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Three-Quasiparticle States in ^{139}La†

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Absolute differential cross sections of transitions to levels in the $N = 82$ nucleus ^{139}La populated by the reaction ^{138}La$(d,p)^{139}$La at 12-MeV bombarding energy have been measured with a magnetic spectrograph. The Q value of the reaction is 6553 ± 3 keV. The reaction strongly populates the one-quasiproton ground state of ^{139}La by $l = 2$ neutron transfer, which establishes positive parity for the ^{138}La ground state. Of the many known states in the region from 1200 to 2000 keV in ^{139}La, only the 1536.3-keV state is weakly populated. The reaction strongly populates a high density of three-quasiparticle states in ^{139}La, beginning at 3355-keV excitation energy, by $l = 3$ neutron transfer. The shell-model multiplet structure of ^{139}La has been calculated using a modified surface δ interaction within a configuration space having $(1g_{7/2})$ and $(2d_{5/2})$ active proton orbitals and $(3s_{1/2})$, $(2d_{3/2})$, $(2f_{7/2})$, and $(3p_{3/2})$ active neutron orbitals. Comparisons between experimental and theoretical multiplet structure are presented.

INTRODUCTION

Opportunities to observe well-defined three-quasiparticle structure in nuclei are rare. Only in a few extraordinary cases can radioactive decay be expected to populate three-quasiparticle states above the pairing-energy gap.[1] Excitation of three-quasiparticle states by single-nucleon stripping in charged-particle reactions requires a stable odd-odd target adjacent to closed nucleon shells or subshells. The present research was motivated by the unique possibility, afforded by the minute natural abundance of ^{138}La, to populate highly excited three-quasiparticle states in the $N = 82$ nucleus ^{139}La by the ^{138}La$(d,p)^{139}$La reaction.

^{139}La is a near neighbor of nuclei in which three-quasiparticle states may be populated in radioactive decay,[1] and it is instructive to compare the experimental multiplet structure. Furthermore, ^{139}La is a stable nucleus whose low-energy spectrum has been thoroughly investigated by a number of different experimental methods: high-resolution γ spectroscopy of transitions in the decay[2] of ^{139}Ba, Coulomb-excitation experiments,[3] population of proton states by the ^{138}Ba$(^3\text{He},d)^{139}$La reaction,[4] and photoexcitation.[5] These papers contain references to earlier work on ^{139}La. It is important to compare neutron states populated by the ^{138}La$(d,p)^{139}$La reaction with other information on the structure of ^{139}La, particularly in regard to the possible mixing of three-quasiparticle components with vibrational states below the energy gap.

EXPERIMENTAL METHOD

The natural isotopic abundance of ^{138}La is about 0.09%. La_2O_3 isotopically enriched to 7% ^{138}La was purchased from the Oak Ridge National Laboratory. A target of essentially 100% isotopically pure ^{138}La was then fabricated using the Florida State University isotope separator. Accelerated ions of mass-to-charge ratio 138 were magnetically selected and deposited on a thin carbon backing mounted on an aluminum frame. The target spot was elliptical in shape, about $1\frac{1}{2} \times 3$ mm. The average thickness of the ^{138}La target spot was measured by deuteron elastic scattering to be about 10 μg/cm^2; whereas the carbon backing was about 50 μg/cm^2 thick.

The ^{138}La target was bombarded by a 12.0-MeV deuteron beam from the Florida State University EN tandem Van de Graaff accelerator. The deuteron beam was collimated by $\frac{1}{4} \times 3$ mm slits in front of the target and finally collected in a Faraday cup. Beam current on target was generally between 0.5 and 1.0 μA. The reaction products were analyzed in a single-gap Browne-Buechner magnetic spectrograph[6] and recorded on an array of three 5×25-cm, 50-μ-thick, nuclear emulsion plates clamped along the focal plane of the spectrograph. These plates were covered with 0.008-in.-thick aluminum foil to stop scattered deuterons (except for a cut-away portion over part of one plate zone to accept elastically scattered deuterons). After plate development, proton tracks were counted in $\frac{1}{2}$-mm strips under microscopes equipped with calibrated stages.

The ^{138}La$(d, d)^{138}$La elastic scattering cross section for 12.0-MeV deuterons was measured using the magnetic spectrograph at 12 reaction angles from 30 to 120°. The target positioning and deuteron beam trajectory were unchanged between runs. The cross sections were normalized to the Coulomb scattering cross section at 30°, and the 30° run was repeated several times during the course of the angular-distribution measurement to check against any change in the average target thickness exposed to the deuteron beam.

