

STUDY OF $N = 82$ NUCLEI IN THE REACTION $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$

HELMUT W. BAER and JOHN BARDWICK

*Cyclotron Laboratory, Department of Physics, The University of Michigan,
Ann Arbor, Michigan 48105* †

Received 5 February 1969

Abstract: The ground state of ^{142}Nd and five states of ^{141}Pr have been studied using the reaction $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$ at an incident deuteron energy of 29.0 MeV. In the region 0–3 MeV excitation of ^{141}Pr , five states at energies 0.0, 0.145, 1.12, 1.30 and 1.61 MeV were observed. The absolute differential cross sections determined for these transitions in the angular range 10° – 40° were analysed with conventional distorted-wave calculations using the code DWUCK. Transferred angular momentum values and spectroscopic factors were determined. The excitation spectrum of ^{141}Pr is compared with other recent reaction and decay scheme studies and is discussed in the framework of the quasiparticle description.

A separate determination of the excitation energy of the first excited state was also obtained by measuring the energy of the γ -ray emitted in the decay of this level following its population in the β^- decay of ^{141}Ce . The measurement was performed with a curved-crystal spectrometer and resulted in the value $E_\gamma = 145.450 \pm 0.005$ keV.

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NUCLEAR REACTIONS $^{142}\text{Nd}(d, ^3\text{He})$, $E = 29.0$ MeV; measured $\sigma(E_{^3\text{He}}, \theta)$. ^{141}Pr deduced levels, I, J, π . Enriched target.RADIOACTIVITY ^{141}Ce [from $^{140}\text{Ce}(n, \gamma)$]; measured E_γ .

1. Introduction

As part of a program ¹⁻⁵) at this laboratory to investigate the structure of 82-neutron nuclei we have studied the reaction $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$ at an incident deuteron energy of 29.0 MeV. Although both nuclei, ^{142}Nd and ^{141}Pr , have been studied through β^- and γ -transitions, very little was known regarding the shell-model wave functions for the low-lying states. Since nucleon transfer reactions are well suited for probing shell-model wave functions, the present investigation was undertaken to provide further information on the proton components of these wave functions.

2. Experimental procedure

A 29.0 MeV deuteron beam from The University of Michigan "83-inch sector-focusing cyclotron" was used to bombard metallic foils of natural Nd and enriched ^{142}Nd . Beam currents ranged typically from 0.1 to 0.4 μA with an energy spread of 10–20 keV. The total charge was measured by means of a Faraday cup and integrator. The ^3He ions were analysed with a 180° , $n = \frac{1}{2}$ magnet and detected in

† This work was supported in part by the U. S. Atomic Energy Commission.

nuclear track plates (Ilford, KO, 100 μm) or with a position sensitive detector (Nuclear Diodes, 1.4 cm \times 5.0 cm, 240 μm depletion). Details on the use of this detector for the (d, α) reaction are described in ref. ⁶); its use in the present experiment was similar except that an Al absorber was placed in front of the detector so as to stop the ^3He particles in the detector.

Thin targets of isotopically enriched ^{142}Nd (75 $\mu\text{g}/\text{cm}^2$) and natural Nd (100–400 $\mu\text{g}/\text{cm}^2$) were prepared by evaporating the metal onto carbon backings (50–100 $\mu\text{g}/\text{cm}^2$). Metallic ^{142}Nd was obtained by reducing $^{142}\text{Nd}_2\text{O}_3$ (97.70 % ^{142}Nd) with powdered thorium using a metallothermic technique similar to the one described by Westgaard and Bjørnholm ⁷). To permit transporting the targets in air a thin layer (10 $\mu\text{g}/\text{cm}^2$) of carbon was deposited onto the Nd foil. The target thicknesses were determined by measuring the energy loss of 5.48 and 8.785 MeV α -particles. To determine what fraction of the energy loss was due to the carbon, a separate control carbon foil was used. The absolute differential cross sections of the transitions to the lowest two states were measured using a natural Nd target since these could be prepared with greater uniformity. The cross sections for the three weaker transitions were determined relative to the ground state transition using an enriched target.

