LBL-36195
UC-413
Preprint

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Submitted to Physical Review A

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September 1994

Nuclear Science Division

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

Comparison of the Cold-Collision Losses for Laser-Trapped Sodium in Different Ground State Hyperfine Sub-Levels

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Abstract:

We have measured the cold-collision loss rates of laser-trapped Na atoms in each ground-state hyperfine sublevel. The laser intensity dependence for the F=1 sublevel agrees with a simple theory and we establish experimentally that hyperfine-changing collision losses are absent as expected. We observed hyperfine changing collisions in the F = 2 sublevel for the first time but the dependence of the loss rate constant on laser intensity disagrees with simple theories. Unexpected behavior observed for total trapping laser light intensity between 4 and 12 mW/cm^2 may be a consequence of the sub-Doppler cooling in the F = 2 trap.

PACS number: 32.80.Pj

Submitted to *Physical Review A*

The recent developments in neutral-atom laser cooling and trapping provides unique opportunities for studying exoergic collisions [1-6]. Indeed, in a collision between two of the ultracold atoms contained in magneto-optical traps only exoergic processes cause an atom to be ejected. Several detailed studies have demonstrated the role of excited atoms and radiationless de-excitations [7-9]. Large effects are expected because atom-atom interaction times are comparable to the radiative decay times. Cold atom collisions also probe the long-range components of atom-atom force. Beyond the inherent interest of these new aspects of collision dynamics a deep understanding is required for achieving high atomic densities and for realizing many of the potential physics applications of neutral atom traps.

Here, we report the results of a study of the cold-collision loss-rate constants for sodium atoms trapped in each of its two ground state hyperfine levels, shown in Fig. 1, which are split by 1772 MHz. Hyperfine changing collision losses have been observed in cesium [2] and rubidium [4], but these effect are harder to see in sodium and they are reported here for the first time along with a comparison of cold-collision losses for both hyperfine sublevels of the sodium ground state. Dramatic differences appear at low laser intensity where hyperfine-changing collisions are important. Compared to cesium or rubidium, sodium hyperfine-changing collisions are difficult to observe because they take effect at laser intensities which are small compared to the saturation intensity. Many interesting aspects of cold collisions in sodium are easily missed. Indeed we were able to see these effects by employing a newly-developed highly-efficient trap-loading scheme. For a trap containing sodium in the F = 2 ground state the cold-collision losses are dominated by hyperfine-changing collisions below intensities of 4 mW/cm^2 (this is the sum intensity of the six trapping laser beams at the carrier frequency). The observation that there are no hyperfine changing collisions in the "F = 1 trap", confirms our interpretation of the operative trapping transition. At higher laser intensity losses from cold collisions should change with the $3P_{3/2}$ excited state population as $n_e n_g = n_e (1 - n_e)$. While this relation appears to hold for the F = 1 trap, the F = 2 trap exhibits anomalies between 4-12 mW/cm^2.

The arrangement of the experiment is shown in Fig. 2, sodium atoms effuse from a 200 ^oC oven 1.5 m from the trap region. The atomic beam passes through a decreasing gradient solenoid magnet [10] and a three-element tunable "extraction" solenoid before stopping at the center of a magneto-optical trap (MOT) [11]. The maximum magnetic field is about 0.1 T at the solenoid entrance, decreasing smoothly to 15 mT in the extraction region. The magnetic gradient in the standard magneto-optical trap is about 2 mT/cm. A Coherent Model 899 ring dye laser produces about 800 mW at the $3S_{1/2} \rightarrow 3P_{3/2}$ sodium transition at $\lambda = 589$ nm. A small fraction of the light goes to a sodium vapor cell, providing a saturated absorption signal for laser locking. The frequency drift is not greater than 0.5 MHz over a run. An electro-optical modulator generates a "repumping" sideband, insuring that the atoms populate only the ground state hyperfine component of interest. The laser beam passes through a spatial filter before it is split into separate circularly-polarized trapping beams all being 6 mm in diameter. The counter-propagating pairs in the six beam trap magneto-optical trap have opposite helicities. We can easily trap more than 10^8 sodium atoms per second using this arrangement. The system is very efficient; about 20% of the thermal beam flux at magneto-optical trap region is captured in the MOT.

