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INTERNATIONAL ATOMIC ENERGY AGENCY

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LASER COOLING OF NEUTRAL ATOMS BY RED–SHIFTED DIFFUSE LIGHT IN AN OPTICAL INTEGRAL SPHERE CAVITY

Yuzhu Wang [1]
International Centre for Theoretical Physics, Trieste, Italy,

Hongxin Chen, Weiquan Cai, Liang Liu, Shanyu Zhou,
Wei Shu and Fosheng Li
Joint Laboratory for Quantum Optics,
Shanghai Institute of Optics and Fine Mechanics, Academia Sinica,
P.O. Box 800–211, Shanghai 201800, People's Republic of China.

ABSTRACT

In this paper, we report a cooling and deceleration experiment of a thermal beam by using a nearly resonant red–shifted diffuse light in an optical integral sphere cavity. With this red–shifted diffuse light, a part of thermal sodium atoms is cooled to 380m/s and the velocity width of cooled atoms is about 20m/s. The mechanism of this kind of laser cooling and the experimental results are discussed.

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[1]Permanent address: Joint Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, P.O. Box 800–211, Shanghai 201800, People's Republic of China.

Preface

The ICTP-LAMP reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

These reports aim at informing LAMP researchers on the activity carried out at ICTP in their field of interest, with the specific purpose of stimulating scientific contacts and collaboration of physicists from Third World Countries.

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ICTP LASER GROUP
P.O. BOX 586
34100 Trieste
Italy
Phone: +39+40+2240322
Fax: +39+40+224559
email: *passarel@ictp.trieste.it*

Laser cooling of an atomic beam is mostly realized by using single-mode lasers either chirping the frequency[1] or tuning the atomic resonance in an inhomogeneous magnetic field[2]. A third possibility consists in the utilization of non-monochromatic radiation, Zueva and Minogin showed that an increase of the number of the laser modes may improve the cooling rate, because a larger number of atoms is in resonance with the field[3]. Instead, Moi[4] suggested the possibility of achieving laser cooling by using "white" light. Zhu et al.[5] reported the observation of laser cooling of an atomic beam by using both a broadband laser and a co-propagating single mode laser beam, as suggested by Hoffnagle[6]. In 1979, We[7] proposed an idea of laser cooling of atoms by red-shifted diffuse light in a optical integral sphere cavity. In this paper we report the experimental demonstration of this idea.

After we finished our experiment, Ketterle et al. reported an experiment of slowing atoms in isotropic light[8]. The principle of their experiment is the similar with ours. But there are several differences between our experiment and theirs. Instead of a tube, in our experiment we use an integral sphere cavity to produce the red-shift diffuse light and the cavity is made of copper with an internal surface covered with a layer of high reflectivity material (MgO). The velocity distribution of cooled atoms is measured by means of spatial Dopper resonance fluorescence in our experiment.

In our experiment, as shown in Fig.1, the optical integral sphere cavity with a 50mm diameter, reflectivity coefficient higer than 99% at the internal surface of the cavity is used. When a laser beam is incident into the cavity, the approximatively homogeneous diffuse light is formed inside the cavity. If we assume that the engery density is U, according to the method of thermodynamics, we can obtain[7]:

$$U = \frac{F\rho}{\pi r^2 c(1-p)} \tag{1}$$

where ρ is the reflection coefficient, r is the radius of the optical integral sphere cavity and F is the optical flux per second into the sphere cavity. The intensity of the diffuse light in the cavity is:

$$I = Uc = \frac{F\rho}{\pi r^2 (1-\rho)} \tag{2}$$

Eq.(2) shows that the flux of the diffuse light in the cavity is enhanced by a factor of $\rho/(1-\rho)$. If ρ is 99%, then the flux in the cavity is two order larger than the incident flux F, thus the power requirements for laser cooling are easily realized in laboratory conditions.

