^{87}Sr(t, p) reaction and the two-particle–one-hole states of ^{89}Sr

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The ^{87}Sr(t, p)^{89}Sr reaction has been studied at a bombarding energy of 20 MeV. The lowest states excited are basically of single particle character and the corresponding (t, p) differential cross sections contain a mixture of L values. A comparison of these cross sections to distorted wave (DW) calculations yields qualitative information concerning configuration mixing in these states based both on the magnitudes as well as the shapes of the angular distributions. Analysis of the data is made partly by a comparison of DW calculations to the observed ^{87}Sr(t, p) differential cross section and partly by comparing experimental angular distributions of the ^{88}Sr(t, p)^{90}Sr reaction with those from ^{87}Sr(t, p). The higher lying states observed in this experiment may be explained from the coupling of the $1g_{9/2}$ neutron hole to the multipole pairing phonons, represented by the low lying states of ^{90}Sr.

[NUCLEAR REACTIONS ^{87}Sr(t, p), E = 20 MeV measured $\sigma(\theta)$, ^{89}Sr levels, DWBA deduced l, π.]

I. INTRODUCTION

^{88}Sr has been established as a near double magic nucleus, i.e., the neutron shell closure ($N = 50$) is good, while $Z = 38$ represents a proton subshell closure (see e.g. Refs. 1–3). It would therefore seem reasonable to describe the excitations in ^{88}Sr and adjacent nuclei in terms similar to those used for ^{208}Pb (Refs. 4, 7, 8). The lowest excitations of the closed shell nucleus (with N_0 neutrons) are collective particle-hole states, while the low lying states in the isotopes with $N_0 \pm 2$ neutrons are considered as pairing vibrations. Each of these types of excitations may be assigned a particle transfer quantum number α in addition to their spin λ and parity π; i.e., $\alpha = 0$ for the excitations in the N_0 system and $\alpha = \pm 2$ for the $N_0 \pm 2$ states. The low lying levels in the odd mass $N_0 + 1$ system are then of three types: single particle states, states with a particle coupled to one of the $\alpha = 0$ vibrational states in N_0, and states with a hole coupled to one of the $\alpha = 2$ pairing states in $N_0 + 2$. The ^{89}Sr single particle states (nlj) have been examined by the (d, p) process[1] and the particle-core $[(nlj)^{+1} \otimes (\alpha = 0)]$ coupled states have largely been identified from ^{88}Sr(p, p') analog state experiments.[5] The $[(nlj)^{-1} \otimes (\alpha = 2)]$ coupled states have previously not been identified.

In the Pb case the $[(nlj)^{-1} \otimes (\alpha = 2)]$ states were first identified through the ^{207}Pb(t, p)^{209}Pb reaction.[6,7] Here the two neutrons are considered to be transferred into orbits which form the ^{210}Pb states (the $\alpha = 2$ states) with the target neutron hole (nlj) $= (3p_{1/2})$ having essentially a spectators's role, so that principally only those $\alpha = 2$ coupled states which contain the ^{207}Pb ground state hole were excited. Additionally, the $[(nlj)^{-1} \otimes (\alpha = 2)]$ states with $\lambda^{\pi} = 0^+$ for the $\alpha = 2$ state and holes different from the $\frac{1}{2}^-$ ground state of ^{207}Pb were found through the ^{210}Pb(p, d)^{209}Pb reaction.[8]

The idea in the present experiment is similar to the one behind the Pb experiments referred to above. The ^{87}Sr(t, p)^{89}Sr reaction should excite states of the type $\{(\frac{9}{2}^+)^{-1} \otimes [\alpha = 2(\lambda^{\pi} = 0^+, 2^+, 4^+, \ldots)]\}$. Two differences between the Sr and Pb situations, however, should be stressed. ^{207}Pb has $J^{\pi} = \frac{1}{2}^-$ character and therefore only one L value contributes in a (t, p) transition. ^{87}Sr has $\frac{9}{2}^+$ character and several L values are usually allowed. In fact the magnitude of each L contribution depends on the microscopic structure of the (t, p) transition, and hence the angular distribution shapes contain in themselves information about the nuclear structure. This situation has not previously been explored in the (t, p) literature. Second, the parity of the hole and particle states is the same in the Sr case, while they are opposite for lead; hence, in ^{89}Sr the single particle states may mix with the $[(g_{9/2})^{-1} \otimes (\alpha = 2, \lambda^+)]$ states. The degree of this mixing can, in principle, be deduced from the comparison of the ^{88}Sr(d, p)^{89}Sr and ^{87}Sr(t, p)^{89}Sr data and is an important test of the hole-pairing coupling model. Mixing between the single particle states and the hole-pairing states is not allowed in Pb because except for the $j_{15/2}$ single particle state, the two types of levels have opposite parity.

