Abstract. The vector analyzing power has been measured for the elastic scattering of neutron-rich $^6$He and $^8$He from polarized protons at 71 MeV/A making use of a newly constructed solid polarized proton target operated in a low magnetic field of 0.1 T and at a relatively high temperature of 100 K. An optical model analysis revealed that the spin-orbit potentials for $^6$He and $^8$He are characterized by shallow and long-ranged shape compared with the global systematics of stable nuclei. Such a characteristics reflect a diffused density distribution of the neutron-rich isotopes.
1. Introduction
Recently, renewed interest has been focused on the manifestation of the spin-dependent interactions in unstable nuclei. One of the most powerful probes to extract the information on the spin-dependent interaction is the direct reaction induced by spin-polarized light ions. In order to investigate the unstable nuclei with spin polarization, a polarized proton solid target, which was specially designed for radioactive-ion beam experiments, has been developed at CNS, University of Tokyo [1, 2, 3, 4]. The most prominent advantage of this target is in its modest operation conditions, i.e. a low magnetic field of 0.1 T and a high temperature of 100 K. These conditions allow us to detect low energy recoiled protons, which are essential for event selection.

Making use of this target, we measured the vector analyzing power for the proton elastic scattering from neutron-rich helium isotopes, $^6$He and $^8$He, at 71 MeV/A in 2005 and 2007. The aim of the measurements is to investigate the characteristics of spin-orbit potentials between protons and $^6$He, and discuss the effect of valence neutrons on the spin-orbit potential. Since the spin-orbit coupling is essentially a surface effect, the spin-orbit potential is usually modeled by a form factor similar to the radial derivative of density distribution. Thus, in neutron-rich nuclei with significantly diffused density distribution, it is naturally expected that the shape of the spin-orbit potential can be considerably different from those in stable nuclei.

Details of the measurement and the optical model analysis are reported in this article.

2. $p^+{^6,8}$He analyzing power measurement
Measurements of the analyzing powers for $p^+{^6,8}$He elastic scattering were carried out at the RIKEN Accelerator Research Facility (RARF) in 2005 and 2007 using the RIKEN Projectile-fragment Separator (RIPS) [5]. Details of the $p^+{^6}$He elastic-scattering measurement are described here. The $^6$He beam was produced by a fragmentation reaction of an $^{12}$C beam with an energy of 92 MeV/A bombarded onto a primary target. As a primary target, we used a rotating Be target [6] with a thickness of 1480 mg/cm$^2$ to avoid the heat damage by the beam. The energy and intensity of the $^6$He beam were 70.6±1.4 MeV/A and 3×10$^5$ pps, respectively. Purity of the beam was 95 %.

As a secondary target, we used a polarized proton solid target. The material of the target was a single crystal of naphthalene with a thickness of 4.3×10$^{21}$ protons/cm$^2$. Protons in the crystal were polarized under a low magnetic field of 0.09 T and at high temperature of 100 K. In order to achieve these “relaxed” conditions, a new polarizing method was employed. Firstly, electron population difference is produced among a triplet state of photo-excited aromatic molecules [7]. Then, this electron population difference is transferred to protons by so-called cross-polarization technique [8]. The target polarization during the beam-time was found to be 13.8±2.7% on average.

Recoiled protons were detected by a pair of detector arrays consisting of a drift chamber (SWDCs) and a CsI (Tl) scintillator. The detector arrays were placed on the left and right sides of the beam line as shown in Fig. 1. Each SWDC was located 138.5 mm away from the target and covered a scattering angle of 39° – 71° in the laboratory system. Their position resolution and detection efficiency were found to be 2.6 mm (FWHM) and 99.3%, respectively. For the measurement of total energy of protons, a CsI scintillator with a sensitive area of 135 mm-H × 60 mm-V was placed just behind the SWDC. Scattered particles were detected using a multiwire drift chamber (MWDC) and $\Delta E – E$ plastic scintillator hodoscopes with thicknesses of 5 and 100 mm.

Elastic-scattering events of the $^6$He from protons can be in principle identified by the coincidence detection of scattered $^6$He particles and recoil protons, since the $^6$He nucleus does not have a bound excited state. Figure 2 shows the angular correlation between scattered particles ($\theta_{\text{Scatt}}$) and recoil protons ($\theta_{\text{c.m.}}$). It is seen from the figure that clear peaks of elastic-scattering events lie along the solid curves indicating the kinematics of the $p^+{^6}$He elastic...
scattering. This shows that detection of low-energy recoil protons was realized by the relaxed operation condition of the polarized proton target, i.e. a low magnetic field of 0.1 T and a high temperature of 100 K. The present result demonstrates the applicability of the solid polarized proton target in the RI-beam experiment.

