$^{89}Y(t,p)^{91}Y$ reaction at $E_t = 20$ MeV

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The reaction $^{89}Y(t,p)^{91}Y$ has been measured at an incident energy of 20 MeV. Differential cross sections were measured at 13 angles and an excitation range of 5 MeV was observed with 18 keV resolution. The data are compared to distorted wave calculations both for L assignments and magnitude relations. Sixteen new levels are reported in ^{91}Y as well as many new limits on spin assignments. An interpretation of the results as a proton hole coupled to ^{92}Zr pairing-multipole states is presented. Such an analysis provides a qualitative description of the observed strength, but a more complex analysis is required for quantitative results.

[NUCLEAR REACTIONS $^{89}Y(t,p)^{91}Y$, $E_t = 20$ MeV; measured $\sigma(E_p, \theta)$; ^{91}Y deduced levels, L, π; DWBA analysis.]

I. INTRODUCTION

The $^{89}Y(t,p)^{91}Y$ reaction provides a useful method for studying the coupling of proton configurations to states composed of two neutrons outside the closed $N=50$ shell. Since this region of the periodic table is also relatively simply described in terms of its proton configurations, experimental data on such reactions may be amenable to both shell model and pairing-multipole model calculations. In particular, there is a weak proton shell closure at $Z=38$, and hence the ground state of ^{88}Sr may be approximately represented by a double shell closure.[1] A shell model description of the $^{89}Y(t,p)^{91}Y$ reaction would thus involve a proton orbital for the ^{89}Y ground state together with states of ^{91}Y composed of a proton and two neutrons outside the ^{88}Sr core.

An alternate description of the ^{91}Y levels excited in this reaction is obtained from the pairing-multipole theory[2] by coupling the odd proton or proton hole to the two-neutron states above the $N=50$ shell which are considered as phonons of various multipolarities. If the two-neutron states are in ^{90}Sr, then a proton is coupled to them; if the neutron states belong to ^{92}Zr, then the coupling is with a proton hole. A similar description was used with considerable success in the interpretation of the $^{207}Pb(t,p)^{209}Pb$ reaction[3] by coupling a neutron hole to the pairing phonons of ^{210}Pb. This method seems particularly applicable to the (t,p) reaction on odd proton targets where the proton is expected to couple weakly to the neutron pairing phonons. Unfortunately, there has been no theoretical investigation of cases involving a proton coupled to neutron pairing phonons to date.

The neutron pairing phonons excited in the (t,p) reaction across the $N=50$ closed shell have been investigated thus far primarily in the $^{90}Zr \rightarrow {}^{92}Zr$ reaction at $E_t = 15$ MeV.[4] The reaction $^{88}Sr \rightarrow {}^{90}Sr$ has been reported at both $E_t = 15$ MeV[5] and 20 MeV,[6] but only to a limited extent in each case. Both of these studies provide knowledge of the excitation energies, cross sections, and enhancements of the two-neutron pairing phonons for the $N=50$ to $N=52$ transitions. In addition, a theoretical description of such phonons is available for the case of the $^{90}Zr(t,p)^{92}Zr$ reaction.[4,7]

The present report describes a study of the $^{89}Y(t,p)^{91}Y$ reaction at 20 MeV bombarding energy. In addition, data were obtained at several angles for the $^{90}Zr(t,p)^{92}Zr$ reaction in order to obtain an accurate comparison of transition strengths between the two reactions and thereby to utilize both the results and the analysis which were previously reported for ^{92}Zr. Since the proton configurations in the ground states of ^{90}Zr and ^{89}Y are different, this comparison may also be sensitive to the influence of the proton configurations on the two-neutron transfer reactions. Ideally, a three-way comparison should be made of the (t,p) reaction on ^{88}Sr, ^{89}Y, and ^{90}Zr to study the coupling of zero, one, and two protons; this will be possible when the $^{88}Sr(t,p)^{90}Sr$ reaction is studied in detail.[8] An earlier study of the $^{89}Y(t,p)^{91}Y$ reaction at a bombarding energy of 12.1 MeV has been reported by Hardy, Davies, and Darcey,[9] but no comparison was made with data from a neighboring even-even target to study particle-core coupling effects. In addition, the low bombarding energy limited the number of excited states that could be examined, and in some cases the angular momentum assignments.

II. EXPERIMENTAL PROCEDURES

The experiment was carried out using a 20 MeV triton beam from the Los Alamos three stage Van de Graaff facility. The target consisted of approximately 200 $\mu g/cm^2$ of monoisotopic ^{89}Y deposited on a 30 $\mu g/cm^2$ carbon backing. The data were collected at 13 angles from a minimum of 9° to a maximum of 72°. A magnetic spectrograph was used to analyze the reaction protons which were detected with NTB-type photographic plates in the focal plane. The typical experimental resolution was 18 keV full width at half-maximum (FWHM). A 2 mm solid state Si detector was used to monitor the elastically scattered tritons and thereby ensure that the data could be normalized correctly in case deterioration of the target occurred during the various exposures. No such deterioration was observed.

In addition to the $^{89}Y(t,p)$ measurements, data were also obtained with a ^{90}Zr target at the three angles which define the peak of the angular distribution for the $L=0$ transfer to the ground state. The ^{90}Zr target was a rolled metallic foil whose thickness had been carefully measured previously by small angle elastic triton scattering in the Rutherford region. The ratio of triton elastic scattering from ^{89}Y and ^{90}Zr was then used to establish an absolute cross section for the ^{89}Y target after correction for the mass difference by an optical model calculation of the elastic scattering. The optical model parameters used in this comparison were from the survey of triton scattering of Flynn *et al.*[10] Proton spectra from the ^{90}Zr target were also recorded on the spectrograph plates simultaneously with the elastic scattering measurements, and cross sections were evaluated and compared with the previous $^{90}Zr(t,p)^{92}Zr$ results.[4] In this manner, the accuracy of the absolute cross sections measured in this experiment is estimated at ±20%, and the relative cross sections between $^{89}Y(t,p)$ and $^{90}Zr(t,p)$ are estimated to be accurate to ±5%.

