Recent Advances of Polarized ^3He Target at Jefferson Lab

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Abstract. Polarized ^3He target has been widely used in nuclear and particle experiments to study the neutron structure in the spin degree of freedom, as most of the ^3He spin is carried by the unpaired neutron. Spin-Exchange Optical Pumping (SEOP) process is used in Jefferson Lab Hall A to polarize its ^3He target. Through developments in recent years, both the performance and corresponding polarimetry of such a target were greatly improved. Several experiments recently carried out in Hall A benefited remarkably from this target for the record highest figure of merit.

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INTRODUCTION

The polarized targets have been widely used in nuclear and particles experiments to study the nucleon structure in the spin degree of freedom. As a free neutron target can hardly to be made dense enough due to its short lifetime, 886 s, polarized nuclear targets such as ^2H or ^3He are commonly used to extract polarized neutron data.

Polarized ^3He targets are widely used in nuclear physics research and there exist two major methods of polarizing ^3He nuclei. The first one is based on the metastability-exchange optical pumping technique which was developed in the early 1960s at Rice university [1] and was later used in HERMES, MAINZ and MIT-Bates.

The second method is based on spin exchange optical pumping [2]. First an alkali metal vapor is polarized by optical pumping, then the polarization is transferred to ^3He nuclei through spin exchange collisions. Targets based on this principle are almost always designed to operate at quite high gas pressures, typically a few atmospheres. The polarized ^3He target using spin-exchange optical pumping was originally developed at SLAC [3] and has been successfully used in JLab Hall A since 1998.

SPIN EXCHANGE OPTICAL PUMPING (SEOP)

Rb Only System

The first step of SEOP is optical pumping of alkali-metal atoms using circular polarized laser light in a magnetic field. Due to the availability of lasers matching the $D1$ transitions of various alkali atoms, Rb is commonly chosen for such kind of target and all experiments in JLab Hall A before 2005 [4, 5, 6, 7, 8, 9] used Rb only ^3He cells. In reality, beside ^3He and alkali, a very small portion of N_2 , $\sim 1\%$ of total density, is added into the cells to increase the optical pumping efficiency by absorbing the unpolarized $D1$ light emitted by de-excited Rb atoms.

The next step is spin-exchange, and the key process is the collisional transfer of polarization between optically pumped alkali-metal atoms and the nuclei of the noble-gas atoms. For ^3He , the transfer of angular momentum occurs mainly through binary collisions between the atoms [2]. The contribution from van der Waals molecules is negligible. The spin-dependent interactions producing the spin transfer and relaxation in collisions are dominated by two processes. One process is the spin-rotation interaction which between the electron spin and the rotational angular momentum of the ^3He -Rb system. The second one is the isotropic hyperfine interaction between electron spin and the noble-gas nuclear spin.

For Rb only target cell, the spin exchange efficiency is defined as

$$\eta_{SE}^{\text{Rb}} = k_{SE}^{\text{Rb}}/\Gamma_{\text{Rb}}, \quad (1)$$

where k_{SE}^{Rb} is the rate of spin exchange and Γ_{Rb} is the spin-destruction rate of the rubidium vapor which is dominated by the spin-rotation interaction during collisions among Rb atoms or between Rb atoms and other gases. The spin

destruction caused by collisions of Rb atoms with the cell wall, and by randomly polarized photons emitted from the decay of excited electrons is small. In general, Γ_{Rb} can be expressed as

$$\Gamma_{\text{Rb}} = k_{\text{Rb-He}} + k_{\text{Rb-Rb}} + k_{\text{Rb-N}_2}. \quad (2)$$

Among $k_{\text{Rb-He}}$, only a small part of the Rb relaxation is caused by the spin exchange between ^3He nuclei and Rb electrons: $k_{SE}^{\text{Rb}} \ll k_{\text{Rb-He}}$. With normal condition, 170 °C and 10 amg, less than 4% of Rb atoms transfer their polarization to ^3He , while the rest is lost in other spin destruction processes.

Rb-K Hybrid System

Recently, study about hybrid cells indicates that the efficiency of SEOP could be increased if K or Na were used as the alkali-metal spin-exchange partner rather than Rb alone, due to their lower electronic spin-destruction rates.

With existence of Rb-K hybrid, the spin-exchange efficiency is now written as

$$\eta_{SE}^{\text{Rb-K}} = \frac{k_{SE}^{\text{Rb}} + k_{SE}^{\text{K}}}{\Gamma_{\text{Rb}} + \Omega \Gamma_{\text{K}} + q_{\text{Rb-K}}}, \quad (3)$$

where Ω is the vapor density ratio of K to Rb, and $q_{\text{Rb-K}}$ is the spin-destruction rate constant for Rb-K collisions. SEOP with Rb-K mixture is more efficient than SEOP with pure Rb because k_{SE}^{K} dominates Γ_{K} and is comparable with k_{SE}^{Rb} . In hybrid cells, rapid electronic spin-exchange between the K and Rb equalizes the polarization of the two alkali-metals, allowing for the benefits of the lower spin-destruction rate of K with no change in the optical pumping laser. The gain in efficiency relative to pure Rb mainly depends on the vapor density ratio Ω .