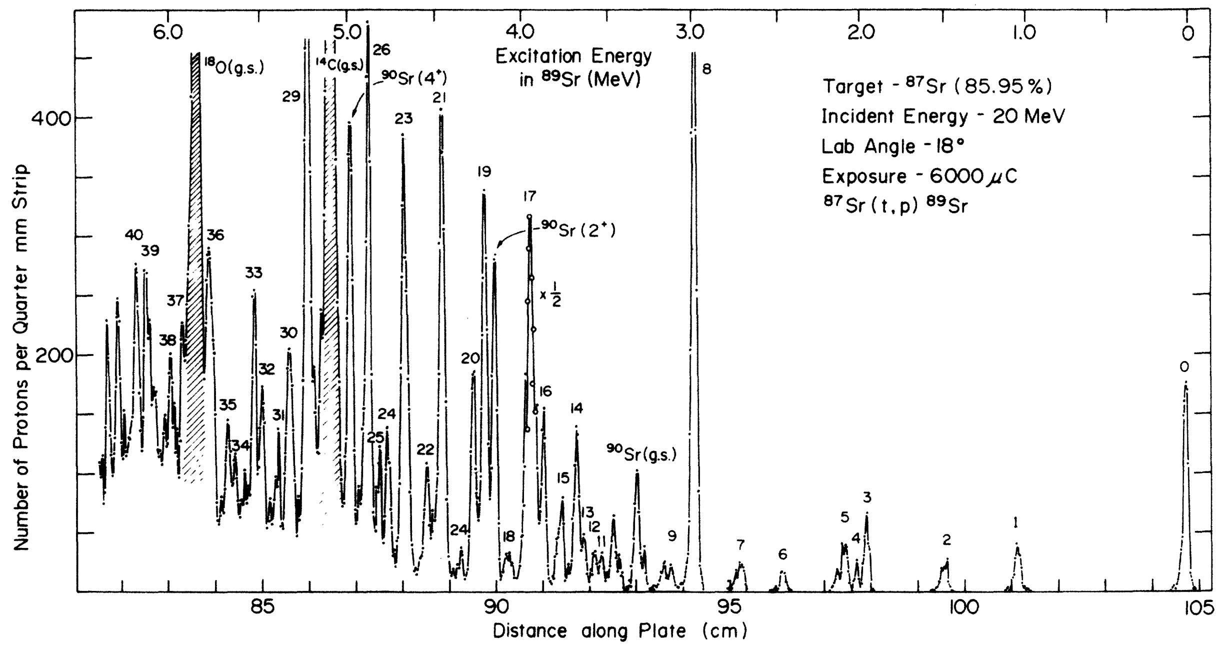

FIG. 1. Energy spectrum of protons from the ^{87}Sr(t, p)^{89}Sr reaction measured with the Los Alamos Scientific Laboratory Elbek type magnetic spectrograph. The numbering scheme shown for the ^{89}Sr levels corresponds to that in Table I and the states labeled ^{90}Sr arise from (t, p) on the ^{88}Sr target contamination. (The peak just below No. 11 should read No. 10.)

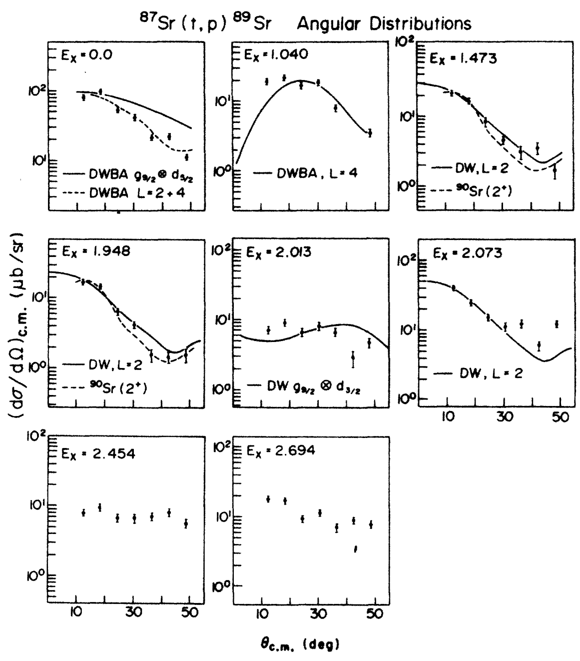

FIG. 2. The ^{87}Sr(t, p)^{89}Sr angular distributions to states with $E_x < 2.97$ MeV. The differential cross sections are in the c.m. system in μb/sr and the c.m. angles are in degrees. Fully drawn curves are DWBA predictions as discussed in the text. Broken curves are either alternative DWBA predictions (denoted as such in the figure) or shapes taken from the ^{88}Sr(t, p)^{90}Sr data of Fig. 6.

