from the dipole moment of HF. The total numbers of electrons for Ar and HF are denoted by Z_{Ar} and Z_{HF}, respectively. Equation (6) yields a result of 3×10^{-17} cm^2 for $(\langle z^2\rangle - \langle x^2\rangle)^{Ar}$ where the error is as large as the value itself. The error arises from the measured value of $\langle z^2\rangle - \langle x^2\rangle$ in Eq. (6). This indicates that the electron cloud distortion cannot be determined within experimental error.

In conclusion, we have presented the first observation of the molecular Zeeman effect of a van der Waals molecule: ArHF. The molecular $g_\perp$ value is $-0.005\,03(12)$ and $\chi_\parallel - \chi_\perp$ is $(-1.7 \pm 1.1)\times10^{-30}$ cm^3. The molecular g value is approximately consistent with the value predicted by use of the electronic and magnetic properties of free Ar and HF, if one assumes a structure Ar···HF. The quadrupole moment $Q_\parallel = -2.79(77)\times10^{-26}$ statcoulomb cm^2. The new technique used here should be applicable to study the molecular Zeeman effect in any weakly bound complex that can be studied by pulsed Fourier-transform microwave spectroscopy in a Fabry-Perot cavity. Further investigation of the rotational Zeeman effect of X-HY complexes is underway.

The support of the National Science Foundation and the University of Illinois School of Chemical Sciences is gratefully acknowledged. The authors are deeply indebted to Professor W. H. Flygare, whose inspiration was responsible for the development of this instrument. We also thank Dr. T. J. Balle and W. H. Flygare for purchasing the magnet, and Mr. Dan Wozniak for designing and building the averager used in this experiment.

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Laser Production of a Very Slow Monoenergetic Atomic Beam

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(Received 2 August 1982)

With use of a resonant, counterpropagating laser beam the velocity of atoms in a neutral, thermal-sodium beam has been reduced to 40 m/s, or 4% of their initial velocity. These atoms have a kinetic energy comparable to the well depth of proposed optical traps. The "temperature" characterizing the atoms' relative motion was reduced to 70 mK.

PACS numbers: 32.80.-t, 07.77.+p, 32.30.Jc

A single, free atom at rest would be the ideal spectroscopic sample. While laser cooling[1] has produced dramatic progress toward this goal for ions,[2] there has been relatively little progress for neutral atoms. In earlier work[3] we reported the first resonant laser deceleration of an atomic beam of neutral Na atoms.[4] In this Letter we describe experiments in which we have deceler-

ated atoms to 4% of their initial velocity, and have reduced the "temperature" of their relative motion to a fraction of a kelvin.

With the production of such very slow, cold atoms, neutral-atom deceleration has been taken from the status of an interesting demonstration to that of a practical tool. For example, in ultra-high-resolution spectroscopy, such slow atoms would reduce spectral width due to transit-time effects by a factor of 25 and second-order Doppler shifts and widths by more than a factor of 600. In addition, the translational energy of our slowest atoms is comparable to the potential-well depth in some proposed laser atom traps.[5] While atom trapping by lasers has yet to be demonstrated, the availability of suitably slow atoms now makes such trapping more feasible.

In addition to extreme deceleration and cooling of the atomic beam, we have observed dramatic compression of the velocity distribution. We have produced a beam with only a 10% velocity spread and a beam density per unit velocity interval 10 times that of a thermal beam. Such velocity modification of atomic beams should prove to be quite useful in spectroscopy or atomic scattering.

The basic method and apparatus for laser deceleration has already been described.[3] We will briefly review these below (see Fig. 1) and describe the key changes which have been made. A collimated atomic Na beam with a source temperature of 950 K is opposed by a counterpropagating, fixed-frequency, cooling laser beam, tuned to induce transitions between $3^2S_{1/2}(F=2, m_F=2)$ and $3^2P_{3/2}(F=3, m_F=3)$. A solenoid produces a uniform "bias" magnetic field along the common laser–atomic-beam axis. This, along with circular polarization of the light, helps suppress unwanted transitions. Repeated unidirectional photon absorption and random reradiation by spontaneous emission reduces the atomic velocity by an average of 3 cm/s per photon absorbed. The resulting slow atoms are optically oriented and aligned.