In this case, we know that all directions of lights exist in the cavity. When an atomic beam enters into the cavity and the laser frequency is red shifted, and when an atom of the beam absorbs a photon from the light field the atomic velocity will be changed. Every time the photon momentum changes the atomic velocity by $\Delta v = h\nu/Mc(= 3cm/sec$ for the D_2 line of Na) in the direction of the light propagation, where M is the atomic mass. The spontaneously radiated photon also changes the atomic velocity by Δv, but the direction of the radiation is isotropically distributed, on an average there is no net contribution to changes of the atomic velocity from spontaneous emission. So the average momentum transfering to the atom is in the propagation direction of the resonant light. When an atom with velocity v in the atomic beam flies along the direction of x axis through the diffuse light field, it interacts resonantly with the light field propagating along the direction, which has an angle θ with the x axis. In this case the resonant condition must be satisfied:

$$\omega_0 = \omega_l[1 + (v/c)\cos\theta] \tag{3}$$

where ω_l is the frequency of laser, ω_0 is the atomic resonant frequency. The radiation force on a two-level atom is given by[9]:

$$F(\omega, v) = \hbar K\Gamma \frac{G}{1 + G + [(\Delta + Kv\cos\theta)/\Gamma]^2} \tag{4}$$

where $\Delta = \omega_0 - \omega_l$ is the detuning of the light-wave frequency ω_l with respect to the atomic transition frequency ω_0. $G = I/I_{sat}$ is the ratio between the light-field intensity I and the saturation intensity I_{sat}. $I = Uc$, 2Γ is the natural atomic transition width.

When we consider the interaction of a two-level atom moving along x axis with homogeneous red-shifted diffuse light (i.e. $\Delta < 0$), the radiation force is[6]:

$$F = -\int_{\omega_l + kv}^{\omega_l} k_0 F(\omega', v)\cos\theta d\omega' \tag{5}$$

where k_0 is the normalized constant, and the direction of this force is along the x axis direction. $\omega' = \omega_l[1 + (v/c)\cos]$ is the effective laser frequency felt by a moving atom. The calculation result of Eq.(5) is expressed as:

$$F = -\frac{\hbar k\Gamma}{2\pi}G[\frac{\Gamma C}{2kv} + \frac{\Delta D}{kv}] \tag{6}$$

where:

$$C = ln\frac{[(1+G)\Gamma^2 + \Delta^2]}{[(1+G)\Gamma^2 + (kv+\Delta)^2]} \tag{7}$$

$$D = -\frac{1}{\sqrt{1+G}}[\tan^{-1}\frac{\Delta}{\Gamma\sqrt{1+G}} - \tan^{-1}\frac{(kv+\Delta)}{\Gamma\sqrt{1+G}}] \tag{8}$$

From Eqs.(6-8), the radiation force can be obtained. When $|Kv| << |\Delta|$, then Eq.(6) is:

$$F \approx 0 \tag{9}$$

When $|kv| >> |\Delta|,|\Delta|$ and $|kv| >> \Gamma$, then Eq.(6) is:

$$F \approx \frac{\hbar\Gamma G\Delta}{2v\sqrt{1+G}} \tag{10}$$

The numerical calculation results depending on Eq.(6) are shown in Fig.2 with $G = 10$ or 1 and $\Delta = -620MHz$. In Fig.2 we can find that the radiation force is large in a wide velocity range from 300m/s to 1200m/s and the direction of light which interacts with moving atoms is changed continuousiy when the atoms are decelerated in the red-shifted diffuse light field. So this kind of cooling mechanism shows that atomic velocity can be slowed continusly with a fixed laser frequency (forming a homogenous red-shifted diffuse light field) in the cavity.

The experimental elements of our apparatus are shown schematically in Fig.1. The sodium atomic beam is formed from a sodium oven with a hole of diamemter of 0.5mm. Another hole with the same diameter was placed at a distance of 50cm from the oven as a collimator. Then the divergence of the atomic beam was 1.4×10^{-3} rad. The distance from the sodium oven to the cavity was 72cm. The sphere cavity is full of the red-shifted diffuse light with two frequencies ω_0 and ω_1 coming from two dye lasers. The second laser beam passes through an opto-acoustic modulator with modulation frequency Ω and is split into a zero order light beam with frequency of ω_0 and a second order light beam with frequency of $\omega_2 = \omega_0 + 2\Omega$. To overcome optical pumping effect and enhance cooling efficiency, we use two lasers with frequency ω_1 and ω_0 to be resonant with the transition frequencies between two ground state sub-levels and their corresponding excited states of sodium atom respectively. After cooled by the diffuse light field, atoms travel through 112cm length and reach the detection region(see Fig.1). A divergent, fan-shaped laser beam, with frequency ω_2, is used to analyse the velocity distribution of the atomic beam by inducing spatial fluorescence method[11,12]. When an atom with resonant transition frequency ω_0 moves with velocity v in the direction of x-axis, due to Doppler effect, the frequency observed by the atom is $\omega_l(1 - v/c \cos\theta')$, where θ' is the oblique angle of the atomic beam and the corresponding probe laser beam, c the light speed, and ω_l is the laser frequency. The atom is stimulated to emit fluorescence when the condition

