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Proton-induced reactions on ^{89}Y†

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The reactions ^{89}Y$(p,t)^{87}$Y, ^{89}Y$(p,d)^{88}$Y, and ^{89}Y$(p,\alpha)^{86}$Sr are studied with 27.8-MeV protons and solid-state-detector telescopes. A recent revision of the mass of ^{87}Y is confirmed. Angular distributions are obtained for the observed states. Several new levels are found in ^{87}Y. The states at 0.98, 1.85, and 2.09 MeV are assigned $J^\pi=\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{3}{2}^-$, respectively. In ^{89}Y, the existence of two low-spin states of opposite parity is established at 0.705 MeV. Distorted-wave Born-approximation (DWBA) calculations are carried out for the (p,d) and (p,t) data. Good fits to the data are obtained for the (p,d) reaction, but the $l=4$ and $l=1$ summed strengths deviate in opposite directions from the sum rules. Poor fits are obtained for $L=0$ transitions in the (p,t) reaction on ^{89}Y and the experimental $L=2$ angular distributions show features that are not reproduced by the DWBA. Multistep contributions are suggested. The data for the (p,α) reaction show some evidence for direct-reaction processes, but DWBA calculations cannot be carried out.

[NUCLEAR REACTIONS ^{89}Y(p,d), (p,t), (p,α), $E=27.8$ MeV; measured $\sigma(E,\theta)$, $\theta=9-50°$, $\Delta\theta=3-4°$, resolution 35–60 keV; deduced ^{87}Y-^{88}Y mass difference, ^{87,88}Y, ^{86}Sr levels; DWBA analysis, deduced S for ^{88}Y.]

I. INTRODUCTION

In an earlier study[1] of proton-pickup reactions on strontium isotopes, and a sum-rule analysis of the observed spectroscopic factors, the angular momenta of several states in the nucleus ^{87}Y were needed. These had not been determined unambiguously in a prior study of the ^{86}Sr$(^3\text{He},d)^{87}$Y reaction.[2] In particular, three states were assigned[2] $J^\pi=(\frac{1}{2},\frac{3}{2})^-$. This ambiguity can be removed by a study of the angular distributions of the ^{89}Y(p,t)-^{87}Y reaction to these states. The $J^\pi=\frac{1}{2}^-$ character of the ^{89}Y ground state and the $S=0$ selection rule for two-neutron pickup imply $L=0$ or 2, uniquely, for final states with $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$, respectively.

At the time of the earlier study of the strontium isotopes,[1] there was no information available in the literature on the (p,t) reaction to the states of interest. Since then, two papers have appeared,[3,4] but neither one reported on experiments that had sufficient resolution to enlighten the issue. We report here a study of the ^{89}Y$(p,t)^{87}$Y reaction that, owing to an improved resolution of about 35 keV, not only provides the appropriate data for the spin-parity assignments, but also shows the existence of many new states in ^{87}Y.

Also discussed here are data for the ^{89}Y$(p,d)^{88}$Y reaction. Of special concern is the region near 710 keV. Data from the ^{87}Sr$(^3\text{He},d)^{88}$Y and ^{88}Sr$(^3\text{He},t)$-^{88}Y reactions have given good evidence[5] for two states, with spin-parity 6^+ and 7^+, near 712 keV while a $J^\pi=2^-$ state at 706 keV is deduced from a study of the ^{88}Sr$(p,n\gamma)^{88}$Y reaction.[6] In the midstream evaluation for $A=88$ of 1970,[7] a state with a 1^+ assignment had been proposed based on older unpublished Oak Ridge data for the ^{89}Y$(p,d)^{88}$Y and ^{90}Zr$(d,\alpha)^{88}$Y reactions. A low-spin positive-parity state at 707 keV is similarly inferred in a recent study of the ^{89}Y$(d,t)^{88}$Y reaction,[8] although $J^\pi=2^+$ is slightly favored over 1^+. Both a high-spin positive-parity state at 715.4 keV and a low-spin state at 706.8 keV are implied by the data for the ^{85}Rb$(\alpha,n\gamma)^{88}$Y reaction.[9] The assignments 7^+ and 2^-, respectively, are favored, but the presence of states with 6^+ and 2^+ (or 1^+) is not excluded.

Since the data for the previous neutron-pickup experiments to the state(s) at 710 keV did not have high yields, it was thought that data for the ^{89}Y$(p,d)^{88}$Y reaction, obtained simultaneously with the present (p,t) data, would have sufficient statistics to either confirm or confound previous interpretations.

Finally, we present angular distributions for the ^{89}Y$(p,\alpha)^{86}$Sr reaction. Although these are relatively nondescript, and thus preclude detailed spectroscopic interpretation, some comparisons can be made with the systematics of this reaction[3] and with level assignments from other studies.[4,10,11] The data were obtained simultaneously with the (p,t) and (p,d) measurements.

II. EXPERIMENTAL PROCEDURES

A proton beam of energy 27.81 MeV was obtained from the Princeton University azimuthally-varying-field cyclotron and bombarded a self-supporting ^{89}Y target foil[12] in a 150-cm-diam scattering chamber. The average effective thickness of the target was about 110 μg/cm^2. Although it had numerous pinholes, the beam spot was large enough to average over a good region of the foil.