III. EXPERIMENTAL RESULTS

A spectrum of the $^{89}Y(t,p)^{91}Y$ reaction is shown in Fig. 1, in which the data extend to an excitation energy of approximately 5 MeV. Results up to 7 MeV were scanned but no significant structure corresponding to excited states could be resolved in the region above 4.5 MeV. Table I contains the levels excited in the present reaction as well as those observed previously from the (t,p) experiments,[9,11] $^{94}Zr(p,\alpha)$ data,[12] $^{92}Zr(t,\alpha)$ data,[9] and $^{92}Zr(d,{}^3He)$ results.[13] These levels have been summarized recently in a nuclear data compilation.[14]

Differential cross sections are shown in Fig. 2 for all levels with sufficient data points to warrant this display. Differential cross sections measured at 15° are contained in Table I for each assigned level. Of the total of 37 levels assigned here, 16 were previously unknown. Angular momentum assignments were made based on an empirical comparison to the previous $^{90}Zr(t,p)$ data[4] together with distorted wave calculations (see below). These results are also shown in Table I where 22 L-value assignments are made, of which 11 were known from previous experiments.[9,11] In cases where angular momentum transfer assignments for the same level have been made in both the (t,p) reaction and either the (t,α) or $(d,{}^3He)$ reactions, it is possible to assign a unique spin and parity to the level. Using the $\frac{1}{2}^-$ spin of the ^{89}Y target and the 0^+ ground state spin of ^{92}Zr,

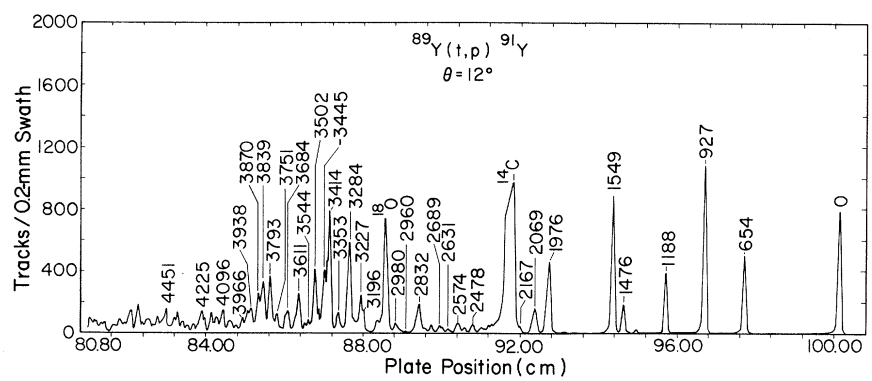

FIG. 1. Spectrum of $^{89}Y(t,p)^{91}Y$ reaction taken at a laboratory angle of 12°. The energies given are from the present experiment. C and O contaminant peaks are labeled.

TABLE I. Excitation energies, cross sections and spin assignments in ^{91}Y from the present (t,p) experiment and previous results. The present L-transfer values are based on a comparison with ^{90}Zr(t,p) measurements as well as with DWBA calculations.

	Present results				Previous results			
Level No.	E_x (MeV)	$\sigma(15°)$ (μb/sr)	L transfer	J^π	E_x [a] (MeV)	(t,α) [b] l transfer	12.1 MeV [b] (t,p) L transfer	J^π [a]
0	0	175	0	$\frac{1}{2}^-$	0	1	0	$\frac{1}{2}^-$
					0.55557	4		$\frac{9}{2}^+$
1	0.654	145	2	$\frac{3}{2}^-$	0.6529	1	2	$\frac{3}{2}^-$
2	0.927	215	2	$\frac{5}{2}^-$	0.9258	3	2	$\frac{5}{2}^-$
3	1.188	112	4	$\frac{7}{2}^-, \frac{9}{2}^-$	1.1869		4	$\frac{7}{2}^-, \frac{9}{2}^-$
					1.3054			$(\frac{5}{2}, \frac{7}{2})$
4	1.476	54	2	$\frac{3}{2}^-$	1.4737	1	2	$\frac{3}{2}^-$
5	1.549 [c]	265	4	$\frac{7}{2}^-, \frac{9}{2}^-$	1.5459 [c]	3		$(\frac{5}{2}^-)$
					1.5800			$(\frac{5}{2}, \frac{7}{2})$
6	1.976	125	2	$\frac{5}{2}^-$	1.9804	3	2	$(\frac{3}{2}^-, \frac{5}{2}^-)$
7	2.069	61	3	$\frac{5}{2}^+, \frac{7}{2}^+$	2.0665		3	$(\frac{5}{2}^+, \frac{7}{2}^+)$
8	2.167	10	(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$	2.159		2	$\frac{3}{2}^-, \frac{5}{2}^-$
9	2.211	245	2	$\frac{5}{2}^-$	2.2069	3	2	$\frac{5}{2}^-$
					2.2794			$(\frac{5}{2}, \frac{7}{2})$
					2.376			
10	2.478	14	(2)	$(\frac{3}{2}^-)$	2.475	1	2	$\frac{1}{2}^-$ [d]
11	2.574	14	0	$\frac{1}{2}^-$	2.569	1	0	$\frac{1}{2}^-$
12	2.631 [e]	5						
13	2.689	17	(4)	$(\frac{7}{2}^-, \frac{9}{2}^-)$				
14	2.832	65	(5)	$(\frac{9}{2}^+, \frac{11}{2}^+)$	2.830		(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$
15	2.960	4						
16	2.980	12	(0)	$(\frac{1}{2}^-)$	2.970			
17	3.045	19	0	$\frac{1}{2}^-$	3.055			
18	3.196 [e]	35	(4, 5)		3.205			
19	3.227	27	(5)	$(\frac{9}{2}^+, \frac{11}{2}^+)$				
20	3.284	185	4	$\frac{7}{2}^-, \frac{9}{2}^-$				
21	3.320	8	6	$\frac{11}{2}^-, \frac{13}{2}^-$				
22	3.353	32	4	$\frac{7}{2}^-, \frac{9}{2}^-$				
23	3.414	175	4	$\frac{7}{2}^-, \frac{9}{2}^-$				
24	3.445	130	4	$\frac{7}{2}^-, \frac{9}{2}^-$				
25	3.502	85	3, 4	$\frac{5}{2}^+, \frac{7}{2}^+, \frac{7}{2}^-, \frac{9}{2}^-$				
26	3.544	19	6	$\frac{11}{2}^-, \frac{13}{2}^-$				
27	3.611	68	(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$				
28	3.684	32	(2, 3)					
29	3.751	35	3, 4	$\frac{5}{2}^+, \frac{7}{2}^+, \frac{7}{2}^-, \frac{9}{2}^-$				
30	3.793	83	5	$\frac{9}{2}^+, \frac{11}{2}^+$				

