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Measurement of potassium–potassium spin relaxation cross sections

Stephen Kadlecek, L.W. Anderson*, Thad Walker

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Abstract

The K–K spin relaxation rate has been measured in an optically pumped K vapor cell. The K–K spin relaxation cross section is determined to be 1.0×10^{-18} cm^2, which is about a factor of two less than a previous measurement.

1. Introduction

Spin exchange optical pumping of ^{3}He is of current interest both intrinsically and for the use in magnetic resonance imaging and polarized targets for particle accelerators. Magnetic resonance imaging requires large quantities of polarized ^{3}He so that the production cost per polarized ^{3}He atom is of great importance. This cost can be minimized by increasing the efficiency of the spin exchange optical pumping.

The highest possible efficiency of ^{3}He spin exchange optical pumping using an alkali vapor is determined by the ratio of the alkali–^{3}He spin exchange polarization rate to the alkali–^{3}He spin relaxation rate. Currently, however, polarized ^{3}He is produced by spin exchange with Rb at high enough Rb densities that Rb–Rb spin relaxation dominates the Rb–^{3}He relaxation and thus limits the spin exchange efficiency. It is not certain which alkali metal vapor should be used to optimize the spin exchange optical pumping of ^{3}He, but K may be an attractive alternative to Rb. The spin exchange rates for Rb–^{3}He and K–^{3}He are believed to be comparable whereas the K–K spin relaxation rate should be smaller than the Rb–Rb spin relaxation rate. If this is so, ^{3}He spin exchange optical pumping would be made more efficient by using K rather than Rb. This paper reports an experimental measurement of the K–K spin relaxation rate as a function of the K density, giving the cross section for the K–K spin relaxation. Our measured cross section is a factor of 2 lower than a previous measurement [1], and a factor of 15 less than the Rb–Rb cross section [1,2].

2. Apparatus

Fig. 1 shows a schematic diagram of the apparatus used for this experiment. An Ar^+ pumped Ti:sapphire laser beam with a wavelength near the $4\ ^2S_{1/2} \rightarrow 4\ ^2P_{1/2}$ transition at $\lambda = 770.1$ nm and with a power of 0.2 W is used to optically pump K in a vapor cell. The laser beam is circularly

* Corresponding author. Tel.: +1 608 262 8962; fax: +1 608 265 2334 e-mail: lwanders@facstaff.wisc.edu.

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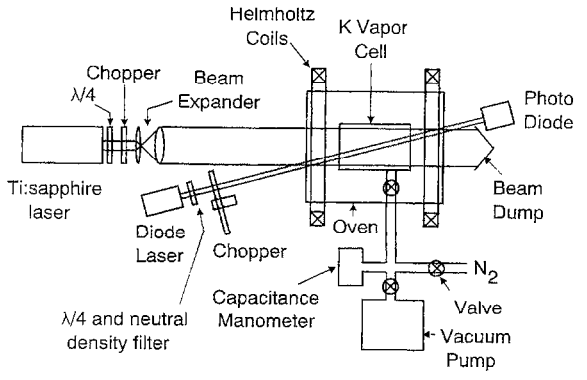

Fig. 1. Schematic diagram of the apparatus.

polarized by a quarter wave plate. The center wavelength of the laser is set to an accuracy of 5 GHz using a Burleigh model WA-1500 wavemeter. The bandwidth of the standing wave Ti:sapphire laser is about 40 GHz. The Ti:sapphire laser beam is chopped mechanically at 2 Hz with a rise time of 0.5 ms. The Ti:sapphire laser beam is expanded, using a telescope made with two converging lenses, so that it largely fills the K vapor cell.

The K vapor cell is made of stainless steel with Pyrex windows attached using a modified knife-edge conflat seal [3]. The cell has an inner radius of $R = 1.75$ cm and a length of $L = 12.5$ cm. Typically the cell contains 200 Torr of N_2 gas at room temperature. The N_2 gas serves to quench the excited K atoms so that the cell can be optically pumped without radiation trapping limiting the K vapor polarization. The N_2 also slows the diffusion of the K atoms to the wall and hence lengthens the spin relaxation time of the K vapor. The N_2 pressure is determined with a capacitance manometer. The K vapor density is controlled by varying the temperature of the oven which contains the cell. The K has Rb and Cs impurities less than 50 ppm. The temperature of the cell is measured using thermocouples attached to the cell and is uniform to within 2 K. A magnetic field of a few Gauss is maintained at the K vapor cell using a pair of Helmholtz coils which are 0.9 m in diameter.

