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Levels of ^{86}Kr from ^{87}Rb$(t, \alpha)^{86}$Kr[†]

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The levels of ^{86}Kr have been investigated by the ^{87}Rb (t, α) reaction with 15-MeV tritons. α-particle spectra were recorded with a semiconductor counter telescope at c.m. angles between 13° and 73°, and excited states were observed up to 4.3 MeV. Differential cross sections for 13 levels were compared with distorted-wave Born-approximation calculations, giving l_p values and spectroscopic factors. The predominant $l_p=1$ and $l_p=3$ reaction amplitudes, which are assumed to represent $2p_{3/2}$ and $1f_{5/2}$ proton pickup, are essentially exhausted by 4 MeV excitation. All of the experimental angular distributions are best fitted with a single value of l_p, although $l_p=1$, 3 mixtures would be expected for population of 2^+ levels. One definite $l_p=4$ angular distribution was observed, indicating a small $1g_{9/2}$ proton component in the ^{87}Rb ground state. Results of this experiment are compared with recently reported ^{86}Kr(p, p') and ^{86}Br decay data.

I. INTRODUCTION

The $N=50$ nuclei in the neighborhood of $Z=35-43$ are a natural group in which to study proton interactions in the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$ shell-model orbits. Closure of the neutron shell should reduce the contributions of excited-neutron configurations to lower-lying ($\lesssim$4-MeV) levels, and the existence of stable $N=50$ target species makes possible the population of these levels by proton pickup and stripping reactions. A considerable body of information has been developed on the higher-Z members of this group, but until recently there have been relatively few data on ^{86}Kr, the lightest stable member.

Two inelastic scattering studies have been reported. In the ^{86}Kr(d, d') reaction, Rosner and Schneid[1] observed population of five excited states, of which only the first, at 1.56 MeV, could be assigned definite spin-parity, $J^\pi=2^+$. By proton inelastic scattering, Hollas *et al.*[2,3] observed a total of 24 ^{86}Kr levels below 5.07 MeV. From angular distributions they identified the first and second 2^+ levels and the first 4^+ and 3^- levels.

Data on the levels of ^{86}Kr have been obtained also from study of ^{86}Br decay. Early measurements[4,5] were handicapped by chemical problems involved in separating this short-lived ($T_{1/2}=54$-sec) nuclide from other fission products, in particular from ^{87}Br, which has essentially the same half-life. However, the recently developed technique of on-line mass separation has been successfully applied to the isolation and study of ^{86}Br. Achterberg *et al.*[6] have constructed a decay scheme derived from Ge(Li) γ-ray spectra and have placed 18 transitions between 10 states. Talbert, Jr., Matsushigue, and Matsushigue[7] reported preliminary γ-ray data in good agreement with this decay scheme, and observed several additional transitions and levels.

In this paper we describe the study of the ^{86}Kr levels populated by proton pickup from ^{87}Rb. The shell-model proton configuration of ^{87}Rb ($Z=37$, $J^\pi=\frac{3}{2}^-$) should be predominantly $2p_{3/2}{}^{-1}$, and thus proton pickup should produce ^{86}Kr levels which have large $2p_{3/2}{}^{-2}$ and $1f_{5/2}{}^{-1}2p_{3/2}{}^{-1}$ components. Our experiment was undertaken to locate these levels and to examine the distribution of hole-state strengths.

II. EXPERIMENTAL TECHNIQUES

The experiment was performed with 15-MeV tritons at the Los Alamos tandem Van de Graaff facility. Detailed descriptions of the apparatus and procedures have appeared in previous publications.[8,9] The targets consisted of isotopically enriched ^{87}RbF and ^{87}Rb^{37}Cl (99.2% ^{87}Rb and 96% ^{37}Cl) evaporated to $\approx$200-μg/cm^2 thickness on 75-μg/cm^2 carbon foils. The choice of rubidium compounds for target material, instead of the pure element, was based on their superior stability and ease of preparation and handling. Triton beam currents up to 250 nA were used. Reaction products were detected by a ΔE-E semiconductor counter telescope, employing a 3-mm Si(Li) E detector

