementary intensity variations of the two output ports observed is a consequence of particle number conservation. The solid line is a fitted sinusoid.

atoms effectively pass thin standing light fields (interaction time $\tau \sim 100$ ns), acting as pure diffraction gratings.

The operation of the standing light waves as diffraction gratings can most easily be understood by realizing that far off resonance the atom sees a time-dependent periodic potential $V(\vec{r},t) = -\frac{1}{2}\alpha(\omega)|\vec{E}(\vec{r},t)|^2$, where α is the frequency-dependent electric polarizability of the atom and $\vec{E}(\vec{r},t) = \vec{E}_0(z)\cos(kx)\cos(\omega t)$ is the electric field of the standing light wave (x is parallel to the k vector of the light, and z is parallel to the atomic beam direction). This provides a temporal and spatial modulation of the total energy of the atom. Following a specific trajectory through a standing light wave, the atom averages over the fast time modulation and experiences a phase shift $\delta\varphi(x) = \varphi_0 \cos^2(kx)$. The atom emerges with a spatial phase modulation equivalent to a sinusoidal phase grating with period $\lambda/2$ and a maximal phase shift φ_0. For a standing light wave with a Gaussian intensity distribution along the atomic beam one finds $\varphi_0 = \sqrt{\pi/2}\,\Omega_0^2\,\tau/\Delta$ (Ω_0 is the Rabi frequency) [11]. The strength of the diffraction orders is given by $P_n = J_n^2(\varphi_0/2)$, where J_n is a Bessel function. The strength of the interaction can be varied by changing either the detuning Δ or the amplitude $\vec{E}_0$ of the light field.

For our interferometer we chose a configuration designed to maximize the signal to noise for optimum phase sensitivity. For an ideal two-level system the optimum interaction strengths are $\varphi_0 = 2.16$ for the first and third gratings, and $\varphi_0 = 3.68$ for the second grating. This gives 100% contrast in the symmetric outgoing beam and an interfering amplitude of 7.8% of the total incoming beam intensity. In our case the diffraction efficiency of the gratings is smeared out of both by the different dipole moments of the different m states of $\mathrm{Ar}^* 1s_5$ and by our 60% FWHM wide velocity distribution. In addition, the stray magnetic field in our apparatus mixes the m states. Taking all these influences into account, the optimum interaction strengths are such that $\varphi_0 = 2.56$ for the first and third gratings, and $\varphi_0 = 4.34$ for the second grating. Then theoretically our configuration has 90% contrast in the symmetric beam and an interfering amplitude of 6.0% of the total incoming beam intensity. This is about an order of magnitude improvement over the optimized absorption grating interferometer [9].

The overall performance of the interferometer depends crucially on grating alignment: For efficient diffraction the standing light waves have to be orthogonal to the atomic beam. Therefore the mirrors have to be oriented parallel along the atomic beam to much better than one grating period over the grating thickness. The mirrors were first aligned parallel to each other to better than 10^{-3} rad, and the atomic beam was finally aligned parallel to the mirror surfaces by optimizing the diffraction efficiency.

For high contrast in the interferometer, the phase gratings and thus the retroreflecting mirrors also have to be oriented parallel to each other along the direction normal to the plane of the interferometer to much better than a grating period over the atomic beam height. We achieved a vertical parallel alignment of the three mirrors to the order of 3×10^{-5} rad (100 nm over the 3 mm beam height).

For the standing light waves we used alternatively either the closed cycle transition $1s_5$ to $2p_9$ at 811 nm or the open transition $1s_5$ to $2p_8$ at 801 nm. In general we chose a large detuning of about 360 MHz (~60 times the natural linewidth). Thus excitation and hence spontaneous emission was largely suppressed. Some experiments with the open transition (801 nm) were performed with small detuning of about 80 MHz. Figure 3 shows typical diffraction patterns for each of the three standing light waves in a configuration used for our interferometer.

The observed interference contrast was of the order of 10% for an interferometer using the closed transition (811 nm) far off resonance. We also successfully operated the interferometer with a smaller contrast of about 4% using the open transition (801 nm) close to resonance [12].