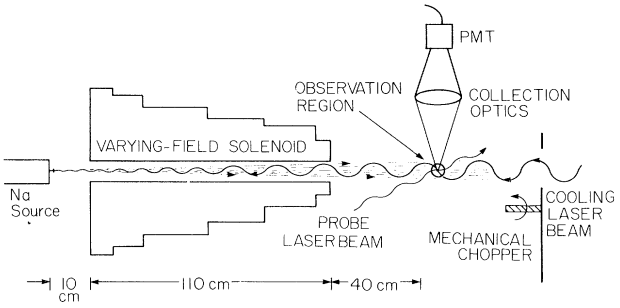

FIG. 1. Experimental setup. The perpendicular part of the probe (for the frequency markers) goes into the page at the intersection of the other beams and is retroreflected.

As the atoms decelerate, their changing Doppler shift tends to take them out of resonance with the cooling laser. This shift is compensated by a changing Zeeman shift from an additional, spatially varying magnetic field produced by extra sections wound on the solenoid. Atoms of a particular velocity begin to decelerate when they reach the position in the solenoid where the magnetic field brings them into resonance with the cooling laser. Those atoms slower than some maximum velocity v_0 are decelerated into a narrow group around a final velocity v_c. Atoms which are so fast that they are never in resonance are never decelerated. The Doppler shift corresponding to $v_0 - v_c$ equals the change in Zeeman shift through the solenoid. At the end of the solenoid, where the field drops rapidly, the atoms go out of resonance with the cooling laser and stop decelerating.

The atomic velocity distribution is determined by observing fluorescence induced by a second, very weak, probe laser which crosses the atomic beam at a slight angle. Because of the Doppler shift, observation of the fluorescence as a function of the slowly scanned probe-laser frequency gives the atomic-beam spatial density per unit velocity interval as a function of velocity. To avoid confusion with the fluorescence from the much stronger cooling laser, the cooling laser is shut off during the observation time.

By coincidence, the mean Doppler shift of the sodium beam is about equal to the hyperfine ground-state (HFGS) splitting (1772 MHz). Therefore the counterpropagating probe as used in the previous experiments[3] would be simultaneously in resonance with slow HFGS $F=2$ atoms and with fast $F=1$ atoms. To avoid this, we have used a probe which is nearly copropagating with the atom beam.

An absolute determination of the Doppler shift (and therefore the atomic velocity) is made by directing a portion of the probe beam perpendicular to the atomic beam. The frequency at which this auxiliary beam is resonant with the atoms is, to first order, the rest-frame resonant frequency ν_0. This frequency corresponds to zero Doppler shift, and thus to zero-velocity atoms for the nearly parallel probe. Frequency dis-

placements from this zero are calibrated in terms of the HFGS splitting. The frequency of the cooling laser relative to the probe is determined by mixing them on a photodiode and recording the zero beat.

A key difference from our previous experiments is that the spatially varying field is now twice as long, with twice the field change. This allows a larger velocity reduction while keeping the rate of change of the field small enough that the atoms can stay in resonance as they decelerate.[3] The field is designed to allow atoms with $v_0 = 900$ m/s to be stopped in 90 cm, as the field drops from a maximum of 0.16 T to the bias level of 0.05 T.

Another modification is that the cooling laser, with a power of 50 mW and a diameter of 20 mm at the observation region, is focused to a diameter of 1 mm at the Na source, 1.6 m away. This convergence leads to a reduction of the atoms' transverse momentum, thus reducing the increase in atomic beam divergence as the longitudinal velocity decreases.

In the previous experiments,[3] we observed the atomic velocity distribution for 50 μs following a short (50 μs) delay after the cooling laser was shut off. This gives a very good measure of the distribution of atoms reaching the observation region, in the presence of the cooling laser. Unfortunately, atoms with very low velocities will be stopped or turned around before traveling the 40 cm from the solenoid to the observation region, and thus will never be detected. To avoid this we introduce a longer delay between turning off the cooling laser and observing the fluorescence induced by the probe. This gives time for slow atoms (which were still in the solenoid when the cooling laser was shut off) to drift, without further deceleration, into the observation region.

Figure 2(a) shows a sequence of velocity distributions obtained in this way for various delay times. (For delays greater than 4.5 ms, a 500-μs sampling time was used, while for shorter delays, 50 μs was used.) For all delay times, the cooling laser was tuned to be in resonance, at the maximum field, with atoms of velocity 900 m/s, which is slightly slower than the most probable velocity in the atomic beam. For each delay, a narrow distribution[6] of slow atoms is seen on top of the broad background from sodium vapor with random velocity directions. At longer delay times, slower atoms are seen since they take longer to arrive. The pair of peaks near $\nu - \nu_0 = 0$ are the frequency markers resulting from the $\perp$ portion of the probe laser. They correspond to $3^2S_{1/2}(F=2) \rightarrow 3^2P_{3/2}(F=2)$ and $3^2S_{1/2}(F=2) \rightarrow 3^2P_{3/2}(F=3)$, the latter being the zero-velocity reference line.