$$\cos\theta' = (\omega_0/\omega_l - 1)c/v \tag{11}$$

is satisfied. Eq.(11) implies that atoms with different velocities interact with the laser beam at different incident angles θ' of the fan-shaped laser beam. In other words, atoms with different velocity v is resonant at different position x, yielding:

$$x/\sqrt{D^2 + x^2} = (\omega_0/\omega_l - 1)c/v \qquad (12).$$

So Eq.(12) becomes:

$$x = B_1 D/\sqrt{(1 - B_1^2)} \tag{13}$$

here $B = (\omega_0/\omega_l - 1)c/v$. Eq.(13) implies that there is a simple relationship between atomic velocity and the position where atoms emit fluorescence. For convenience of following discussion, we let F(v) represent atomic velocity distribution function, S(x) represent the spatial Doppler resonance fluorescence distribution. In this case, we can obtain[12]:

$$F(v) \approx \frac{B_1 D}{K_0' v} S(x) \tag{14}$$

where, k_0' is the normalized constant. We can use this method to analyses the velocity distribution of the slowed atomic beam. Substituting experimental results of spatial distribution fluorescence in Fig.4 into Eq.(13) and Eq.(14) gives the corresponding atomic velocity distribution. The fan-shaped laser beam is circularly polarized and a magnetic filed is applied in the direction of the central part of the fan-shaped laser beam so that laser will excite almost all sodium atoms from $3S_{1/2}(F = 2)$ to $3P_{3/2}(F = 3)$ state because of optical pumping effect and then the atom achieves a two-level system. Although the direction of megnetic field is not always along the direction of the probe laser beam, the angle between the megnetic field and the probe laser beam is small, and the decay rate from $3P_{3/2}(F = 2, 1)$ to $3S_{1/2}(F = 2)$

state is about 3/7 of the decay rate from $3P_{3/2}(F = 3)$ to $3S_{1/2}(F = 2)$ so that we can consider approximatively that most fluorescence comes from $3P_{3/2}(F = 3)$ state to $3S_{1/2}(F = 2)$ state and other fluorescence is very small. The intensity of the fluorescence in a fixed point is proportional to the density of the atoms with a definite velocity. Therefore the spatial distribution of the fluorescence represents the profile of the atomic velocity distribution of the atomic beam. A camera lens is used to image the spatial distribution of the fluorescence on the sensitive surface of the detector of an optical multichannel analyser (OMA), and the longitudinal spatial (x-axis direction) distribution of the atomic intensity VS velocity is directly shown on the screen. The exposurative time of the detector system is 40ms which enabled us to collect data in a very short duration of time. The divergent laser beam is formed when a laser beam pass through a cylinder lens and the laser beam has an oblique angle with respect to the atomic beam in order to detect appropriate velocity range of the atomic beam. The distance between the lens and the atomic beam is $D = 180mm$. The total power and the detuning of the probe beam is 20mw and -400MHz ($\Omega = 125$MHz) respectively.

The involved energy levels of sodium and the tuning position of the laser frequency are shown in Fig.3. Laser 2 is tuned into resonance with the strongest of the various possible transitions, that is the $3S_{1/2}(F = 2) \rightarrow 3P_{3/2}(F' = 3)$ transition. Laser beam 1 is used to repump atoms to $3S_{1/2}(F = 2)$, as shown in Fig.3. When both two lasers is simultaneously applied, all ground-state levels are resonantly optically coupled to some excited states[10], and then all atoms can be cooled.

In our experiment, the frequencies of the two lasers are adjusted to have detuning $\Delta_1 = -650MHz$ and $\Delta_2 = -650MHz$ as shown in Fig.4. The experimental procedure is as follows. First the velocity distribution of the atomic beam is measured in order that two lasers are tuned to have appropriate detunings as given above by using of a wavemeter (this case is shown in Fig.3). The experiment is started with blocking the acting laser beams. The measured intensity distribution of the fluorescence represented the initial velocity distribution of the atomic beam. After two laser beams entered into the cavity to form the diffuse light field which interactes with the atomic beam, a small peak of the spatial fluorescence intensity distribution is observed, which shows the cooling of atoms in the diffuse light field. These results are shown in Fig.4(a) and Fig.4(b).