3. Experimental results and distorted-wave analysis

A ^3He spectrum obtained at a laboratory angle of 40° using an enriched ^{142}Nd target is shown in fig. 1. The line widths (FWHM) are approximately 50 keV. The presence of ^{14}N on the target resulted in the broad out of focus group at 100 mm which moved across the three adjacent weak groups at angles between 19° and 28° thus removing several points from each of the three angular distributions. An upper limit on the cross sections for transitions other than the five shown in fig. 1 leading to states in the excitation region 0–3.0 MeV can be placed at 10 $\mu\text{b}/\text{sr}$ within the angular range 20 – 40° .

The measured excitation energies corresponding to the five observed transitions are given in column 1 of table 1. The energies were determined by adjusting the magnetic field of the analyser so as to place each of the groups near the optic axis, thus reducing the error due to uncertainty in the dispersion of the magnet. The energy uncertainties given in the table result from the uncertainty in the dispersion and in the uncertainty in determining the peak centroids.

An independent measurement of the excitation energy of the first excited state was obtained by measuring the energy of the γ -ray emitted in the decay of this level following its population in the β^- decay of ^{141}Ce . The UM 2 meter curved-crystal spectrometer ⁸) with Ge(022) crystal was employed. Radioactive ^{141}Ce was obtained by irradiating Ce_2O_3 with thermal neutrons in the UM reactor. A series of 11 measurements in first through fifth order diffraction resulted in the value $E_\gamma = 145.450 \pm 0.005$ keV.

The experimental angular distributions together with the distorted-wave predictions

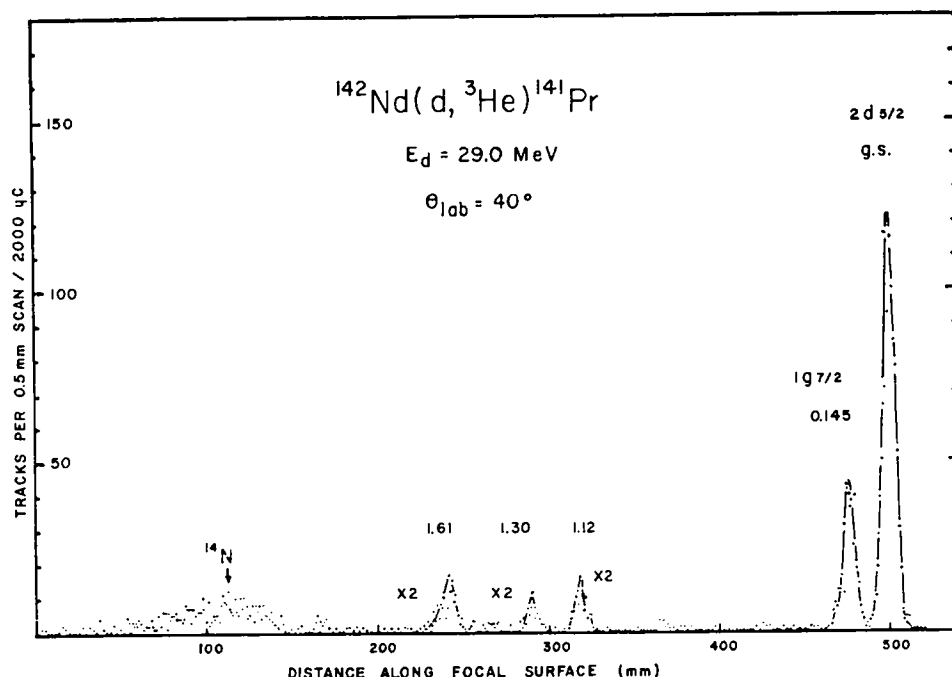


Fig. 1. A ^3He spectrum at 40° from the reaction $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$. The excitation energies in ^{141}Pr are given in MeV.