TABLE I *(Continued)*

Present results					Previous results			
Level No.	E_x (MeV)	$\sigma(15°)$ (μb/sr)	L transfer	J^π	E_x [a] (MeV)	(t,α) [b] l transfer	12.1 MeV [b] (t,p) L transfer	J^π [a]
31	3.839	89	5	$\frac{9}{2}^+, \frac{11}{2}^+$				
32	3.870	64	2	$\frac{3}{2}^-, \frac{5}{2}^-$				
33	3.938	38	(5)	$(\frac{9}{2}^+, \frac{11}{2}^+)$				
34	3.966	18	(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$				
35	4.096	27	(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$				
36	4.225 [e]	20	(0)	$(\frac{1}{2}^-)$				
37	4.451	26	(2)	$(\frac{3}{2}^-, \frac{5}{2}^-)$				

[a] From Refs. 9, 11–14.
[b] From Ref. 9.
[c] Possible doublet with different levels observed in different experiments (see text).
[d] This assignment of $\frac{1}{2}^-$ as given by the Nuclear Data group in Ref. 14 is incorrect.
[e] Possible unresolved doublet.

the value of J is given by[3]

$$J = \frac{L+l}{2}, \qquad (1)$$

and the parity is $\pi = (-1)^l = (-1)^{L+1}$, where L and l are the angular momenta transferred in the (t,p) and either the (t,α) or $(d,{}^3\text{He})$ reactions, respectively. These assignments are included in Table I where possible.

An example of L-value assignments in the ^{89}Y-(t,p) reaction made by comparison with known ^{90}Zr(t,p) transitions[4] is shown in Fig. 3 for values of $L=0$, 2, 3, and 4.

IV. DISTORTED WAVE ANALYSIS

Distorted wave (DW) calculations were performed with the code DWUCK[15] which uses the two-nucleon form factor method of Bayman and Kallio.[16] The optical model parameters chosen were identical to those previously used with the ^{90}Zr(t,p) data[8] and are from the work of Flynn *et al.*[10] and Perey[17] for the triton and proton channels, respectively. The bound state parameters were the same as in previous work.[18] Since the best method for assigning L values from angular distributions is the empirical one based on the ^{90}Zr(t,p) data, the principal efforts in these calculations were directed toward (1) correcting for the difference of mass and charge between the yttrium and zirconium nuclei, (2) establishing the Q-value dependence of angular distributions, and (3) assigning L values where empirical assignments could not be made, such as for L values higher than 4 for which no angular distributions were measured in the Zr data. The DW results were obtained, in general, using simple two-neutron wave functions with no configuration mixing. An absolute normalization for the DW results was accomplished using the value of Flynn and Hansen.[18]

V. DISCUSSION OF RESULTS

A. Comparison of ^{89}Y(t,p) and ^{90}Zr(t,p) reactions

The two models which have enjoyed considerable success in describing low energy excitations in magic regions of the Periodic Table are the nuclear shell model and the particle-core coupling model, and the success has been particularly striking in the case of states reached via two-particle transfer reactions.[2,3] However, the shell model calculations performed thus far on ^{91}Y are severely limited in their model space and are inadequate to permit a realistic comparison of observed and predicted level schemes (see Sec. V B). Even a simple microscopic model of ^{91}Y would require that three particles be considered with respect to the ground state of ^{88}Sr taken as the vacuum state. Thus the configurations would be of the form $(\pi\nu_1\nu_2)$, where the proton could occupy the $p_{1/2}$ or $g_{9/2}$ orbitals and the neutrons any of the orbits in the shell $50 > N > 82$. An additional complexity which results from the close spacing of single particle levels near the $Z=38$ core is the possibility of two protons in the $p_{1/2}$ or $g_{9/2}$ orbits together with a proton hole in the $f_{5/2}$ or $p_{3/2}$ orbits. Indeed, the first four states of ^{89}Y are described primarily as $p_{1/2}$, $g_{9/2}$, $f_{5/2}^{-1}$, and $p_{3/2}^{-1}$ proton states.[19]

In cases where the microscopic configurations can become extremely complicated due to three particles ranging over many orbitals, the model of a particle or hole coupled to core excitations often provides a simple interpretation of experimental data. In the present example of ^{91}Y reached by two-neutron transfer, detailed information exists on the neutron pairing states of ^{92}Zr, and it is interesting to examine the extent to which ^{91}Y may be treated as a proton hole coupled to these states. The data presently available on the $^{88}Sr(t,p)^{90}Sr$ reaction[6] are too limited to make a detailed comparison at this time based on coupling a proton particle to the neutron pairing states of ^{90}Sr. Those states in ^{91}Y involving a single proton outside the $Z = 38$ core may be better described as a proton coupled to the phonon states of ^{90}Sr, whereas the configurations with two protons above $Z = 38$ and a proton hole below may follow more closely the representation of a proton hole coupled to states of ^{92}Zr.

