NEW DIRECTIONS IN SPIN-EXCHANGE OPTICAL PUMPING POLARIZED ^{3}HE TARGETS

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Nuclear spin-polarized ^{3}He is often used as an effective polarized neutron target for nuclear physics experiments. Polarized helium-3 (^{3}He) targets using spin-exhcange optical pumping (SEOP) routinely achieve polarizations of $\approx 40\%$, which is well below the theoretical expectation of $\approx 70\%$. Hybrid SEOP using potassium (K) in addition to rubidium (Rb) has the potential to increase target performance. This is because K-^{3}He spin exchange is up to an order of magnitude more efficient than Rb-^{3}He spin exchange. Other proposed upgrades that are discussed include a large pumping chamber cell geometry and the use of combiner and homogenizer optical fibers. Using hybrid SEOP, we have polarized 3.3 liters of ^{3}He to 43%, which to our knowledge is the largest volume of ^{3}He polarized to $\geq$40%.

1. Spin-Exchange Optical Pumping

A two step process called spin-exchange optical pumping (SEOP)[1] is used to polarize the nucleus of ^{3}He. First the single valence electron of a Rb atom is polarized by optical pumping. Second this electronic polarization is transferred to the ^{3}He nuclear spin by spin-exchange collisions with Rb.

The left half of figure 1 depicts the optical pumping of a Rb atom without nuclear spin. Circularly polarized light (σ_+) tuned to the D_1 transition[a] is absorbed only by a Rb atom in the $m_J = -\frac{1}{2}$ Zeeman ground state due to the conservation of angular momentum. Since the excited states of a

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[a] D_1 refers to the transition between the $n\mathrm{S}_{\frac{1}{2}}$ and $n\mathrm{P}_{\frac{1}{2}}$ levels and D_2 refers to the $n\mathrm{S}_{\frac{1}{2}} \leftrightarrow n\mathrm{P}_{\frac{3}{2}}$ transition where n labels the valence shell.

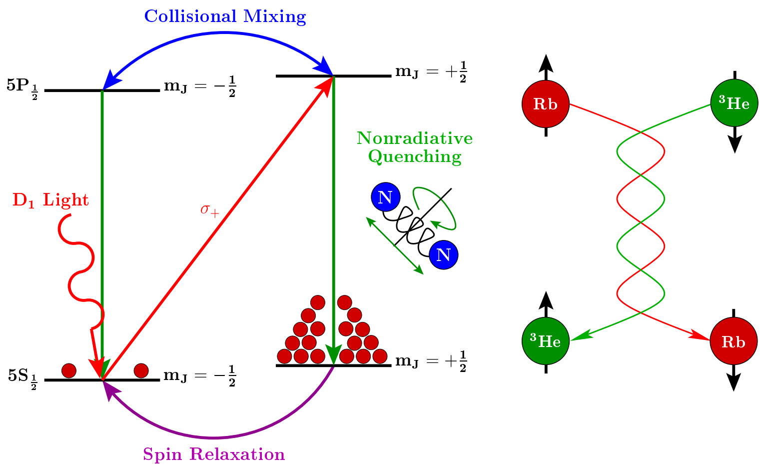

Figure 1. *Left:* Energy level diagram of Rb in a magnetic field (omitting the nuclear spin of the Rb). *Right:* Spin-exchange collision between Rb and ^{3}He.

Rb atom are mixed due to collisions, an excited Rb atom can decay into either ground state with equal probability. These decay transitions can occur via radiation or via radiationless collisions[b] with nitrogen molecules (N_2). Decay via radiation is undesirable because the emitted photon generally has a polarization that limits the optical pumping efficiency. Therefore just enough N_2 is added to provide adequate nonradiative quenching. The equilibrium Rb polarization is:

$$P_{\rm Rb}^{\infty} = P_{\rm light}\frac{R}{R+\gamma} \tag{1}$$

where R is the photon-absorption rate and γ is the Rb spin-relaxation rate, which in part includes the ^{3}He spin-exchange rate. On a timescale of milliseconds, the Rb polarization saturates at $\geq 70\%$.[c]