The ^{138}La target spot was positioned by careful alignment with a telescope previously fixed on the position of a beam spot burned in a paper target. A short deuteron elastic scattering run was taken before each (d,p) run, under identical geometry and target positioning. Then absolute differential cross sections for the (d,p) reaction at each reaction angle were calculated by spectral-peak-area proportionalities, normalized to the difference in exposure for the (d, d) and (d,p) runs as determined by the beam current integrator.

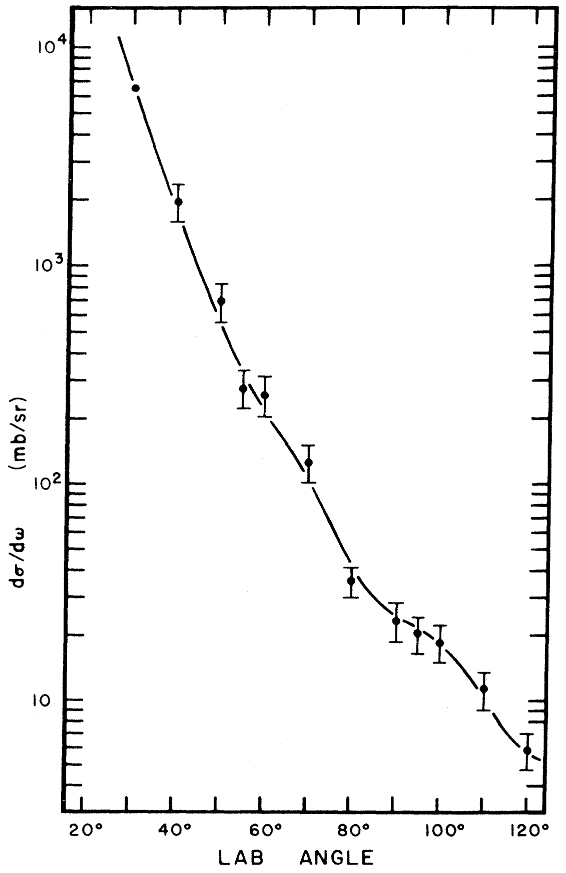

FIG. 1. ^{138}La$(d,d)^{138}$La elastic scattering cross-section angular distribution, for 12.0-MeV deuterons, with fitted optical-model curve. The angular distribution is normalized to the Coulomb scattering cross section at 30°. The error bars arbitrarily represent 20% probable error in the average target thickness.

Spectral peak positions and areas were extracted by a computer code which made a least-squares fit of the proton spectra to Gaussian functions. A short (d,p) exposure was taken at each angle to determine the position of the intense ^{12}C$(d,p)^{13}$C ground-state peak. Then the positions of the ^{12}C$(d,p)^{13}$C and ^{13}C$(d,p)^{14}$C ground-state peaks were inserted into a kinematic code, using tabulated Q values for these reactions,[7] to compute precisely the average deuteron beam energy and spectrograph magnetic field for that (d,p) run. These calibration values were inserted into another kinematic code used to compute Q values, excitation energies, and absolute cross sections and to identify impurity peaks.

RESULTS

The ^{138}La$(d, d)^{138}$La elastic scattering cross section angular distribution data are plotted in Fig. 1. The error bars arbitrarily represent 20% probable error in the average target thickness (statistical error is negligible). The curve represents an optical-model cross-section calculation fitted to the data by the computer code ABACUS-2.[8] Beginning with optical-model parameters for 12.0-MeV deuterons taken from the survey of Perey and Perey,[9] the code ABACUS-2 varied the real and surface imaginary Woods-Saxon potential well depths to obtain the best statistical fit (using no spin-orbit potential) to the experimental data. An upper cutoff radius of 16 F was used. The fitted optical-model parameters for 12.0-MeV deuterons are given in Table I. Elastic scattering cross sections given by the fitted curve were used in the calculation of absolute differential cross sections for the ^{138}La$(d,p)^{139}$La reaction.

The ^{138}La$(d,p)^{139}$La reaction spectrum was measured at 45, 65, 72, 78, and 92°. The range of reaction angles was restricted at forward angles by the intense ^{13}C peak kinematically shifting into and obscuring the ^{139}La three-quasiparticle region. At angles larger than 90°, the $l = 3$ and $l = 1$ angular distributions are not distinctively different, and the combination of very thin target and very small cross sections necessitates prohibitive exposures.

TABLE I. Optical-model parameters.