The reaction particles passed through a double-slit collimator in front of the detector housing and into a silicon surface-barrier charged-particle telescope. This consisted of a 312-μm ΔE detector, a 1500-μm E detector, and a thick veto detector. The telescope was cooled by a freon refrigerator system to about −40°C. A U magnet between the collimator slits prevented electrons from entering the telescope. The collimator subtended an angle of about 1° and defined a solid angle of about 0.7 msr.

Signals from the detectors were amplified by Sherman-Roddick preamplifiers,[13] processed by fairly conventional electronics, and transmitted to an on-line computer that computed a particle-identification function and stored the event in an appropriate array. A pileup-rejection subcircuit was included in the electronics setup.[14] This enabled total event rates in the telescope to be as high as about 25 kHz. Beam currents ranged from 200 nA to 2 μA.

Angular distributions for (p, t), (p, d), and (p, α) reactions on ^{89}Y were obtained at 13 angles between 9° and 50° in 3–4° intervals. A monitor counter was not available but previous experience with very similar experimental arrangements have shown that the charge integrator provides excellent relative normalization between runs. Furthermore, the data gave no hint of any irregularities. The runs were not taken with a monotonic change in angle. The uncertainty in relative cross sections is dominated by the statistical errors except perhaps for the stronger cross sections that exceed 100 μb/sr. The absolute cross sections are believed to be accurate to about 20%.

The data were analyzed with the computer programs QPLOT and AUTOFIT.[15] Representative spectra are shown in Fig. 1. The resolution was about 35, 50, and 60 keV for the (p, t), (p, d), and (p, α) reactions, respectively. It is not entirely clear why the resolution was worse for the (p, d) reaction than for the (p, t) reaction. The shapes of the peaks were also distorted at forward angles. The analysis of the data made allowances for these factors.

III. EXPERIMENTAL RESULTS

A. Calibration and the mass of ^{87}Y

The locations of the peaks in the spectra were used in conjunction with known excitation energies and Q values to obtain calibration coefficients. The α-particle spectra were treated separately

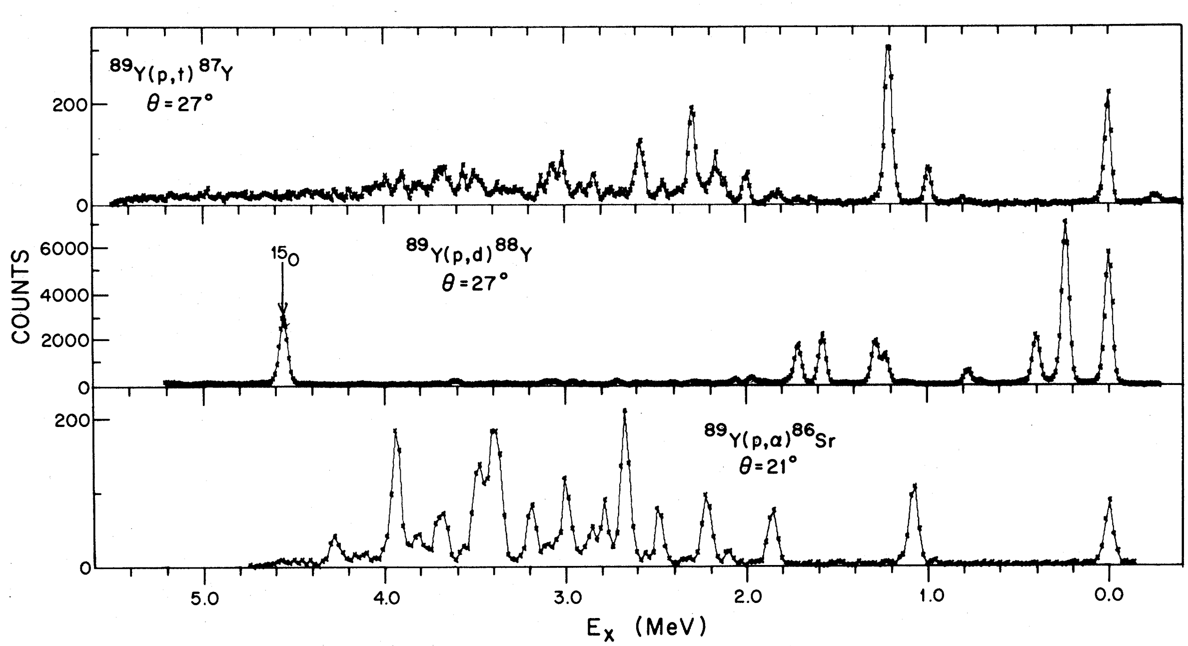

FIG. 1. Representative spectra for (p, t), (p, d), and (p, α) reactions on ^{89}Y, with excitation energy as the abscissa. The laboratory angle is indicated for each spectrum.

TABLE I. Energy levels in ^{87}Y. The favored L values for the (p, t) reaction on ^{89}Y, and some J^{π} assignments, are also given. Energies are in units MeV. Errors in E_x in the present work are less than 7 keV for energies below 2 MeV, and less than 10 keV above 2 MeV.

