PHYSICAL REVIEW C VOLUME 12, NUMBER 5 NOVEMBER 1975

Proton states in ^{85}Y†

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(Received 7 August 1975)

The ^{84}Sr(^{3}He,d)^{85}Y reaction has been studied at a bombarding energy of 18 MeV to extend the systematics of proton states in the odd-A yttrium nuclei. Thirty-seven states in the previously uninvestigated $^{85}_{39}$Y$_{46}$ were observed. A distorted-wave analysis was used to determine l values and spectroscopic strengths. The ground state of ^{85}Y is assigned $J^\pi = 1/2^-$ and the first excited state (at 20 keV) $9/2^+$. The results are compared with previous (^{3}He,d) reaction studies on ^{86}Sr and ^{88}Sr.

[NUCLEAR REACTIONS ^{84}Sr(^{3}He,d), $E = 18$ MeV; enriched target; measured $\sigma(E_d, \theta)$; deduced ^{85}Y levels, l, j, G_{lj}.]

I. INTRODUCTION

The yttrium nuclei near $A \approx 90$ have been studied[1,2] with the (^{3}He,d) reaction to investigate the closed-shell behavior of the $Z = 38$ configuration. The behavior of proton strengths as one goes away from the $N = 50$ closed shell in ^{89}Y is of interest and should aid in testing various deformed-nucleus[3] and weak-coupling[4,5] models used in current calculations. The present work extends the systematic study of $Z = 39$ nuclei to the $N = 46$ nucleus, ^{85}Y. The present work is the first direct information on the levels in ^{85}Y. A previous study[6] of the decay of ^{85}Zr assigned three γ rays to transitions in ^{85}Y.

In the β decay of ^{85}Y, two activities are observed. One, with a transition energy of 3.26 ± 0.01 MeV, has a half-life of 4.8 h and populates states with $J^\pi = (\frac{7}{2})^+$ and $(\frac{9}{2})^+$, suggesting that this β-decaying level of ^{85}Y has $J^\pi = \frac{9}{2}^+$. The other has $T_{1/2} = 2.68$ h, with a transition energy of 3.30 ± 0.02 MeV, and populates $(\frac{1}{2}, \frac{3}{2})^-$ levels in ^{85}Sr, suggesting $J^\pi = \frac{1}{2}^-$ for the second β-decaying level. Those authors placed the $(\frac{1}{2}^-)$ level above the $(\frac{9}{2})^+$.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with an 18-MeV ^{3}He beam from the University of Pennsylvania tandem accelerator. The outgoing deuterons were momentum-analyzed with a multiangle spectrograph. Spectra (see Fig. 1) were recorded on Ilford K2 emulsion plates in 3.75° steps, starting at 3.75°. The energy resolution was about 23 keV full width at half maximum (FWHM). The target was enriched ^{84}Sr (99.78%) and peaks arising from the (^{3}He,d) reaction on ^{12}C, ^{16}O, and small amounts of contaminants from the target evaporation were identified or were negligibly small. The data were analyzed with the program AUTOFIT[7] in order to obtain yields and excitation energies. Cross sections were calculated from the measured integrated charge and the target thickness (~50 μg/cm^2), the uncertainty in the latter being responsible for uncertainties of about ±30% in the absolute magnitude of the cross sections.

The measured angular distributions were compared with the results of distorted-wave Born-approximation (DWBA) calculations, using the code DWUCK.[8] The optical model parameters used in the present analysis were the same as those in Ref. 9. The spectroscopic strengths $G_{lj} = (2J_f + 1)\, C^2 S_{lj}$

