Observation of vector analyzing power in elastic scattering of 150-MeV ^{6}Li on ^{12}C

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The absolute value of the vector analyzing power, $|iT_{11}|$ has been measured for elastic scattering of 150-MeV ^{6}Li from ^{12}C at $\theta_{\text{lab}}=7.7°$ from the observation of the left-right asymmetry in double scattering. A magnetic spectrograph was applied for focusing elastically scattered particles ejected from the first target onto the second one. The deduced $|iT_{11}|$ was $|iT_{11}|=(2^{+11}_{-2})\times10^{-2}$. The observed value was reproduced within the experimental errors by a cluster folding coupled channel calculation involving the effect of projectile excitations.

The spin dependence of heavy ion interactions is not well known despite a growing number of data compilations on heavy ion scattering. Experimental approaches have been so far restricted to low energy measurements of vector and tensor analyzing powers with the use of 10–44 MeV polarized ^{6,7}Li beams[1] or to those of spin flip probabilities[2–4] in inelastic scattering of ^{13}C and ^{15}N. Through the low energy work mentioned above, it was found that the phenomenologically obtained strengths of spin-orbit (SO) interactions were much larger than the prediction of the folding models. Recent coupled channel (CC) calculations[5–12] demonstrated that the effect of multistep processes involving projectile excitations and nucleon transfers played predominant roles in polarization phenomena, whereas the effect of the original folding SO potential was masked by the Coulomb repulsion and the CC effect.[6,7,11,12]

On the other hand, raising the bombarding energy higher than ~10 MeV/nucleon, the Coulomb repulsion becomes less pronounced and the CC effect tends to cancel. Then the effect of the original folding SO potential is expected to manifest itself. So far, discussions at these high incident energies have been focused only on the behavior of the differential cross sections[13–15] and there has been no report on the polarization itself. Therefore, high energy polarization measurements will be performed not only to deduce the magnitude of the original folding SO potential, but also to test the validity of models established through the low energy work and the analyses of the differential cross sections at higher energies. On the basis of the above aspect, we have measured the vector analyzing power, $iT_{11}(\theta)$, of elastic scattering of the $^{6}\text{Li}+{}^{12}\text{C}$ system at $E_{\text{lab}}=150$ MeV.

For this purpose, we employed a double scattering method in which carbon was used both as a polarizer and as an analyzer. Because the spin of ^{6}Li is $1\hbar$, the exact formalism representing double scattering is a complicated function of the vector and tensor analyzing powers.[16–18] However, as will be described later, the theoretical calculation predicts that tensor analyzing powers are far smaller than $iT_{11}(\theta)$ and that $iT_{11}(\theta)$ is approximately energy independent, at least for E_{lab} ranging from 140 to 150 MeV. This indicates that $iT_{11}(\theta)$, though it is only the absolute value, can be determined only from the measurement of the left-right asymmetry, written as

$$A(\theta)=(L-R)/(L+R)=2[iT_{11}(\theta)]^2 ,$$

where L and R are the cross sections to the left and right in the second scattering. In order to reduce a false asymmetry due to the scattering angle difference between the left and right detector, double scattering was undertaken at $\theta_{\rm lab}=7.7°$ and $12.3°$, which corresponds to the second and third maxima of the elastic scattering cross section, respectively.

A brief description of our preliminary work on the present subject was presented in Ref. 19.

A schematic view of the experimental arrangement is shown in Fig. 1. The 150-MeV $^6Li^{3+}$ ions provided by the 230-cm isochronous cyclotron of the Research Center for Nuclear Physics (RCNP), Osaka University, were achromatically focused on a 50 mg/cm^2 thick carbon target. A typical beam intensity was about 10 nA on target. The direct ^{6}Li beam passing through the target was stopped by a graphite Faraday cup in a scattering chamber. The quadrupole-dipole-quadrupole-dipole-quadrupole (QDQDQ) magnetic spectrograph, "DUMAS,"[20] operated with an achromatic mode, was applied to suppress unwanted particles like inelastically scattered ones (dotted curves in Fig. 1) impinging into the second target. The acceptance angle and the solid angle of DUMAS were chosen to be, respectively, 1.7° and 2 msr, whose values were enough to cover the peak area of elastic scattering cross section. Thus the elastically scattered ^{6}Li was focused on the second target in the polarization analyzer chamber as illustrated by the solid curves in Fig. 1. The thickness of the second target was also 50 mg/cm^2. It was a strip with a 5 mm width, the shape of which could reduce the background due to the small angle scattering of a flare beam coming from the upstream of DUMAS. A 5 mm thick copper baffle with a 20-mm aperture was located just on the backside of the second target to stop unwanted beam components far outside normal trajectories of DUMAS. Thus, the counting rate of the background was kept less than 10^{-3} count/nC, which was sufficiently lower than that of true events (~ 1 count/nC).