	12.0-MeV Deuterons	18.5-MeV Protons	15.0-MeV Protons
Depth of real potential (MeV)	64.0	51.5	54.0
Nuclear radius of real potential and charge radius (F)	1.25	1.25	1.25
Diffuseness of real potential (F)	0.87	0.65	0.65
Depth of surface imaginary potential (MeV)	12.0	18.0	16.0
Nuclear radius of imaginary potential (F)	1.37	1.25	1.25
Diffuseness of imaginary potential (F)	0.7	0.47	0.47

The reaction spectrum at 78° is plotted in Fig. 2. The over-all energy resolution for this spectrum is about 11-keV full width at half maximum (FWHM). The target impurities, identified by their kinematic shift with changing reaction angle, are ^{28}Si and ^{56}Fe, in addition to carbon and oxygen.

The reaction spectrum, at each of the five reaction angles, was analyzed over the excitation energy range from ground state to 4400 keV. The data for higher excitation energies were obscured by the ^{13}C peak at 45°. Peaks Nos. 7 and 8 were used to determine the line width for fitting Gaussian functions to two or more unresolved peaks in the process of extracting peak areas and centroids.

The experimental excitation energies and absolute differential cross sections for the reaction ^{138}La$(d,p)^{139}$La are given in Table II, with peak numbers corresponding to Fig. 2. For the excitation energies, we assign a probable error of 2 keV for all levels above 3300 keV on the basis of the deviations of single values at different angles from the average value. The statistical probable error is given below each cross section. Only those peaks which clearly reproduce from one angle to another are listed in Table II.

The ground-state Q values at different reaction angles for the ^{138}La$(d,p)^{139}$La reaction fall within 3 keV of the weighted average value, with the exception of the 78° value which deviates by 4 keV. We report $Q = 6553 \pm 3$ keV. This gives a binding

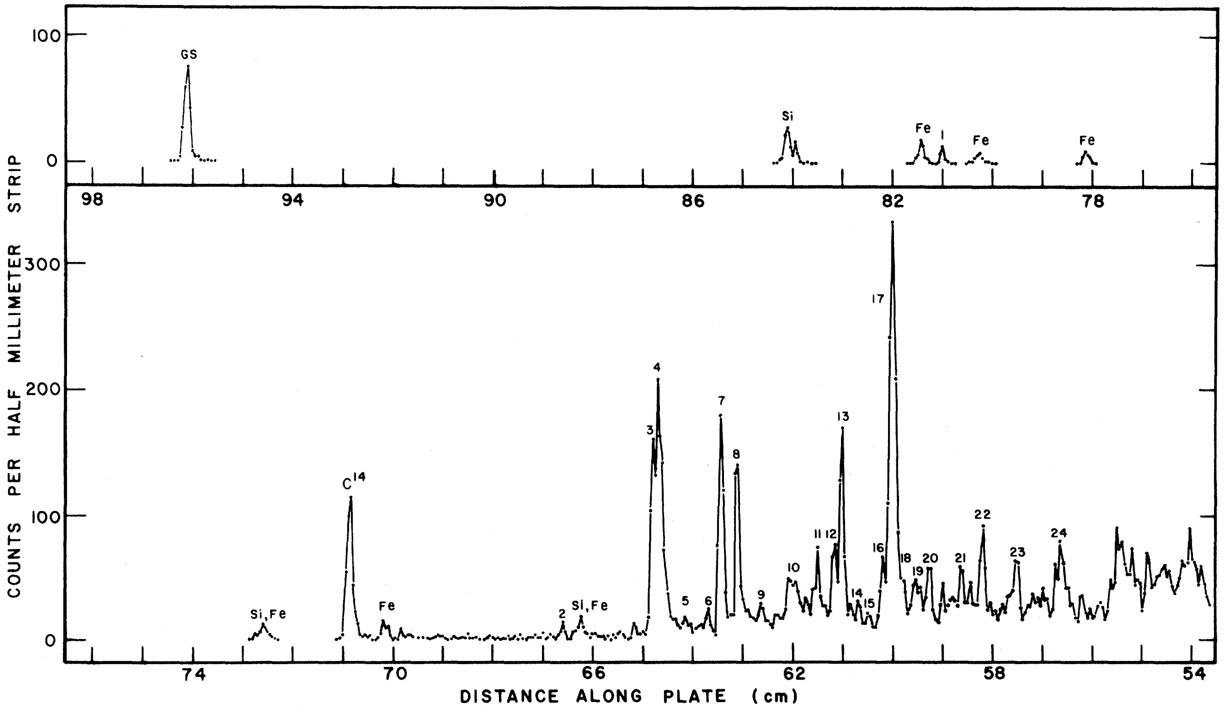

FIG. 2. Proton spectrum for the reaction ^{138}La$(d,p)^{139}$La at 12.0-MeV bombarding energy and lab reaction angle 78°. Exposure is 21 200 μC

TABLE II. ^{138}La$(d,p)^{139}$La level energies (keV) and differential cross sections (μb/sr). The statistical probable error is given below each cross section. The probable error in excitation energy is 4 keV for level Nos. 1 and 2, and 2 keV for the remaining levels. Where noted, the listed cross section represents the summed strength of unresolved levels, or possibly contains a contribution from excited states of target impurities observed in the energy gap.