^{89}Y$(p,t)^{87}$Y Present work		^{89}Y$(p,t)^{87}$Y Ref. 3			^{89}Y$(p,t)^{87}$Y Ref. 4		^{86}Sr$(^3$He$,d)^{87}$Y Ref. 2	
E_x	L	E_x	L	J^{π}	E_x	L	E_x	J^{π}
0.000	0	0.000	0	$\frac{1}{2}^-$	0.00	0	0.000	$\frac{1}{2}^-$
					0.38		0.380	$\frac{9}{2}^+$
0.795	2	0.792	2	$(\frac{5}{2}^-)$			0.793	$\frac{5}{2}^-$
0.986	2	0.986	2	$\frac{3}{2}^-$	0.95	2	0.982	$(\frac{1}{2}, \frac{3}{2})^-$
							1.155	$\frac{5}{2}^+$
1.201	2	1.187	2	$(\frac{3}{2}, \frac{5}{2})^-$	1.18	2		
1.622	(4, 5)						1.605	$\frac{9}{2}^+$
1.713	2							
1.809								
1.856	0				1.85		1.848	$(\frac{1}{2}, \frac{3}{2})^-$
1.990	4	1.97	4	$(\frac{7}{2}, \frac{9}{2})^-$	2.00	4		
2.090	2						2.085	$(\frac{1}{2}, \frac{3}{2})^-$
2.114								
2.161	4	2.14	4	$(\frac{7}{2}, \frac{9}{2})^-$	2.15	3		
2.207							2.203	$\frac{9}{2}^+$
2.251								
							2.278	$\frac{5}{2}^-$
2.290	(3)	2.26	3	$(\frac{5}{2}, \frac{7}{2})^+$				
2.375								
							2.407	$\frac{5}{2}^+$
2.453								
2.485								
2.570	(5)	2.57	5	$(\frac{9}{2}, \frac{11}{2})^+$	2.51	(5)		
2.609								
2.681								
2.748							2.730	$\frac{5}{2}^-$
2.838								
2.917							2.907	$\frac{5}{2}^+$
3.010		3.00	4	$(\frac{7}{2}, \frac{9}{2})^-$			2.995	$\frac{5}{2}^+$
							3.043	$\frac{5}{2}^+$
3.070		3.07	2	$(\frac{3}{2}, \frac{5}{2})^-$				
							3.090	$\frac{5}{2}^+$
3.130								
							3.195	$\frac{1}{2}^+$

from the deuteron and triton spectra since any gain mismatch in the electronics circuitry would affect them more distinctly. In fact, the calibration for the α particles was found to be close to, but slightly different from, the calibration for the hydrogenic particles. Calibrations for both were found to be linear.

The four states at 0.000, 0.234, 0.393, and 1.573 MeV in ^{88}Y were used for the deuteron calibration, and those at 0.000 and 0.986 MeV in ^{87}Y for the triton calibration. These two states in ^{87}Y were the only ones whose positions could be determined with sufficient precision. The slopes of the linear calibration of these two sets of data, treated separately, were found to be identical. However, it was not possible to obtain a consistent over-all calibration for both sets, treated together, if the Q values provided by the 1971 Atomic Mass Evaluation[16] were used. In this evaluation, the mass of ^{87}Y is determined solely by the measured Q value for ^{86}Sr$(p, \gamma)^{87}$Y reaction.[17] This mass has subsequently been remeasured[18] and found to be about 17 keV lighter. The new Q value that is implied for the (p, t) reaction yields a much more consistent over-all calibration. We find, however, that an additional shift of 7 keV in the relative Q values for

TABLE II. Energy levels and spectroscopic factors for states in ^{88}Y. Energies are in units MeV.

^{89}Y(p,d)^{88}Y Present work				^{89}Y(d,t)^{88}Y Ref. 8	
E_x	l	j	C^2S	E_x	C^2S (15.8 MeV)
0.000	4	$\frac{9}{2}$	5.2	0.000	3.71
0.233	4	$\frac{9}{2}$	6.9	0.233	4.88
0.393	1	$\frac{1}{2}$	1.2	0.393	0.94
0.705	1, 2	$\frac{1}{2}$, $\frac{5}{2}$	0.021, 0.061	0.707	0.04 for $l=1$
0.768	1	$\frac{1}{2}$	0.43	0.763	0.35
1.125	4	$\frac{9}{2}$	0.19	1.127	0.10
1.223	1	($\frac{3}{2}$)	0.66	1.225	0.48
1.279	1	($\frac{3}{2}$)	1.1	1.276	0.87
1.573	1	($\frac{3}{2}$)	1.2	1.573	0.92
1.708	3	$\frac{5}{2}$	2.5	1.705	>1.0

the (p,d) and (p,t) reactions is required for best results. This shift of 7 keV is consistent with the combined uncertainties in the masses of ^{87}Y (updated by Ref. 18), ^{88}Y, and the present data.

The new value of the ^{87}Y mass[18] implies a Q value for the ^{86}Sr(^{3}He, d)^{87}Y reaction of 0.287 MeV. This is 59 keV more negative than the value reported in Ref. 2. No reason for the discrepancy can be ascertained at this time.

B. Energy levels

Tables I–III list the energy levels that were observed in ^{87}Y, ^{88}Y, and ^{86}Sr as well as the states observed in previous studies of these nuclei. There is excellent general agreement with previous work for the nuclei ^{88}Y and ^{86}Sr. However, the levels in ^{87}Y observed in the (p,t) reaction on ^{89}Y appear to be systematically higher than energies assigned in the high-resolution study of the ^{86}Sr(^{3}He, d)^{87}Y reaction.[2] As discussed above, the calibration for the present (p,t) data is in excellent agreement with that for the (p,d) data. Since the measured ground-state Q value for the (^{3}He, d) reaction is known to be in error, it is likely that a calibration discrepancy is present in all the (^{3}He, d) data.