TABLE 1
Excitation energies and spectroscopic factors for the reaction $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$

Excitation energy (MeV)	Assumed orbit	$S(j)^a$	$(2j+1)^{-1}S(j)$	BCS Theory (Rho)	
				v_j^2	$E_j - E_{\frac{1}{2}}(\text{MeV})$
0	$2d_{\frac{5}{2}}$	2.53	0.422	0.40	0
0.14 ± 0.01	$1g_{\frac{7}{2}}$	6.28	0.786	0.77	0.10
1.12 ± 0.03	$1h_{\frac{9}{2}}$	0.74	0.062	0.093	0.50
1.30 ± 0.03	$3s_{\frac{1}{2}}$	0.11	0.060	0.042	1.41
1.61 ± 0.03	$2d_{\frac{3}{2}}$	0.35	0.088	0.067	1.20

^a) Overall normalization determined by requiring $\sum_j S(j) = 10$.

are displayed in fig. 2. The error bars on the data points represent the uncertainties due to counting statistics and background subtractions. The largest systematic error in the cross section determination is expected to be in the measurement of target thickness; this error is estimated to be $\pm 20\%$. The angular distributions for the two stronger transitions were obtained with the position sensitive detector; data for the three weaker transitions were recorded with nuclear emulsions.

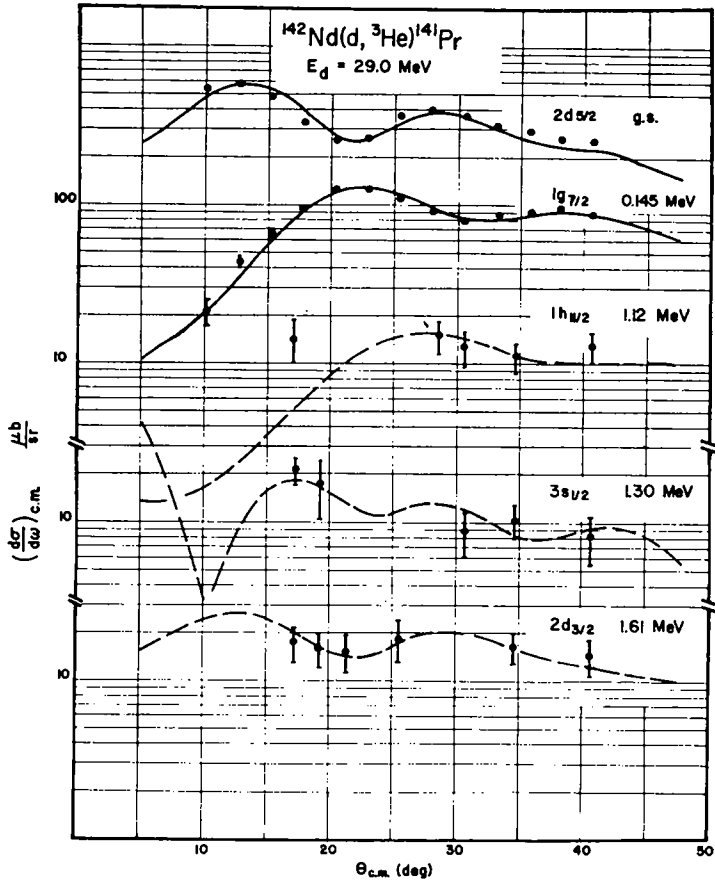


Fig. 2. Differential cross sections and local, zero-range distorted-wave predictions for transitions to states in ^{141}Pr observed in the reaction $^{142}\text{Nd}(d, {}^3\text{He})^{141}\text{Pr}$.