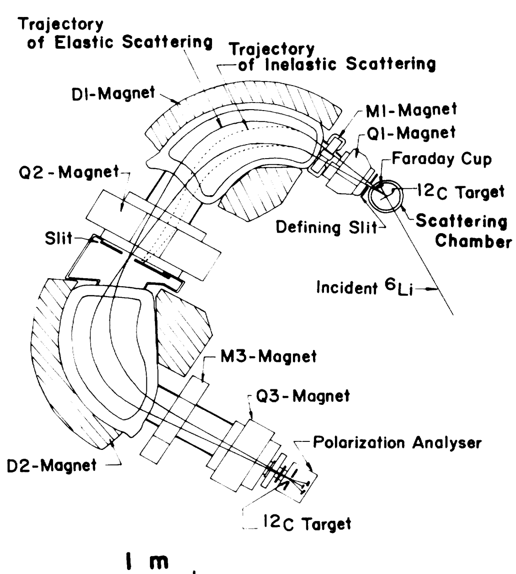

FIG. 1. Schematic top view of the spectrograph DUMAS used in the double scattering experiment. The solid curves are trajectories for elastic scattering; the dashed are for inelastic scattering.

Reaction products from the second target were detected by the left-right detector system with Si solid state detector (SSD) telescopes attached on movable arms in the polarization analyzer chamber. The chamber was designed to be rotatory around the secondary beam axis by 180° in order to eliminate, in first order, the differences of the solid and scattering angles between the left and right detectors. Each SSD telescope with a 300-μm-thick position sensitive ΔE detector and a 5000-μm-thick E detector could cover the scattering angular range from $\theta_{\rm lab}=5°$ to 15°. A false asymmetry due to the scattering angle difference between the left and right detectors was reliably corrected by comparing position spectrum shapes for elastic scattering.

An array of other two position sensitive SSD's were mounted on the lid of the polarization analyzer chamber and used for diagnosis of the secondary ^{6}Li beam during fine tuning of DUMAS. The intensity of the secondary ^{6}Li beam passing through the second target was monitored by a 2-mm-thick plastic scintillator whose outputs were fed into a photomultiplier mounted outside the chamber via an optical fiber cable. Signals from each detector were sent to the on-line computer through the raw data processor,[21] and the list mode data were stored in magnetic tapes for off-line analysis.

The inelastic peak corresponding to the 2_1^+ state in ^{12}C is not completely separated from the elastic one as a result of an insufficient energy resolution due to target thicknesses and reaction kinematics. In order to subtract the contribution from the 2_1^+ peak, the least squares fitting method was applied, where the shapes of peaks were assumed to be a Gaussian, and widths and peak locations were fixed for every spectrum measured.

In the measurement of the left-right asymmetry, $A(\theta)$, the scattering angle of DUMAS, was set at $\theta_{\rm lab}=-7.7°$ and $+7.7°$ with respect to the primary beam axis. Observed values of $A(\theta)$ and their weighted means at $\theta_{\rm lab}=7.7°$ and $12.3°$ are summarized in Table I for four runs. An error of $A(\theta)$ includes the following:

(1) a statistical error,

(2) an error caused by the least squares fitting procedure in determining peak yields from the energy spectra, and

(3) an instrumental asymmetry.[22]

As summarized in Table I, we can determine $A(\theta)$

TABLE I. Summary of observed asymmetries.

Run no.	$\theta_{\rm lab}$ (deg)	A (in units of 10^{-2})	Weighted means of A (in units of 10^{-2})
1	$+7.7$	$+(0.96\pm0.93)$	
2	-7.7	$-(0.66\pm0.93)$	
3	$+7.7$	$+(2.56\pm1.24)$	
4	-7.7	$-(1.90\pm1.06)$	$+(0.1\pm0.90)$
2	$+12.3$	$-(1.1\pm7.5)$	
4	-12.3	$+(6.4\pm7.0)$	$+(3\pm4)$