Figure 4 illustrates the excited states of ^{92}Zr as

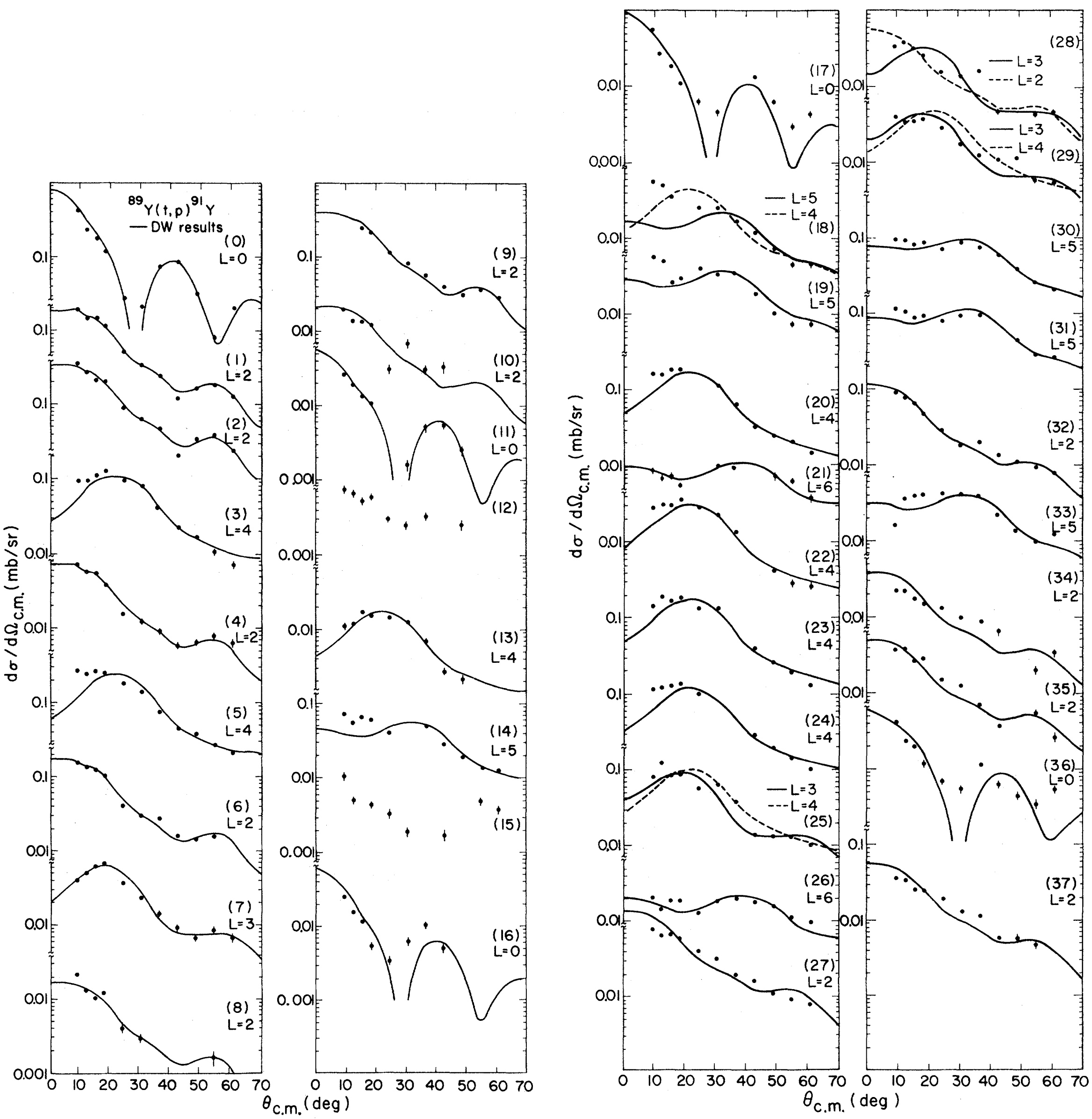

FIG. 2. Differential cross sections for all levels observed at a sufficient number of angles. The numbers refer to the level numbers of Table I. DW results are also shown for the L assignments suggested in the figure and in Table I. Dashed lines are used to indicate a possible alternate L valve. The adopted assignment is due both to the DW results and a comparison to $^{90}Zr(t,p)^{92}Zr$ results as shown in Fig. 3.

measured in the previous (t, p) reaction[4] together with results of the present measurement on ^{91}Y. The dashed lines indicate possible related states between the two nuclei, and the ratio of cross sections leading to the related states is also expressed both in the figure and in Table II. The ground states of the two nuclei have been aligned on the figure for comparison purposes. A similar comparison should be made between ^{91}Y and ^{90}Sr, but only the transitions to the lowest states with $L = 0$, 2, and 4 have been reported for ^{90}Sr, with the $L = 4$ assignment listed as tentative.[6] Since the energies and strengths of the first 0^+, 2^+, and 4^+ transitions are quite similar[6] in ^{90}Sr and ^{92}Zr, the comparison of each of them with ^{91}Y would appear to be equivalent. However, a more detailed comparison among the three nuclei must await the complete results of the ^{88}Sr$(t, p)^{90}$Sr experiment which is in progress.[8] The following discussion is devoted therefore to the comparison between ^{91}Y and ^{92}Zr in which we try to draw relationships between the (t, p) strength leading to the two nuclei.

