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Reflection of thermal Cs atoms grazing a polished glass surface

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We present an experimental study which shows that a large fraction ($\geq 50\%$) of thermal Cs atoms are nearly specularly reflected by polished glass surfaces at grazing incidence. This effect is interesting in the context of projects aimed at storing cold alkali-metal atoms in boxes.

Specular reflection of atoms by surfaces can occur when the de Broglie wavelengths corresponding to the atomic motion perpendicular to the interface are larger than the characteristic lengths associated with the surface. For heavy alkali-metal atoms at room temperature and usual glass surfaces such as the walls of a resonance cell, the atom-surface interaction is quite different: The atoms are scattered from the walls after dwelling on the surface for a wide range of times, some of them even sticking permanently. In this case, the surface is expected to reemit the atoms diffusively with a distribution obeying Lambert's law (i.e., with an intensity proportional to the sine of the angle θ between the outgoing atom velocity and the surface). The atom-surface collision is then seen as "classical," since the atom de Broglie wavelength (of the order of 0.1 Å for Cs at room temperature) is very small compared to the characteristic surface roughness (usually several hundred angstroms).

In a series of experiments involving thermal Cs atoms impinging at grazing incidence ($\theta \leq 1°$) on carefully polished fused silica surfaces, we have observed a scattering regime intermediate between the specular and diffuse ones, with a large fraction of the atoms undergoing a nearly specular bounce on the surface. In these experiments, the de Broglie wavelength of the atomic motion perpendicular to the surface, λ_B/θ, is of the order of the local surface roughness (~ 10 Å), so that the quantum-mechanical requirement for specular reflection is met in spite of the high temperature and large atomic mass. Although the occurrence of specular atomic reflection has already been reported for atoms impinging on a surface at grazing incidence,[1,2] our result is interesting because it is, to our knowledge, the first observation of the effect for a reactive atom impinging at thermal energy on a surface at room temperature. It will be interesting to check whether the same surface should specularly reflect slower atoms at larger angles and whether very slow Cs atoms should elastically bounce off room-temperature polished fused silica surfaces at all angles of incidence. This would be very promising, as has already been suggested, for trapping and storing laser-cooled Cs atoms in a box.[3]

We started to investigate the interaction of Cs atoms with polished glass in the process of developing very narrow collimating slits for atomic beam-surface experiments. The slits were made from two fused silica blocks stacked against each other but separated at the top and bottom by thin spacers. The two adjacent surfaces are planar to $\lambda/10$ over the whole 3×0.8 cm^2 area and the local flatness, checked by interferometry, is much better (the irregularities are beyond the resolution of our angstrometer, i.e., less than 25 Å over a few square mm area). The spacing between the flats was fixed by evaporation of aluminum layers onto the edges of the surfaces or by using calibrated tantalum foils as spacers, the flats being pressed against each other by springs. In this way, we have built long tunnel-like slits as narrow as 1 μm. The ratio between the slit width g and its length $L = 8$ mm determines the "collimating angle" $\theta_0 = g/L$ of the tunnel, which is only $\sim 10^{-4}$ rad for $g = 1$ μm. The inner surfaces of the tunnel are either left uncoated (glass tunnel gap) or covered with a 500-Å-thick gold evaporation coating (metal tunnel gap). The inset in Fig. 1 shows a scanning electron microscope picture of a part of the tunnel exit ($g = 1$ μm) in the case of a metal gap. This picture gives an idea of the quality of the block edges.

We have sent a Cs atomic beam through such tunnels. The Cs atoms are produced by an oven mounted at a distance $R = 15$ cm away from the gap. The oven has a slit of width $w = 50$ μm, oriented parallel to the tunnel entrance and can be translated in the direction perpendicular to the slit and the beam propagation directions. The atomic transmission through the tunnel is monitored either by

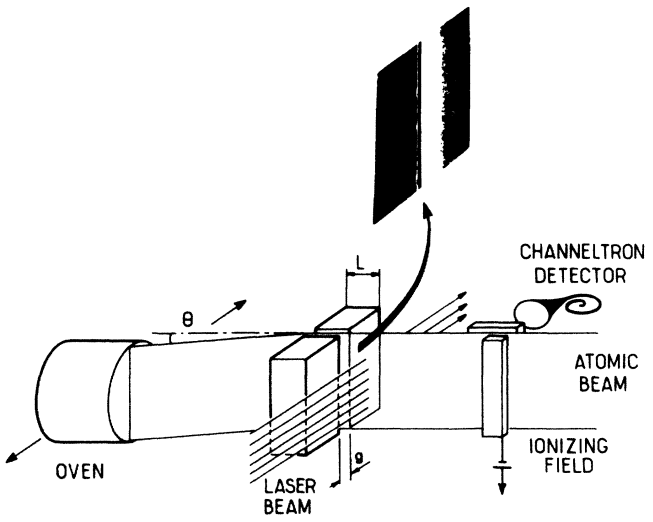

FIG. 1. Scheme of Cs beam collimation setup. Inset: scanning electron microscope picture in which the dark vertical stripe is exit of tunnel gap.