TABLE 2

Optical-model and bound-state well parameters used in the distorted-wave analysis of the reaction $^{142}\text{Nd}(d, {}^3\text{He})^{141}\text{Pr}$

Reaction	V_0 (MeV)	r_0 (fm)	a (fm)	r_C (fm)	$V_{s.o.}$ (MeV)	W_0 (MeV)	$4W_D$ (MeV)	r'_0 (fm)	a' (fm)
$d + {}^{142}\text{Nd}$ ^{a)}	100.4	1.119	0.814	1.30	7	0	63.2	1.244	0.861
${}^3\text{He} + {}^{141}\text{Pr}$ ^{b)}	170.0	1.140	0.723	1.40	0	17.4	0	1.600	0.810
$p + {}^{141}\text{Pr}$ ^{c)}		1.240	0.650	1.25	$\lambda_p = 25$				

^{a)} Obtained from the average parameters determined by Newman *et al.* ¹¹⁾ from 34.4 MeV deuteron elastic scattering.

^{b)} Correspond to the standard parameters determined by Gibson *et al.* ¹²⁾ for ${}^3\text{He}$ elastic scattering on ${}^{90}\text{Zr}$ at 43.7 MeV.

^{c)} The bound-state well depths were adjusted to reproduce the proton separation energies from the various levels. Spin-orbit coupling of λ_p times the Thomas term was used. The value $\lambda_p = 25$ corresponds to $V_{s.o.} \approx 8.5$ MeV.

A conventional distorted-wave analysis of the differential cross sections was performed using the University of Colorado code DWUCK⁹⁾. The validity of such an analysis for the (d, ${}^3\text{He}$) reactions has been discussed by Hiebert *et al.*¹⁰⁾. The optical potential and bound state parameters used in the calculation are given in table 2. The deuteron potential parameters were determined from the average sets obtained by Newman *et al.*¹¹⁾ and the ${}^3\text{He}$ potential parameters from the standard parameter set derived by Gibson *et al.*¹²⁾. The bound-state potential parameters are the ones used in the analysis of the (d, ${}^3\text{He}$) reaction on ^{144}Sm and ^{138}Ba reported by Wildenthal *et al.*¹³⁾. Although these authors did not list the optical model parameters used in their analysis, they cite the same references as in the present analysis. Thus a direct comparison of spectroscopic factors for the various $N = 82$ nuclei should be possible.

The spectroscopic factors S_j were extracted from the differential cross sections $d\sigma/d\omega$ using the relation

$$\frac{d\sigma}{d\omega} = 29.5 S_j \frac{\sigma_j(\theta)}{2j+1} \text{ mb/sr},$$

where $\sigma_j(\theta)$ are the reduced cross sections calculated by the code DWUCK⁹⁾. The normalization is due to Bassel²⁰⁾.

The effect on the angular distributions and spectroscopic factors of lower cut-offs (LCO) in the radial integrals was investigated for the local, zero-range (L/ZR) calculations. The reduced cross sections for $2d_{\frac{1}{2}}$ and $1g_{\frac{7}{2}}$ proton pick-up using values LCO = 0 and LCO = 8.0 fm are shown in fig. 3. Also shown are the results of non-local finite-range (NL/FR) calculations. The latter were calculated in the local energy approximation in the manner discussed by Hiebert *et al.*¹⁰⁾. The range parameter R was taken to be 1.54 fm for the calculations and the non-locality parameters for the deuteron and ${}^3\text{He}$ potentials were 0.54 fm and 0.3 fm, respectively. The bound-state wave functions did not include corrections for non-locality. From the curves shown in fig. 3 one can see that the shapes of the angular distributions for angles up to 70° are very similar for the NL/FR and L/ZR calculations without cut-offs. The L/ZR calculations with an 8.0 fm cut-off result in a small reduction in the ratio of the first to second maximum and a shallower minimum. These effects gave an improved fit to the experimental $l_p = 2$ and $l_p = 4$ angular distribution and therefore these curves were used for the extraction of spectroscopic factors. The effects of using other cut-off radii were examined, but the values near 8 fm resulted in the best fits. The variations in the spectroscopic factors that result from using the different calculations can be estimated from fig. 3. The difference in spectroscopic factors for L/ZR calculations with LCO = 0 and LCO = 8 fm is less than 10%. The difference in the L/ZR and NL/FR calculations without cut-offs is approximately 25%.

