Trap for polarized atoms based on light-induced drift

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A polarization of sodium atoms in a simple trap based on the light-induced drift effect is reported. A sapphire capillary with one side closed and heated up to high temperature was used as the trap. The capacity of the trap is about 5×10^{11} atoms. The achieved polarization of trapped atoms in the gas phase is about 90%. The full polarization of atoms in the trap is estimated at 25% at the temperature of 1400 °C. The adsorption energy of sodium atoms on a sapphire surface is determined to be 2.5 eV. [S1050-2947(96)02110-5]

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Over the past three decades there have been numerous efforts devoted to the preparation of samples of polarized nuclei using optical pumping [1]. Such a sample allows highly sensitive laser spectroscopy of radioisotopes (see, for example, [2]) and detailed studies of fundamental processes such as β decay [3]. There are serious problems with the creation of optically polarized radioactive samples. The atoms adsorbed on the walls of the experimental cell and chemically bounded into compounds are depolarized. This is why the optical pumping experiments with detection of nuclear radiation anisotropy have been successful only with nonreactive elements or very short-lived isotopes (see, for example, [2,4]). The problem of depolarized atoms can be solved by using a wall-free magneto-optical trap technique [5]. The magneto-optical traps are rather complicated apparatuses with the following main parameters achieved so far: the capacity is more than 10^{10} atoms [6,7], the collection efficiency is 6% [8], the time of retention is 6 min [5], and the polarization in the volume of the trap is 75% [9]. The full polarization of the magneto-optical traps has not been published yet.

The present paper exhibits an alternative means of preparing of optically polarized nuclei: optical pumping of atoms confined in a long cylinder by light-induced drift (LID) [10,11]. The trap based on LID (LID trap) for atoms was proposed and realized by Atutov and Shalagin [12]. The idea of this LID trap for atoms is simple. If the drift of atoms in a buffer gas in a tube is limited by a solid wall, the atoms accumulate at the wall. The density of the atoms will increase since the drift will be compensated by the opposing diffusive flow. If an atom for any reason does not absorb the light radiation (for example, because it is bound into a molecule) it is not under the influence of the LID and it diffuses from the trap. This means that the LID trap is selective and it keeps only a certain species in the atomic form. A paraffin coating was used to eliminate sodium adsorption on the cell walls in the first LID trap experiment [12]. The chemical lifetime of sodium atoms was not longer than 10^{-1} s in the cell. Other experiments were carried out with radioactive sodium atoms in a heated metallic capillary [13]. The main properties of the trap are the following: the density of the trapped atoms is about 10^{13} cm^{-3} [14] and the capacity of the trap is determined by its volume, the atom retention time is several hours, a collection efficiency of 20–50 % has been achieved [13], and nearly 100% could be achieved under optimum conditions. These properties present possibilities to use this trap for some interesting applications. (i) The trap can be used for the optical polarization of trapped radioactive atoms and the study of the angular correlation of decays of polarized nuclei. (ii) Atoms in the trap can be kept in a very narrow volume near the closed end of the tube [12]. After the laser radiation is switched off the spatial distribution of the atoms smears due to diffusion. The smearing time contains information about the adsorption time and adsorption energy of the atoms on the cell surface [14]. (iii) The trap can be used as the isotope purifier. It keeps only one isotope, while other isotopes leave the trap if their optical spectra are sufficiently different.

We have investigated the possibility of optical polarization of the ^{23}Na atoms [1] in the trap. The transition $S_{1/2}$-$P_{1/2}$ is suitable for optical pumping and polarization because a sodium atom in the $m_F=+2$ sublevel of the $S_{1/2}$ ground state cannot absorb a σ^+ photon owing to the conservation of angular momentum projection, while atoms in the another ground-state sublevels can absorb a σ^+ photon and jump to the $P_{1/2}$ excited level. After spontaneous emission some of the excited atoms decay to the $m_F=+2$ sublevel and are trapped there. In the absence of relaxation mechanisms all atoms will be ''pumped'' into this sublevel with the maximum atomic angular momentum projection.

The optical pumping of sodium atoms in the presence of a buffer gas has some special features. The Doppler broadening of the optical transition and the hyperfine splitting of the ground state have similar values. Sodium atoms in a buffer gas at a pressure of 10 Torr undergo approximately 10^8 velocity-changing collisions per second and so sodium atoms in both states $F=1$ and $F=2$ come accidentally but very often into resonance with the laser radiation. This condition is necessary for effective polarization. The polarization of sodium atoms in a rare gas can be conserved because the depolarization cross section of the $S_{1/2}$ state is very small [1] and time of optical polarization can be as short as 10^{-7} s.

It is well known that sodium atoms with the maximum atomic angular momentum projection become completely transparent on the D_1 line when circular polarization is used.

