WHAT THE THIRD RANK TENSOR ANALYZING POWERS CAN TELL US*

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The odd rank analyzing powers ${}^{T}T_{10}$ and ${}^{T}T_{30}$ for ${}^{12}\mathrm{C}({}^{7}\vec{\mathrm{Li}},{}^{7}\mathrm{Li}){}^{12}\mathrm{C}$ and ${}^{12}\mathrm{C}({}^{7}\vec{\mathrm{Li}},\alpha){}^{15}\mathrm{N}$ have been measured with high precision for a ${}^{7}\vec{\mathrm{Li}}$ bombarding energy of 34 MeV. The angular distributions of the ${}^{T}T_{10}$ and ${}^{T}T_{30}$ data are strongly correlated, marking the first experimental evidence of a relationship between analyzing powers of different rank. The ratio of ${}^{T}T_{30}$ to ${}^{T}T_{10}$ obeys limits derived from the assumptions that the reaction is both peripheral and well localized in the reaction plane, allowing, for the first time, a third rank analyzing power to contribute to our understanding of ^{7}Li.

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1. Introduction

A surprising result has been found experimentally. For scattering and reactions induced by a polarized ^{7}Li beam, the first rank (${}^{T}T_{10}$) and transverse third rank (${}^{T}T_{30}$) analyzing powers follow each other. A rather simple model that only assumes that the scattering takes place in a plane and is peripheral is able to predict this result.

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The major thrust of the Florida State University polarized Li scattering and reaction program has been to measure complete sets of analyzing powers for both ^{6}Li and ^{7}Li beams. The Florida State University accelerator system consists of a Super FN tandem, capable of terminal voltages up to 10 MV, that can inject a superconducting linac which uses Argonne type resonators. The system can be used as a tandem alone or in its coupled mode. The Florida State laser pumped polarized Li ion source [1] is based on the very successful Hamburg, Heidelberg, Marburg source [2]. Typical on-target beam currents are 150 μA with beam polarizations of 70% of the theoretical maximum for ^{7}Li and 90% for ^{6}Li beams. The experimental detector chambers consist of a main scattering chamber followed by a helium filled one.

The Madison reference frame is sometimes used, but often the transverse coordinate system provides a better frame with which to characterize the data. The transverse frame or Basel frame [3] is defined with the $\hat{y}$ axis along the incoming beam momentum and the $\hat{z}$ axis normal to the scattering plane. The direction of the spin axis on target is defined by the angles ψ and ρ where ψ is the polar angle from the $\hat{z}$ axis to the spin axis and ρ is the azimuthal angle measured from the $\hat{x}$ axis to the projection of the spin axis in the $\hat{x}-\hat{y}$ plane. The analyzing powers expressed in this frame are denoted by a left superscript T, and the polarized cross section $\sigma_{\rm pol}$ is written

$$\begin{aligned}\sigma_{\rm pol} = \sigma_{\rm unp} & \Big[1 + \cos\psi\, t_{10}\, {}^T T_{10} + \tfrac{1}{2}\left(3\cos^2\psi - 1\right)\, t_{20}\, {}^T T_{20} \\ - & \sqrt{3/8}\,\sin^2\psi\, t_{20}\, \left({}^T T_{2,-2}\ e^{2i\rho} + {}^T T_{22}\ e^{-2i\rho}\right) \\ + & \tfrac{1}{2}\left(5\cos^3\psi - 3\cos\psi\right)\, t_{30}\, {}^T T_{30} \\ + & \sqrt{15/8}\,\sin^2\psi\,\cos\psi t_{30}\, \left({}^T T_{3,-2}\, e^{2i\rho} + {}^T T_{32}\ e^{-2i\rho}\right)\Big] . \end{aligned} \quad (1)$$

For spin 1/2 projectile one just has the first two terms in the expression above; for spin 1, terms through second rank are needed, and for spin 3/2 projectile, the cross section and seven analyzing powers must be measured.

To measure all analyzing power ranks it was necessary to first establish both calibration and monitoring reactions. The easiest way to measure the tensor polarization of the beam is to place a detector at 0°, where the only analyzing power is T_{20} and its value is -1.0 for the reaction $p(^7\mathrm{Li},\alpha)$. While one can use 0° detector to establish the beam polarization, the main problem with using it to monitor the beam polarization is that the intense neutron flux produced in the foil that stops the primary beam from reaching the detector causes the detector rapidly fails. Consequently it was found necessary to establish secondary standards for ^{7}Li + ^{4}He scattering. Once this work was completed by Cathers *et al.* [4], it was possible to begin the experimental program.