The polarization of the optically pumped vapor is monitored with a single frequency diode probe laser. The diode laser beam is circularly polarized with a quarter wave plate and is attenuated using neutral density filters to less than 1 μW so that it does negligible optical pumping. The diode laser beam is chopped at 2.6 kHz. The chopper provides the reference signal for a lock-in-detector. The diode laser beam traverses the K vapor cell, making an angle of about 0.15 radians with the Ti:sapphire laser beam axis. The diode laser beam is detected using a photo-diode. The output for the photo-diode serves as the input for the lock-in detector.

3. Experimental results

The Ti:sapphire laser wavelength is set to a wavelength that is slightly below line center of the $4\,^2S_{1/2} \rightarrow 4\,^2P_{1/2}$ transition in K, allowing the laser beam to penetrate through the optically thick K vapor cell. This tends to excite primarily the lowest longitudinal diffusion mode of the cell. The polarization is kept low $P \approx 0.01$–0.05, and the diode probe laser is weakly attenuated so that its absorption is proportional to the polarization. For relatively low temperatures and hence relatively low K vapor density the Ti:sapphire laser is set to 770.0 nm and for relatively high temperatures the laser is set to 769.7 nm. The spatial profile of the Ti:sapphire laser beam is approximately Gaussian and is expanded so that the laser beam fills the K vapor cell with the ratio of the intensity at the cell wall to the intensity on axis being about $\exp(-2)$. The radial dependence of the intensity of the laser beam is such that the optical pumping of the cell excites primarily the lowest transverse diffusion decay mode of the cell. The K vapor in the cell is polarized by the optical pumping when the Ti:sapphire beam is allowed to pass through the cell. When the Ti:sapphire beam is blocked off by the chopper the K vapor polarization decays in the dark. The build up of the polarization when the Ti:sapphire laser is on and the decay in the dark are monitored with the diode laser. The relaxation in the dark occurs due to the following three mechanisms: (i) K–N_2 relaxation collisions, (ii) relaxation due to wall collisions, and (iii) K–K relaxation collisions. Fig. 2(a) shows a typical relaxation time measurement for the polarization of the K vapor cell.

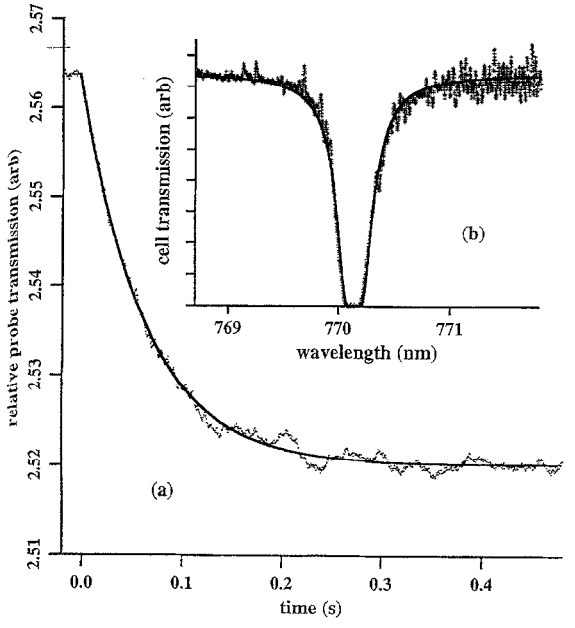

Fig. 2. (a) Transmission as a function of time for relaxation in the dark. (b) Transmission as a function of the frequency, used to determine the vapor pressure.

We assume that the K spins depolarize at every collision with the stainless steel walls so that the relaxation rate of the slowest mode is given by $\Gamma_{11} = [(\mu_1^2 + v_1^2)D + k(\text{K–N}_2) + k(\text{K–K})]A$ where $\mu_1 = 2.405/R$, $v_1 = \pi/L$, D is the diffusion constant for K in N_2 at the N_2 density and temperature of the cell, $k(\text{K–N}_2)$ is the relaxation rate due to K–N_2 collisions, and $k(\text{K–K})$ is the relaxation rate due to K–K collisions. The factor $A = 3/[3 + 4I(I+1)] = 1/6$ takes into account the slowing down of the electron relaxation rate due to the angular momentum stored in the nuclear spin of $I = 3/2$ [4]. The K–K relaxation rate is given by $k(\text{K–K}) = n_K\langle\sigma_{K-K}v_{K-K}\rangle$ where n_K is the K number density and $\langle\sigma_{K-K}v_{K-K}\rangle$ is the average over the Boltzmann distribution of the K–K relaxation cross section and the relative K–K velocity, and the K–N_2 relaxation rate is given by $k(\text{K–N}_2) = n_N\langle\sigma_{K-N}v_{K-N}\rangle$ where n_N is the N_2 number density and $\langle\sigma_{K-K}v_{K-N}\rangle$ is the average over the Boltzmann distribution of the K–N_2 relaxation cross section times the relative K–N_2 velocity. The K number density depends strongly on the temperature of the K vapor cell. At a low temperature the K–K relaxation rate is very small so that the relaxation rate is $\Gamma_{11} \approx [(\mu_1^2 + v_1^2)D + k(\text{K–N}_2)]$. We have studied the relaxation at low K density and at N_2 densities where the diffusion contributed less than 5% to Γ_{11} and have obtained $\sigma_{K-N} \approx 7.9\times10^{-23}$ cm^2 at $T = 437$ K. Then keeping the value of n_N constant we have measured the temperature dependence of the relaxation rate. While there is a weak temperature dependence for D, $\langle\sigma_{K-N}v_{K-N}\rangle$, and $\langle\sigma_{K-K}v_{K-K}\rangle$, the primary temperature dependence for Γ_{11} arises from the strong temperature dependence of n_K. Thus we can measure the value of $\langle\sigma_{K-K}v_{K-K}\rangle$ if we know n_K.