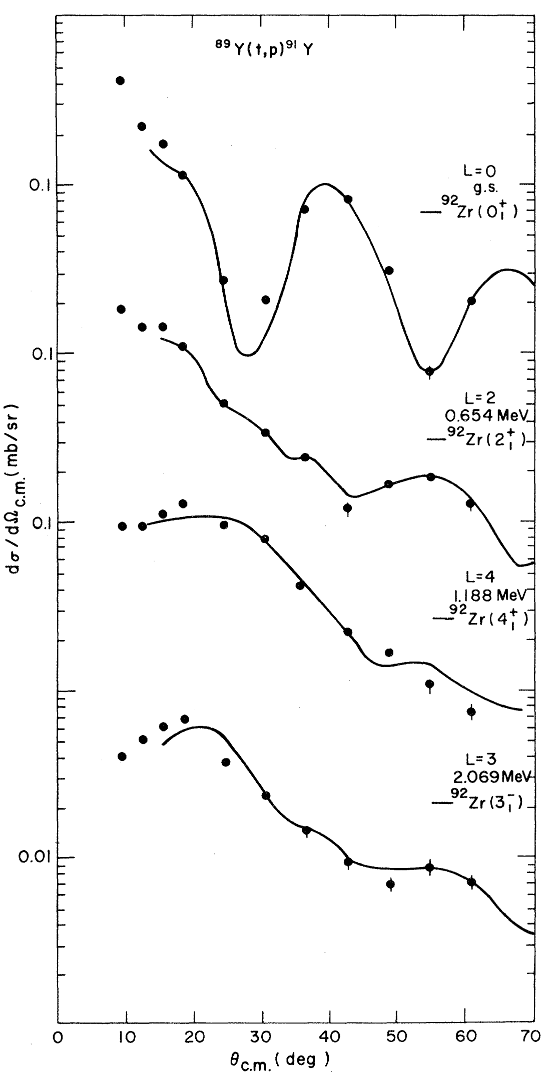

FIG. 3. A comparison between angular distributions of the ^{89}Y$(t,p)^{91}$Y experiment and the ^{90}Zr$(t,p)^{92}$Zr results of Ref. 8. The solid lines representing the Zr data have been normalized to the Y data, which are shown as filled circles. These normalization factors are listed in Table II.

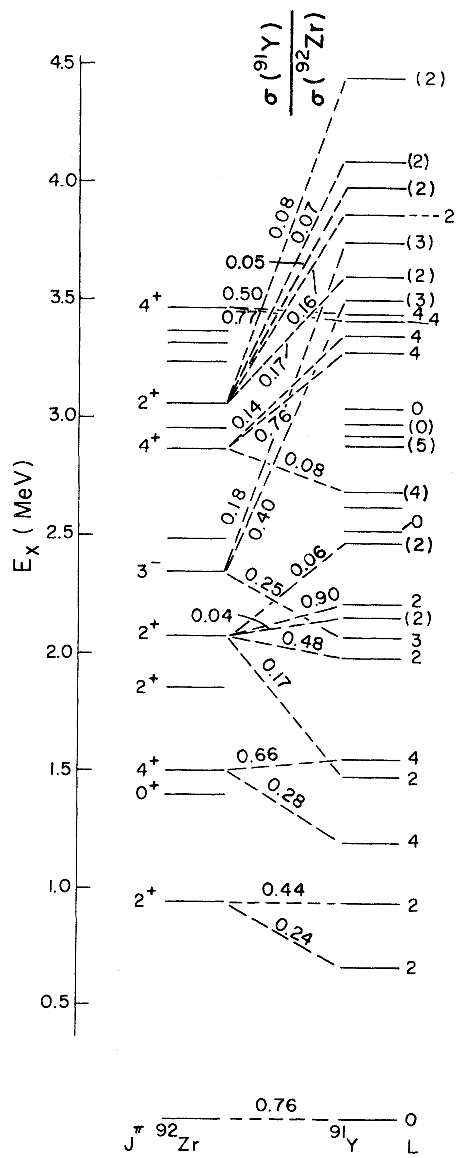

FIG. 4. The relationship between levels in ^{91}Y and ^{92}Zr as seen by the (t,p) reaction. The dashed lines connect levels in ^{91}Y, which may contain particle-phonon strength, to the corresponding phonon states in ^{92}Zr. The cross section ratios between these states are also indicated. Above 3.0 MeV only selected states in ^{91}Y are shown.

According to the particle-core coupling model, levels in ^{91}Y may be described by configurations of the form $[\pi^{-1}\otimes{}^{92}Zr(J)]$, where J refers to core states in ^{92}Zr. This description of the states of odd mass Y nuclei as a proton hole in the neighboring Zr nuclei is strictly accurate for the case of a $p_{1/2}$ hole, only when the two valence protons in Zr occupy the $p_{1/2}$ orbit. Normally, however, the protons possess mixed configurations of the form $[\alpha p_{1/2}{}^2 + \beta g_{9/2}{}^2]$, and for nonnegligible values of β, the hole-core coupling scheme breaks down. Nevertheless, for the purpose of comparing two-neutron transfer reactions in Y and Zr nuclei, it is convenient to use this scheme since the summed two-neutron strength should not be affected by an additional proton, and the extent to which the (t,p) strengths leading to related states of ^{91}Y and ^{92}Zr are equal should reflect the extent of the interaction between the valence protons and the core states. An additional assumption is that both reactions proceed by a predominantly one-step process.

