THE JLAB POLARIZED ^{3}HE TARGET

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The polarized ^{3}He target has been used successfully in several recent experiments investigating the spin structure of the neutron at Thomas Jefferson National Accelerator Facility (JLAB). In this note we discuss the two step polarization process of optical pumping of Rb vapor and spin exchange to the ^{3}He nucleus, along with the independent polarimetries used to characterize the high density target cells.

1. Optical Pumping

Polarized ^{3}He provides a practical polarized neutron target due to the fact that its ground state configuration is dominated by the S-wave contribution in which the protons are spin-paired. To polarize the JLAB ^{3}He target, an alkali metal vapor (rubidium) is optically pumped. The Rb polarization is then transferred from the valence electron to the ^{3}He nucleus by spin exchange collisions.

Naturally occurring rubidium consists of approximately 72% ^{85}Rb and 28% ^{87}Rb. Right circularly polarized light from a diode laser array centered at 794.7 nm is used to stimulate the transition of the ^{85}Rb valence electrons from the $5^2\mathrm{S}_{1/2}$ ($F = 2, m = -2 \ldots 2$ and $F = 3, m = -3 \ldots 3$) levels to the $5^2\mathrm{P}_{1/2}$ ($F = 2, m = -2 \ldots 2$ and $F = 3, m = -3 \ldots 3$) levels subject to the selection rule $\Delta m = +1$. (See Fig. 1.) The excited electrons can then decay by a $\Delta m = 0, \pm 1$ transition, since the photon can be emitted in any direction, not only along the quantization axis z. D1 photons making $\Delta m = -1$ transitions would act to depopulate the F=3,m=3 level, so photon emission is suppressed by introduction of a small amount of N_2 buffer gas. Rb-N_2 collisions radiationlessly de-excite the Rb. A few percent of the excited atoms still decay by emitting a D1 or D2 photon. D2 photons are present because electrons in the $5^2\mathrm{P}_{1/2}$ state can make the small jump to the $5^2\mathrm{P}_{3/2}$ state due to their thermal energy.

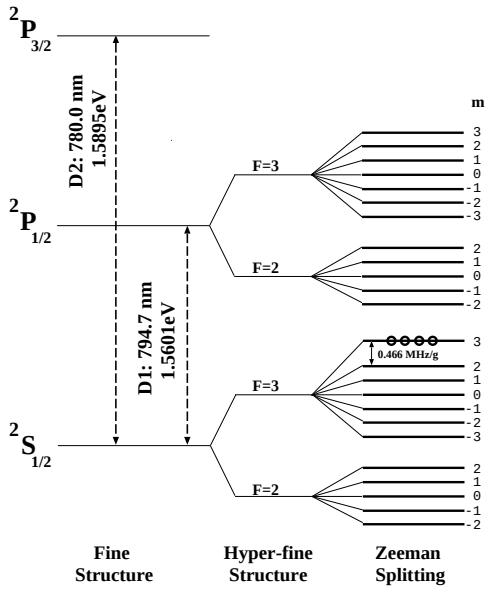

Figure 1. Energy level diagram for ^{85}Rb, I=5/2.

After relaxation, the ground state electrons are able to absorb another photon. That is, all electrons except for those in the F=3,m=+3 state, because there is no m=4 state available from the D1 transition. Eventually, the majority of atoms collect in $^2S_{1/2}$ F=3,m=3 state and the Rb is polarized.

2. Spin Exchange

The cross section for spin exchange between the Rb valence electron and the ^{3}He nucleus is about 10^{-24} cm^2 and the rate of transfer [4] of polarization from the rubidium valence electron to the ^{3}He nucleus is given by:

$$\gamma_{se} = \langle \sigma_{se} v \rangle [Rb] \tag{1}$$

where $\langle \sigma_{se} v \rangle$=1.2·10^{-19} cm^3 s^{-1} is the velocity averaged ^{3}He-Rb spin exchange rate constant [5], and [Rb] is the rubidium number density.

The temperature dependence of the Rb density can be described by the Killian formula: [1]

$$[Rb] = \frac{10^{10.55-\frac{4132}{T}}}{1.38 \cdot 10^{-16} T} \tag{2}$$

Wagshul [3] showed that this formula is accurate up to 180°C. Above 200°C

the formula tends to overestimate the density. At typical operating temperatures (170°C), the rubidium number density is about $2.7{\cdot}10^{14}$ cm^{-3}, so the spin exchange rate is expected to be about $(8.5\text{h})^{-1}$.

The ^{3}He polarization as a function of time is given by:

$$P = \frac{\gamma_{se} P_{Rb}}{\gamma_{se} + \Gamma} \left[1 - e^{-(\gamma_{se}+\Gamma)t} \right] \tag{3}$$

where Γ is the total relaxation rate and P_{Rb} is the Rb polarization. At equilibrium: $P \longrightarrow \left(\frac{\gamma_{se}}{\gamma_{se}+\Gamma} \right) P_{Rb}$. So we need $\gamma_{se} \gg \Gamma$ and $P_{Rb} \simeq 1$ in order to achieve highly polarized ^{3}He.

