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Section A

Laser optical pumping of potassium in a high magnetic field using linearly polarized light

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It is shown experimentally that in a high magnetic field a potassium vapor can be optically pumped to a high electron spin polarization by light polarized parallel to the magnetic field and incident normal to the magnetic field. The polarization of the K vapor is measured both by observing the fluorescence and by the Faraday effect. This method of optical pumping may be useful for spin polarized targets.

1. Introduction

The optical pumping of an alkali metal vapor in a high magnetic field is of intrinsic interest. In addition there are important applications of the optical pumping in a high magnetic field. For example, optically pumped polarized H^- ion sources use a spin-polarized alkali metal vapor as a charge exchange medium [1–6]. The optically pumped spin exchange polarized D target developed at Argonne National Laboratory also uses an optically pumped alkali metal vapor for the spin exchange polarization transfer medium [7]. For the optically pumped polarized H^- ion source it is necessary that the optical pumping be carried out in a high magnetic field in order to avoid the loss of polarization by radiation after charge transfer and to avoid polarization loss at high alkali density due to radiation trapping. For the optically pumped spin exchange D target it is necessary to use a high magnetic field in order to avoid polarization loss due to radiation trapping at high alkali density. Any alkali vapor can be used for the charge exchange target for the optically pumped H^- ion source but because of the high power output possible with the Ti:sapphire laser at the 770 nm wavelength of the $4^2S_{1/2}$–$4^2P_{1/2}$ transition of K and lack of complications due to isotope shifts and hyperfine structure, it is common to use K as the optically pumped alkali vapor. The Argonne optically pumped spin exchange D target also uses K as the optically pumped vapor.

In the experimental setups used for the optically pumped polarized ion sources and for the optically pumped spin exchange polarized target at Argonne to date only σ^+ or σ^- circularly polarized light incident parallel to the magnetic field has been used for the optical pumping of the alkali vapor. Anderson and Walker have suggested that the use of light that is polarized parallel to the magnetic field B and therefore is incident normal to B may be advantageous for high field optical pumping [8]. The average number of photons required to polarize a K atom should be less for $P_{1/2}$ π-light incident normal to the magnetic field than for σ^+ or σ^- light incident parallel to the magnetic field. The use of π-light may also enable one to use a simpler or more efficient experimental setup for the optical pumping. In particular for a long alkali target with its axis parallel to the magnetic field it may be possible to use mirrors to multipass the alkali vapor to assure efficient use of the pump laser light. This paper reports the first experiments on the high field polarization of a K vapor by optical pumping with π-light incident normal to the magnetic field.

Optical pumping using $P_{1/2}$ π-light incident normal to the magnetic field works as follows. Fig. 1 shows the energy levels in a high magnetic field of an idealized K atom with no nuclear spin. The wavelength of the light is set to match one of the $\Delta m_J = 0$ transitions. In order to be concrete we take the wavelength of the light to correspond to the $4^2S_{1/2}(m_J = -1/2) \rightarrow 4^2P_{1/2}(m_J = -1/2)$ transition. A K atom absorbs a photon and is excited to the $4^2P_{1/2}(m_J = -1/2)$ level. This level undergoes spontaneous radiative decay to both the

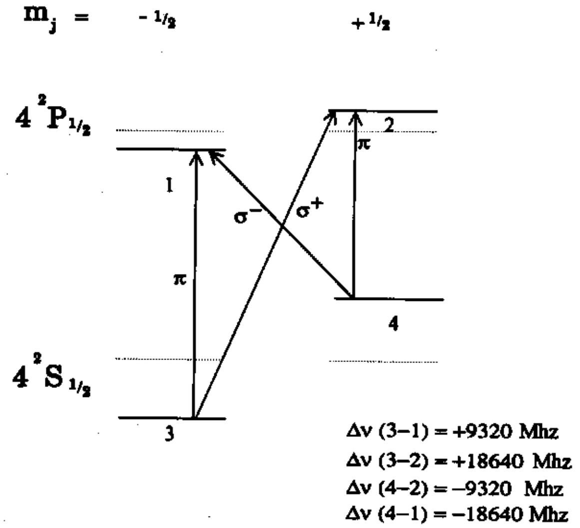

Fig. 1. Energy levels of ^{39}K in ignoring nuclear spin in a magnetic field of 10000 G, showing both the π ($\Delta m_J = 0$), and $\sigma^{+/-}$ ($\Delta m_J = +/-1$) transitions.