The differential cross sections and analyzing powers are shown in Fig. 3 by closed circles. The present data are consistent with those reported in Ref. [9] in the overlapping angular region. For comparison, data for the \( p + ^4\text{He} \) [10] and \( p + ^6\text{Li} \) [11] elastic scatterings at 72 MeV/A are also shown by open squares and triangles, respectively. It is found that the \( \frac{d\sigma}{d\Omega} \) of \( p + ^6\text{He} \) are almost identical with those of \( p + ^6\text{Li} \) up to backward angles of \( \theta_{\text{c.m.}} \approx 90^\circ \). By contrast, the \( A_y \) data are widely different between \( p + ^6\text{He} \) and \( p + ^6\text{Li} \).

3. Optical model analysis

3.1. Phenomenological optical potential

A phenomenological optical model analysis of the elastic scattering of \( p + ^6\text{He} \) was performed. For the central and spin-orbit terms, we assumed the Woods-Saxon type and Thomas type functions, respectively. We searched a parameter set that reproduces both differential cross section and analyzing power data by using a code ECIS79 [12]. As an initial potential, a parameter set which reproduces \( p + ^6\text{Li} \) elastic scattering at 72 MeV/A [11] was used. The dashed lines in Fig. 4 show the calculation with initial parameters. Results of the best-fit parameters are presented in Fig. 4 by solid curves. The characteristic behavior of the analyzing power data is well reproduced.

The radial dependence of the obtained potential is shown in Fig. 5. The upper panel displays real (solid) and imaginary (dashed) parts of the central term, while the lower one shows a spin-orbit term (dotted) with an error band that represents the fitting ambiguities. There is an additional scale error of 19% on the depth of the spin-orbit potential, which resulted from the uncertainty in the target polarization.
3.2. Characteristics of the spin-orbit potential

Radial dependence of the spin-orbit potential between a proton and a $^6\text{He}$ is discussed here. In order to extract the gross characteristics of the potential, we focus on the radius and the amplitude of the peak of spin-orbit potential. We call the former LS radius and the latter LS amplitude. Since the spin-orbit potential is generally approximated by the radial derivative of density distribution, LS radius and LS amplitude should be related to the radius and the gradient of the density distribution, respectively. The LS radius and LS amplitude of $^6\text{He}$ were found to be $2.34\pm0.24$ fm and $1.32\pm0.46$ MeV, respectively. Analysis of the $p+^8\text{He}$ elastic scattering, which will be reported elsewhere, revealed that those of $^8\text{He}$ are $2.22\pm0.27$ fm and $2.02\pm0.52$ MeV, respectively, which are similar to those of $^6\text{He}$. Compared with these values, LS amplitudes of neighboring even-even stable nuclei [13, 14, 15] and global optical potentials [16, 17] are considerably different. The LS amplitudes of stable nuclei are distributed at around 5 MeV, whereas those of $^6\text{He}$ and $^8\text{He}$ are as small as 1.3 and 2.0 MeV. It is clearly demonstrated that the LS amplitudes of $^6\text{He}$ and $^8\text{He}$ are significantly reduced from the global systematics of stable nuclei. As for the LS radius, that of $^6\text{He}$ ($2.34\pm0.24$ fm) is slightly larger than the typical value (global potential: 1.98 fm for $A=6$). Thus, it can be concluded that the spin-orbit potentials in neutron-rich helium isotopes are characterized by significantly shallow and slightly long-ranged (for $^6\text{He}$ case) radial dependence. This can be intuitively explained from the largely diffused density distributions of $^6\text{He}$ and $^8\text{He}$, whose radial gradients are more than twice as small as that of $^4\text{He}$. 

Figure 2. Angular correlation between scattered particles and recoil protons. The solid curves indicate the kinematics of the $p+^6\text{He}$ elastic scattering.

Figure 3. The $d\sigma/d\Omega$ and $A_y$ of the $p+^6\text{He}$ elastic scattering at 71 MeV/A (circles), $p+^4\text{He}$ at 72 MeV/A (squares) in Ref. [10], and $p+^6\text{Li}$ at 72 MeV/A (triangles) in Ref. [11].
Figure 4. Calculation of $d\sigma/d\Omega$ and $A_y$ by the phenomenological optical potentials. The dashed and solid lines show the calculations by initial and best-fit parameters, respectively.

Figure 5. Radial dependence of the obtained optical potential. Solid and dashed lines in the upper panel and a dashed line in the lower panel indicate real, imaginary, and spin-orbit terms, respectively.

4. Summary
The vector analyzing power of the proton elastic scattering from neutron-rich $^6$He have been measured at 71 MeV/A. We found that the spin-orbit potentials in $^6$He and $^8$He are significantly shallower than those in stable nuclei. This shallowness can be naturally explained by the large diffuseness of the density distribution in neutron-rich helium isotopes.

The present study demonstrated that the polarized proton solid target working in a low magnetic field plays an important role in revealing new aspects of reactions involving unstable nuclei. Polarized protons will be one of the powerful probes to investigate the manifestation of spin-dependent interactions in the structure and reaction of unstable nuclei.

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