Diffraction of atoms from optical potentials

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Introduction

Atom optics, in analogy to electron or neutron optics, is concerned with the manipulation of atomic matter waves [1-3]. Experiments on atomic beams have been performed since the nineteen-twenties, but recently the improvement of tools, like free-standing microstructures and tunable laser light, has lead to a rapid development of the field. Beams of atoms have been split coherently, focussed and reflected from mirrors. "Optical instruments" for atoms have a number of potential applications: Atom interferometers could be well suited as gravitational and inertial sensors and may allow precision measurements of atomic properties. A number of such measurements have already been carried out. An "atom-microscope" - investigating the interaction of atoms with surfaces with high spatial resolution - may provide an interesting new tool for surface physicists. "Atom lithography" may allow the deposition of atoms on surfaces with high precision. Cavities for atoms could be interesting to store cold atoms and for the study of quantum-statistical effects.

In the first part of this article we attempt to provide a very brief introduction to atom optics. In the second part we report on a recent experiment in our group on an atom-optical element that may be useful in atom interferometers and atom cavities: the demonstration of a new beam splitter based on the diffraction of atomic matter waves from a "magneto-optical grating" .

1 Atom optics

Particle beams exhibit many phenomena well known from classical optics like diffraction and refraction. Particle optics based on electrons and neutrons [4] are well established fields. Experiments with these particles have played an important role in exploring the puzzling wave-particle duality. Both neutron and electron interferometers have been used in many beautiful experiments, which have improved our understanding of quantum mechanics. The interactions of neutron and electron beams with matter have become indispensable tools in the analysis of structures and surfaces, consider e.g. neutron scattering and the electron microscope.

As atoms are different from electrons and neutrons, particle optics with atoms promises a wealth of new effects and applications. Like neutrons, atoms are neutral and therefore cannot be manipulated as easily as electrons or ions using static electromagnetic fields. In return beams of atoms and neutrons are less susceptible to electromagnetic stray fields. Atoms are heavier, which makes them more suitable as gravitational and inertial sensors and means that very short de Broglie wavelengths can be obtained for lower particle energies. Atoms come in many species, which can be either bosons or fermions, and may have a total angular momentum or magnetic moment much larger than neutrons or electrons. Beams of atoms are easier and cheaper to produce than neutron beams as there is no need for a nuclear reactor. And maybe most importantly, atoms have a complex internal structure that can be probed and manipulated using resonant laser light or static electromagnetic fields.

As in classical optics, the building blocks of any experiment are optical elements e.g. beamsplitters, mirrors and lenses. Light can be manipulated by transmission through interfaces between materials with different refractive indices. Electrons, due to their charge, couple strongly to static electric or magnetic fields. Neutrons penetrate through solids and can be diffracted from crystal lattices.

As atoms experience much smaller forces in static fields and do not penetrate through matter, none of these approaches are suitable for atom optics.

So far optical elements for atoms have been demonstrated using diffraction, refraction or the recoil due to the stimulated emission or absorption of a single photon. "Diffractive optical elements" achieve the desired distortion of an incoming wave front by interaction with small structures, thus exploiting the wave nature of the atomic centre of mass motion. "Refractive optics" is based on introducing phase shifts by a spatial modulation of the index of refraction experienced by the atoms. In analogy to standard optics the index of refraction is defined as the ratio of a particle's group velocity and the vacuum group velocity. The index of refraction can be adjusted by shifting the potential energy of the atom. Intuitively this means: If the internal energy of an atom is e.g. decreased, energy conservation demands an acceleration of the centre of mass motion (i.e. an increase in the group velocity of the atomic matter wave). The phase velocity on the other hand is decreased in this case. The phase fronts are consequently retarded with respect to the unperturbed propagation. The principle of refractive optical elements is to choose the spatial dependence of these phase shifts to obtain the desired distortion of the incoming wave fronts. In static electric or magnetic fields the atomic internal energy can be changed by the Zeeman or Stark shift, in near-resonant light fields by the light shift.

