Evidence for core-coupled states in ^{87}Y from a ^{89}Y$(p,t)^{87}$Y and ^{88}Sr$(p,t)^{86}$Sr comparison*

I. C. Oelrich, K. Krien,† R. M. DelVecchio, and R. A. Naumann
Joseph Henry Laboratories and Frick Chemical Laboratories, Princeton University, Princeton, New Jersey 08540
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The ^{89}Y$(p,t)^{87}$Y and ^{88}Sr$(p,t)^{86}$Sr reactions were studied at 42 MeV proton energy, using a quadrupole-dipole-dipole-dipole spectrograph. Comparison of excitation energies, (p,t) cross-section strengths, and angular distribution shapes indicates that basic features of the core-coupling model apply to these nuclei. However, mixing of single-particle states with the core-coupled states is evident. The (p,t) cross-section strength summed over the ^{87}Y multiplet is found with few exceptions to be nearly a constant multiple of the (p,t) strength of the associated ^{86}Sr state.

[NUCLEAR REACTIONS ^{88}Sr, ^{89}Y(p,t), $E=42$ MeV; measured $\sigma(\theta)$ and level energies; DWBA analysis, deduced L, J^{π}. Resolution 12 keV for ^{86}Sr levels and 17 keV for ^{87}Y levels. Enriched targets. Core-coupling model.]

INTRODUCTION

The particle-core weak coupling model has been a useful guide to the understanding of the spectra of odd-A nuclei. The simplest example of this model involves the coupling of a spin $\frac{1}{2}$ particle onto states of an even-even core. The resulting multiplets are either singlets or doublets depending on whether the core state spin is zero or nonzero. Experimentally, spin $\frac{1}{2}$ coupling is a welcome simplification in view of generally high densities found in the heavier nuclei studied here. Previous work in this laboratory found the expected multiplets arising from the coupling of a $2p_{1/2}$ proton state onto vibrational core states in several nuclei near mass 100, using the (p, t) reaction.[1,2] In an effort to further explore the systematics of this coupling, we have performed the (p, t) reaction on $^{89}_{39}$Y$_{50}$, another example of an odd proton nucleus with a ground state spin of $\frac{1}{2}$ where the $2p_{1/2}$ proton configuration is expected to be important. The core ^{88}Sr(p, t) ^{86}Sr reaction was studied to aid in the identification of weak coupled states via cross-section and angular distribution comparisons.

The ^{89}Y(p, t) reaction as well as the ^{88}Sr(p, t) reaction have been studied previously.[3-6] However, the resolution attained and low yields hampered the identification of core-coupled states. The present work utilized the large solid angle and high resolution of the Princeton quadrupole-dipole-dipole-dipole (QDDD) spectrograph to help extend the previous experimental information. The proximity of these nuclei to magic or near magic proton and neutron configurations makes more detailed experimental data on ^{86}Sr and ^{87}Y of interest apart from weak coupling considerations.

A previous ^{86}Sr(^{3}He, d) ^{87}Y high resolution study[7] found significant $1f_{5/2}$, $2p_{3/2}$, $1g_{9/2}$, and $2d_{5/2}$ single-particle strength in the excitation region investigated here. Mixing of such states having single-particle strength other than $2p_{1/2}$ with levels arising from coupling the ^{87}Y ground state proton configuration onto even-even core states may therefore be anticipated. In fact, a ^{89}Y(t, p) study[8] reported significant fractionation of core-coupled states in ^{91}Y.

EXPERIMENTAL PROCEDURE

The ^{89}Y target of $\sim 300\,\mu$g/cm^2 thickness was prepared from naturally monoisotopic yttrium metal by vacuum deposition onto a 250 μg/cm^2 aluminum backing. The ^{88}Sr target was prepared by vacuum deposition of 99.8% isotopically pure material onto a 20 μg/cm^2 carbon film to a thickness of $\sim 50\,\mu$g/cm^2. The Sr layer was then covered with a thin ($\sim 6\,\mu$g/cm^2) film of Formvar to prevent peeling. The targets were bombarded with a 41.9 ± 0.1 MeV proton beam from the Princeton azimuthally varying field cyclotron. Outgoing tritons were focused by a QDDD spectrograph onto a 60 cm wire proportional counter backed by a plastic scintillator. The detection system allowed on-line particle identification as well as position determination. Since the detector did not cover the total excitation energy range of interest, it was necessary to take two overlapping spectra at each angle for each target.

