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# POLARIZED PROTON INDUCED REACTIONS ON LITHIUM ISOTOPES

N. Koori, I. Kumabe, M. Hyakutake,* K. Orito, K. Akagi, Y. Watanabe,
K. Ogawa, N. Oda, J. Yano, and A. Iida

Department of Nuclear Engineering, Kyushu University,
Fukuoka, 812 Japan

K. Sagara, H. Nakamura, K. Maeda, T. Nakashima, and M. Kamimura

Department of Physics, Kyushu University, Fukuoka, 812 Japan

Abstract: Double differential cross sections and analyzing powers have been measured for $^{7}$Li(p,p'), (p,d), and (p,t) reactions at 12, 14, and 16 MeV, and for $^{6}$Li(p,p'), (p,d), and (p,$^{3}$He) reactions at 14 MeV. Theoretical analyses were performed for the elastic and inelastic scatterings on the basis of the spherical optical model and the coupled channel method. Adoptability of the coupled discretized-continuum channel method, and final state interaction theory are discussed for the energy spectra of the continuum inelastic protons and the other reaction products, respectively.

($^{7}$Li(p,p'), (p,d), (p,t) reactions, $^{6}$Li(p,p'), (p,d), (p, $^{3}$He) reactions, Experimental data, Optical potential, Theoretical analysis of continuum spectrum)

## Introduction

Nuclear data for $^{6,7}$Li isotopes are important for fusion reactor development. In the evaluation of the nuclear data for lithium isotopes, however, experimental data have been treated on the basis of simple theories because of difficulties in theoretical analyses including three-body breakup processes.[1] It is highly necessary to establish nuclear theories of reaction involving lithium isotopes for the nuclear data evaluation.

As recently reported, the coupled discretized-continuum channel (CDCC) calculation has reproduced well lithium breakup reactions.[2] Three-body breakup reactions in rather simple nuclear systems have successfully been analyzed by means of the Faddeev approach.[3] Precise double differential cross sections and analyzing powers are required to study the adoptability of the above theories to the reactions on $^{6,7}$Li isotopes. Proton induced reactions are preferable to the purpose, being superior in precision against neutron induced reactions.

The optical potentials for $^{6,7}$Li have been determined without the data of analyzing powers, that is, the spin dependent terms of $V_{so}$, $r_{so}$ and $a_{so}$ were fixed a priori in the search. Analyzing powers have been measured for the $^{6}$Li(n,n) elastic scattering around 14 MeV,[4] but polarization data for reaction channels have not been reported.

On the other hand, there are no experimental data of polarized proton induced reactions on the lithium isotopes in the region of incident energy of 10-18 MeV. Hence, systematic study of scatterings and reactions on the lithium isotopes by the use of polarized proton beam will give valuable information for modelling of nuclear reactions involving the lithium isotopes.

## Experimental Procedure

We have measured the $^{7}$Li(p,p'), (p,d), and (p,t) reactions at 12, 14, and 16 MeV, and the $^{6}$Li(p,p'), (p,d), and (p,$^{3}$He) reactions at 14 MeV. Polarized and unpolarized proton beams from the tandem accelerator at Kyushu University were used for measurements of the reactions above. Emitted particles were detected with a counter telescope, which consisted of 15.5 μm and 75 μm thick transmission-type Si detectors and a 2000 μm thick Si detector. The lowest energy of the measurement was 1.0 MeV for protons, 1.3 MeV for deuterons, 1.5 MeV for tritons, and 4.7 MeV for $^{3}$He. The over-all energy resolution for protons was about 95 keV in fwhm, which was mainly due to the kinematical spreading.

Self-supporting $^{6,7}$Li metallic foils were used as targets; $^{7}$Li (enrichment: 99.99%) foils were of 0.867 mg/cm$^2$ (for 12 and 14 MeV) and 0.324 mg/cm$^2$ (16 MeV) and $^{6}$Li (enrichment: 95.59%) foils of 1.47 mg/cm$^2$ and 0.611 mg/cm$^2$ (14 MeV).

Beam polarization was monitored at the down stream of scattering chamber. The polarimeter consisted of a $^{4}$He gas target and two ΔE+E Si detector system fixed at ±113° with respect to the beam direction, where the analyzing power of $^{4}$He was known to be 1.00-0.98 for 12-18 MeV protons.

## Experimental Results

The differential cross sections and analyzing powers for the $^{7}$Li(p,p') and $^{6}$Li(p,p') scatterings are shown in Figs. 1 and 2: Figs.1 (a-f) are those for the ground (3/2$^-$), 1st excited (0.478 MeV,1/2$^-$) and 2nd excited (4.63 MeV, 7/2$^-$) states of $^{7}$Li, and Figs.2 (a-b) those for the ground (1$^+$), 1st excited (2.185 MeV, 3$^+$), and 2nd excited (3.562 MeV, 0$^+$) states of $^{6}$Li.