The diffraction of atoms from the surface of single crystals was studied by Stern et al. as early as 1929 [5]. In 1969 Leavitt and Bills [6] observed a single-slit diffraction pattern using a thermal potassium beam. The progress in micro-fabrication technology now permits the production of structures sufficiently fine to diffract thermal atoms, whose de Broglie wavelengths are typically below 1 Å. The diffraction of thermal atoms from free-standing micro-fabricated gratings has been studied by several groups [7,8]. The first deflection of an atomic beam by the light pressure force was already demonstrated by Frisch in 1933 [9]. In recent years the availability of intense tunable laser radiation has again focussed interest on the mechanical effects of atom-light interactions. The feasibility of such experiments has stimulated considerable theoretical interest. In addition to the conservative interaction using the dipole force, the spontaneous decay of excited electronic states can be utilized for the preparation of atomic beams by laser cooling techniques to obtain well-collimated, dense atomic beams with a well defined velocity.

2 The magneto-optical beamsplitter

2.1 Introduction

A coherent beam splitter couples an incoming momentum state to a coherent superposition of outgoing momentum states. Beam splitters for atoms are not only important for atom interferometry, they also could be used for correlation measurements or as in/outcouplers for atomic cavities. Beam splitters have been produced using the magnetic [10] or optical Stern-Gerlach effect [11], reflection from crystalline surfaces [12], the recoil due to a single absorption or stimulated emission [13,14], diffraction from micro-fabricated transmission gratings (amplitude gratings) [7,8] and the diffraction from standing wave light fields (phase gratings) [15,16].

We present a new type of beam splitter which is a modification of the diffraction of atoms from an optical standing wave. This diffraction can be looked upon as a beam splitter both in the regime of long and short interaction times. For short interaction times the change in "transverse" kinetic energy can be neglected. In the following we are concerned with this regime, which is called the Raman-Nath regime.

As for the diffraction of two-level atoms from a standing wave the magneto-optical beamsplitter is based on introducing position dependent phase shifts. The advantages of the diffraction from a phase grating over diffraction from an amplitude grating are that there is no absorption and that by changing the phase modulation amplitude it is possible to change the envelope of the diffraction pattern. For a two-level atom the eigenenergies of the two energy eigenstates in a near-resonant light field with Rabi frequency $\omega_R = \langle e|d \cdot E|g\rangle E_0 / \hbar$ and resonance detuning Δ are (using the rotating wave approximation)

$$E_\pm(x) = -\frac{\hbar\Delta}{2} \pm \frac{\hbar}{2}\sqrt{\omega_R(x)^2 + \Delta^2} \ .$$

In a standing wave light field with large detuning these eigenergies display a roughly sinusoidal modulation. In the Raman-Nath regime and if neither spontaneous emission nor non-adiabatic following induce transitions between the eigenstates the phase modulation $\Delta\Phi(x) = \int E(x,t)/\hbar \, dt$ displays the same sinusoidal modulation. The momentum distribution and therefore the far-field spatial distribution (for a monochromatic beam) is given by the square of the Fourier transform of $e^{i\Delta\Phi(x)}$ with respect to x. For a sinusoidal phase modulation the population of the n^{th} diffraction peak is given by the square of the n^{th} order Bessel function $J_n(\Delta\Phi_{max})$ wherein the argument is the amplitude of the phase modulation [17]. Diffraction from a standing wave can therefore be looked upon as an effective beam splitter only for momentum transfers of a few $\hbar k$. In order to obtain a phase grating which diffracts all intensity into a few high order momentum states a triangular phase modulation is necessary. Such a triangular phase modulation can be obtained if a combination of light shifts and Zeeman shifts are used to control the spatial modulation of the eigenenergies [18,19]. We consider the experimental situation shown in figure 1: a V-type three-level system interacts with two counterpropagating crossed linearly polarized light beams and a static magnetic field applied parallel to the light beams. The level scheme contains the Zeeman shifts but not the light shifts.

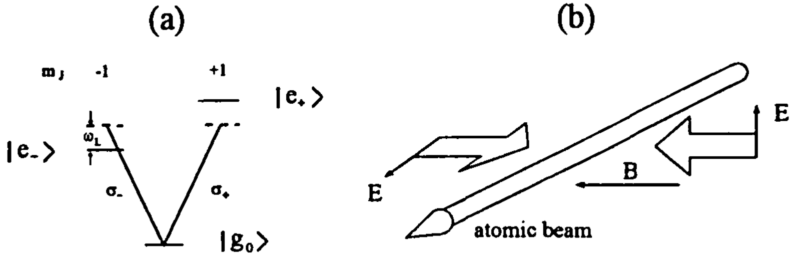

Figure 1: (a) Level scheme for a J=0 to J'=1 transition with the quantization axis chosen parallel to the magnetic field. (b) Configuration of the counterpropagating light beams which orthogonally intersect the atomic beam. The light fields are linearly polarized and the polarization vectors enclose an angle of 90°. A magnetic field is aligned parallel to the light beams.