detecting laser-induced fluorescence (see below), or by laser exciting the atoms into a Rydberg state and detecting the Rydberg electrons by field ionization using a channeltron. Figure 2(a) shows the tunnel transmission versus oven position in the case of a 1.5-μm-wide metal gap cooled to liquid-nitrogen temperature. The oven position is characterized by the angle θ between the Cs beam axis and the tunnel axis. With the oven at 140°C, typical electron counts at maximum transmission are in the kHz range, corresponding to atom fluxes through the gap of 10^4–10^5 sec^{-1}. The transmission curve implies in this case a ballistic atom flight through the tunnel since we observe that the signal drops linearly with θ and cuts off for an angle greater than $\theta_0+w/2R=3.5\times10^{-4}$ rad (the limiting angle is larger than θ_0 because of the finite value of the slit width). This means that the metal gap surface has a large sticking factor for Cs atoms and only those atoms which have not touched the tunnel walls emerge on the other side. Figure 2(b) shows a very different transmission curve for the case of a 3 μm wide glass tunnel gap. There is clear evidence that the atoms are now transmitted when θ is much larger than $\theta_0+w/2R=5.4\times10^{-4}$ rad, i.e., necessarily experiencing several bounces on the surface. This result does not depend appreciably upon the gap temperature ($T=300$ K or $T=77$ K).

Our observation is not by itself surprising. It is well known that the sticking factor for Cs on glass is much smaller than on gold, a fact that is directly related to the different electron affinities of the two kinds of surface. Narrow gaps have been used as collimators since the early days of atomic beams[4] and it is well known that the collimating process—in the low-pressure regime—is a combination of direct ballistic flight and scattering of atoms on surfaces.[5] However, a simple model assuming a purely diffuse process in which the atoms are scattered by the surface according to Lambert's law should give a transmission given roughly by $\theta_0/2\theta$ [dashed curve on Fig. 2(b)] and not the flat transmission curve observed in the experiment over a wide range of θ values. A qualitative description of diffuse scattering along the tunnel goes as follows: The lateral gap surface directly exposed to the incoming atomic beam acts as an effective source of atoms emitted in all directions according to Lambert's law. The atoms then diffuse inside the gap following a random walk. The density of scattered atoms along the tunnel should thus decrease (in fact nearly linearly) and drop to zero at the exit. The exiting atoms are the directly transmitted ones (for which $\theta<\theta_0$), plus those which have been scattered into the exit from the various positions along the gap. In this sum, the decrease of atom density along the gap is partially compensated by the increase of solid angle subtended by the exit and eventually all parts of the tunnel contribute to the exit signal. The integrated atomic flux is proportional to the gap surface area directly exposed to the impinging beam, which varies as $1/\theta$.

The results in Fig. 2(b), clearly at variance with a $1/\theta$ law, show that the above model does not account properly for the observed transmission. A simple way of explaining the discrepancy is to assume that the atoms have a large probability of bouncing when incident at a small angle—of the order of θ_0—to the surface. By such a process, the atoms would penetrate much deeper into the gap after a few bounces, with the effect of strongly increasing the overall transmission for θ values larger than θ_0.

In order to check this assumption, we have performed the direct Cs-atom scattering experiment at nearly grazing incidence whose setup is shown in Fig. 3. The Cs beam now impinges on a single glass surface (identical to the ones used to build the "tunnels") at a small angle of incidence θ which can be varied from 0° to 2°. In order to rotate the beam with respect to the surface, a collimating slit (40 μm wide) is placed 7.5 mm from the upstream edge of the surface and, as in the previous experiment the oven is translated perpendicular to the beam direction (oven to slit distance: 15 cm). This translation then directly results in a rotation of the Cs beam with respect to the surface. The Cs atoms are excited downstream from

