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Proton states in ^{87}Rb†

L. R. Medsker,* H. T. Fortune, S. C. Headley, and J. N. Bishop‡
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19174
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The ^{86}Kr(^{3}He, d)^{87}Rb reaction has been studied at a bombarding energy of 18 MeV. The isotopically enriched ^{86}Kr target was contained in a gas cell with no entrance window. Excitation energies and angular distributions were obtained for 60 levels below 7 MeV in ^{87}Rb. A distorted-wave analysis was used to determine l values and spectroscopic strengths. The results are compared with previous data from transfer reactions and radioactive decay.

[NUCLEAR REACTIONS ^{86}Kr(^{3}He, d), E = 18 MeV; enriched target; measured $\sigma(E_d, \theta)$; deduced ^{87}Rb levels, l, j, G_{lj}.]

I. INTRODUCTION

Nuclei near A = 90 are receiving increased attention because of the success of various theoretical models. Spherical shell-model calculations[1] have had some success for cases of a few particles outside a ^{88}Sr core. As nucleons are subtracted from the $(Z, N) = (38, 50)$ core, the nuclei may possibly be described also by deformed-nucleus calculations,[2] weak-coupling models,[3] or the coupling of a few particles or holes.[4] Systematic studies of nuclei for $(Z, N) < (38, 50)$ should provide good tests of the various models. In addition, the increasing interest in high-spin states through (HI, $xn\gamma$) reactions requires a complete knowledge of low-lying states as a basis for constructing decay schemes and to identify reaction products. As part of a systematic study[5] of proton states in this region, we have investigated the N = 50 nucleus ^{87}Rb.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with the 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 at 7.5° and in 7.5° steps from 11.25 to 41.25°. The target was enriched ^{86}Kr gas (99.2%) which was purified and recirculated through a gas cell with no entrance window.[6] The pressure in the gas cell was maintained at 12 Torr, which corresponds to an effective target thickness of about 50 μg/cm^2. The energy resolution was 20 keV full width at half maximum (FWHM). Contamination peaks due to ^{40}Ar (~2%) were identified or were negligibly small. The data were analyzed with the program AUTOFIT[7] in order to obtain excitation energies and cross sections. The cross sections, calculated from the measured gas pressure and amount of collected charge, were uncertain to 10%. 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. 5. The spectroscopic strengths $G_{lj} = [(2J_f + 1)/(2J_i + 1)]C^2 S_{lj}$ 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_i, J_f, and j are the total angular momenta of the target nucleus, residual nucleus, and the transferred proton, respectively. Unless the spin is known otherwise, the l_p = 1, 2, and 4 calculations were made for $2p_{1/2}$, $2d_{5/2}$, and $1g_{9/2}$, respectively. (See footnotes in Table III.)

III. RESULTS

In the present experiment, 60 levels in ^{87}Rb were observed up to an excitation energy 6989 keV.

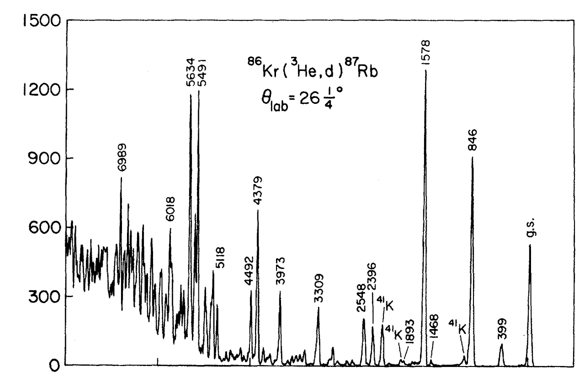

FIG. 1. Typical deuteron spectrum of the ^{86}Kr(^{3}He, d)-^{87}Rb reaction.

From the DWBA analysis, the l_p values could be determined and the results are shown in Figs. 2–5 and in Table I. The results for the 1579-keV level were reported earlier.[9]

The information for 10 levels in ^{87}Rb has been summarized in Ref. 10, and subsequent to that, data have been reported from works on the decay[11,12] of ^{87}Kr, Coulomb excitation,[13] ^{87}Rb-$(n, n'\gamma)$,[14,15] and ^{88}Sr$(d, {}^3$He$)$.[16,17] These available data are shown in Table II together with the results of the present $(^3$He$, d)$ study.