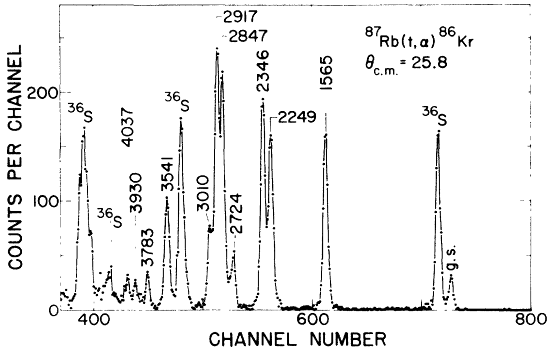

FIG. 1. Spectrum of α particles from 15-MeV tritons on a ^{87}Rb^{37}Cl target.

and a 75- or 100-μm totally depleted Si surface-barrier ΔE detector, mounted in a 20-in.-diam scattering chamber. Particle identification and energy-spectra recording were performed by an on-line computer.

Figure 1 shows a typical α-particle spectrum from a ^{87}Rb^{37}Cl target. Although the energy range spanned included excitations up to 8 MeV, no ^{86}Kr levels above 4.3 MeV were populated with observable intensity. In the α-particle energy range recorded, the over-all resolution was 40-50 keV full width at half maximum (FWHM). Spectra taken with ^{87}RbF targets had more background lines in the energy range corresponding to 2-4 MeV excitation in ^{86}Kr, but at low angles they permitted clearer resolution of the ^{86}Kr ground-state peak and, in the triton spectra, of the ^{87}Rb elastic scattering peak.

III. RESULTS

A. Triton Elastic Scattering

The differential triton elastic scattering cross section was measured at 2.5° intervals from 13 to 87° c.m. in a series of overlapping sets of measurements with the ^{87}RbF and ^{87}Rb^{37}Cl targets. Changes in the target condition during the course of these measurements were monitored by a separate counter set at 30° and by periodic repetition of the ^{87}Rb scattering measurement at a fixed reference angle. Count-rate data were converted to mb/sr by normalizing to the Rutherford cross section at low angles. Optical-model parameters were fitted to these data with the automatic search routine by Perey.[10] Initial values of the parameters were taken from the analysis[9] of 15-MeV triton elastic scattering on ^{86}Sr. Listed in Table I are two parameter sets, differing by 40 MeV in real well depth, which were found to give equally good fits to the data. The differential cross section computed from the T2 parameters is compared with the experimental data in Fig. 2. Statistical and systematic errors in the data points were less than 4%. The differential cross section given by the T1 set is essentially indistinguishable from that given by the T2 parameters.

TABLE I. Optical-model parameters. No spin-orbit or surface-peaked terms were used in the triton or α potentials.

Set	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r'_0 (fm)	a' (fm)	r_{0C} (fm)	a_C (fm)
Tritons								
T1	162	1.19	0.75	13.4	1.60	0.69	1.25	0.65
T2	122	1.23	0.76	12.0	1.63	0.68	1.25	0.65
α-particles								
A1	202	1.25	0.68	18.0	1.25	0.70	1.30	0.65
A2	178	1.25	0.70	20.0	1.23	0.68	1.30	0.65

B. (t, α) Cross Sections and Distorted-Wave Analysis

α-particle spectra were recorded between 13 and 73° c.m. The background lines from the ^{37}Cl-(t, α) reaction to excited levels of ^{36}S, the energies of which have been accurately determined by Olness *et al.*,[11] provided convenient energy calibration points over the range of interest. Absolute (t, α) cross sections for each angle were computed from the ratios of α-peak areas to the ^{87}Rb elas-