2. EXPERIMENTAL METHODS AND RESULTS

The target consisted of ~200 μg/cm^2 $Sr(NO_3)_2$ which had been evaporated onto a ~30 μg/cm^2 C backing. The $Sr(NO_3)_2$ was enriched in ^{87}Sr to 86.0% with 12.7% ^{88}Sr as the major contaminant. The presence of the ^{88}Sr impurity was of help in correlating ^{89}Sr and ^{90}Sr cross sections.

The target was bombarded with 20 MeV tritons from the Los Alamos three stage Van de Graaff facility and the reaction protons were momentum analyzed in a broad range spectrograph of Elbek geometry. Kodak NTB 50 μm nuclear emulsions were used as a focal plane detector; the emulsions were covered by graded Al foils of sufficient thickness to stop all heavy charged particles other than the protons. Typical exposures were 6 mC and the angular range from 12° to 48° was covered in steps of 6°.

Figure 1 shows a proton spectrum at 18° for the ^{87}Sr(t, p) reaction. The energy resolution was 20 keV full width at half-maximum and as can be seen from the figure, several groups from the ^{88}Sr-(t, p)^{90}Sr reaction were identified in addition to the ^{87}Sr(t, p) and light impurity groups. Since the kinematics of the ^{88}Sr and ^{87}Sr(t, p) reactions are too close to allow positive differentiation between the two processes, the identification of the ^{88}Sr transitions was made based on the ground state Q value[9] of 5.723 MeV and the ^{90}Sr level scheme as reported in Refs. 10 and 11. The uncertainty in excitation energy is ±10 keV.

The differential cross sections were obtained by simultaneously measuring the elastic triton scattering and the (t, p) intensity to the strong transition No. 8 with a solid state counter telescope. The elastic scattering was normalized to optical model predictions at forward angles. The error on the cross sections is less than ±25%. The proton angular distributions are shown in Figs. 2–5 (^{89}Sr) and in Fig. 6 (^{90}Sr). The maximum observed center of mass (c.m.) cross section for each transition is also quoted in Table I together with the corresponding laboratory angle.

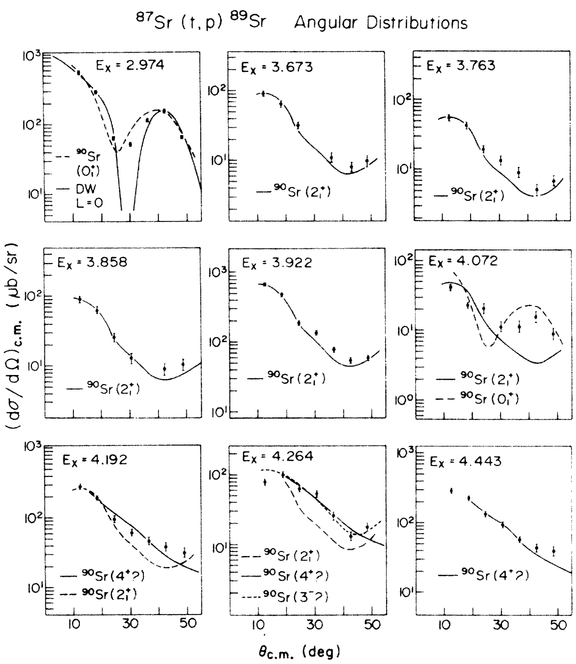

FIG. 3. The ^{87}Sr$(t, p)^{89}$Sr angular distribution to states with $2.97 < E_x < 4.44$ MeV. The measured angular distributions are compared with DW predictions or with empirical shapes from the ^{88}Sr$(t, p)^{90}$Sr reaction. The notation ^{90}Sr(2_1^+) refers to the (t, p) transition to the 0.833 MeV 2^+ state in ^{90}Sr, and ^{90}Sr(0_1^+) refers to the $L = 0$ ground state transition. Curves that fit the ^{88}Sr-$(t, p)^{90}$Sr angular distribution observed for the 1.66 MeV state are denoted as ^{90}Sr$(4^+?)$, where the question mark should be a reminder that the spin of this particular state is not known with certainty. The mark ^{89}Sr$(3^-?)$ refers to the transition to the ^{90}Sr state at 1.89 MeV which in Table I is denoted as group 29 reflecting that the identification of the final state mass (89 or 90) for this particular level is not clear. The curves for this transition are drawn to show that if the final state mass is 90 and the final state spin is 3 (as argued in Ref. 11) it is not possible with the present data to distinguish $L = 4$ from $L = 3$.