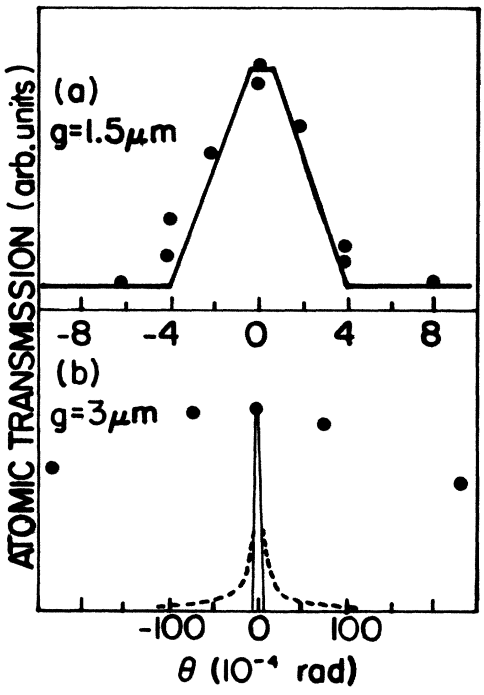

FIG. 2. Tunnel transmission vs angle between atomic beam and tunnel direction: (a) for a metal gap ($g=1.5$ μm); (b) for a glass gap ($g=3$ μm). We show for comparison the theoretical profiles corresponding to a metallic absorptive gap (solid lines) and to a diffusive gap (dashed lines).

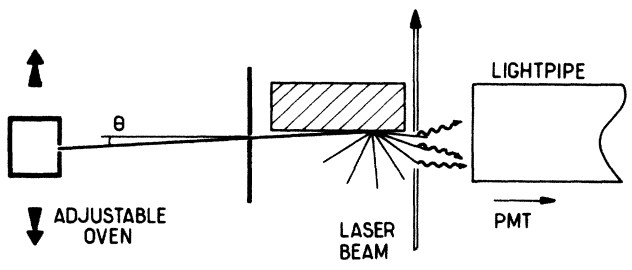

FIG. 3. Experimental setup of Cs-glass scattering experiment. The final velocity perpendicular to the surface is analyzed by laser fluorescence spectroscopy.

the surface by a cw dye laser beam tuned to the $6S \rightarrow 7P_{3/2}$ resonance line of cesium at 4555 Å and the subsequent fluorescence (infrared cascade on the $6p \rightarrow 6s$ transition) is collected by the light pipe and sent to a photomultiplier. The laser beam is carefully made perpendicular to the plane surface. The recording of the fluorescence spectrum versus the laser frequency provides a measurement of the projection of the atomic velocity along the direction perpendicular to the scattering surface. Figure 4(a) shows a typical fluorescence spectrum observed for $\theta = 0°$, i.e., for an atomic beam flying parallel to the surface. The atoms are not scattered at all in this case and we observe a Doppler-free spectrum exhibiting the three $6S_{1/2}$, $F=4 \rightarrow 7P_{3/2}$, $F=5,4,3$ hyperfine components of the second Cs resonance line. Figure 4(b) shows a similar spectrum recorded for $\theta = 4\times10^{-2}$ rad. The fluorescence now comes from atoms excited *after* they have been scattered by the surface. If the scattering process obeyed Lambert's law, the spectrum—shown by the dashed curve—would be very wide with a large average red shift (since the atoms fly toward the laser after scattering, the laser frequency should be red-shifted to be on resonance). Taking into account the geometry of the apparatus and the detection efficiency for the fluorescence produced at various points along the laser beam, one would expect an average red shift of 200 MHz, i.e., an effective velocity toward the laser beam of 80 m/s. The hyperfine structure (83- and 66-MHz splittings) would be completely washed out in this case. The observed spectrum presents on the contrary relatively narrow and almost unshifted hyperfine features, on top of a broad Doppler background. From an analysis of these spectra, we conclude that at least 50% of the atoms undergo a nearly specular reflection.

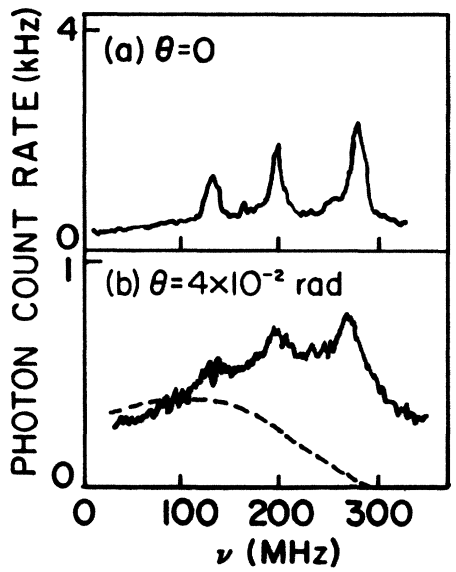

FIG. 4. Fluorescence spectra of the $6S_{1/2}$, $F=4 \rightarrow 7P_{3/2}$, $F=5,4,3$ hyperfine components observed in the Cs-glass surface scattering experiment: (a) for $\theta=0$ (atoms flying parallel to surface); (b) for $\theta=4\times10^{-2}$ rad. The resolved hyperfine structure is evidence of near specular reflection. For comparison, dashed line shows the Doppler profile corresponding to a purely diffusive scattering process. Laser frequency detuning ν is in MHz. Vertical scale gives photon count rate in kHz.