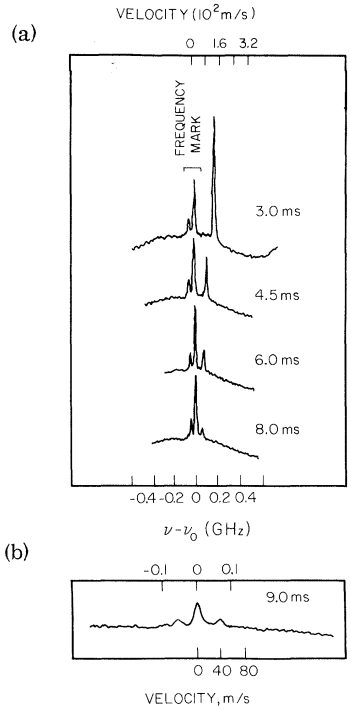

FIG. 2. (a) Velocity distribution of cooled atomic beam for various observational delay times. The broad background is from nonbeam Na atoms. (b) Slowest observed velocity distribution, obtained with 9-ms observational delay.

Based on the kinematic effects of angular divergence (due to both finite collimation and momentum of transverse spontaneous emissions) and longitudinal compression of the atomic beam which accompany the deceleration, we expect the observed density of slow atoms to vary linearly with the velocity. In fact, we observe a stronger dependence, a discrepancy which we believe is at least partly due to scattering from background gases. For all the data shown here we used a liquid-N_2 trap to reduce background pressure (estimated to be 10^{-5} to 10^{-6} Torr) near the observation region; this greatly increases the number of slow atoms observed. The improvement is most dramatic at the lowest velocities. A better vacuum near the observation region should give further improvement.

Various refocusing techniques may also be useful for increasing the observed slow-atom beam density. Dipole focusing in a Gaussian laser beam,[7] magnetic focusing in a hexapole magnet,[8]

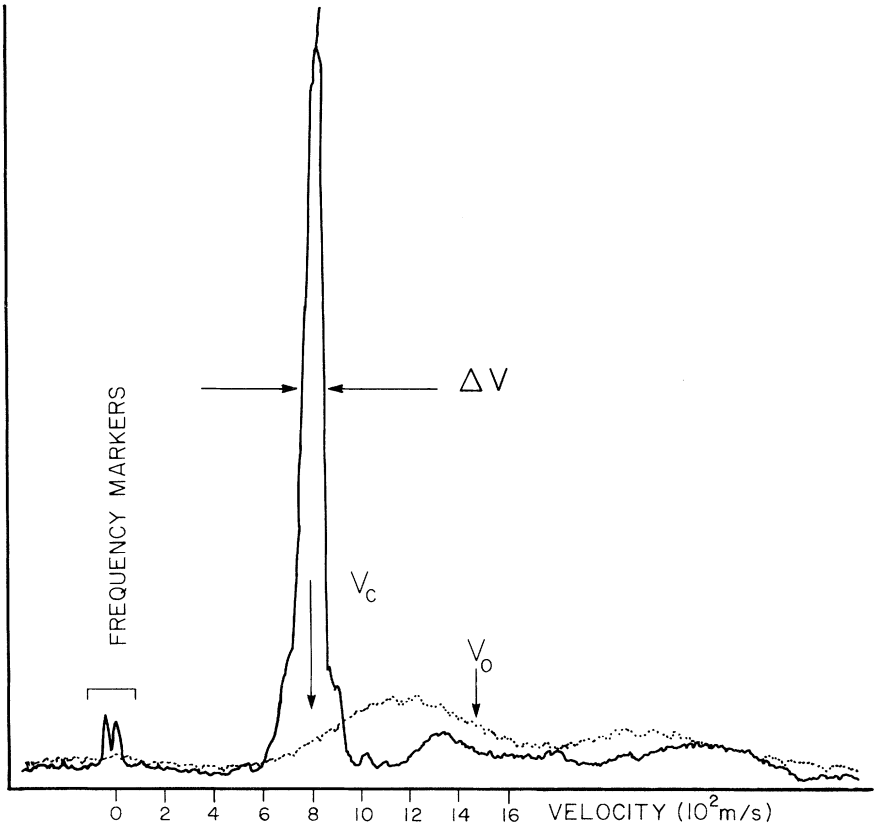

FIG. 3. Laser-compressed velocity distribution (solid line). The unmodified distribution is shown dotted. The broad feature with apparent velocity near 2×10^3 m/s is actually from atoms in the $F=1$ ground state having velocities around 10^3 m/s.

and compression of the atomic beam with transversely directed resonant laser beams are all possibilities.