3. *L* ASSIGNMENTS AND DISTORTED-WAVE ANALYSIS

^{90}Sr states

The ground and first excited states of ^{90}Sr have $J^\pi = 0^+$ and 2^+, respectively,[10] while spin and parity assignments have not been published for those higher ^{90}Sr states which fall inside the excitation range covered here, i.e., the 1.6555, 1.8921, 2.2068, 2.4972, 2.5271, and 2.5712 MeV levels (see Ref. 10). Unpublished data from the ^{88}Sr(t, p) reaction (see Ref. 11) show that the three first mentioned states (1.66, 1.89, and 2.21 MeV) are excited, the remaining three probably not. Tentative assignments from these (t, p) data were[11] 1.66 MeV 4^+, 1.89 MeV 3^-, and 2.21 MeV 2^+, respectively. The 4^+ assignment fits well into the 4^+ systematics as known for other $N = 52$ nuclei,[12] whereas a 3^- assignment to the 1.89 MeV level falls well outside the systematics of 3^- states in this region. Proton group No. 29 (see Table I) coincides in energy with the group expected from the ^{90}Sr 1.89 MeV level, and group No. 33 coincides with the ^{90}Sr, $E_x = 2.21$ MeV group; both transitions exhibit angular distribution shapes that are similar to the 1.66 MeV $L = 4$ shape. These transitions cannot on the basis of the present data be assigned to a definite final mass; they may represent unresolved transitions to levels in both ^{89}Sr and ^{90}Sr.

The distorted wave (DW) calculations were made using the code TWOPAR by Bayman.[13]

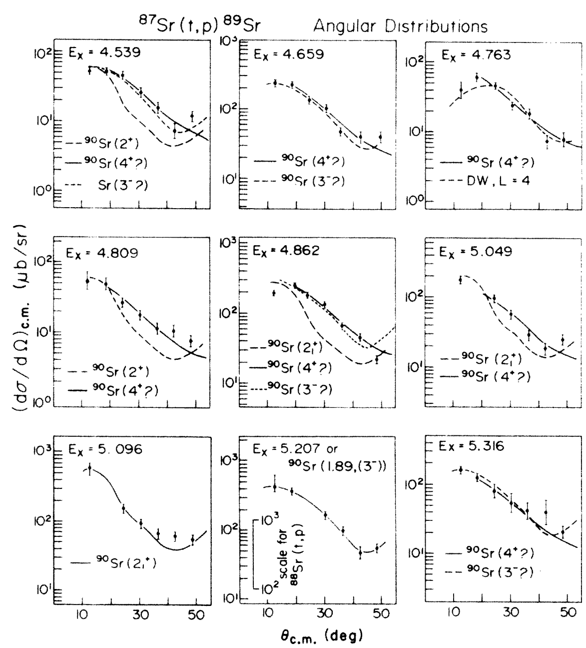

FIG. 4. The ^{87}Sr$(t, p)^{89}$Sr angular distributions to states with $4.53 < E_x < 5.32$ MeV. For notation see caption to Fig. 3.

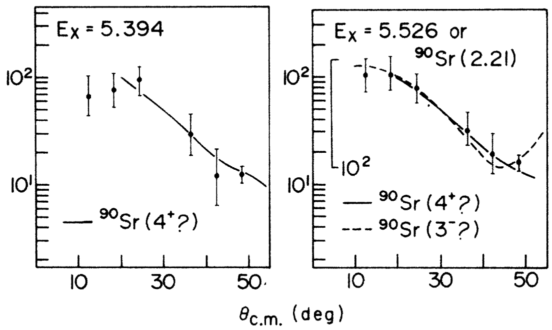

FIG. 5. The ^{87}Sr(t, p) angular distributions for the 5.394 and 5.526 MeV levels. The inserted cross section scale is for ^{90}Sr as a final nucleus. See also caption for Fig. 3.

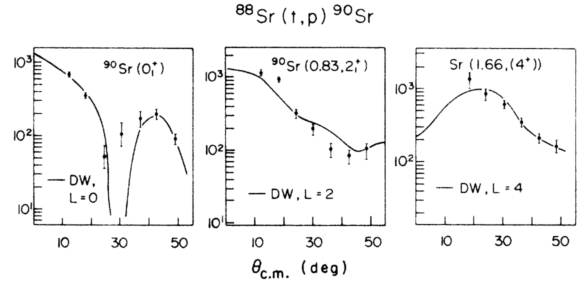

FIG. 6. ^{88}Sr(t, p) results. The angular distributions are shown in comparison with DWBA predictions. The cross sections are in μb/sr in the c.m. system and the c.m. angles are in degrees.

TABLE I. ^{89}Sr results.