The ground state and 403-keV states have well established[10] $J^\pi = \frac{3}{2}^-$ and $\frac{5}{2}^-$, respectively, and were observed with strong $l_p = 1$ and $l_p = 3$ transfers in the present $(^3$He$, d)$ experiment. The strong $l_p = 1$ transfer to the 846-keV level is consistent with the tentative $\frac{1}{2}^-$ assignment from ^{87}Kr decay.[10–12] That state probably has the major $2p_{1/2}$ strength in ^{87}Rb.

States at 1349 and1390 keV were reported in ^{87}Kr decay and $(n, n'\gamma)$, respectively, but neither were observed in $(^3$He$, d)$. Therefore, as discussed earlier,[9] the 1349-keV state cannot contain the $1g_{9/2}$ strength in ^{87}Rb, and the 1578-keV state, reached by $l_p = 4$ with $(2J+1)C^2S \approx 10$, is the most probable candidate for the $g_{9/2}$ proton state. The 1468-keV state populated weakly by $l_p = 1$ in $(^3$He$, d)$ may be the same as the 1463-keV state from ^{87}Rb $(n, n'\gamma)$. As discussed earlier,[9] because of a $(\frac{7}{2}^-)$ assignment from ^{87}Kr decay and $l_n = (1)$ from $(d, {}^3$He$)$, a second state may exist near 1578 keV. However, those assignments are sufficiently ambiguous that further data are necessary to establish the existence of a doublet at 1578 keV.

Above $E_x = 1578$ keV, only fair correlation was found between levels observed in $(^3$He$, d)$ and those