Figure 3 shows typical frequency scans of the optical fluorescence from the trap over the range of frequencies containing resonance transitions originating from the F = 2 ground-state hyperfine level. Scans are shown for different sideband frequency shifts. The scans indicate that atom traps are being formed at two different frequencies. The high-frequency trap does not change its position in the scan as the sideband frequency is changed. This is the expected behavior of the well established trap associated with the F = 2 to F' = 3 cycling transition. In contrast, the fluorescence signal of the low-frequency trap changes position with the sideband frequency shifts. This behavior indicates that the trap is not associated with the F = 2 ground state. Indeed it is easy to see that for the low-frequency trap, the trapping force comes from the sideband light interacting with the F = 1 ground state. A sodium trap at a lower frequency was reported in the initial work on magneto-optical trapping where it was denoted as a "type-II trap"[12]. Up to now, the precise nature of this type-II trap has not been explained. Referring to the level scheme in Fig. 1, we note that for the scans in Fig. 3 the trapping-light frequency is always less than the F = 1 to F' "slow-down" laser beam were blocked by shutters. As the trap decayed, we observed the optical fluorescence with a calibrated PIN diode. The number of trapped atoms is determined from the measured fluorescence and the laser beam intensity, assuming equal population of the relevant m_F-sublevels. As noted in Ref. 4, this crude procedure is consistent with more exact measurements within an overall systematic error of about 20%. The atomic density was determined by measuring the volume of cold atoms with a charged-coupled device (CCD) camera. The uncertainty in the trap size, about 50 μm, due to the finite CCD pixel size, was the main systematic uncertainty, leading to a 20% error in the density in the worst case. As noted in Ref. 2, the density in magneto-optical trap is limited by radiation trapping effects, and, in general, the volume of atoms grows in proportion to the number of atoms at high densities. But for low densities, reabsorption is negligible, and the distribution atoms is a well defined Gaussian sphere independent of the number. For the F = 1 trap, the diameter of the atomic cloud was about 1 mm over the range of experimental parameters. For the F = 2 trap, the cloud had a diameter of about 0.5 mm when the laser intensity was above 30 mW/cm^2. The diameter decreases gradually with lower intensity to about 0.35 mm below 6 mW/cm^2. Below 1.7 mW/cm^2 the volume of trapped atoms abruptly increased to about 1 mm diameter. The initial density was well below 10^9 $atoms/cm^3$ for the measurements reported here.

With the atomic beam blocked the time evolution of the atomic density n, is governed by a simple relation: $dn/dt = - \alpha n - \beta n^2$,

= 1 transition frequency. On the other hand the trap exists for frequencies both above and below the F = 1 to F' = 0 transition. In separate measurements in which only one of the trapping beam had a repumping sideband only a single trap formed for frequencies just below the F = 1 to F' = 1 transition. In addition, in this configuration, only F = 2 to F' = 3 trap formed when the laser was scanned across the resonances connected to the F = 2 ground state. These observations indicate that the type-II trap is associated with the F = 1 to F' = 1 transition and that the Na atoms are trapped in the lowest hyperfine sublevel of the ground state. Since the nuclear spin of ^{23}Na is 3/2, the Lande g-factor of all the hyperfine sublevels of the excited $P_{3/2}$ state are equal. To the extent that the ground state magnetic moments are small compared to the excited state, a magnetic field configuration that allows trapping by the F = 2 to F' = 3 transition, will also be appropriate for traps associated with other transitions. The F = 1 to F' = 1 transition is not a cycling transition, but a substantial number, approximately 80%, of atoms excited to the F' = 1 decay back to the F = 1 ground state, making the F = 1 to F' = 1 transition more effective for trapping than other non-cycling transitions. Indeed, because of the high trapping efficiency, we were able to find even weaker traps associated with less favorable non-cycling transitions. A more detailed description of these new traps will be given elsewhere.

The measurements of the cold-collision loss constant involved a simple sequence. First the trap was loaded with sodium. After the number of atoms reached equilibrium, both the atomic beam and the where α, which depends on vacuum pressure, is the loss rate due to collisions between trapped atoms and hot background gas molecules, and β is the cold-collision loss-rate constant for collisions between trapped atoms. During our measurement, the background pressure was about 1×10^{-8} Pa, yielding $\alpha \approx 2.5 \times 10^{-2}$ sec^{-1}. The decreasing fluorescent light was monitored for about 6 α^{-1}, insuring that the background, mostly from scattered light, could be well determined. A three parameter fit to the density gave α, β and the initial density. Statistical errors were negligible comparing to the systematic uncertainties discussed above.

