Study of ^{101}Rh with the (p, t) reaction*

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The ^{103}Rh(p, t)^{101}Rh reaction has been studied at bombarding energies of 17, 30, and 42 MeV. The 30 MeV data, which was taken with a quadrupole-dipole-dipole-dipole magnet QDDD, provided the most information on the ^{101}Rh spectrum. The (p, t) reaction is apparently exciting ^{101}Rh states which look like a $2p_{1/2}$ proton weakly coupled to states of the ^{100}Ru core. This is suggested by the multiplet structure observed up to about 1 MeV of excitation. Considerable (p, t) strength is observed above 2 MeV of excitation but multiplet structure is not so apparent. Although two of the strong states above 2 MeV may carry expected $L=3$ (p, t) strength, the others are more surprising.

[NUCLEAR REACTIONS ^{103}Rh(p, t), $E=17$, 30, and 42 MeV; measured energy levels, $\sigma(\theta)$; DWBA analysis, deduced L, J, Π. Weak coupling model. Resolution 10 keV for 17 and 30 MeV data.]

INTRODUCTION

The weak coupling model of Lawson and Uretsky[1] has been very useful in furthering our understanding of the spectra of odd-A nuclei. This model, in its simplest form, asserts that a certain class of states in odd-A nuclei arises from coupling the odd particle onto a basically undisturbed state of the $(A-1)$ even-even nucleus. From the coupling of the odd particle of spin J_p with a "core" of spin J_c, one expects a multiplet of states of spin $J=|J_p-J_c|, \cdots, |J_p+J_c|$. The center of gravity of the multiplet, i.e., its $2J+1$ weighted energy centroid, and the splitting between its various members, provide clues concerning the nature of the particle-core interaction.

Should the core state be collective or have some other distinguishing property which the weak coupled state is expected to inherit, then this property may be useful in identifying such states. For instance, the first excited 2^+ state of ^{102}Ru has an enhanced $B(E2)$ transition to the ground state of about 40 times the single particle value.[2] The $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states in ^{103}Rh which presumably arise from coupling a $2p_{1/2}$ proton onto this collective 2^+ state have $B(E2)$'s to the ground state of comparable strength.[3]

A comparison of inelastic (p,p') scattering on ^{107}Ag and ^{109}Ag with that from the collective states of the neighboring even-even Pd isotopes illustrates the success of the weak-coupling approach.[4,5] Arguments that the (p, t) reaction should also favor the excitation of collective states have been advanced by several theorists.[6,7] However, experiments to exploit this expected characteristic of the (p, t) reaction for the identification of weak coupled states have been reported only recently.[8,9]

In this paper we report a study of the ^{103}Rh(p, t) ^{101}Rh reaction.[10] The ground states of ^{103}Rh and ^{101}Rh are both $\frac{1}{2}^-$ states and can be described as arising from a coupling of a $2p_{1/2}$ proton with the even-even ^{102}Ru and ^{100}Ru cores, respectively. If in the (p, t) dineutron pickup reaction the extra proton behaves as a spectator, then the states reached in the residual ^{101}Rh nucleus should correspond to states in ^{100}Ru coupled to a $2p_{1/2}$ proton. These states would occur as singlets or doublets, depending on whether the core spin was zero or nonzero. In the simplest model the (p, t) angular distributions of the two members of the doublet would have identical shapes and magnitudes in the ratio $(2J_1+1)/(2J_2+1)$, where J_1 and J_2 are the spins of the two states.

EXPERIMENTAL PROCEDURES

The ^{103}Rh(p, t)^{101}Rh reaction has been studied at 17, 30, and 42 MeV in different laboratories with different detection systems. The first experiment at the University of Pittsburgh employed a 17 MeV proton beam. Tritons were detected with photographic plates in the focal plane of an Enge split-pole spectrograph with a resolution of 10–12 keV. The plates were hand scanned in 2 mm steps. Targets of about 100 μg/cm^2 were obtained by

TABLE I. Energies (in keV) of states seen in $^{103}Rh(p,t)^{101}Rh$. (Errors apply to subsequent numbers until the next stated error.)

30 MeV	17 MeV	Ref. 15
0	0	0
156 ±2		157.3
305	305 ± 2	305.3
354	353	355.1
849	850	(851.0)
898	898	
977		
966	995	
1057	1058	1057.7
1464 ±8		
	42 MeV	
1531	1550 ±20	
1541		
1569		
1598		
1640		
1689		
1730		
1771		
1813		
1904		
1935		
1960		
1997 } 2009	2009	
2038		
2075		
2087		
2113		
2146 } 2166	2183	
2188		
2225 } 2242	2257	
2292		
2328 } 2352	2351	
2361		
2386	2413	
2455		
2492		
2521	2552	
2577		

vacuum evaporation of ^{103}Rh metal (100% natural abundance) onto thin carbon films. A NaI detector was kept at a fixed angle of 39° in order to monitor the elastic peak. From the known p-elastic cross section at this angle[11] and the solid angles subtended by the monitor and spectrograph apertures, we obtained absolute (p,t) differential cross sections.