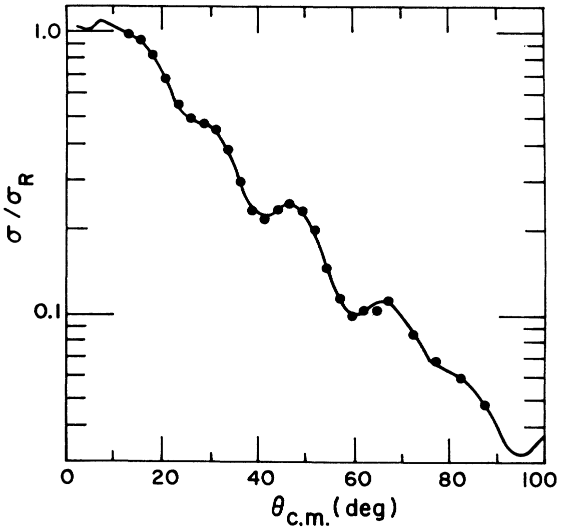

FIG. 2. Differential elastic scattering cross section for 15-MeV tritons on ^{87}Rb. Data points and optical-model cross section, shown by the solid line, have been divided by the Rutherford scattering cross section. Errors are smaller than the plotted points.

tic scattering peak area in the simultaneously recorded triton spectrum, multiplied by the previously determined elastic cross section (Sec. III A). The systematic errors in this procedure were estimated to be less than ±5%.

The angular distributions were analyzed by comparison with distorted-wave Born-approximation (DWBA) cross sections computed by the code DWUCK.[12] The calculations used the zero-range approximation, and the radial integrations proceeded from the nuclear center. With each set of triton parameters from the elastic scattering analysis of Sec. III A, a set of α parameters was developed, starting with a trial set taken from analysis of the ^{86}Sr(t, α)^{85}Rb reaction[13] and adjusting the parameters individually to obtain the fits shown in Fig. 3. Since the angular momentum of the proton picked up is single-valued for a $J^\pi = 0^+$ final state, the ^{86}Kr ground-state angular distribution should have been best suited for comparison with model distributions. However, because of its low cross section and of interference from nearby ^{36}S or ^{18}O lines, these data had relatively large uncertainties. Moreover, the mismatch between the semiclassical angular momentum transfer $(k_\alpha - k_t)R \approx 4$ and the angular momentum of the transferred particle, $l_p = 1$, reduces the validity of the DWBA calculation for this final state.[14] Since the reaction to the 2249-keV 4^+ level must occur almost entirely by $l_p = 3$ pickup, and the angular momentum mismatch is small, final adjustment of α-particle parameters in the distorted-wave analysis was based on the angular distribution to this level. The parameters which gave the best fits for the two sets of triton parameters are listed in Table I. Overall, the T2-A2 parameters gave slightly better fits than the T1-A1 set; and, since the computed proton wave function converged at a potential well depth of 56 MeV, the T2-A2 set satisfies the criterion that the sum of the well depths for the incoming and bound particles be approximately equal to the well depth of the outgoing particle.[14]

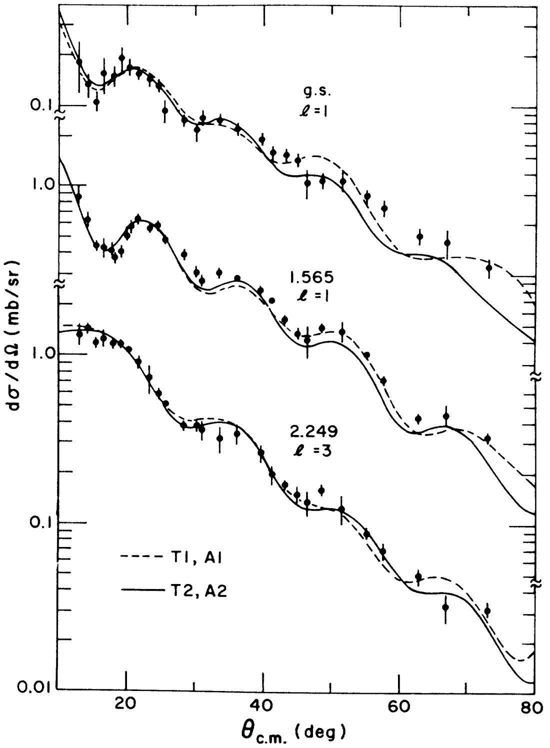

FIG. 3. Comparison of DWBA model angular distributions with experimental cross sections.