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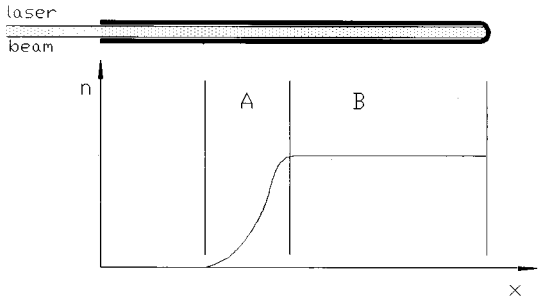

FIG. 1. Illustration of the operation of the optical trap for polarized atoms and an example of the vapor density distribution in the trap. The light-induced drift is directed along the laser beam propagation. The linearly polarized part of the laser radiation is absorbed in zone *A* and the steep gradient of the atom density appears here. Zone *A* works as a LID stopper for the trapped atoms. The circularly polarized part of the light penetrates the LID stopper and the trapped atoms are optically polarized in zone *B*.

But atoms to be held in the LID trap must continually absorb the radiation. Fortunately, it is possible to separate the LID action region from the region with maximum polarization of sodium atoms. For this purpose we used elliptically polarized light and an optically thick sodium medium. A light with elliptical polarization consists of circularly and linearly polarized components. The linearly polarized component is completely absorbed in the forward part of the optically thick medium and a steep gradient of atom density appears here due to LID (zone *A* in Fig. 1). This is the regime of the optical piston investigated in detail in [15,16]. The circularly polarized part of the light passes through this region and penetrates the dense sodium vapor because the optical pumping acts there and the medium becomes transparent to it. The region of absorption of the linearly polarized component of the light (optical piston) operates as a stopper for the sodium atoms. Behind the stopper these atoms interact only with the circularly polarized component of the light and are polarized.

The main part of the LID trap consists of a sapphire capillary with a length of 10 cm, an inner diameter of 1.2 mm, and one closed side. Sapphire is the only material possessing the necessary properties: it is optically transparent, it does not interact chemically with sodium, and it can be heated up to a high temperature. The sapphire capillary is located in a platinum or tantalum spiral (see Fig. 2). The spiral provides both a very high temperature and a magnetic field parallel to the laser beam. The temperature was changed from 1000 °C to 1400 °C and measured with both an optical pyrometer and a Pt-PtRh thermocouple. The magnetic field was 40–60 G,

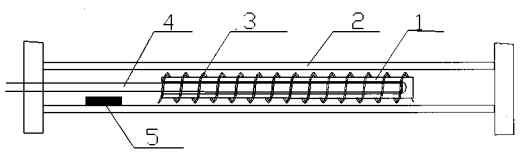

FIG. 2. Experimental cell. 1, the sapphire capillary with one closed side; 2, the sapphire tube with a larger diameter; 3, the platinum or tantalum spiral; 4, the laser beam; 5, the ampoule with metallic sodium.

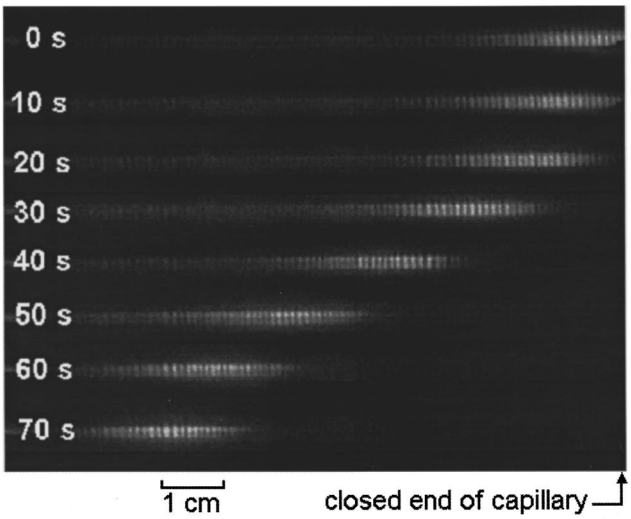

FIG. 3. Video records illustrating the filling of the trap. The position of the shining LID stopper is at 10-s intervals. The vertical dark stripes are the shadow of the heating spiral. The pressure of the buffer gas is 15 Torr and the temperature is 1060 °C.

significantly higher than the residual one. The external sapphire tube was used as a vacuum jacket and filled with krypton. The krypton pressure was changed from 15 to 120 Torr. A heated ampoule with metallic sodium near the entrance of the capillary was used for sodium injection. The beam of a cw dye laser (joint product of Inversion LTD and the University Laser Center, Novosibirsk) passed through the capillary from the open side to the closed one. The transverse profile of the laser beam was Gaussian and its diameter was adjusted so that the radiation maximally filled the capillary, but did not reflect from the walls. The laser power was about 200 mW, the wavelength was 589.6 nm (D_1 line), and the polarization of the laser radiation was linear. The laser wavelength was tuned to maximize the LID velocity of sodium atoms in a reference cell with a paraffin coating. The frequency detuning was about 800 MHz to the ''blue'' side of the adsorption line center [14]. The resonance fluorescence of the sodium atoms in the trap was easily observable by the naked eye. This fluorescence was registered by a video camera (Sony, model CCD-TR18E). The video records were later digitized and processed on a computer.

