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Diffraction of Metastable Helium Atoms by a Transmission Grating

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Abstract. We report on the diffraction of metastable helium atoms (de Broglie wavelength $\lambda_{dB} \cong 1$ Å) passing a free-standing gold grating with a periodicity of 0.5 μm. The observed positions and intensities of the different diffraction peaks are in good agreement with a theoretical model for the grating shape. The overall transmission of the grating for the excited state atoms is about 30%, mainly determined by the grating geometry. Our result indicates that microfabricated transmission gratings can be used as efficient and coherent beam splitters for rare gas atoms in long-lived excited states. This fact offers interesting possibilities in view of atom interferometry with metastable noble gas atoms.

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During the last years, there has been considerable interest in the realization of an atom interferometer [1]. Recently, the first atom interferometer has been demonstrated, which is based on a Young-type double slit arrangement [2]. This interferometer belongs to a class of interference devices which make use of the division of wavefronts. Another class of interferometers is based on amplitude splitting like the perfect crystal neutron interferometer [3]. Atom interferometers using amplitude splitting require as a key element an efficient and coherent beam splitter for atoms which can be realized, e.g., by diffraction of atoms from periodic structures like corrugated surfaces [4], standing laser fields [5] or microfabricated transmission structures [6]. Especially transmission gratings are attractive because they are easy to handle and can be produced with high mechanical regidity and quality. Most recently, such transmission gratings have been used in a three-grating interferometer for sodium atoms [7].

In this paper, we report on the diffraction of metastable helium atoms (de Broglie wavelength $\lambda_{dB} \cong 1$ Å) passing a free-standing gold grating. Our work is closely related to the studies by Keith et al. [6], but our experiments with metastable helium atoms additionally add various new aspects which are interesting from the experimental viewpoint [8]. In contrast to alkaline atoms, helium atoms are inert which greatly facilitates the use of the very delicate microfabricated grating structures. Moreover, metastable helium atoms can be very efficiently detected on almost zero background by a secondary electron multiplier. Similar to alkalines, optical transitions in the near infrared are available, so that they can be manipulated with laser light. Moreover, preliminary studies have shown that essentially no deexcitation from the metastable to the ground state occurs during the passage through the microstructure [9]. Therefore, metastable rare gas atoms seem to be of great interest for the development of new optical elements based on microfabricated transmission structures.

1. Experiment

In our experiments we used a supersonic beam apparatus [10] in which the helium gas, kept at some temperature T, expands under high pressure through a small nozzle (diameter: 25 μm) into the vacuum and passes 12 mm downstream a skimmer (diameter: 0.5 mm), after which the atoms continue their flight in a free jet. The adiabatic cooling during the supersonic expansion reduces at the same time the longitudinal and the transverse velocity spread, which leads to a highly collimated and monoenergetic atomic beam [11]. After leaving the expansion region, the atoms are excited to different metastable states by electron impact. In our case, the direction of the electron beam is collinear with the atomic beam which minimizes the spread in the final velocity distribution of the metastable atoms. After leaving the excitation re-

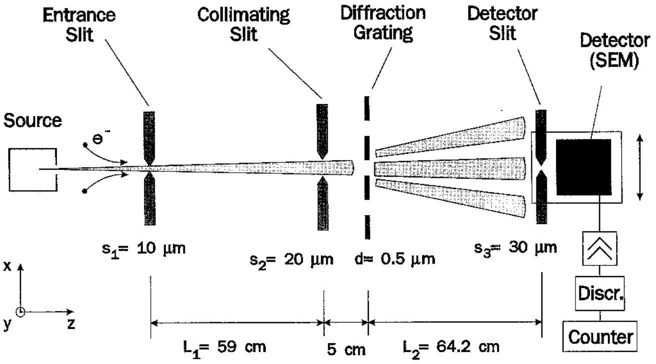

Fig. 1. Experimental setup. The diffraction pattern is monitored with a moveable slit in front of a secondary electron multiplier. The detector system can be moved in steps of 7.5 µm