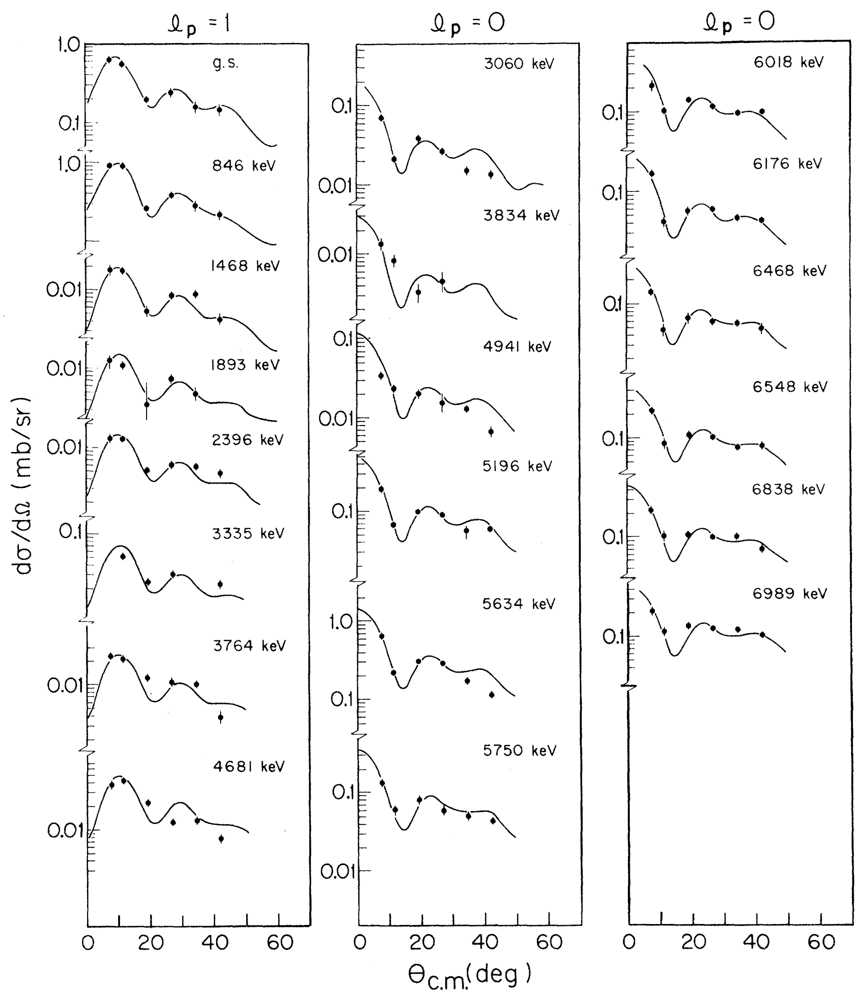

FIG. 2. Angular distributions of the deuterons leading to states in ^{87}Rb from the ^{86}Kr$(^3$He$, d)$ reaction. The solid lines are the distorted-wave Born-approximation calculations for $l_p = 1$ and $l_p = 0$ transfers.

reported in previous work. The $(\frac{5}{2}^-)$ state at 1741 keV, observed in ^{87}Kr decay and in $(n, n'\gamma)$ was not observed in the present work but it might be expected to be weak in (^{3}He, d). The 1893-keV state, previously unreported, is populated by $l_p = 1$ transfer and hence has $J^\pi = (\frac{1}{2}, \frac{3}{2})^-$. If the 2378-keV $(\frac{3}{2}^-, \frac{5}{2}^-)$ level from ^{87}Kr decay is the same as the 2396-keV level observed with $l_p = 1$ in (^{3}He, d) then that state has $J^\pi = \frac{3}{2}^-$; however, the difference in energies is outside the expected range. Of the six remaining states up to 3309 keV, the 2548-, 2810-, and 3309-keV states agree in energy with levels reported in ^{87}Kr decay. Since $J^\pi = (\frac{5}{2}^\pm, \frac{7}{2}^-)$ assignments were made in the decay work, the present observation of $l_p = 2$ for the 2548- and 2810-keV states would imply $J^\pi = \frac{5}{2}^+$ for both states. Above 3309 keV, 47 states are reported for the first time from the present (^{3}He, d) work. 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 ^{86}Kr(^{3}He, d) are shown in Table III in comparison with the results[5] for ^{84}Kr(^{3}He, d). Assuming the configurations mentioned earlier, the total strength for $l_p = 1$, 3, and 4 is 15.25 (this value would change by $\lesssim 2\%$ if states with ambiguous J assignments have the alternative configurations). The value expected from the sum rule is

$$\sum G_{lj}\,(T_<) = (\text{No. proton holes in } N = 50) - \sum G_{lj}\,(T_>) = 14\,.$$

This agreement is good, since uncertainties in target thickness and in the DWBA formalism are ~20%.

The comparison in Table III shows that in both ^{84}Kr and ^{86}Kr the $1f_{5/2}$ orbital is significantly empty. This orbital appears to be more empty in ^{84}Kr than in ^{86}Kr, but the sum of $l_p = 3$ and $l_p = 1$ is about the same for the two nuclei, implying a sharper Fermi surface for the closed-neutron-shell nucleus ^{86}Kr. The summed $l_p = 4$ strength is somewhat weaker in ^{84}Kr, but small fragments of this strength may have been missed. The centroids in Table III indicate that the $1g_{9/2}$, $2d_{5/2}$, and

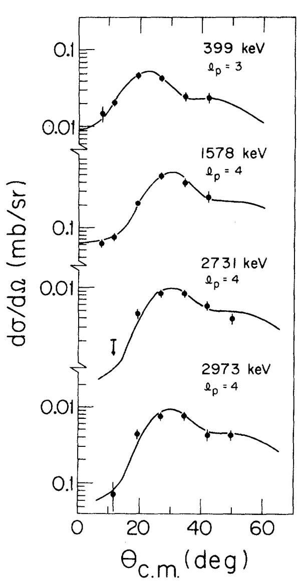

FIG. 3. Angular distributions for levels excited in the ^{86}Kr(^{3}He, d) reaction. The solid lines are the distorted-wave Born-approximation calculations.