Figure 4 shows the value of β obtained for different laser intensities. For atoms trapped in the F = 2 ground state, β increased with laser intensity above 4 mW/cm^2. This is the expected behavior for collisions of cold atoms in the ground state with cold atoms in the excited state [7-9]. Below 4 mW/cm^2 hyperfine-changing collisions are effective and the loss rate increases rapidly. In a hyperfine changing collision, two atoms in the F = 2 state undergo an exoergic spin exchange leaving one atom in the F = 1 ground state. The conversion of hyperfine energy into kinetic energy increases each atoms velocity by about 6 m/s, allowing both to escape. Under some circumstances, however, an escaping atom is cooled below the trapping potential and recaptured. In fact for many sodium trap configurations, particularly with large-diameter intense lasers beams, recapture is likely. In our case hyperfine changing collisions should dominate at total intensities below about 3 mW/cm^2, corresponding to only about 3% of the single laser beam saturation intensity. Consequently the effects of hyperfine changing collisions are much more easily observable in cesium or rubidium where the atoms are heavier and damping coefficient are smaller. The efficiency loading scheme used in the present experiment permits low laser intensities and small diameter laser beams which reduce recapturing effects. The measured values of β in the region where hyperfine-changing collisions dominate agrees with low-field-extrapolated predictions of Tiesinga et al. [14]. For the F = 1 trap, hyperfine-changing collisions are absent, and β increases with laser intensity over the whole experimental range. The absence of hyperfine-changing collisions supports our association of the type-II trap with sodium in the lower hyperfine sub-level of the ground state.

The data points in Fig. 4 were taken from two different runs of the experiment. The reproducibility of the measurements indicates that variations from possible changes in the laser alignment are small. The fraction of laser light in the repumping sideband varied slightly for the runs but the sideband intensity was always about 1/3 of the carrier. For comparison, a theoretical prediction of L. Marcassa et al. (Fig. 2 from Ref. 5) is shown in Fig. 3. The prediction is in better agreement with the data from the F = 1 trap but the calculation does not take the effect of hyperfine structure into account.

To better display the influence of excited state populations on the collisional loss process we rewrite the two body collision term as:

$-\beta n^2 = -\beta^* n_g n_e$, where n_g and n_e are the density of ground- and excited-state atoms respectively; β^* is the appropriate parameter for ground- plus excited-state atomic collisions [8]. The resulting β^* from this experiment is plotted in Fig. 5 for laser intensities above 4 mW/cm^2. The independence of β^* on intensity above about 12 mW/cm^2 for the F = 2 trap indicates that the intensity dependence of β is explained by the magnitude of the excited state population. The average value of β^* is $(7.6 \pm 0.7) \times 10^{-12}$ cm^3/sec. For the F = 1 trap β^* is independent of laser intensity over the entire range of measurement and the average value of β^* is $(1.64 \pm 0.07) \times 10^{-11}$ cm^3/sec. A constant β^* is expected if the temperature is constant [7-9]. Below 12 mW/cm^2, however, the measured β^* decreases until hyperfine-changing collisions become important below 4 mW/cm^2. This feature could be explained if the effective temperature of the atoms trapped in the F = 2 ground state sublevel decreases rapidly with laser intensity between 12 and 4 mW/cm^2. Obviously colder atoms collide less frequently. This explanation is supported by observations of the atomic cloud which has a minimum in this range of intensities. Previous studies indicate that sub-Doppler cooling mechanisms should be effective at low laser intensities for atoms with multilevel ground states [14, 15]. The F = 2 to F' = 3 transition to satisfies these requirements. On the other hand, sub-Doppler cooling for F = 1 to F' = 1 transitions does not come out of one dimensional models so it may also be absent in our three dimensional experiment. Our results suggest the need for theoretical treatments which account for the multilevel atomic structure in order to facilitate more detailed comparisons with experiment.

