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Magneto-optical trapping of metastable xenon: Isotope-shift measurements

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We have magneto-optically trapped the nine stable isotopes of xenon. Using the Zeeman slowing method to decelerate a beam of xenon atoms in the metastable $6s\ 3/2\ [3/2]_2$ state (notation representing $nl\ J_{\text{core}}\ [K=J_{\text{core}}+l]_J$), we load our trap to a collisionally limited density of more than 10^{10} atoms/cm^3. The two odd isotopes are trapped without a repumping frequency, even though they have hyperfine structure. The sensitivity of the trapping process to the laser frequency is exploited to make accurate measurements of the isotope shifts for the $6s\ 3/2\ [3/2]_2 \rightarrow 6p\ 3/2\ [5/2]_3$ laser-cooling transition and of the hyperfine constants for ^{131}Xe.

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In this paper we report the laser cooling and trapping of xenon. We have selectively trapped all nine stable isotopes, including two with less than 0.1% natural abundance. We also present accurate measurements of isotope shifts for the $6s\ 3/2\ [3/2]_2 \rightarrow 6p\ 3/2\ [5/2]_3$ laser-cooling transition (pair-coupling notation: $nl\ J_{\text{core}}\ [K=J_{\text{core}}+l]_J$). Trapping xenon is important for several reasons. Like cesium, it can be cooled to a few microkelvin, or an average speed of about 1 cm/s, in optical molasses. Collisions between such slow xenon atoms can be studied easily by detection of ions produced by Penning ionization. In addition, Rolston and Phillips have proposed a laser-cooled optical frequency standard which would operate on a two-photon transition between the metastable $6s\ 3/2\ [3/2]_2\ (^3P_2)$ and $6s\ 1/2\ [1/2]_0\ (^3P_0)$ states [1]. Finally, two of the stable xenon isotopes are fermions, and the remaining seven bosons, so the effects of different spin statistics may be studied using the same element.

In our experiment a beam of xenon atoms in the metastable $6s\ 3/2\ [3/2]_2$ state is decelerated using the familiar Zeeman slowing technique [2] and collected in a magneto-optical trap (MOT) [3]. Our apparatus is shown schematically in Fig. 1. The metastable source, which is similar in design to that of Fahey, Parks, and Shearer [4], is a quartz chamber filled with xenon gas to a pressure of 100 to 250 Pa. Atoms escape from the source with an average speed of about 300 m/s through an aperture 0.14 mm in diameter. The beam is collimated by a 1-mm skimmer aperture placed 1 cm from the source and by an aperture of similar size 30 cm further downstream. As the gas leaves the source, it is excited by a dc discharge running between the skimmer and a cathode filament inside the quartz chamber. Atoms that emerge from the source in the $6s\ 3/2\ [3/2]_2$ state, which has a predicted [5] lifetime of greater than 100 s, are accessible for laser cooling. All of the laser beams in the experiment are derived from a single titanium:sapphire laser, which is locked to the $6s\ 3/2\ [3/2]_2 \rightarrow 6p\ 3/2\ [5/2]_3$ cooling transition at 882 nm using saturated absorption in a dc discharge cell. Frequencies for the slowing, trapping, and probe laser beams are generated by acousto-optic modulators (AOM's).

Our method of Zeeman deceleration draws on techniques developed in Refs. [6] and [7]. The slowing magnet is composed of two tapered solenoids placed end to end and producing fields in opposite directions. The field along the atomic beam decreases monotonically in the first solenoid from 16 mT near the last collimating aperture to zero 1.1 m downstream. In the second solenoid the field continues to decrease from zero to -6.5 mT over a distance of 0.4 m. A 10-mW, circularly polarized laser beam is directed against the atomic beam and detuned 135 MHz below the atomic resonance frequency. This slowing laser beam is 2 cm in diameter as it enters the low-field end of the magnet and is focused on the quartz nozzle. As atoms travel the length of the magnet, they scatter photons from the slowing beam and decelerate. The changing Zeeman shift compensates for the changing Doppler shift, so that resonant scattering is maintained in the usual way. At the end of the slowing region, the magnetic field changes from -6.5 mT to