We have measured the dependence of n_K on the temperature by measuring the transmission of a linearly polarized laser beam as a function of the wavelength across the $4\ ^2S_{1/2} \rightarrow 4\ ^2P_{1/2}$ line shape as shown in Fig. 2(b). The laser beam transmission is given by $I/I_0 = \exp(-n_K\sigma_{ABS}L)$ where σ_{ABS} is the optical absorption cross section and where I_0 is the incident laser intensity. In order to eliminate uncertainities in the lineshape at high N_2 densities the measurement is made with the N_2 evacuated from the cell. In this case σ_{ABS} is dominated by resonance broadening [5]. Our vapor pressure measurements, which are reproducible to about 10%, are about 40% lower than tabulated vapor pressure measurements [6] and are parameterized by the equation $\log_{10} P = 4.14 - 4450/T$ where P is in atmospheres and T is the absolute temperature. Fig. 3 shows the relaxation rate, Γ_{11}, obtained as a function of n_K. Defining an average cross section, $\sigma(\text{KK})$, by $\langle\sigma_{K-K}v_{K-K}\rangle = \sigma(\text{KK})v(\text{KK})$ where $v(\text{KK})$ is the RMS value of the relative velocity we obtain $\sigma(\text{KK}) = 1.0\times10^{-18}$ cm^2 at 500 K. This value of the K–K relaxation cross section is about a factor of two smaller than the value obtained in a previous experiment which used tabulated vapor pressure curves to determine the K density. Since our measured vapor pressures are 40% below the tabulated values we would obtain a cross section of 6.2×10^{-19} cm^2 if we had used the tabulated vapor pressures. This is a factor of four lower than in Ref. [1]. We do not know the reason for this difference. Our measurement of the K–K spin relaxation cross section is about a factor of 15 smaller than the measured Rb–Rb spin relaxation cross section [1,2].

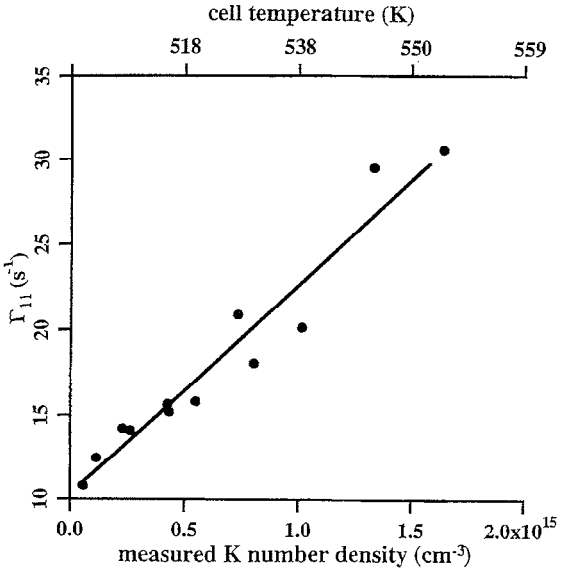

Fig. 3. Observed spin relaxation rate, Γ_{11}, as a function of our measured K density and temperature.

Our measured K–K spin relaxation rate is about a factor of 10 larger than a simple estimate based on the magnetic-dipole–magnetic-dipole interaction in the K–K dimers and classical hard sphere trajectories. The K–K and Rb–Rb spin relaxation rates are much larger than can be explained by the magnetic-dipole–magnetic-dipole interaction even if second order spin orbit interactions are included [7].

The small K–K spin relaxation cross section suggests that the use of K might lead to more efficient spin exchange optical pumping of ^{3}He.

Acknowledgements

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