New (p,n) Reaction Studies at E_p = 23 MeV*

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The (p,n) reaction has been studied at $E_p = 23$ MeV on 35 nuclei ranging in mass from ^{9}Be to ^{208}Pb. Overall energy resolution for the levels of interest ranged from 50 to 200 keV. Compound-nucleus contributions appear to be generally small at this bombarding energy. Early distorted-wave Born-approximation analysis of the data reveals several difficulties, both for macroscopic and microscopic forms of analysis.

The (p,n) and $(^3\mathrm{He}, t)$ charge-exchange reactions have been widely studied in the past few years both for their utility as spectroscopic tools and as a measure of the isospin dependence of the appropriate optical-model potentials. These studies have been somewhat hampered by the technical difficulties of (p,n)-reaction measurements, on the one hand, and by the difficulty of obtaining truly satisfactory agreement between direct-reaction theory [usually distorted-wave Born-approximation (DWBA)] and $(^3\mathrm{He}, t)$ measurements, on the other hand. This latter difficulty could be due, in part, to the lack of a well-defined optical potential for complex projectiles. For this reason we decided to study the (p,n) reaction on a wide variety of nuclei with techniques which could yield data of reasonably high technical quality. Previous studies sometimes lacked sufficient energy resolution and/or sufficiently detailed angular distributions for careful comparison with theory. Since nucleons are not so rapidly absorbed as are mass-3 projectiles, the (p,n) reaction is quite sensitive to contributions from the nuclear interior and accurately measured angular distributions should, in principle, be able to detect configuration mixing of nuclear wave functions.

The experiments were carried out with a 23-MeV proton beam from the University of Colorado alternating-gradient variable-frequency cyclotron. The time width of beam bursts from the cyclotron was found to be approximately $\frac{1}{3}$ nsec when the machine was carefully adjusted for single-turn extraction. Three out of every four beam bursts were suppressed by a "repeller electrode" inside the ion source[1] in order to provide sufficient neutron flight time between beam bursts. Shielded 1-in.×6-in.-diam liquid scintillators were placed at laboratory angles between 10° and 152° with flight paths ranging from 6 to 9 m. Overall time resolution was less than 1 nsec full width at half-maximum. Sample spectra are shown for ^{27}Al and ^{54}Fe targets in Fig. 1. The targets studied in our survey included ^{9}Be, ^{14}N, ^{16}O, ^{20}Ne, $^{24-26}$Mg, ^{27}Al, ^{28}Si, ^{31}P, ^{40}Ar, ^{40}Ca, ^{49}Ti, ^{50}Cr, ^{54,56,58}Fe, ^{58,61,62,64}Ni, ^{64}Zn, ^{90}Zr, ^{93}Nb, ^{96}Zr, ^{96}Mo, ^{96}Ru, ^{104}Ru, ^{115}In, $^{117-120}$Sn, ^{165}Ho, and ^{208}Pb.[2] For low- and medium-A nuclei, both analog and nonanalog states were generally observed. As A increased, the analog transitions dominated the spectrum. In those cases, the analog transitions were superimposed upon a strong evaporation neutron spectrum.

Some representative angular distributions for ground-state analog transitions are shown in Fig. 2. These data are sufficiently detailed and have

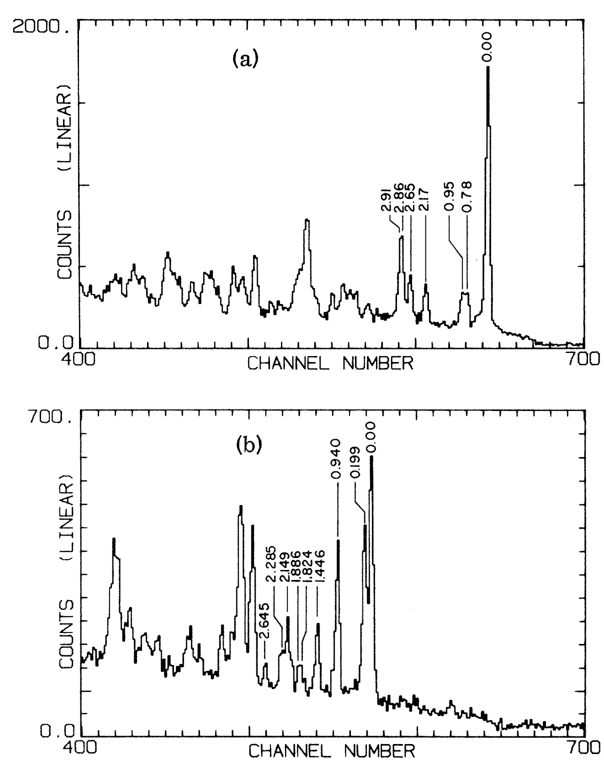

FIG. 1. Time-of-flight spectra for the reactions (a) $^{27}\mathrm{Al}(p,n)^{27}\mathrm{Si}$ and (b) $^{54}\mathrm{Fe}(p,n)^{54}\mathrm{Co}$, both for $E_p = 22.8$ MeV. Time per channel is 0.3 nsec. For (a), $\theta_{\mathrm{lab}} = 47.5°$ and the flight path is 9.01 m; for (b), $\theta_{\mathrm{lab}} = 40.0°$ and the flight path is 8.72 m.