$4^2S_{1/2}(m_J = -1/2)$ and $4^2S_{1/2}(m_J = +1/2)$ states with transition probabilities of 1/3 and 2/3 respectively. Since some of the radiative decays take atoms to the $m_J = +1/2$ state and no absorption out of this level occurs, the K atoms are optically pumped out of the $m_J = -1/2$ state and into the $m_J = +1/2$ state. The fluorescence photons carry away a net angular momentum so that the K atoms become polarized even though the incident light does not bring any angular momentum into the K vapor.

2. Apparatus

Fig. 2 shows a schematic diagram of the experimental apparatus for this experiment. An Ar$^+$ laser pumped Ti:sapphire laser beam operated at the wavelength of either the $4^2S_{1/2}(m_J = -1/2) \rightarrow 4^2P_{1/2}(m_J = -1/2)$ transition or to the $4^2\mathrm{Si}_{1/2}(m_J = +1/2) \rightarrow 4^2P_{1/2}(m_J = +1/2)$ transition is chopped by a rotating wheel at a waist. The wavelength of the laser is set by observing the fluorescence from the K reference cell. The chopped beam turns on or off in less than 1 μs. The laser beam is then steered through a crystal polarizer and a $\lambda/2$ plate. The linearly polarized light is incident on a cell containing K vapor plus 100 Torr of He. The pump light is incident on the cell in a direction normal to the magnetic field at the cell. The cell is held in an oven in order to control the K vapor density. The cell and oven are located between the poles of an electromagnet. The pole faces are 24 cm in diameter and are separated by 7.62 cm. The pole faces have a 1.27 cm diam. hole bored through their center. The crystal polarizer in the absence of the $\lambda/2$ plate is adjusted to transmit light polarized parallel to the pole face of the magnet and thus perpendicular to the magnetic field. The $\lambda/2$ plate is adjusted to change the polarization of the laser light from perpendicular to the magnetic field to parallel to the magnetic field. The magnetic field is set to 1 T (10^4 G).

We measure the polarization of the optically pumped K vapor in two different ways. The first way is to measure the polarization of the K vapor by the Faraday effect and the second way is to observe the

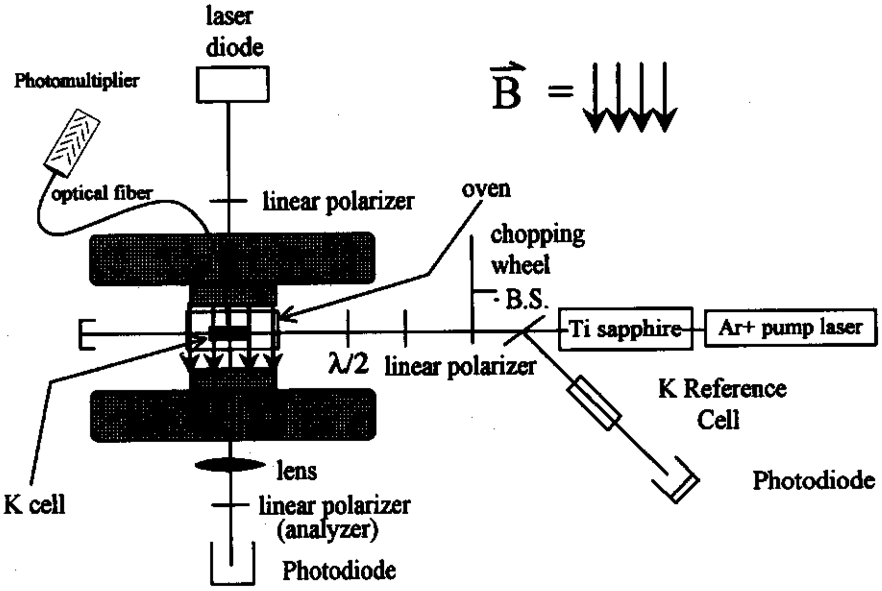

Fig. 2. Schematic diagram of experimental apparatus.

resonance fluorescence from the vapor as it is pumped. The Faraday effect measurements are carried out as follows. The beam from a Liconix diode laser is used as a probe. The probe beam is linearly polarized, passes through the pole faces of the magnet and is incident on the K vapor cell parallel to the magnetic field. The polarization of the probe beam is analyzed after passage through the K vapor cell, and the beam is then focused by a lens onto a fast photodiode. If the K vapor is polarized the induced optical activity rotates the plane of polarization of the probe beam. The analyzer is adjusted to pass the minimum intensity when the K vapor is unpolarized. The time dependent polarization of the K due to optical pumping can be obtained from the time dependent intensity at the photodiode. The time dependent intensity is recorded using a LeCroy transient digitizer. The polarization of the vapor can be obtained from the rotation of the polarization of the diode laser light [9].

