Diffraction of Atoms by a Transmission Grating

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We have demonstrated a novel diffraction grating for atoms. A collimated beam of sodium atoms with a de Broglie wavelength of 17 pm was diffracted by transmission through an array of slits with a spatial period of 0.2 μm formed in a gold membrane. This is the first reported diffraction of atoms by a fabricated periodic structure. Our transmission grating for atoms can divide or recombine an atomic beam coherently, and may provide the easiest route to the realization of an atom wave interferometer.

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We report the first observation of the diffraction of atoms from a fabricated diffraction grating. More specifically, we observed diffraction of a highly collimated beam of atomic Na from a transmission grating of narrow slits in a gold foil. We note that the diffraction of atoms by an edge has been previously observed,[1] as well as the diffraction of atoms reflected from the periodic potential of a crystal surface,[2] and the diffraction of atoms by a standing wave of light.[3] Our observation seems significant because these transmission diffraction gratings, when used as beam splitters and combiners, may be the best technology for the construction of an atom interferometer. We discuss this application at the end of this paper.

Our diffraction gratings, which were developed for soft x-ray spectroscopy, consist of a 0.5-μm-thick, 9×4-mm^2 array of gold bars each about 0.1 μm wide with 0.1-μm slits in between. The grating fabrication process is described in detail elsewhere.[4] The grating periodicity is established by exposing a photoresist film to a uv optical interference pattern (so-called holographic lithography). Subsequent processing yields a mask suitable for x-ray lithography which is used to form a relief grating in a 0.5-μm-thick polymethyl methacrylate (PMMA) film. The substrate for the PMMA is a Si wafer coated with $\sim$5 nm of chromium and $\sim$10 nm of gold (the "plating base"). Gold is electroplated to fill the slots in the relief grating, and then the PMMA is removed leaving the gold bars on the thin plating base supported by the silicon wafer. Because such a structure would be too weak to stand on its own, a 4-μm period grating, formed by gold electroplating, is superimposed orthogonally onto the 0.2-μm period grating, and a 150-μm period grating is superimposed orthogonal to the 4-μm period grating to form a support grid. Finally, the silicon is dissolved and the plating base is removed by ion beam bombardment leaving a free-standing grating. Figure 1 shows scanning-electron-microscope micrographs of a completed grating.

The atomic beam system, described elsewhere,[3] is a supersonic nozzle beam of sodium in argon carrier gas. Adiabatic expansion of the gas after it leaves the nozzle results in a fairly monochromatic beam; $\Delta v/v=12\%$ with $v=10^3$ m/s. The sodium has the same velocity as the carrier gas giving it a de Broglie wavelength (λ_{dB}) of 17 pm. The beam is collimated by two 10-μm slits spaced 1 m apart to form a 2-mm$\times$10-μm ribbon-shaped

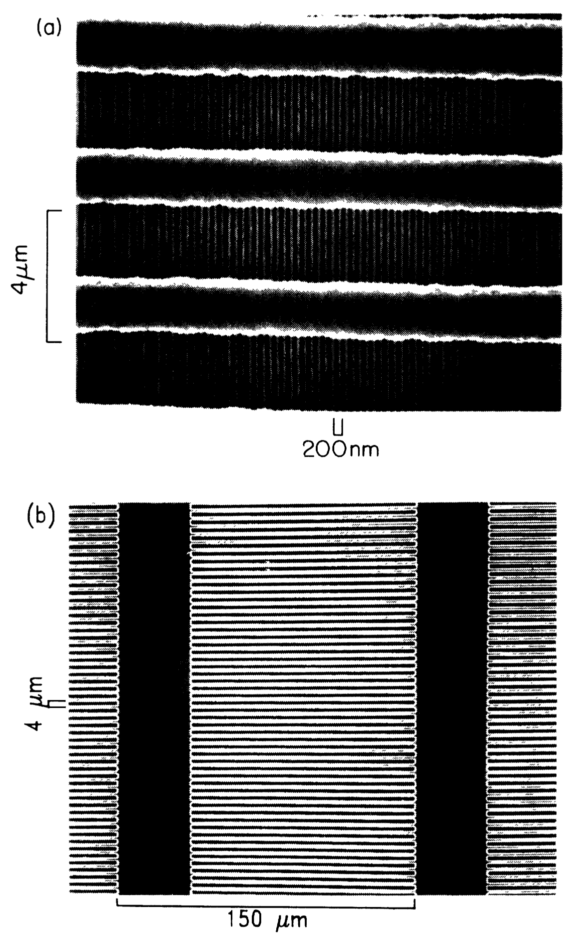

FIG. 1. Scanning-electron-microscope micrographs of the completed grating at two different scales. (a) 0.2-μm period grating overlaid with the 4-μm period grating. (b) 150×4-μm^2 support grid on a larger scale.

beam with a divergence of 10 μrad. Individual atoms are detected after surface ionization on a 25-μm-diam hot wire (Pt-W alloy) located 1.5 m downstream from the second slit. The detector can be moved perpendicularly to the beam in 10-μm (7 μrad in angle) steps to measure the profile of the beam. The resulting angular resolution is $\sim$25 μrad as can be seen in Fig. 2(a).