Because of the rather negative $^{103}Rh(p,t)$ Q value (−8.275 MeV), tritons in the 17 MeV experiment emerged close to the Coulomb barrier, and the angular distributions for all but the ground state transition were quite structureless. (See Fig. 2.) It seemed appropriate to repeat the experiment at higher bombarding energy. This was accomplished with a 42 MeV proton beam from the Princeton azimuthally varying field cyclotron. Tritons were detected in a freon cooled counter telescope. On-line computer particle identification was used. New targets were obtained by vacuum deposition of Rh metal onto thin Formvar backings to a thickness of about 60 $\mu g/cm^2$. Although more of the ^{101}Rh spectrum at higher excitation was seen in this study, the interpretation of the experiment was hampered by the lower resolution achieved. Some of the doublets seen in the 17 MeV experiment remained unresolved at the higher energy. Nevertheless, the expectation that more structured angular distributions would emerge was confirmed (Fig. 3).

Relative differential cross sections at 42 MeV were based on the charge collected. Absolute cross sections were obtained by selecting the elastic protons with the particle identification system. The proton optical parameters of Becchetti and Greenlees[12] were used to predict absolute elastic cross sections which in turn permitted the deduction of absolute (p,t) cross sections.

With the completion of the quadrupole-dipole-dipole-dipole magnet (QDDD) at Princeton, it was possible to repeat the (p,t) experiment at high resolution and high bombarding energy. Some preliminary 30 MeV data indicated that the angular distributions were sufficiently structured, so this energy was chosen. A spectrograph solid angle of 10 msr corresponding to a 5° angle bite was employed. The tritons were detected in the focal plane of the QDDD by a 60 cm long position sensitive wire proportional counter backed by a plastic scintillator. The height of the counter collimator was 2.5 cm to insure that all tritons were collected. A mixture of 90% argon and 10% methane at 1 atm continuously flowed through the proportional counter. The thickness of this counter was 1.25 cm. Particle identification was achieved by setting a window in the matrix of the ΔE(sum) signal from the gas proportional counter versus the scintillator (E) signal.[13] The computer then accumulated a position spectrum for the selected particle type. Relative cross sections were based on charge collected while absolute cross sections were based on elastic scattering at this energy.

DATA ANALYSIS

A. Excitation energies

Excitation energies for the ^{101}Rh levels seen at 17 MeV bombarding energy were obtained from an empirical calibration of the Pittsburgh spectrograph.[14] As seen in Table I, where there are obvious correspondences with levels based on a γ-decay study with Ge(Li) resolution,[15] the agreement is within a few keV. Energies of states seen in the 42 MeV counter telescope data were determined by using the previously measured energies of the low-lying states for calibration. The 30 MeV QDDD energies were likewise based on the energies of the states determined in the 17 MeV experiment or in the γ-ray work. The energies listed in Table I are averages over the angles used in the angular distributions.

States having peak cross sections of less than 1 μb/sr would probably not have been detected in the 30 MeV experiment. References 15, 16, and 17 indicate that there are many levels in ^{101}Rh not seen in this experiment. The parenthesized 851.0 keV level in Table I was chosen in preference to an alternative level at 974.7 keV, which, as mentioned in Ref. 15, would be equally consistent with their γ-ray coincidence data. Our