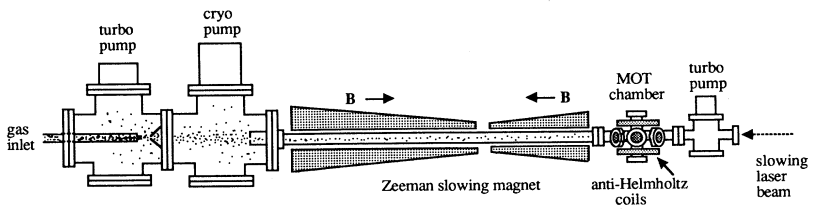

FIG. 1. Apparatus for decelerating and trapping metastable xenon.

nearly zero over a few centimeters, and the atoms stop scattering resonantly, having reached an average velocity of 20 m/s with a spread of about 5 m/s.

The slow atoms are captured in a MOT positioned 15 cm beyond the end of the slowing magnet. The trap is formed at the intersection of three orthogonal pairs of counterpropagating, oppositely circularly polarized laser beams, and at the center of a quadrupolar magnetic field produced by a pair of anti-Helmholtz coils. The field gradient along the MOT coil axis is typically 0.5 mT/cm, and the MOT beams are 2 cm in diameter, with approximately uniform intensity. The laser power in each beam is normally about 15 mW, and the trap is brightest for a MOT laser detuning of about 3 MHz, or approximately half a linewidth, below resonance. The background pressure in the system is 4×10^{-6} Pa. A notable feature of our trap is that is resides directly in the path of the slowing laser beam. Because of the large detuning of this beam, the MOT is virtually unaffected by its presence, though the loading is enhanced by the favorable geometry.

We have used our trap to capture selectively all nine stable isotopes of xenon. These include ^{124}Xe and ^{126}Xe, each of which has less than 0.1% natural abundance. Trap lifetime measurements indicate that all but these two isotopes are loaded into the trap until the density becomes limited by collisions between trapped atoms. We perform the lifetime measurements by recording the level of trap fluorescence after turning off the loading of the MOT, either by closing a shutter in the atomic beam or by switching off the slowing laser beam. Typically we find that the fluorescence decreases to half its initial value in a few tenths of a second. For the more abundant isotopes, we consistently see a nonexponential decay of the MOT fluorescence at shorter times, indicating a density-dependent loss mechanism due to collisions between trapped atoms. The lifetime due to background gas collisions, observed at longer times, is of order 1 s, which is consistent with measurements in other metastable atom traps [8,9].

To estimate the density of atoms in the MOT, we measured the size and brightness of the trapped cloud for the most abundant isotope, ^{132}Xe. A camera was used to image the cloud, and the spatial profile was found to be approximately Gaussian with a full width at half maximum of 0.3 mm. To measure the intensity of the fluorescence, we imaged the MOT on a photodiode, periodically opened and closed the shutter in the atomic beam, and recorded the change in diode photocurrent as the trap filled and decayed. Accounting for the solid angle of collection and the quantum efficiency of the detector, and assuming about half the atoms to be in the upper state (the total laser intensity was $\sim$30 times the saturation intensity), we obtained an estimate of 2×10^{5} atoms in the trap. From this number and the cloud size we estimate the mean atomic density in the MOT to be about 2×10^{10}/cm^3. This value is higher than densities obtained in traps for other metastable rare gases, which are more strongly limited by Penning ionization. Densities in He* and Ar* MOT's, for example, are typically found in the range of 10^{9}/cm^3 or less [8,10].

For intensities of a few mW/cm^2 in each MOT laser beam, the two odd (fermionic) isotopes were trapped efficiently without a second "repumping" frequency coupling the excited state to any untrapped hyperfine level in the ground state [2]. This is possible in xenon because the hyperfine splittings in the excited $6p\ 3/2\ [5/2]_3$ state are so large that transitions to levels other than the desired one are relatively unlikely. For example, in ^{129}Xe, laser cooling operates on the $F=5/2\rightarrow F'=7/2$ transition, and the transition to the $F'=5/2$ excited state is detuned by $\sim$3000 MHz (or $\sim$500 linewidths). Only infrequently do atoms undergo nonresonant transitions to this level, decay to the $F=3/2$ ground level, and cease to be trapped. By increasing the MOT laser power we were able to power broaden these nonresonant transitions and cause the trap brightness and lifetime to decrease.