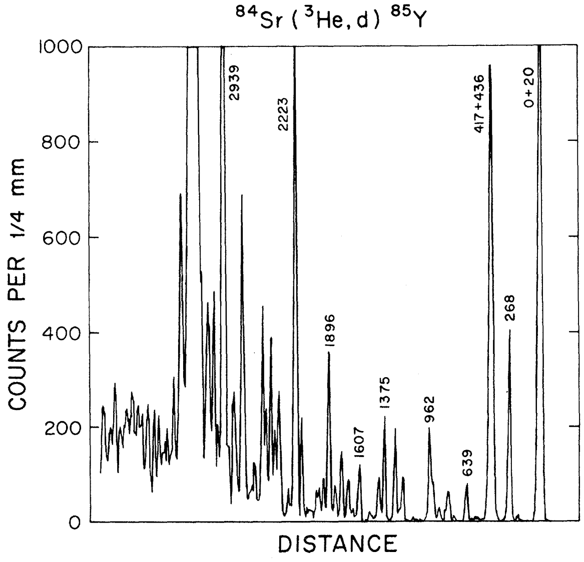

FIG. 1. Typical deuteron spectrum of the ^{84}Sr(^{3}He,d)-^{85}Y reaction.

TABLE I. Present results for the ^{84}Sr(^{3}He,d)^{85}Y reaction.

E_x [a] (keV)	l_p	J^π	$(2J+1)C^2S$ [b]
0	1	$(\frac{1}{2})^-$	1.48
20	4	$(\frac{9}{2})^+$	6.0
268	3	$(\frac{5}{2})^-$	1.80
417	1	$(\frac{1}{2},\frac{3}{2})^-$	0.96
436	2	$(\frac{3}{2},\frac{5}{2})^+$	0.20
639	1	$(\frac{1}{2},\frac{3}{2})^-$	0.072
803	2	$(\frac{3}{2},\frac{5}{2})^+$	0.041
883	2	$(\frac{3}{2},\frac{5}{2})^+$	0.015
936	1	$(\frac{1}{2},\frac{3}{2})^-$	0.054
962	1	$(\frac{1}{2},\frac{3}{2})^-$	0.138
1212	1	$(\frac{1}{2},\frac{3}{2})^-$	0.078
1278	2	$(\frac{3}{2},\frac{5}{2})^+$	0.084
1375	0	$\frac{1}{2}^+$	0.030
1428	2	$(\frac{3}{2},\frac{5}{2})^+$	0.034
1607	2	$(\frac{3}{2},\frac{5}{2})^+$	0.053
1716	2	$(\frac{3}{2},\frac{5}{2})^+$	0.040
1776	4	$(\frac{7}{2},\frac{9}{2})^+$	1.10
1837	0	$\frac{1}{2}^+$	0.036
1896	0	$\frac{1}{2}^+$	0.054
1992	1	$(\frac{1}{2},\frac{3}{2})^-$	0.028
2156 [c]	0	$\frac{1}{2}^+$	0.012
	2	$(\frac{3}{2},\frac{5}{2})^+$	0.059
2223 [c]	0	$\frac{1}{2}^+$	0.054
	2	$(\frac{3}{2},\frac{5}{2})^+$	0.31
2427	2	$(\frac{3}{2},\frac{5}{2})^+$	0.050
2472	0	$\frac{1}{2}^+$	0.050
2519	2	$(\frac{3}{2},\frac{5}{2})^+$	0.066
2551	2	$(\frac{3}{2},\frac{5}{2})^+$	0.10
2748	2	$(\frac{3}{2},\frac{5}{2})^+$	0.22
2840	(0)	$(\frac{1}{2}^+)$	(0.040)
2939	2	$(\frac{3}{2},\frac{5}{2})^+$	0.56
3041	0	$\frac{1}{2}^+$	0.058
3110	0	$\frac{1}{2}^+$	0.096
3168	(0)	$(\frac{1}{2}^+)$	(0.036)
3230	2	$(\frac{3}{2},\frac{5}{2})^+$	0.16
3270	2	$(\frac{3}{2},\frac{5}{2})^+$	0.22
3375	0	$\frac{1}{2}^+$	0.088

[a] Excitation energies if the lower member of the g.s. doublet is assigned $E_x \equiv 0$. The values for known states in ^{13}N and ^{17}F from target impurities were used in the energy calibration. Uncertainties in the energies are ±4 keV below 1 MeV excitation energy and ±6 keV above.

[b] Calculations assume $2p_{1/2}$, $2d_{5/2}$, $1f_{5/2}$, and $1g_{9/2}$ for $l_p = 1$, 2, 3, and 4, respectively.