The right half of figure 1 depicts a spin-exchange collision. A hyperfine-like[d] interaction couples the nuclear spin $\vec{K}_{^3\rm He}$ with the electronic spin $\vec{S}_{\rm Rb}$. The spin-exchange hamiltonian also includes a Fermi contact term $\phi(\vec{r})$, which is essentially the probability density of finding the Rb electron

[b]The energy of the transition is transferred to the rotational and vibrational modes of oscillation of the N_2.
[c]Plans to measure the Rb polarization under typical experimental conditions for the first time are under way.
[d]Hyperfine-*like* because *hyperfine* usually refers to the interaction between the eletronic and nuclear spins *of the same atom.*

at a distance $\vec{r}$ from the ^{3}He nucleus:[2]

$$H_{\rm se} = \frac{8\pi}{3}\left(g_{^3\rm He}\mu_{\rm B}\right)\left(2\mu_{\rm B}\right)|\phi(0)|^2\,\vec{K}_{^3\rm He}\cdot\vec{S}_{\rm Rb} \qquad (2)$$

where $g_{^3\rm He}$ is the magnetic moment of ^{3}He in units of the Bohr magneton $\mu_{\rm B}$. The spin-exchange rate to Rb from ^{3}He is $\gamma'_{\rm se} = \langle\sigma v\rangle_{\rm se}\left[{}^3{\rm He}\right]$ and the spin-exchange rate to ^{3}He from Rb is $\gamma_{\rm se} = \langle\sigma v\rangle_{\rm se}[{\rm Rb}]$ where $\langle\sigma v\rangle_{\rm se}$ is the velocity averaged spin-exchange cross section and [X] refers to number density.

2. Hybrid SEOP

Hybrid SEOP[3] differs from conventional SEOP described in section 1 by the addition of K to the polarization process. Optically pumped Rb spin exchanges with K which subsequently spin exchanges with ^{3}He. If the ratio of Rb to K is low, then the Rb mainly spin exchanges with the K and the ^{3}He is polarized mostly by K-^{3}He spin exchange.

The spin-exchange efficiency η ($\equiv \gamma'_{\rm se}/\gamma$) is defined as the ratio of the alkali metal-^{3}He spin-exchange rate to the alkali metal spin-relaxation rate. A dominant source of spin relaxation is from the spin-rotation interaction,[4] which is essentially a spin-orbit coupling between the alkali electron spin and the orbital angular momentum associated with the alkali-^{3}He pair. The strength of this coupling increases with the size of the alkali metal, which chiefly explains the greater efficiency of K-^{3}He spin exchange.[5]

K-Rb hybrid SEOP is potentially more useful than pure K SEOP for two reasons. First, hybrid SEOP can be performed using the same set of lasers and polarizing optics that are currently used for pure Rb SEOP. Pure K SEOP would require lasers and polarizing optics that operate at a different wavelength than presently used. Second, the optical pumping efficiency of K might be limited because of the inadvertent excitation of the D_2 transition by the broadband diode lasers typically used. This is not an issue for the optical pumping of Rb because the separation of its D_1 and D_2 transitions is four times larger than for K.[e]

3. Large Pumping Chamber

The target cell is designed so that ^{3}He is polarized in a spherical pumping chamber while electron scattering occurs in the cylindrical target chamber

[e] A bigger atom has a stronger spin-orbit coupling which gives a larger spin-orbit splitting.

simultaneously. Unpolarized ^{3}He atoms diffuse into the pumping chamber through a transfer tube, while polarized ^{3}He atoms diffuse into the target chamber. In the approximation that the diffusion rates are much greater than both $\gamma_{\rm se}$, the ^{3}He-alkali metal spin-exchange rate, and Γ, the spin-relaxation rate of the ^{3}He, the equilibrium polarization is:

$$P^{\infty}_{^3\rm He} = P^{\infty}_{\rm Rb} \frac{\langle\gamma_{\rm se}\rangle}{\langle\gamma_{\rm se}\rangle + \langle\Gamma\rangle} \qquad \langle\gamma_{\rm se}\rangle = \frac{N_p}{N}\gamma_{\rm se} \qquad \langle\Gamma\rangle = \frac{N_p}{N}\Gamma_p + \frac{N_t}{N}\Gamma_t \quad (3)$$

where the brackets refer to volume averages defined above, N is the total number of ^{3}He atoms, and the subscripts refer to a particular chamber.

