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^{84}Kr(*t,p*)^{86}Kr and ^{86}Kr(*t,p*)^{88}Kr reactions

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The ^{86}Kr and ^{88}Kr nuclei have been studied by the ^{84,86}Kr(t,p) reactions at $E_t = 17.0$ MeV. Energy levels up to 6400 and 4400 keV excitation in ^{86}Kr and ^{88}Kr, respectively, were observed. Differential cross sections for many excited states have been extracted from 12° to 50° c.m. for ^{88}Kr and 12° to 55° c.m. for ^{86}Kr. The data are compared with DWBA calculations in order to obtain the angular momentum (L) transfer as well as nuclear structure information. The excited $L=0$ strength leading to ^{86}Kr in the region where the pairing vibration is expected is found to be fractionated and about $\frac{2}{3}$ of the intensity of the ^{86}Kr $\to ^{88}$Kr (g.s.) transition strength. Strong $L=2$ transitions are found above this excited $L=0$ strength in ^{86}Kr and appear to have their parentage in the pairing quadrupole states represented by the first 2^+ level in ^{88}Kr. The ^{86}Kr spectrum and transition strengths as found in the (t,p) reaction are compared with the ^{86}Kr(p,p') and ^{87}Rb(t,α) experiments.

[NUCLEAR REACTIONS ^{86,88}Kr(t,p) $E_t = 17.0$ MeV; measured $\sigma(\theta)$ and level energies; deduced J^π and enhancement factors from DWBA.]

I. INTRODUCTION

Two-nucleon transfer reactions provide an important experimental method for studying pairing phenomena in nuclei and in particular, the pairing vibration (pv) collective excitations.[1-3] For example, the zero-order harmonic pv theory predicts the existence in a closed neutron shell nucleus (N) of an excited 0^+ state of two-neutron two-neutron hole character that should be populated on the one hand by the $N-2$ $(t,p)N$ reaction and on the other hand by the $N+2$ $(p,t)N$ reaction. In each case the reaction should proceed with the same Q value and intensity as in the $N(t,p)N+2$ and $N(p,t)N-2$ ground state transitions, respectively. This picture is largely substantiated at the $N=28$[4] and $N=126$[5] neutron shell closures. At other closed neutron shells (but open proton shells), e.g., $N=50$[6-8] and $N=82$,[9] the (t,p) $L=0$ strength is fractionated and the experimentally observed summed transition strengths do not add up to the strength found in the (t,p) reaction to the $N+2$ ground state.

The present study of the ^{84,86}Kr(t,p) reactions was initiated to provide additional information on the neutron pairing structure in the region of $N=50$.[6-8] The Kr nuclei had not been studied previously with this reaction. Transitions proceeding to states in ^{88}Kr provide the energies and intensities of the pair addition quanta with $L=0$, 2, 4, ... for $N=50\to 52$. It is then of interest to locate this strength in the $N=48\to 50$ reaction leading to ^{86}Kr. A summary describing some of the present data as well as results that show coupling of the pv to other nuclear excitation modes has recently been given.[10]

Another motivation for studying the ^{86}Kr$(t,p)^{88}$Kr reaction is that the only previous study of ^{88}Kr is from the β decay of ^{88}Br, and hence the (t,p) reaction provides the first comprehensive spectroscopic information on ^{88}Kr based on nuclear reaction data. Part of these data was summarized in a recent letter.[11]

Section II summarizes the experimental details, while the third section describes data analysis, the distorted wave Born approximation (DWBA) calculations, the L and J^π values extracted from angular distribution shapes, and the enhancement factors found by normalizing the DWBA predictions to the data. The fourth part first discusses the reactions individually and then combines the results in a discussion of the monopole and quadrupole pv theory. The final section is a summary.