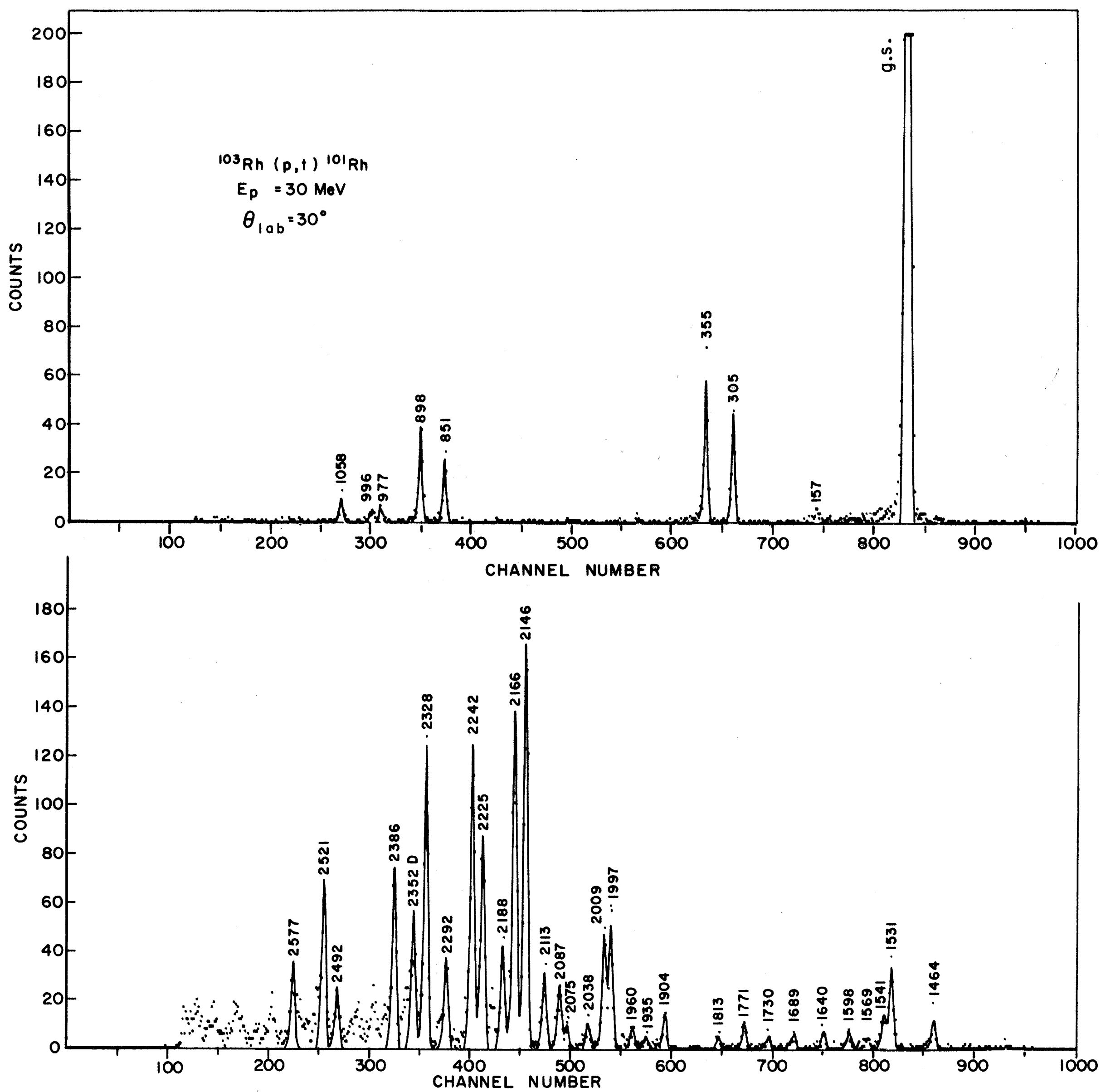

FIG. 1. ^{103}Rh$(p,t)^{101}$Rh spectrum taken with a position-sensitive 60 cm gas proportional counter in the QDDD focal plane at $E_p = 30$ MeV and $\theta_{lab} = 30°$. The numbers above the peaks are excitation energies in keV. The lower spectrum was taken with 1.25 times the integrated charge of the upper spectrum.

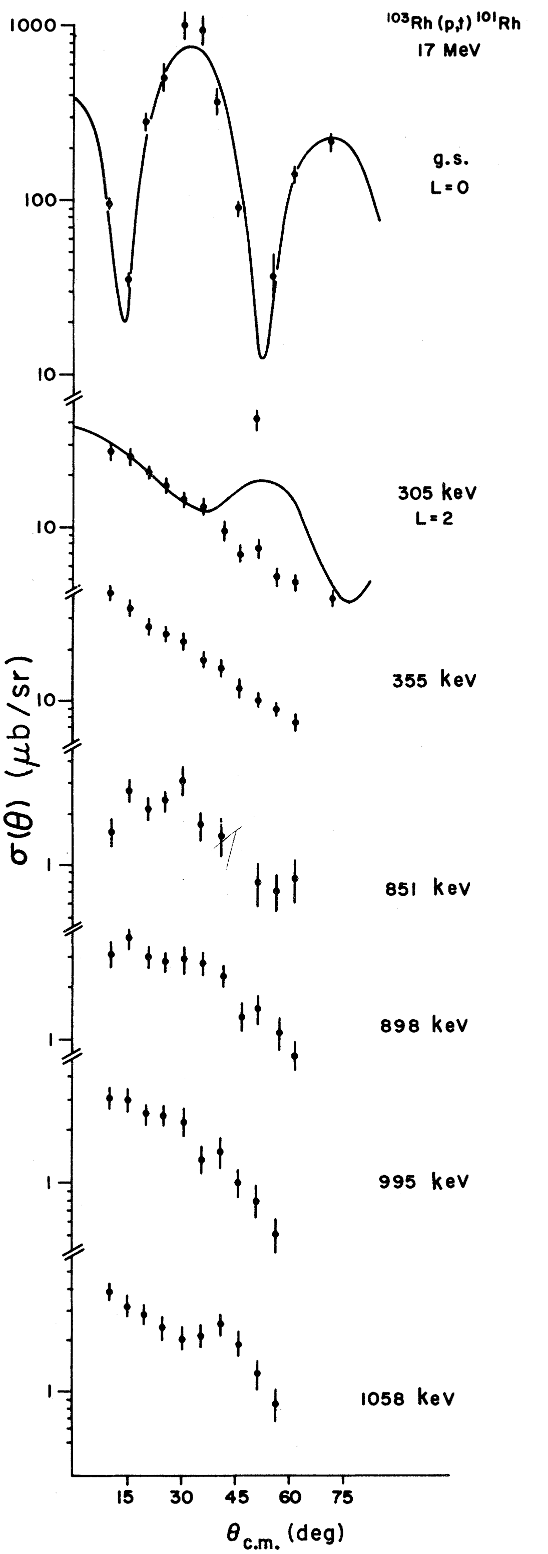

FIG. 2. ^{103}Rh(p,t)^{101}Rh, E_p=17 MeV, angular distributions. The solid curves are DWBA fits.