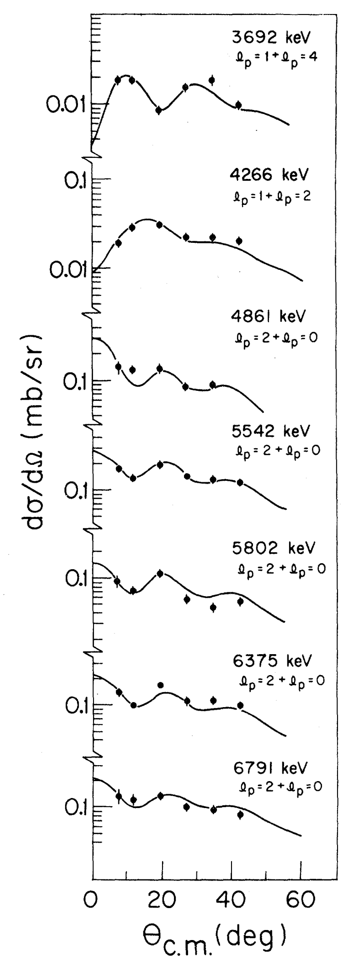

FIG. 4. Angular distributions requiring two l values (implying unresolved states). The solid lines are the distorted-wave Born-approximation calculations for the indicated combinations of l transfers.