Figure 2(b) shows the profile of the atomic beam diffracted by the grating which is placed $\sim$1 cm on the detector side of the second collimating slit. The positions of the diffracted orders are given by the usual grating equation for small angles, $\theta_n = n\lambda_{dB}/d$ where d is the grating period, which gives $\theta_{\pm 1} = 85$ μrad for our standard case. The second-order peaks are suppressed because the slit width is half the grating period. The higher orders are lost in the noise (e.g., the intensity of the $n = \pm 3$ orders should be only 4.5% of $n = 0$).

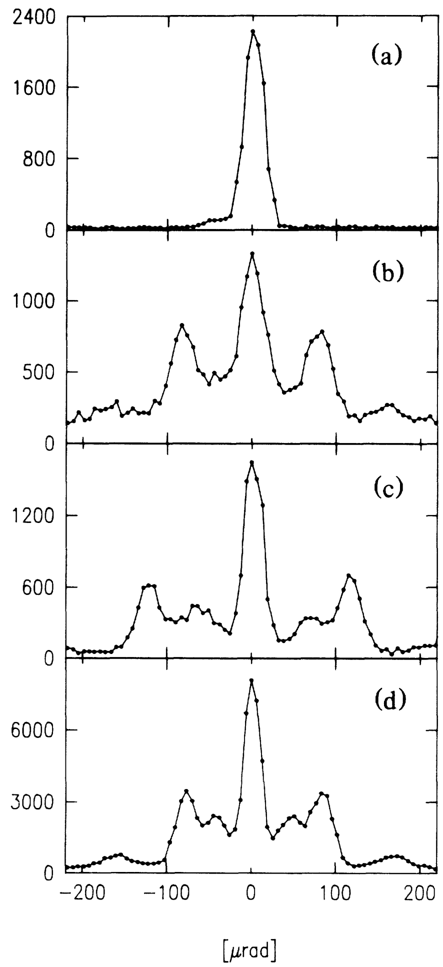

FIG. 2. Experimental profile of the Na beam. The y axes are the number of detected atoms; the counting time at each point is $\sim$1 sec. The line through the points is only for visual effect. As explained in the text, (a) is the undiffracted beam, and (b)–(d) show the beam diffracted by transmission through the grating. In (c) the carrier gas is Xe, in the other cases it is Ar.

In order to increase the separation of the diffracted beams it is possible to lower the velocity of the sodium, and hence increase its de Broglie wavelength, by using a heavier carrier gas. This is because the gas velocity after expansion is inversely proportional to the square root of the mass. It is helpful to use a noble gas in order to suppress the formation of molecules and clusters; we chose xenon. Figure 2(c) shows the diffraction of the slow beam by the grating. The separation of the first-order peaks is 240 μrad, which is 1.5 times the separation for argon carrier gas. This indicates that we did not realize the full slowing predicted by the mass ratio, $(m_{Xe}/m_{Ar})^{1/2} = 1.8$. We presume that this is due to residual argon in the reservoir or to a velocity slip of the two components.

The strong intermediate peaks visible in Fig. 2(c) must be caused by a grating aberration with a period twice the fundamental. The deformation responsible is clearly evident in Fig. 3. This aberration is only present in isolated regions of the grating; it is caused by uneven tension in the grating membrane. Figure 2(d) shows the beam seeded with argon diffracted by a region of the grating with the same aberration. The variation in total signal strength between the data sets is due to long-time scale fluctuations in the raw beam intensity.

The diffraction gratings demonstrated here offer significant advantages over existing beam splitters which might be used to construct an atom interferometer. We first present some reasons for our interest in an atom interferometer, followed by a discussion of the relative merits of beam splitters which could be used to build one.

