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Reaction ^{6}Li$(n,p)^6$He at 118 MeV

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Cross sections at six angles from 0° out to 20° in the c.m. system have been measured for the $1^+ \rightarrow 0^+$ transition in the reaction ^{6}Li$(n,p)^6$He at $E_n = 118$ MeV. The 0° cross section is in good agreement with measurements of the same quantity on ^{6}Li$(p,n)^6$Be at similar energies. The 0° (n,p) cross section gives a value of 161 ± 17 MeV fm^3 for the volume integral of the central part of the spin-isospin interaction; a theoretical value of 161 MeV fm^3 is in good agreement. A distorted wave calculation for a pure, Gamow-Teller transition is in fair agreement with the measured (n,p) angular distribution. An approximate resolution of the weak $1^+ \rightarrow 2^+$ transition to the first excited state of ^{6}He at 1.8 MeV shows an angular distribution of a very different character corresponding to a transition of mixed angular momenta.

Mirror charge-exchange reactions, such as $(\pi^{\pm},\gamma)$ (Ref. 1) and $(\pi^{\pm},\pi^0)$,[2] have provided important information on giant resonances. Together with noncharge-exchange reactions of the type (γ,x), (e,e'), and (p,p'),[3] they can be used, for example, to identify and separate isovector from isoscalar resonances, to study all three isospin components of an isovector resonance, and to test the isospin dependence of giant resonance sum rules. In this paper we report measurements on the (n,p) reaction at $E_n = 118$ MeV which is a favorable energy for exciting spin-flip giant resonances.[4] The (n,p) reaction is the isospin analog of the (p,n) reaction, which has been of great importance in the study of the so-called Gamow-Teller (GT) resonances.[5]

The excitation strengths of GT resonances by (p,n) and (n,p) reactions on the same target nucleus are linked by the sum rule[5]

$$S_\beta^- - S_\beta^+ = \sum B^-(\mathrm{GT}) - \sum B^+(\mathrm{GT}) = 3(N-Z) ,$$

where S_β is the sum of the reduced GT transition strengths $B(\mathrm{GT})$ to all possible final states, and the plus and minus signs correspond to (n,p) and (p,n) transitions, respectively. This nonenergy-weighted sum rule can be tested if all (n,p) and (p,n) transitions on the same target nucleus are measured. In the special case of a self-conjugate target, $N = Z$, the (p,n) and (n,p) reactions excite only $T+1$ states, where T is the isospin of the target nucleus. The sum rule then reduces to $S_\beta^- = S_\beta^+$ and provides an especially simple test case. We have selected the self-conjugate nucleus ^{6}Li for study. Measurements already exist for the mirror reaction ^{6}Li$(p,n)^6$Be.[6,7] In the general case, $N > Z+1$, the (p,n) reaction excites states with isospin $T+1$, T, and $T-1$, whereas only $T+1$, states are excited by the (n,p) reaction. The (p,n) reaction has been studied systematically[5] since the late 1970s. The need for corresponding (n,p) measurements is apparent from the above brief discussion.

The design, construction, and commissioning of the (n,p) setup that was used in this study at the Indiana University Cyclotron Facility (IUCF) is described elsewhere.[8] Here we give only a brief outline. A novel feature of the setup is that the reaction products are detected in good geometry with several high purity Ge telescopes providing reliable particle identification and an energy resolution of approximately 60 keV for energetic protons. Therefore, the overall energy resolution of the experiment is determined by the thicknesses of the neutron production and the (n,p) targets. The (n,p) experiment is conducted in a well shielded and isolated vault and because of the good geometry (3.14 m between targets) time-of-flight techniques contribute essentially to particle identification, background suppression, and spectral purity.

The proton beam from the IUCF cyclotron strikes a thin neutron production target of ^{7}Li and is then swept by a magnet into a beam pipe leading to a well isolated and shielded beam stop which provides an effective Faraday cup for collecting the beam. A thick concrete wall separates the neutron production area from the (n,p) experimental vault and provides an effective shield against unwanted neutrons from the production target. A collimator encased in this wall selects a neutron beam emitted at 0° relative to the proton beam. The (n,p) target is placed at the exit of the neutron collimator. Because of the low background in the vault it was found that tag and veto detectors were not needed at the (n,p) target. At a distance of 1.7 m behind the (n,p) target a neutron monitor[9] is set up to measure the intensity and energy spectrum of the neutron beam.

Protons emitted at 0° in the (n,p) target could be deflected out of the neutron beam, through angles out to about 12°, by means of a small dipole magnet. This arrangement introduces a known correlated variation of momentum and reaction angle at any given detection angle. Protons emitted at three angles are detected simultaneously by three telescopes each composed typically of three hyperpure Ge detectors mounted inside a common cryostat. The telescopes are arranged so as to accept protons emitted typically at 7.5°, 12.5°, and 17.5° when the deflecting magnetic field is turned off. With one additional run with field on, a complete six point angular distribution out to 20° can be obtained. A typical Ge telescope 2.5 cm in diameter selects a momentum bite of 20% and an angle bite of 1.8°. These values are suitable for the particle spectra and angular distributions expected in GT transitions in (n,p) reactions.