Typical triton spectra are shown in Figs. 1 and 2. The solid angle of the QDDD was set at 10 msr for all runs. The resolution achieved for

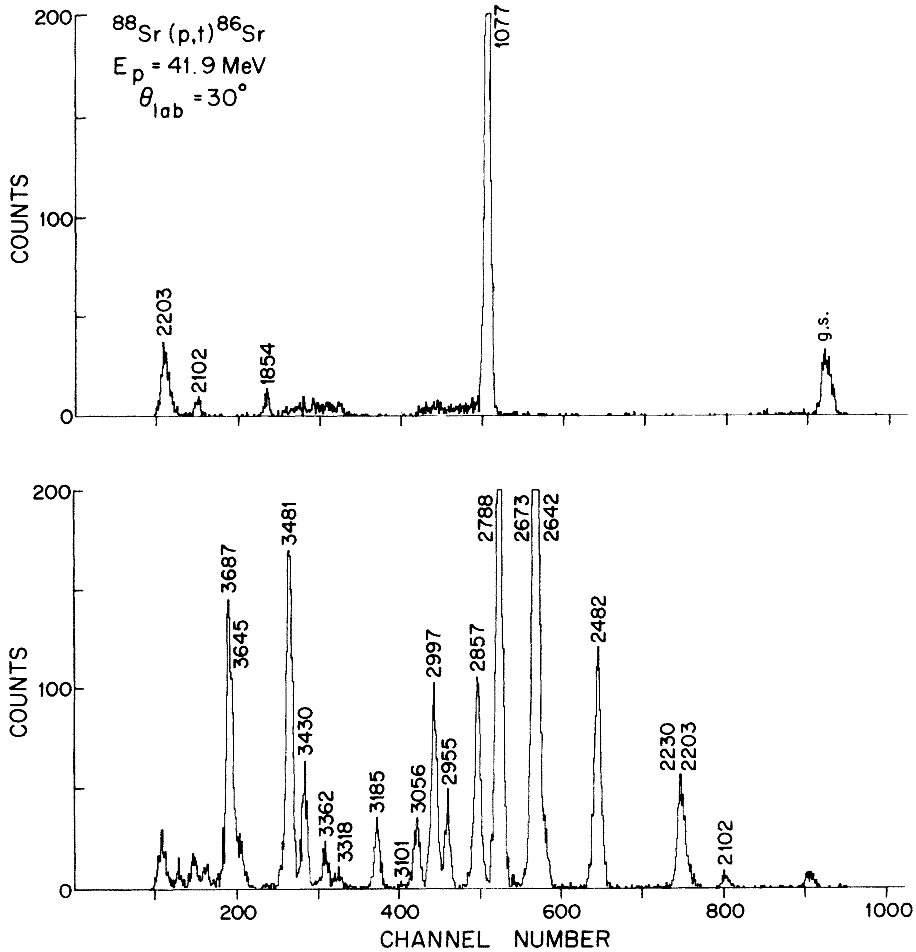

FIG. 1. $^{88}Sr(p,t)^{86}Sr$ position spectrum obtained with a wire proportional counter in the QDDD focal plane. The peaks are labeled with excitation energy in keV.

^{87}Y was 17 keV full width at half maximum (FWHM), and that for ^{86}Sr was 12 keV FWHM, the difference resulting from the different target thicknesses.

Areas and centroids of the triton peaks were determined by use of the computer code AUTOFIT.[9] The focal plane was calibrated by means of levels in ^{86}Sr and ^{87}Y with excitation energies determined from γ-ray work.[10,11] The energies of the levels excited in this (p, t) investigation are given in Tables II and III for ^{86}Sr and ^{87}Y, respectively. When available, the more accurate γ-ray energies are quoted. Our energy determinations are believed accurate to ± 2 keV in ^{86}Sr and ± 5 keV in ^{87}Y.

Differential cross sections were measured at angles from 10° to 50° in 5° steps. Relative normalization was based on the charge accumulated in the Faraday cup. In addition, a NaI crystal scintillation detector at 90° to the beam direction monitored the elastically scattered protons. The monitor-to-charge comparison indicated that no target deterioration occurred during the runs. Absolute cross sections were based on elastic scattering and (p, t) measurements carried out in our large (1.5 m diameter) scattering chamber. Global formulas of Ref. 12 were used to compute absolute p-elastic cross sections, relative to which (p, t) cross sections could be determined. Since data were taken over a range of angles, slight disagreements observed between the predicted and measured shapes of the elastic angular distributions should not greatly affect our results. Considering such differences, we assign an overall normalization error of $\pm 40\%$ in our absolute cross sections.