The observed cross section in Table II indicates that 76% of the ^{92}Zr ground state cross section is present in the corresponding ^{91}Y transition. Although the deviation between the coupling model prediction and the experiment is not large, it does lie outside of the experimental errors, and therefore suggests that the simple particle-phonon coupling scheme is not entirely correct. Additional $L=0$ strength is seen in transitions leading to higher lying states at 2574, 3045, and possibly 2980 keV. The only excited 0^+ state measured in the $^{90}Zr(t,p)^{92}Zr$ reaction is at 1343 keV with a cross section of about 20% of the total cross section for the three $L=0$ transitions to excited states in ^{91}Y. Centroids for $L=0$ strength are not shown in Table II because it is likely that most of the excited $L=0$ transitions in ^{91}Y correspond to undetected $L=0$ strength in the $^{90}Zr(t,p)$ experiment which possessed poorer resolution.

TABLE II. Ratio of $^{89}Y(t,p)$ and $^{90}Zr(t,p)$ cross sections. Parentheses correspond to numbers that are uncertain because of tentative L-value assignments.

	E_x ^{92}Zr (MeV)	E_x ^{91}Y (MeV)	$\frac{\sigma(^{91}Y)}{\sigma(^{92}Zr)}$	$E_{centroid}$ (MeV)
$L=0$ states	0.0	0.0	0.76	
		2.574	0.05	
		2.980	(0.05)	
		3.045	0.09	
$L=2$ states	0.923	0.654	0.24	0.856
		0.927	0.44	
	2.071	1.476	0.17	
	+	1.976	0.48	(2.059)
	(1.842)	2.167	(0.04)	
		2.211	0.90	
		2.478	(0.06)	
	3.063	3.611	(0.17)	
		3.870	0.16	(3.889)
		3.966	(0.05)	
		4.096	(0.07)	
		4.451	(0.08)	
$L=3$ states	2.346	2.069	0.25	
		3.502	(0.40)	(3.124)
		3.751	(0.18)	
$L=4$ states	1.497	1.188	0.28	
		1.549	0.66	1.442
	2.871	2.689	(0.08)	
		3.284	0.76	(3.256)
		3.353	0.14	
	3.473	3.414	0.77	3.426
		3.445	0.50	

The next two levels observed in this study proceed by $L=2$ transfers and according to weak coupling should possess primarily the $[\pi^{-1}\otimes{}^{92}Zr(2_1^+)]$ configuration with spins $\frac{3}{2}^-$ and $\frac{5}{2}^-$. Their observation in the (t,α) experiment[9] with $l=1$ for the 654 keV level and $l=3$ for the 927 keV level identifies their spins as $\frac{3}{2}^-$ and $\frac{5}{2}^-$, respectively, according to Eq. (1). The total (t,p) strength observed for these levels is 68% of the strength measured in the $^{90}Zr(t,p)^{92}Zr(2_1^+)$ reaction which is again lower than expected from a simple model. However, the centroid of the two levels in ^{91}Y is only slightly lower than the 2_1^+ state of ^{92}Zr at 923 keV, and the $(2J+1)$ rule is reasonably well obeyed. The latter would predict a ratio of 1.5 for the (t,p) cross sections to the 927 and 654 keV levels, whereas a ratio of 1.8 is observed. As before, a mixing of strength with higher lying levels of the same spin and parity may be indicated. Two obvious nearby configurations for mixing with $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states are the $p_{3/2}{}^{-1}$ and $f_{5/2}{}^{-1}$ proton orbitals of the form $[\pi^{-1}\otimes{}^{92}Zr(0_1^+)]$. The (t,α) and $(d,{}^3He)$ spectroscopic factors leading to ^{91}Y imply that approximately 15 to 20% of the proton-hole strengths are contained in the 654 and 927 keV levels, which is consistent with the 68% parentage of these levels based on the $[\pi^{-1}\otimes{}^{92}Zr(2_1^+)]$ configuration that is obtained in the present experiment.

Five additional $L=2$ transitions (two of which are tentative) are seen in the excitation range of 1.0 to 2.5 MeV in ^{91}Y. While it is possible that these states are related to the $^{92}Zr(2_2^+)$ and $^{92}Zr(2_3^+)$ levels which lie at 1.842 and 2.071 MeV respectively, the relationship is not the simple one implied by the weak coupling model. The distribution of strength does not obey a $(2J+1)$ rule, and the summed strength of the five ^{91}Y levels is about 1.5 times that of the two ^{92}Zr levels. On the other hand, the possibility that a relationship does exist is supported by the location of the centroid of the five levels in ^{89}Y at 2.06 MeV compared with the ^{92}Zr centroid at 2.048 MeV, although the discrepancy in over-all strength indicates that this extraordinarily close agreement is probably fortuitous. There is additional possible $L=2$ strength contained in five more levels between 3.5 and 4.5 MeV in ^{91}Y. When this strength is combined with the lower $L=2$ strength, the total is about 85% of the $L=2$ strength measured up to 3.063 MeV in ^{92}Zr.