Table II summarizes our findings for the 16 ^{86}Kr levels observed. Peaks for the 3117-, 4173-, and 4277-keV states were obscured by background lines at most angles, so the variation of cross section with angle could not be determined. Differential cross sections for all the other states are shown in Figs. 4 and 5. The solid curves are DWBA angular distributions calculated with T2-A2 parameters. The $l_p = 1$ angular distributions are characterized by occurrence of the first diffraction minimum at less than 20° and a rapid rise at smaller angles; the corresponding minimum for $l_p = 3$ pickup lies above 20° and the cross section at small angles is almost flat. The 4037-keV state has an angular distribution unlike that for either $l_p = 1$ or $l_p = 3$, but is fitted well with $l_p = 4$.

It is noteworthy that all of the experimental angular distributions are best fitted by a single value

TABLE II. ^{86}Kr level energies and spectroscopic factors (calculated with T2-A2 parameters).

E (keV)	l_p	$\frac{\sigma_{\text{exp}}}{\sigma_{\text{DWBA}}}$	$S(2p_{3/2})$	$S(1f_{5/2})$	$S(1g_{9/2})$
0	1	1.9	0.53		
1565 ± 2	1	3.2	0.88		
2249 ± 2	3	4.3		1.78	
2346 ± 3	1	2.2	0.61		
2724 ± 5	1	0.52	0.14		
2847 ± 5	1	1.6	0.44		
2917 ± 6	3	4.9		2.03	
3010 ± 6	3	1.4		0.58	
(3117 ± 25)	4[a]	0.055			0.04
3322 ± 8	(1)	0.43	0.12		
3541 ± 6	1	0.80	0.22		
3783 ± 6	(1)	0.2	0.06		
3930 ± 15	(3)	0.3		0.12	
4037 ± 12	4	0.12			0.08
4173 ± 20	···				
4277 ± 10	···				
			3.00	4.51	0.12

[a] Assumed. See Sec. IV.

of l_p, although $l_p = 1, 3$ mixtures would be expected for population of ^{86}Kr 2^+ levels (and for 1^+ levels, depending on the $2p_{1/2}$ amplitude in the ground-state proton configuration of ^{87}Rb). Such mixing, with roughly equal intensities for the two components, has been observed for 2^+ final states in the similar ^{89}Y$(d, {}^3\mathrm{He})^{88}$Sr reaction.[15] In contrast, careful comparison of our experimental and theoretical angular distributions for the 2^+ levels at 1565, 2346, and 2847 keV showed that within the limits of accuracy of the data and the DWBA model, approximately 10%, these distributions contain no $l_p = 3$ component.