In the ^{89}Y(p,t)^{87}Y reaction, there is no persuasive evidence for the population of the state at 0.38 MeV, as indicated in an earlier experiment.[4] The state at 1.201 MeV is certainly not the same as the state at 1.155 MeV that is observed in the (^{3}He, d) reaction and it has an energy that is higher than reported in earlier work.[3,4] A number of new states are also found. Many more exist above 3.2 MeV, but the spectra were too complex for reliable analysis.

The observed levels in ^{86}Sr generally agree very well with known states. The existence of states at 2.10 and 2.78 MeV is affirmed.[11] There is some indication that two states are present near 3.05 and 3.12 MeV, although the yields are small. Only four states were clearly identified between 3.38 and 3.69 MeV, but the resolution would preclude definite identification of five states at the known energies. A new state of moderate intensity is present near 4.27 MeV.

IV. ANALYSIS AND DISCUSSION

A. Distorted-wave Born-approximation parameters

The observed angular distributions for the (p,d), (p,t), and (p,α) reactions on ^{89}Y are shown in Figs. 2–7. The angular distributions for the (p,d) and (p,t) reactions were calculated in the distorted-wave Born approximation (DWBA) by use of the program DWUCK4.[19] The optical-model parameters are listed in Table IV. The proton potential is taken from the "best fit" universal potential of Becchetti and Greenlees.[20] The deuteron potential is the same as was used in the study of (d,α) reactions in Ref. 3. Some potentials other than those listed in Table IV for deuterons and tritons were also considered. Discussion of these variations is given below in relation to each particular reaction.

B. ^{89}Y(p,d)^{88}Y reaction

Angular distributions, including the DWBA calculations, are displayed in Figs. 2 and 3. Spectroscopic factors for the observed transitions are listed in Table II. These were computed from the expression

$$\frac{d\sigma}{d\Omega}=2.3C^2S\frac{\sigma_{\rm DW}}{2j+1}\,,$$

where C^2S is the spectroscopic factor, weighted by the isospin Clebsch-Gordan coefficient, $\sigma_{\rm DW}$ is the cross section computed by DWUCK4, and j is the assumed total-angular-momentum transfer.

The DWBA calculations include correction factors for finite-range effects (FR) and for nonlocal-

TABLE III. Energy levels in ^{86}Sr, in units MeV. Comparisons are made with the levels listed in the Nuclear Data Sheets (Ref. 10), augmented in a few cases by Ref. 11.

Present work E_x	Ref. 10 E_x	J^π
0.000	0.000	0^+
1.007 ± 0.010	1.0766	2^+
1.855 ± 0.010	1.8542	2^+
2.106 ± 0.010	2.100	$0^{+\,a}$
2.223 ± 0.010	2.2297	4^+
2.365 ± 0.012		
2.484 ± 0.010	2.4819	3^-
	2.6419	(2^+)
2.670 ± 0.010	2.6728	5^-
2.796 ± 0.010	2.785	$2^{+\,a}$
	2.860	$(5^-,\ 6^+)^{a}$
2.874 ± 0.010	2.8783	$(2–4)^+$
2.995 ± 0.010	2.9973	3^-
	3.0557	$(3–5)^-$
3.096 ± 0.015 [b]		
3.195 ± 0.010	3.1852	$(3,\ 4)^-$
	3.2915	
	3.3175	$(3–5)^-$
3.388 ± 0.010	3.3621	
3.480 ± 0.015	3.4998	$(3–5)^-$
3.573 ± 0.025	3.5557	
	3.6448	
3.688 ± 0.010	3.6867	
	3.7656	
	(3.7748)	
3.820 ± 0.010	3.8311	$(3–5)^-$
	3.8715	
	3.9259	
3.940 ± 0.010	3.9424	
	3.9688	
	4.1460	
	4.2060	
4.270 ± 0.010		
	(4.339)	
	4.4105	
	4.718	
	4.954	

[a] Reference 11.

[b] A probable doublet with states near 3.05 and 3.12 MeV.

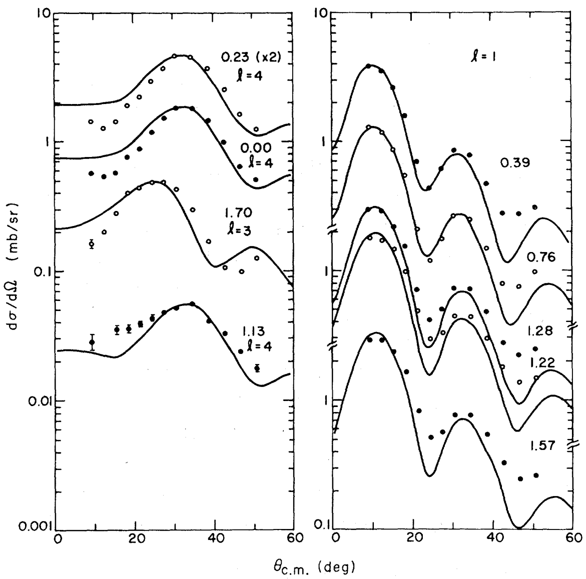

FIG. 2. Angular distributions for the ^{89}Y$(p, d)^{88}$Y reaction. Error bars are shown if larger than the data points. Each distribution is marked by the excitation energy of the state in MeV and the orbital-angular-momentum transfer l is also indicated. The curves are DWBA calculations.