Level energy		Differential cross section					Comments
		45°	65°	72°	78°	92°	
g.s.	0	277	71	81	103	58	
		14	8	9	7	9	
1	1535	17	31	13	12	13	^{57}Fe at 65°
		3	5	8	2	4	
2	3147	21	11	18	14		^{57}Fe at 72°
		3	3	4	2		
3	3355	384	159	140	127	166	^{24}Na at 78°
		15	11	11	7	14	
4	3375	621	406	274	260	220	^{29}Si, ^{57}Fe at 65°
		19	17	16	10	16	
5	3433	33	38	9	11	14	^{29}Si at 92°
		4	5	3	2	4	
6	3485	62	39	21	17	22	^{29}Si at 72°
		6	5	4	3	5	^{57}Fe at 65°
7	3517	308	194	141	152	110	
		13	12	11	8	11	
8	3555	267	173	138	120	102	^{57}Fe at 92, 72°
		12	11	11	7	11	
9	3611	47	26	17	20	15	
		5	4	4	3	4	
10	3688	211	137	116	85	107	(doublet)
		11	10	10	6	11	^{57}Fe, ^{24}Na at 92° ^{29}Si at 45°
11	3748	144	77	66	45	47	
		9	8	8	4	8	
12	3785	99	77	45	59	53	^{24}Na at 92°
		7	8	6	5	8	
13	3805	404	202	143	139	141	
		15	12	11	7	13	
14	3841	32		17	16	28	
		4		4	3	6	
15	3868	19	24	32	7	12	
		3	4	5	2	4	
16	3905	118		47	43	29	
		8		6	4	6	
17	3927	948	543	402	339	348	
		23	20	19	12	20	
18	3952	128		59	63	38	
		8		7	5	7	
19	3980	174	94	66	53	68	(doublet)
		10	8	8	5	9	^{29}Si at 65°
20	4014	117	82	51	44	47	
		8	8	7	4	7	
21	4095	108	66	47	41	34	^{24}Na at 45°
		8	7	6	4	6	
22	4148	139	86	60	66	68	
		9	8	7	5	9	
23	4230	87	48	30	44	32	^{24}Na at 78°
		7	6	5	4	6	
24	4336	244	78	94	72	88	(doublet)
		11	8	9	5	10	
25	4394	29	15	9	12	34	
		4	3	3	2	6	

energy $B_n = 8778 \pm 4$ keV for the last neutron in ^{139}La, which lies within the error range of the tabulated value.[7]

The angular distribution of the transition to the ^{139}La ground state is plotted in Fig. 3, and the angular distributions of a number of the stronger transitions above the energy gap are shown in Fig. 4, with distorted-wave Born-approximation (DWBA) fitted curves. The DWBA code DWMAIN[10] was used to fit the angular distributions. Optical-model parameters for 18.5- and 15.0-MeV protons were taken from the survey of Perey[11] and varied slightly to best fit the data. The parameters used are given in Table I.

DISCUSSION

The 5+ ground state of the ^{138}La target is expected, from the systematics of neighboring nuclei,[12] to be predominantly the $(\pi g_{7/2})^{-1}$ $(\nu d_{3/2})^{-1}$ configuration. The $\frac{7}{2}$+ one-quasiproton ground state of ^{139}La is populated by $l = 2$ neutron stripping in the ^{138}La$(d,p)^{139}$La reaction (see Fig. 3). However, this reaction gives no evidence of the well-known 166-keV state in ^{139}La, identified as the $d_{5/2}$ one-quasiproton state.[4] Failure to observe the 166-keV state precludes any appreciable component of $(\pi g_{7/2})^{-2}$ $(\pi d_{5/2})^{1}$ coupled to a $g_{7/2}$ or $d_{5/2}$ neutron hole in the ground state of ^{138}La.