Fig.4 shows the experimental results with the probe laser frequency detuning -

450MHz. Fig.4(a) shows the the initial velocity distribution of the atomic beam and Fig.4(b) shows the velocity distribution of the atomic beam after laser cooling of the red-shifted diffuse light at the detuning of $\Delta_1 = \Delta_2 = -650MHz$ and the saturation parameter $G_1 = G_2 = 3.1$, $G_i(i = 1, 2)$ is defined as $G_i = I_i/I_{isat}$, where I_i is the intensity of the diffuse light and I_{isat} is the saturation intensity, and where $i = 1, 2$ is shown $3S_{1/2}(F = 2)$ and $3S_{1/2}(F = 1)$ states to $3P_{3/2}$ states transitions respectively. In the experiment, the tempreture of sodium oven is 515K. Because of our probe condition, we only measured part of atoms that the velocity was less than 750m/s.

We have obtained the atomic velocity distribution of Fig.4 and Fig.5(a) and Fig.5(b) corresponding to Fig.4(a) and Fig.4(b). Fig.5 shows one of laser cooling by the red-shifted diffuse technique. The Fig.5(a) curve shows the unmodified velocity distribution, while the Fig.5(b) curve shows the distribution after application of the red-shifted cooling diffuse light field. With this cooling mechanism, part of atoms is decelerated and concentrated to the velocity of 380m/s with the velocity-width about 20m/s. With the red-shifted diffuse light method, the final velocity is determined by laser frequencies and the cooling peak density is determined by the interaction distance. If one uses two or more optical integral sphere cavities to increase the interacting distance, all atoms can be decelerated to the definite velocity.

We have studied longitudinal velocity cooling of atoms in a red-shifted diffuse light field. It shows that the atomic velocity can be decelerated by red-shfited diffuse light in theory and experiment. We have obtained reduction of the longitudinal velocity and a part of atoms are concentrated to 380m/s, which is dependant on the detuning of laser frequencies and the atomic transition frequency. The velocity width of the cooling atoms is about 20m/s and the density of this peak is the largest of all. It should be noted that in principle there is no difficulty to use two or even more hollow balls with high reflection to increase the interacting distance to cool all atoms to low velocity by this cooling mechanism. In experiment, it is possible to use ideal optical integral sphere cavity to form a isotropic light to obtain optical molasses, and these are under investigation.

Acknowledgments

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Figure captions:

FIG. 1. Experimental Setup

FIG. 2. Resonance radiation pressure VS velocity and saturation paramenter in a diffuse light field with detuning -620Mhz.

FIG. 3. The atomic energy levels of sodium relevant for our experiments. Typical tunings for laser 1 and laser 2 are also shown.

FIG. 4. Experimental results of spatial fluresence of atomic beam: (a) laser off, (b) laser on.

FIG. 5. Experimental result for sodium atomic velocity distribution corresponding laser off and laser on respectively.