Group No.	E_x (MeV) (t,p)	E_x (MeV) (d,p)	$L(t,p)$	σ_{max} (μb/sr)	θ (deg)	$l(d,p)$	$(2J+1)S$ (d,p)	J^π Previous	J^π (t,p)
0	0	0	2+4	95	18	2	4.8	$\frac{5}{2}^+$	
1	1.040	1.031	4	21	18	0	1.8	$\frac{1}{2}^+$	
2	1.473	1.460	2	20	12				$\frac{5}{2}-\frac{13}{2}^+$
3	1.948	1.931	2	37	12	2	0.5	$(\frac{5}{2}^+)$	
4	2.013	2.000	No $L=2$	10	30	2	1.9	$\frac{3}{2}^+$	
5	2.073	2.057	2	37	12				$\frac{5}{2}-\frac{13}{2}^+$
		2.071							
		2.266				1	0.01		
6	2.454	2.455	No $L=2$	10	18	2	1.4	$\frac{3}{2}^+$	
		2.558				1	0.02		
		2.671				4	5.0	$\frac{7}{2}^+$	
7	2.694	2.691		17	12				
		2.805							
		2.918							
8	2.974		0	551	12				$\frac{9}{2}^+$
9	3.116	3.128		20	12	2	0.317	$\frac{3}{2}^+$	
10	3.448			31	12				
11	3.528			17	12				
12	3.566			27	12				
13	3.633			24	18				
14	3.673		2	90	12				
15	3.763		2	54	12				
16	3.858		2	89	12				
17	3.922		2	663	12				
18	4.072		(2)	40	12				
19	4.192		2+3, 4	286	12				

TABLE I (*continued*)

Group No.	E_x (MeV) (t,p)	E_x (MeV) (d,p)	$L(t,p)$	σ_{max} (μb/sr)	θ (deg)	$l(d,p)$	$(2J+1)S$ (d,p)	J^{π} Previous	J^{π} (t,p)
20	4.264		3, 4	99	18				
21	4.443		3, 4	277	12				
22	4.539		3, 4	52	12				
23	4.659		3, 4	239	12				
24	4.763		3, 4	60	18				
25	4.809		3, 4	55	12				
26	4.862		3, 4	249	18				
27	5.049		3, 4	166	(12)				
28	5.096		2	584	12				
(29) [a]	(5.207)		(3, 4)	429	18				
30	5.316		(3, 4)	160	12				
31	5.482			55	18				
32	5.394		(3, 4)	95	24				
(33) [a]	(5.526)		(3, 4)	102	18				
34	5.632			22	18				
35	5.670			42	12				
36	5.762			170	(18)				
37	5.925			26	12				
38	5.995			50	18				
39	6.115			118	12				
40	6.188			81	18				

[a] These transitions may partially be to states in ^{90}Sr, see Table II.

The triton and proton optical potentials as well as the bound state parameters are the same as used in Ref. 12. All parameters were chosen according to the recipe of Ref. 14 with triton parameters from Flynn *et al.*[15] and proton potentials from Perey.[16]

The distorted-wave Born-approximation (DWBA)

TABLE II. ^{90}Sr levels observed in the present experiment.

Group No.	E_x (MeV)	L	σ_{max} (μb/sr)	θ (deg)
0	0	0	723	12
1	0.833	2	1096	12
2	1.66	(4)	1308	18
29 [a]	1.89	3, 4	2905	18
33 [a]	2.21		691	18

[a] These transitions may partially be to states in ^{89}Sr, see Table I.

angular distributions are compared to the $^{88}Sr(t, p)$ data in Fig. 6 and it seems that the agreement between predictions and data for the lowest three states is reasonably good. The measured absolute cross sections are 2.5 times larger than the $(d_{5/2})^2$ predictions at 12° for the 0^+ and 2^+ states and 3 times larger at 15° for the supposed 4^+ state. In this comparison a D_0^2 of 22.5 MeV^2 fm$^3 \times 10^{+4}$ was used for the DW normalization factor (see also Refs. 14 and 17). These enhancements are identical with the $^{90}Zr(t, p)^{92}Zr$ enhancements[12] for the 0^+, 2^+, and 4^+ transitions.

^{89}Sr states at $E_x > 2.95$ MeV

The L assignments in the Q-value region corresponding to the observed ^{90}Sr transitions were made primarily by comparison between the ^{90}Sr and the ^{89}Sr angular distributions. Only one $L=0$ distribution was assigned, at $E_x = 2.974$ MeV (state No. 8 in Table I); both the DW and ^{90}Sr comparisons to this state are acceptable (see Fig. 3). Examples of typical $L=2$ distributions (Fig. 3) are those for states No. 14 (3.673 MeV), No. 16 (3.858 MeV), and No. 17 (3.922 MeV); these distributions are nearly identical to the ^{90}Sr $L=2$ example. The distribution to state 21 (4.443 MeV) provides an example of good agreement between a ^{89}Sr distribution and the assumed ^{90}Sr (1.66 $L=4$) distribution. Level No. 19 (4.192 MeV) has an angular distribution with a shape between the $L=2$ and 4 standard shapes and thus probably represents a mixture of $L=2$ and 4 shapes.

