Spin observable in proton elastic scattering of \(^6\)He and its relevance to cluster structure

Tomohiro Uesaka  
Center for Nuclear Study, University of Tokyo, Tokyo 113-0033, Japan  
E-mail: uesaka@cns.s.u-tokyo.ac.jp

Satoshi Sakaguchi  
RIKEN Nishina Center, Saitama 351-0198, Japan  
E-mail: satoshi@ribf.riken.jp

Abstract. Vector analyzing power for the proton elastic scattering of \(^6\)He has been measured at 71 MeV/nucleon by using a polarized proton solid target. Through comparisons with cluster-folding model calculations, a role played by the \(\alpha\)-core in \(^6\)He is discussed.

1. Introduction  
Proton elastic scattering is one of the simplest hadronic reactions and has been used to study various aspects of nuclei. Recently the proton elastic scattering studies are applied for light neutron-rich nuclei\([1, 2, 3]\). A major goal of the studies is to determine matter distributions, more specifically neutron distributions, in the neutron-rich nuclei and to argue existence of halo and/or skin structures.

The aim of this article is to discuss how the cluster formation in a nucleus affects spin observable in proton elastic scattering, taking an example of the \(p-^6\)He elastic scattering. The \(^6\)He nucleus is known to be well modeled as a weakly bound system of \(\alpha\)-core and two neutrons. In addition, because of the small two-neutron separation energy of 1.86 MeV, \(^6\)He is considered to have a very extended neutron distribution and to be a halo nucleus.

Vector analyzing power \(A_y\) in the proton elastic scattering originates from a spin-orbit coupling between the proton and the target nucleus. The spin-orbit coupling is usually modeled by a spin-orbit part of optical potential which has a functional form of Thomas-type as

\[
V_{LS}(r) \sim \left( \frac{\hbar}{m_\pi c^2} \right)^2 \frac{1}{r} \frac{d}{dr} \rho(r) .
\]

One can expect that distinctive neutron distribution in \(^6\)He cause possible modifications in magnitude and radial shape of the spin-orbit potential.

2. Experiments  
The polarized proton target working in a low magnetic field of 0.1 Tesla and at high temperature of 100 K was used in the vector analyzing power measurement for the \(p-^6\)He elastic scattering
experiment[4, 5]. The target material was a crystal of naphthalene with a small amount (∼0.005 mol%) of pentacene as a dopant. The dimensions of the target were 1 mm in thickness and 14 mm in diameter. The proton polarization was 20% at maximum and 14% on average.

![Polarized Proton Target](image)

**Figure 1.** Setup of the p-\(^6\)He elastic scattering experiment at RIPS.

A radioactive \(^6\)He beam with an energy of 70.6±1.4 MeV/nucleon was produced via the projectile fragmentation reaction of a primary \(^{12}\)C beam on a 1.39 g/cm\(^2\) beryllium target. Intensity and purity of the \(^6\)He beam was 3.0×10\(^5\) cps and 95%, respectively, after separation in RIPS[6].

The \(^6\)He particles scattered at forward angles in the laboratory frame were detected by a multi-wire drift chamber (MWDC) and plastic scintillators placed about 1 m downstream of the target. Since the \(^6\)He nucleus has no bound excited state, particle identification by \(\Delta E-E\) in the scintillator is sufficient, in principle, for identifying elastic scattering events. The MWDC provides the \(^6\)He scattering angle and the reaction point on the target.

Two counter telescopes to detect recoiled protons were placed left and right with respect to the beam axis. Each telescope consisted of a single-wire drift chamber (SWDC) for a position measurement and a CsI(Tl) scintillator for a total energy measurement. They covered an angular range of \(\theta_{\text{c.m.}} = 35^\circ - 90^\circ\) in the center of mass system. It should be emphasized that the low-magnetic field (0.1 Tesla) operation of the polarized proton target is inevitable for detection of the low-energy recoil protons.

### 3. Results and discussions

Figure 2 shows the measured angular distributions of differential cross section \((d\sigma/d\Omega)\) and vector analyzing power \((A_y)\) for the p-\(^6\)He elastic scattering by filled circles. Only statistical uncertainties are shown in the figure. Systematic uncertainty in \(A_y\), mainly due to uncertainty in absolute normalization of proton polarization, is 19% independent of scattering angles. Open circles and open squares are p-\(^6\)He data by Korsheninnikov [7] and p-\(^4\)He data by Burzynski[8] at the same incident energy. It should be noted that the \(^4\)He data are plotted at the angle where momentum transfer for p-\(^4\)He is the same as that for the corresponding p-\(^4\)He data.

The steeper angular distribution of \(d\sigma/d\Omega\) for the \(^6\)He differs considerably from the gradual
He elastic scattering at 71 MeV/u

Figure 2. Cross section and vector analyzing power for the $p^{-6}\text{He}$ elastic scattering experiment at 71 MeV/u.

one for the $^{4}\text{He}$, which is a natural consequence of a larger size of $^{6}\text{He}$. On the other hand, the $A_y$ data are similar to each other within the experimental error bars.

