Collective Effects Shown by the (p, t) Reaction on the Closed-Shell Nucleus, ^{141}Pr

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The reaction ^{141}Pr$(p,t)^{139}$Pr at 40 MeV strongly populates collective states in the residual nucleus. The shapes of the angular distributions, taken at 5° intervals between 15 and 65°, show the inadequacies even of finite-range, two-nucleon-pickup distorted-wave Born-approximation calculations and the need for inclusion of higher-order effects.

The (p, t) reaction on ^{141}Pr has been studied as part of a general investigation of the systematics of the (p, t) reaction on spherical and deformed rare-earth nuclei. The residual nucleus of this reaction, ^{139}Pr, has been extensively studied through the ϵ/β^+ decays of the ground and metastable states of ^{139}Nd.[1] Because of the large number of very dissimilar states established in this decay scheme, 23 below 2.2 MeV, it was thought that here would be an excellent place to begin this general investigation.

In the present work, ≈800-μg/cm^2 ^{141}Pr targets prepared by vacuum evaporation on 25-μg/cm^2 carbon backings were bombarded with 500-nA beams of 40-MeV protons from the Michigan State University sector-focused cyclotron. A dE/dX, E counter telescope consisting of two cooled Si surface-barrier detectors was used to identify and measure the energies of the outgoing scattered particles. Triton spectra were taken between 15 and 65° at 5° intervals. Figure 1 contains triton spectra taken at the laboratory scattering angles of 25 and 35°. The over-all experimental resolution was 50 keV full width at half maximum. The excitation energies corresponding to the various triton peaks were determined internally by making a correspondence between some of the more obvious triton groups and the previously determined states in ^{139}Pr. In addition, an independent energy measurement of some of the more intense triton groups was conducted using a broad-range magnetic spectrometer, utilizing a 3-cm Si position-sensitive detector.

The experimental angular distributions, together with distorted-wave Born-approximation (DWBA) predictions, are displayed in Fig. 2. The distorted-wave predictions for various l transfers were calculated using a zero-range, cluster-transfer approach[2] as well as a more rigorous finite-range, two-nucleon-pickup formalism.[3] These are denoted by broken and continuous curves, respectively. Optical-model and bound-state parameters used in generating these theoretical curves appear in Table I.

The angular distribution corresponding to the $\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$ ground-state transition corresponds to an ap-

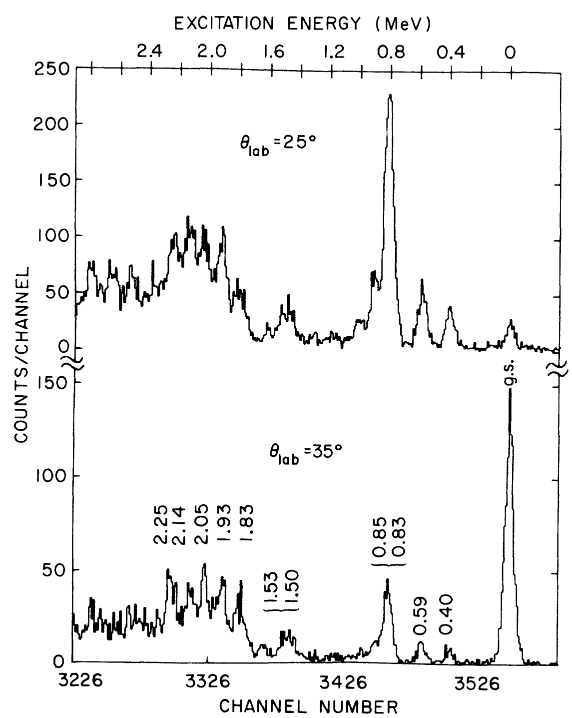

FIG. 1. Two spectra (θ_{lab} = 25 and 35°) of tritons from the ^{141}Pr(p,t) reaction at 40 MeV.

parently pure $l=0$ transfer. The finite-range calculation of the transfer of two $d_{3/2}$ neutrons fits the lower-angle data much better than does the cluster-transfer analysis; however, the latter calculation does a better job of predicting the position of the relative maxima occurring toward 55°. The overall agreement between theory and experiment is moderately good, and, since the angular shape of an $l=0$ transfer is sufficiently different from all other l values, the ground state of the residual nucleus ^{139}Pr appears to be populated by a *pure* $l=0$ wave.