The DW predictions suggest that it is difficult to distinguish between $L=3$ and $L=4$ distributions in this mass region with the present data and it cannot be excluded that some $L=3$ strength is indeed present in the region of excitation above 4.0 MeV in ^{89}Sr. Specifically, if the state in ^{90}Sr at 1.89 MeV is a 3^- state it is seen (e.g. Fig. 3, E_x =4.264 MeV level) that its shape is very similar to that of the assumed ^{90}Sr (4^+, 1.66) state, making L =3 versus 4 assignments in ^{89}Sr by the ^{90}Sr template rather tenuous. For these reasons Table I quotes all $L=3$ or 4 candidates above 2.95 MeV as $L=3, 4$.

^{89}Sr states below 2.95 MeV

Most of the low lying ^{89}Sr states (see Fig. 2) have single particle strength and they are reached in the (t,p) reaction by depositing one of the transferred neutrons in the $g_{9/2}$ hole of the ^{87}Sr target, while the second neutron is transferred into one of the single particle orbits. The transition to the 1.040 MeV level must be pure $L=4$, since this state has $\frac{1}{2}^+$ character. The observed (t,p) distribution shape agrees well up to the forward-most angles with the $L=4$ DW prediction, a discrepancy also noted in the Zr nuclei.[12] Also the distributions for states 2 (1.473 MeV) and 3 (1.948 MeV) agree well with the $L=2$ DW shapes.

4. DISCUSSION

^{89}Sr ground state

If we describe the ^{87}Sr $\frac{9}{2}^+$ ground state as a pure $g_{9/2}$ neutron hole relative to the ^{88}Sr ground state core (Ref. 2) and further take the ^{89}Sr ground state to be a pure $2d_{5/2}$ single particle state [the (d,p) spectroscopic factor[1] is 0.8], the (t,p) transition connecting the two states has a $g_{9/2}d_{5/2}$ form factor and spectroscopic amplitudes

$$B(\tfrac{9}{2}+L\rightarrow\tfrac{5}{2})=[(2L+1)/(2\times\tfrac{5}{2}+1)]^{1/2};$$

i.e., $B^2\,(L=2):B^2\,(L=4):B^2\,(L=6)=5:9:13$. Figure 2 shows the corresponding predicted differential cross section as a function of angle in comparison with the data. There is little resemblance between experiment and DW prediction. A very good fit to the data can be obtained by mixing $L=2$ and $L=4$ and omitting altogether the $L=6$ contribution. Thus, from the observed angular distribution shape we may infer that the transition to the ground state cannot be accounted for within a pure shell model description. It would seem reasonable to assume that the further degrees of freedom present in these states derive from the coupling between the core degrees of freedom and the single nucleon degrees of freedom.

^{89}Sr 1.04 MeV $\frac{1}{2}^+$ state

The 1.04 MeV state has a (d,p) $l=0$ spectroscopic factor of 0.9 and this state should therefore be largely of single particle character. The maximum differential cross section predicted for a $\frac{9}{2}^+\rightarrow\frac{1}{2}^+ g_{9/2}s_{1/2}(t,p)$ transition is 21 μb/sr in agreement with the observed cross section. Thus, this particular transition is well described as a pure configuration transition of single particle strength in both one and two nucleon transfer reactions.

Other low lying states

The states at 1.47 and 2.07 MeV were excited by $L=2$ transitions in the (t,p) process, while no single particle strength was measured for these states. It may therefore be inferred that they are essentially core coupled states. The 2^+ state of ^{88}Sr is at 1.84 MeV; it is weakly excited in the ^{86}Sr$(t,p)^{88}$Sr reaction,[11] and it carries little (d,p) single particle strength.[1] This ^{88}Sr state is therefore mainly a proton excitation and it seems reasonable to describe the ^{89}Sr states near 1.8 MeV as deriving mainly from the coupling of the ^{89}Sr $(d_{5/2})$ ground state neutron to this ^{88}Sr 2^+ state. Such states can be excited in the (t,p) process through the ^{87}Sr ground state component of $(g_{9/2})^{-1}$ coupled to the same ^{88}Sr 2^+ state. It is our conclusion that core coupling in ^{87}Sr as well as in ^{89}Sr must be taken into account in order to explain the present data quantitatively.

The levels at 2.013 and 2.454 MeV are supposed to carry the majority of the $d_{3/2}$ single particle strength. A spin parity assignment of $\frac{3}{2}^+$ excludes $L=2$ (t,p) strength and the transition must go as mixtures of $L=4$ and 6. Both of these levels are very weak in the (t,p) process and do not show $L=2$ distribution shapes. The summed maximum cross sections for these two transitions is 20 μb/sr, whereas a total $g_{9/2}\times d_{3/2}$ cross section of ~34 μb/sr is predicted. The 2.67 MeV $g_{7/2}$ single particle state was not observed in the (t,p) experiment. The predicted (t,p) strength for a single $\frac{9}{2}^+$ hole to single $\frac{7}{2}^+$ particle transition is ~12

TABLE III. Comparison of the 2p-1h states in ^{89}Sr and the pairing phonon states in ^{90}Sr. The ratios $\sigma/\sigma[^{90}Sr(L)]$ correspond to the maximum cross sections quoted in Tables I and II.