II. EXPRIMENTAL METHODS AND RESULTS

These experiments used a 17.0 MeV triton beam generated by the Los Alamos tandem Van de Graaff accelerator. Beam currents were typically 400 nA in the Faraday cup with exposures on the ^{84}Kr and ^{86}Kr targets normally amounting to 6000 and 4800 μC, respectively. The reaction protons were mo-

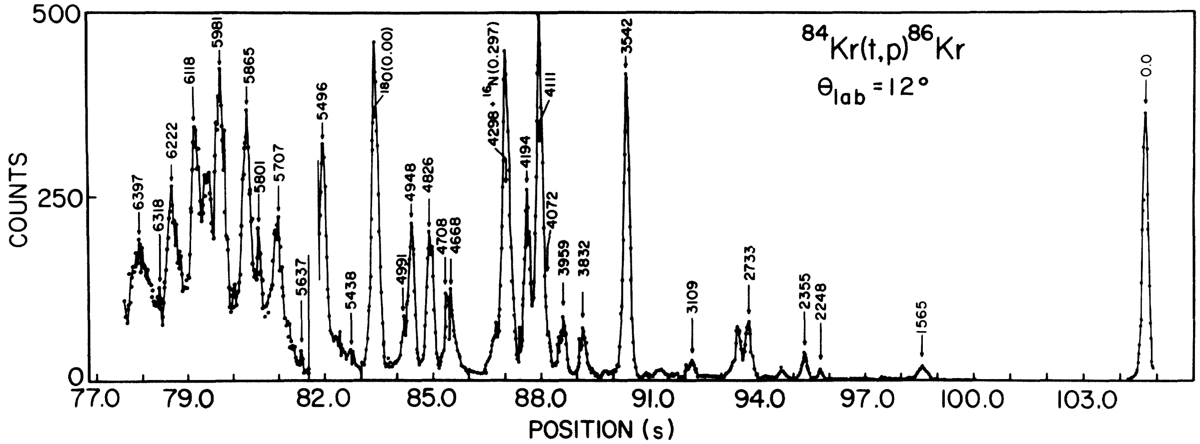

FIG. 1. ^{84}Kr$(t,p)^{86}$Kr position spectrum at θ_{lab} = 12°.

mentum analyzed in an Elbek-type magnetic spectrograph, and were recorded at the focal plane by use of nuclear emulsions. Aluminum foils placed in front of the emulsions stopped all charged particles except protons. The principal features of the gas cell design[11,12] have been discussed previously. The present experiments used 30 Torr Kr pressure, and the ^{84}Kr and ^{86}Kr isotopes were enriched to 90% and 99%, respectively, with the principal impurity in ^{84}Kr being 10% ^{86}Kr. The experimental energy resolution of 45–50 keV [full width at half maximum (FWHM)] was largely determined by straggling in the gas cell. Representative proton spectra at 12° laboratory scattering angle for the ^{86}Kr and ^{88}Kr residual nuclei are given in Figs. 1 and 2. The vertical line occurring at a position of 81.7 cm in Fig. 1 shows the boundary between two plates.

Data were obtained at eight angles for the ^{84}Kr(t,p) reaction, and seven angles for the ^{86}Kr(t,p) reaction. All angles were utilized in extracting excitation energies in the residual nuclei and the averaged energies are internally consistent with an error of ±10 keV. Proton groups from ^{84}Kr(t,p) were analyzed up to an excitation energy of 6400 keV and angular distributions were extracted for levels up to 5000 keV in this nucleus. Table I summarizes this analysis. Most groups above 5000 keV probably represent (t,p) strength to unresolved levels. Excitation energies in ^{88}Kr were analyzed up to 4430 keV and are summarized in Table II; angular distributions were extracted for most of these levels. Tables I and II give the differential cross sections at 18° lab angle in column 2.

The differential cross sections were calculated on the basis of known geometry, gas cell pressure, and beam integration via the Faraday cup. The accuracy of the absolute cross sections is estimated to be ±15%. An exposure was made on a natural Kr target, and a comparison of proton groups leading to ^{86}Kr and ^{88}Kr from this natural