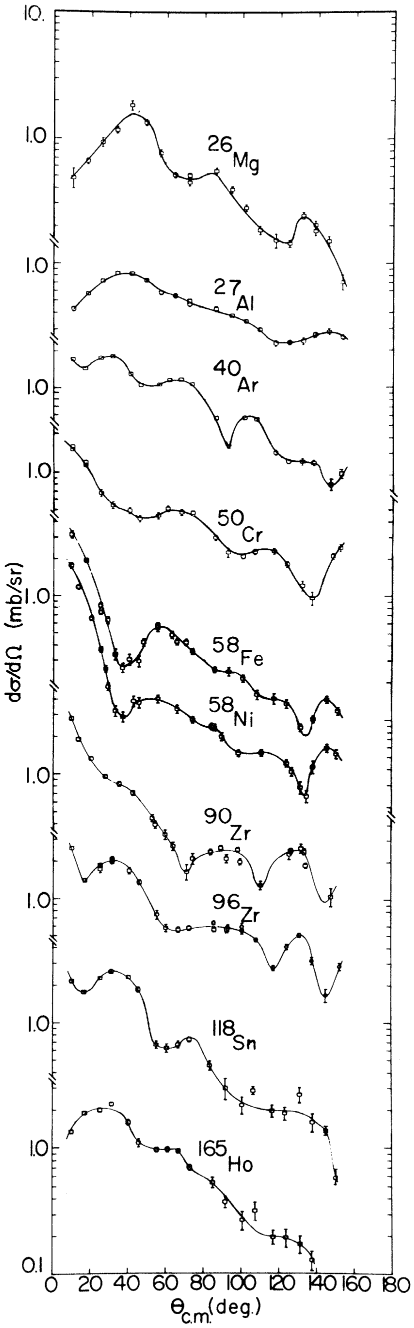

FIG. 2. Angular distributions for analog transitions in ^{26}Mg, ^{27}Al, ^{40}Ar, ^{50}Cr, ^{58}Fe, ^{58}Ni, ^{90}Zr, ^{96}Zr, ^{118}Sn, and ^{165}Ho. The curves merely serve to guide the eye.

sufficiently small statistical errors to make detailed comparison with theory possible. A first attempt to fit these analog-state data with a DWBA was carried out in a straightforward manner. Following the prescription of Lane,[3] the nucleon optical potential was taken to be of the

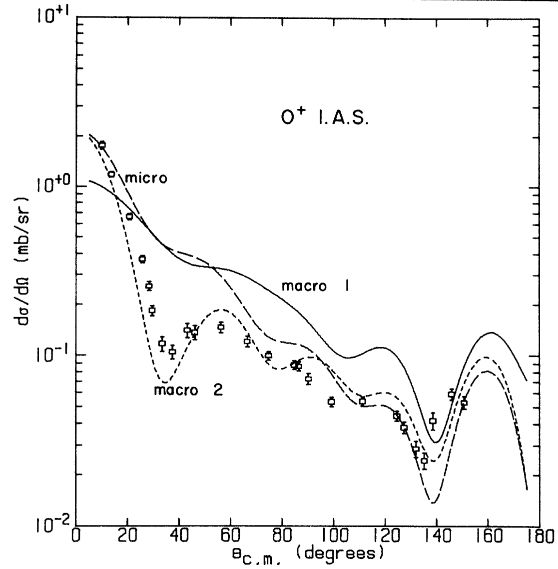

FIG. 3. Comparison of both microscopic- and macroscopic-model predictions with $^{58}Ni(p,n)^{58}Cu$ (analog) data.

form

$$U(r) = U_0(r) + 4U_1(r)tT/A.$$

The diagonal isospin matrix elements of this potential give proton and neutron potentials separately, and one of the off-diagonal terms leads to (p,n) reactions. The proton and neutron potentials were taken from the review of Becchetti and Greenlees[4] and used for the distorting potential in a DWBA calculation. The difference between proton and neutron potentials with appropriate scaling factors was used as the form factor. The calculations were carried out with the code DWUCK.[5] An example for ^{58}Ni is shown in Fig. 3 with the above calculation labeled macro 1. Also shown in Fig. 3 is a microscopic calculation (labeled micro) in which an $f_{7/2}$ neutron in ^{58}Ni was charge exchanged via a Yukawa central interaction with the incident proton. The range parameter of this microscopic interaction was 1 fm. The range parameter was varied and different configurations ($2p_{3/2}$ and $2p_{1/2}$) were tried with little improvement in the quality of the fit. This difficulty in fitting the analog-transition angular distribution is quite general for targets with Z nearly equal to N and may point to a shortcoming in the presently accepted methods of analysis of charge-exchange reactions for these nuclei. The possibility that compound-nucleus contributions caused these difficulties was considered. A measurement of the excitation function of the 1.6-