Interferometers measure the difference in phase accumulated by a particle while traveling between two points over different paths. The phase of the quantum-mechanical amplitude for a particle to go between two

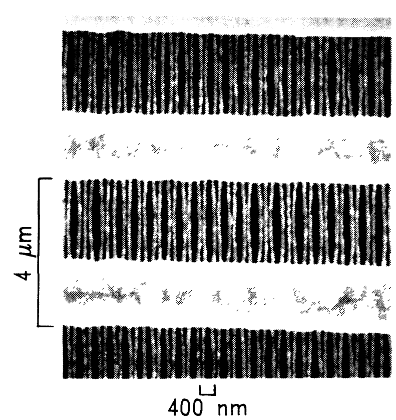

FIG. 3. Scanning electron microscope micrograph of a portion of the grating that was damaged during mounting.

points over a given path is proportional to the classical action for that path. Thus, an interferometer is sensitive to anything that affects the classical action, either changes in relative path length or any interaction (e.g., electromagnetic or gravitational) which changes the energy of the particles. To date, matter wave interferometers have been realized for neutrons[5] and electrons.[6]

An atom interferometer would allow a number of new experiments in atomic physics such as measurement of the Casimir atom-wall potential, the phase shift on rotation of bosons, and various manifestations of Berry's phase (e.g., of atoms in spatially varying magnetic fields). Atom interferometers could lead to large improvements in the resolution of certain null searches such as the electron-proton charge difference.

For applications involving measurement of absolute rotation (Sagnac effect), relative translation, or gravitation, atoms appear to be better for matter wave interferometers than either electrons or neutrons. The neutrality of atoms means that they are far less sensitive to stray fields than electrons, allowing the operation of much larger area interferometers. Atoms are more useful than neutrons because they are available (at thermal energies) with 1 to 100 times shorter wavelengths, and are produced by cheap compact sources. More importantly, the detected spectral brightness (particles sr^{-1} $time^{-1}$ $area^{-1}$ $v/\Delta v$) of available atomic beam sources is from 10^4 (our source) to 10^6 times brighter than the best neutron source.[7] High fluxes should enable an atomic interferometer to make use of the fringe splitting techniques developed for optical interferometers (e.g., servo to the steepest point on a fringe and measure the error signal). Because the magnitude of the Sagnac effect scales with the rest energy (the energy for a photon) of the particles, the intrinsic sensitivity of atom interferometers to rotations 10^{10} times greater than that of a geometrically similar laser gyro. It is possible that such a gyro could eventually be used to detect the dragging of inertial frames (lense Thirring effect) predicted by general relativity.[8]

The key component necessary for an atom interferometer is a coherent beam splitter. Because of the large potential energy of atoms in solids the tunneling depth of a free atom with thermal energy is less than atomic dimensions; thus, beam splitters based on partial transmission appear impossible. We envisage four types of beam splitters for atoms; all are based on diffraction by periodic media. Two types involve reflection: diffraction from the atomic planes of a crystal surface and grazing incidence diffraction from a fabricated surface. The other two types are diffraction by transmission through a fabricated structure or through a standing wave of light. All of these methods, except diffraction by grazing incidence reflection from a fabricated surface, have now been demonstrated.

In addition to a beam splitter, one must be able to achieve sufficient mechanical rigidity, flatness, and alignment of the separate components of an interferometer to observe fringes. The required resistance to relative vibration scales with the de Broglie wavelength and the angle of incidence (the grazing angle θ_{gr} is the complement of the conventional angle of incidence). Specifically, for beam splitters involving a reflection the surface must be flat (over the area of the beam) and mechanically stable (during the detector response time) relative to other surfaces to order $\theta_{gr}\lambda_{dB}$. For transmission gratings one requires stability to order $\theta_{gr}d$ (the "effective" grating period), a less restrictive condition. For some, "space-invariant" transmission grating interferometers the requirements are even weaker.[9] To build a successful interferometer one wants diffracted angles large enough for a useful separation of the beams, but not so large that the required alignment and stability are too difficult to achieve. With this condition in mind we will now discuss the merits of existing beam splitters.

Although it was not recognized as such, the first atomic beam splitter was demonstrated in 1929[2]; it was the diffraction of atoms from the surface of ionic crystals. Because the interatomic spacing in a crystal surface is of the same order as the de Broglie wavelength of typical atomic beams, the angular separation of the diffracted beam is of order unity (i.e., ~ 1 rad). Constructing an interferometer from these crystal surface beam splitters would be exceptionally challenging because it requires relative flatness and rigidity of separate surfaces to less than atomic dimensions.

In 1983 our group demonstrated the Kapitza-Dirac effect in which atoms are diffracted from a standing wave of near resonant light.[3] The grating period in the standing wave is $\frac{1}{2}$ the optical wavelength; thus the angular separation of the diffracted orders is $2\lambda_{dB}/\lambda_{light}$ which is ~ 60 μrad for a thermal sodium beam. Interferometers based on this technique have been proposed,[10] but the diffracted angles are frustratingly small. In addition, this method is limited to atoms that have accessible laser transitions (frequently requiring optical state preparation of the atoms), which are not the atomic species most suitable for the production of intense atomic beams (e.g., He).