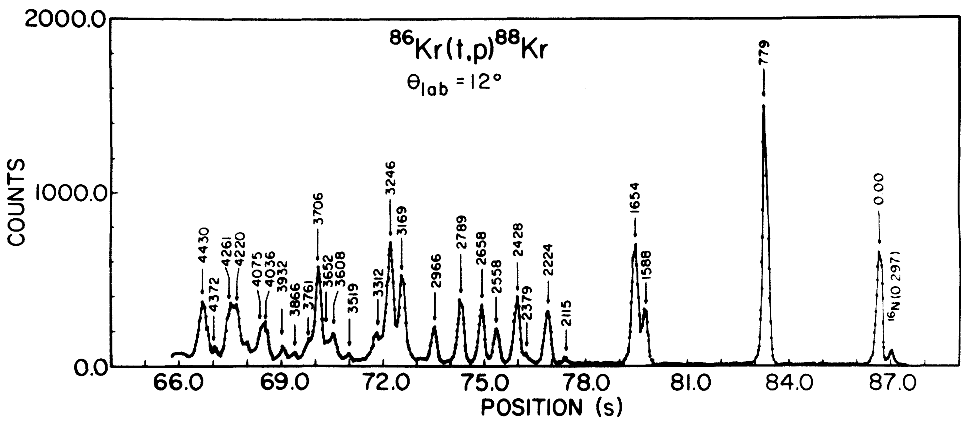

FIG. 2. ^{86}Kr$(t,p)^{88}$Kr position spectrum at θ_{lab}= 12°.

TABLE I. A summary of the ^{86}Kr excitation energies, cross sections at $\theta_{lab} = 18°$, J^π values, and enhancement factors. Where two enhancement factors are given, they correspond to the two possible spin assignments. A comparison of the ^{86}Kr levels with other reactions and decay data can be found in Ref. 21.

E_x (t,p) (keV)	$d\sigma/d\Omega$ (18°) (mb/sr)	L	$J^{\pi\,a}$	ϵ	Known $J^{\pi\,b}$
0.0	0.034	0	0^+	0.38	0^+
1563 ± 10	0.008	2	2^+	0.018	2^+
2248	0.002	3,4	$3^-,4^+$	0.015	4^+
2355	0.015	2	2^+	0.028	2^+
2733	0.006	0	0^+	0.092	
3109	0.018	3,4	$3^-,4^+$	0.046	3^-
3542	0.045	0	0^+	0.48	
3832	0.006	0	0^+	0.087	
3959	0.046	3,4	$3^-,4^+$	0.12, 0.11	
4072	0.019(36°)				
4111	0.293	2	2^+	0.47	
4194	0.130	2	2^+	0.21	
4298	0.020	3,4	$3^-,4^+$	0.041, 0.038	
4668	0.043	3,4	$3^-,4^+$	0.10 , 0.087	
4708	0.043				
4826	0.093	(2)	(2^+)	(0.14)	
4948	0.105	(2)	(2^+)	(0.20)	
4991	0.019				
5438	0.034				
5496	0.110				
(5637)					
5707	0.091				
5801	0.074				
5865	0.156				
5981	0.212				
6118	0.069				
6222	0.118				
6318	0.045				
6397	0.075				

[a] From present experiment.
[b] Reference 21.

target is consistent with the isotopic experiments to 15% without renormalization of the isotopic data. Normally, this procedure should result in better accuracy. However, in this case, the relative isotopic abundances (^{84}Kr 57% and ^{86}Kr 17%) resulted in poor statistics for the ^{88}Kr peaks; furthermore, these peaks occur in a region where the ^{84}Kr(t,p) reaction gives a large yield. Differential cross sections for the ^{84}Kr$(t,p)^{86}$Kr and ^{86}Kr$(t,p)^{88}$Kr reactions are shown in Figs. 3 and 4.

The ^{86}Kr$(t,p)^{88}$Kr(g.s.) Q value[11] was determined to be +4091 ± 15 keV by comparison with ^{16}O$(t,p)^{18}$O which was recorded simultaneously with the ^{86}Kr(t,p) reaction. By taking the mass excess of ^{86}Kr from a mass compilation,[13] the mass excess of ^{88}Kr was found to be −79691 ± 16 keV, which is an improvement over the old value of −79674 ± 34 keV determined by a decay measurement.[14] The ^{84}Kr$(t,p)^{86}$Kr Q value is consistent with the literature[13,15] to within the ±15 keV error.

III. DWBA ANALYSIS

Distorted wave Born approximation (DWBA) analysis has been done for all levels with characteristic angular distributions; these calculations are summarized in Figs. 3 and 4. The code DWUCK[16] with triton[17] and proton[18] optical model (OM) potentials from the literature was used in these calculations. The proton potential well depth was increased about 1 MeV from that predicted for ^{86}Kr from Ref. 18 in order to obtain good phase agreement between theoretical and experimental angular distributions for $L = 0$ transitions. Table III summarizes the OM parameters used for both the ^{84}Kr and ^{86}Kr targets. The form factors were constructed from the $(2d_{5/2})^2$ and $(2d_{5/2}1h_{11/2})$ neutron configurations for the even and odd parity states, respectively. The bound state parameters are also summarized in Table III.