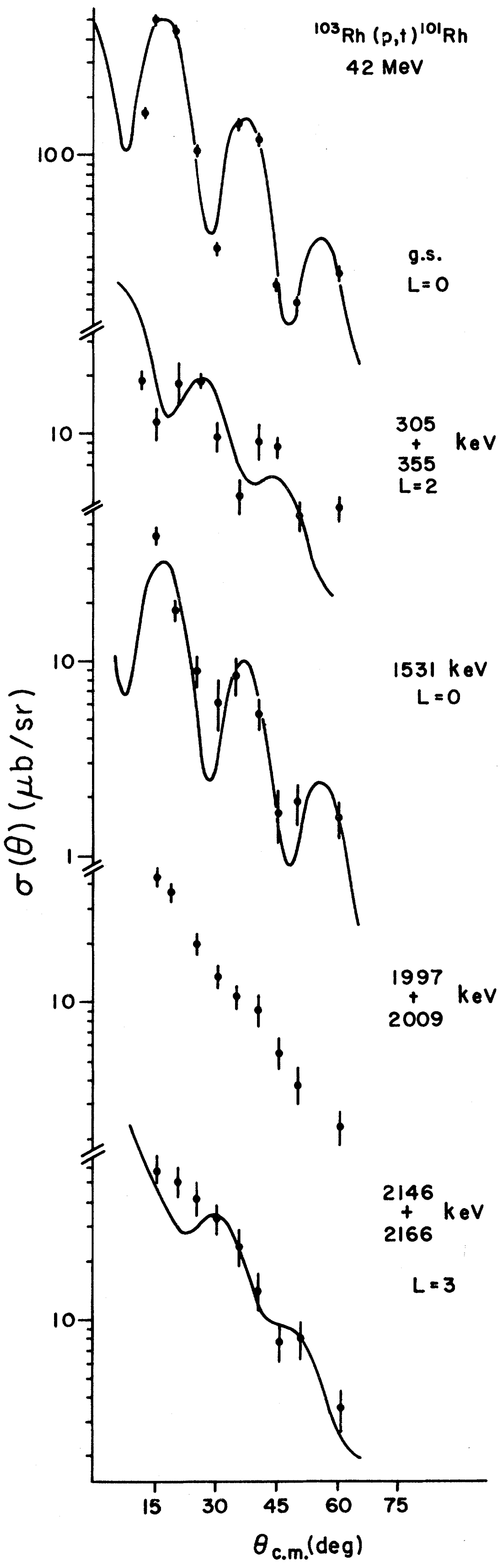

FIG. 3. ^{103}Rh(p,t)^{101}Rh, E_p=42 MeV, angular distributions. The solid curves are DWBA fits.