Our ability to select and trap each of the xenon isotopes by sweeping a single laser frequency has enabled us to make an accurate determination of the isotope shifts for the $6s\ 3/2\ [3/2]_2\rightarrow 6p\ 3/2\ [5/2]_3$ laser-cooling transition. With the relative frequencies of the trapping and slowing beams fixed, we scanned the frequency of the Ti:sapphire laser over the range of frequencies spanned by the cooling transitions of the different isotopes. The fluorescence from the trap was monitored with a photomultiplier and recorded by computer as a function of time. To ensure the calibration of the frequency scan, we also recorded the transmission of the laser light through a confocal Fabry-Pérot cavity with a free spectral range of 74.71$\pm$0.07 MHz. An example of the data we obtained is shown in Fig. 2. Because of collisional limitations on the trap density, the relative heights of the nine peaks do not reflect the relative abundances of the isotopes.

A close look at a single fluorescence peak, as in Fig. 3, reveals a sharp blue edge corresponding to the abrupt turn-off of the MOT as the laser frequency approaches resonance. For each peak we fit a line to the data on this blue edge and noted its point of intersection with the baseline. Frequency separations were measured between such baseline points without regard to the actual positions of the peaks with respect to the atomic resonance. This approach is valid since only relative frequency differences between isotopes are of interest here. The measured isotope shifts for the nine isotopes were found to be independent of MOT density and laser power. Data were analyzed for four frequency scans over all nine peaks and nine scans of the range containing just the even isotope resonances. For each scan, the Fabry-Pérot signal was fit to the usual transmission function, and the frequency scale was determined at the 10^{-3} level.

Obtaining the isotope shifts for ^{129}Xe and ^{131}Xe requires knowledge of the hyperfine structure constants for both states in the laser-cooling transition. The constants of the $6s\ 3/2\ [3/2]_2$ state have been measured previously with kHz accuracy for both odd isotopes [11,12]. We obtained those for the $6p\ 3/2\ [5/2]_3$ state of ^{131}Xe using an AOM to shift the frequency of a weak probe laser beam to the $F=7/2\rightarrow F'=7/2$ and $F=7/2\rightarrow F'=5/2$ transitions. At these two resonances the probe induced trap loss through optical pumping and the brightness of the MOT decreased by about 50%. The loss signals in the

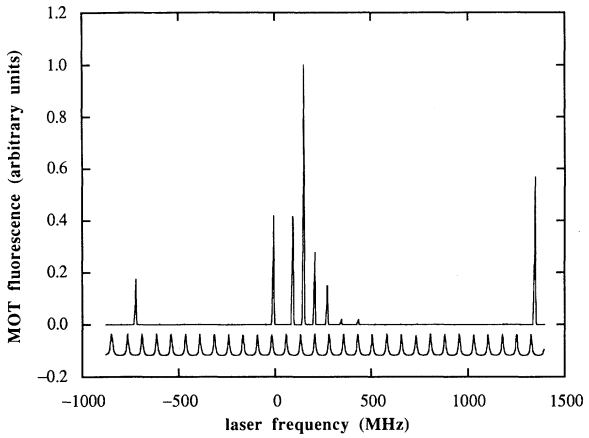

FIG. 2. As the frequencies of the slowing and trapping lasers are scanned simultaneously, the fluorescence from the MOT exhibits nine peaks, corresponding to trapping of the nine xenon isotopes. From left to right, the peaks are identified as ^{131}Xe, ^{136}Xe, ^{134}Xe, ^{132}Xe, ^{130}Xe, ^{128}Xe, ^{126}Xe, ^{124}Xe, and ^{129}Xe. Also shown is the periodic transmission of the laser light through the Fabry-Pérot étalon.