The DWBA cross section is related to the ex-

TABLE II. A summary of the ^{88}Kr excitation energies, cross sections at $\theta_{lab}=18°$, J^π values, and enhancement factors. Where two enhancement factors are given, they correspond to the two possible spin assignments. For comparison, energy levels of ^{88}Kr deduced from ^{88}Br β^- decay are given.

E_x (t,p) (keV)	$d\sigma/d\Omega$ (18°) (mb/sr)	L	J^π	ϵ	E_x [a] $^{88}Br(\beta^-)$
0.0	0.089	0	0^+	1.01	0.0
779±10	0.771	2	2^+	1.40	775
1588	0.188	2	2^+	0.36	1578
1654	0.448	3,4	$3^-,4^+$	1.24 ,0.92	
2115	0.025	3,4	$3^-,4^+$	0.055,0.046	
2224	0.171	2	2^+	0.33	
2379					
2428	0.322	3,4	$3^-,4^+$	0.64,0.50	
2558	0.144	3,4	$3^-,4^+$	0.41,0.28	
					2631
2658	0.190	2	2^+	0.32	2651
2789	0.012	0	0^+	0.064	
					2930
2966	0.150	3,4	$3^-,4^+$	0.36,0.24	2946
					3045
3169	0.274	$(L\geq 5)$	$(J\geq 5)$		
3246	0.462	3,4	$3^-,4^+$	1.15,0.69	
					3279
3312	0.105	$(L\geq 5)$	$(J\geq 5)$		
3519					
3608	0.061	2	2^+	0.15	
3652	0.089	3,4	$3^-,4^+$	0.20,0.12	
3706	0.390	3,4	$3^-,4^+$	1.10,0.69	
3761	0.087	3,4	$3^-,4^+$	0.21,0.13	
3866					
3932	0.065				
4036	0.079	(2)	(2^+)	(0.19)	
4075	0.107	(3)	(3^-)	(0.21)	4072
4220	0.248	(3,4)	$(3^-,4^+)$	(0.46)	
4261					4269
4372	0.053				
4430	0.109	(2)	(2^+)	(0.28)	
					4664
					4708
					5044
					5218
					5338
					6364
					6597
					6942
					7056

[a] Reference 25.

perimental differential cross sections by[19]

$$\sigma_{exp}(\theta)=N\epsilon\sigma_{DW}, \quad (1)$$

where the normalization factor N and the enhancement ϵ are discussed below and the initial even-even target has angular momentum and parity $J_i^\pi=0^+$. In this case the residual state's angular momentum (J_f) equals the orbital angular momentum transfer (L) and has natural parity, i.e.,

$$J_f=L\,, \quad \pi_f=(-1)^L\,. \quad (2)$$

These simple selection rules, which are applicable except in deformed nuclei where two-step processes dominate the transitions, provide reliable J^π assignments based on the proton angular distributions.

As shown in Figs. 3 and 4, in the present data the $L=0$ and $L=2$ angular distributions are distinctive and well fitted by DWBA calculations.

This procedure is less differentiating for the $J^\pi = 3^-$ and $J^\pi = 4^+$ cases. Both the $L = 3$ (solid curves) and $L = 4$ (dashed curves) DWBA predictions are given in Figs. 3 and 4 for the $J^\pi = 3^-$ and 4^+ assignments. The most distinguishing characteristic between these transitions according to the DWBA is the shift of the maximum of the angular distributions ~10° higher in angle for $L = 4$ compared with $L = 3$. In some cases the experimental cross sections seem to show this difference as, for example the 4298 keV level in ^{86}Kr and the 2115 keV level in ^{88}Kr, which favor the $L = 3$ assignments based on their fits. Generally, however, it is not possible to make an unambiguous choice between the $L = 3$ and $L = 4$ cases based on DWBA calculations. The predicted transitions for $L \geq 5$ have much less structure and it is difficult to make assignments for these higher multipolarities. The 4072 keV level in ^{86}Kr is consistent with $L = 5$, although a suggested J^π is not given in Table I because of the incomplete angular distribution.