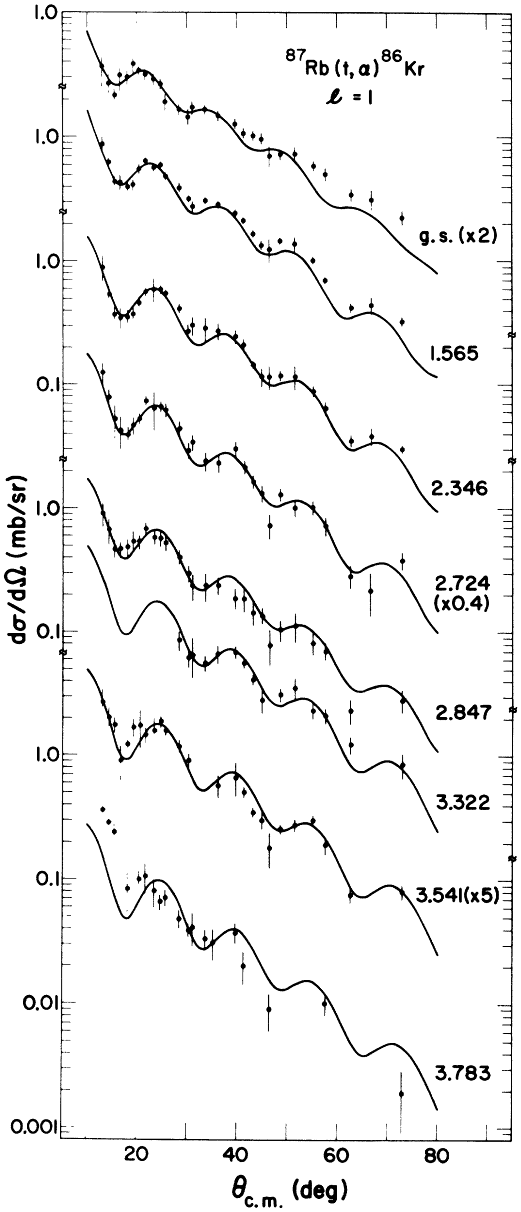

FIG. 4. Differential cross-section data for all levels populated by $l_p = 1$ pickup. Solid curves are fixed-parameter DWBA cross sections with magnitudes adjusted to fit the data. To improve the spacing in this figure, three data sets have been multiplied by the factors shown in parentheses.

Spectroscopic factors given in Table II were calculated from the relation[12]

$$\sigma_{\exp} = NS(lj)\frac{\sigma_{\mathrm{DWBA}}}{2j+1},$$

where $\sigma_{\exp}$ and σ_{DWBA} are the experimental and model differential cross sections and $S(lj)$ is the spectroscopic factor for pickup of a proton with orbital angular momentum l and total angular momentum j. The normalization factor $N = 14.5$ was derived empirically from the differential cross

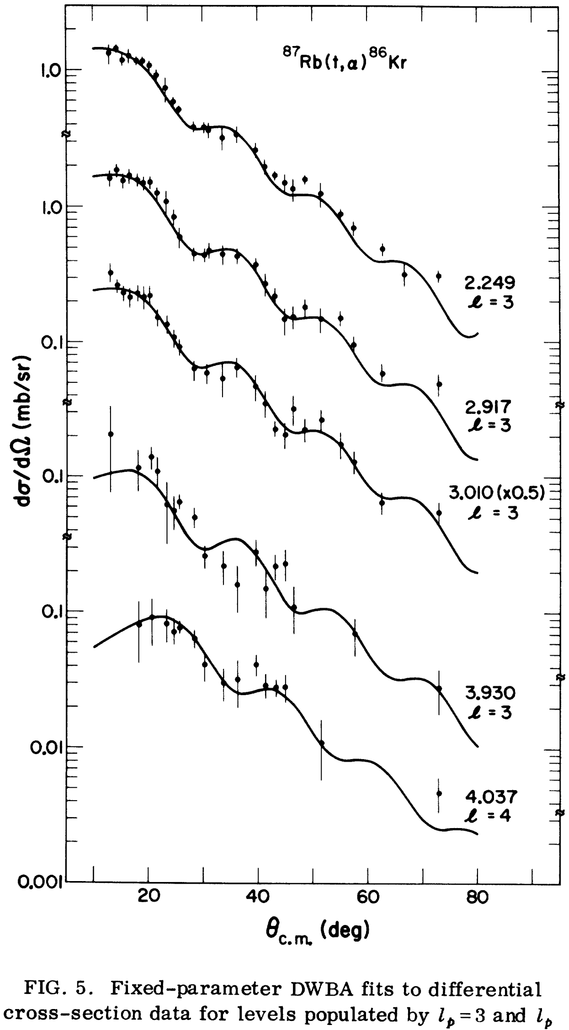

FIG. 5. Fixed-parameter DWBA fits to differential cross-section data for levels populated by $l_p = 3$ and $l_p = 4$ proton pickup. Data points for the 3010-keV state have been multipled by 0.5 to improve spacing in this figure.