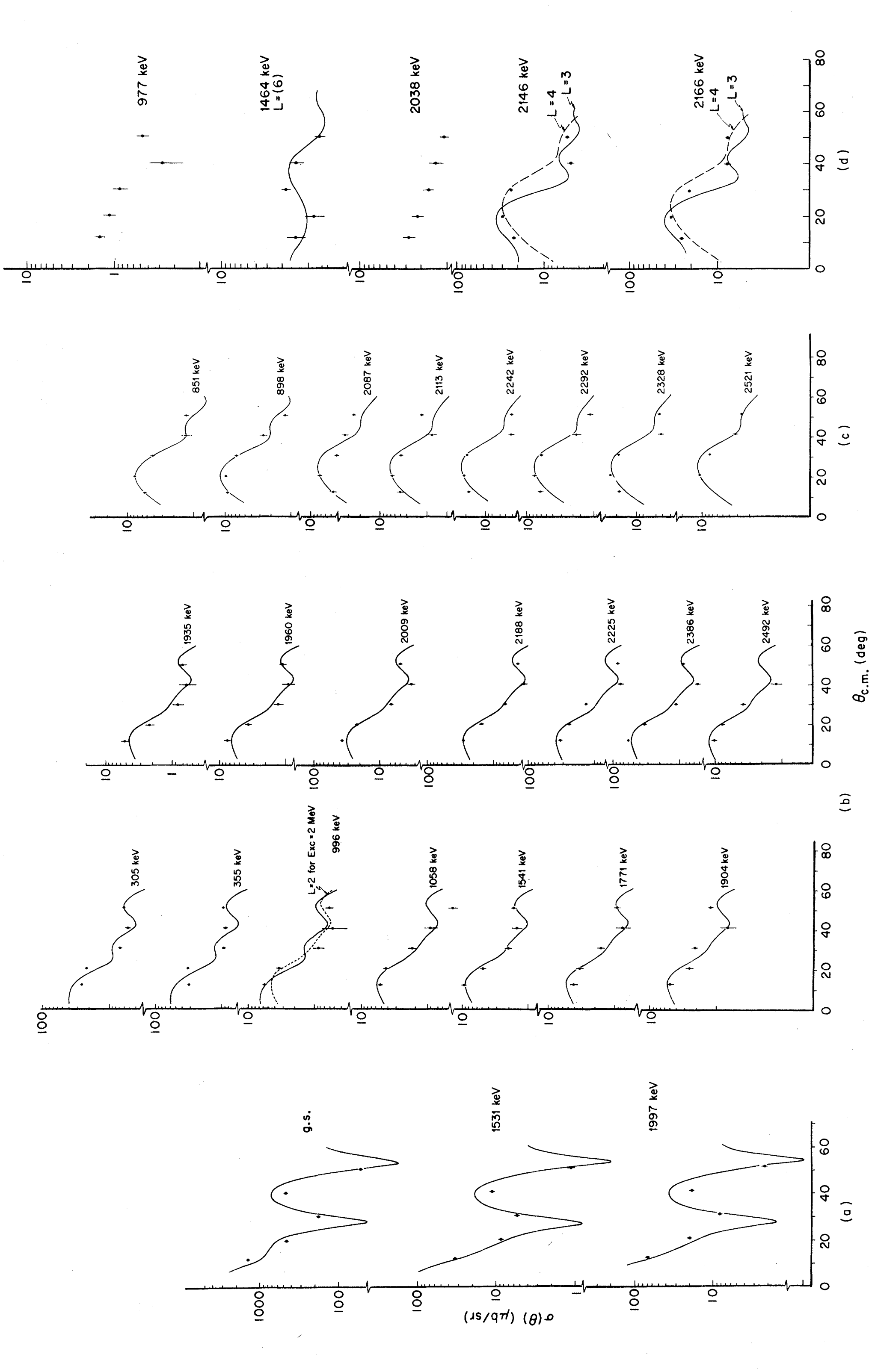

FIG. 4. ^{103}Rh(p,t)^{101}Rh, E_p=30 MeV angular distributions. The solid curves are DWBA fits. (a), L=0; (b), L=2; (c), L=4; (d), unknown or miscellaneous L transfers; dotted curves are also DWBA fits.

TABLE II. Optical parameters. Spin orbit for protons: $V_{so}=6.2$ MeV, $r_{so}=1.01$ fm, $a_{so}=0.75$ fm. Cluster description: Bound state potential depth adjusted to produce $2n$ binding energy; $r_0=1.2$ fm, $a_0=0.75$ fm. Microscopic calculations: Bound state potential depth adjusted to produce the single neutron binding energy; $r_0=1.25$ fm, $a_0=0.75$ fm.

E (MeV)	V (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	$4W_D$ (MeV)	r_i (fm)	a_i (fm)	X^2/N
				Protons [a]				
17	55.4	1.17	0.75	1.04	36.2	1.32	0.6	
30	51.2	1.17	0.75	3.9	23.0	1.32	0.6	
42	47.5	1.17	0.75	6.5	11.2	1.32	0.6	
				Tritons				
Set a [b]	171.0	1.16	0.752	16.5		1.498	0.817	
Set b [c]	134.0	1.166	0.784	14.0		1.55	0.795	0.06

[a] Calculated from general formula in Ref. 12.
[b] From interpolation of neighboring nuclei given in Ref. 20.
[c] Used Set a to generate "data points," and used these (with assigned errors of 10%) to search for new optical potential, Set b.

direct observation of a level at 850 keV, however, supports the former choice. The 977 keV level was also seen at 17 MeV, but poorer statistics at this energy prevented a good energy assignment. The 978.4 keV level of Ref. 15 may not correspond to this level, although they agree in energy within the errors.

Figure 1 shows a spectrum of ^{101}Rh taken with the QDDD at 30°. Since the detector covered an excitation energy range of about 1.2 MeV, two magnetic field settings were used at each angle to cover excitations up to about 2.5 MeV. Beyond 2.5 MeV, our 42 MeV data indicated numerous unresolved low cross-section states with no especially strong peaks. A slight gap between the 1058 and 1464 keV states was tolerated because a preliminary QDDD run showed an absence of states in this region. The resolution achieved in the QDDD run was about 10 keV full width at half-maximum (FWHM). The energies given above the peaks in Fig. 1 are derived from the spectrograph experiments or, when available, the γ-ray work as given in Table I. They represent, therefore, the best available energies and will be used in later references to a state.

B. Angular distributions

The angular distributions obtained at 17 MeV incident energy are shown in Fig. 2. The error bars in this and later figures are due to statistical and background subtraction errors except for a few of the points in the ground state transition, where larger errors resulted from overexposure of the photographic plates. The absolute cross-section uncertainties are estimated at ±15%. Beginning at about 1.1 MeV in the ^{101}Rh spectrum obtained at 17 MeV, α particles from the ^{103}Rh(p, α) reaction appeared on the plates so that higher excited states from the (p, t) reaction were obscured.

The angular distributions taken with the 42 MeV proton beam are shown in Fig. 3. The error in the absolute cross sections is about ±20%. Owing to the poorer resolution of this experiment, most of the angular distributions contain contributions from more than one state. Table I indicates which states dominantly contribute to these cross sections as deduced from the 30 MeV data.

The data obtained at 30 MeV were analyzed with the peak fitting routine AUTOFIT.[18] The quality of the fits is shown in Fig. 1, which is a plot produced by this program. Figures 4(a)–4(d) show the 30 MeV angular distributions. Absolute cross sections were obtained by repeating the (p, t) ground state transition along with proton elastic scattering in our large scattering chamber. The absolute elastic cross sections as given by the Becchetti and Greenlees[12] parameters were used to infer the (p, t) cross sections. The error is estimated at ±40%.