Figure 2(b) shows the slowest velocity we have observed—40 m/s, or about $\frac{1}{25}$ of the initial, thermal velocity. The density of these atoms is about $1\times10^5/\text{cm}^3$, or 30 times less than the density of the most probable velocity atoms in the original beam. The full width at half maximum in velocity is about 10 m/s. If the distribution were Maxwellian this would correspond to a temperature of 70 mK. The kinetic energy of the slow atoms is about 2×10^{-4} eV. This is comparable to the well depth of proposed optical traps[5,9] which may confine atoms through radiative dipole forces and, in some cases, radiation pressure.

Figure 3, obtained with a 50-μs delay, shows the effect of tuning the cooling laser to be initially in resonance with atoms which are too fast to be decelerated to near zero velocity. While the atoms only decelerate to a velocity v_c about half of the initial velocity v_0, the density of decelerated atoms per unit velocity interval is 10 times that at the peak of the original, undecelerated velocity distribution. This results from sweeping atoms with velocities between v_0 and v_c into v_c. The integral of the modified velocity distribution is larger than that of the thermal distribution since for constant flux and lower velocity, the density must increase.

The width Δv of the peak at v_c is $v_c/10$, demonstrating the utility of laser deceleration for atomic-beam "velocity selection." The advantage of this laser velocity selection over mechanical selection is that unwanted velocities are compressed into the desired velocity rather than being discarded.

In summary, we have used momentum transfer from a counterpropagating laser beam to reduce the velocity of atoms in a beam by a factor of 25, while reducing the effective "temperature" to 70 mK. These slow atoms may be used directly for high-resolution spectroscopy to reduce drasti-

cally spectral width due to transit time and second-order Doppler effects. We have also demonstrated the use of laser deceleration as a highly efficient means of producing a monoenergetic atomic beam which should have important applications in spectroscopy, collision work, and other areas which use atomic beams. Slow atoms could be confined in optical traps by the sudden turning on of a trapping laser when the atoms were near the center of the trap. Alternatively, the atoms could be further decelerated and focused[7] into a continuously operating trap.[5] The atoms could also be trapped by magnetic fields, in much the same way that cold neutrons are trapped.[10] Such traps have been constructed with well depths greater than the energy of our slowest atoms.

We are continuing to work on improving the slow-atom density, which should allow the observation of still slower atoms. We are also pursuing applications of slow atoms to trapping and ultrahigh-resolution spectroscopy.

This work was supported in part by the U. S. Office of Naval Research. One of us (J.V.P.) is the recipient of a National Research Council postdoctoral fellowship.

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Double Ionization of Helium by Protons and Electrons at High Velocities

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(Received 28 June 1982)

Double ionization of helium at high projectile velocities, v, is considered in terms of two mechanisms. In the shakeoff mechanism the ratio of double- to single-ionization cross sections, σ^{ii}/σ^{i}, is independent of v. In the two-step mechanism it is shown that $\sigma^{ii}/\sigma^{i} \sim (v^2 \ln v)^{-1}$. Combining amplitudes gives a reasonable fit to the observed velocity dependence as well as an explanation of the observed factor-of-2 differences between double ionization of helium by protons and electrons near $v \simeq 10 v_{\mathrm{Bohr}}$.

PACS numbers: 34.50.He, 34.80.Dp

At high velocities the physics of atomic collisions becomes relatively simple. For example, single ionization of atoms by charged particles is fairly well understood[1] in terms of the Born approximation at high projectile velocities, $v > v_{\mathrm{orbit}}$. Here the total cross sections for single ionization by protons and electrons are the same and vary as $v^{-2}\ln v$. However, double ionization at high velocities is not so well understood, even for the simplest two-electron targets. Over the past twenty years double ionization of helium has been observed by a number of independent groups[2-9] at v up to almost $40 v_B$ (where v_B is the Bohr velocity), or 20 times the electron orbit velocity in helium. There has been no satisfactory explanation of the velocity dependence of these data. And there has been no explanation of the ~ 50% differences between double ionization by electrons and protons.

In this Letter double ionization of helium is