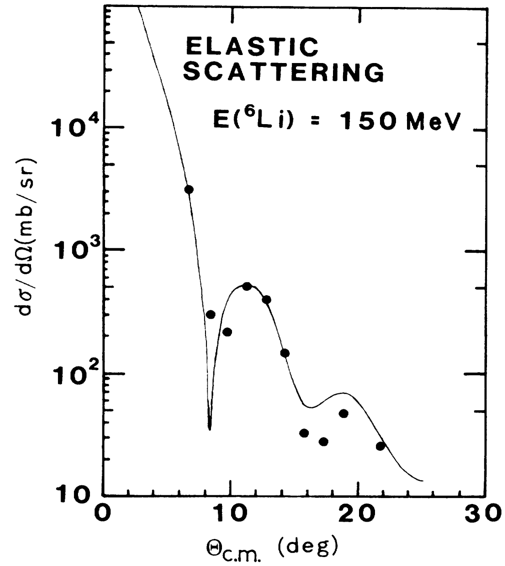

FIG. 2. Observed and calculated angular distributions of elastic scattering for ${}^6Li + {}^{12}C$ at $E_{lab} = 150$ MeV.

with a precision better than 1×10^{-2} for data at $\theta_{lab}=7.7°$. Then the absolute value of iT_{11} at $\theta_{lab}=7.7°$ is deduced to be

$$|iT_{11}| = (2^{+11}_{-2})\times10^{-2} .$$

On the other hand, using the result at $\theta_{lab}=7.7°$, $|iT_{11}|$ for $\theta_{lab}=12.3°$ is given by

$$|iT_{11}| = (8^{+28}_{-8})\times10^{-1} .$$

The large error at the latter scattering angle is mostly due to poor statistics and the smallness of $|iT_{11}|$ at the former scattering angle.

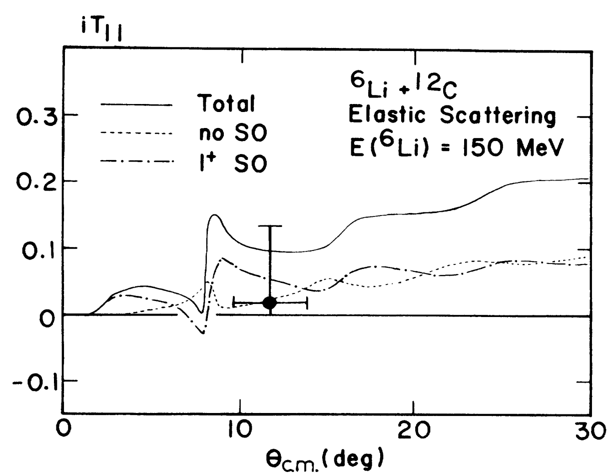

FIG. 3. Observed and calculated vector analyzing powers. The notations given by 1^+ SO, no SO, and Total represent the calculated results without projectile excitations, without SO potential, and with both projectile excitations and SO potential, respectively.

The observed angular distributions of the differential cross section for elastic scattering and $|iT_{11}|$ are plotted in Figs. 2 and 3. The results of the cluster folding CC calculations involving the projectile excitations are also given in these figures. Most of the calculations are grounded upon Ref. 7. Here, the optical potential parameters are folded from the d-${}^{12}C$ and α-${}^{12}C$ potentials, which were determined to fit the data at 56 MeV (Ref. 23) and those at 104 MeV (Ref. 24), respectively. As shown in Fig. 2, the observed $\sigma(\theta)$ is reproduced fairly well by the CC calculation. This supports the contention that the parameters for d- and α-optical potentials are reasonable.

To demonstrate the roles of the SO interaction and the CC effect in iT_{11}, the results of the calculation which do not include the CC effect and which do not include the SO interaction are individually illustrated in Fig. 3. Though the experimental errors are too large to attain a stringent test of the theory, the observed $|iT_{11}|$ is found to be within the result of the CC calculation including the projectile excitations.

In contrast to iT_{11}, tensor analyzing powers are found to be negligibly small. This is partly due to the small electric quadrupole moment of the projectile. It is, in addition, noticed that the smallness of the tensor analyzing powers ensures the deduction of $|iT_{11}|$ only from the left-right asymmetry.

We will shortly mention the incident energy dependence of iT_{11} because the constancy of iT_{11} is needed for the deduction of iT_{11} in the present measurement. The incident energy of ${}^6Li$ differs by about 10 MeV between first and second scattering because of reaction kinematics and target thickness. The same CC calculation carried out at $E_{lab}=140$ MeV shows that there is almost no change in iT_{11}.

It is necessary to obtain more precise experimental values in order to fully understand the phenomena at this energy region. It is interesting to notice that the same distorted-wave Born approximation calculation extended up to the 600-MeV ${}^6Li$ beam demonstrates the more predominated effect[25] of the folded SO potentials on iT_{11} than the case of the present incident energy region. These aspects show that a high energy (if possible, $E_{lab}\sim100$ MeV/nucleon) polarized heavy ion beam may be available.

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