There is a higher density of ^{3}He in the target chamber due to a temperature gradient.[f] Therefore the spin-relaxation rate due to ^{3}He-^{3}He dipolar interactions is greater in the target chamber. In addition, ^{3}He$^+$ and ^{3}He$_2^+$ ions created by interactions with the electron beam causes spin relaxation mainly in the target chamber. Since $\Gamma_t > \Gamma_p$ for the reasons just mentioned and because spin exchange occurs only in the pumping chamber, increasing the fraction of ^{3}He atoms in the pumping chamber increases $P^{\infty}_{^3\rm He}$ (all else being equal). Presently being explored is a target cell geometry in which the pumping chamber diameter is increased by a factor of 40% while keeping the target chamber unchanged. Unfortunately, a larger pumping chamber requires more laser power to maintain a constant optical pumping rate, which is proportional to the power per unit area. Hybrid SEOP might require less laser power than coventional SEOP which could allow the use of a large pumping chamber cell with the laser power presently used.

4. Combiner and Homogenizer Optical Fibers

Two problems arise from the fact that six or more beam spots illuminate the pumping chamber for optical pumping.[g] First, precious space in the experimental hall is needed for the lasers and a large number of optics. Second, each beam line must have a small angular offset with respect to the magnetic holding field in order to converge onto the pumping chamber. It has been shown[6] that the efficiency of optical pumping is reduced when the light propagation vector $\hat{k}$ has a non-zero angle with the quantization axis of the spin $\hat{b}$ which is defined by the field. The alkali polarization is reduced by a factor of $\hat{k}\cdot\hat{b}\,(=\cos(\theta))$ and the laser power needed for optical

[f]The pumping chamber is heated to >440 K in order to vaporize the Rb atoms, while the target chamber is kept at room temperature.
[g]The polarization optics split the beam from each of the three or more lasers needed to provide the requisite laser power for optical pumping.

pumping increases by a factor:

$$\Upsilon = \frac{\text{Power}(\theta \neq 0)}{\text{Power}(\theta = 0)} = 1 + \frac{R}{\gamma}\sin^2(\theta) \tag{4}$$

A more compact combiner/homogenizer optical fiber system that should minimize θ is being investigated. A combiner fiber accepts light from up to five separate sources and outputs five beam spots in a closely packed pentagonal pattern. A homogenizer fiber attached to the output end of the combiner outputs one nearly homogenous beam spot.

5. Preliminary Results

Studies[7] seem to indicate that the ideal vapor ratio of K to Rb is ≈30:1. For some cells, a glovebox was used to prepare an alloy of Rb and K with a prescribed ratio. Temperatures up to ≈525K are needed to reach suitable vapor densities of K for spin exchange. Therefore a forced-air oven made of alumina silicate ceramic has been constructed for those tests at higher temperatures. Cells filled at UVa and W&M with different geometries and with different ratios of Rb to K have been tested. While all of these hybrid cells have shown increased spin-exchange performance, the best has been the polarization of 3.3 liters of ^{3}He to 43% with an estimated 20:1 vapor ratio of K:Rb. To our knowledge, this represents the largest volume of ^{3}He polarized to ≥40% using SEOP (pure or hybrid). Plans are underway to build diagnostic tools that will allow us to measure the alkali metal polarization and vapor ratio *in situ*. In addition, a prototype combiner/homogenizer optical fiber setup has been in use at the Department of Radiology at UVa. Significant heating at the fiber interfaces due to power loss has limited the combined power that can be transported in the combiner/homogenizer system. Work on these upgrades has just begun and prospects look good.

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