In figure 2 the energy eigenvalues of this three-level atom are displayed as a function of the transverse position in the light field for three ratios of the Larmor frequency $\omega_L = g_J \mu_B B / \hbar$ and the Rabi frequency $\omega_R = \langle e_\pm | d \cdot E | g_0 \rangle E_0 / \hbar$. For small Rabi frequencies the levels are split by the Zeeman effect, for large Rabi frequencies by the light shift – for $\omega_R = 2\omega_L$ the Zeeman shift and the light shift at positions of circularly polarized light are equal and the eigenstate $|2\rangle$ displays the desired triangular modulation. For the V-system the ground state $|g\rangle$ evolves adiabatically into this eigenstate $|2\rangle$. If nonadiabatic processes and spontaneous emission do not populate the two other eigenstates the diffraction pattern obtained from this phase grating should display two distinct peaks.

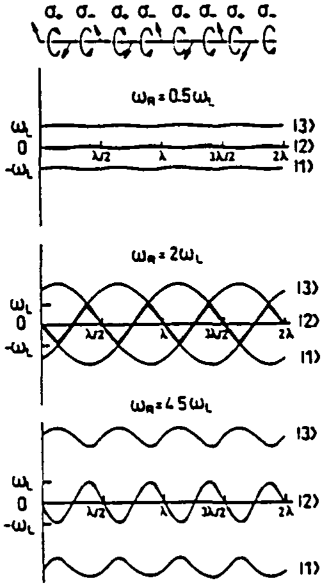

Figure 2: Plots of the spatial dependence of the eigenenergies of a three-level atom in a light field created by two counterpropagating orthogonally linear polarized light beams and a static magnetic field for three different ratios of Rabi frequency ω_R and Larmor frequency ω_L. a) ω_R= 0.5 ω_L, b) ω_R = 2 ω_L and c) ω_R = 4.5ω_L

2.2 Experiment

We investigated the magneto-optical beamsplitter in an experiment using helium atoms in the triplet state. The light field was resonant with the transition at 1083 nm from the metastable 2^3S_1 state to the 2^3P_1 state. If the incoming metastables are optically pumped into the $m_J=0$ substate a V-type three-level system as depicted in figure 1a is obtained. A schematic of our experimental setup is displayed in figure 3. The laser beam, which was derived from a Ti:sapphire ring laser, was focussed to a waist of 21 μm in the beam direction. The polarization of the back-reflected beam was rotated by double pass through a λ/4-plate. As a consequence of the large mean velocity in the supersonic beam of 2000 m/s and the long lifetime of the excited state of 100 ns it was possible to largely avoid spontaneous emission. The superimposed magnetic field was produced by a pair of Helmhotz coils. The far-field diffraction pattern of the supersonic helium beam was observed with a scanning slit detector.

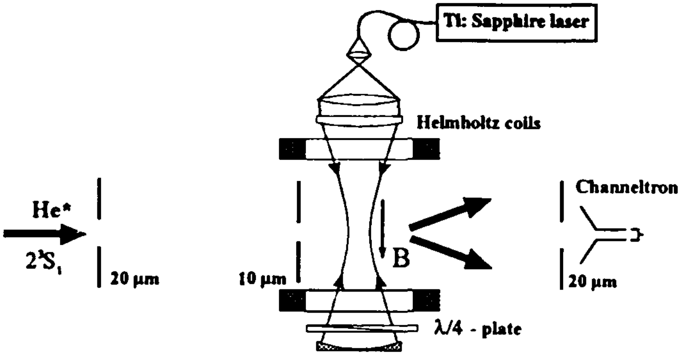

Figure 3: Experimental setup of the magneto-optical beamsplitter. A beam of triplet helium atoms interacted with two counterpropagating orthogonally linear polarized laser beams and a static magnetic field. The far-field diffraction pattern was detected with a scanning slit and a channeltron detector.