The five angular distributions appearing below the $l=2$ designation in Fig. 2 all exhibit a characteristic $l=2$ angular shape. Again, at lower angles the finite-range $(d_{3/2})^2{}_{l=2}$ calculations fit the data much better than do the cluster predictions, although beyond 25° both curves are remarkably similar. Moreover, since the states populated through these $l=2$ waves have all been previously[1] classified as being collective in nature, the purity of these experimental $l=2$ curves is assured.[4]

The remaining angular distributions appearing in Fig. 2 correspond to four states populated

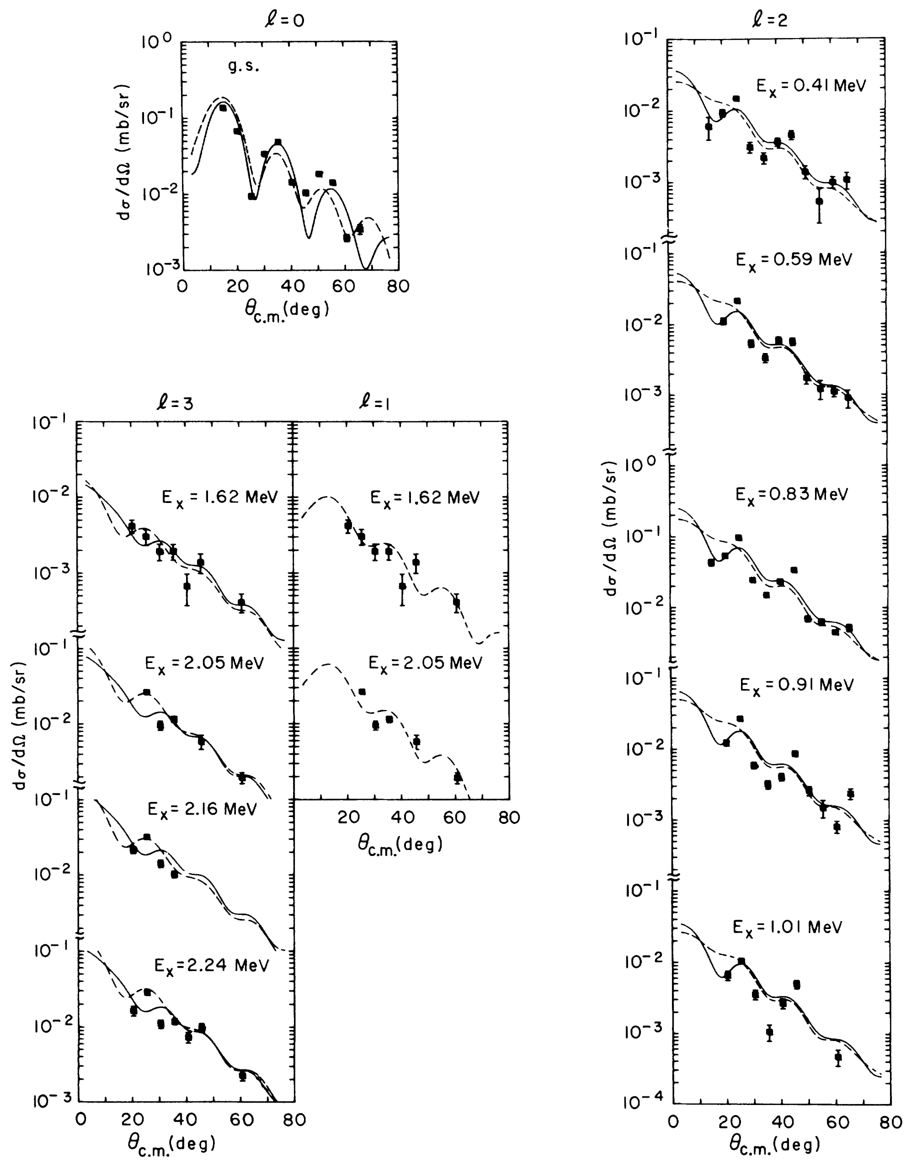

FIG. 2. Some angular distributions for the ^{141}Pr(p,t) reaction at 40 MeV. The intensity errors are indicated when they exceed the width of the experimental points. The curves are calculated DWBA analyses, the broken one a simple zero-range, cluster-transfer approach and the continuous one a more rigorous finite-range, two-nucleon-pickup formalism.

TABLE I. Optical-model and bound-state well parameters used in the distorted-wave analysis of the reaction, $^{141}Pr(p,t)$.

$$U_{OM}(r) = V_C(r) - V_0 \frac{1}{1+e^x} - \left(W_0 - 4W_D \frac{d}{dx'}\right)\frac{1}{1+e^{x'}} + \left(\frac{\hbar}{m_\pi c}\right)^2 V_S \frac{1}{r}\frac{d}{dr}\left(\frac{1}{1+e^{x''}}\right)\vec{l}\cdot\vec{\sigma}$$

Particle	V_0 (MeV)	W_0 (MeV)	W_D (MeV)	V_S (MeV)	r_0 (f)	a (f)	r'_0 (f)	a' (f)	r''_0 (f)	a'' (f)	r_{0C} (f)
Proton [a]	49.95	4.97	5.00	6.04	1.16	0.75	1.370	0.63	1.026	0.738	1.25
Triton [b]	169.6	12.00	···	···	1.14	0.795	1.48	0.824	···	···	1.40
Dineutron	···	···	···	···	1.25	0.650	···	···	···	···	1.25