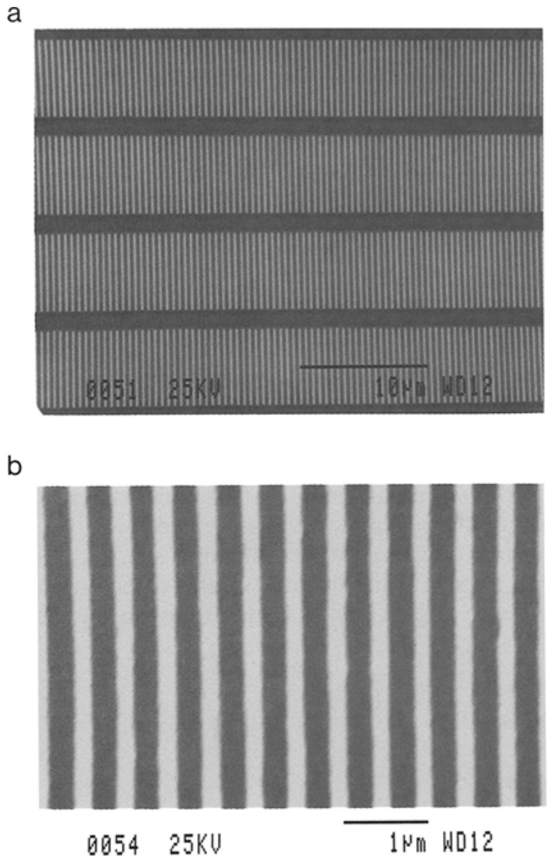

Fig. 2a, b. Scanning electron microscope pictures of the gold grating. **a** General view of the grating structure: the fine grating in the vertical direction is the diffraction grating with a periodicity of 0.5 µm. The overlaid solid bars in horizontal direction are the support structure. **b** Details of the fine grating, showing the grating imperfections

gion the beam of metastable atoms has a velocity ratio $v_0/\Delta v \cong 10$–20 (v_0: mean velocity in the beam, Δv: full width at half maximum of the Gaussian velocity distribution) and a brightness $B \cong 10^{16}$–10^{17} particles/(s sr cm^2) [12]. Two metastable states are excited: 2^1S_0 and 2^3P_1, with relative populations of 90% and 10%, respectively [13]. The beam machine is pumped differentially, so that a pressure of 5×10^{-7} mbar results in the main experimental chamber.

The experimental setup for the diffraction experiment is shown in Fig. 1: the atomic beam is collimated by two 5 mm high slits (s_1 and s_2 in Fig. 1) which are $L_1 = 59$ cm apart, the slits are 10 and 20 µm wide, respectively. This highly collimated beam passes through a free standing gold grating [14] with a periodicity of $d = 0.5$ µm and a thickness of 0.1 µm (Fig. 2b). To support this delicate structure an additional support grating with a 8 µm period is superimposed onto the diffraction grating which reduces the total transmission by approximately 10%. This support structure can be seen in Fig. 2a. The diffraction pattern is monitored $L_2 = 64.2$ cm behind the grating with a 30 µm wide slit (s_3 in Fig. 1), mounted on the same translation stage as the detector. The three slits and the grating were adjusted parallel to better than 10^{-3} rad. The translation stage of the detector is moved by a stepper motor, each step corresponding to a transverse displacement of the detector of 7.5 µm. A metastable atom passing the detector slit hits the conversion dynode of a secondary electron multiplier (SEM) and emits an electron, which triggers an avalanche of electrons. Both 2^1S_0 and 2^3P_1 metastable atoms are detected with the same probability. The SEM pulses are then preamplified, discriminated to eliminate the background noise, and integrated with a counter.

Typical experimental results are shown in Fig. 3a–c: the dots represent the measured number of counts accumulated in a time period of 1 min for each detector position. In a first measurement (see Fig. 3a), we have monitored the beam profile without grating in the atomic beam path and with the gas reservoir kept at room temperature ($T = 295$ K). The observed beam width is in good agreement with the actual geometrical apertures of the three slits. Since the mean velocity in the beam is inversely proportional to the square root of T, the de Broglie wavelength can be varied by simply changing the temperature T of the gas reservoir and the nozzle system. Figure 3b shows the diffraction pattern after inserting the grating into the beam with the gas reservoir kept at room temperature ($\lambda_{dB} = 0.56$ Å). One can distinguish two diffraction orders ($n = \pm 1, \pm 2$), whereas higher orders can not be resolved due to the wings of the zeroth order peak. The diffraction angles are in the order of the lateral resolution of the detector system so that the different diffraction orders overlap and are not properly resolved. The spatial separation between two diffraction maxima can be increased by approximately a factor of 2 by cooling the gas reservoir and the nozzle system down to liquid nitrogen temperature. Figure 3c shows the experimental results at a temperature of $T = 83$ K ($\lambda_{dB} = 1.03$ Å), with clearly resolved diffraction maxima.