Angular distributions at 30 MeV are not shown for states which had fewer than four data points. Since the 2352 and 2361 keV pair of states was unresolved at most angles, these angular distributions are not given either, although they have significant (p, t) strength.

C. DWBA calculations and extraction of L values

The DWBA calculations followed closely the well-matching prescription of Ref. 19. Triton optical parameters[20] were refitted with the requirement that the real radius and diffusitivity parameters r_0 and a_0, remain close to the corresponding values for the proton parameters. This, together with the requirement that the real well depth for tritons be approximately three times the proton real well depth, insured that the well-matching condition be satisfied. Table II gives the optical parameters used in this study. The refitted triton parameters (Set b) differ principally from the original parameters (Set a) in the real well depth. Figure 5 shows that the refitted parameters do better in fitting the ground state transition and were used for the distorted-wave Born-approximation (DWBA) calculations of Figs. 2–4.

The cluster description of the bound state[19] was used in the DWBA calculations for the 17 and 42 MeV data. In the microscopic description of the bound state which was employed for the 30 MeV DWBA calculations, the pair of neutrons was coupled explicitly by the DWBA code.[21] Either method of calculation produces angular distributions having basically the same shape but not, of course, magnitude, provided the parameter r_0 of the single nucleon well is chosen slightly larger than that of the cluster well.

The nonlocality parameters $\beta = 0.85$ for the proton and $\beta = 0.2$ for the triton were used. A finite range parameter of 0.4 was also used. Some sensitivity in the microscopic calculations was noted when the single particle neutron orbitals were changed. The use of $2d_{5/2}$ neutron orbitals gave a somewhat better fit for the $L = 0$, 2, and 4 transfers than did the $1g_{7/2}$, so the former choice was made for the curves of Fig. 4. Similarly a $(2d_{5/2}, 2p_{1/2})$ description was used for $L = 3$ transfer, while a $(1g_{9/2}, 1g_{9/2})$ choice was made for the $L = 6$ transfer. Such simple configurations were chosen for the purpose of extracting L-transfer values only. No attempt was made to predict strengths. The DWBA curves are quite different for different L transfers except that the 30 MeV $L = 3$ and $L = 4$ shapes are fairly similar. Table III lists the L values extracted. Where the fits are poor or the statistical errors in the data large, the L value is parenthesized or several alternatives are given.

In view of the 5° acceptance angle of the QDDD used for this experiment, the theoretical DWBA cross sections were averaged over the experimental angular acceptance. The curves shown in Fig. 4 are, in fact, smoothed in this fashion. The principle effect of this averaging was to fill in the sharp dips in the $L = 0$ DWBA curve.

DISCUSSION OF SELECTED LEVELS

Ground state. An early (p, t) study of ^{101}Rh established the reaction Q value of -8.275 ± 0.017 MeV and $J^\pi = \frac{1}{2}^-$ for the ground state.[22]

157 keV level. Weakly excited in this work, this level has been assigned $J^\pi = \frac{9}{2}^+$.[15,17] Its strong

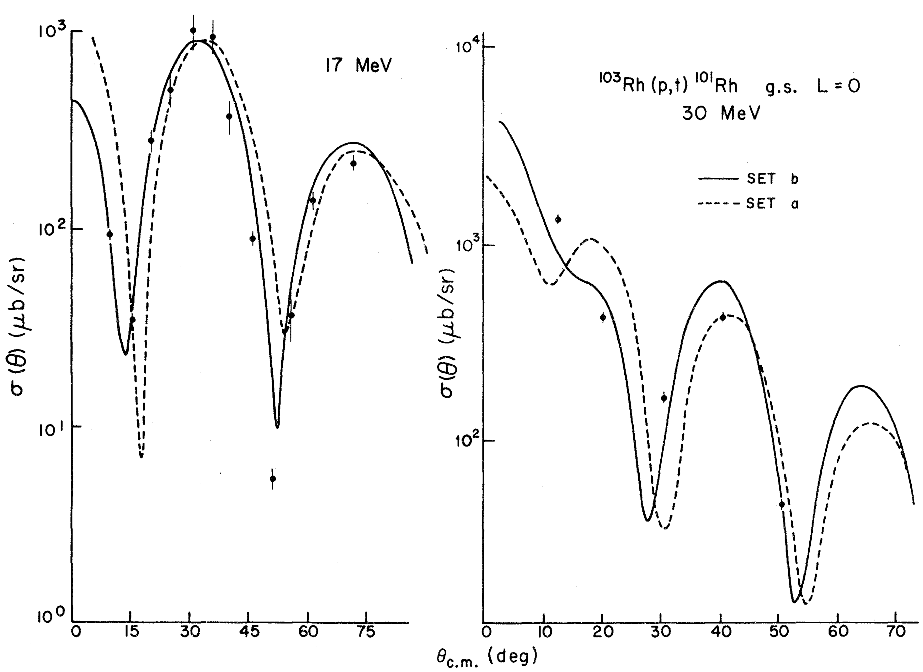

FIG. 5. Comparison of DWBA fits to the ^{103}Rh$(p,t)^{101}$Rh $L = 0$ ground state transition with different triton parameters (Sets a and b).