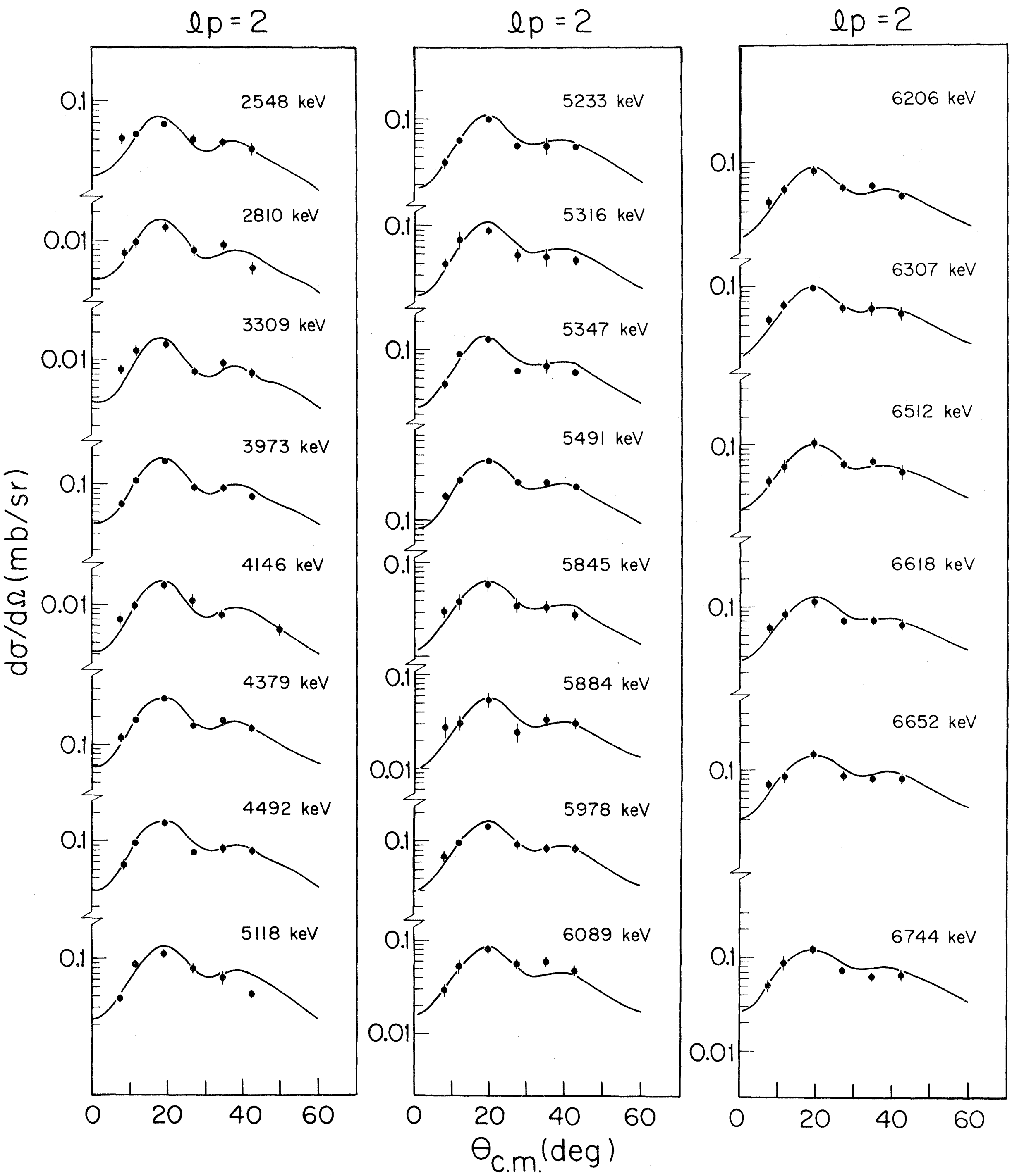

FIG. 5. Angular distributions for levels reached by $l_p=2$ transfers in the ^{86}Kr(^{3}He, d)^{87}Rb reaction. The solid lines are the distorted-wave Born-approximation calculations.

TABLE I. Present results for the ^{86}Kr(^{3}He, d)^{87}Rb reaction.

E_x [a] (keV)	l_p	J^π	$(2J+1)C^2S$ [b]	E_x [a] (keV)	l_p	J^π	$(2J+1)C^2S$ [b]
0	1	$\frac{3}{2}^{-}$ [c]	1.36	5233	2	$(\frac{3}{2},\frac{5}{2})^+$	0.11
399	3	$\frac{5}{2}^{-}$ [c]	1.18	5316	2	$(\frac{3}{2},\frac{5}{2})^+$	0.089
846	1	$(\frac{1}{2})^-$	2.04	5347	2	$(\frac{3}{2},\frac{5}{2})^+$	0.13
1468	1	$(\frac{1}{2},\frac{3}{2})^-$	0.031	5491	2	$(\frac{3}{2},\frac{5}{2})^+$	0.43
1578	4	$\frac{9}{2}^+$	9.87	5542 [d]	(0+2)	$(\frac{1}{2}^+)+(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.026)+(0.17)
1893 ± 10	1	$(\frac{1}{2},\frac{3}{2})^-$	0.023	5634 ± 7	0	$\frac{1}{2}^+$	0.17
2396	1	$(\frac{1}{2},\frac{3}{2})^-$	0.17	5750	0	$\frac{1}{2}^+$	0.044
2548 ± 7	2	$(\frac{3}{2},\frac{5}{2})^+$	0.11	5802 [d]	(0+2)	$(\frac{1}{2}^+)+(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.016)+(0.081)
2731	4	$(\frac{7}{2},\frac{9}{2})^+$	0.14	5845	2	$(\frac{3}{2},\frac{5}{2})^+$	0.056
2810	2	$(\frac{3}{2},\frac{5}{2})^+$	0.024	5884	2	$(\frac{3}{2},\frac{5}{2})^+$	0.051
2973	4	$(\frac{7}{2},\frac{9}{2})^+$	0.13	5978	2	$(\frac{3}{2},\frac{5}{2})^+$	0.13
3060	0	$\frac{1}{2}^+$	0.036	6018	0	$\frac{1}{2}^+$	0.076