[c] Doublet.

were derived from the differential cross sections by use of the expression

$$\frac{d\sigma}{d\Omega} = 4.42\, G_{lj}\sigma_{\mathrm{DWUCK}}/2j+1,$$

where J_f and j are the total angular momenta of the residual nucleus and the transferred proton, respectively. The $l_p = 1$, 2, 3, and 4 calculations were made for $2p_{1/2}$, $2d_{5/2}$, $1f_{5/2}$, and $1g_{9/2}$, respectively.

III. RESULTS

Thirty-seven levels in ^{85}Y were observed in the present (^{3}He,d) experiment up to an excitation energy of 3375 keV. The l_p values and excitation energies determined in the DWBA analysis are shown in Table I and in Figs. 2–5. The "g.s." peak is assigned as a $\frac{1}{2}^-$ - $\frac{9}{2}^+$ doublet on the basis of the angular distribution which can be fitted only by a combination of $l = 1$ and $l = 4$ calculated curves. Also, the spectroscopic strengths of 1.48 and 6.0, respectively, are consistent with the observed[1,2] strengths of the $2p_{1/2}$ and $1g_{9/2}$ transfers on ^{86}Sr and ^{88}Sr targets. The systematics of the $\frac{1}{2}^-$ - $\frac{9}{2}^+$ energy differences in the $N = 50$ and 48 nuclei suggest that the two states should lie quite close in energy in ^{85}Y. The question of whether the $\frac{1}{2}^-$ or $\frac{9}{2}^+$ state is the g.s. was answered from the present (^{3}He,d) data by the observed broadening of the "g.s." peak for $\theta_{\mathrm{c.m.}} \geq 23°$. Beyond that angle, two peaks with energy separation 20 ± 3 keV can be fitted to the g.s. doublet. At small angles where $l_p = 1$ is much stronger than $l_p = 4$, only the lower energy (and hence g.s.) member is observed. We therefore propose the $l_p = 1$ transfer to the g.s., and the $l_p = 4$ to an excited state at 20 keV.

As shown in Fig. 1, two strong peaks were observed at 268 and ~420 keV. The 268-keV angular distribution is reproduced well by an $l_p = 3$ calcu-

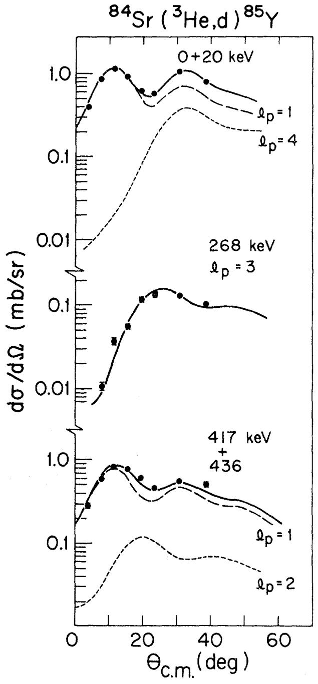

FIG. 2. Angular distributions of the deuterons leading to states in ^{85}Y from the ^{84}Sr(^{3}He, d) reaction. The lines are the distorted-wave Born-approximation calculations for the indicated l_p values.

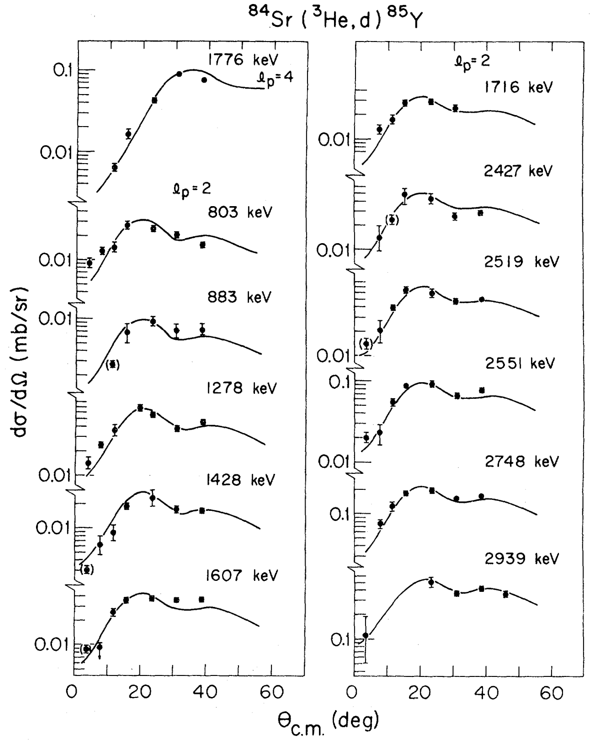

FIG. 4. Angular distributions for states with $E_x \geq 793$ keV reached by $l_p = 2$ and $l_p = 4$ transfers. The lines are the DWBA calculations.