In front of each Ge telescope a thin ΔE plastic scintillator is placed to provide a fast trigger in coincidence with signals in the first detector of the corresponding telescope. Essential particle timing information was obtained between these fast trigger pulses and phase-stabilized beam pickoff signals from the cyclotron. At each angle a proton spectrum was obtained by recording events of summed energy E in the telescope which satisfied cuts on ΔE timing, ΔE energy, and E_1, the energy in the first detector in the given telescope. The data acquisition and analysis were performed with the XSYS/IUCF code[10] on a VAX computer.

The ^{6}Li$(n,p)^6$He measurements, which cover six angles, $\theta_{\rm lab}=0°$, 5°, 7.5°, 10°, 12.5°, and 17.5°, were taken with the field of the proton deflection magnet set at $B=0.7$ T and $B=0$. At each field setting the ^{1}H$(n,p)n$ scattering was also measured to provide an absolute normalization of the neutron flux as well as a direct calibration of the acceptance for each individual telescope. Background was measured with the target removed. Thus, a measurement at a given field setting was accomplished by cycling back and forth through the target sequence: ^{6}Li, CH_2, blank. The proton energy resolution in the experiment (typically ~2.3 MeV full width at half maximum) was dominated by the thickness of the production target (290 mg/cm^2 of ^{7}Li) and the (n,p) target (462 mg/cm^2 of ^{6}Li).

Figure 1 shows the ^{6}Li$(n,p)^6$He spectra measured at the six angles $\theta_{\rm c.m.}\cong 0°$, 5.9°, 8.9°, 11.9°, 14.8°, and 20.7°. If the ground-state transition is a relatively pure Gamow-Teller excitation, its cross section is expected to be strongly forward-peaked, as confirmed in Fig. 1. It is seen that the continuum region in the reaction has a different, much less pronounced dependence on θ, and remains relatively featureless throughout the angular range covered. From this we conclude that there is relatively little GT strength in the continuum. The ground-state peaks in Fig. 1 are broadened possibly by contributions from the known 2^+ state in ^{6}He at 1.80 MeV, which lies at the limit of our experimental energy resolution. At 0° this contribution appears to be small because of the different nature of the two transitions; however, around $\theta_{\rm c.m.}=20°$ the 2^+ state is excited with comparable strength to that of the ground state, as has been observed in ^{6}Li(p,n) measurements at 120 MeV.[8] To quantify these observations the two overlapping peaks were unfolded through a two-line fitting procedure involving appropriate line shapes deduced from measurements on the reaction ^{1}H$(n,p)n$. This unfolding procedure introduces rather large errors into the results presented below, especially for the (n,p) transition to the excited state since it is difficult to extract the continuum contribution in the region of the excited state.

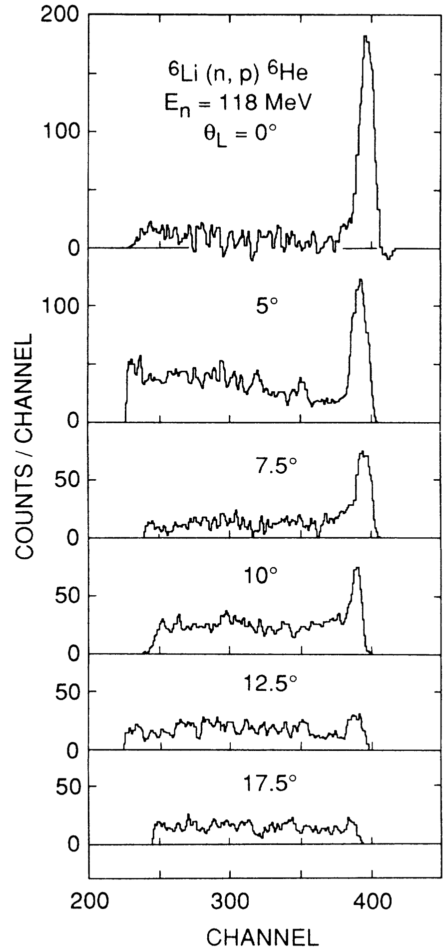

FIG. 1. Energy spectra of protons from ^{6}Li$(n,p)^6$He detected at various laboratory angles for 118 MeV neutrons.