sections by setting $\Sigma S(p_{3/2})=3$, based on the simplifying assumptions that: (1) The angular distributions assigned $l_p=1$ are unmixed; (2) all the $l_p=1$ strength is contained in the levels observed; and (3) the proton configuration in the ^{87}Rb wave function is $1f_{5/2}{}^6 2p_{3/2}{}^{-1}$. Although a 25-MeV spin-orbit term was included in the potential for the bound proton, the calculated angular distributions and spectroscopic factors were insensitive to j; the $j=\frac{3}{2}, \frac{5}{2}$ assignments were based on shell-model systematics. The spectroscopic factors listed in Table II were derived from the T2-A2 optical-model parameter set; spectroscopic factors calculated from the T1-A1 set differ by no more than 15% for any level.

With the normalization factor $N=14.5$, the sum of the $1f_{5/2}$ and $1g_{9/2}$ spectroscopic strengths is 4.63, whereas according to our simple model the sum should be 6.0. A major part of this discrepancy may lie in our determination of the quantities $\sigma_{\text{exp}}/\sigma_{\text{DWBA}}$, for which the error is estimated to be 10%. There are additional sources of error that are not easily estimated: (1) Small amounts of spectroscopic strength may be contained in levels too weakly populated for quantitative analysis; (2) small amounts of $l_p=3$ strength may have been contained in levels assigned $l_p=1$; and (3) the DWBA model itself and the parameters we have incorporated are approximations to the true nuclear processes.