Examples of double differential cross sections (DDX) of the inelastic scatterings are shown for $^{7}$Li and $^{6}$Li in Figs.3 (a-c). The three-body breakup processes of $^{7}$Li(p,p')tα and $^{6}$Li(p,p')dα are dominant in the spectra for $^{7}$Li and $^{6}$Li, respectively.

The differential cross sections and analyzing powers for the $^{7}$Li(p,d) reaction were measured for the ground, 1st excited, and 2nd excited states of $^{6}$Li. The $^{7}$Li(p,d)dα process was observed in the deuteron continuum spectra, as well as the peaks corresponding to the ground and excited states of $^{6}$Li.

The $^{7}$Li(p,t)pα and $^{6}$Li(p,d)pα three-body breakup processes indicate very similar spectrum shapes, as shown in Figs.4 (a-c). The p-α final state interaction dominates in the highest energy region of the spectra. The three-body decays from the 7/2$^-$ excited state of $^{7}$Li and from the 3$^+$ excited state of $^{6}$Li are clearly seen as bumps in the spectra of $^{7}$Li(p,t)pα and $^{6}$Li(p,d)pα, respectively.

The $^{6}$Li(p,$^{3}$He)α reaction, which may have similar reaction mechanism to the $^{6}$Li(n,t)α reaction, was measured for their comparison. The differential cross sections and analyzing powers are shown in Fig.5 (a-b).

* Present address: Sasebo Technical College, Sasebo, 857-11 Japan.