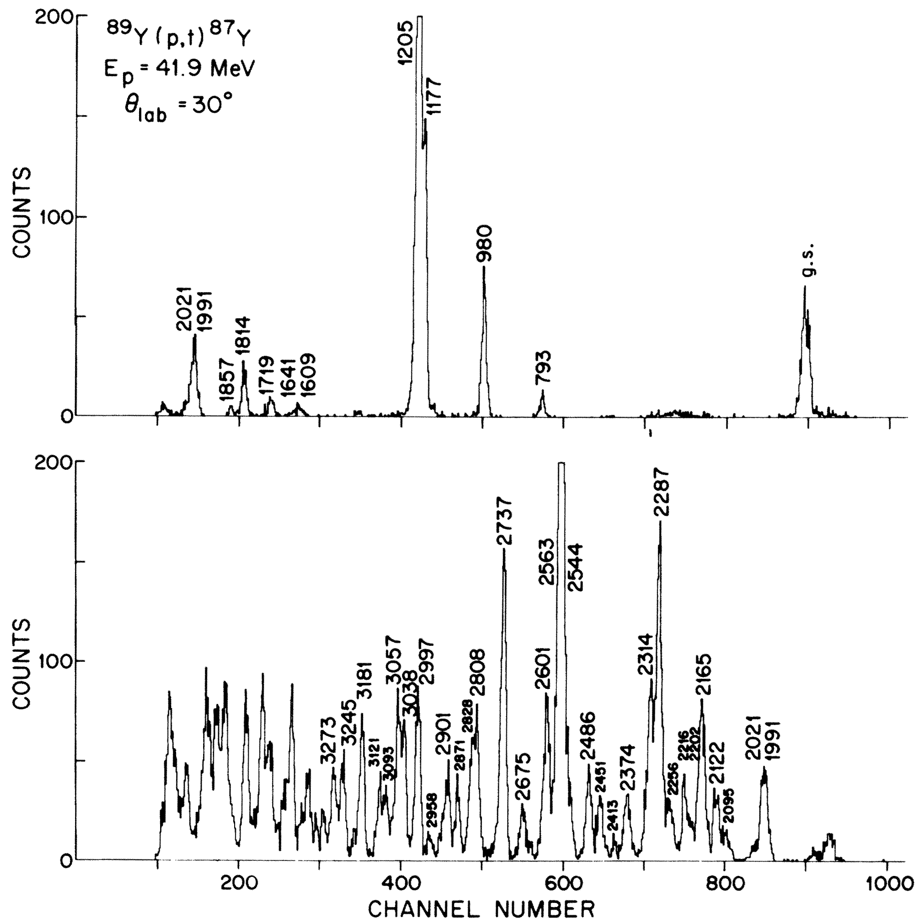

FIG. 2. ^{89}Y$(p,t)^{87}$Y position spectrum obtained with a wire proportional counter in the QDDD focal plane. The peaks are labeled with excitation energy in keV.

DWBA ANALYSIS

The distorted wave Born approximation (DWBA) calculations were performed with the two nucleon transfer option of the code DWUCK.[13] The optical model parameters employed are shown in Table I. These parameters, as taken directly from the literature, produced acceptable fits to the data. A finite range correction of exponential form[14] was used with the finite range parameter =0.6. Some trials using a shallower triton well ($V_0 \approx -133$ MeV) were made. A well depth of this order was previously used to fit 30 MeV (p, t) data on ^{103}Rh.[1] While the shallower triton well gave somewhat better $L=0$ fits here, it was virtually equivalent to the deeper well for $L=2$ and 4, and noticeably inferior for $L=3$, 5, and 6.

Simple two-particle configurations were used in the DWBA calculations. For $L=0$, 2, 4, 6, and 8 transfers the neutrons were assumed to be picked up from a $1g_{9/2}{}^2$ configuration, while for $L=3$, 5, and 7 transfers a $1f_{5/2}$, $1g_{9/2}$ configuration for the neutrons was employed.

EXPERIMENTAL RESULTS AND COMPARISON WITH OTHER WORK

The (p, t) angular distributions for states in ^{86}Sr and ^{87}Y are given in Figs. 3, 4, and 5. Figure 3 compares the angular distributions for proposed core-coupled states in ^{87}Y with the corresponding core (p, t) angular distribution and will be discussed further in the next section. Figures 4 and 5 present the remaining angular distributions for ^{86}Sr and ^{87}Y states, respectively. The error bars reflect statistical and background subtraction errors only. The solid curves are DWBA calculations, arbitrarily normalized by eye to achieve a best fit. The dashed lines in Fig. 3 are the empirical angular distribution shapes for the core (p, t) transition. Since a number of the spin-parity (J^π) assignments to levels in ^{86}Sr were known from previous γ-ray work,[10] it was possible to deduce angular momentum transfers (L transfers) for many of the ^{87}Y levels based simply on an empirical shape comparison. A summary of the experimental

TABLE I. Optical model parameters.

Proj.	Nucl.	E_{beam} (MeV)	V_0	r_0	A_0	W	$4W_D$	r_i	a_i	χ^2/N	Ref.
t	^{90}Zr	20	170.2	1.16	0.739	18.8	···	1.520	0.751	1.9	17
p	^{89}Y	42	47.0	1.17	0.75	6.54	11.1	1.32	0.60	(a)	12
n	Bound state		(b)	1.20	0.75						

[a] Calculated from general formula in Ref. 12. The geometric parameters for the volume and derivative imaginary potentials are the same. A spin-orbit term of the Thomas form was also included with $V_{so}=6.2$, $r_{so}=1.01$, $a_{so}=0.75$.