The polarization of the K vapor is measured using resonance fluorescence as follows. The resonance fluorescence of the K cell is detected using a lens that images the fluorescence from the center of the K vapor cell onto a photomultiplier via a fiber optic cable. The K cell temperature is adjusted to produce about 50% absorption of the pump beam from the Ti:sapphire laser. The fluorescence signal is recorded by a LeCroy transient digitizer. The polarization of the K vapor is obtained from the magnitude of the fluorescence.

3. Experimental procedures and results

There are three naturally occurring isotopes of K. The abundances are 93.1% for ^{39}K, 0.0119% for ^{40}K, and 6.9% for ^{41}K. Because of its abundance we have primarily optically pumped ^{39}K. Since the isotope shift is very small we also pump the other isotopes. The nuclear spin of ^{39}K is 3/2. The ground level hyperfine separation in zero field is 461.7 MHz. Fig. 3 shows an energy diagram of the $4^2P_{1/2}$ and $4^2S_{1/2}$ levels in a field of 1 T. In a high magnetic field the selection rules

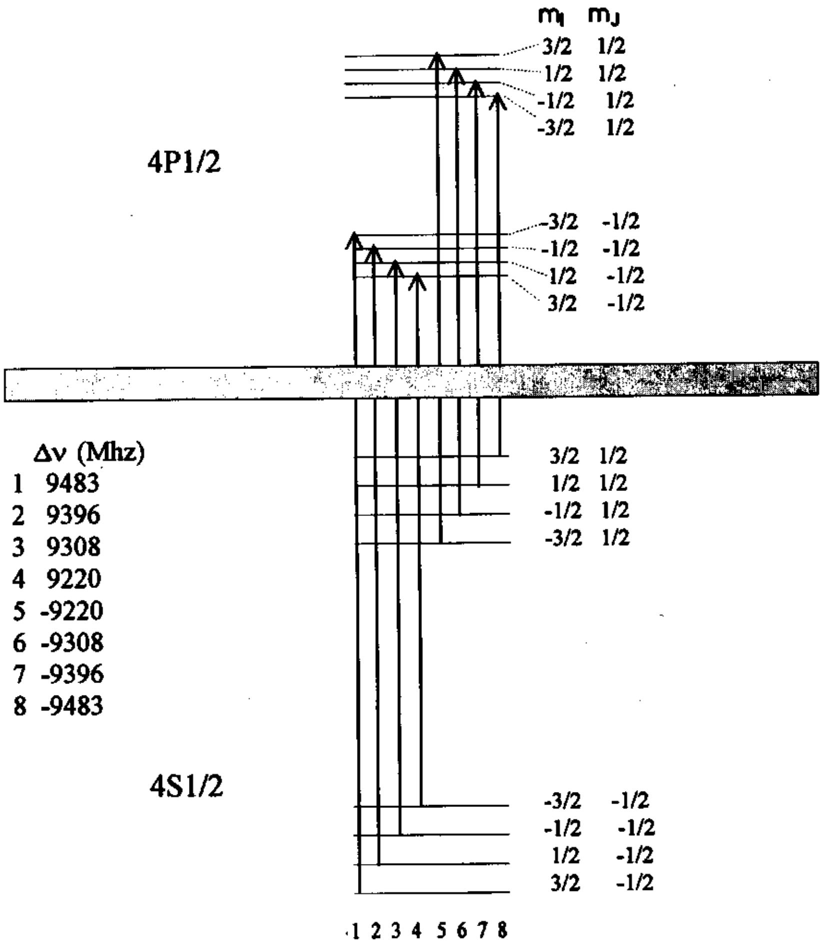

Fig. 3. Energy levels of ^{39}K in a magnetic field of 10000 G showing allowed π ($\Delta m_J = 0$, $\Delta m_I = 0$) transitions.

