Polarization Measurement of Polarized Proton Solid Target via the $\bar{p} + ^4$He Elastic Scattering

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1. Introduction

We have recently succeeded in constructing a polarized solid proton target which has a unique capability of operating in a low magnetic field of 80 mT at a high temperature of 100 K \cite{1}. The target was used, for the first time, in an experiment to measure the spin-dependent asymmetry of $\bar{p} + ^4$He elastic scattering in 2003 \cite{2}. During the scattering experiment, proton polarization was monitored with nuclear magnetic resonance (NMR) measurement. The NMR signal is usually calibrated by measuring a polarization under thermal equilibrium (TE), which is a function of temperature and magnetic field. For our target, however, there is difficulty in measuring the TE signal, primarily because of the small TE proton polarization in a low magnetic field of 80 mT at a high temperature of 100 K, and secondarily because of the limited NMR sensitivity due to the target design specialized to scattering experiment. It is thus impractical to relate the NMR signal to the absolute polarization using TE measurement technique. As an alternative method, a nuclear reaction was used for determination of the absolute value of proton polarization. Accordingly, spin-dependent asymmetry of the $\bar{p} + ^4$He elastic scattering at the energy of 80 MeV/nucleon was measured. Polarization $P_y$ is obtained as

$$ P_y = \frac{1}{A_y} \frac{N_L - N_R}{N_L + N_R}, \quad (1) $$

where $A_y$ is the analyzing power, and $N_L/N_R$ are left/right yields. The analyzing power $A_y$ of this reaction at the same energy has already been measured by Togawa \textit{et al.} \cite{3}. Details of the experiment are reported in this article.

2. Experiment

The experiment was performed in the E3 experimental area of RIKEN Accelerator Research Facility. The energy and the typical intensity of $^4$He beam were 80 MeV/nucleon and 200 kcps, respectively. The beam size on the target was 3 mm$\phi$ (FWHM).

The target material was a single crystal of naphthalene doped with 0.01 mol% pentacene. The cross section and thickness of the target were 14 mm$\phi$ and 1 mm, respectively. Protons in the target were polarized at 88 mT and 100 K making use of a spontaneous electron alignment in the photo-excited triplet state of aromatic molecules and of the cross-polarization method \cite{4}. Figure 1 shows the time development of the NMR signal amplitude, which is proportional to proton polarization. Polarization measurements for spin “up/down” were carried out for compensation of spurious asymmetry. The target was polarized in the “up” direction from $t = 0$ to 29.2 h. The polarization was once broken, and then built up in the “down” direction from $t = 33.1$ to 52.6 h. Polarization measurements using $^4$He beam were carried out during periods shown as shaded regions in Fig. 1. Decrease in polarization was observed with the beam irradiation. This effect is considered to depend on beam intensity per unit area of the target \cite{5}. The decrease in polarization will be much smaller in RI beam experiments, since typical spot size of RI beam is almost one order of magnitude larger than that of $^4$He beam used in this experiment.

![Figure 1. Time development of proton polarization measured by pulsed NMR. The vertical axis denotes the NMR signal amplitude, which is proportional to the proton polarization. The origin of the horizontal axis denotes the time when proton polarization was started in the “up” direction.](image-url)

Figure 1 shows a schematic view of the experimental setup. Scattered $^4$He particles were detected with a multiwire drift chamber (MWDC) and three layers of plastic scintillation detectors placed downstream of the MWDC. The MWDC provides the scattering angle of $^4$He. The $\Delta E$ and $E$ information is given by three-layers of plastic scintillation detectors, whose thicknesses are 5 mm in the first layer and 30 mm in the other.

Recoiled protons were detected with a pair of counter telescopes placed left and right sides of the beam axis. Each telescope consists of two layers of position sensitive silicon detectors (X-PSD, Y-PSD) and plastic scintillation detectors. The PSD has a $50 \times 50$ mm$^2$ active area divided into...
10 strips on the front face. Two PSDs with an orthogonal strip direction located at 120 mm and 140 mm from the target, respectively, provided scattering angles and $\Delta E$ information of recoiled protons. The $E$ information of protons was given by the plastic scintillation detectors.