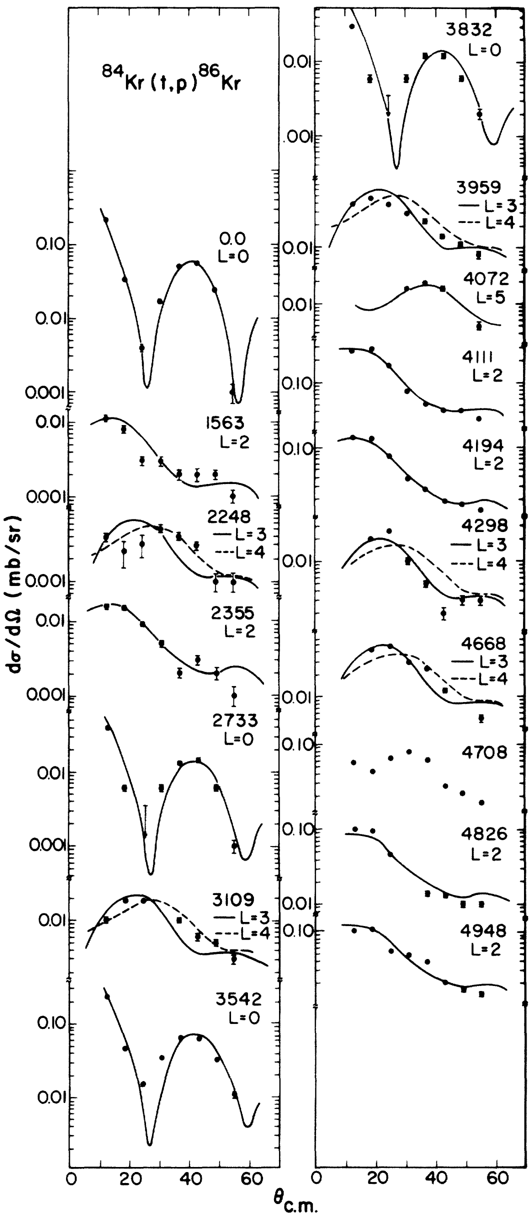

FIG. 3. Angular distributions for the ^{84}Kr(t,p) reaction. The curves are DWBA calculations for the indicated L values. For possible $L = 3$ or $L = 4$ transitions, DWBA calculations for both multipolarities are shown.

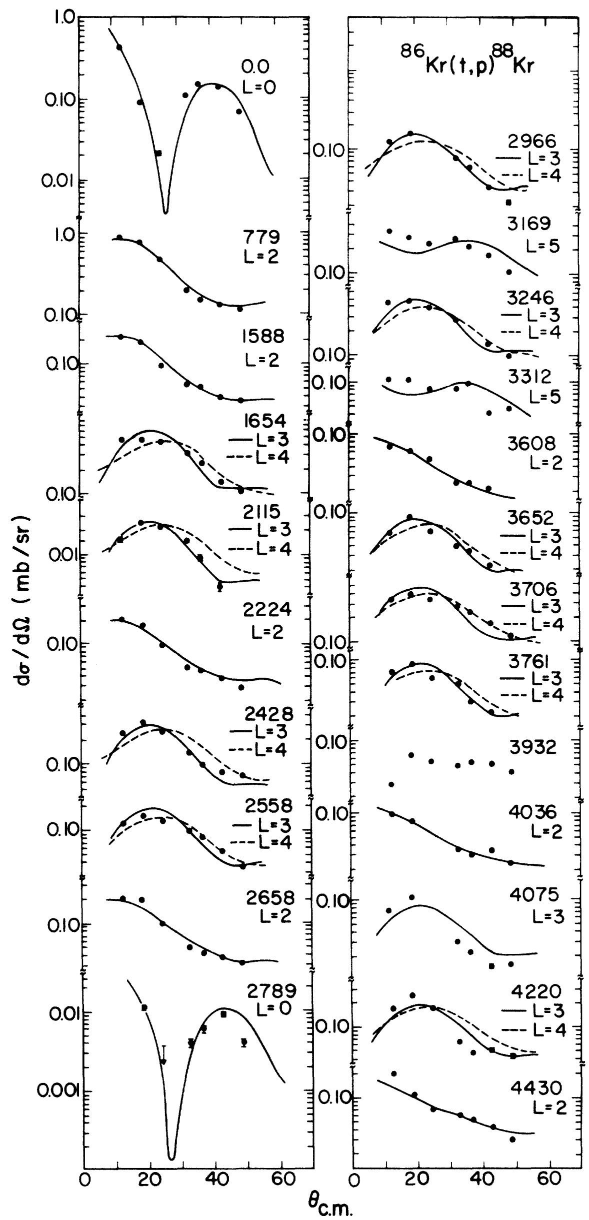

FIG. 4. As in Fig. 3 except for the ^{86}Kr target.