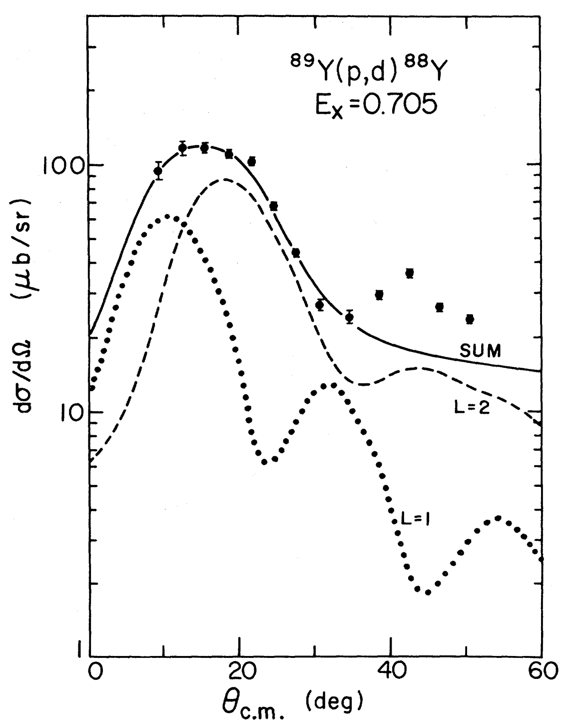

FIG. 3. Angular distribution for the observed state(s) near 0.705 MeV in ^{88}Y from the (p, d) reaction on ^{89}Y. The dotted and dashed curves are DWBA calculations for pure-l transfers, and the solid curve is their sum.

ity effects (NL) in the scattering channels. The Hulthén form of the correction factor is used (as in program DWUCK2). The potentials used for the corrections include the Coulomb potentials, but not the spin-orbit potentials. The correction factors were necessary in order to obtain the best fits to the data and reasonable spectroscopic factors. A nonlocality correction for the bound neutron was also considered. It did not affect the shapes of the angular distributions and increased σ_{DW} by about 20%.

The fits to the data are very good for the $l=1$ transitions, at least over the first two maxima. For the $l=4$ and $l=3$ transitions, the fits are less satisfactory, especially at forward angles. Other choices of optical potentials, or different forms of the FR-NL corrections, gave less satisfactory results.

Another difficulty with the DWBA calculations is contained in the spectroscopic factors, particularly as manifested in the sum rules given in Table V. The strength for pickup of $g_{9/2}$ neutrons exceeds the sum rule by nearly 25%, while that for $p_{1/2}$ and $p_{3/2}$ neutrons falls below the limit by about 25%. The $l=4$ strength can be reduced easily by a number of modifications in the calculations, but these also reduce the $l=1$ strength and/or make the fits to the data inferior. The effects of other deuteron potentials has been considered. In particular, calculations were also made with the parameter sets used in Refs. 1 and 8. The results did not affect the problem that is noted here.

This same problem with the $l=1$ and $l=4$ sum rules has also been observed by Daehnick and Bhatia[8] for the ^{89}Y$(d,t)^{88}$Y reaction at two bombarding energies. It was proposed in Ref. 8 that additional $l=1$ strength must lie at higher excitation energies. This is indeed probable. No detailed effort was made to find such strength in the present work.

The state at 0.705 MeV has been an enigma for many years. As discussed in the Introduction, there is good likelihood that there may be four states present within about 10 keV. This is the possibility that is argued in Ref. 8. In that work, the existence of a low-spin positive-parity state, in addition to a known 2^- state,[6] is based on DWBA calculations for a low-yield angular distribution.

Figure 3 shows the angular distribution for this state from the present work. DWBA calculations for $l=1$ and $l=2$ pickup, and their sum, are also displayed. Neither one of the pure-l calculations will fit the data. Furthermore, the combination $l=1$ and $l=3$, as preferred in Ref. 8, will not work. This combination cannot fit simultaneously the flat top between 10–20° and the width of the first maximum. The $l=2$ contribution is in agreement with the assignment of a 2^- state.[6] The $l=1$ contribution demonstrates the presence of a state with $J^\pi=(0-2)^+$. No preference for $J^\pi=2^+$ can be made from the present data since an $l=3$ contribution is

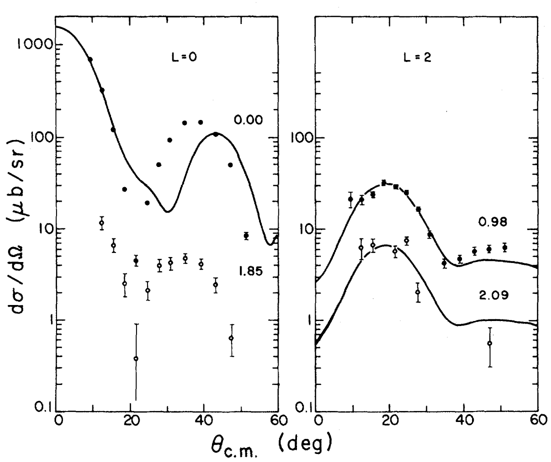

FIG. 4. Angular distributions for selected states from the ^{89}Y$(p,t)^{87}$Y reaction. See also the caption for Fig. 2.