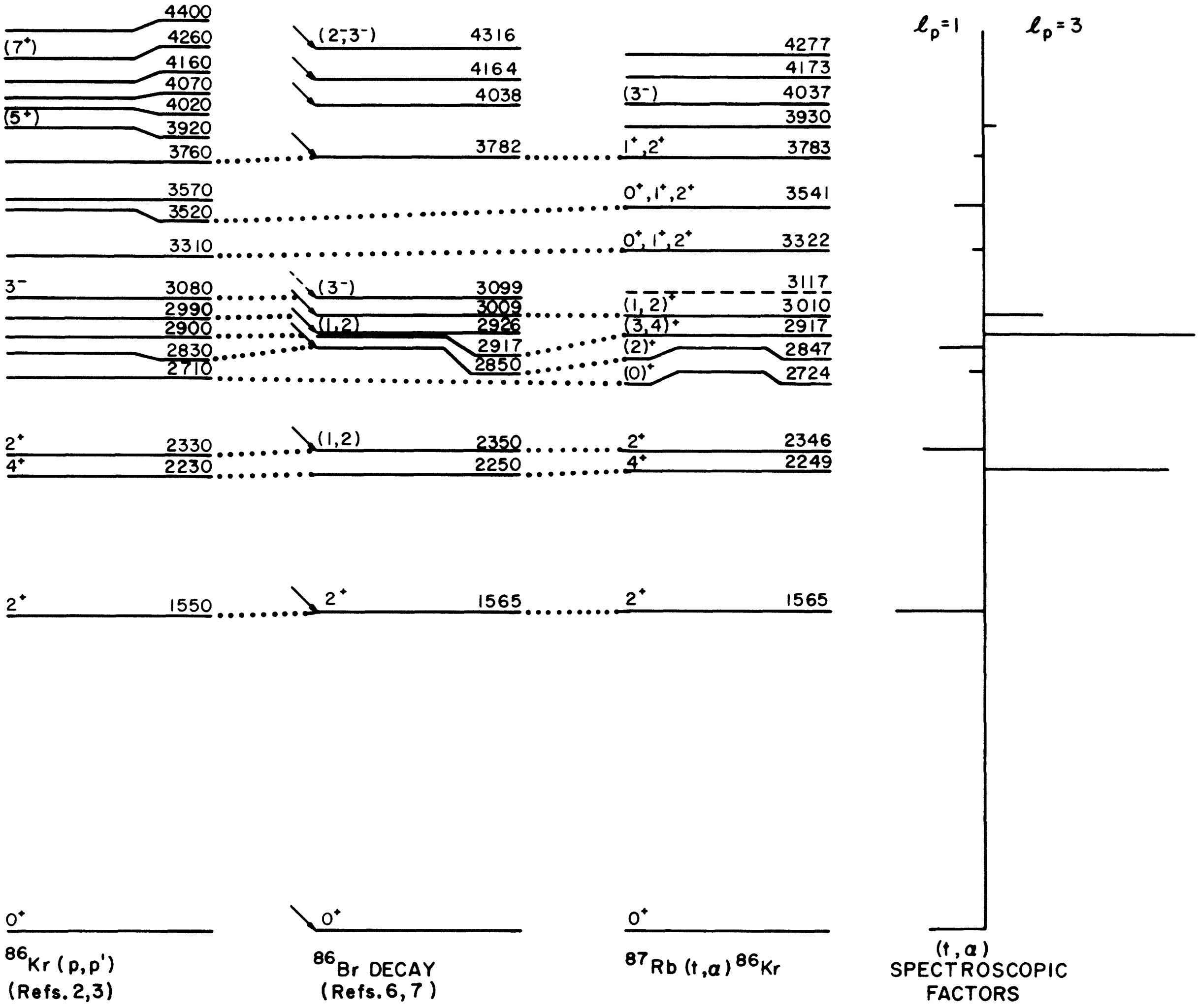

FIG. 6. Energy level diagram for ^{86}Kr up to 4.4 MeV. In the ^{86}Br decay scheme, arrows indicate β branches. Dotted lines connect levels that are believed to be identical.

Our normalization may be compared with the value $2N=38$ obtained by Blair and Armstrong[16] (N in their notation is equivalent to $2N$ in ours), who studied the 15-MeV (t, α) reaction on the even isotopes of Ni, and to the value $N=20$ obtained by Ragaini, Knight, and Leland,[13] who studied the 15-MeV (t, α) reaction on ^{86}Sr. Since the factor N depends on the triton energy, as well as on the optical-model parameters selected, and since there are few other (t, α) data reported, we are unable to draw any conclusions from the differences in N.

IV. DISCUSSION

Figure 6 shows the energy-level structure of ^{86}Kr below 4.4 MeV as determined by proton inelastic scattering, ^{86}Br decay, and this experiment. Relative to the accurate values determined by Ge(Li) γ-ray spectroscopy, the excitation energies reported from proton inelastic scattering appear to be systematically about 20 keV low. Taking into account this deviation, we have indicated by dotted connecting lines those cases for which there is reasonable confidence that the levels observed in the different experiments are the same. Above 3 MeV, correlations are more conjectural because of the increased level density.

The l_p values determined in the present experiment can be used in conjunction with the ^{86}Kr(p,p') data and with β and γ branchings seen in ^{86}Br decay to deduce possible spins and parities for excited states in ^{86}Kr. Consider first the ^{86}Kr states produced by $l_p=1$ pickup from ^{87}Rb. The proton configuration of these levels is predominantly $p_{3/2}{}^2$, which can have $J^\pi=0^+$ or 2^+. Small $p_{1/2}{}^2$ terms in the ground-state wave function of ^{87}Rb could lead to $p_{1/2}{}^1p_{3/2}{}^1$, $J^\pi=1^+$ levels in ^{86}Kr, but cross sections and spectroscopic factors should be small. Observation in ^{86}Br decay of ground-state γ transitions from any of these levels would exclude the 0^+ possibility. Three levels, at 1565, 2346, and 3783 keV, meet this condition. Spectroscopic factors for the first two are large, and thus these levels are unequivocally $J^\pi=2^+$, in agreement with assignments from the ^{86}Kr(p,p') work. For the remaining levels populated by $l_p=1$, no unique spin-parity assignments are possible, although γ transitions (assumed to be $E1$) from the $2^-, 3^-$ level at 4316 keV to lower-lying positive-parity states may be used to exclude the 0^+ possibility in some cases. The 2847-keV level, populated in this experiment with a spectroscopic factor of 0.44 and fed by a strong γ transition from the 4316-keV level, is probably 2^+. The levels at 2724, 3322, and 3541 keV all have small $l_p=1$ spectroscopic factors and therefore may have $J^\pi=0^+$, 1^+, or 2^+. The absence of any γ transitions to the 2724-keV level is evidence favoring a 0^+ assignment.