As the ampoule with sodium was heated sodium atoms were evaporated into the volume. When they reached the capillary entrance they rapidly moved to its closed side (see Fig. 3). Soon the sodium vapor became optically dense and the light could not penetrate through it and we observed only the shining forward part of the sodium cloud (''LID stopper''). It moved from the closed end of the capillary to the open one as sodium atoms filled the trap. When the sodium ampoule heating was interrupted the movement of the LID stopper stopped. Then we gradually changed the light polarization from linear to elliptical. The circularly polarized part of the light passed through the LID stopper and penetrated into the trap (see Fig. 4).

The polarization effect (induced transparency) disappeared in the presence of transverse magnetic field of a permanent magnet and did not appeared on the D_2 line of sodium. This confirmed that the induced transparency was caused by optical pumping and polarization.

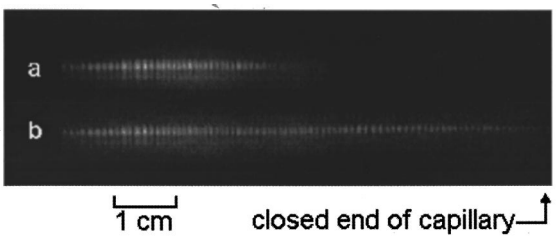

FIG. 4. Optical polarization of atoms in the trap: *a*, the radiation is linearly polarized; *b*, the radiation is elliptically polarized with a 1:1 relation between linear and circular parts of radiation. The pressure of Kr is 15 Torr and the temperature is 1060 °C.

The absorption length for light with the circular polarization contains the information about the polarization of the sodium vapor. The change of the absorption length of the light behind the LID stopper allows us to estimate the fraction of atoms with the maximum angular momentum projection m_F. In our experiments the absorption length increases ten times when the linear polarization of the light is replaced by a circular one. This means that the number of sodium atoms with the ability to absorb the circularly polarized light drops by a factor of 10 owing to optical pumping into the state with the maximum m_F indicating a polarization of atoms behind the LID stopper of about 90%. The number of sodium atoms is adjusted so that the circularly polarized radiation nearly reaches the closed end of the capillary and the length of the dark part of the capillary with unpolarized atoms is negligible. The volume of the trap is about 5×10^{-2} cm^{-3}, hence the number of trapped polarized atoms is about 5×10^{11}.

The depolarization processes are not quite clear. We investigated the influence of a magnetic field on the induced transparency. It decreased considerably only when the magnetic field dropped below 6 G. This confirmed that the experimental magnetic field (40–60 G) is sufficiently parallel with the laser beam and that any residual magnetic field cannot have a considerable depolarizing effect. Collisions between polarized sodium atoms at a density of 10^{13} cm^{-3} were not frequent enough to cause a perceptible part of the observed depolarization. The influence of a depolarization interaction of sodium atoms with the walls was not significant because the average diffusion time of the sodium atom from the wall to the volume (3×10^{-4} to 3×10^{-5} s) was much longer than the time of optical pumping ($\sim10^{-7}$ s). The reflected and scattered laser radiation from the closed end of the sapphire capillary could not depolarize sodium atoms because even circularly polarized light was not penetrating there (see Figs. 4 and 5). The polarization degree did not depend on either the buffer-gas pressure or on the temperature within the accuracy of observation. Hence neither collisions with the walls and krypton atoms nor thermal ionization of sodium atoms could have significant influence on sodium polarization in the volume. In our opinion the most probable depolarization processes were reabsorption of a depolarized fluorescent light or collisions with some residual chemically inert molecular gas.

Since the sodium vapor does not become completely transparent for circularly polarized light we realized the LID trap for polarized atoms using circularly polarized laser radiation only (see Fig. 5). In that case the LID velocity was