[b] Well depth adjusted to bind the neutrons at $\frac{1}{2}$ the two neutron separation energy from ^{89}Y. A spin-orbit term of the Thomas form with parameter $\lambda=25$ was also included.

information obtained in this study on ^{86}Sr and ^{87}Y levels is given in Tables II and III, where a comparison with some previous work is also shown.

A. ^{86}Sr

As Table II indicates, our results on ^{86}Sr agree well with previous work. The one exception is the 3686.7 keV level with an $L=2$ (p, t) angular distribution which disagrees with the γ-ray work.[10] This may indicate a doublet in this region with the two experiments each populating a different member. It is interesting to note that no excitation of the 3^+ unnatural parity state at 2878.3 MeV[15] was observed in our (p, t) work. We find a 0^+ level at 2203 keV which has not been previously reported. Such a level fits in well with systematics on the second excited 0^+ level observed in other Sr isotopes.[5]

The poor DWBA $L=2$ fit to the 1854.2 keV known 2^+ state deserves mention. This angular distribution was recorded twice as a result of taking two overlapping spectra. Both determinations gave nearly identical angular distribution shapes. Similar DWBA difficulties with this level were apparently encountered in previous (p, t) work at different energies.[4,5]

B. ^{87}Y

Table III shows new information on ^{87}Y levels found in the present work in comparison with previous results. The direct one-step (p, t) selection rules without spin-flip require that $J=|L\pm\frac{1}{2}|$ and $\pi=-(-)^{L+1}$ for a $J^\pi=\frac{1}{2}^-$ target. Hence, when the L transfer is given for a level in Table III, the parity is determined and the spin is restricted to at most two values. Our L transfers agree with previously determined values when available. Also shown in Table III are some comparisons with single-particle transfer work of Ref. 7. Only likely correspondences are given; one does not necessarily expect the (p, t) and $(^3He, d)$ reactions to excite the same class of states.

The level density above 2 MeV of excitation in ^{87}Y is high enough to begin creating problems due to our 17 keV resolution. A fairly high incidence of peaks separated by <40 keV is observed. A rather careful determination of the peak shapes was made as required input to AUTOFIT; nevertheless, when a small peak lies close to a large peak the cross-section determination may be subject to considerable uncertainty. Probably some of the poorly determined or undetermined L transfers in Tables II and III are due to this effect.

DISCUSSION AND CONCLUSIONS

In order to identify core-coupled states, we have compared excitation energies, angular distribution shapes, and cross-section strengths of states in ^{86}Sr and ^{87}Y. One expects a core-coupled multiplet to occur at nearly the excitation energy of the parent state, to have (p, t) angular distributions closely resembling that of the associated core state, and to have a summed cross-section strength nearly equal to that of the core state. During our analysis, it was observed that ^{87}Y states with nonzero L transfers tended to group into quartets rather than the expected doublets. Two of the members of the quartet usually had significantly smaller (p, t) cross sections than the remaining two members. This suggests that some strength of the core-coupled states is mixed into other nearby states; the relative (p, t) cross sections can be considered as a measure of the extent of this mixing.

The core-coupled multiplets determined from the criteria outlined above are given in Table IV. The (p, t) angular distribution shapes are compared with that of the corresponding core state in Fig. 3. The dashed curve is the empirical shape of the core angular distribution. The irregular shape of the 1854 keV 2^+ state in ^{86}Sr is not inherited by the core-coupled states; this