The first two states reached by $L=4$ transitions lie at 1.188 and 1.549 MeV in ^{91}Y with their centroid at 1.442 MeV, and together they comprise 94% of the strength observed for the ^{92}Zr(4_1^+) state at 1.497 MeV. However, the cross section ratio of the two states in ^{91}Y is inconsistent with a simple weak coupling picture. In addition, the large $l=3$ spectroscopic factor measured in the (t,α) reaction[9] for the 1.549 MeV state is very surprising. If this state is the same one assigned $L=4$ in the present (t,p) experiment, then the spin-parity must be $\frac{7}{2}^-$, which implies that it exhausts at least 50% of the ${f_{7/2}}^{-1}$ proton-hole strength. This result would appear to be inconsistent with shell model systematics in this region of the periodic table according to which the ${f_{7/2}}^{-1}$ strength should lie at much higher excitation energies and be considerably fragmented.[1] Thus it is possible that the 1.549 MeV level is in fact an unresolved doublet with two different levels strongly excited in the two reactions. The spin would be $\frac{5}{2}^-$ or $\frac{7}{2}^-$ for the level reached via (t,α), and $\frac{7}{2}^-$ or $\frac{9}{2}^-$ for the one excited by (t,p). The level at 1.188 MeV was not observed in the (t,α) experiment; its spin is either $\frac{7}{2}^-$ or $\frac{9}{2}^-$ according to the present (t,p) data.

Five additional $L=4$ transitions are measured between 2.5 and 3.5 MeV, compared with four that would be expected based on coupling to the second and third 4^+ states in ^{92}Zr. The summed cross section of these five states is 1.13 times the sum of the transitions leading to the ^{92}Zr(4_2^+) and ^{92}Zr(4_3^+) states. The presence of five states instead of four may be due to weak 4^+ states not seen in ^{92}Zr, or perhaps mixing with other states in this region of ^{91}Y.

$L=3$ strength observed to a single level in ^{92}Zr appears to be considerably fragmented in ^{91}Y. The only $L=3$ transition in ^{91}Y near the expected excitation energy lies at 2.069 MeV and contains 25% of the ^{92}Zr(3_1^-) state at 2.346 MeV. Two other transitions above 3.5 MeV are assigned $L=3$ or 4, and if they are indeed $L=3$ transitions the total $L=3$ strength in ^{91}Y up to 3.75 MeV would amount to 83% of the ^{92}Zr(3_1^-) state.

A number of $L=5$ and 6 transitions are seen in the region above 2.5 MeV of excitation in ^{91}Y. However, no such levels were identified in the ^{92}Zr study and it is not possible to compare the two nuclei in this respect. A possible 5^- state at 3.62 MeV in ^{92}Zr was noted in the (t,t') reaction,[20] which may correspond to the 3.609 MeV level seen in the ^{90}Zr$(t,p)^{92}$Zr study.[4] If the 3.609 MeV level is indeed 5^-, it may indicate a possible source for the $L=5$ strength in ^{91}Y.

B. Comparison of the observed levels to structure calculations

The most recent calculation available of the level scheme for ^{91}Y was performed some time ago by Vervier in his shell model study of the mass-90 region.[21] The results for ^{91}Y and ^{92}Zr are shown in Fig. 5, where they are compared with the experimental level schemes. There are several reasons not to expect good agreement between experiment and this calculation. Most importantly, the three orbitals used in the calculation, $(\pi p_{1/2})$, $(\pi g_{9/2})$, and $(\nu d_{5/2})$, provide too small a set of basis states to account for more

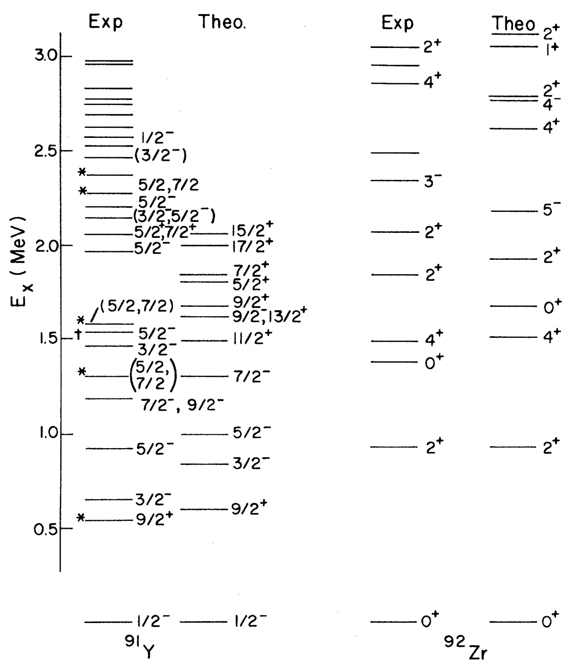

FIG. 5. A comparison between the experimental spectra of ^{91}Y and ^{92}Zr and the theoretical results of Vervier (Ref. 21). The asterisks (*) indicate levels not observed in the present experiment. The dagger (†) indicates a level which is suspected to be a doublet based on a comparison of (t,α) and (t,p) strengths. Arguments presented in the text suggest spin assignments of $\frac{5}{2}^-$, $\frac{7}{2}^-$ or $\frac{9}{2}^-$ for members of this doublet. Experimental spin assignments above 2.5 MeV in ^{91}Y have been omitted.

than the first few levels in the spectrum. The higher lying levels excited by the (t, p) reaction should be dominated by the $3s_{1/2}$ and $2d_{3/2}$ orbitals, and the calculation of ^{92}Zr by Ball and Bhatt,[4, 7] which includes these orbitals, does show somewhat better agreement for that nucleus. In addition, the calculation of Vervier does not include levels based on the $f_{5/2}{}^{-1}$ and $p_{3/2}{}^{-1}$ proton orbitals which are expected to mix strongly with other low-lying $\frac{3}{3}^-$ and $\frac{5}{2}^-$ levels. Another factor to note when comparing theory with experiment is that the $^{89}Y(t, p)^{91}Y$ reaction should not be directly sensitive to configurations involving the $\pi g_{9/2}$ orbit if it is assumed that the odd proton remains in the $\pi p_{1/2}$ orbit during the reaction. States with a $\pi g_{9/2}$ proton could be reached via configuration mixing or higher order reaction processes. The predicted positive parity states of high spin above the first excited state, which depend on the $\pi g_{9/2}$ orbit, have not yet been observed in the ^{91}Y spectrum, although there is no doubt that such states do exist.