We are pleased to acknowledge the helpful suggestions of C. Wieman, W. Phillips, S. Roltson, F. Shimizu, L. Young and W. Ketterle. We are grateful to P. Julienne for useful discussions. We are especially indebted to K. Coulter for his contributions at the early stages of this project. This work was supported in part by US Department of Energy under Contracts DE-AC03-76SF00098 and W-31-109-ENG-38 and a LBL Laboratory Directed Research and Development Program Award. We are also grateful for the support of an AT&T Foundation 1992 Special Purpose Grant in Science and Engineering.

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Figure Captions

1. Energy levels of the ^{23}Na atom showing the two transitions used to trap atoms in the: (a) F = 2, and (b) F =1 ground state hyperfine sublevels.

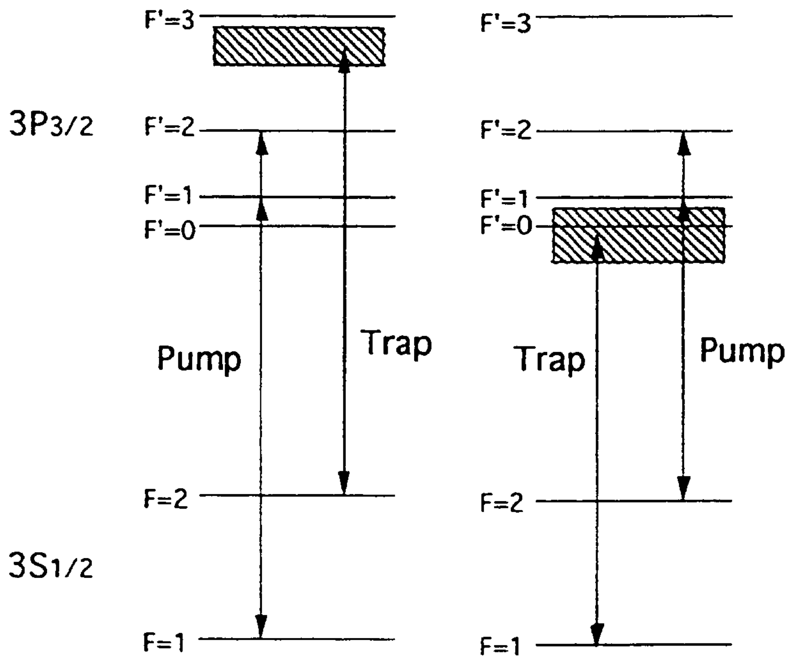
2. Layout of the experimental apparatus.

3. Frequency scans of the laser trap fluorescence in the region of resonances from the F = 2 ground state to the various excited state hyperfine sublevels. The four upper traces correspond to different repumping sideband frequencies (SF). The lower trace is the fluorescence signal from a saturated absorption cell; resonance transition features are indicated by the arrows. The arrow indicated with the letter A is at the F=2 to F'=3 resonance frequency in each scan (A is at the zero detuning point). The letter B indicates the detuning of the laser from the 2-3 transition when the sideband is at the F=1 to F'=1 resonance in each scan, and C is the corresponding point for the F=1 to F'=0 resonance.