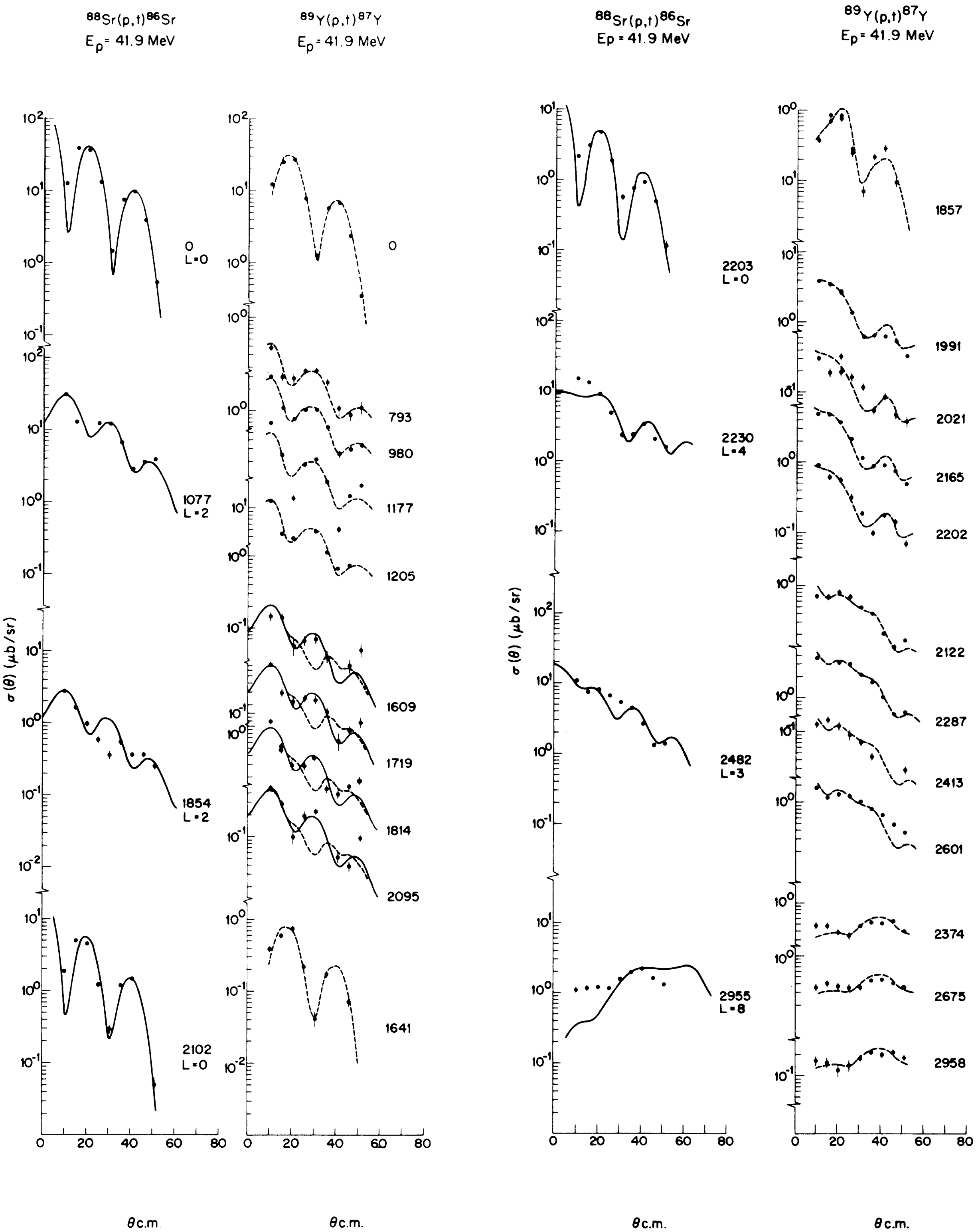

FIG. 3. (p,t) angular distributions of core-coupled states in ^{87}Y and of the corresponding ^{86}Sr core state. The solid curves are DWBA calculations and the dashed curves are the empirical angular distribution shapes of the associated ^{86}Sr core state. The distributions are labeled with the excitation energy of the level in keV.

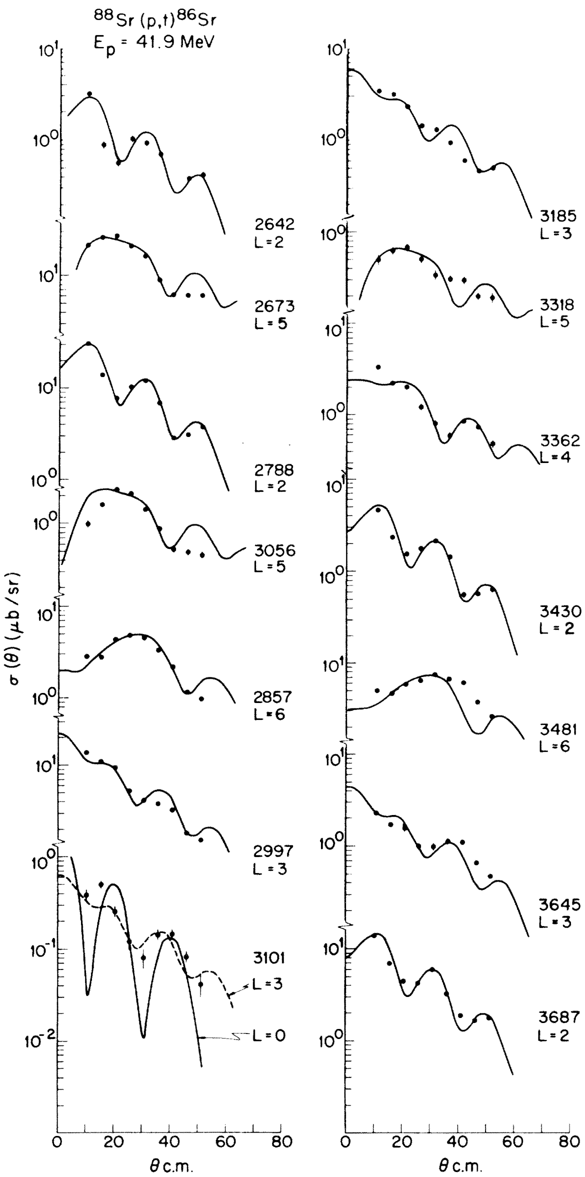

FIG. 4. Angular distributions of the remaining states observed in the ^{88}Sr$(p,t)^{86}$Sr reaction for which core-coupled ^{87}Y levels were not assigned. The solid curves are DWBA calculations.