TABLE III. Optical model parameters used in DWBA analysis of the $^{84,86}Kr(t,p)$ reactions.

	V (MeV)	r_r (fm)	a_r (fm)	W_v (MeV)	W_s (MeV)	r_i (fm)	a_i (fm)	r_c (fm)	V_{so} (Thomas units)
tritons	−166.7	1.16	0.752	−22.9		1.498	0.817	1.25	
protons	−50.0	1.25	0.65		−13.6	1.25	0.47	1.25	
bound state	a	1.27	0.67					1.24	32.0

[a] Adjusted to give each neutron one-half the two neutron separation energy.

The 4708 keV level in ^{86}Kr may have a high spin; the angular distribution is not characteristic of other observed states. States with $L \geq 5$ occur at 3169 and 3312 keV in ^{88}Kr. A summary of L and J^π assignments is given in Tables I and II.

Enhancement factors[3] [ϵ of Eq. (1)] for the ^{84}Kr, $^{86}Kr(t,p)$ reactions have been calculated through the use of Eq. (1); these results are listed in Tables I and II. The factor N of Eq. (1) is an empirical normalization[19] of the zero range DWBA calculation. This factor was derived[19] by comparing the Bayman-Kallio[20] treatment of two-nucleon transfer reactions with experiments on a broad range of nuclei whose nuclear structures are reasonably understood. The procedure described in Ref. 19 produced a value of $N = 218 \pm 15\%$ for most of the cases considered, when accepted triton and proton optical model parameters are used in the DWBA code DWUCK.[16] In the present experiment where the proton potential is modified from the accepted value in order to produce a better fit to the $L = 0$ angular distribution, an average increase of a factor of 1.4 occurs in the predicted DWBA cross section. This change has been incorporated into the values of ϵ in the tables because the normalization factor N was maintained at 218 in the present work. Thus the value of ϵ for the $^{86}Kr(t,p)^{88}Kr$(g.s.) transition is reduced by a factor of 0.7 compared with the value that would have been obtained following the procedure of Ref. 19, and this should be considered when comparing the present values of ϵ with others previously published.

IV. DISCUSSION

A. $^{84}Kr(t,p)^{86}Kr$ reaction

The ^{86}Kr nucleus has been studied by $^{86}Kr(p,p')$,[21] the β^- decay of ^{86}Br,[22] and the $^{87}Rb(t,\alpha)$ reaction.[23] A comparison of these data including an early analysis of the present $^{84}Kr(t,p)$ reaction is given in Ref. 21. Good agreement among the level energies up to about 4 MeV excitation is found whereas above 4 MeV the level density is too great to make such a correspondence. The J^π's derived from the (t,p) angular distribution (see column 4 of Table I) are in agreement with Refs. 21–23 when such unambiguous energy comparisons can be made.

In Fig. 5 the transition strengths of the three types of nuclear reactions leading to final states in ^{86}Kr are given. These include the enhancement factors ϵ derived from the $^{84}Kr(t,p)$ reaction (cf. column 5 of Table I), the deformation parameters β taken from the $^{86}Kr(p,p')$ work,[21] and the (t,α) spectroscopic factors from the $^{87}Rb(t,\alpha)$ reaction.[23] Between the ground state and approximately 3.5 MeV excitation energy in ^{86}Kr, a gap in (t,p) excitation strength occurs; the strong excitations of the ground state and 3.5–4.5 MeV excitation region are due to large correlations in the two particle configurations brought about by the pairing force