The angular distribution of the ^{6}Li$(n,p)^6$He ground-state transition is plotted in Fig. 2 along with the result of a distorted-wave impulse approximation (DWIA) calculation (solid curve). The calculation was performed using the DW81 code[11] with the N-N effective interaction t matrix from Franey and Love,[4] optical-potential parameters from Meyer, Schwandt, Jacobs, and Hall[12] and the L-S coupling transition strengths from Lee and Kurath.[13] In the calculation the L-S coupling strengths are transformed to j-j strengths by the standard procedure. The large error bars on the data, particularly at the larger angles, reflect the uncertainties in the unfolding procedure outlined above. At 0° the measured differential cross section is $\sigma(0°)=11.7\pm0.8$ mb/sr.

Table I summarizes the (n,p) and (p,n) results at 0° and includes a recent (n,p) measurement at 198 MeV.[14] Also given in this table are values for $\hat{\sigma}^{\pm}_{\rm GT}$, the so-called unit cross section, which relates the zero degree cross section to the inverse Gamow-Teller beta decay strength through the relation[14,15]

$$\sigma^{\pm}(q,\omega,A,\alpha)=\hat{\sigma}^{\pm}_{\rm GT}(A)F(q,\omega)B^{\pm}_{\rm GT}(A,\alpha)\,,$$

where q is the momentum transfer, ω the energy loss, and α specifies the particular states of the transition. The +

TABLE I. Comparison of zero-degree cross sections for ^{6}Li(n,p) and ^{6}Li(p,n) reactions. The various quantities are discussed in the text. It is assumed that $B^+_{GT} = B^-_{BT} = 1.59$ (Ref. 16). In $\hat{\sigma}^{\pm}_{GT}$ the plus or minus signs refer to the (n,p) and (p,n) reactions, respectively.

Reaction	Projectile energy (MeV)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$F(q,\omega)$	$\hat{\sigma}^{\pm}_{GT}$ (mb/sr)	References
^{6}Li$(n,p)^6$He	118	11.7 ± 0.8	0.98	7.5 ± 0.6	This work
^{6}Li$(p,n)^6$Be	120	12.0 ± 1.5	0.96	7.9 ± 1.0[a]	7
^{6}Li$(p,n)^6$Be	144	13.1	0.97	8.5[a]	6
^{6}Li$(p,n)^6$Be	160	14.4 ± 0.8	0.97	9.3 ± 0.6[a]	15
^{6}Li$(n,p)^6$He	198	15.51 ± 0.55	0.98	9.90 ± 0.36	14
^{6}Li$(p,n)^6$Be	200	14.2 ± 0.7[b]	0.98	9.1 ± 0.5[c]	14,15

[a]Calculated by present authors.
[b]Obtained from given $\hat{\sigma}_{GT}^-$.
[c]As given in Ref. 14.

and − signs designate the (n,p) and (p,n) reactions or β^- and β^+ decays, respectively. $F(q,\omega)$ is a form factor which accounts for the dependence of the cross station on q and ω such that $F(q,\omega) \rightarrow 1$ as $(q,\omega) \rightarrow (0,0)$. The $F(q,\omega)$ in Table I were calculated in the DWIA.

In Table I it appears that the sum-rule relationship for the GT transitions from ^{6}Li, $S_\beta^- = S_\beta^+$, is satisfied experimentally to better than 10%. This statement takes into account only the 0° cross sections and shapes of the angular distribution of the ground-state transitions.[7] In particular the excited-state transition is not included. Finally, using the well known relation[4] between the 0° cross section, the reduced Gamow-Teller matrix element, and the volume integral of the central part of the spin-isospin interaction $V^c_{\sigma\tau}$, we obtain from our measurement

$$V^c_{\sigma\tau} = 161 \pm 17 \text{ MeV fm}^3 ,$$

in good agreement with the theoretical value of 161 MeV fm^3 at 118 MeV interpolated from Franey and Love.[4]

In Fig. 3 we give the angular distribution obtained for the excited state transition. Despite the low precision of the measurement, it is clear the nature of the transition is markedly different from that of the ground-state transition. In the latter transition the spin sequence, $1^+ \rightarrow 0^+$, dictates a pure GT transition, whereas in the former case the sequence $1^+ \rightarrow 2^+$ allows total angular momentum changes with magnitudes 1, 2, or 3. The plotted curve represents a simple incoherent superposition of the three DW81 curves corresponding to these three values; at 0° the three cross sections are in the proportion of 71.0:10.5:18.5, respectively. Further improvement in this fit must await better data for the excited-state angular distribution. Similarly, further refinement of the sum rule test above would require better measurements of the angle integrated GT strength in the excited state and in the continuum in both the (n,p) and (p,n) reactions.