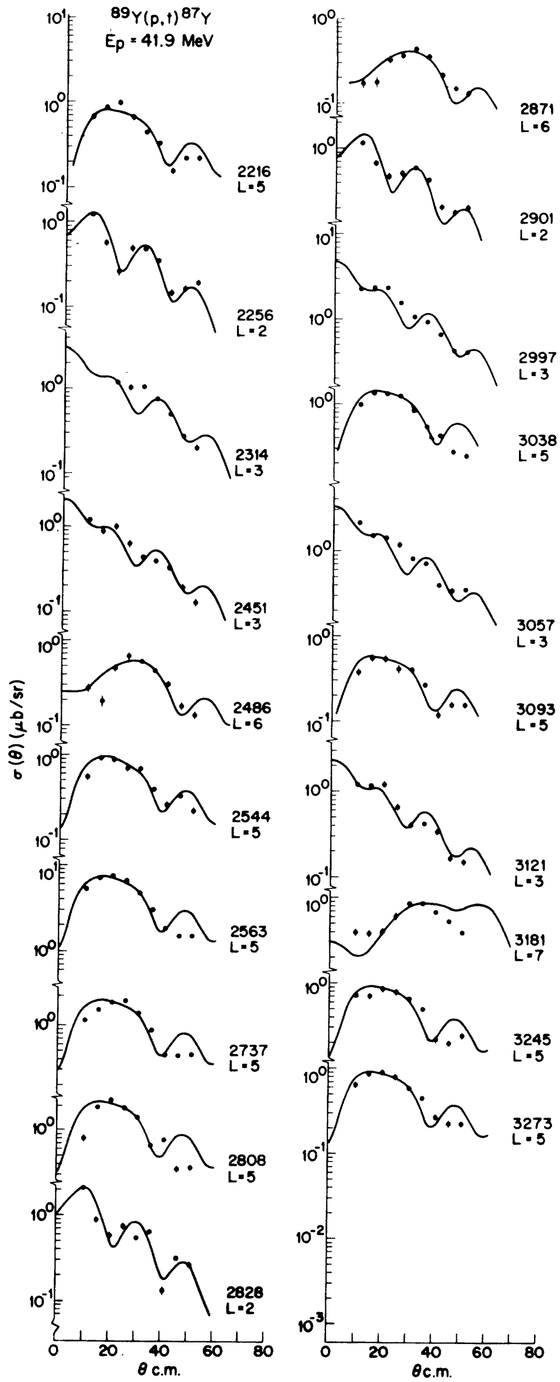

FIG. 5. Angular distributions of the remaining states observed in the ^{89}Y$(p,t)^{87}$Y reaction for which core-coupling correspondences were not obtained. The solid curves are DWBA calculations.

result of our study is presently not understood. The remaining comparisons are generally quite striking.

The excitation energy comparisons are illustrated in Fig. 6. In the excitation energy range displayed, grouping into multiplets was quite unambiguous due to the relative isolation of the core states of a given spin-parity. The energy centroids (centers of gravity) of the multiplet were found by weighting the excitation energy by the (p, t) strength and are given in Table IV. Except for the two excited 0^+ singlets and the 8^+ multiplet, deviations of the multiplets center of gravity from the core state energy are $<8\%$.

In order to compare the (p, t) cross-section strengths of the members of the multiplet with

TABLE II. Spectroscopic data on ^{86}Sr levels seen in (p,t).

Exc [a] (keV)	This work σ [b] (μb/sr)	This work $L(p,t)$ 42 MeV	Ref. 5 $L(p,t)$ 31 MeV	Literature [c] J^{π}	New J^{π}
0	125.2	0	0	0^+	
1076.6	92.6	2	2	2^+	
1854.2	8.2	(2)	(2)	2^+	
2102	16.0	0	0	0^+	
2203	14.6	0			0^+
2229.7	52.9	4	4	4^+	
2481.9	41.8	3	3	3^-	
2642.3	8.2	2	(2)	(2^+)	2^+
2672.8	196.8	5	5	5^-	
2788.2	90.4	2	2	2^+	
2857	26.6	6	(5,6)	6^+	
2955	13.3	(8)		8^+	
2997.3	53.3	3	3	3^-	
3055.7	10.8	5		$(4,5)^-$	5^-
3101	1.7	(0,3)		(0^+)	
3185.2	14.0	3		(3^-)	3^-
3317.6	3.6	5		$(3,4,5)^-$	5^-
3362.1	12.1	4		$(3^{\pm},4^+)$	4^+
3430	15.5	2			2^+
3481	48.6	(6)			(6^+)
3644.9	10.9	3		3^-	
3686.7	44.0	2		$(3^{\pm},4^+)$	2^+

[a] Energies given to nearest 0.1 keV are from Ref. 10. The rest are obtained from this work and are believed accurate to ±2 keV. Not shown are levels at 2878.3, 3291.5, 3499.8, and 3555.7 keV observed by Ref. 10 and not seen in this work.