TABLE III. (p,t) L transfer assignments and deduced J^π values.

Exc. (keV)	30 MeV $\sigma(20°)$ (μb/sr)	L transfer	J^π This work	J^π Ref. 15	(keV)	30MeV $\sigma(20°)$ (μb/sr)	L transfer	J^π This work	J^π Ref. 15
0	437	0	$\frac{1}{2}^-$	$\frac{1}{2}^-$	1960	3.7	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
157	~1			$\frac{9}{2}^+$	1997	18	0	$\frac{1}{2}^-$	
305	21	2	$\frac{3}{2}^-$	$\frac{3}{2}^-(\frac{5}{2}^-)$	2009	22	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
355	32	2	$\frac{5}{2}^-$	$\frac{5}{2}^-(\frac{3}{2}^-)$	2038	2.2			
851	7.5	4	$\frac{7}{2}^-$	(−)	2075	~4			
898	9.2	4	$\frac{9}{2}^-$		2087	6.8	(4)		
977	1.2		$(\frac{1}{2}^-)$		2113	6.2	4	$\frac{7}{2}^-, \frac{9}{2}^-$	
996	3.4	2	$\frac{3}{2}^-$		2146	30	3, (4)	$(\frac{5}{2}^+, \frac{7}{2}^+)$	
1058	4.1	2	$\frac{5}{2}^-$	(−)	2166	33	3, (4)	$(\frac{5}{2}^+, \frac{7}{2}^+)$	
1464	0.9	(6)			2188	15	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
1531	8.2	0	$\frac{1}{2}^-$		2225	23	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
1541	4.8	2	$\frac{3}{2}^-, \frac{5}{2}^-$		2242	20	4	$\frac{7}{2}^-, \frac{9}{2}^-$	
1569	~1				2292	7.1	4	$\frac{7}{2}^-, \frac{9}{2}^-$	
1598	~1				2328	23	4	$\frac{7}{2}^-, \frac{9}{2}^-$	
1640	~1				2352 }	~23			
1689	~1				2361 }				
1730	~2				2386	33	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
1771	3.4	2	$\frac{3}{2}^-, \frac{5}{2}^-$		2455	~8			
1813	~1				2492	7.5	2	$\frac{3}{2}^-, \frac{5}{2}^-$	
1904	2.4	2	$\frac{3}{2}^-, \frac{5}{2}^-$		2521	10	(4)		
1935	2.2	2	$\frac{3}{2}^-, \frac{5}{2}^-$		2577	~6			

excitation in (^{3}He, d)[16] indicates that it is predominantly a single particle $g_{9/2}$ proton state. The excitation of other $g_{9/2}$ proton-core coupled states would be expected to be much reduced in strength compared with this barely discernible level. The mechanism for exciting this state is likely to require a two-step process.

305 and 355 keV doublet. These are undoubtedly states which arise from coupling a $2p_{1/2}$ proton onto the first excited 2^+ state of the ^{100}Ru core. They are populated by $L=2$ in (p, t) and the ratio of their strengths is 1.42 compared to the expected ratio of 1.5 for the spin sequence indicated in Table III. This spin sequence is also preferred by the γ-ray work.[15]

851 and 898 keV doublet. These levels are excited by nearly identical $L=4$ shapes in (p, t) and are therefore likely to be the expected weak coupled doublet associated with the first excited 4^+ core state. Their center of gravity is shifted in the same direction as that of the 305-355 keV pair. The ratio of their (p, t) strengths is 1.52 and would argue for the spin sequence given in Table III. A negative parity is also indicated for the 851 keV level by Ref. 15. Although the 898 keV level was not observed in the γ-ray work of Ref. 15, a close-by level at 905.6 keV tentatively assigned $J^\pi = (\frac{5}{2})^+$ by Ref. 15 is outside the energy uncertainties and is to be regarded as a different level. This is probably the $2d_{5/2}$ proton single particle state, since its (^{3}He, d) cross section is rather large.[16]

977 keV level. This (p, t) transition is almost an order of magnitude weaker than the (p, t) strengths of its neighboring states. A state arising from coupling to the first excited 0^+ state of the core is expected in this excitation region. Its strength relative to the ground state agrees with that of the 1130 keV, 0^+ to g.s. ratio obtained in the ^{102}Ru$(p, t)^{100}$Ru reaction at 19 MeV.[23] Its uncharacteristic angular distribution could be the result of nondirect contributions.

996 and 1058 keV doublet. These transitions have $L=2$ (p, t) shapes and a cross-section ratio of 1.23 and are most likely the doublet arising from the coupling of the $2p_{1/2}$ proton onto the second excited 2^+ core state. The cross-section ratio differs from the statistical value of 1.5 for weak coupled states, but still supports the spin sequence shown in Table III. The 1058 keV level is seen in the γ-ray work where a negative parity is indicated.[15]

1531 and 1997 keV levels. Both of these are populated with appreciable (p, t) strength by $L=0$. They could be the weak coupled states associated with the 0^+ states in ^{100}Ru at 1741 and 2052 keV,[24] respectively.