In practice, the Rb-K hybrid cells run at higher temperature, 230 °C, to obtain enough K vapor pressure. The higher spin-exchange efficiency greatly shorten the spin-up time of such kind of cells, 4 hours compared to 10 hours of Rb only cells. And the first batch of hybrid cells used in Hall A during G_E^n experiment [10] in 2006 achieved significantly higher in-beam polarization, 50% vs 40%. Further study showed that Ω of 5~10 gives optimal polarization performance, and most of the cells used after 2008 in Hall A have Ω in that range.

Narrow Line-Width Lasers

The initial target system in Hall A used high power Fiber Array Package (FAP) laser system from Coherent[®]. The typical FWHM of such a laser is about 2 nm while the Rb D1 absorption has a width of 0.3 nm at optical pumping temperature. Therefore, only part of the laser power will be absorbed by Rb atoms. The rest of the power is not just wasted but depolarizes the target through thermal process. It means that by simply adding more laser power will not necessarily increase the target polarization, and on the contrary it will reduce the target performance once certain limit exceeded.

Before the start of the Hall A experiments [11, 12, 13, 14, 15, 16] in 2008, a new type of high power narrow line-width diode laser system became available from Spectra-Physics[®]. The laser from such a system has a typical width of 0.2 nm which is even narrower than the Rb D1 line and provides a much higher optical pumping efficiency. By implementing this new laser, all these experiments benefit greatly from the huge improvement of the target polarization, which generally exceeds 60%.

HARDWARE SETUP

The ^3He target system in Hall A was redesigned in 2008 to fit the requirements of the series of six experiments with minimum change-over and very tight space constraints. A number of modifications and upgrades were implemented in the new design.

The target cells used in all experiments have a 3 inch pumping chamber and a 40 cm long target chamber with density of about 10 amg. The luminosity is about 3×10^{36} nuclei/s/cm² with 15 μA beam.

A third set of Helmholtz coils was added to the existing two pairs of coils to provide additional vertical magnetic field. Using all three sets of coils, target polarization in any direction in 3-D space is possible. A bigger oven which

FIGURE 1. The polarized ^3He target setup (left) and a ^3He cell (right).

allows all three pumping directions (longitudinal, horizontal transverse and vertical) was built with CS85 structural insulation material. This new material has just half of the density compared to the ceramics used in old ovens and much better insulation. The interior of the oven was painted to black to reduce the internal laser reflection.

A total of fifteen long optical fibers connected the lasers from the remote laser room to the hall. They were then connected to three 5-to-1 optical fiber combiners so that up to five lasers could be used in each single polarizing direction. Three higher-power (30 W) narrow line-width lasers were used together to provide optimal pumping efficiency with pumping chamber heated to 230 °C. The laser beam for each pumping direction was first polarized by passing through polarizing optics above the target and then got reflected into the pumping chamber by two mirrors.

POLARIMETRY

Two kinds of polarimetry, NMR (Nuclear Magnetic Resonance) and EPR (Electron Paramagnetic Resonance), were used to measure the polarization of the target.

Two pairs of RF coils (vertical and longitudinal) and five pairs of NMR pickup coils (three on the pumping chamber and two on the target chamber) were mounted to perform NMR measurements for different spin directions. The magnetic flux of the polarized ^3He passing through the target chamber pickup coils was calibrated using water NMR measurements with the calculable proton polarization. The statistical uncertainty of water NMR signal is much better than 1% and the total uncertainty of water NMR calibration is better than 3%.

The EPR measurement took place in the pumping chamber and both K and Rb EPR signals were used. Due to the much larger size of the oven, to have enough perturbative RF power, an EPR RF coil made of high temperature enameled wire was put inside the oven. A collection system with two lenses was installed to have better EPR D2 light detection. A typical EPR calibration has a statistical uncertainty better than 1% .

FIGURE 2. A water NMR signal (left) and an EPR measurement on K atom (right).

The target density and its distribution are crucial parameters for both NMR and EPR measurements. The densities of all production cells have been measured at JLab using pressure broadening with less than 2% statistical uncertainties.

SUMMARY

For a couple of decades of development and technology breakthroughs, the performance of polarized ^3He target with SEOP technique has been improved steadily. Recent implement of hybrid Rb-K optical pumping and narrow line-width laser further increases both the target polarization and luminosity and provides a greater figure-of-merit for nuclear physics research.

FIGURE 3. The evolution of figure of merit of polarized ^3He target with SEOP technique.

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