[b] σ is the sum of the differential cross sections at all angles measured here.

[c] Taken primarily from work and summary of previous work given in Refs. 10 and 4.

the (p, t) strength of the core state, the sum of the differential cross sections at all angles investigated was taken. The usual integrated cross section over the angular region studied would have weighted the larger angles more than the smaller ones due to the $\sin\theta$ term appearing in $d\Omega$, whereas the differential cross sections at these larger angles usually have poorer statistics. In a few cases where the cross section at a particular angle could not be obtained, a value was interpolated from neigboring data points. As Table IV indicates, the summed multiplet (p, t) strength is fairly close to 70% of the (p, t) strength of the associated core state with the exception of the two excited 0^+ and associated $\frac{1}{2}^-$ states. The somewhat larger percentage (85%) for the 1854 keV 2^+ state and corresponding multiplet is probably the result of the irregular shape of the angular distribution of the core state which is not characteristic of the multiplet members.

In view of the stated errors in our absolute cross sections, the 70% ratio cannot be considered significant. For example, blocking effects cannot be inferred from these comparisons. The constancy of the percentage from multiplet to multiplet, however, is a further indication of the common origin of these states.

The high incidence of fractionation of the anticipated doublets into quartets is not unexpected. Wave function mixing should produce irregular numbers of associated states. Perhaps the observation of four states is somewhat fortuitous and a more sensitive experiment would detect more. For instance, a level at 2413 keV in ^{87}Y may belong to the 3^- multiplet indicated in Table IV. Its location, very near a much larger state, made it difficult to obtain an angular distribution. The 2451 keV level in ^{87}Y, while proceeding by $L=3$, has a rather different angular distribution shape from that of the 2482 keV state in ^{86}Sr or from that of the other members of the ^{87}Y multiplet. Already at this excitation energy the high level density makes multiplet association difficult.

Some insight into the nature of state mixing in ^{87}Y can be obtained by comparison with a previous ^{86}Sr(^{3}He, d) study.[7] As the spectroscopic factors in Table III indicate, the two lowest members of the first excited multiplet have significant single-particle character. The $1f_{5/2}$ and $2p_{3/2}$ single-particle states have the right spin and parity to mix with the core-coupled states associated with the first 2^+ core state. The (p, t) strength to these single-particle mixed states is appreciably reduced compared with the higher two members. Another example of this mixing is the 2216 keV level in ^{87}Y which, according to its $L=5$ angular distribution, is $\frac{9}{2}^+$ or $\frac{11}{2}^+$. The 2203 keV level of Ref. 7 is probably the same state. Its appreciable $1g_{9/2}$ single-particle character implies that it is mixing with the $\frac{9}{2}^+$ member of the core-coupled doublet. The other members of the multiplet have not been cleanly identified.

Because of high level densities, it is difficult to detect multiplets with much certainty above 2.5 MeV of excitation. Attempts were made to correlate higher excited ^{87}Y states into multiplets, but the summed (p, t) strength usually deviated significantly from the 70% value of the core strength expected from analysis of the low lying multiplets.

It appears that the basic features of the core-coupling model hold for low lying states of the ^{86}Sr-^{87}Y system. However, as noted previously for the similar ^{92}Zr-^{91}Y system,[8] the core-coupled states are fractionated by mixing with other

TABLE III. Spectroscopic data on ^{87}Y levels seen in (p,t).

This work			Ref. 6		^{86}Sr(^{3}He,d)^{87}Y		
Exc [a] (keV)	σ [b] (μb/sr)	$L(p,t)$ 42 MeV	Exc [c] (keV)	$L(p,t)$ 28 MeV	Exc [d] (keV)	nlj	Ref. 7 $(2J_F+1)C^2S$
0	87.9	0	0	0	0	$2p_{1/2}$	1.15
793	1.3	2	795	2	793	$1f_{5/2}$	1.15
980	8.4	2	986	2	982	$2p_{3/2}$	0.54
1177	16.5	2					
1205	37.0	2	1201	2			
1609	0.85	2 }	1622	(4,5)			
1641	2.1	0 }					
1719	1.5	2	1713	2			
1814	3.1	2	1809				
1857	3.0	0	1856	0	1848	$2p_{1/2}$	0.07 [e]
1991	14.2	4	1990	4			
2021	1.3	(4)					
2095	1.5	2	2090	2	2085	$2p_{3/2}$	0.09
2122	4.3	3	2114				
2165	19.5	4	2161	4			
2202	3.1	4	2207				
2216	4.5	5			2203	$1g_{9/2}$	0.79
2256	3.9	2	2251				
2287	19.2	3	2290	(3)			
2314	(6.1)	(3)					
2374	4.1	8	2375				
2413	1.0	(3)			2407	$2d_{5/2}$	0.03
2451	5.1	3	2453				
2486	3.1	6	2485				
2544	4.9	5					
2563	38.8	5	2570	(5)			
2601	8.6	3	2609				
2675	3.1	8	2681				
2737	13.6	5	2748				
2808	6.0	5					
2828	6.2	(2)	2838				
2871	2.3	6					
2901	4.4	2	2917				
2958	1.5	8					
2997	11.9	3	3010		2995	$2d_{5/2}$	0.11
3038	7.2	5					
3057	8.8	(3)	3070		3043	$2d_{5/2}$	0.20
3093	2.9	5					
3121	5.7	3	3130				
3181	5.1	(7)					
3245	4.8	5					
3273	4.7	5					