The main uncertainty in the data points is due to the statistical nature of the arrivals of the atoms on the detector. If one assumes that the number of detected atoms in a given time interval is distributed around an average number according to Poissonian statistics, the mean relative error at each detector position is given by the root of the number of counts. This uncertainty in the measurement is indicated in Fig. 3a–c by the error bars. We point out that the background signal level is extremely low (less than 20 counts/min). Since the grating can be introduced

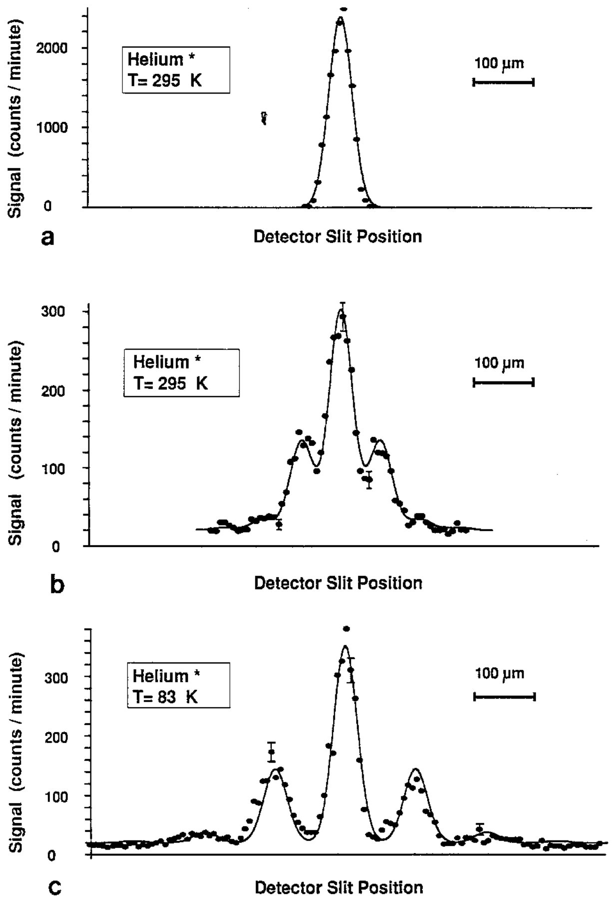

Fig. 3a–c. Experimental data. **a** Intensity distribution of the undiffracted beam in the detector plane, **b** diffraction pattern at a nozzle temperature $T = 295\,\mathrm{K}$ ($\lambda_{dB} = 0.56\,\text{Å}$), **c** diffraction pattern at $T = 83\,\mathrm{K}$ ($\lambda_{dB} = 1.03\,\text{Å}$)

without breaking the vacuum, it was possible to compare directly the total flux of atoms without and with the grating. The total transmission of the grating was determined to be better than 30%, which corresponds to the geometrical aperture of the grating (Sect. 2). This indicates that no significant de-excitation of the metastable helium atoms takes place when the atoms are passing the grating. The diffraction experiments were repeated several times without any reduction in the total transmitted flux of the atoms through the grating or any significant change in the atomic diffraction patterns.

2. Discussion of Experimental Results

For a comparison of the experimental results with theoretical predictions, let us first outline the theoretical approach to the problem in order to motivate a model for the grating shape.

The amplitude distribution of the particle wavefunction in the detector plane is given by the Kirchhoff integral theorem, in analogy to classical optics [15]. In our special case, where the distances L_1 and L_2 are much larger than the grating dimensions, we can approximate the diffraction pattern by the Fraunhofer-diffraction theory [16]. In this approximation, the amplitude distribution in the detector plane is connected to the transmission function of the grating $t(x', y')$ (where x' and y' are the coordinates in the grating plane) by a simple Fourier transform. Due to the vertical symmetry of the grating structure, this transform reduces to a one-dimensional integral over x'. The grating can be modelled as follows: on the *average* the centres of the single slits of the grating are perfectly aligned with a grating period of $d = 0.5\,\mu\mathrm{m}$. All possible imperfections of the grating, like displacements or variations of the slit widths are taken into account in the transmission function of a single slit $t_{\mathrm{slit}}(x')$, which thus represents an average slit transmission function. The total transmission function can then be written as a convolution of a finite sum of equidistant delta-functions with the transmission function of a single slit $t_{\mathrm{slit}}(x')$. In the detector plane this corresponds to an intensity distribution with distinct peaks at positions $x_n = n \cdot x_0 = n \cdot L_2 \lambda_{dB}/d = L_2 \cdot \theta_n$. In addition, the relative intensities in the different orders are given by the square of the Fourier transform of $t_{\mathrm{slit}}(x')$. In other words: a measurement of the positions of the diffraction peaks determines the de Broglie wavelength of the atoms (if d and L_2 are measured before), whereas a measurement of the relative intensities reveals details on the quality of the slits.