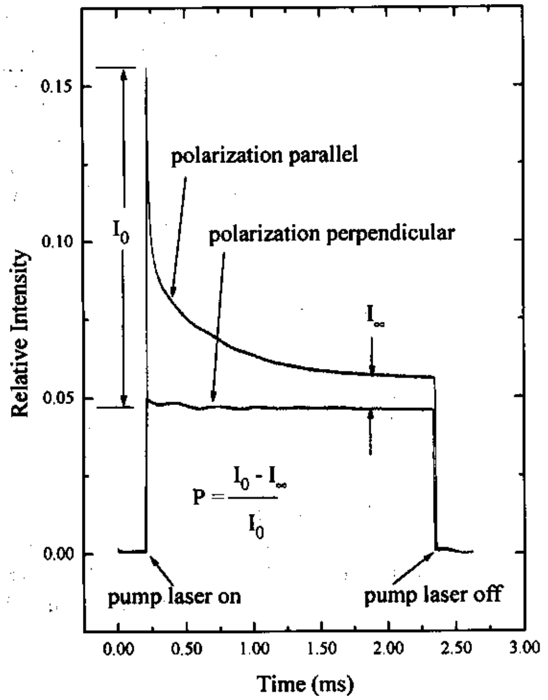

Fig. 4. The resonance fluorescence signal when the pump beam turns on with the pump beam polarized perpendicular to the magnetic field and polarized parallel to the magnetic field.

for an allowed dipole transition with light linearly polarized parallel to an external magnetic field and incident at right angles to the magnetic field are $\Delta m_J = 0$ and $\Delta m_I = 0$. Fig. 4 shows the resonance fluorescence signal when the K vapor is pumped on the $4^2S_{1/2}(m_J = -1/2) \to 4^2P_{1/2}(m_J = -1/2)$ transition. Data is shown for both situations when the pump beam is polarized parallel to the magnetic field and polarized perpendicular to the magnetic field in fig. 4 The chopping of the pump beam achieves a turn on and turn off time less than 1 μs. The K vapor relaxes in the dark. The $4^2S_{1/2}(m_J = -1/2) \to 4^2P_{1/2}(m_J = -1/2)$ transition can only absorb light polarized parallel to the magnetic field. Thus we expect to absorb light and to optically pump the vapor when the light is polarized parallel to the magnetic field, whereas when the light is polarized perpendicular to the magnetic field we expect no absorbed light although there will be some scattered light for this polarization. As is seen in fig. 4 there is almost no optical pumping when the pump light is polarized perpendicular to the magnetic field. The signal with the light polarized perpendicular to the magnetic field is almost independent of wavelength and we believe it represents primarily scattered light. The signal in fig. 4 shows a large initial fluorescence immediately after the pump beam is turned on and then a rapid decrease in the fluoresence as the K is optically pumped to a high polarization. The initial fluorescence with the pump light polarized parallel to the magnetic field minus the steady state fluorescence with the pump light polarized parallel to the magnetic field ($I_0 - I_\infty$ in fig. 4) divided by the initial fluorescence when the pump light is polarized parallel to the magnetic field minus the steady state fluorescence when the pump light is polarized perpendicular to the magnetic field (I_0) is taken as being equal to the K polarization in the steady state i.e. $P = (I_0 - I_\infty)/I_0$. This assumes that the scattered light intensity is the same for each polarization. The scattered light intensity is found to be independent of the polarization for the cell at room temperature when the K vapor density is very low. This analysis yields a steady state polarization of 0.9. The pumping rate, τ_p^{-1}, is determined both by the pump laser intensity I_ν and the electron polarization loss rate of the K vapor τ_L^{-1}. The pumping rate τ_p^{-1} is given by

$$\tau_p^{-1} = \tau_L^{-1} + \frac{ph\nu}{\sigma_{lu} I_\nu},$$

where σ_{lu} is the absorption cross section at the pump wavelength and p is the average number of photons required to polarize a K atom. As shown in fig. 4a the time to pump the K vapor cell to a steady state polarization is equal to 69 μs for a laser intensity of 300 mW/cm^2. The Ti:sapphire laser lases on several modes and the exact frequencies of the pumping light are not known. Obviously there is no fluorescence when the pump light is blocked off so there is no way to obtain the loss rate using this method. It is also possible to optically pump the cell using light at a wavelength corresponding to the $\Delta m_J = \pm 1$ transitions if the polarization of the light is linearly polarized perpendicular to the magnetic field and incident normal to the magnetic field.

The average number of photons required to polarize a K vapor using $P_{1/2}$ π polarized light incident normal to the high magnetic field is 1.5 photons per K atom at low buffer gas density. As the buffer gas density increases, the K atoms excited to the $4^2P_{1/2}$ level begin to make collisions with the buffer gas while in the $4^2P_{1/2}$ level. These collisions reorient the angular momentum of the excited K atom. At high buffer gas densities the atoms excited to the $4^2P_{1/2}$ level are completely reoriented and the probability that an atom decays back to a given m_J state in the ground level is the same for all m_J states. In this situation the average number of photons required to polarize a K vapor is 2 photons per K atom. The average number of photons required to polarize a K vapor using σ^+ or σ^- polarized light incident parallel to the high magnetic field is 3 photons per K atom at a low buffer gas density and 2