[a] Errors are ±5 keV.
[b] σ is the sum of the differential cross sections at all angles measured here.
[c] Errors for states below 2 MeV are < 7 keV, and < 10 keV for states below 2 MeV.
[d] Errors quoted as ±4 keV.
[e] Preferred $2p_{3/2}$ but $2p_{1/2}$ allowed by $l=1$ transfer.

states. Because of this fractionation, the possibility of assigning spins to the members of the multiplet according to a distribution of (p, t) strength in proportion to $2J+1$ is doubtful; however, much can probably be learned about wave function mixing from the observed (p, t) strengths when more J^{π} determinations become available for ^{87}Y levels. Owing to the feasibility of shell model calculations for both ^{86}Sr and ^{87}Y, it should be possible to probe the nature of core-coupling

TABLE IV. Core-coupled states in ^{87}Y.

^{86}Sr Exc (keV)	J^{π}	σ [a] (μb/sr)	^{87}Y Exc (keV)	σ (μb/sr)	$\sum\sigma$ [b] (μb/sr)	$(\sum\sigma)^{87}$Y / $(\sigma)^{86}$Sr	$E_{c.g.}$ (keV)	$E_{c.g.}/E_{core}$
0	0+	125.2	0	87.9	87.9	0.70	0	
1077	2+	92.6	793	1.3	63.0	0.68	1159	1.076
			980	8.4				
			1177	16.5				
			1205	37.0				
1854	2+	8.2	1609	0.85	7.0	0.85	1829	0.987
			1719	1.5				
			1814	3.1				
			2095	1.5				
2102	0+	16.0	1641	2.1	2.1	0.13	1641	0.781
2203	0+	14.6	1857	3.0	3.0	0.21	1857	0.843
2230	4+	52.9	1991	14.2	38.1	0.72	2098	0.941
			2021	1.3				
			2165	19.5				
			2202	3.1				
2482	3−	41.8	2122	4.3	33.1	0.79	2351	0.947
			2287	19.2				
			2413	1.0				
			2601	8.6				
2955	8+	13.3	2374	4.1	8.7	0.65	2582	0.874
			2675	3.1				
			2958	1.5				

[a] σ is the sum of the differential cross sections at all angles measured here.
[b] The sum of the σ's for the group of states in the indicated multiplet.

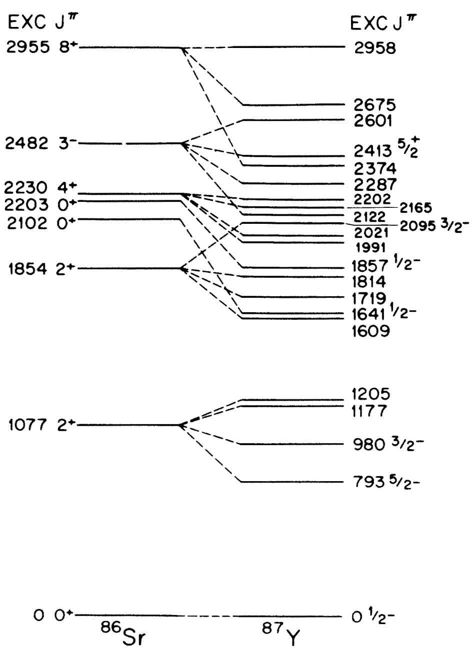

FIG. 6. Energy level diagram showing the proposed multiplets in ^{87}Y which arise from coupling of the extra $2p_{1/2}$ proton onto ^{86}Sr core states.

on a deeper theoretical level. Some efforts in this direction have been made in s-d shell nuclei[16] with encouraging results.

We find that, in spite of mixing of the core-coupled states and a resultant dilution of the (p, t) strength among a number of levels, the sum of the cross-section strength over the multiplet is close to a constant multiple of the core (p, t) strength. Exceptions to this rule are the associated 0^+ and $\frac{1}{2}^-$ levels. Even if a sum of $L=0$ (p, t) strengths were taken for levels up to ~3 MeV in both ^{86}Sr and ^{87}Y, the ratio of the strengths would deviate significantly from that found for the other multiplets. Perhaps the missing $L=0$ strength lies at even higher excitation energy than was considered in this experiment. The operation of such a sum rule, if supported by further examples, could be a useful guide to the study of core-coupling in off-A nuclei.

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