3. Results

The p+$^4$He elastic scattering events are identified by requiring kinematical consistency to identified protons and $^4$He particles. Proton identification is mainly carried out with the $\Delta E$ data from the PSDs and $E$ data from the plastic scintillation detectors. About half of the protons recoiled to backward angle of 68–70° do not fire plastic scintillator, since they have low energy of 10–20MeV. Part of these protons can be identified by the energy loss correlation between X-PSD and Y-PSD. The overall efficiency of proton detection and identification in the most backward strip (strip #10) was about 70% while those in other strips were almost 100%. Scattered $^4$He particles were identified using the $\Delta E$ and $E$ data from three-layers of plastic scintillation detectors.

Figure 2. Schematic view of experimental setup. The distances from the target to plastic scintillators for $^4$He and protons are approximately 1 m and 180 mm, respectively.

Figure 3. The correlation between the proton recoiling angle and the $^4$He scattering angle. Proton recoiling angle is represented by X-PSD strip ID. The broad lines in the left and right show the kinematically calculated angular correlation.

Figure 3 shows correlation between the scattering angle of $^4$He measured by the MWDC and the recoiling angle of proton, represented by X-PSD strip ID. Clear peaks are observed corresponding to p+$^4$He elastic scattering events. Yields $N_L$, $N_R$, and $N_U$ are obtained by integrating the peaks of left and right detectors in both cases where the polarizations are “up” and “down”. Here, indices $L/R$ represent the direction of scattering left/right and $|\ell|$ represent the direction of the polarization up/down. Averaged polarization $P_y$ is obtained as

$$P_y = \frac{1}{A_y} \sqrt{\frac{N_L^1 N_R^2}{N_L^2 N_R^1} - \frac{N_L^2 N_R^1}{N_L^1 N_R^2}}$$

canceling spurious asymmetry due to imbalance of detection efficiency and instrumental geometry.

Results obtained in X-PSD strips #7–10 ($\theta_p = 62.1–70.3^\circ$) are shown in Table 1. The averaged proton polarization is observed to be 4.8±1.9%. NMR signal amplitude is calibrated using this value. The maximum polarization during the experiment was then determined to be 15.5±6.3 % corresponding to the point $t = 14.3$ h in Fig. 1. The offline maximum polarization, achieved 20 hours before the beam irradiation, was 23±9.1 %.

<table>
<thead>
<tr>
<th>X-PSD strip ID</th>
<th>$P_y$</th>
<th>$\Delta P_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#10 ($\theta_p = 68.3–70.3^\circ$)</td>
<td>2.9%</td>
<td>3.2%</td>
</tr>
<tr>
<td>#9 ($\theta_p = 66.2–68.3^\circ$)</td>
<td>4.0%</td>
<td>3.5%</td>
</tr>
<tr>
<td>#8 ($\theta_p = 64.2–66.2^\circ$)</td>
<td>7.5%</td>
<td>4.9%</td>
</tr>
<tr>
<td>#7 ($\theta_p = 62.1–64.2^\circ$)</td>
<td>6.1%</td>
<td>9.6%</td>
</tr>
<tr>
<td>#7–10 ($\theta_p = 62.1–70.3^\circ$)</td>
<td>4.8%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

Table 1. Averaged proton polarization obtained in X-PSD strips #7–10.

4. Summary

We have constructed a polarized solid target which can be operated under a low magnetic field of 80 mT at a high temperature of 100 K. The absolute value of the proton polarization was measured via the $\vec{p}$+$^4$He elastic scattering. The averaged and the maximum value of the proton polarization were 4.8±1.9% and 15.5±6.3 %, respectively. This target will be used in the $\vec{p}$+$^4$He elastic scattering experiment where analyzing power is to be measured with improved resolution and accuracy from the previous measurement[2].

References