Neutron	···	···	···	$\lambda=25$ ($\Rightarrow V_S \approx 8.5$)	1.25	0.650	···	···	···	···	1.25

[a] M. P. Fricke, E. E. Gross, B. J. Morton, and A. Zucker, Phys. Rev. 156, 1207 (1967).
[b] G. J. Igo, P. D. Barnes, E. R. Flynn, and P. D. Armstrong, Phys. Rev. 177, 1831 (1969).

TABLE II. States populated through the $^{141}Pr(p,t)$ reaction.

This work Energy (keV)	l value	Radioactivity [a] Energy (keV)	J^π	Classification
0	0	0	$\frac{5}{2}^+$	$(\pi d_{5/2})^1$
···	···	113.8	$\frac{7}{2}^+$	$(\pi d_{5/2})^2(\pi g_{7/2})^{-1}$
405 ± 10	2	405.0	$\frac{3}{2}^+, \frac{1}{2}^+$	$(\pi d_{5/2})^1(2^+)$
590 ± 10	2	589.2	$\frac{5}{2}^+$	$(\pi d_{5/2})^1(2^+)$
···	···	821.8	$\frac{11}{2}^-$	$(\pi h_{11/2})^1$
830 ± 10	2	{828.1	$\frac{7}{2}^+, \frac{9}{2}^+$	$(\pi d_{5/2})^1(2^+)$
		851.9}	$\frac{9}{2}^+, \frac{7}{2}^+$	$(\pi d_{5/2})^1(2^+)$
910 ± 15	2	916.8	$\frac{1}{2}^+, \frac{3}{2}^+$	$(\pi d_{5/2})^1(2^+)$
1010 ± 20	2	1024.0	$\frac{7}{2}^+, \frac{9}{2}^+, \frac{11}{2}^+$	Collective
1330 ± 20	?	{1311.8	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	Collective
		1328.2	$\frac{5}{2}^+$	Collective
		1369.6}	$\frac{9}{2}^+, \frac{11}{2}^+, \frac{13}{2}^+$	Collective
1520 ± 20	?	{1501.2	$\frac{1}{2}^+, \frac{3}{2}^+$	Collective
		1523.2}	(+)	···
1623 ± 20	1, 3	1624.5	$\frac{9}{2}^-, \frac{11}{2}^-$	$(\pi d_{5/2})^1(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$
2050 ± 30	1, 3	2048.8	$\frac{9}{2}^-, \frac{11}{2}^-$	$(\pi d_{5/2})^1(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$
2160 ± 50	3	2174.3	$\frac{9}{2}^-, \frac{11}{2}^-$	$(\pi d_{5/2})^1(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$
≈ 2240	3	···	···	···
≈ 2660	···	···	···	···
≈ 2740	···	···	···	···
≈ 2800	···	···	···	···