3309	2	$(\frac{3}{2},\frac{5}{2})^+$	0.25	6089	2	$(\frac{3}{2},\frac{5}{2})^+$	0.073
3335 ± 8	1	$(\frac{1}{2},\frac{3}{2})^-$	0.058	6176	0	$\frac{1}{2}^+$	0.030
3692 [d] ± 7	1+(4)	$(\frac{1}{2},\frac{3}{2})^-+(\frac{7}{2}^+,\frac{9}{2}^+)$	0.016+(0.12)	6206	2	$(\frac{3}{2},\frac{5}{2})^+$	0.071
3764	1	$(\frac{1}{2},\frac{3}{2})^-$	0.021	6307	2	$(\frac{3}{2},\frac{5}{2})^+$	0.085
3834	0	$\frac{1}{2}^+$	0.024	6375 [d]	(0+2)	$(\frac{1}{2}^+)+(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.022)+(0.083)
3973	2	$(\frac{3}{2},\frac{5}{2})^+$	0.24	6468	0	$\frac{1}{2}^+$	0.034
4146	2	$(\frac{3}{2},\frac{5}{2})^+$	0.021	6512	2	$(\frac{3}{2},\frac{5}{2})^+$	0.086
4266 [d]	(1)+2	$(\frac{1}{2}^-,\frac{3}{2}^-),(\frac{3}{2},\frac{5}{2})^+$	(0.014)+0.031	6548	0	$\frac{1}{2}^+$	0.056
4379	2	$(\frac{3}{2},\frac{5}{2})^+$	0.39	6618	2	$(\frac{3}{2},\frac{5}{2})^+$	0.092
4492	2	$(\frac{3}{2},\frac{5}{2})^+$	0.19	6652	2	$(\frac{3}{2},\frac{5}{2})^+$	0.12
4681	1	$(\frac{1}{2},\frac{3}{2})^-$	0.034	6744 ± 10	2	$(\frac{3}{2},\frac{5}{2})^+$	0.10
4862 [d]	(0+2)	$\frac{1}{2}^++(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.003)+(0.008)	6791 [d] ± 9	(0+2)	$(\frac{1}{2}^+)+(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.022)+(0.075)
4941	0	$\frac{1}{2}^+$	0.012	6838	0	$\frac{1}{2}^+$	0.056
5118 ± 9	2	$(\frac{3}{2},\frac{5}{2})^+$	0.12				
5196	0	$\frac{1}{2}^+$	0.056	6989	0	$\frac{1}{2}^+$	0.053