We have systematically studied these fluorescence spectra as a function of the incidence angle in the range $1° < \theta < 2°$ and measured the average Doppler shift of the largest hyperfine component of the spectrum. We have found that in this range of incidence angles, the Doppler red shift remains smaller than 10 MHz, which corresponds to an average reflected beam angle smaller than 2°. Thus it seems—but here we are at the limit of our frequency shift measurement accuracy—that the reflection even exhibits a subspecular character: The atoms have a large probability of emerging from the scattering process with their velocity direction closer to the surface than the incident beam.

No basic difference was found in these experiments between surfaces at room and slightly elevated ($T=80°C$) temperatures. We have on the other hand observed that the results are subject to variations with the state of the surface. The scattering signal increases with time at the start of a new run, as if an initial surface passivation process were necessary. After several hours of operation, the scattering signal disappears (and is restored only by heating the surface). This can be attributed to Cs-atom contamination which eventually increases the sticking factor on the surface.

From this scattering experiment, a new picture of atom collimation in the glass tunnel emerges in which the atoms have a probability of being guided along the surface at grazing incidence. The atomic medium in the gap contains a class of atoms behaving as a kind of two-dimensional gas propagating along the surface. We have started to study this gas by laser spectroscopy. It is indeed very easy to excite atoms inside the tunnel by sending the blue laser beam through the transparent glass blocks and to detect the fluroescence photons channeled along the gap toward the light pipe placed at the tunnel exit. The spectrum exhibits sharp Doppler-free features, which means that most of the atoms inside the gap propagate along the surface. A detailed analysis of the spectrum, including its intensity as a function of the atom position along the gap, should allow us to determine which fraction of the atoms is diffusely scattered and which undergoes grazing reflection. These intensity measurements are difficult because the fluorescence detection efficiency also strongly depends upon the atom position since the photons are themselves scattered along the surface.

The occurrence of a specular reflection lobe for thermal atoms impinging at grazing incidence on polished glass was reported thirty years ago in a review of classical atom-surface scattering experiments.[1] However, those experiments involved argon, i.e., a nonreactive gas, whereas we have observed it with a very reactive species which for obvious reasons is not usually studied in surface experiments. On the other hand, also for obvious reasons, cesium is a prime candidate in laser-cooling atomic beam experiments. It is thus very interesting to know that even at thermal energies it can experience nearly elastic bouncing on solid surfaces. This knowledge should stimulate similar studies with the much slower alkali-metal atoms (temperatures $\sim10^{-3}$ K) which are now being produced in several

laboratories.[6] For these slow atoms, the de Broglie wavelength λ_B is so large (~ 50 Å) that the condition for specular reflection on polished glass should be met for all angles of incidence. It is important to notice, however, that in the experiments reported here, the atoms have a large tangential momentum with respect to the surface. This momentum might very well help prevent the atoms from dwelling on the surface and make the specular bounce more likely to occur. We cannot accurately predict the behavior of slow atoms of large de Broglie wavelength but small tangential momentum, since to our knowledge there is no detailed understanding of the atom-surface scattering mechanism leading to specular or subspecular reflection of atoms on surfaces such as fused silica. Such a theory will be much needed in order to understand what happens to the external and internal degrees of freedom of slow atoms confined in boxes.

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[1]F. C. Hurlbut, in *Recent Research in Molecular Beams,* edited by I. Estermann (Academic, New York, 1959).

[2]V. U. Nayak, D. O. Edwards, and N. Masuhara, Phys. Rev. Lett. **50**, 990 (1983).

[3]S. Chu, J. E. Bjorkholm, A. Ashkin, L. Hollberg, and A. Cable, in *Proceedings of the Fritz Haber Symposium on Methods of Laser Spectroscopy,* edited by Y. Prior (Plenum, New York, 1986).

[4]M. Smoluchowski, Ann. Phys. (Leipzig) **33**, 1559 (1910); J. G. King and J. R. Zacharias, in *Advances in Electronics and Electron Physics,* edited by L. Marton (Academic, New York, 1956), Vol. 8, and references therein.

[5]J. A. Giordmaine and T. C. Wang, J. Appl. Phys. **31**, 463 (1960); G. R. Hanes, *ibid.* **31**, 2171 (1960).

[6]A. Migdall, J. Prodan, W. D. Phillips, T. H. Bergeman, and H. T. Metcalf, Phys. Rev. Lett. **54**, 2596 (1985); W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, *ibid.* **54**, 996 (1985); S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, and A. Ashkin, *ibid.* **55**, 48 (1985).