[a] Beery, Kelly, and McHarris, Ref. 1.

through $l=1$ and/or $l=3$ transfers. The 1620- and 2050-keV states clearly exhibit an odd-l character; however, unique l assignments cannot be made on the basis of shape alone, since both $l=1$ and $l=3$ angular predictions fit the experimental points equally well. However, because these are relatively low-energy states populated by odd-l waves, their origins can be explained only in terms of an octupole core excitation or a transferred $h_{11/2}$ neutron. The former explanation, of course, immediately eliminates the possibility of any $l=1$ strength in the angular distributions of these states. If, on the other hand, an $h_{11/2}$ neutron participates in the pickup process leading to these excited odd-parity states, then of the possible even-parity orbitals available, energetics alone makes a $d_{3/2}$ neutron the most probable candidate for the second neutron transferred. Assuming this transfer configuration, one finds that of the two possible l values associated with these two states, only the $l=3$ value is allowed by the conservation of angular momentum. This pickup mode, moreover, is consistent with the shell-model configurations assigned to states of similar energy characterized by radioactivity studies.[1,5] The remaining two states appear to exhibit a unique $l=3$ shape, although the limited number of experimental points in these distributions makes these assignments tentative at best.

A comparison of the results of our (p, t) data with the previously described decay-scheme studies appears in Table II. The first thing to be noted is that the l values assigned to the transitions to the various states in ^{139}Pr are in every way consistent with the spin and parity assignments of the corresponding states established through radioactivity studies.

Furthermore, the $l=2$ assignments for the five states listed corroborate the collective vibrational character previously ascribed to them. Since unique spin assignments have not been made for most of these collective states, an attempt was made to clarify this situation through use of the weak-coupling model. Since these states are presumed to be members of a multiplet constructed from the coupling of the $d_{5/2}$ ground state with the first excited 2^+ state of the core, the weak-coupling model would predict the presence of five pure collective excited states with spins ranging from $\frac{1}{2}$ to $\frac{9}{2}$ whose relative cross sections are in a ratio of 1 : 2 : 3 : 4 : 5, respectively, and whose energy center of gravity corresponds to the first 2^+ excitation in the ^{138}Ce nucleus. Although several combinations of these six states would satisfy the latter constraint, the former cross-sectional relationship expected for pure vibrationally excited states cannot be satisfied by any combination of these states, indicating that much configuration mixing must occur.

Finally, as expected, only those excited states corresponding to excited neutron components or core excitations were populated by this reaction. Conspicuously absent are the 113-keV $\frac{7}{2}^+$ and the 821.8-keV $\frac{11}{2}^-$ proton states, even though neutron and core-excited states of similar spin and parity were observed to be strongly populated by this reaction. Nevertheless, the only approximate fits to the data by the DWBA calculations indicate that such calculations are not adequate for this reaction. Although the $l=2$ strengths are not enhanced to the extent found with the (p, t) reaction on even-even deformed rare-earth nuclei,[6,7] it is clear that the reaction mechanism is complex and that higher-order effects and coupled-channel calculations must be invoked even for spherical nuclei.

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[3]DWUCK, written by P. D. Kunz, University of Colorado, and described by E. Rost and P. D. Kunz, Nucl. Phys. A162, 376 (1970); adapted for use on the MSU Cyclotron Laboratory Sigma-7 computer by I. Proctor.

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[7]R. J. Ascuitto, N. K. Glendenning, and B. Sørensen, Phys. Letters 34B, 17 (1971).