In Figure 4 the atomic intensity is plotted as a function of transverse position in the detection plane 0.85 m downstream from the interaction zone. The choice of parameters was such that the Rabi frequency ω_R in the centre of the Gaussian beam was twice the Larmor frequency ω_L. It can be seen that the incoming atomic matter wave is largely diffracted into two groups of diffraction orders as expected from theory. The finite velocity distribution leads to a broadening of the split beams in the real space distribution. The splitting of 1.5 mm between the two peaks observed in the detection plane corresponds to a momentum splitting of 42 $\hbar k$. This is a large splitting compared to the splitting typically achieved by diffraction from an amplitude grating or compared to the 1 $\hbar k$ achieved with a single $\pi/2$-pulse.

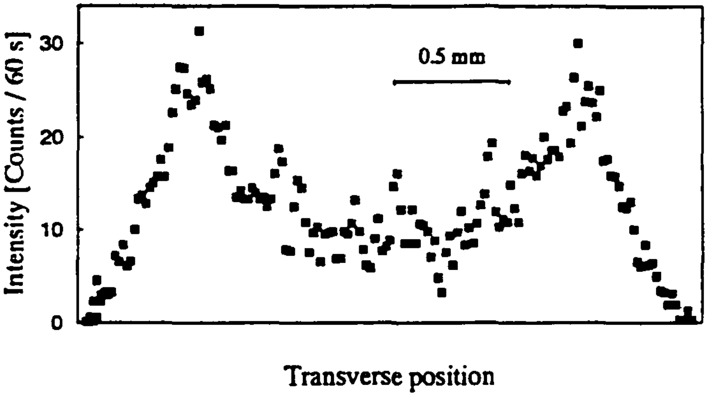

Figure 4: Measured far-field intensity distribution for the diffraction of triplet helium atoms from a magneto-optical grating for $\omega_R = 2\,\omega_L$.

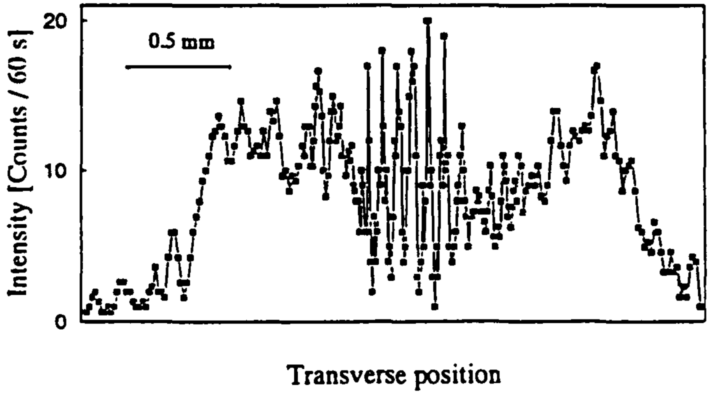

Figure 5: Measured far-field intensity distribution for the diffraction of triplet helium atoms from an optical standing wave.

For comparison we also examined the diffraction of atoms from an "ordinary" standing wave. Figure 5 shows a far-field diffraction pattern we obtained for a laser intensity comparable to the one used in figure 4. It displays the expected broad, Bessel function shaped envelope. In the real space distribution the $2\hbar k$ structure is only resolved for low diffraction order. For larger diffraction order the finite width of the velocity distribution smears out distinct diffraction peaks.

3 Conclusion

After a short introduction in the field of atom optics we presented experimental results for a new type of beamsplitter. The beamsplitter relies on the diffraction of atomic matter waves from a phase grating with triangular phase modulation produced by a combination of a light field and a magnetic field. We observed a momentum splitting of $42\hbar k$. To our knowledge this is the largest splitting in momentum space observed so far. A next step could be to investigate the coherence of this beamsplitter by recombining the two output ports in a Mach-Zehnder type interferometer. Another interference effect should occur in the near field of the magneto-optical grating, where the triangular shape of the phasemodulation acts as an array of Fresnel biprisms.

Acknowledgement

C.S.A. acknowledges support of the Royal Society's European Science Exchange Programme. This work was supported by the Deutsche Forschungsgemeinschaft.

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