3. Relaxation Mechanisms

There are several relaxation mechanisms that compete with the spin exchange and act to destroy the polarization. The total relaxation rate without beam is given by:

$$\Gamma = \Gamma_D + \Gamma_w + \Gamma_\nabla \tag{4}$$

Here, Γ_D signifies the relaxation rate due to the ^{3}He-^{3}He magnetic dipolar interaction [6], Γ_w is the relaxation due to magnetic impurities in the glass wall that disorient the noble gas spins, and Γ_∇ represents the relaxation rate due to the spins interacting with gradients in the holding field. The first two relaxation rates are of order $(100\text{h})^{-1}$. Field mapping [2] of the Helmholtz coils revealed that the third rate was of the order of $(1000\text{h})^{-1}$. Total relaxation rates, in the absence of beam, for typical cells used at JLAB are $(50\text{h})^{-1}$. The high energy electron beam ionizes ^{3}He atoms and thus introduces another relaxation mechanism. In beam, the target typically reaches average polarizations above 40%.

4. Experimental Setup

The longitudinal or transverse holding field of up to 30 gauss is provided by two pairs of Helmholtz coils (only one pair shown in Fig. 2). The target is a double chambered glass cell containing approximately 10atm of ^{3}He, with a small admixture of N_2 and Rb. The target chamber can be up to 40 cm long. The pumping chamber sits in an air blown oven at typical temperatures of 170°C to vaporize the Rb. About 100 watts of circularly polarized diode laser light is used to optically pump the Rb. An RF(Radio Frequency) coil operating at 92kHz is used to flip the ^{3}He spins during polarization measurements. The small coil just above the pumping chamber is used during EPR measurements to induce the Zeeman transition which is then detected with a photodiode. Polarimetry is discussed in sections 5 & 6.

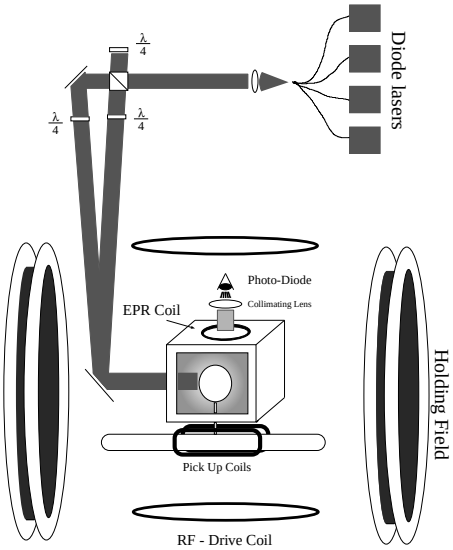

Figure 2. The polarized ^{3}He target.

5. Electron Paramagnetic Resonance (EPR) Polarimetry

In the absence of polarized ^{3}He, the Zeeman splitting (0.466MHz/g) of the F=3 sublevels of the Rb ground state is proportional to the holding field. The presence of magnetically oriented ^{3}He causes a small but measurable increase in this splitting, which is proportional to the ^{3}He polarization. The polarized target holding field is typically 25.5 gauss, which causes a level splitting of about 11.8 MHz. To measure the deviation $\Delta\nu$ from this value, a small coil is used to probe the Rubidium energy levels. An oscillating magnetic field at the proper frequency will be able to excite the F=3,m=3 to F=3,m=2 transition of the ground state. This increases the number of F=3,m=2 ground state atoms that can be excited by the incident laser light, and there is a corresponding increase in the number of photons emitted as these excited states decay. At resonance, the EPR coil frequency equals the Zeeman frequency and the fluorescence is maximized [a]. The change of the Zeeman frequency due to the polarized ^{3}He magnetic field can be determined by flipping the ^{3}He spins while monitoring the resonance frequency. Initially the spins will add to the main holding field and after

[a] Since the cell is bathed in D1 pumping light from the lasers it is difficult to see the small variation in D1 light due to the increased intensity. Instead, a D2 filter is used and we detect the resonance from the D2 light.

they will subtract. By taking the difference of the measured frequencies in these two states we can extract $\Delta\nu$ and hence the polarization. The frequency variation is given by [7]:

$$\Delta\nu = \left[\frac{8\pi}{3}\frac{\mu_0}{4\pi}\left(\frac{d\nu}{dB}\right)\kappa_0\mu_3[^3He]\right]\mathbf{P}_3 \tag{5}$$

for the F=I+1/2, m=±F state. Here, $\left(\frac{d\nu}{dB}\right)$ depends only on the magnetic field and κ_0 is a temperature dependent factor.

6. Nuclear Magnetic Resonance (NMR) Polarimetry

As a spin 1/2 system in a magnetic field, the ^{3}He nucleus has two discrete energy levels: $\pm(\mu_3 B_0)$ depending on the orientation of the magnetic moment with respect to the field. A magnetically oriented ensemble can be induced to make transitions from one level to the other by resonant frequency photons. The frequency of resonance is $\omega = 2\frac{\mu_3 B_0}{\hbar}$.

To detect the NMR, an RF magnetic field is applied to the target orthogonally to the holding field. The polarization is measured by holding the RF frequency fixed and sweeping the main magnetic field through the RF resonance. At resonance, the spins flip and this is detected by a pair of pickup coils placed around the cell. The precessing ^{3}He nuclei induce an AC voltage in the pickup coils which is detected with a lock-in amplifier referenced to the RF frequency. The detected signal is proportional to the ^{3}He polarization. An absolute polarization can be determined by calibrating the NMR apparatus with an identical water sample. The polarization of the water sample is known in advance as it follows a Boltzman distribution.

7. Conclusion

The Jefferson Lab polarized ^{3}He target provides reliable performance with high polarization ($\geq$40%) and extremely high luminosity ($10^{36}\mathrm{cm}^{-1}\mathrm{s}^{-1}$). The two independent polarimetries agree within a total error of 4%.

References

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