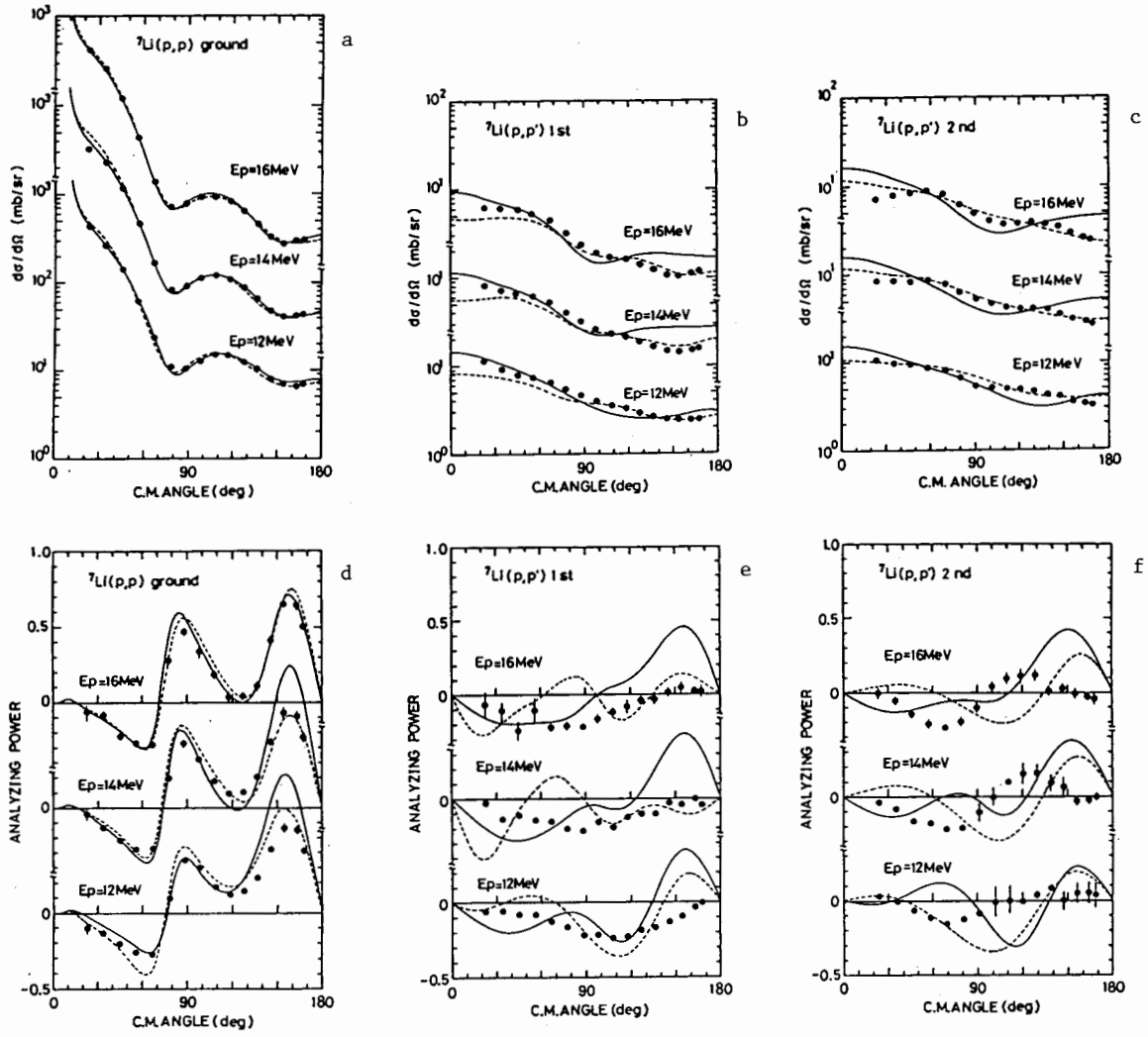


Fig.1. Differential cross sections and analyzing powers of $^{7}$Li(p,p') scatterings. Solid lines are for calculations with the spherical optical model (for the ground state) and with DWBA (for the excited states), and dashed lines for CC calculations.

## Theoretical Analyses and Discussion

Elastic and Inelastic Scatterings

On the basis of the spherical optical model (SOM), the optical potential parameters including the spin dependent terms were searched with the elastic scattering data of differential cross sections and analyzing powers. The standard form of optical potential with the Wood-Saxson type form factors was taken in the model. As shown in Figs.1 and 2, the elastic scattering data are fitted very well with the spherical optical model. The analyzing powers of inelastic scattering data, however, could not be reproduced with the DWBA calculation in which the optical potential parameters obtained above were used and the momentum transfer was assumed to be $l$ =2 for both $^{7}$Li and $^{6}$Li. In the analysis of $^{6}$Li data, results with the form factors derived from the microscopic cluster model[2] are compared with the others, showing a similar shape to the DWBA calculation.

Coupled channel calculations were performed with the ECIS79 code, in which three lowest states in the rotational model were assumed to be coupled each other; the coupled states are the ground, 1st excited, and 2nd excited states belonging to the K=1/2 band for $^{7}$Li, and are the ground, 1st excited, and 3rd excited states belonging to the K=1 band for $^{6}$Li. Starting from the resultant parameters from the spherical optical model calculations, the ECIS79 code searched the optical potential and deformation parameters so as to a give good fit with the measured data. The results are compared with the data in Figs. 1 and 2. Even this coupled channel calculations could not reproduce well the analyzing powers of inelastic scatterings.

DWBA calculation for discretized-continuum states

The proton continuum spectra for $^{7}$Li and $^{6}$Li are mainly due to the $^{7}$Li(p,p')t$\alpha$ and $^{6}$Li(p,p')d$\alpha$ three-body breakup reactions, respectively. Instead of complete CDCC calculations, we tried to calculate the spectra in the framework of the DWBA using the $^{7}$Li and $^{6}$Li form factors extended to resonant and non-resonant discretized-continuum states, which are shown for $^{6}$Li in Fig.6. The form factors for $^{7}$Li and $^{6}$Li were obtained on the basis of microscopic t-$\alpha$ and d-$\alpha$ cluster models, respectively, by Sakuragi et al.[2] Transition probabilities were calculated from the ground to the discretized excited states including resonant ones, using the optical potential derived from the SOM calculation for the entrance channel and assuming, for the exit channel, the potential with the energy dependence given by Dave and Gould.[5]

On the basis of the differential cross sections calculated for resonant and non-resonant states, proton energy spectra were constructed; the resonant components must spread with their widths. The calculated spectra are compared

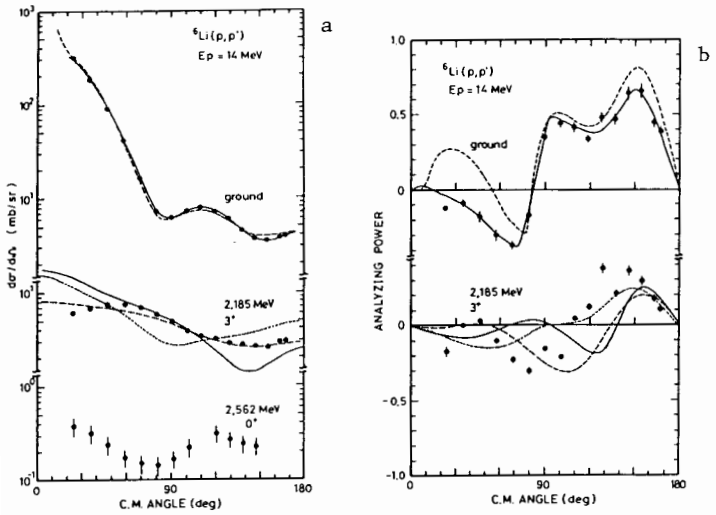


Fig.2. Differential cross sections and analyzing powers of $^7$Li(p,p') scatterings. Solid lines and dashed lines indicate the results of the same calculation methods as in Fig.1. Dotted lines are for DWBA calculation with the form factors of microscopic cluster model .