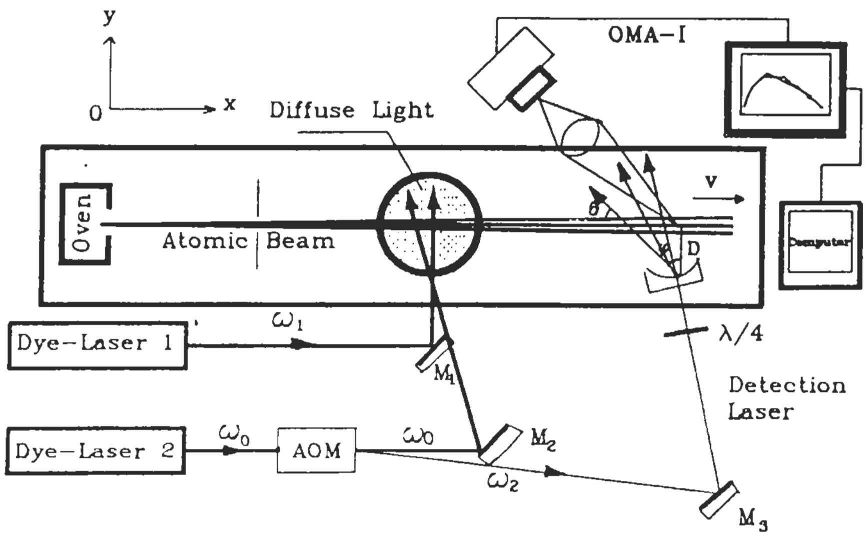

Fig.1 Experimental Setup

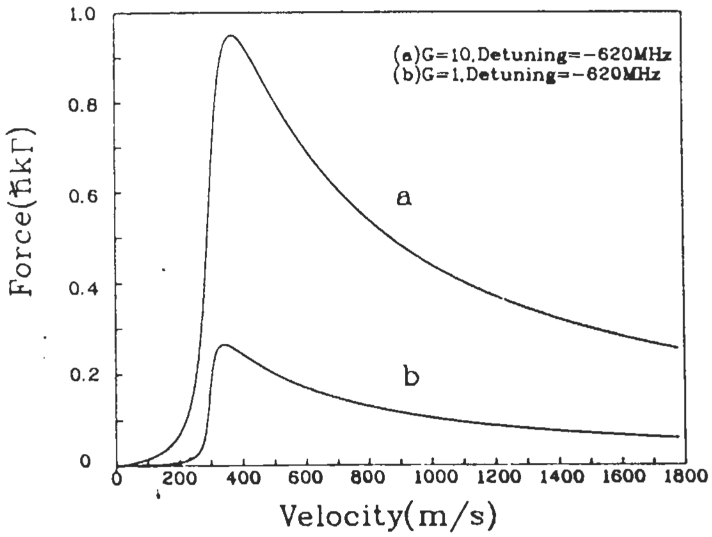

Fig.2

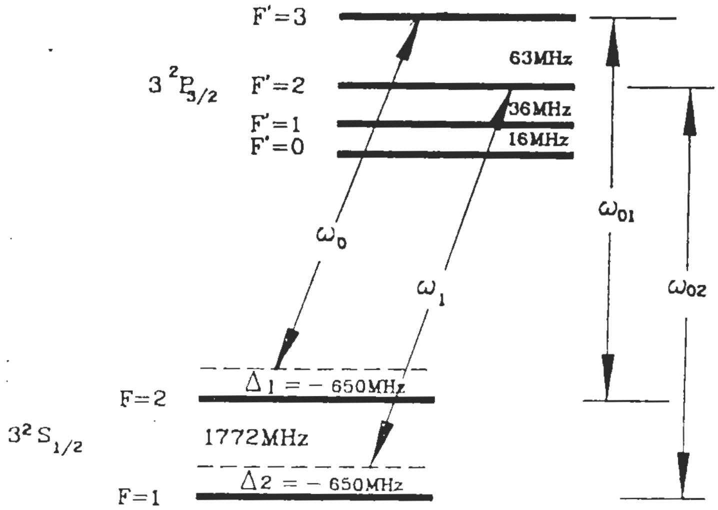

Fig.3 The atomic energy levels of sodium relevant for our experiments

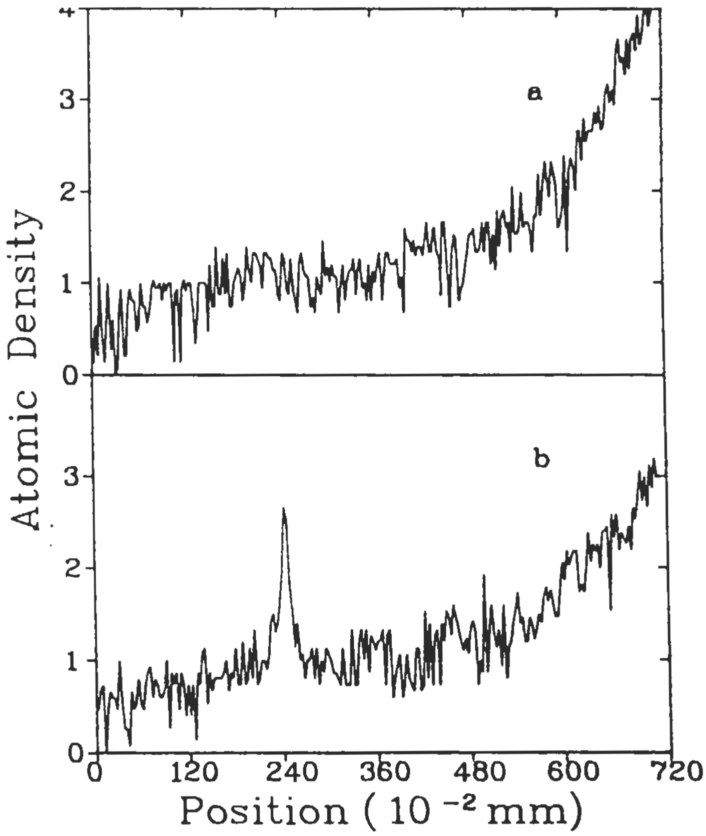