Comparison of the experimental and calculated angular distributions shows the l values to be uniquely determined as $l_p = 2$ and $l_p = 4$ for the transitions to the

ground and 0.145 MeV states in ^{141}Pr , respectively. This is consistent with the known spin-parity values $\frac{5}{2}^+$ and $\frac{7}{2}^+$ for these two states ¹⁴⁾. Due to the small cross sections and the presence of target impurities, the l -values for the transitions to the 1.12, 1.30 and 1.61 states could not be determined, nor can the presence of weaker groups

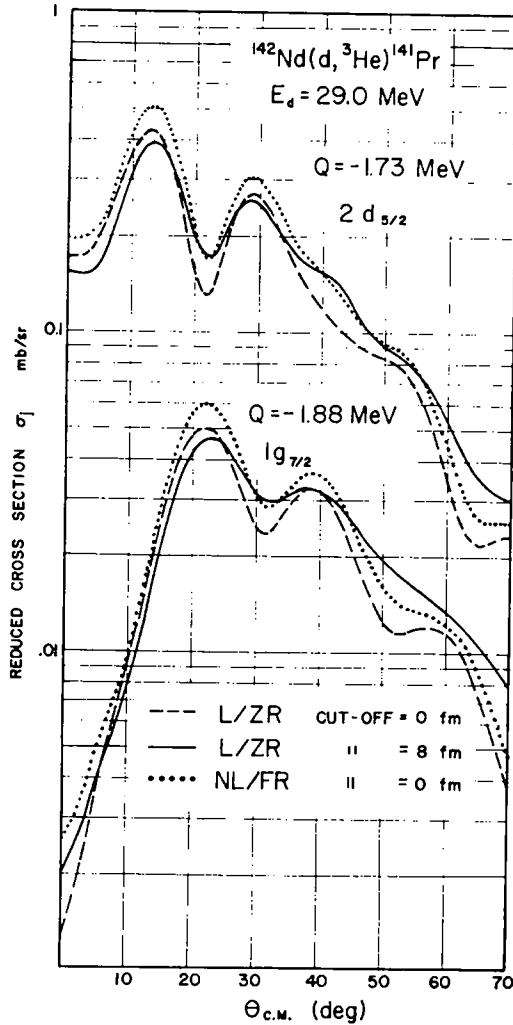


Fig. 3. Comparison of non-local, finite-range (NL/FR) with local, zero-range (L/ZR) distorted wave calculations for proton-pickup reactions with $l_p = 2$ and $l_p = 4$.

within 50 keV be ruled out. However the systematics of this region ^{13,15)} and the fact that states at these excitations are populated in the $^{140}\text{Ce}(^3\text{He}, d)^{141}\text{Pr}$ reaction with $l_p = 5, 0$, and 2 transfers ¹⁶⁾ suggest that these three transitions correspond to pick-up of $1h_{7/2}$, $3s_{1/2}$, and $2d_{3/2}$ protons. Assuming these orbits, the spectroscopic

factors are listed in column 3 of table 1. The uncertainties in the spectroscopic factors resulting from the comparison of the distorted-wave curves with the data are $\pm 10\%$ for the two strong transitions and approximately $\pm 30\%$ for the three weak transitions. The overall normalization was determined by requiring the sum of the spectroscopic factors to be 10. The renormalization factor required by this condition was 0.83.