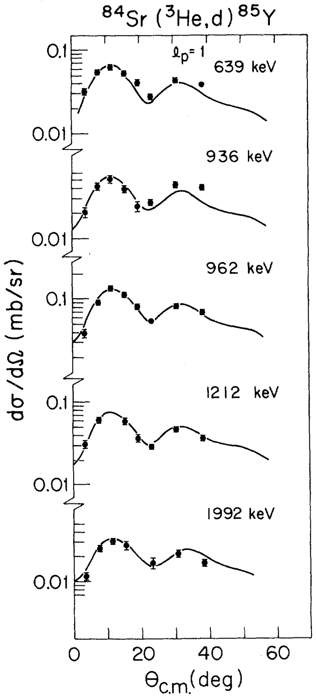

FIG. 3. Angular distributions of the deuterons leading to states in ^{85}Y. The lines are the DWBA calculations for $l_p = 1$ transfers.

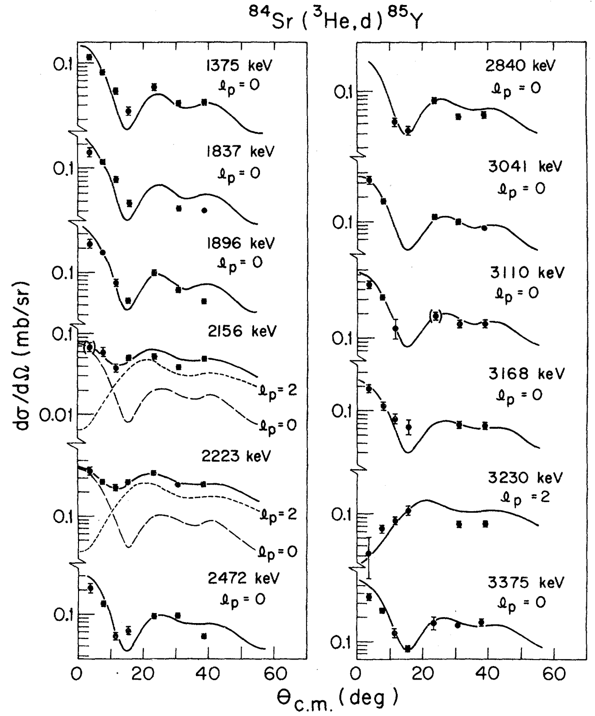

FIG. 5. Angular distributions for states with $E_x \geq 1366$ keV reached by $l_p = 0$ and $l_p = 2$ transfers. The lines are the DWBA calculations.

TABLE II. Sums of spectroscopic strengths and centroid energies (MeV) for various l_p transfers in the (^{3}He, d) reactions on ^{84}Sr (present work), ^{86}Sr (Ref. 1), and ^{88}Sr (Ref. 2).

	$^{84}_{38}\mathrm{Sr}_{46}$		$^{86}_{38}\mathrm{Sr}_{48}$		$^{88}_{38}\mathrm{Sr}_{50}$	
l_p	E_x	G_{lj}	E_x	G_{lj}	E_x	G_{lj}
1 $2p_{1/2}$	(0)	(1.48)	0	1.15	0	1.80
1 $2p_{3/2}$	(0.59)	(1.33)	(1.21)	(0.70)	(1.77)	(0.51)
3	0.27	1.80	1.15	1.45	1.74	0.55
4	0.29	7.10	0.63	8.51	0.90	8.80
2	2.33	2.21	2.67	1.39	4.49	3.15
0	2.69	0.55	3.20	0.04	···	···
Sum	0.0–3.38	14.47	0.0–3.5	13.24	0.0–5.3	14.81