The assignment of positive parity to the ground state of ^{138}La stands in contradiction to the 5− assignment in the *Table of Isotopes*[12] based on log*ft* values of the decay of ^{138}La to 2+ first-excited states in ^{138}Ba and ^{138}Ce. The log*ft* values of approximately 18 suggest third-forbidden β transitions. However, a 5+ ground state is predicted by shell-model calculations using even-parity active neutron orbitals (as described below), and the

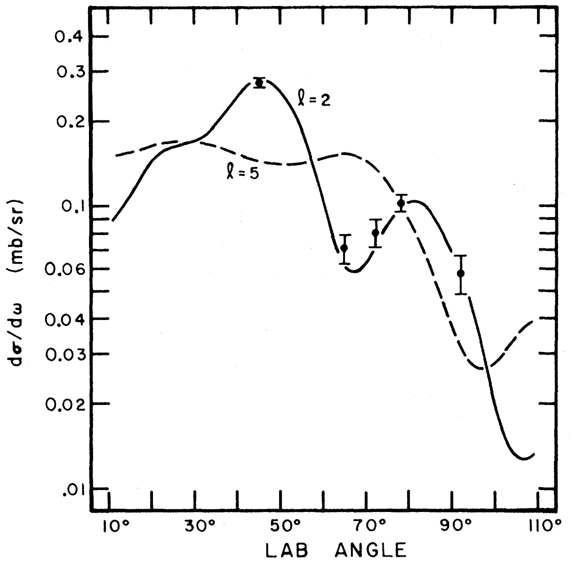

FIG. 3. ^{138}La$(d,p)^{139}$La ground-state reaction cross-section angular distribution at 12.0-MeV bombarding energy with DWBA curves for $2d_{3/2}$ or $1h_{11/2}$ neutron transfer.

positive-parity assignment is required by the $l=2$ angular distribution of the ^{138}La$(d,p)^{139}$La ground-state transition (see Fig. 3). Kisslinger and Wu[13] have shown that hindered first-forbidden β transitions from the ground state of odd-odd nuclei, in the region $50 \leq Z \leq 60$, to first-excited quadrupole vibrational daughter states result from cancellation of the $\int B_{ij}$ matrix element due to particle-phonon coupling. The unusually large logft value of the second-forbidden β decay of ^{138}La is probably to be understood in terms of the same mechanism.

The ^{138}La$(d,p)^{139}$La reaction spectrum (see Fig. 2) reveals an unusually large energy gap extending from the ground state to above 3 MeV. The large gap presumably results from the closed-neutron-shell nature of ^{139}La. Most of the peaks appearing in this region in our data are identified as impurity levels from their kinematic shift with changing reaction angle. Only the very weak peaks No. 1, at 1535 ± 4 keV (which coincides with a ^{139}La state at 1536.3 keV observed in the decay[2] of ^{139}Ba), and No. 2, at 3147 ± 4 keV, reproduce from one reaction angle to another and appear to be ^{139}La levels. The failure to observe the other well-known ^{139}La states in the region of 1200 to 2000 keV implies the absence of one-proton two-neutron three-quasiparticle components of the type which can be populated in the (d,p) reaction.

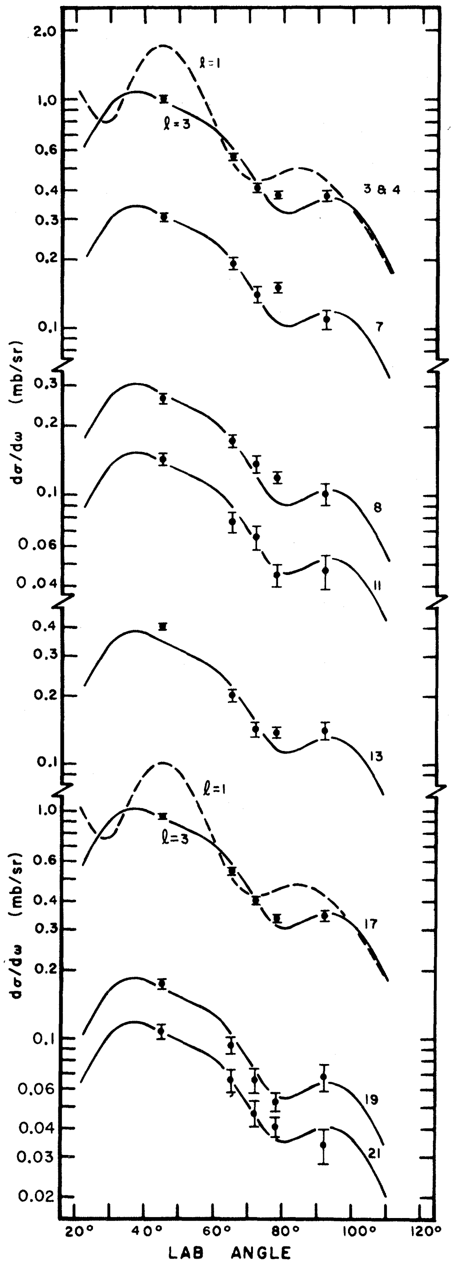

FIG. 4. ^{138}La$(d,p)^{139}$La reaction cross-section angular distributions for transitions to members of the three-quasiparticle multiplet in ^{139}La, as numbered in Fig. 2 and Table II. DWBA curves represent the $l=3$ transitions except where dashed $l=1$ curves are shown for comparison.