The states produced by $l_p=3$ pickup have an $f_{5/2}{}^{-1}p_{3/2}{}^{-1}$ configuration, allowing $J^\pi=1^+$ to 4^+. The 2249-keV level has been assigned $J^\pi=4^+$ on the basis of proton inelastic scattering angular distribution. In ^{86}Br decay, Talbert, Jr., Matsushigue, and Matsushigue[7] report γ rays feeding and deexciting this level consistent with a 4^+ assignment.

We believe that the level at 2917 ± 6 keV seen in this experiment is not the same as the level at 2926.2 ± 0.2 keV in the ^{86}Br decay schemes. One of the ^{86}Br decay investigations,[7] however, reports evidence for a weakly γ-populated level at 2916.8 ± 0.3 keV, which probably corresponds to the one we observed. The 2.90-MeV level seen in the ^{86}Kr(p,p') work may correspond to either or both. The very strong α peak for this level could have contained an unresolvable component corresponding to the 2926-keV level. The apparently pure $l_p=3$ character of the angular distribution associated with this line indicates that if it contained a significant contribution from the 2926-keV level, that component must also be $l_p=3$. There are insufficient data for a firm spin-parity assignment, but the absence of direct β feeding and of a ground-state γ transition favors $J^\pi=3^+$ or 4^+.

For the 3010-keV level, the ground-state γ transition observed by Talbert, Jr., Matsushigue, and Matsushigue[7] implies $J^\pi=1^+$ or 2^+. The 3930-keV level has been provisionally assigned to the $l_p=3$ series, but because of the large uncertainty in the data, other angular momentum transfers cannot be excluded.

We observe one level, at 4037 ± 12 keV, for which the angular distribution is well fitted by $l_p=4$. On a shell-model basis, this assignment implies a $p_{3/2}{}^{-1}g_{9/2}{}^2$ component in the proton part of the ^{87}Rb ground-state wave function. Pickup of a $g_{9/2}$ proton would then produce ^{86}Kr states with $J^\pi=3^-$ to 6^-. Talbert, Jr., Matsushigue, and Matsushigue[7] observed a 4037.6 ± 0.5-keV γ ray in ^{86}Br decay, but its occurrence as a ground-state transition would limit the spin of the state to 1 or 2. Considering the large energy uncertainty in our measurement, we believe different levels were observed.

The ^{86}Kr(p,p') study[2,3] identified the first 3^- level at 3.08 MeV, which, with the systematic energy correction, corresponds to the 3099-keV level observed in ^{86}Br decay. Our α spectra indicated a weakly populated level at 3117 ± 25 keV, for which the data points were too scattered to permit an l_p

assignment. If we assume that this level is the 3^- state at 3099 keV, and with the data available estimate the ratio of the experimental cross section to the $l_p = 4$ DWUCK cross section, we obtain an approximate $1g_{9/2}$ spectroscopic factor of 0.04.

In summary, the distribution of $2p_{3/2}{}^{-2}$ and $1f_{5/2}{}^{-1}2p_{3/2}{}^{-1}$ strengths for energy levels in ^{86}Kr produced by proton pickup has been determined. The absence of $l_p = 1, 3$ mixing in 2^+ levels is surprising. An interesting subject for future research would be identification of the other significant configurations in the 2^+ levels in addition to the $2p_{3/2}{}^{-2}$ proton component observed in this experiment. The ^{84}Kr(t, p) reaction, for example, would be of particular value in determining neutron particle-hole contributions.

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