lation. An analysis of the 420-keV peak shape suggests the presence of a doublet, with a separation between the two members of 19 ± 3 keV. The angular distribution is fitted in Fig. 2 with a combination of $l_p = 1$ and $l_p = 2$. The strong transfers to the first four states are consistent with assigning them to the major components of the $2p_{1/2}$, $1g_{9/2}$, $1f_{5/2}$, and $2p_{3/2}$ strengths, analogous to previous studies[1,2] of (^{3}He, d) on ^{86}Sr and ^{88}Sr.

Above 436 keV excitation energy, 32 states were observed in the present (^{3}He, d) experiment. Only one other $l_p = 4$ transfer was observed, to a state at 1776 keV. The remaining states were reached by $l_p = 0$, 1, or 2 transfers. No further $l_p = 3$ transitions were seen. The energies, J^π restrictions, and spectroscopic strengths are shown in Table I.

The summed spectroscopic strengths and energy centers of gravity for the various l_p transfers in ^{84}Sr(^{3}He, d) are shown in Table II in comparison with the results[1,2] for (^{3}He, d) on ^{86}Sr and ^{88}Sr. The total spectroscopic strength measured for $l_p = 1$, 3, and 4 transfers to states in ^{85}Y is 11.7. The value expected from the sum rule is

$$\sum G_{lj}(T_<) = [\text{Number of proton holes in } N = 50] - \sum G_{lj}(T_>) = 12 - \tfrac{4}{9} = 11.56.$$

The summary in Table II shows that the $1f_{5/2}$ and $2p_{3/2}$ orbitals become more empty as one moves away from the $N = 50$ closed shell. The summed $l_p = 4$ strength is weaker, indicating either that the $1g_{9/2}$ orbital is more full in ^{84}Sr or that some $1g_{9/2}$ strength was missed. The centroids of the observed strength for all the orbitals decreased in energy as the neutrons are removed.

IV. DISCUSSION

In the compilation[10] for $A = 85$, the 4.8-h ($\frac{9}{2}^+$) state was tentatively assigned to the g.s. and the 2.68-h

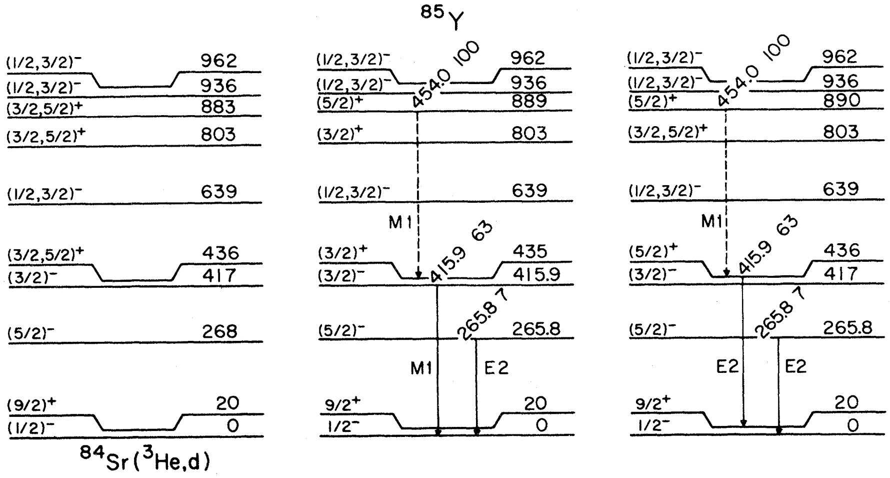

FIG. 6. Level diagrams for states below 1 MeV excitation in ^{85}Y. Column 1 is the information from the present (^{3}He, d) work, and columns 2 and 3 are proposed schemes incorporating the γ rays assigned to ^{85}Y in Ref. 6.

$(\frac{1}{2}^-)$ state to a low-lying excited state on the basis of measured energies of the β^+ decays of ^{85}Y and ^{85}Y^m. The order of the two states was considered[10] uncertain, though, because of the uncertainty in the deduced decay energies $Q^+(4.8\text{ h}) = 3.26 \pm 0.01$ MeV and $Q^+(2.68\text{ h}) = 3.30 \pm 0.02$ MeV.