The three-quasiparticle states in ^{139}La lie above the energy gap associated with neutron pairing and with the $N=82$ closed neutron shell. The lowest-lying three-quasiparticle states are expected to be populated by stripping an $f_{7/2}$ neutron into ^{138}La. However, the $p_{3/2}$ neutron orbital lies only 600 to 700 keV above the $f_{7/2}$ orbital in ^{139}Ba and ^{141}Ce.[12] Figure 2 shows a high density of levels in ^{139}La beginning with prominent peaks above 3300 keV.

The angular distributions of the transitions to eight of the prominent peaks are shown in Fig. 4

to be well fitted by DWBA curves for $l=3$ transitions. In addition to the levels shown in Fig. 4, the data for level Nos. 6, 9, 10, 12, 16, 18, 20, 22, and 23 indicate pure, or nearly pure, $l=3$ transitions; while level Nos. 24 and 25 appear to have a mixed $l=1$ plus $l=3$ character. The distinction between $l=1$ and $l=3$ transitions is seen, in Fig. 4, to depend heavily on the 45° data. Peak Nos. 12 and 13 are not fully resolved, and the angular distributions indicate that, at 45°, peak No. 12 is fit too small and peak No. 13 too large by about 30 μb/sr.

The multiplet structure of ^{139}La has been calculated in the framework of the spherical shell model within a configuration space having ($1g_{7/2}$) and ($2d_{5/2}$) active proton orbitals and ($3s_{1/2}$), ($2d_{3/2}$), ($2f_{7/2}$), and ($3p_{3/2}$) active neutron orbitals. Complete details of the calculations will be given elsewhere. Briefly, the two-body interactions were calculated using the modified surface δ interaction (MSDI),[14] the single-particle energies were chosen to reproduce known excited levels and ground-state binding energies for nearby nuclei, and the energy matrices were constructed and diagonalized with the Oak Ridge–Rochester Multishell program.[15] The $\frac{7}{2}+$ ground state and $\frac{5}{2}+$ first excited state of ^{139}La were constructed by allowing only the $(g_{7/2})^7{}_{7/2}(d_{5/2})^0{}_0$, $(g_{7/2})^5{}_{7/2}(d_{5/2})^2{}_0$, $(g_{7/2})^3{}_{7/2}(d_{5/2})^4{}_0$, and $(g_{7/2})^6{}_0(d_{5/2})^1{}_{5/2}$, $(g_{7/2})^4{}_0(d_{5/2})^3{}_{5/2}$, $(g_{7/2})^2{}_0(d_{5/2})^5{}_{5/2}$ proton couplings, respectively. The proton-proton MSDI was very similar to that used by Wildenthal in a study of the $N=82$ nuclei.[16] The higher-seniority proton couplings do not contribute significantly to the low-lying states, and we have retained only the six large components listed above to reduce the size of the model space. Levels in ^{138}La were calculated by coupling these proton configurations to the neutron configurations $(s_{1/2})^2{}_0(d_{3/2})^3{}_{3/2}$ and $(s_{1/2})^1{}_{1/2}(d_{3/2})^4{}_0$. The neutron-neutron MSDI interaction was taken to be the same as the proton-proton interaction. The proton-neutron interaction was chosen to reproduce, as well as possible, the multiplets observed in ^{140}La.[17] The ground state of ^{138}La is predicted to be 5^+ in agreement with experiment. In the complete calculation for ^{139}La, the $\frac{7}{2}^+$ and $\frac{5}{2}^+$ levels were calculated by allowing all possible one-particle–one-hole excitations within this neutron space.

TABLE III. Calculated relative intensities for the principal $l=3$ transitions in the reaction ^{138}La$(d,p)^{139}$La.