The general experimental procedure is similar to that described in Ref. [4], and here only the features relevant to the present experiment are given. The Florida State University (FSU) optically pumped polarized lithium ion source [1] was used to produce polarized ^{7}Li ions in the four polarization states $N_{\frac{3}{2}}$, $N_{\frac{1}{2}}$, $N_{-\frac{1}{2}}$ and $N_{-\frac{3}{2}}$ that correspond to populating the ^{7}Li beam magnetic substates $m_I = \frac{3}{2}$, $\frac{1}{2}$, $-\frac{1}{2}$, and $-\frac{3}{2}$. The data acquisition system cycled the polarization state of the beam automatically through the unpolarized and all polarized states N_i, spending approximately three minutes in each state.

Figure 1 shows the angular distributions of the analyzing powers $^TT_{10}$ (solid circles) and $^TT_{30}$ (open circles) measured for the elastic and inelastic scattering of ^{7}Li by ^{12}C at 34 MeV with purely statistical error bars. As previously observed [5,6], the analyzing power $^TT_{30}$ is small, so that extremely

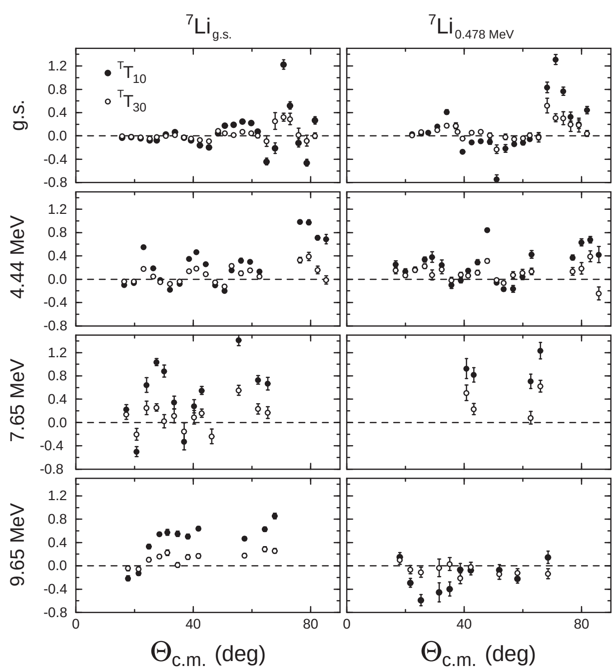

Fig. 1. Angular distributions of the analyzing powers $^TT_{10}$ (solid circles) and $^TT_{30}$ (open circles) for the elastic and inelastic scattering of ^{7}Li on ^{12}C at 34 MeV. The left and right columns show the nucleus ^{7}Li elastically scattered and inelastically scattered to its first excited state, respectively.

low statistical errors are required in order to get meaningful results. The most striking feature of the data is that the third rank analyzing power ${}^{T}T_{30}$ closely follows the vector analyzing power ${}^{T}T_{10}$, with both analyzing powers having the same zeroes and maxima. Similar strong correlations were also observed in the ${}^{12}\mathrm{C}({}^{7}\vec{\mathrm{Li}},\alpha)$ transfer reaction whose analyzing powers were measured during the same experiment.

To understand the observed trends in the data, a simple reaction model is presented next. In the following discussion, the analyzing powers ${}^{T}T_{kq}$ are meant to be measured and expressed in the "transverse" frame in which the $\hat{z}$ axis points up, normal to the scattering plane. In the two-body nuclear reaction $\vec{a}+A \to b+B$, very general results can be obtained for the analyzing powers ${}^{T}T_{kq}$ from the relation [7, 8]

$$\begin{aligned} \sigma\, {}^{T}T_{kq} \;=\; & \frac{1}{(2I_a+1)(2I_A+1)} \sum_{m_a\, m_A\, m_b\, m_B} \left| {}^{T}M_{m_b\, m_B,\, m_a\, m_A} \right|^2 \\ & \times\sqrt{2k+1}\; \langle I_a\, k\, m_a\, q | I_a\, m_a \rangle \;, \end{aligned} \tag{2}$$

where ${}^{T}M$ is the matrix of scattering amplitudes in the transverse frame, and σ is the unpolarized cross section. In the particular case where spin $3/2$ projectile (*e.g.*, ^{7}Li) impinges on spin zero target (*e.g.*, ^{12}C) with the spin axis oriented along $\hat{z}$, Eq. (2) simply reduces to the following set of equations for the analyzing powers ${}^{T}T_{k0}$