4. Discussion of results and comparison with other data

A comparison of the excitation spectrum of ^{141}Pr as observed through various reaction $^{16,17})$ and decay scheme studies $^{14})$ together with a theoretical spectrum $^{18})$

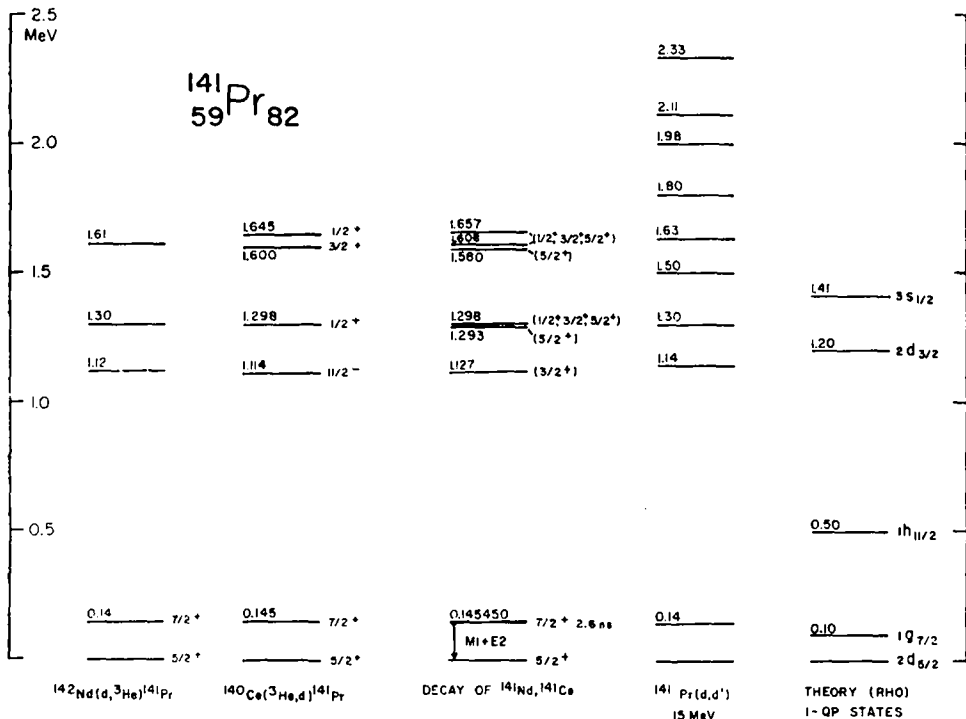


Fig. 4. Comparison of the excitation spectrum of ^{141}Pr observed through various reaction $^{16,17})$ and decay scheme $^{14})$ studies and as calculated $^{18})$ using the quasiparticle (qp) description.

for one quasiparticle states shown in fig. 4. In all four experimental studies the only excited state observed up to 1.1 MeV excitation was the 0.145 MeV level. In the region 1.1–1.7 MeV the various experiments indicate the presence of at least eight levels. The levels above 1.7 MeV have so far been observed only through the $^{141}\text{Pr}(d, d')$ reaction $^{17})$.

It is interesting to interpret the results of the proton transfer experiments in the framework of the quasiparticle (qp) description. In this description one expects the

proton transfer reactions to connect the ground states of even- Z , $N = 82$ nuclei with the 1-qp components of states in adjacent odd- Z nuclei. For the pickup reaction one has $^{19)} \sum_m S_j^m = (2j+1)v_j^2 = \langle n_j \rangle$ and for the stripping reaction $^{19)} \sum_m S_j^m = u_j^2$. The v_j^2 and u_j^2 are the pair-occupation and non-occupation probabilities, respectively, for protons in orbit j in the ground state of the even- Z nucleus, and $\langle n_j \rangle$ is the average number of such protons in the ground state.