E^* (MeV)	Spin $2J$	$\frac{2J+1}{11}S$
3.48	15	1.211
3.52	11	0.490
3.54	11	0.218
3.55	9	0.338
3.56	13	0.830
3.57	7	0.085
3.58	5	0.069
3.61	7	0.154
3.61	9	0.169
3.65	5	0.056
3.66	9	0.182
3.67	13	0.286
3.72	7	0.216
3.73	11	0.296
3.77	7	0.130
3.80	15	0.141
3.81	17	1.634
3.83	5	0.055
3.90	5	0.204

For this restricted model space there are 375 negative-parity levels in ^{139}La with spins ranging from $\frac{1}{2}$ to $\frac{17}{2}$. Only the $\frac{1}{2}^-$ levels cannot be populated by transfer of an $f_{7/2}$ neutron with the stripping reaction on the 5^+ ground state of ^{138}La. The neglect of the deeper-lying neutron orbitals ($2d_{5/2}$) and ($1g_{7/2}$) seems justified by the failure to observe any stripping strength to the $\frac{5}{2}^+$ excited level of ^{139}La. Similarly, the higher-seniority proton couplings and the higher-lying proton orbitals are neglected, since they are not expected to contribute significantly to the structure of levels in the region of excitation energy of interest to this study.

Because of the great complexity of the ^{139}La

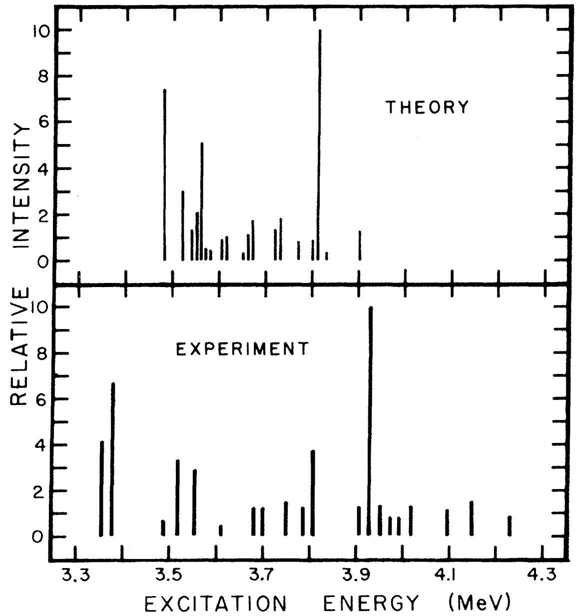

FIG. 5. Comparison of measured and calculated relative intensities of $l=3$ transitions in the reaction ^{138}La$(d,p)^{139}$La. The vertical scales are normalized to unit intensity for the strongest transition.

three-quasiparticle multiplet, only partial results of the calculations are given in Table III, which lists the strongest $l = 3$ transitions to members of the ^{139}La multiplet below 4 MeV. Excitation energies and spins are given along with relative intensities (proportional to $2J+1$ times the calculated spectroscopic factors) for $l = 3$ transfer. The $l = 1$ spectroscopic factors are negligible for levels in this energy region, in qualitative agreement with the experimental angular distributions. For spins $\frac{11}{2}$ through $\frac{17}{2}$, the levels listed in Table III comprise 90% or more of the total strength in $l = 3$ transfer. The strength becomes increasingly fragmented in lower spin states. The data of Table III are plotted in Fig. 5 along with experimental relative intensities.

Detailed comparison of experimental and theoretical distributions of relative $l = 3$ transition intensities shows only minimal similarity (aside from good agreement in the centers-of-gravity) in regard to the strongest levels lying near the extremes of the multiplet. The calculations predict 99.8% of the $\frac{17}{2}$ strength in one level. The strength of this level relative to the total $l = 3$ strength is then 0.20, which equals the relative intensity of peak No. 17 at 3927 keV, if we suppose that the summed strength of the peaks identified as $l = 3$ transitions represents about 95% of the total $l = 3$ strength. We suggest tentative spin assignments of $\frac{17}{2}$ to the 3927-keV peak and $\frac{15}{2}$ to the second strongest peak, No. 4, partially resolved at 3375 keV. With reference to the 3927-keV peak, the 3375-keV peak accounts for 0.75 of the experimental $\frac{15}{2}$ strength, as compared with 0.83 of the $\frac{15}{2}$ strength theoretically predicted in the second strongest level. Further attempts at detailed spin assignments are hardly justified by the nature of the calculations. Although the surface δ interaction usually produces a good qualitative description of the proton-neutron interaction, the detailed level spacings are not reproduced with the degree of accuracy that would be required for a level-by-level comparison in the present case. One important result of the calculation is to indicate the large number of levels expected with the same spin-parity and the high degree of fragmentation of the neutron transfer strength among these levels. This leads to the conclusion that any attempt to correlate observed transfer intensities with level spin on an assumption of $2J+1$ dependence is inappropriate. The calculation also suggests that many of the experimental peaks identified as $l = 3$ transitions involve the superposition, within instrumental resolution, of several spin-state fragments.