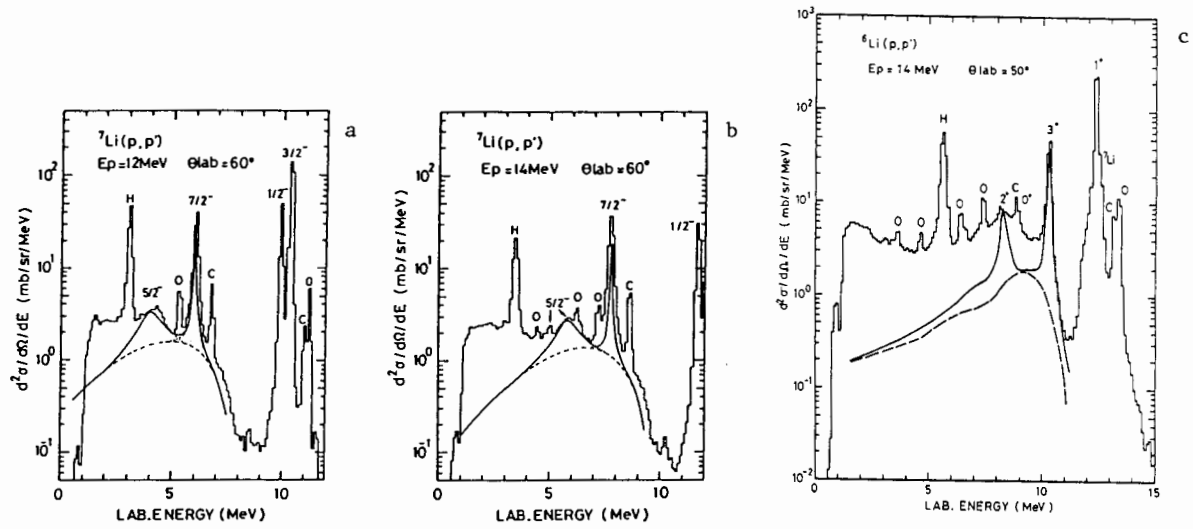


Fig.3. Examples of DDX of the $^7$Li(p,p')tα and $^6$Li(p,p')dα reactions. Solid lines indicate the results of DWBA calculations with the microscopic cluster model form factors of the resonant and non-resonant (dashed lines) discretized continuum states.

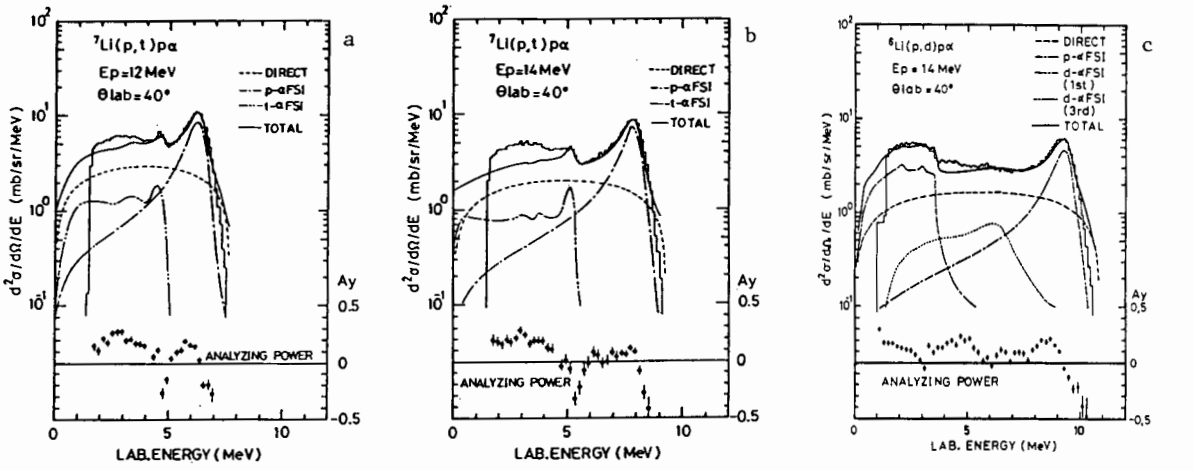


Fig.4. Examples of DDX of the $^7$Li(p,t)pα and $^6$Li(p,d)pα reactions. Lines indicate the contributions of final state interactions. Analyzing powers change clearly around the FSI regions.