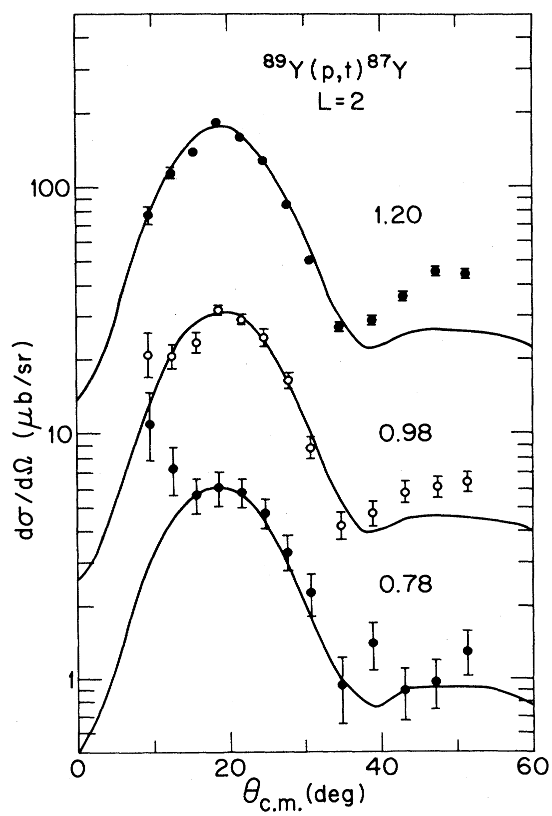

FIG. 5. Angular distributions for three states from the ^{89}Y$(p,t)^{87}$Y reaction characterized by $L=2$. See also the caption for Fig. 2.

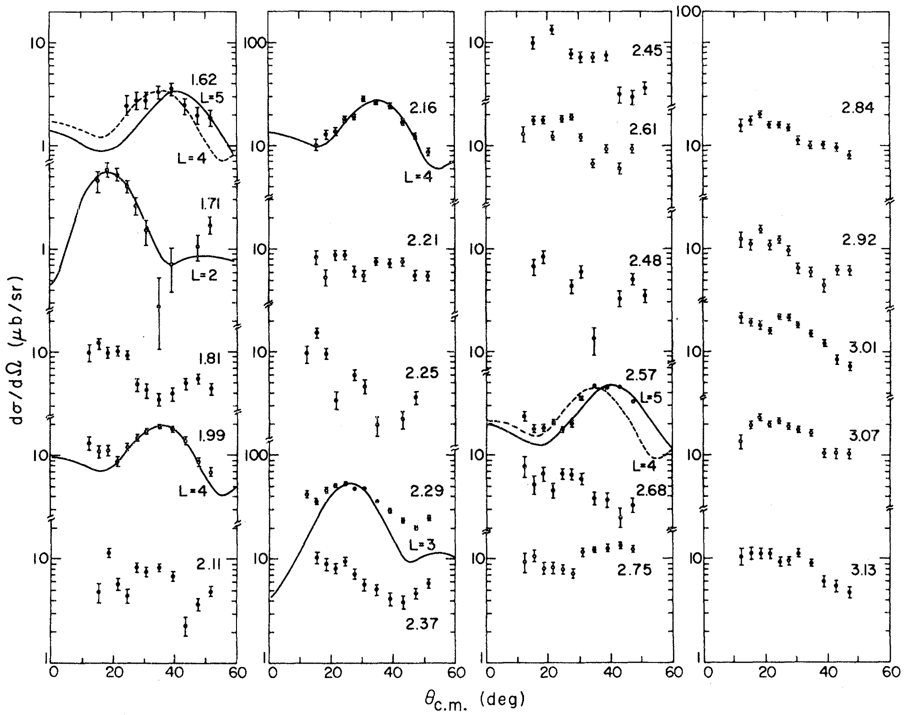

FIG. 6. Angular distributions for states observed in the ^{89}Y$(p, t)^{87}$Y reaction. See also the caption for Fig. 2.