CONCLUSION

The reaction ^{138}La$(d,p)^{139}$La strongly populates the one-quasiparticle ground state and three-quasiparticle states beginning just above 3 MeV in ^{139}La. The unusually large energy gap is indicative of the closed-neutron-shell character of ^{139}La. The many known states in ^{139}La having considerable vibrational strength in the region from 1200 to 2000 keV are for the most part not populated in the reaction ^{138}La$(d,p)^{139}$La. This indicates the virtual absence of components of three-quasiparticle states which can be populated in the (d,p) reaction. The one exception to this generalization is the state at 1536.3 keV, which is weakly populated. Qualitative comparison between experiment and a modified surface-δ-interaction calculation reveals similarity in the three-quasiparticle multiplet, but a detailed comparison appears to require a more sophisticated theoretical treatment.

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Collective States in the $N = 82$ Nuclide ^{141}Pr Excited by the (α, α') Reaction at 45 MeV*

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The ^{141}Pr(α, α') reaction at $E_\alpha = 45.0$ MeV and $\Delta E_{\alpha'} \approx 35$ keV was studied to investigate the particle-vibration interaction in this $N = 82$ nuclide and to elucidate the ^{141}Pr level structure in the 0–4-MeV region. The α-particle angular distributions were measured in ≤2° steps over ranges of 7–80° for elastic scattering and 12–66° for inelastic scattering. A ^{141}Pr(d, d') spectrum at $E_d = 28.7$ MeV and with higher resolution (20 keV) was also recorded. These measurements, in combination with other high-resolution studies, establish the existence of approximately 50 levels with excitation energies of 1.1–3.0 MeV. Approximately 20 of these levels can be identified in the (α, α') spectra and are interpreted as states with significant collective components. Although most of these levels are in either a positive-parity group between 1.1 and 1.9 MeV or a negative-parity group between 2.0 and 2.5 MeV, it is found that the assumption of a weak particle-vibration interaction based on the 2^+ and 3^- core states of ^{140}Ce and the $d_{5/2}$ ground state of ^{141}Pr is inadequate to explain the results. Qualitative agreement is found with the results of recent shell-model studies which assumed nine active protons outside an inert $Z = 50$, $N = 82$ core. In addition, some evidence is found for the approximate validity of the $\Delta B = 0$ selection rule for inelastic scattering transitions which was recently proposed by Hecht and Adler.

I. INTRODUCTION

In recent years there has been considerable interest in the study of $N = 82$ nuclei. This interest has been stimulated largely by the hope that the properties of most of the low-lying levels can be described in terms of configurations involving only the protons outside the $Z = 50$ core. The success of the recent shell-model studies performed by Wildenthal,[1] Hecht and Adler,[2] and Jones *et al.*[3] has shown that this assumption provides a reasonable basis for describing some properties of $N = 82$ nuclei. These calculations, which take into account only positive-parity proton excitations, are able to reproduce the main features of the observed excitation spectra up to approximately 2.5 MeV. Moreover, they are in moderately good agreement with the spectroscopic information which has been obtained from recent proton-transfer experiments using the $(d, {}^3\mathrm{He})$, (t, α), and $({}^3\mathrm{He}, d)$ reactions, which have now been performed for each of the seven stable $N = 82$ targets.[3-9]

There were, however, questions which were not resolved by the existing experiments. In the $({}^3\mathrm{He}, d)$ experiments, for example, a single $l = 5$ transition was reported for each of the even-A targets, but with a spectroscopic factor closer to 0.7 than the value near unity expected if the $1h_{11/2}$ proton state is a pure one-quasiparticle (1-qp) state. The reduction in the $l = 5$ spectroscopic strength could be understood if, as has been suggested by Ellegaard *et al.*[7] in the case of ^{141}Pr, the $1h_{11/2}$ 1-qp state mixes strongly with a particle-vibration state based on the coupling of the $2d_{5/2}$ 1-qp state with an octupole vibration of the ^{140}Ce core. While this explanation appeared plausible, there had been no quantitative measurements of the extent of particle-vibration coupling in the $N = 82$ nuclei.

The more general question of the role played by collective excitations in the $N = 82$ nuclei has been little studied. It is known that a collective 3^- state exists at about 2–3 MeV in the even-A nuclei. In ^{140}Ce the 3^- state is at 2.464 MeV and is highly collective.[10,11] Also the $B(E2)$ value measured for the first 2^+ state at 1.597 MeV in ^{140}Ce