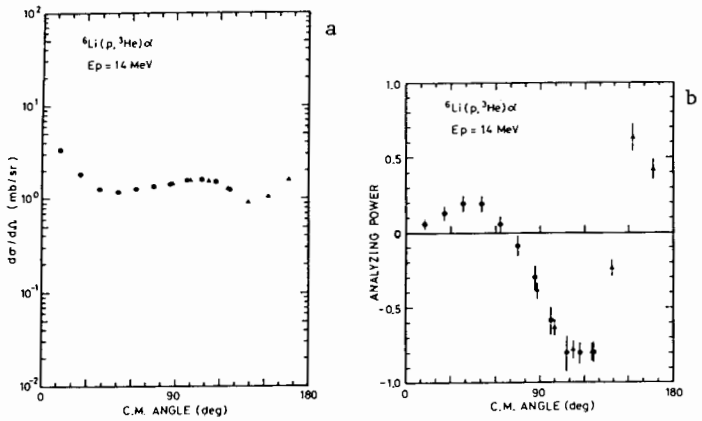


Fig.5. Differential cross sections and analyzing powers for the $^6$Li(p,$^3$He)α reaction.

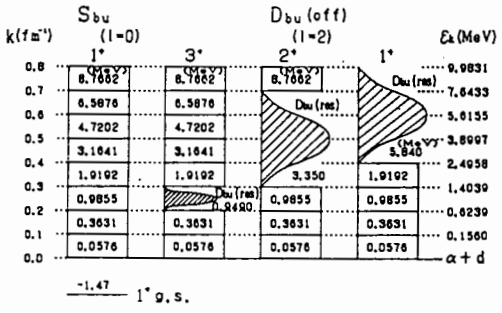


Fig.6. Discretized-continuum states of $^6$Li.

with the measured ones in Fig.3. Rather good agreement is indicated in a wide energy region, except in lower energies. The DWBA calculation with the form factors for discretized-continuum states explains qualitatively the measured continuum spectra. Angular dependence of the spectra, however, was not reproduced so well, because the calculated angular distribution of the 1st excited state was not in agreement with the experimental data. More comprehensive CDCC calculations would be necessary.

Calculation with final state interaction theory

Triton energy spectra of the $^7$Li(p,t)pα reaction and deuteron energy spectra of the $^6$Li(p,d)pα reaction were calculated by means of the final state interaction (FSI) theory, where only the p-α FSI, the t-α (for $^7$Li) and d-α (for $^6$Li) FSI, and direct-breakup processes were taken into account as main contributions. The p-wave (3/2) phase shift of p-α scattering was taken from the R-matrix theory. The f-wave ($7/2^-$) phase shift of t-α scattering and the p-wave ($3^+$ and $2^+$) phase shifts of d-α scattering were obtained from experimental data. Three-body decay through the 7/2 excited state of $^7$Li was interpreted as the t-α FSI. In addition, three-body decays through the $3^+$ and $2^+$ excited states were also interpreted as the d-α FSI. These three contributions were added incoherently so as to give a good fit with the measured spectra. The energy spectra were explained very well by means of the FSI theory. It is interesting that analyzing powers of the spectra indicate rather large asymmetries at the FSI regions, as shown in Figs.4(a-c). However, they cannot be predicted in the framework FSI theory.

## Summary

Double differential cross sections and analyzing powers were measured for $^7$Li(p,p'), (p,d), and (p,t) reactions at 12, 14, and 16 MeV, and $^6$Li(p,p'), (p,d), and (p,$^3$He) reactions at 14 MeV. The experimental data of the elastic scattering were excellently reproduced by calculations based on the spherical optical model (SOM) and the coupled channel (CC) method. The DWBA and CC calculations did not predict correctly the analyzing powers in the inelastic channel leading to the 1st and 2nd excited states. The three-body breakup process observed in (p,p') continuum spectra were qualitatively explained by DWBA calculations with the microscopic form factors for discretized-continuum states. Continuum spectra of the (p,t) and (p,d) reaction were reproduced well by calculations based on the FSI theory. Distinct change in analyzing powers, furthermore, were observed in the FSI region of the (p,t) and (p,d) spectra.

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