We expect to improve the contrast significantly in the near future by using slower atoms to achieve larger

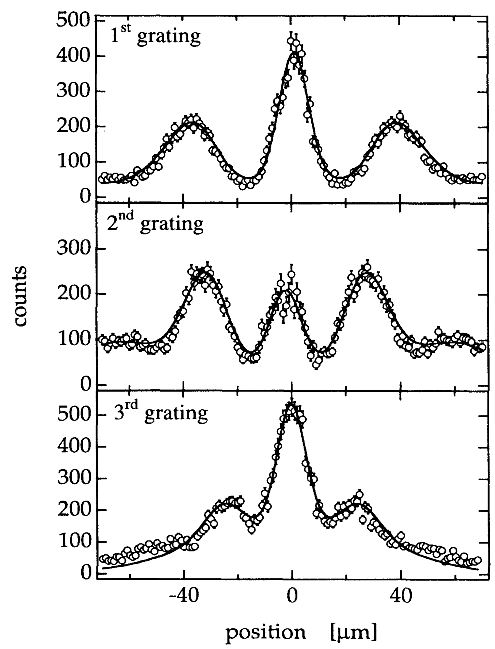

FIG. 3. Atom diffraction from the three standing light waves ($\lambda = 811$ nm) used in the atom interferometer. The solid lines show a theoretical calculation including the various effects of the magnetic sublevel structure, of the velocity distribution and divergence of the atomic beam, and of spontaneous emission. The separation between the diffraction orders is best for the first grating, which has the farthest distance (1.25 m) from the detector.

beam separation, by better collimation, and by position monitoring of the mirrors.

Finally, we would like to mention the advantages of the present interferometer and compare them to existing atom interferometers.

Our interferometer shares with the absorption grating interferometer [9] the feature to be nondispersive; i.e., the fringe position depends only on the relative orientation of the three diffraction gratings. This means that, if the interferometer is aligned for one wavelength, it is aligned for all wavelengths.

In contrast to atomic state interferometers [6,7], de Broglie interferometers provide a spatial separation which allows the insertion of any material or field in one of the interferometer arms [14]. Our interferometer is the only one where that spatial separation is achieved by splitting based on the interaction with light.

Compared to existing de Broglie interferometers, a significant advantage of gratings of light is that frequencies, and hence the period of our gratings of light, can be much better defined than the dimensions of mechanical slits or gratings [15]. It has recently been pointed out [16] that this feature will be important in future precision experiments.

Due to the use of gratings of light, our interferometer distinguishes between different states if they are far enough detuned so that their contribution to diffraction can be neglected. In this sense it is state selective, since the interferometer can be arranged to act for one specific internal state by choosing the right photon wavelength. This will be important in molecular interferometry [17], where experiments with specific vibration and rotational states will become possible. Furthermore, by selecting a detuning in between two levels, or by choosing two different laser frequencies, a great variety of superpositions between different states inside a separated beam interferometer can be created.

Another striking advantage of our interferometer rests in the fact that phase, polarization, or amplitude of the three standing light waves can be varied rather easily corresponding to rapid change or modulation of beam splitter properties, unachieved in any previous type of matter-wave interferometers. In addition the diffraction characteristics of standing light waves can also be changed by changing their Fourier decomposition. It is obvious that the ease of manipulation and modulation of the standing light wave opens up the door for fundamental coherence studies in questions of quantum chaos and quantum localization [18] and of time-dependent quantum mechanics.

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[12] These results are in good agreement with Monte Carlo simulations. Our beam collimation is not perfect and therefore the detector sees also parts of other noninterfering diffraction orders reducing the contrast to 40%. For instance, according to this model an improvement of our atomic beam collimation by a factor of 2 would yield a contrast of 60%. Misalignment of the gratings and residual spontaneous emission (15% at each grating for 811 nm) further lower the contrast to 25%. For matter-wave interferometers with nonzero enclosed area, Sagnac phase noise, like rotational vibrations, is significantly more detrimental than phase noise caused by translational vibrations [13]. Optically measured rotations of our interferometer then decrease the contrast to 17%. The final discrepancy can be attributed to mechanical drifts during a 1 h interference scan.

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