Subsequent to the compilation, three γ rays were assigned[6] as transitions in ^{85}Y following the 6-min decay of ^{85}Zr. Their energies (intensities) were 265.8 (7 ± 2), 415.9 (63 ± 5), and 454.0 (100) keV; however, no decay scheme was deduced. It is interesting to try to place these γ rays with the aid of the present ^{84}Sr(^{3}He,d) ^{85}Y results. In the latter, the separation between the g.s. and the first $(\frac{5}{2})^-$ excited state is 268 ± 4 keV. The 265.8-keV γ ray could therefore be due to a transition from this state to the lower member of the g.s. doublet (see Fig. 6). The strong 415.9-keV γ ray is likely due to an $M1$ transition from the 417-keV state observed in (^{3}He,d) by $l_p = 1$ transfer. Then, from the measured separation (19 ± 3 keV) between the members of this doublet, the $l = 2$ state would be at 435 ± 3 keV.

Alternatively, the 415.9-keV γ ray could arise from the decay of the higher member of the doublet to the 20 keV $\frac{9}{2}^+$ excited state. In that case, the $l_p = 2$ state has an energy of 436 ± 3 keV, and the $l_p = 1$ member 419 ± 4 keV. The $l_p = 2$ state is then very likely $\frac{5}{2}^+$.

The 454.0-keV γ ray cannot be due to a transition to the g.s. or to the first $\frac{9}{2}^+$ state unless a state exists at 454 or ~474 keV which was not populated with the (^{3}He,d) reaction. Of the levels observed here, the energies are consistent with a 454-keV transition from a state at 889 ± 3 keV to the state at $E_x = 435$ keV with $J^\pi = \frac{5}{2}^+$.

Several possible J^π assignments can be inferred from the proposed decay scheme. For example, the strong population of the 889-keV state in the decay of ^{85}Zr, together with $l_p = 2$ in (^{3}He,d), suggests $J^\pi = \frac{5}{2}^+$.

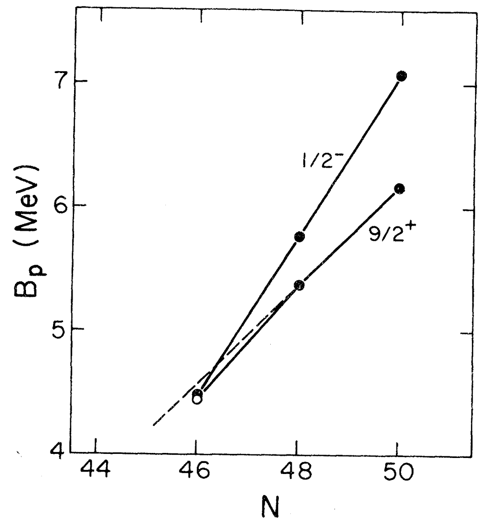

FIG. 7. Binding energies of the $\frac{1}{2}^-$ ground states and $\frac{9}{2}^+$ excited states in Y nuclei for different values of neutron number N.

Thus, all the known odd-A Y nuclei have $\frac{1}{2}^-$ ground states and $\frac{9}{2}^+$ first excited states. In Fig. 7 is shown the binding energies of the $\frac{1}{2}^-$ and $\frac{9}{2}^+$ states in the $N = 46$, 48, and 50 nuclei. For simple single-particle nuclei the values would be approximately linear with respect to N. On the basis of the splitting in ^{87}Y and ^{89}Y, the $\frac{1}{2}^-$ and $\frac{9}{2}^+$ states should lie very close in ^{85}Y, as observed. These same systematics would suggest that the $\frac{9}{2}^+$ should become the g.s. for lighter Y nuclei. It will be interesting to see if this behavior does occur as more neutrons are removed and if calculations will be able to explain these systematics.

ACKNOWLEDGMENTS

The authors thank Laszlo Csihas for preparation of the target. We also thank V. Adams for careful scanning of the nuclear emulsion plates.

[†] Work supported by the National Science Foundation.

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