[a] The values for known states in ^{87}Rb and ^{41}K were used in the energy calibration. Uncertainties in the energies are ±5 keV unless otherwise indicated.

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

[c] See Ref. 10.

[d] Doublet.

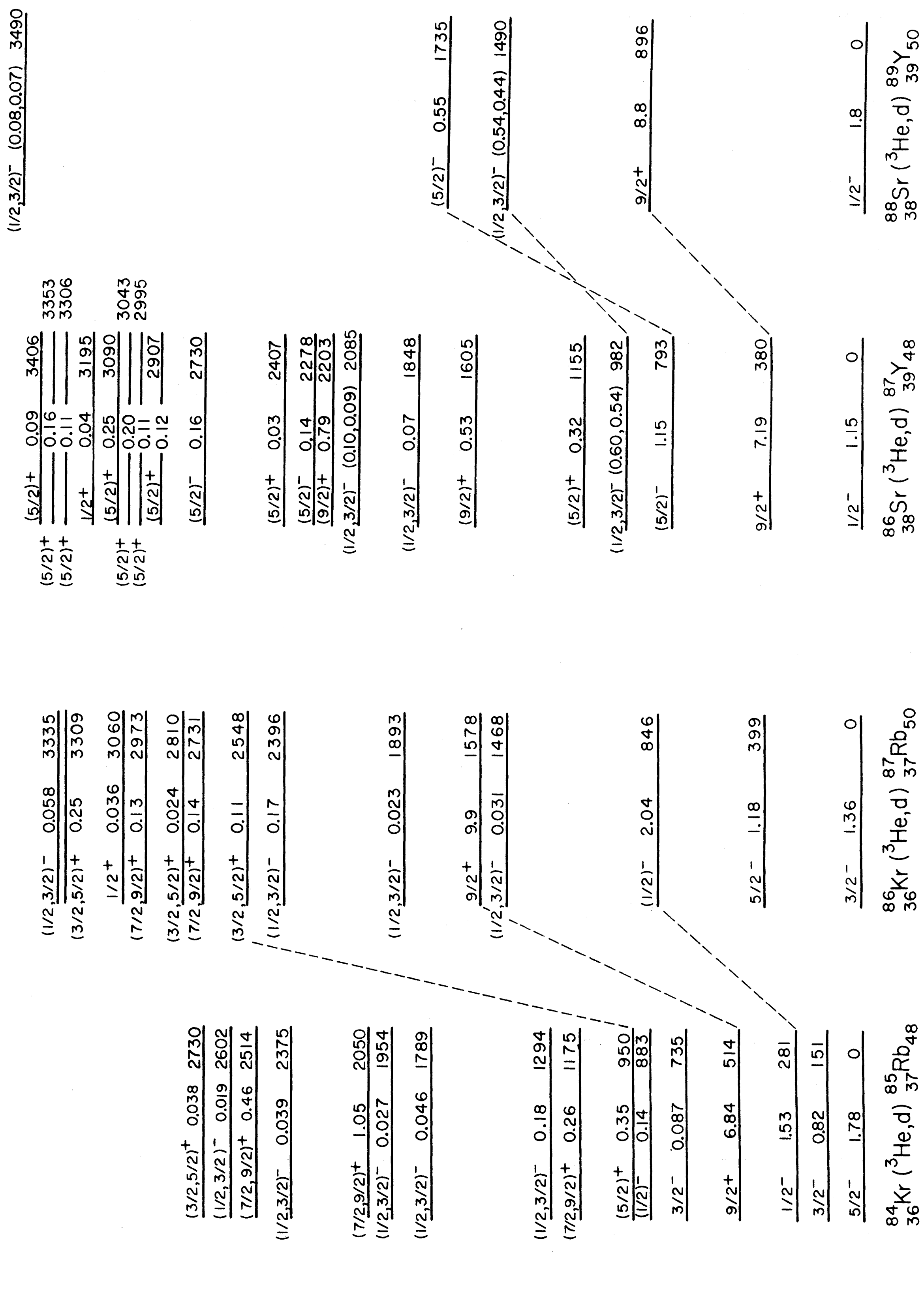

FIG. 6. Comparison of energy levels, J^π, and spectroscopic strengths for the (^{3}He,*d*) reactions on ^{84}Kr (Ref. 5), ^{86}Kr (present), ^{86}Sr (Ref. 18), and ^{88}Sr (Ref. 19).

TABLE II. Low-lying energy levels, l_p, J^π, and spectroscopic strengths from the present ^{86}Kr(^{3}He,d) study compared with results from previous studies of ^{87}Rb.

NDS, $(n,n'\gamma)$ [a], and Coul. ex. E_x (keV)	J^π	^{87}Kr decay [b] E_x (keV)	J^π	^{88}Sr(d, ^{3}He) [c] E_x (keV)	l_p	C^2S	^{86}Kr(^{3}He,d)^{87}Rb E_x (keV)	l_p	J^π	$(2J+1)C^2S^d$
0	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$	0	1	2.9	0	1	$\frac{3}{2}^-$	1.36
403.0± 0.5	$\frac{5}{2}^-$	403	$\frac{5}{2}^-$	403	3	5.1	399	3	$\frac{5}{2}^-$	1.18
845.8± 0.5	$(\frac{1}{2}^-)$	846	$(\frac{1}{2}^-)$	846	1	0.4	846	1	$(\frac{1}{2})^-$	2.04
		1349	$(\frac{9}{2}^\pm)$							
1389.7± 0.9										
1463 ?							1468	1	$(\frac{1}{2},\frac{3}{2})^-$	0.031
1578.5± 1.1	$(\frac{7}{2}^-)$	1578	$(\frac{7}{2}^-)$	1578	(1, 3)	(0.2, ≤0.54)	1578	4	$(\frac{9}{2})^+$	9.87
1741.0± 0.7	$(\frac{5}{2}^-)$	1740	$(\frac{5}{2}^-)$							
							{ 1893± 10	1	$(\frac{1}{2},\frac{3}{2})^-$	0.023
		2378	$(\frac{3}{2}^-, \frac{5}{2}^-)$				{ 2396	1	$(\frac{1}{2},\frac{3}{2})^-$	0.17
2415.0± 0.6		2414	$(\frac{7}{2}^+)$							
2556.0± 2.0		2555	$(\frac{5}{2}^\pm, \frac{7}{2}^-)$				2548± 7	2	$\frac{5}{2}^+$	0.11
							2731	4	$(\frac{7}{2},\frac{9}{2})^+$	0.14
2811.2± 3.0		2811	$(\frac{5}{2}^\pm, \frac{7}{2}^-)$				2810	2	$\frac{5}{2}^+$	0.024
2962.3± 1.3		2960	$(\frac{5}{2}^+)$							
							{ 2973	4	$(\frac{7}{2},\frac{9}{2})^+$	0.13
		3055					{ 3060	0	$\frac{1}{2}^+$	0.036
3309.8± 2.0		3308					3309	2	$(\frac{5}{2})^+$	0.25