fluorescence were fit by Lorentzian curves, and the shifts in their center frequencies were found to be approximately linear in MOT laser power. To account for ac Stark shifts, the true positions of the resonances were taken to be the zero-power extrapolations of the data. Respectively, the $F=7/2\rightarrow F'=7/2$ and $F=7/2\rightarrow F'=5/2$ transitions were observed 1348±3 MHz and 2172±3 MHz below the $F=7/2\rightarrow F'=9/2$ cooling transition frequency. The uncertainty in these measurements includes the possible errors in our saturated absorption lock frequency, where frequency drift and pressure shifts could be on the order of half a linewidth. The following hyperfine constants for the $6p\ 3/2\ [5/2]_3$ state of ^{131}Xe were de-

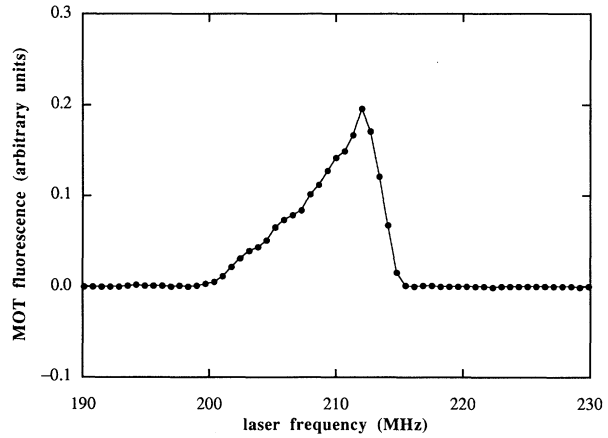

FIG. 3. A close look at a single MOT fluorescence peak (in this case that of ^{130}Xe) reveals a sharp turn-off of the trap as the laser frequency approaches resonance. Frequency separations between various peaks are measured between points at which these sharp edges intersect the baseline.

TABLE I. Measured isotope shifts (IS) for the laser-cooling transition in Xe*.

	$6s\ 3/2\ [3/2]_2$	IS (MHz)	
Isotope	angular momentum	This work	Ref. [16]
136	$J=2$	0	0
134	$J=2$	101.0(9)	99(6)
132	$J=2$	158.1(7)	153(6)
131	$F=7/2$	240(7)	
130	$J=2$	215.0(7)	210(6)
129	$F=5/2$	285(5)	270(9)
128	$J=2$	281.5(10)	273(5)
126	$J=2$	352.4(14)	354(5)
124	$J=2$	441.2(11)	441(5)

rived from our frequency interval measurements: $A_{131}=259.4\pm0.9$ MHz and $B_{131}=241\pm9$ MHz. For ^{129}Xe there is no quadrupole hyperfine interaction, so only the A constant is required, and it is related to A_{131} by the ratio of the nuclear g factors of the two isotopes (assuming a negligible hyperfine anomaly [13]), so that $A_{129}=876\pm3$ MHz. These determinations of the hyperfine structure constants agree with the best previous measurements, but our uncertainties are smaller by more than a factor of 2 [14,15].

With all of the necessary structure constants in hand, we were able to extract the isotope shifts for all of the trapped isotopes. Table I summarizes our results and the previous measurements of Ref. [16]. The total angular momentum in the $6s\ 3/2\ [3/2]_2$ state is given for each isotope, along with the designation of F or J to indicate whether or not hyperfine structure is present. The quoted isotope shifts are measured with respect to the ^{136}Xe resonance and are the mean values of our data. For the even isotopes the errors represent standard deviations of the data. However, since the odd isotope shifts were obtained by subtracting hyperfine shifts from measured frequency splittings, the relatively large uncertainties in A and B enter in their errors. Our results generally agree with the best previous measurements, though we have improved the uncertainties by roughly a factor of 5 [16].

The work presented here demonstrates and exploits the high degree of isotope discrimination that is inherent in laser-cooling and trapping processes. We have easily resolved the signals from the nine stable isotopes of naturally abundant xenon in a MOT, and we have used the frequency sensitivity of the trap to measure the isotope shifts of the laser-cooling transition. Because both odd and even isotopes can be easily trapped, laser-cooled xenon is a promising candidate for comparisons between bosonic and fermionic statistics at low temperatures. We are currently extending the experiments described above to address this possibility as well as collision studies, development of an optical frequency standard, and research in atom optics.

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