$$\begin{aligned} \sigma\, {}^{T}T_{10} &= \tfrac{3}{\sqrt{5}}\left[\, (\sigma_{3/2}-\sigma_{-3/2}) + \tfrac{1}{3}(\sigma_{1/2}-\sigma_{-1/2})\right], \\ \sigma\, {}^{T}T_{20} &= \left[\, (\sigma_{3/2}+\sigma_{-3/2}) - (\sigma_{1/2}+\sigma_{-1/2})\, \right], \\ \sigma\, {}^{T}T_{30} &= \tfrac{3}{\sqrt{5}}\left[\tfrac{1}{3}\, (\sigma_{3/2}-\sigma_{-3/2}) - (\sigma_{1/2}-\sigma_{-1/2})\, \right], \end{aligned} \tag{3}$$

where σ_i denotes the cross section measured with the beam in the polarization state N_i. The ratio R_{31} of the odd-k analyzing powers ${}^{T}T_{30}$ and ${}^{T}T_{10}$ follows from Eq. (3) and can be simply written as

$$R_{31} = \frac{3\, {}^{T}T_{30}}{{}^{T}T_{10}} = \frac{1-3\,Y}{1+\frac{1}{3}\,Y}\,, \tag{4}$$

where $Y = (\sigma_{1/2}-\sigma_{-1/2})\,/\,(\sigma_{3/2}-\sigma_{-3/2})$ and is a function of the scattering angle and the final states which occur.

In the present work, we propose a more general treatment which is not restricted to any given final state. For the entrance channel considered here (^{7}Li and ^{12}C), it is assumed that all the final channels (elastic and inelastic) have transition densities in the peripheral region, *i.e.*, at impact parameter values where the two nuclei are just grazing (for smaller impact parameters, strong absorption into other reaction channels occurs). It is also assumed that the interaction causing $\sigma_m \neq \sigma_{-m}$ is well localized in the peripheral region of the projectile and target. The combined effect of these assumptions is to constrain the origins of $(\sigma_{m_a} - \sigma_{-m_a})$ to a small overlap region which is close to the equatorial $(x-y)$ plane of each nucleus when the transverse frame is chosen.

To estimate the possible values Y can take within this model, one needs to assess how the initial density distribution of ^{7}Li in the reaction plane depends on the initial state spin projection m_a of the beam. The $(\alpha + t)$-cluster model [9] provides a simple and reasonably accurate model for this purpose, and in the transverse frame, the wave functions can be simply written as

$$\begin{aligned}\psi_{\frac{3}{2},\pm\frac{3}{2}} &= \frac{u(r)}{r}\, iY_{1,\pm 1}(\theta,\phi)\ \chi_{\frac{1}{2},\pm\frac{1}{2}}(\xi_t,\xi_\alpha)\,,\\ \psi_{\frac{3}{2},\pm\frac{1}{2}} &= \frac{1}{\sqrt{3}}\frac{u(r)}{r}\, iY_{1,\pm 1}(\theta,\phi)\ \chi_{\frac{1}{2},\mp\frac{1}{2}}(\xi_t,\xi_\alpha)\\ &\quad +\sqrt{\frac{2}{3}}\frac{u(r)}{r}\, iY_{1,0}(\theta,\phi)\ \chi_{\frac{1}{2},\pm\frac{1}{2}}(\xi_t,\xi_\alpha)\,,\end{aligned} \tag{5}$$

where $\chi_{\frac{1}{2},\pm\frac{1}{2}}(\xi_t,\xi_\alpha)$ is a product of the intrinsic states of the triton and the α particle, and the spherical harmonics $Y_{\ell,m}$ describe the angular part of the relative motion of the α particle and the triton in ^{7}Li which has an orbital angular momentum $\ell = 1$. If the reaction mechanism responsible for $(\sigma_{m_a} - \sigma_{-m_a})$ is predominantly sampling regions close to the $x-y$ plane, then $\theta \approx \frac{\pi}{2}$, and since $Y_{1,0}$, $Y_{1,\pm 1}$ involve $\cos\theta$ and $\sin\theta$, respectively, one expects the term containing $Y_{1,0}$ in Eq. (5) to be negligible. In that case, the ratio of densities for $m_a = \frac{1}{2}$ and $\frac{3}{2}$ is given by:

$$\frac{\left|\psi_{\frac{3}{2},\frac{1}{2}}\right|^2}{\left|\psi_{\frac{3}{2},\frac{3}{2}}\right|^2} = \frac{1}{3} = \frac{\left|\psi_{\frac{3}{2},-\frac{1}{2}}\right|^2}{\left|\psi_{\frac{3}{2},-\frac{3}{2}}\right|^2}\,, \tag{6}$$

and provides an expected upper limit on $|Y|$ of $\frac{1}{3}$ since the cross section σ_{m_a} is directly proportional to $|\psi_{\frac{3}{2},m_a}|^2$.

This restriction yields a positive value for R_{31} (see Eq. (4)) so that ${}^T T_{10}$ and ${}^T T_{30}$ have the same signs and the same zeroes, as experimentally observed (see Fig. 1).

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