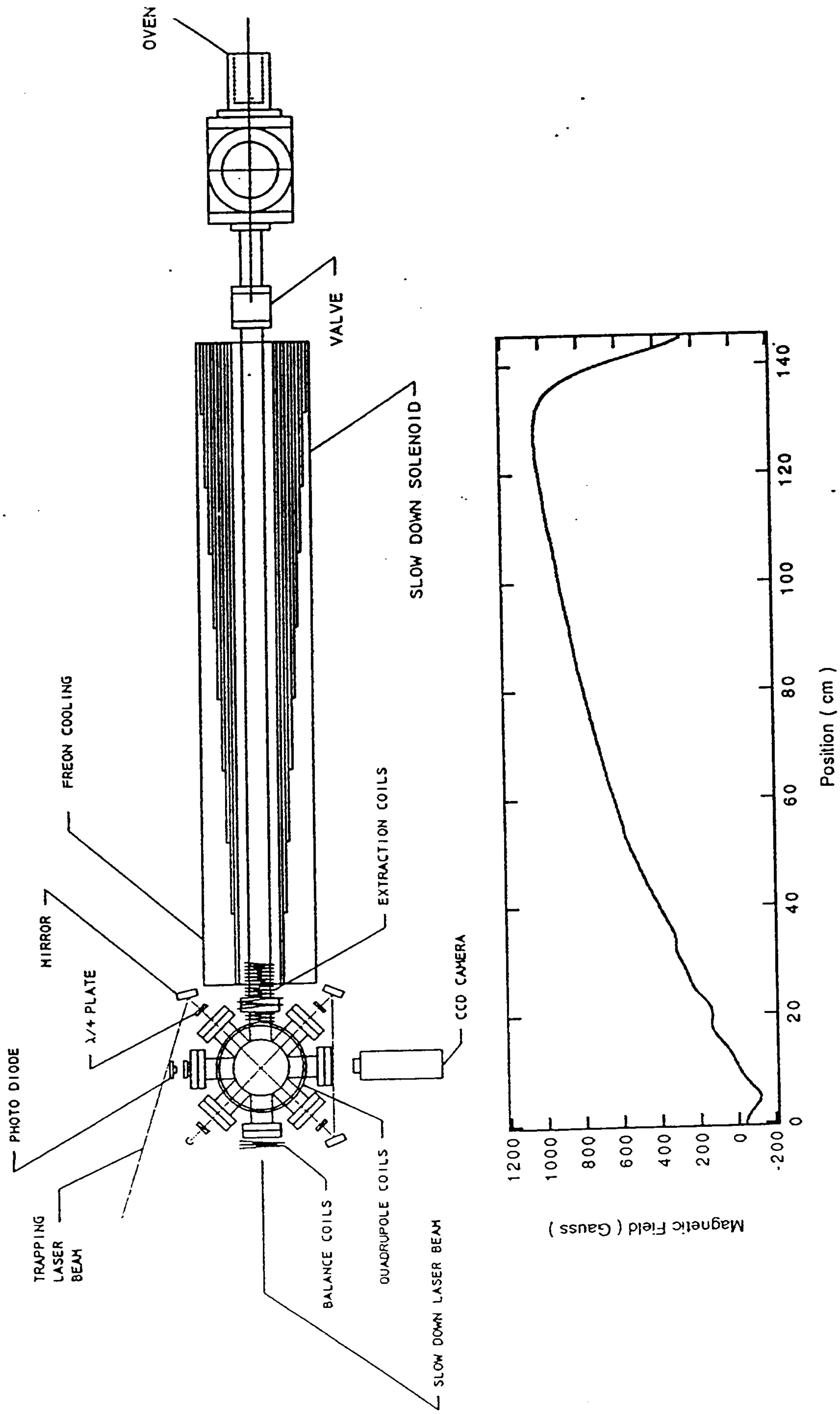
4. The cold-collision loss rate constant β as a function of trapping laser intensity. The laser frequency is detuned -10 MHz from the F = 2 to F' = 3 transition for the F = 2 trap, and -21 MHz from the F = 1 to F' = 1 transition for the F = 1 trap. The repumping sideband is 1712 MHz in each case. The

repumping sideband intensity is about 1/3 of the carrier intensity. The Solid curve is a theoretical prediction from Ref. 5. The 20% error bars reflect the systematic uncertainty in the measurements. Solid and open points indicate data from separate runs of the experiment.

5. The cold-collision loss rate constant β^* for the ground-plus excited state collision as a function of laser intensity