DISCUSSION OF (p,t) STRENGTH ABOVE 2 MeV

It was rather surprising to see so many states with significant (p, t) strength in the region of 2–2.5 MeV of excitation. A collective 3^- core state is expected which would give rise to two states roughly in this excitation region of ^{101}Rh. The 2146 and 2166 keV states are likely candidates for this doublet even though the 3^- ^{100}Ru level has not yet been identified. The remaining strong states above 2 MeV are more difficult to explain. From Table III, we see that there is appreciable $L=2$ and $L=4$ strength. The weak coupling model would suggest looking to the even-even core for collective 2^+ and 4^+ states at roughly 2–3 MeV of excitation. The spectrum of ^{100}Ru[23,24] becomes quite dense above 2 MeV, indicating many possibilities for further study.

It is unlikely that we have missed any significant (p, t) strength, at least of the type that is concentrated in a single level. As mentioned previously, our 42 MeV study looked up to about 6 MeV of excitation without uncovering any additional prominent peaks.

CONCLUSIONS

Figure 6 illustrates the proposed weak coupling scheme at low excitation for the $2p_{1/2}$ proton in ^{101}Rh. The spectrum of ^{101}Rh has been shifted so that the center of gravity of the first $L=2$ doublet coincides with the 540 keV 2^+ state in ^{100}Ru. The major uncertainty is the association of the 977 keV state in ^{101}Rh with the 1130 keV, 0^+ state of ^{100}Ru. As can be seen from the figure, the center of gravity of the weak coupled multiplets has shifted downward relative to the corresponding ^{100}Ru state when the ground states are aligned. The shift for the first doublet is 205 keV, while that for the two higher doublets is about 340 keV. The shift for the 997 keV $(\frac{1}{2}^-)$ state, while downward, is only 153 keV. Perhaps a better way of expressing this shift is to take the ratio of the multiplet's center of gravity to the excitation energy of the corresponding ^{100}Ru state. This ratio is, in increasing order of excitation energy, 0.62, 0.71, and 0.76 for the doublets and 0.86 for the singlet.

The splitting is about 50 keV for both $L=2$ and $L=4$ doublets. If the particle-core interaction were proportional to $\vec{J}_p \cdot \vec{J}_c$, one would expect the $L=4$ splitting to be about twice the $L=2$ splitting, which is not the case. The smallness of this splitting, together with the simplicity of the multiplet structure for $J_p=\frac{1}{2}$, has simplified the experimental study of weak coupling in this nucleus. This suggests, as was pointed out some time ago,[25] that it might be fruitful to investigate other nuclei where the extra particle has spin $\frac{1}{2}$ so that systematics can be established.

Above 2 MeV of excitation, the density of states seen in (p, t) is sufficiently high to make it difficult to choose doublets, assuming they are present. Some reasonable pairings can be made from the data presented, but this becomes rather speculative. The fairly large (p, t) strength to many states in this excitation region is an interesting and unexpected phenomenon. These (p, t) cross sections are comparable to those of the first excited $L=2$ doublet. Although two of these states could be associated with expected $L=3$ (p, t) strength, the remainder may be more challenging to explain.

The (p, t) reaction appears to be a very nice tool for selectively exciting core coupled states with the extra particle in the same orbital as that of the target nucleus. At 17 MeV, the angular distributions were quite structureless and, except

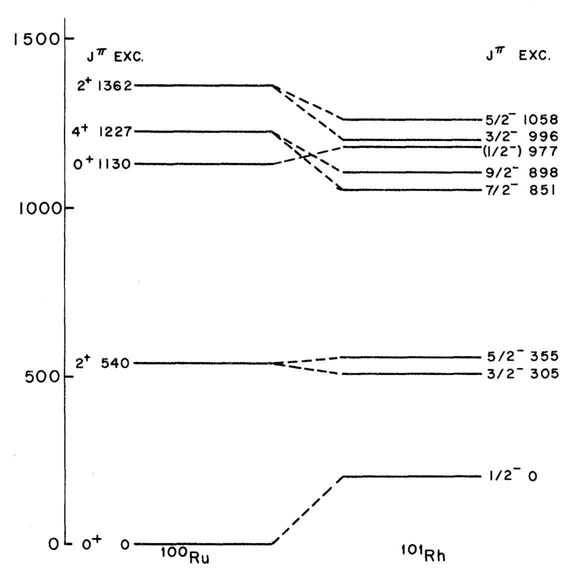

FIG. 6. Proposed structure of weak coupling of the $2p_{1/2}$ proton for low-lying states in ^{101}Rh.

for the ground state transition, could not be fitted by a simple direct DWBA calculation (see Fig. 2). At 30 and 42 MeV bombarding energy, the situation improved so that quite reasonable DWBA fits were possible. The low-lying states seen at both 17 and 30 MeV were excited with very similar strength relative to the ground state. The cross-section ratios for the members of the doublets differed by no more than 5% at 17 and 30 MeV. The investigation of weak coupling in other nuclei with the (p, t) reaction would seem a worthwhile experimental endeavor and would provide systematics useful for a better theoretical understanding of the particle-core interaction.

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