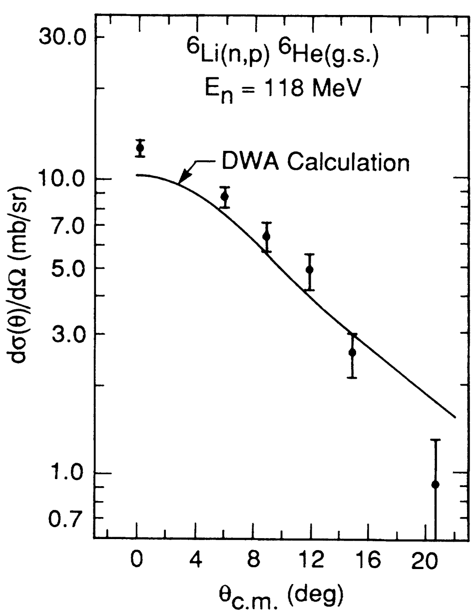

FIG. 2. Angular distribution of the ^{6}Li$(n,p)^6$He (0^+, g.s.) reaction in the c.m. system. The curve is the distorted-wave impulse approximation calculation described in the text.

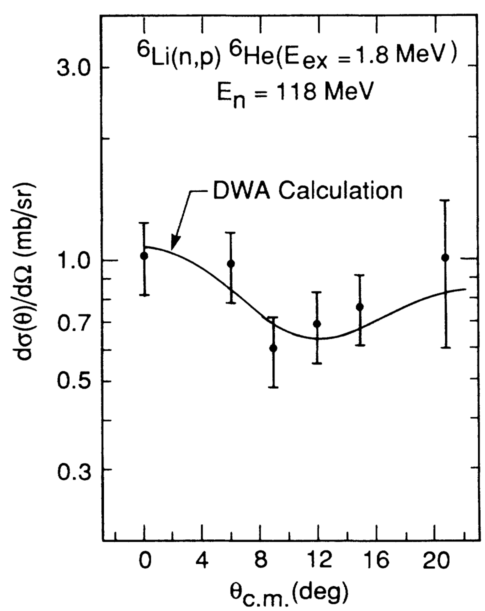

FIG. 3. Angular distribution of the ^{6}Li$(n,p)^6$He (2^+, 1.8 MeV) reaction in the c.m. system. The curve is the distorted-wave impulse approximation calculation discussed in the text.

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[1]C. J. Martoff, J. A. Bistirlich, C. W. Clawson, K. M. Crowe, M. Koike, J. P. Miller, S. S. Rosenblum, W. A. Zajc, H. W. Baer, A. H. Wapstra, G. Strassner, and P. Truöl, Phys. Rev. C **27**, 1621 (1983).

[2]A. Erell, J. Alster, J. Lichtenstadt, M. A. Moinester, J. D. Bowman, M. D. Cooper, F. Irom, H. S. Matis, E. Piasetzky, and U. Sennhauser, Phys. Rev. C **34**, 1822 (1986).

[3]S. S. Hanna, in *Giant Multipole Resonances,* edited by F. E. Bertrand (Harwood-Academic, Chur, 1979), p. 1.

[4]M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).

[5]K. Ikeda, S. Fujii, and J. I. Fujita, Phys. Lett. **3**, 271 (1963); C. Gaarde, J. Rapaport, T. N. Taddeucci, C. D. Goodman, C. C. Foster, D. E. Bainum, C. A. Goulding, M. B. Greenfield, D. J. Horen, and E. Sugarbaker, Nucl. Phys. **A369**, 258 (1981).

[6]G. L. Moake, L. J. Gutay, R. R. Scharenberg, P. T. Debevec, and P. A. Quin, in *The (p,n) Reaction and the Nucleon-Nucleon Force,* edited by C. D. Goodman, S. M. Austin, S. D. Bloom, J. Rapaport, and G. R. Stachler (Plenum, New York, 1980), p. 179.

[7]J. Rapaport (private communication).

[8]C. J. Martoff, K. Wang, D. Počanić, S. S. Hanna, C. C. Foster, D. L. Friesel, and J. Rapaport (unpublished).

[9]J. L. Romero, M. W. McNaughton, F. P. Brady, N. S. P. King, T. S. Subramanian, and J. L. Ullmann, Phys. Rev. C **17**, 468 (1978).

[10]C. R. Gould, Triangle Universities Nuclear Laboratory; modified version, N. R. Yoder, Indiana University Cyclotron Facility.

[11]R. Schaeffer and J. Raynal, DWBA70 code; extended version, J. Comfort.

[12]H. O. Meyer, P. Schwandt, W. W. Jacobs, and J. R. Hall, Phys. Rev. C **27**, 459 (1983).

[13]T.-S. H. Lee and D. Kurath, Phys. Rev. C **21**, 293 (1980).

[14]K. P. Jackson *et al.*, Phys. Lett. B **201**, 25 (1988).

[15]T. N. Taddeucci *et al.*, Nucl. Phys. **A469**, 125 (1987).

[16]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **A227**, 1 (1974).