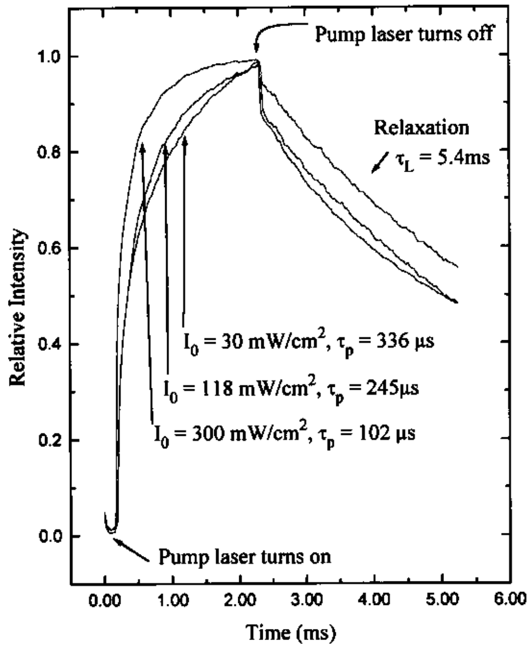

Fig. 5. The Faraday rotation signal for pump laser light intensities of 300, 118 and 30 mW/cm^2. The traces show three distinct regions. The first displays the increase of the rotation signal as the pump beam turns on and θ increases with the polarization of the K vapor. The time to polarize the vapor is seen to decrese with increasing pump light intensity. The second region shows a sharp transient feature of 50–60 μs duration. The third region shows a slow relaxation of $\tau_L = 5.4$ ms.

photons per K atom at high buffer gas density. At the He buffer gas density in our K cell the reorientation in the excited $4^2P_{1/2}$ level is complete and $p = 2$. The optically pumped alkali targets used for the optically pumped H^- ion source contain no buffer gas and p will be 1.5 for π polarized pump light. Thus there may be a major advantage to use π polarized pump light for the ion source. Likewise there is an advantage in the use of π polarized pump light for the Argonne optically pumped target which operates with an atomic deuterium density of about 10^{14} cm^{-3}, so that there is very little redistribution in the excited level.

Fig. 5 shows a typical Faraday rotation signal showing both the pumping and the relaxation in the dark for three different pump laser intensities. The Faraday rotation angle θ is given by $\theta = VBnl$, V is the verdet constant, B is the magnetic field intensity, and nl is the product of the K average number density times the cell length. The Verdet constant depends both upon the population densities of the magnetic sublevels and upon the transition frequencies of the respective polarization components of the light [9]. Therefore it depends on the magnetic field strength through the Zeeman splitting of the energy levels and upon the polarization of the vapor. The transmitted intensity through the analyzer is governed by $I(\theta) = (I_{max} - I_{min}) \cos^2(\theta - \phi) + I_{min}$. For our experiment I_{min} is very near zero and ϕ is chosen to be $\pi/2$. Fig. 5 shows $I(\theta)$ as a function of time for three different pump laser intensities. We do not know the diode laser frequency with sufficient accuracy to obtain absolute values for the K vapor polarization and number density. We can, however, analyze the Faraday effect data to obtain pumping and relaxtion times. The pumping times and the relaxation time are given in fig. 5. As expected the pumping rate increases as the pump laser intensity increases.

The electron spin relaxation in these traces has an interesting unexplained dependence on time. The polarization loss rate is very high for the first 60 μs and then decreases to a much slower rate. The polarization can decrease in the dark due to various effects. For example diffusion of polarized atoms out of and the diffusion of unpolarized atoms into the probe laser beam causes polarization loss. The electron spin relaxation in collisions of a polarized alkali with the He buffer gas or the cell walls can cause polarization loss. Other effects can also cause a loss of polarization. We can not quantitatively explain the time dependence of the polarization loss in the dark.

4. Conclusions

In summary, this paper has shown that a K vapor can be optically polarized by the absorption of π polarized light incident at right angles to a high magnetic field. The polarization and the pumping time of a K vapor have been measured both by the use of the scattered resonance fluorescence and the pumping and relaxation times have been measured by the use of the Faraday effect. The use of light incident at right angles to the magnetic field has potential advantages for optical pumping of alkali vapors for polarized ion sources or targets. These advantages include the reduction in the number of photons required to polarize a K atom and the possible development of targets that have very high target thickness parallel to the magnetic field but that are thin enough perpendicular to the magnetic field that optical pumping is both possible and efficient. In addition, for reasons of geometrical convenience optical pumping with linearly polarized light may be desirable.

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