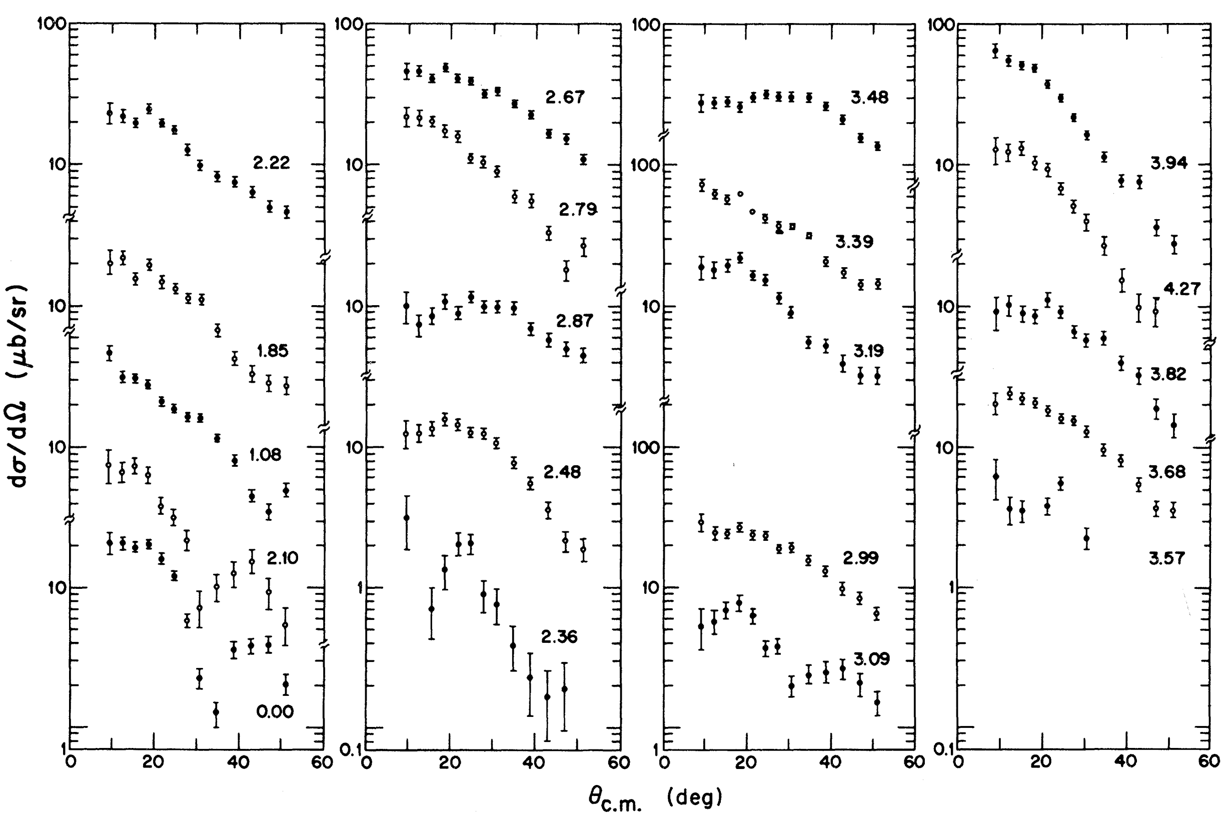

FIG. 7. Angular distributions for states observed in the ^{89}Y$(p, \alpha)^{86}$Sr reaction. See also the caption for Fig. 2.

TABLE IV. Optical-model parameters used for the DWBA calculations. The potentials are standard Woods-Saxon potentials, as defined in Ref. 19. Well-depths have units MeV and radii have units F. The non-locality factor β is also listed.

Particle	V	r_0	a	W	W'	r'	a'	V_{so}	r_{so}	a_{so}	r_c	β
p	51.6	1.17	0.75	3.4	25.3	1.32	0.60	6.2	1.01	0.75	1.20	0.85
d	98	1.10	0.85	···	72	1.40	0.70				1.30	0.54
t	170	1.16	0.752	24	···	1.50	0.817				1.25	0.25
n	a	1.25	0.65					$\lambda = 25$			1.25	

[a] Well depth adjusted to produce the proper separation energy for the bound neutrons.

not unambiguously present. Since $l = 5$ transitions would peak near 40°, the rise in the data at that angle might support the presence of a 6^+ and/or 7^+ state, but this evidence is not very strong.

The present data do not shed much more information about the structure of ^{88}Y than is contained in earlier work.[5,8] We remark that the observed cross sections for the pair of states at 0.000 and 0.233 MeV, and the pair at 0.393 and 0.768 MeV, scale exactly as $(2J_f + 1)$. This would be in good agreement with the supposition that the pairs have pure $(p_{1/3} g_{9/2})$ and $(p_{1/2}{}^2)$ configurations, respectively. Other considerations would seem to preclude this, however,[5,8] so that this good agreement would seem to be fortuitous.

C. ^{89}Y$(p,t)^{87}$Y reaction

The DWBA calculations for the (p, t) reaction on ^{89}Y proved to be much less satisfying that those for (p, d) reactions. This was especially so for the observed $L = 0$ transitions but was also true for $L = 2$ transitions. The difficulties are illustrated in Figs. 4 and 5.

The transition to the ground state of ^{87}Y is restricted to $L = 0$. The experimental angular distribution in Fig. 4 has a characteristic oscillatory pattern peaking at forward angles. However, the DWBA curve gives a very poor fit for angles beyond 15°. In Fig. 5, three angular distributions that have been assigned[3] $L = 2$ are compared with DWBA calculations. In this case, the fits are very good, except for angles less than 15°.

The discrepancies for the $L = 2$ curves cannot be attributed to a Q dependence of these DWBA calculations. Nor can the difficulties for the $L = 0$ transition be attributed to reasonable variations of optical potentials. The triton parameters in Table IV were taken from the work of Flynn *et al.*[21] The potential family with $V = 150$ MeV was considered, but results from it were quite inferior. The triton potential used for the analysis of very similar data by Peterson and Rudolph[3] also gave similar results. Finally, the effects of FR-NL corrections were investigated. They also did not improve the situation.

The difficulties discussed here are very similar to problems that have been noted previously for (p, t) reactions on nuclei in other mass regions.[22,23] In the case of (p, t) reactions on cadmium isotopes,[23] the difficulties have been successfully eliminated by inclusion of two-step and three-step processes.[24] Such processes are undoubtedly present in the data that are considered here. Since they would preclude inferences made about the structure of ^{87}Y that are based on calculated DWBA cross sections, the DWBA is used here only as a guide for L-value assignments. Thus, refinements such as FR and NL corrections were not included in the final calculations.