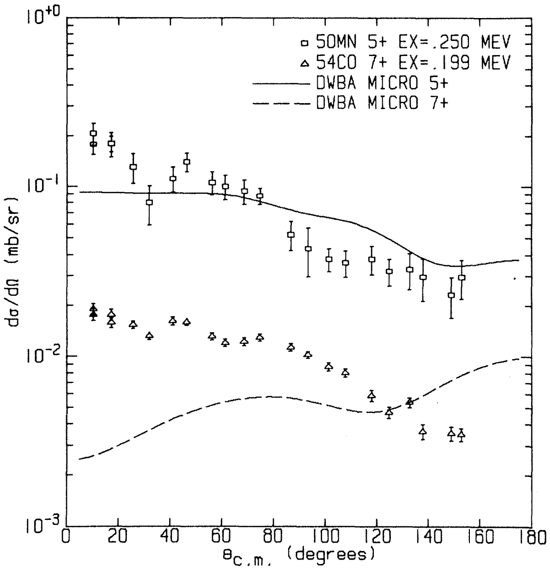

FIG. 4. Angular distributions for two low-lying, high-spin states. One is the 230-keV 5^+ level in ^{50}Mn; the other is the 200-keV 7^+ level in ^{54}Co.

MeV level in ^{54}Co, which is apparently only populated via the compound-nucleus mechanism, showed it to be negligibly populated at $E_p = 23$ MeV, though it was quite strong at 14 MeV. Further, the depths of the large-angle minima in analog transitions exclude appreciable compound-nucleus contributions. An attempt was made to determine a form factor empirically for the DWBA calculation of the ^{58}Ni analog transition which would give agreement with the data. An acceptable fit was found with a form factor consisting of a Woods-Saxon real volume and imaginary surface term in which the diffuseness had been increased by 50% over that for the optical-model potentials. That fit is shown also in Fig. 3 and labeled macro 2. For ^{90}Zr and ^{118}Sn, both of which have a substantial neutron excess, the macroscopic model gives satisfactory agreement with our data. Thus it may be that poor agreement between theory and experiment only occurs for nuclei with a very small neutron excess.

Another puzzle found in the early analysis of these data is seen in the angular distributions for two high-spin states shown in Fig. 4. One of these these is the 230-keV 5^+ level in ^{50}Mn; the other is the 199-keV 7^+ level in ^{54}Co. Simple diffraction-model arguments would predict a large angle for the first peak of these angular distributions. Indeed, DWUCK calculations with a microscopic model for the 7^+ level predict backward-peaked angular distributions. The data, however, rise steadily toward small angles in direct opposition to the calculations. The effects of coupling to the analog state were calculated[6] for the case of the 7^+ level in ^{54}Co with a coupled-channels code (CHUCK) with no significant change in the calculated results. The presence of the tensor force in the microscopic interaction does not change the prediction of a backward peak in the angular distribution. As seen in Fig. 4, a poor fit is also obtained for the 5^+ level in ^{50}Mn. Our DWBA calculations do not include exchange terms, but their effect on the *shape* of the angular distribution is expected to be small.[7] The possibility that poor resolution could be responsible for a distortion of the observed shape of the ^{54}Fe(p, n)^{54}Co(7^+) angular distribution was considered since the strong analog state was only marginally resolved. Two points ($\theta = 18°$ and $\theta = 50°$) were checked with long-flight-path (26-m), high-resolution measurements. These measurements agreed with the data of Fig. 4. Hence, we are again left with a rather serious discrepancy between experiment and theory.

A series of papers containing a complete presentation and analysis of the data are in preparation.

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[1] R. F. Bentley, L. A. Erb, D. A. Lind, C. D. Zafiratos, and C. S. Zaidins, Nucl. Instrum. Methods 83, 245 (1970).

[2] Some of these data are available upon request.

[3] A. M. Lane, Phys. Rev. Lett. 8, 171 (1962).

[4] F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[5] P. D. Kunz, private communication.

[6] E. S. Rost, private communication.

[7] K. A. Amos, V. A. Madsen, and I. E. McCarthy, Nucl. Phys. A94, 103 (1967); V. A. Madsen, private communication.