Based on an assumption that $^{6}\text{He}$ is well modeled by an $\alpha-n-n$ cluster structure, we compare the data with a cluster-folding (CF) calculations. The CF optical potential can be written as

$$U_{CF} = \sum_{i=1,2} \int V_{pn_i}\rho_n(r_i)dr_i + \int V_{p\alpha}\rho_\alpha(r_\alpha)dr_\alpha,$$

where $V_{pX}$ includes both central and spin-orbit parts. As the $p-\alpha$, a phenomenological optical potential which reproduces the $p^{-4}\text{He}$ elastic scattering data at 72 MeV/nucleon [8] is used. The phenomenological optical potential includes complicated effects in the $p-\alpha$ scattering, such as non-locality due to exchange process, at least in part and can serve as a reasonable model of the $p-\alpha$ interaction. The complex effective interaction (CEG)[9] is adopted as the $p-n$ interaction. The interactions are folded with the $\alpha-n-n$ cluster distributions obtained by the Gaussian expansion method [10]. Details of the calculation will be reported elsewhere [5].

In Fig. 2, results of the full CF calculation (solid lines) are compared with the $^{6}\text{He}$ data. The CF calculation reproduces both of $d\sigma/d\Omega$ and $A_y$ reasonably, in particular at $\theta_{\text{c.m.}} \sim 35^\circ-60^\circ$. 
On the other hand, folding model calculations without the cluster assumption cannot reproduce the data as well within the present framework[5]. This supports the α-n-n cluster assumption introduced in the CF calculation. Reasonable reproduction without the cluster assumption requires detailed calculations which explicitly treat non-locality in the scattering[11].

To separate the valence neutron and the α-core contributions, calculations without the central part of the p-n interaction (dashed lines) and without all the p-n interactions(dot-dashed lines) are carried out. The latter corresponds to extraction of a “pure” α-core contribution. It is interesting to note that the calculation for the pure α-core contribution sits in between the 6He data and the 4He data. This indicates that a matter distribution of the α-core part in 6He is wider than that of a bare 4He nucleus due to the α-core motion in 6He, while it is, by definition, narrower than that of 6He as a whole. The spin-orbit interaction \( V_{\text{pm};\ell s} \) gives negligible effects on \( d\sigma/d\Omega \) and \( A_y \), which is consistent with predictions in Ref. [12].

From the comparisons with CF, it is concluded that the spin-orbit coupling, which brings about a finite value of vector analyzing power, does not originate from interaction with the valence neutron but from the interaction with the α-core. The α-core distribution in 6He, which is largely affected by recoil of the valence neutrons, seems to be a possible key to understand the behavior of \( A_y \). The α-core motion in 6He make the α-core distribution extended and gradual, which in turn makes the spin-orbit coupling between proton and 6He weaker. This conclusion is consistent with the result of phenomenological optical model analyses[5].

4. Summary
Cross section and vector analyzing power for the proton elastic scattering of 6He has been measured at 71 MeV/nucleon by using a polarized proton solid target. Low-magnetic field operation of the target is inevitable for detection of low-energy recoil protons. Data are compared with cluster-folding model calculations. It is concluded that the α-core in 6He gives dominant contribution to the spin-orbit coupling in the proton elastic scattering of 6He and that the α-core distribution in 6He is a possible key to understand the p-6He elastic scattering.

Acknowledgements
The authors thank the RIKEN and CNS staffs for operation of accelerators during the measurement. One of the authors (S.S.) expresses his gratitude for financial support by a Grant-in-Aid for Japan Society for the Promotion of Science (JSPS) Fellows (No. 18-11398). The authors are also grateful to the JSPS Core-to-Core Program. This work was supported by the Grant-in-Aid No. 17684005 of the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

References
[1] A. Korsheninnikov et al., Physics Letters B 316, 38 (1993).
[2] M. D. Cortina-Gil et al., Physics Letters B 401, 9 (1997).
[3] P. Engels et al., Progress in Particle and Nuclear Physics 46, 307 (2001).
[4] T. Uesaka, S. Sakaguchi et al., Phys. Rev. C 82, 021602(R) (2010).
[5] S. Sakaguchi, Y. Iseri et al., submitted to Physical Review C.
[6] T. Kubo et al., Nuclear Instruments and Methods in Physics Research B 70, 309 (1992).
[7] A. Korsheninnikov et al., Nuclear Physics A 617, 45 (1997).
[8] S. Burzynski et al., Physical Review C 39, 56 (1989).
[9] N. Yamaguchi, S. Nagata, and T. Matsuda, Progress of Theoretical Physics 70, 459 (1983).
[10] E. Hiyama, Y. Kino, and M. Kamimura, Progress in Particle and Nuclear Physics 51, 223 (2003).
[11] S. Karatağlidis, P. J. Dortmans, K. Amos, and C. Bennhold, Physical Review C 61, 024319 (2000).
[12] R. Crespo and A. Moro, Physical Review C 76, 054607 (2007).