Some important conclusions may be reached, however, even in the absence of a full DWBA treatment. As mentioned in the Introduction, the three states at 0.98, 1.85, and 2.09 MeV did not have unique spin assignments in the analysis of the ^{86}Sr$(^3$He$, d)^{87}$Y data.[2] The angular distributions for these states are shown in Fig. 4. It is clear that the angular distribution for the 1.85-MeV state is very similar to that for the ground state while those for the other two states are different from the ground state, but similar to each other. The DWBA calculations with $L = 2$ fitted these data very well. We conclude that the state at 1.85 MeV has $J^\pi = \frac{1}{2}^-$, while those at 0.98 and 2.09 MeV have $J^\pi = \frac{3}{2}^-$. Even though the 2.09-MeV state is weakly

TABLE V. Sums of the spectroscopic factors for the ^{89}Y$(p, d)^{88}$Y reaction, taken from the values of C^2S in column 4 of Table II. The $l = 1$ strengths are divided between $p_{1/2}$ and $p_{1/3}$ pickup according to the assumed values of j given in Table II.

Orbit	$\sum C^2S$	Shell-model limit
$p_{1/2}$	1.65	2
$p_{3/2}$	3.0	4
$d_{5/2}$	0.06	0
$f_{5/2}$	2.5	6
$g_{9/2}$	12.3	10

populated, it is unlikely that it is an $L=0$ transition that is shifted in angle, as has been observed in the (p, t) data on cadmium.[23]

The data from this experiment may be compared with those obtained at the nearby energy of 27.3 MeV[3] and at 49.5 MeV.[4] The unusual features at forward angles of the $L=2$ transitions in Fig. 5 were present in the data obtained by Peterson and Rudolph,[3] although the yields in Ref. 3 were somewhat less and no remark was made in that paper.

The present resolution of about 35 keV is a marked improvement over the 90 keV[3] and 75 keV[4] of the earlier work. Many new states have been identified, as is clear from an examination of Table I. Most of these were weakly populated. The angular distributions for the rest of the states in ^{87}Y, and some DWBA curves, are shown in Fig. 6.

The spins of states below 1 MeV in excitation are now well established. The state at 1.201 MeV is very strongly populated by the (p, t) reaction, but a unique assignment cannot be given, even though $J^\pi = \frac{5}{2}^-$ is preferred in Ref. 3. The angular distribution for the state at 1.622 MeV can be fitted by an $L=5$ curve, in agreement with a $\frac{9}{2}^+$ assignment for a state at 1.605 MeV seen in the (^{3}He, d) reaction.[2] However, $L=4$ also seems to be possible and a second state is possible.

Two states are almost certainly present near 2.28 MeV. The $\frac{5}{2}^-$ assignment for a state at 2.278 MeV[2] is not consistent with the $L=3$ pattern that appears to be favored for the angular distribution to a state at 2.290 MeV in this work and in Ref. 3. The angular distribution in Fig. 6 for this state also seems to be flatter than the curve and supports the idea of two states.

The value $L=4$ is affirmed for the (p, t) transition to the state at 2.161 MeV. The values $L=4$ and $L=2$ given in Ref. 3 for states at 3.01 and 3.07 MeV, respectively, are not fully substantiated here. Although the states are resolved in the present work, their angular distributions do not have clear patterns. Other states are known to be present within the limits of resolution.

D. ^{89}Y$(p,\alpha)^{86}$Sr reaction

The observed angular distributions for the ^{89}Y$(p, \alpha)^{86}$Sr reaction are shown in Fig. 7. As a whole, they do not exhibit much structure but simply show cross sections that decrease as the angle increases.

Some patterns, however, may be discerned. First, the angular distributions for the two states at 0.000 and 2.106 MeV are very similar, both showing a pronounced minimum near 35°. The latter state has been assigned $J^\pi = 0^+$ in a recent study of the ^{88}Sr$(p, t)^{86}$Sr reaction.[11] Thus, we would expect pure $l=1$ for both states in the (p, α) reaction. Second, the angular distributions for the two 2^+ states at 1.077 and 1.855 MeV are very similar to each other, and yet do not have the minimum at 35° that is characteristic of the 0^+ states. These should be described by mixed $l=1$ and $l=3$ transfers. Finally, the angular distribution for the 4^+ state at 2.223 MeV declines less rapidly at larger angles than those for the other states. It should be described by $l=3$ and $l=5$ transfers.

These patterns are certainly indicative of a direct-reaction mechanism for the (p, α) reaction. However, the difficulty of unravelling the contributions of different l values from structureless angular distributions is large. In addition, uncertainties in α-particle optical potentials and in the proper treatment of the form factor preclude attempts at analysis at this time.

V. CONCLUSIONS

Definite answers have been obtained for the principle issues that were the goals of the experiments reported here. In ^{87}Y, unique spin-parity assignments have been given to the states at 0.98, 1.85, 2.09 MeV. In ^{88}Y, the presence of two low-spin states of opposite parity is clearly established. New energy levels have also been identified in ^{87}Y and ^{86}Sr.

The analysis of the data by the DWBA has led to a number of distinct problems, however. In the ^{89}Y$(p, d)^{88}$Y reaction, the spectroscopic factors do not properly satisfy the expected sum rules. Although adjustments and excuses are readily available for the $l=4$ and $l=1$ summed strengths, taken separately, the failure of these to satisfy the sum rules in opposite directions does raise a particular concern. This feature had been previously noted[8] and should perhaps be investigated further. Clear evidence for multistep processes in the (p, t) reaction on ^{89}Y is also present in the data presented here. If these could be properly calculated, the data would be most interesting for studying in greater detail the effects of removing two neutrons from the $N=50$ closed shell in ^{89}Y.[1,2]

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