The reflection,[11] focusing,[12] and diffraction of atoms have been realized using their interaction with intense near-resonant laser light. We believe that it will be fruitful to look for alternative atomic optical elements based on the technology developed for x-ray optics. It should be possible to adopt grazing incidence x-ray mirrors, lenses, and diffraction gratings for use with atom beams. These techniques would be based on the specular reflection of atoms from smooth surfaces, which occurs when the surface roughness is much less than the wavelength corresponding to the momentum of the atom perpendicular to the surface. For example, efficient specular reflection of reactive atoms with thermal velocity at angles (θ_{gr}) of up to 40 mrad has recently been reported by Anderson *et al.*[13] A disadvantage of these methods is that they are critically sensitive to contamination of the reflecting surface. Another class of x-ray optical elements that could be adapted for use with atoms is based on transmission through microfabricated structures. In addition to the diffraction gratings described in this paper, we believe that similar methods could be used to produce zone plates and eventually waveguide arrays, for atoms.

In conclusion, the transmission diffraction grating reported here has many advantages over a Kapitza-Dirac grating which has been suggested as a beam splitter for an atom interferometer. It has $\frac{2}{3}$ the period, will work with any atomic species, and requires neither a frequency stabilized laser nor optical preparation of the atoms. In the near future we hope to achieve diffracted angles more than an order of magnitude larger than are demonstrated here. We expect to do this by halving the grating period and by using the gratings at grazing incidence. The effective spatial period of the gold-foil grating can be varied by changing its orientation with respect to the beam. We expect that it will be possible to reduce the thickness of the gratings so that the ratio of slit depth to separation is 1/10 instead of the current 5/1. This would allow the grating to be used at a grazing angle of $\sim \frac{1}{5}$ rad giving a fivefold increase in effective line density and thus in the beam separation. Such a grating would be ideal for the construction of the first atom interferometer.

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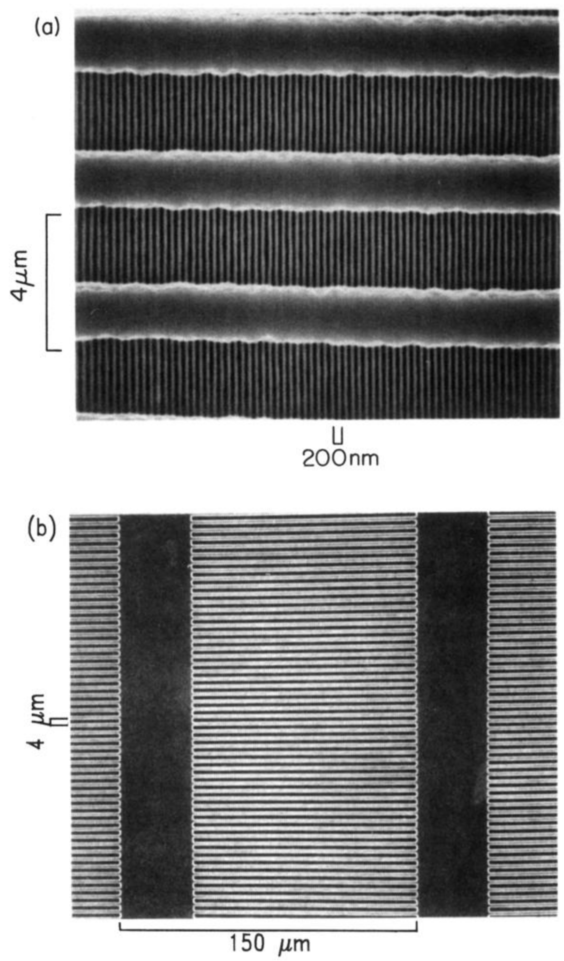

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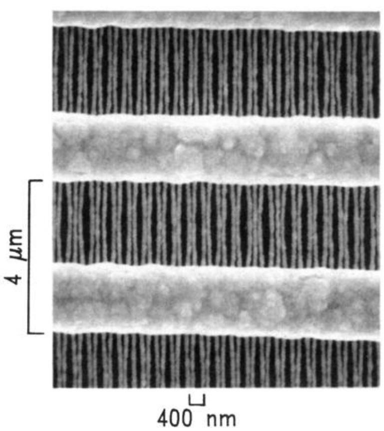

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