Fig.4

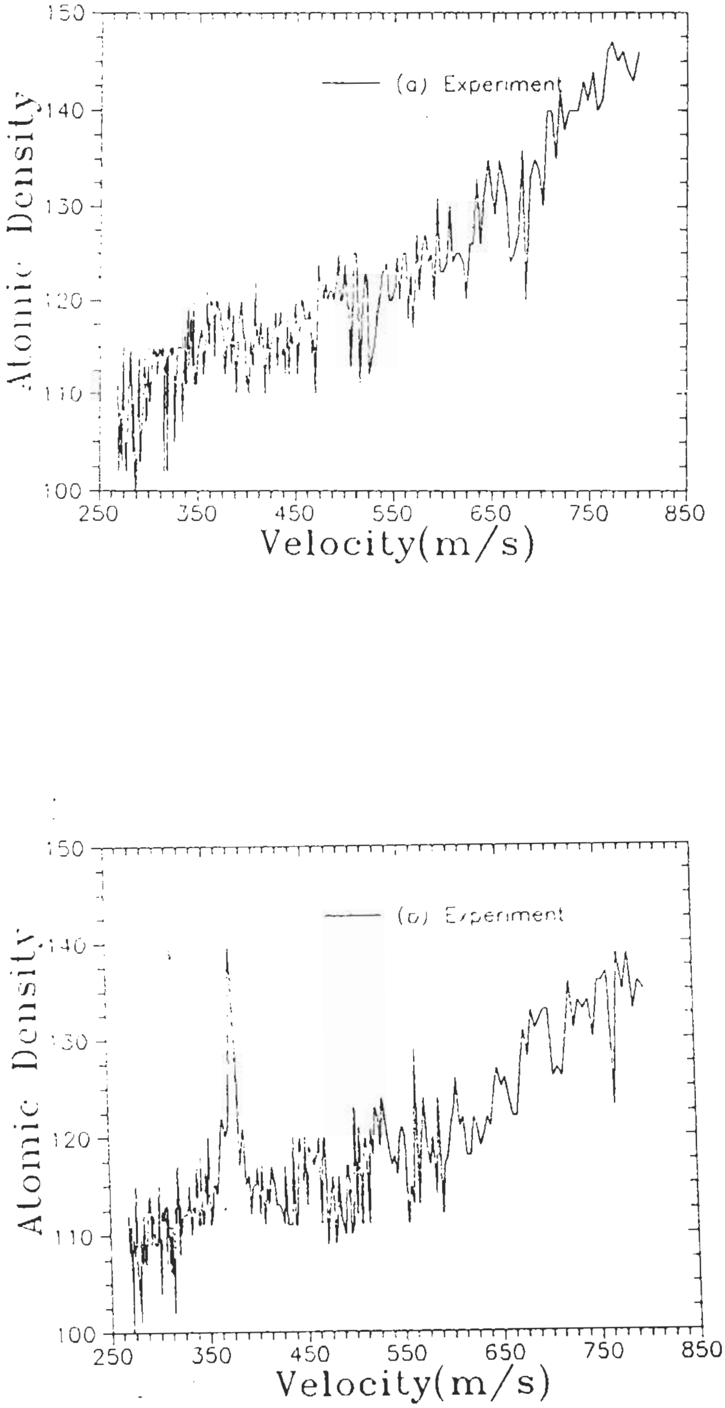
(a) Experiment
Atomic Density
Velocity(m/s)
150
140
130
120
110
100
250
350
450
550
650
750
850
(b) Experiment
Atomic Density
Velocity(m/s)
150
140
130
120
110
100
250
350
450
550
650
750
850

FIG. 5.