C. Conclusions

The simplest model of particle-phonon coupling would predict that the spectrum of ^{91}Y excited by the (t, p) reaction should consist of doublets based on coupling the $\frac{1}{2}^-$ ground state of ^{91}Y to the levels in the ^{92}Zr spectrum excited by the same reaction. In reality, however, these configurations are expected to mix with additional particle-phonon configurations involving, for example, various proton orbitals, and such mixing will quickly fragment and redistribute the basic doublet strength. Nevertheless, the results of the present experiment show that particle-phonon coupling can describe to some extent the magnitude of the summed cross sections leading to states with the same L values, and in addition describe moderately well the lowest transitions of $L = 0$, 2, and 4. For the higher energy transitions of each L value, the simple model fails to account for either the distributions of strength or the number of levels observed. An obvious source of additional levels are the $f_{5/2}{}^{-1}$ and $p_{3/2}{}^{-1}$ proton-hole states which lie at low excitation in ^{91}Y; these can couple with various neutron pairing phonons to produce states of the same spin and parity as the primary configurations reached in the (t, p) reaction. Mixing among these configurations is the likely explanation of the fact that fragmentation occurs in the ^{91}Y spectrum while at the same time the total strength remains comparable with ^{92}Zr. The effect of mixing among the phonons as considered by Paar[22] can provide yet additional fragmentation.

In the previous study of ^{91}Y by Hardy *et al.*,[9] the experimental data were compared with the shell model calculation of Vervier,[21] and the main conclusion was that the discrepancies between theory and experiment result from the failure to include the proton-hole states in the calculation. While we agree on the importance of the proton hole states, we also believe that the neutron orbits above the $d_{5/2}$ level are equally important in attempting to explain the experimental spectrum in ^{91}Y. These were also omitted from Vervier's calculation[21] and were not cited in the previous explanation[9] of the disagreement with the experimental data. The additional neutron orbitals above the $d_{5/2}$ actually provide configurations and strength for many of the excited states reached by the (t, p) reaction leading to ^{91}Y and ^{92}Zr.

Another factor which limits the validity of the simple coupling picture between Y and Zr nuclei is the role of the 39th and 40th protons. In the case of Zr, the proton pair occupies a mixed configuration composed of the $p_{1/2}$ and $g_{9/2}$ orbits, and hence it is only a rough approximation to construct levels in the corresponding Y nucleus by coupling a $p_{1/2}$ proton hole. It will be extremely interesting to compare the results for both ^{91}Y and ^{92}Zr with results from the $^{88}Sr(t, p)^{90}Sr$ reaction when they become available.[8] This would then provide information about neutron pairing phonons as the proton coupling changes from the basic $Z = 38$ core alone to one and two protons outside. It is clear from the results thus far that the protons in the neighborhood of the $Z = 38$ core exert an important influence on the spectrum of two-neutron transitions excited by the (t, p) reaction in the mass-90 region.

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[1] J. R. Comfort, J. R. Duray, and W. J. Braithwaite, Phys. Rev. C 8, 1354 (1973).

[2] A. Bohr, in *Proceedings of the International Symposium of Nuclear Structure, Dubna, 1968* (International Atomic

Energy Agency, Vienna, Austria, 1969), p. 169; R. A. Broglia, O. Hansen, and C. Riedel, Adv. Nucl. Phys. 6, 287 (1974).
[3]D. R. Bes and R. A. Broglia, Phys. Rev. C 3, 2349 (1971); E. R. Flynn, G. Igo, P. D. Barnes, D. Kovar, D. R. Bes, and R. Broglia, *ibid.*, 3, 2371 (1971).
[4]E. R. Flynn, J. G. Beery, and A. G. Blair, Nucl. Phys. A218, 285 (1974).
[5]R. C. Ragaini, J. D. Knight, and W. T. Leland, Phys. Rev. C 2, 1020 (1970).
[6]E. Cosman, D. Slater, R. Casten, E. R. Flynn, and O. Hansen, Phys. Rev. C 10, 671 (1974).
[7]J. Ball and K. Bhatt, private communication.
[8]E. Cosman, E. R. Flynn, O. Hansen, J. Sherman, N. Stein, and J. W. Sunier, unpublished.
[9]J. C. Hardy, W. G. Davies, and W. Darcey, Nucl. Phys. A121, 103 (1968).
[10]E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, Phys. Rev. 182, 1113 (1969).
[11]D. C. Williams, O. E. Johnson, J. D. Knight, and W. T. Leland, Bull. Am. Phys. Soc. 13, No. 1, 119, HG4 (1968).
[12]R. J. Peterson, private communication.
[13]B. M. Preedom, E. Newman, and J. C. Hiebert, Phys. Rev. 166, 1156 (1968).
[14]The results referenced here are principally from Refs. 9, 11, and 13. These results have been compiled in Nucl. Data B8 (No. 6), 477 (1972).
[15]P. D. Kunz, private communication.
[16]B. F. Bayman and A. Kallio, Phys. Rev. 156, 1121 (1967); B. F. Bayman, private communication.
[17]F. G. Perey, Phys. Rev. 131, 745 (1963).
[18]E. R. Flynn and O. Hansen, Phys. Lett. 31B, 135 (1970).
[19]C. F. Kavaloski, J. S. Lilley, D. C. Shreve, and Nelson Stein, Phys. Rev. 161, 1107 (1967).
[20]E. R. Flynn, D. D. Armstrong, and J. G. Beery, Phys. Rev. C 1, 703 (1970).
[21]J. Vervier, Nucl. Phys. 75, 17 (1966).
[22]V. Paar, Nucl. Phys. A164, 576 (1971).