Level No.	L	E_x (MeV)	Q (MeV)	$Q_{90}-Q_{89}$	$\sigma/\sigma[^{90}Sr(L)]$
8	0	2.974	6.037	−0.314	0.76
14	2	3.673	5.338	−0.448	0.082
15	2	3.763	5.248	−0.358	0.049
16	2	3.858	5.153	−0.263	0.081
17	2	3.922	5.089	−0.199	0.60
18	(2)	(4.072)	(4.939)	−0.049	(0.04)
19	2, 4	4.192	4.819	+0.071	0.26
28	2	5.096	3.915	+0.975	0.53

Including level Nos. 14, 15, 16, 17, 18, 19: $\sum \sigma/\sigma[^{90}Sr(2_1^+)] = 1.11$
$\overline{\Delta Q} = -207$ keV.

μb/sr, i.e., near the lower limit for an observable cross section in the present experiment.

Hole-pairing phonon states

In the simplest form of the particle-pairing–phonon-coupling model, one expects to see states in the N_0+1 nucleus consisting of $\alpha=2$ phonons coupled with holes in the N_0 core, with these states exhibiting properties similar to those of the $\alpha=2$ states in the N_0+2 nucleus. In particular, in the (t,p) reaction starting from the N_0-1 nucleus, states should be observed with the same cross section, angular-momentum transfer, and Q values as if the target had been with N_0 neutrons. This simple model is equivalent to stating that the hole and phonon do not interact and that there is no mixing of final states. (In the following, we shall call such pairing hole-coupled states 2p-1h states for short.) A summary of the present results on the 2p-1h states in ^{89}Sr are given in Table III and Fig. 7.

The lowest $L=0$ transition observed in the present ^{87}Sr$(t,p)^{89}$Sr study is at 2.974 MeV, and it is the principal candidate for the first 2p-1h state. Its structure would be mainly $[(1g_{9/2})^{-1}\otimes{}^{90}\mathrm{Sr(g.s.)}]_{9/2^+}$. The observed cross section is 76% of the corresponding ^{88}Sr$(t,p)^{90}$Sr ground-state strength, and the Q value is only 314 keV higher (see Table III). It thus fits the simple model predictions quite well. The small amount of missing strength may be due to final-state mixing with higher $\frac{9}{2}^+$ states in ^{89}Sr or to mixing of the pure $(g_{9/2})^{-1}$ hole with core-excited configurations in the target, such as $[(g_{9/2})^{-1}\otimes{}^{88}\mathrm{Sr}(2_1^+)]_{9/2}$. (See also the discussion above). It is of interest to note that the locations of $[lj\otimes(g_{9/2})^{-1}]_J$ multiplets from ^{87}Sr$(d,p)^{88}$Sr (Ref. 1) are shifted downward by between 160 and 200 keV for $lj=2d_{5/2}$, $3s_{1/2}$, and $2d_{3/2}$ relative to the positions expected from the binding energies of the ^{88}Sr$(d,p)^{89}$Sr single particle centroids.

This implies an attractive interaction between the $g_{9/2}$ hole and the extra core lj particles of an approximately constant amount. Assuming that the $\alpha=2$, 0^+ pairing phonon is a linear superposition of pairs of lj particles, one would in first approximation expect this interaction to lower the $[(g_{9/2})^{-1}\otimes{}^{90}\mathrm{Sr(g.s.)}]_{9/2}$ state by twice the ^{88}Sr 1p-1h shift; that is, by about 320 to 400 keV which is close to the observed value.

The 2.974 MeV $\frac{9}{2}^+$ state was not excited in the ^{88}Sr(d,p) reaction with measurable strength, a further indication of the 2p-1h nature of this state.