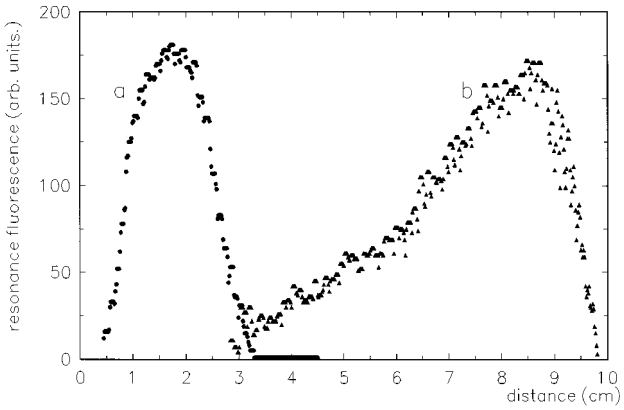

FIG. 5. Resonance fluorescence of sodium atoms in the trap: *a*, the linearly polarized laser radiation; *b*, the circularly polarized one. The closed end of the capillary is situated at 10 cm. The characteristic lengths of increase of the sodium density on the forward edges of the LID stoppers are 0.2 ± 0.03 cm for the linear polarization and 2 ± 0.4 cm for the circular polarization. The pressure is 30 Torr and the temperature is 1060 °C.

considerably lower but still sufficient for retention of sodium atoms in the trap. The LID velocity of atoms is directly proportional to the probability of light absorption [17]. Comparing the drift velocities for linear and circularly polarized radiation, we obtain another method to measure the atomic polarization. A density of drifting atoms on the light side of the ''optical stopper'' increase exponentially with distance [14] with a characteristic length $L=D/v$, where D is the diffusion coefficient and v is the LID velocity. The vapor density is proportional to the intensity of the resonance fluorescence on the forward edge of the LID stopper. The LID velocity was decreased ten times when the light polarization was changed from linear to circular. This proves that the polarization degree is about 90%.

The trapping and polarization of atoms using only circularly polarized light has an important advantage. It does not require an optically thick vapor to separate the regions of the LID stopper and optical pumping. Because the atomic polarization is not decreased by partially depolarized atoms in the LID stopper region it can be effectively used for polarization of any small number of trapped atoms.

Since studies of the angular correlation of decays of polarized nuclei require a high degree of polarization of all atoms, we must take into consideration the atoms adsorbed on the cell walls. The full polarization degree of all atoms could be measured by an anisotropy of the nuclear γ radiation of radioactive sodium [18]. In experiments with stable sodium we can make only an estimate. Let us suppose the sodium atoms on the walls are quite depolarized. Then it is sufficient to determine the relation between the number of sodium atoms in the volume and on the walls.

The diffusion time in the sapphire capillary was measured for this purpose. Using LID we localized sodium atoms into a small volume at the closed end of the trap. Then we intercepted the laser beam for some time. We observed the atom distribution smearing owing to diffusion after the laser beam was switched on again. The adsorption of atoms on the tube walls decreases the effective diffusion coefficient in the comparison with the gas kinetic one according to the expression [14]

$$D_{\text{eff}} = D\left(1 + \frac{N_a}{N_g}\right)^{-1} = D\left(1 + \frac{\overline{v}\,\tau_a}{\sqrt{\pi} r}\right)^{-1}, \qquad (1)$$

where $N_{a,g}$ are the number of adsorbed atoms and atoms in the gas phase per unit of length of the tube, $\overline{v} = \sqrt{2kT/m}$ is the most probable velocity of atoms, τ_a is the adsorption time of an atom on the wall, and r is the capillary radius. Comparing D_{eff} with the gas kinetic diffusion coefficient [19,20], we estimated that the ratio of sodium atoms in the gas phase and adsorbed on the sapphire capillary surface was about 3:7 at the maximum temperature of 1400 °C. This allows us to estimate the full polarization degree of sodium in the sapphire capillary at 25%.

The adsorption time τ_a is known to be related to the adsorption energy E_a by the expression

$$\tau_a = \tau_0 \exp\left(\frac{E_a}{kT}\right), \qquad (2)$$

where the preexponential vibrational time τ_0 is of the order of 10^{-13} s. The measured value of the adsorption energy is 2.5 ± 0.1 eV for our experimental conditions. This value seems to be extremely large. For comparison, the results of previous measurements are 0.75 eV [21] and 1 eV [14]. This discrepancy can be explained by the different temperatures used in our experiment and the previous ones. They were carried out at relatively low temperatures of 300 °C–450 °C and a monolayer of sodium probably covered the sapphire surface. Their results could therefore be the adsorption energy of sodium atoms on a sodium surface. This hypothesis is supported by the very long time it takes to initially fill the capillary with sodium in the experiment [14]. We estimate from (1) and (2) that the sodium adsorption on a sapphire surface will be negligible at temperatures higher than 1500 °C.

This work has demonstrated that atoms in LID trap can be easily polarized by circularly polarized light. The LID trap parameters reached in our experiments are a density of trapped sodium vapor of 10^{13} atom/cm^3, a capacity of 10^{11} atoms, an atomic polarization of shining sodium vapor of 90%, and a full atomic polarization of 25%. These are much higher than the same parameters obtained with magneto-optical traps. We are optimistic that this type of LID trap will find effective application in experiments aimed at detection of nuclear radiation anisotropy from polarized samples.

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