The pair-occupation probabilities $S_j/(2j+1)$ for the ground state of ^{142}Nd determined in the present experiment are given in column 4 of table 1. In columns 5 and 6 we give the theoretical occupation probabilities and energies calculated by Rho $^{18)}$. The agreement between theoretical and experimental occupation probabilities is quite good; the calculated excitation energies do not agree as well.

The concentration of the $l_p = 2, 4, 5$, and 2 strengths in both the $^{142}\text{Nd}(d, ^3\text{He})^{141}\text{Pr}$ and $^{140}\text{Ce}(^3\text{He}, d)^{141}\text{Pr}$ reaction is interpreted as indicating that the levels g.s. ($\frac{3}{2}^+$), 0.145 MeV ($\frac{7}{2}^+$), 1.12 MeV ($\frac{11}{2}^-$), and 1.61 MeV ($\frac{3}{2}^+$) are nearly pure 1-qp excitations. The relative purity of the $2d_{\frac{3}{2}}$ and $1g_{\frac{7}{2}}$ 1-qp states might be expected since they are isolated by 1 MeV from other levels. The purity of the $1h_{\frac{9}{2}}$ 1-qp state also appears plausible on the basis of the negative parity and high spin value. However, the absence of fragmentation of the $2d_{\frac{3}{2}}$ strength is remarkable since the high excitation energy of this state (1.61 MeV) places it in the region of many other states, and thus one might expect some mixing. In the reaction $^{138}\text{Ba}(^3\text{He}, d)^{139}\text{La}$ the $2d_{\frac{3}{2}}$ strength is spread over a minimum of five states $^{13)}$.

The splitting of the $l = 0$ strength between states at 1.298 MeV ($\frac{1}{2}^+$) and 1.645 MeV ($\frac{1}{2}^+$) in the $^{140}\text{Ce}(^3\text{He}, d)^{141}\text{Pr}$ reaction indicates a coupling of the $3s_{\frac{1}{2}}$ qp to another type of excitation, possibly a 3-qp configuration involving the $1g_{\frac{7}{2}}$ and $2d_{\frac{3}{2}}$ orbits. The energy difference between the lowest 3-qp states and the lowest 1-qp states is expected to be about 1.5 MeV since in neighboring even nuclei the separation between the lowest 2-qp states and the 0-qp state is of this order.

The study $^{14)}$ of the decay $^{141}\text{Nd} \rightarrow ^{141}\text{Pr}$ indicates the presence of levels in the 1.1–1.7 MeV region not observed or resolved in the reaction experiments. The levels 1.127 MeV ($\frac{3}{2}^+$), 1.293 MeV ($\frac{5}{2}^+$), and 1.580 MeV ($\frac{3}{2}^+$) do not appear to be strongly populated in the $^{140}\text{Ce}(^3\text{He}, d)^{141}\text{Pr}$ reaction. This suggests that they are 3-qp states. The $\frac{11}{2}^-$ level at 1.114 MeV seen in both reaction experiments is not populated in the decay of ^{141}Nd . One might expect the 1.114 MeV state to be populated directly from the $\frac{11}{2}^-$ isomeric state in ^{141}Nd since this would be an allowed Fermi transition. However, since the $1h_{\frac{9}{2}}$ proton occupation probability in ^{141}Pr is so small ($v^2(1h_{\frac{9}{2}}) = 0.06$) this β -transition is expected to be hindered.

The levels at 1.298, 1.608, and 1.657 MeV seen in the decay of ^{141}Nd probably correspond to the levels at very nearly the same energies seen in the transfer reactions. The spin-parity values compatible with all data are $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{1}{2}^+$, respectively.

The authors are grateful to P. D. Kunz of The University of Colorado for making available the distorted-wave code DWUCK and to K. Erb for making the modifica-

tions needed for its use on the Michigan IBM 360/67 computer. We also wish to thank Professors W. S. Gray and K. T. Hecht for many helpful discussions. The very capable assistance of the Cyclotron operating staff under the direction of W. E. Downer is gratefully acknowledged.

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