The next 2p-1h states expected are the $[(1g_{9/2}{}^{-1}$

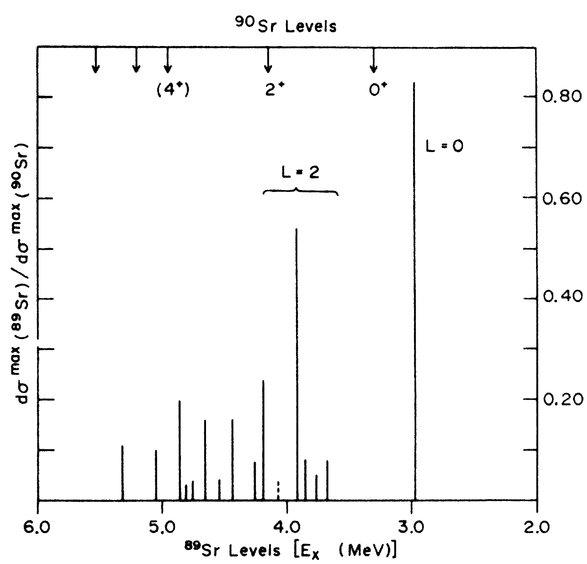

FIG. 7. Selected transitions plotted versus ^{89}Sr excitation energy. The ^{89}Sr levels are those of Table III with the omission of the 5.096 MeV $L=2$ transition and the suspected ^{90}Sr transitions (Nos. 29 and 33). The vertical scale is J/max for a ^{89}Sr transition divided by J/max for the corres- nding ^{90}Sr transition, i.e., ^{90}Sr-(g.s.) for $L=0$, ^{90}Sr(2^+) for $L=2$, and ^{90}Sr(1.66) for the remaining cases.

$\otimes{}^{90}\mathrm{Sr}(2_1^+)]_J$ multiplet which should consist of five states with spins $J^\pi = \frac{5}{2}^+$ through $\frac{13}{2}^+$ and have a centroid at $E_x = 4.12$ MeV [calculated from the Q value of 4.89 MeV for the ${}^{88}\mathrm{Sr}(t,p){}^{90}\mathrm{Sr}(2_1^+)$ transition]. Indeed, we find five states with appreciable $L=2$ strength in the appropriate region (groups 14–17 and 19) plus one tentative $L=2$ transition at $E_x = 4.072$ (group 18) and another at 5.096 MeV (No. 28). The latter state may be unrelated to the multiplet. The sum of the cross sections for the first six $L=2$ transitions is 1.11 times that for ${}^{90}\mathrm{Sr}(2_1^+)$ [if level 19 is omitted the sum is 0.85 times that of ${}^{90}\mathrm{Sr}(2_1^+)$], and their centroid is at $E_x = 3.913$ MeV, 207 keV lower than the zeroth order value. The over-all spread of these levels is only 500 keV, indicating small residual interactions. Again the simple picture seems to be nearly correct if one accepts the proposed identifications.

The following remarks on the multiplet are rather speculative and they are presented mainly because they may provide useful points to be tested by future work. For example, an attempt at spin assignments by the $2J+1$ rule can be made. In the simple model, the yields for $J = \frac{5}{2}, \frac{7}{2}, \frac{9}{2}, \frac{11}{2}$, and $\frac{13}{2}$ should be 0.12, 0.16, 0.20, 0.24, and 0.28 of that for the ${}^{90}\mathrm{Sr}(2_1^+)$ transition, respectively. From the cross section values in Table III (right most column), one would say that the 4.192 level has $J \geq \frac{9}{2}$ (although the possible $L=4$ admixture makes this assignment rather uncertain) and that the level at 3.922 MeV must be a doublet containing two states of spins $\frac{9}{2}$, $\frac{11}{2}$, or $\frac{13}{2}$. The latter point is supported by a broader half-width for the 3.922 MeV groups. A state at 3.691 MeV was reported from ${}^{88}\mathrm{Sr}(d,p){}^{88}\mathrm{Sr}$ (Ref. 1) as $l_n = 2$. If it is identical to the present 3.673 MeV state, then this would imply it has $J^\pi = \frac{5}{2}^+$, and thus by elimination, one or more of the 3.763, 3.858, or 4.072 MeV states should have $\frac{7}{2}^+$ spin. Of these, the 3.858 MeV state is more likely $\frac{7}{2}^+$ because of its relatively larger strength. The observed shifts and splittings of these states contain further important information on the hole-pairing phonon interaction and will also be essential input to a more quantitative analysis. If the transition to level 28 at 5.096 MeV is included the cross section sum is 1.6 times that for ${}^{90}\mathrm{Sr}(2_1^+)$, indicating that another degree of freedom is present.

The situation for the $[(g_{9/2})^{-1} \times {}^{90}\mathrm{Sr}(4_1^+)]_J$ states is unclear because of the difficulty in distinguishing $L=4$ shapes from $L=3$ as mentioned above.

5. CONCLUSIONS

The levels excited in the ${}^{87}\mathrm{Sr}(t,p)$ reaction fall into two main groups. The states below 2.95 MeV are either single particle fragments or states formed mainly by coupling the single particles to the ${}^{88}\mathrm{Sr}(2^+)$ state at 1.8 MeV. The levels observed above 2.95 MeV are two-particle–one-hole states formed by removing a $g_{9/2}$ neutron $(\alpha = -1)$ from the $(\alpha = 2)$ ${}^{90}\mathrm{Sr}$ states. Comparison of ${}^{87}\mathrm{Sr}(t,p)$ and ${}^{88}\mathrm{Sr}(d,p)$ results indicate that these two classes of states are not significantly mixed. Most of the expected $L=0$ and 2 strength for these 2p-1h states is located at energies near those expected from the lowest order estimates, making these levels especially amenable to quantitative theoretical analysis.

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