(a) Type I (b) Type II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VALVE
SLOW DOWN SOLENOID
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MIRROR
λ/4 PLATE
CCD CAMERA
PHOTO DIODE
TRAPPING LASER BEAM
BALANCE COILS
QUADRUPOLE COILS
SLOW DOWN LASER BEAM
Magnetic Field (Gauss)
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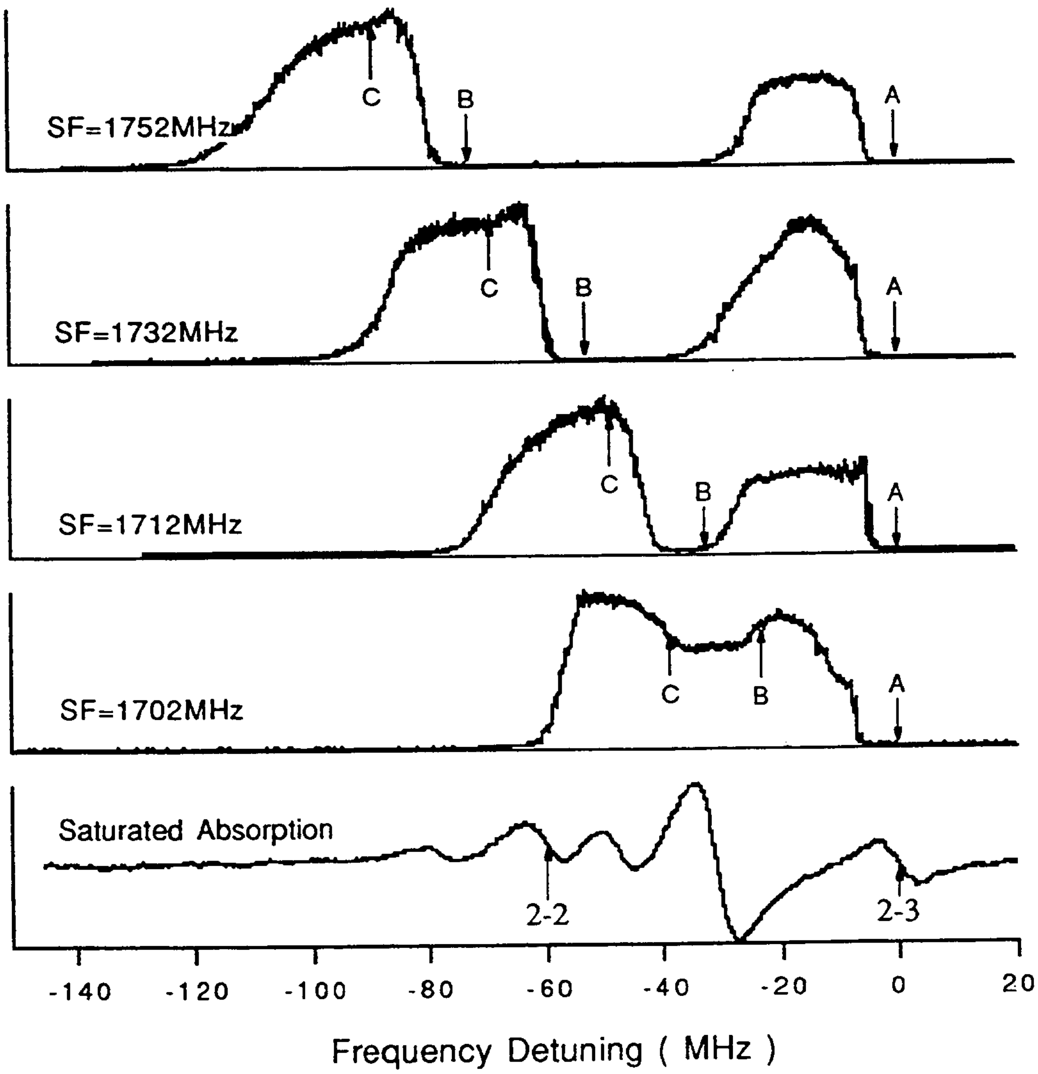
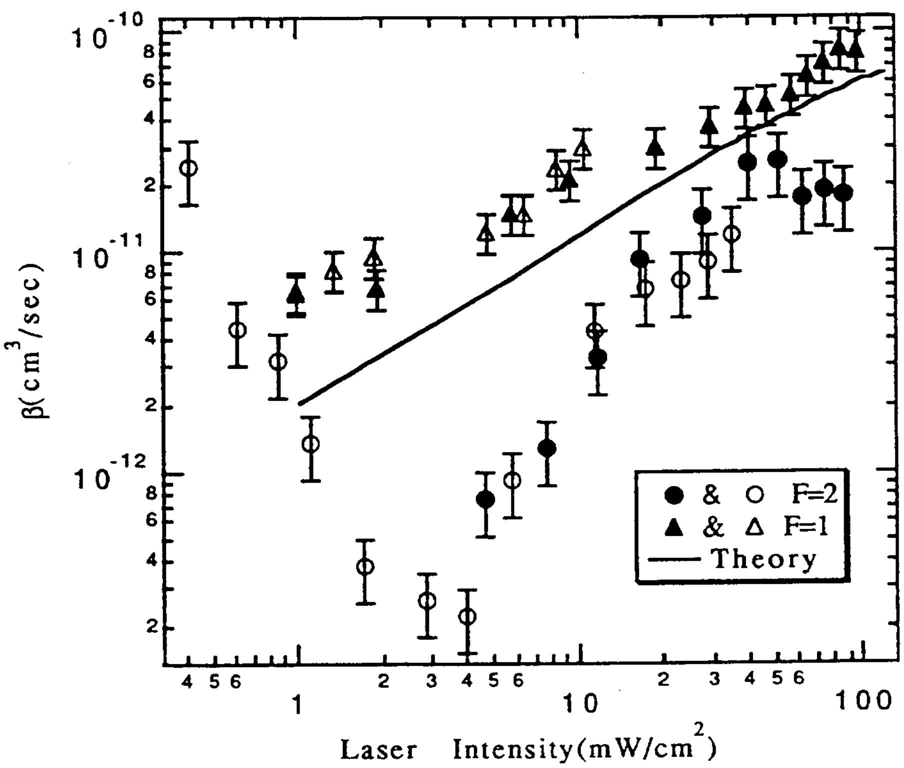