Since the exact form of a single slit and the grating imperfections are not known a priori, we have to evaluate the exact diffraction parameters from the data points. This is done by fitting a semiempirical curve into the data. With the actual transverse resolution of the setup, we could not observe significant broadening of the higher order peaks due to the velocity spread in the atomic beam. It is therefore sufficient, in first order, to assume that all diffraction peaks have the same width w given by the geometrical apertures of the defining slits (s_1, s_2, s_3). The atomic intensity distribution in the detector plane can therefore be approximated by the following function $I(x)$:

$$I(x) = \sum_{n=-3}^{3} i_n \cdot \exp\left(- \frac{(x - n \cdot x_0)^2}{2w^2} \right) + C,$$
$$i_n = i_{-n}, \quad n \in Z, \qquad (1)$$

where x denotes the detector position, x_0 the distance between two adjacent diffraction maxima, C the background level, and i_n the intensities in the different orders, grouped symmetrically around the zeroth order. First, the parameter w has been determined by fitting a simple Gaussian into the data points of Fig. 3a. Then, $I(x)$ has been adjusted to the data taken with the grating inserted (Fig. 3b and c) by a least square fit and is displayed in Fig. 3b and c as a solid line. The good correspondence between the data points and the fitted curve justifies this approach. As one can see in Fig. 3b and c, the third order peaks are not significantly above background: they are therefore omitted in the following discussion.

The fit yields the following experimental results: the diffraction maxima for a nozzle temperature of $T = 295\,\mathrm{K}$ are at angles $\theta_n = n \cdot (105 \pm 15)\,\mu\mathrm{rad}$, corresponding to a de Broglie wavelength of $\lambda_{dB} = 0.53 \pm 0.08\,\text{Å}$. For $T = 83\,\mathrm{K}$ we find $\theta_n = n \cdot (186 \pm 16)\,\mu\mathrm{rad}$, corresponding to $\lambda_{dB} = 0.93 \pm 0.08\,\text{Å}$. Let us compare these experimental values with the theoretically predicted ones $\theta_n = n \cdot \lambda_{dB}/d$ (where $d = 0.5\,\mu\text{m}$ is determined from a scanning electron microscope picture of the grating and λ_{dB} is derived from the measured mean velocity in the atomic beam): For $T = 295\,\text{K}$ one expects angles $\theta_n = n \cdot (112 \pm 11)\,\mu\text{rad}$, corresponding to a de Broglie wavelength of $\lambda_{dB} = 0.56 \pm 0.06\,\text{Å}$ and for $T = 83\,\text{K}$ we find $\theta_n = n \cdot (206 \pm 20)\,\mu\text{rad}$, corresponding to $\lambda_{dB} = 1.03 \pm 0.10\,\text{Å}$. The main uncertainty in the theoretical values is due to the limited accuracy in the measured mean velocity. The comparison yields a relative error between theory and experiment of 10% or less, which is within the experimental uncertainty.

The relative intensities in the different diffraction orders i_n are evaluated to be $i_0 : i_1 : i_2 = 100 : 40 : 5$ for both nozzle temperatures. These values are not in agreement with theory, if one assumes a perfect grating. However, a more detailed look at the electron microscope picture (Fig. 2b) shows that there are deviations from the ideal grating. This experimental fact can be approximated by setting the transmission function of a single slit to:

$$t_{\text{slit}}(x') = t_0 \exp\left(-\frac{x'^2}{2 \cdot dx^2}\right) \tag{2}$$

that means the transmission function is not perfectly rectangular, but smeared out according to a Gaussian distribution. The only parameter dx is determined by using this transmission function in the Fraunhofer integral and fitting it to the observed intensity distribution. In this case, one obtains almost perfect agreement with the experimental intensity distribution with errors less than 5%. The fitted value of $dx = 0.16 \cdot d = 0.08\,\mu\text{m}$ is in very good agreement with the electron microscope picture and corresponds to a total transmission of the grating of 32%, which is also in excellent agreement with the experiment.

This model for the grating transmission function is not the only possible one to explain the observed intensity distribution in the different diffraction peaks. A specific complex transmission function $t_{\text{slit}}(x') = t_0(x')\, e^{i\phi(x')}$ (both amplitude and phase modulation) with rectangular $t_0(x')$ and triangular $\phi(x')$ can also be fitted to the data to good approximation. Such a complex transmission function would result, e.g., if one assumes a van der Waals interaction of an atom with the grating walls [17]. Nevertheless, a Gaussian shape model of a single slit seems to be a much more appropriate model for the real situation and it explains all the observed effects within our experimental accuracy.

3. Conclusion

Our experiments have shown that transmission structures made of gold are ideal beam splitters for metastable helium atoms since they combine many interesting features: the gratings are easy to handle, they represent stand-alone systems and have a transmission ratio for metastable helium atoms that is equal to the geometrical aperture. Although we have only performed experiments with helium atoms, similar results should also be obtained with the other rare gas atoms neon, argon, krypton, and xenon. The diffraction efficiency into higher orders is in good agreement with a simple model for the grating.

The metastable helium atoms have the advantage to be inert and to be detected on nearly zero background, which could be of great importance for the future development of an atom interferometer based on diffraction gratings. Thus beams of metastable noble gas atoms, in connection with microfabricated structures, represent very interesting systems to study atom optics [8].

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