[a] See Refs. 10, 13, 14, and 15. (NDS denotes Nuclear Data Sheets.)
[b] See Refs. 11 and 12.
[c] See Refs. 16 and 17.
[d] Calculations assuming $2p_{1/2}$, $2d_{5/2}$, and $1g_{9/2}$ orbitals for l_p=1, 2, and 4 transfer, respectively.

TABLE III. Sums of spectroscopic strength and centroid energies (MeV) for various l_p transfers in the (^{3}He,d) reactions on ^{84}Kr (Ref. 5) and ^{86}Kr (present work). The region of excitation energy E_x over which data are available is indicated in the last line.

l_p		$^{84}_{36}$Kr$_{48}$ $\overline{E}_x$	G_{lj} [a]	$^{86}_{36}$Kr$_{50}$ $\overline{E}_x$	G_{lj} [a]
1	{ $2p_{3/2}$	0.21	0.91	0.0	1.36
	{ $2p_{1/2}$	(0.88) [b]	(2.16) [b]	(1.15) [b]	(2.41) [b]
3		0.0	1.78	0.40	1.18
4		0.83	8.61	1.64	10.3
2		3.79	2.45	5.15	3.42
0		4.34	0.38	5.82	0.74
Sum		0.0–6.2	16.3	0.0–7.0	19.4

[a] Unless known otherwise, the orbitals $2p_{1/2}$, $2d_{5/2}$, and $1g_{9/2}$ are assumed in the calculations. The value of G_{lj} for $J=l_p+\frac{1}{2}$ is lower than that for $J=l_p-\frac{1}{2}$ by ~15, 25, and 50% if l_p=1, 2, or 4, respectively.
[b] Values for all l_p=1 not known to be $2p_{3/2}$.

$3s_{1/2}$ strengths all decrease in energy as two neutrons are removed from the $^{86}_{36}$Kr$_{50}$ nucleus.

The information from the present work on ^{87}Rb is shown in Fig. 6 in comparison with the results of previous (^{3}He,d) studies[5,18,19] on ^{84}Kr and ^{86,88}Sr targets. For both Rb and Y, the states with the major $2p_{1/2}$ and $1g_{9/2}$ strengths decrease in energy as neutrons are removed. Furthermore, the $1g_{9/2}$ strength is more fragmented in the two $N=48$ nuclei than in the nuclei with $N=50$, although ^{89}Y does not show as much fragmentation of the $1g_{9/2}$ strength as does ^{87}Rb. The similarity of the distributions of strength in the $N=48$ nuclei suggests the existence of previously unobserved $l_p=4$ transfers in ^{88}Sr(^{3}He, d).

Finally, the $2d_{5/2}$ proton strength extends to much lower excitation energy in ^{85}Rb and ^{87}Y than in ^{87}Rb and ^{89}Y. These qualitative features should provide motivation for extended shell-model calculations for nuclei below ^{88}Sr.

IV. ACKNOWLEDGMENT

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†Work supported by the National Science Foundation.
*Present address: Department of Physics, Florida State University, Tallahassee, Florida 32306.
‡Present address: Center for Nuclear Studies, University of Texas, Austin, Texas 78712.
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