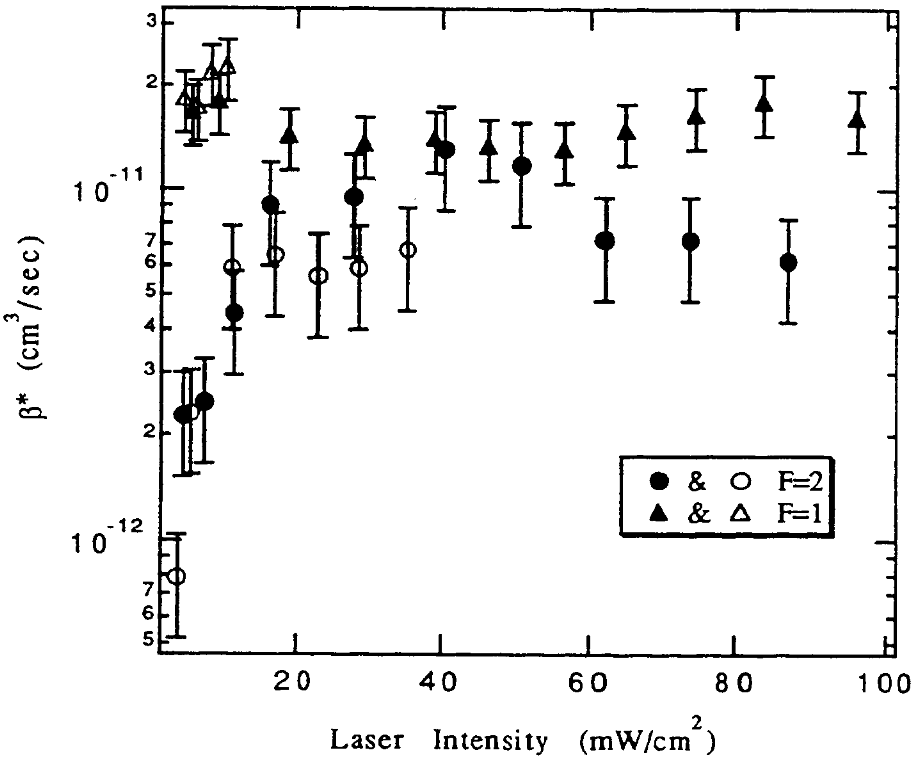
1000
800
600
400
200
0
-200
0
20
40
60
80
100
120
140
Position (cm)


SF=1752MHz
C
B
A
SF=1732MHz
C
B
A
SF=1712MHz
C
B
A
SF=1702MHz
C
B
A
Saturated Absorption
2-2
2-3
-140
-120
-100
-80
-60
-40
-20
0
20
Frequency Detuning (MHz)



β(cm³/sec)
Laser Intensity(mW/cm²)
● & ○ F=2
▲ & △ F=1
Theory



β* (cm³/sec)
10⁻¹¹
10⁻¹²
20
40
60
80
100
Laser Intensity (mW/cm²)
● & ○ F=2
▲ & △ F=1