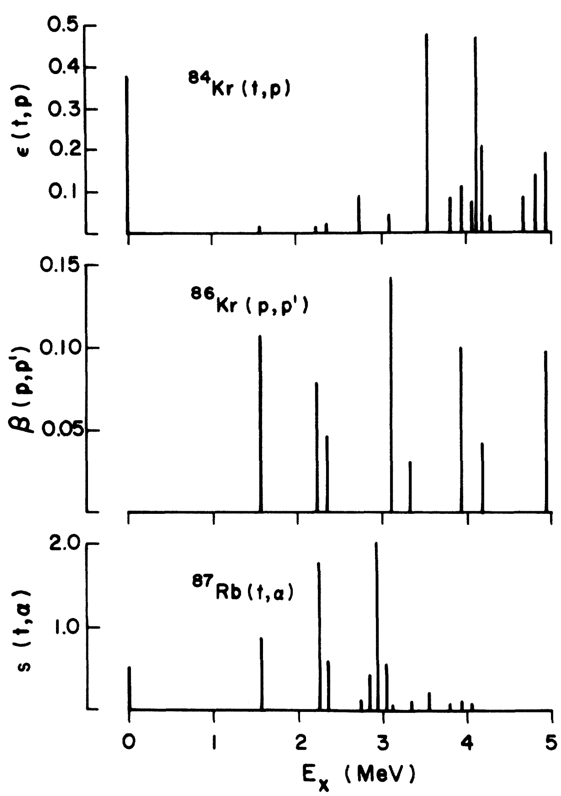

FIG. 5. A comparison of reaction data leading to the residual ^{86}Kr nucleus. Enhancement factors (ϵ), deformation parameters (β), and spectroscopic factors (s) are plotted versus ^{86}Kr excitation energy.

at these excitations in ^{86}Kr. The gap corresponds to the energy necessary to excite the lowest 2p-2h neutron state. The harmonic pairing vibrational model[1,3] postulates that the (t,p) reaction should strongly excite the ground state of the closed shell nucleus by annihilation of a pair removal quantum consisting of two holes below the closed shell. In addition, strongly excited states of various multipolarities should be excited by transfer of pair addition quanta which consist of particles in orbitals above the Fermi level. The lowest such 2p-2h state in this model will have $J^{\pi}=0^{+}$ and an excitation energy given by[3]

$$E_{2p-2h}(0^{+})=2B(^{86}\mathrm{Kr})-B(^{88}\mathrm{Kr})-B(^{84}\mathrm{Kr})=4398\text{ keV}, \tag{3}$$

where the B's are the binding energies for the indicated isotopes. The pv theory through use of Eq. (3) thus provides a qualitative explanation for the gap in (t,p) excitation strength observed in the top portion of Fig. 5. The pv model analysis will be discussed in conjunction with the ^{86}Kr(t,p) reaction in Sec. IV C.

The ^{86}Kr levels strongly populated in the (t,α) proton pickup reaction[23] are not the same levels observed with large enhancements in the (t,p) reaction. However, there is some common excitation of certain levels by the two reactions. Thus both reactions populate the levels at 2733 and 3542 keV. The proton pickup reaction reaches both levels with small spectroscopic strength while the 2733 and 3542 keV levels have moderate and strong enhancement factors, respectively, in the (t,p) reaction. The 2733 and 3542 keV levels are assigned $J^{\pi}=0^{+}$ based on the (t,p) work; these assignments are consistent with both the $l=1$ (t,α) angular distributions and the decay data.[23] The 3542 keV level is thought to contain a large fragment of the theoretical neutron pv state, while a possible explanation for population of the 2733 keV state in the (t,p) reaction is that this level is an excited two-proton state[24] with $J^{\pi}=0^{+}$ which could mix with the monopole neutron pair vibration state. The 2733 keV state has about 20% of the intensity of the strongest $L=0$ transition. This is a large fragment compared to the analogous transition to a predominantly proton state found in ^{92}Zr(p,t), although the ^{94}Mo, ^{96}Ru(p,t) reactions[24] find fractions of $L=0$ strength to the lowest 0^{+} proton states comparable to that seen in the ^{84}Kr(t,p) reaction to the 2733 keV state. A reasonable explanation for this behavior is that the first excited proton 0^{+} states in ^{86}Kr, ^{92}Mo, and ^{94}Ru lie much nearer in energy to the main two-neutron transfer $L=0$ strength, thus allowing the 0^{+} states to mix to a larger extent.

Figure 5 also compares the ^{84}Kr(t,p) and ^{86}Kr(p,p') reactions. A detailed level comparison has already been given.[21] Strong (p,p') excitations occur in the region below the excited 2p-2h neutron states; however, none of the transitions can be correlated with the strong (t,p) transitions discussed above. This is a clear indication of the sensitivity of the (p,p') reaction to surface vibrations of 1p-1h configurations, whereas the (t,p) reaction picks out states of two-neutron pairing character.

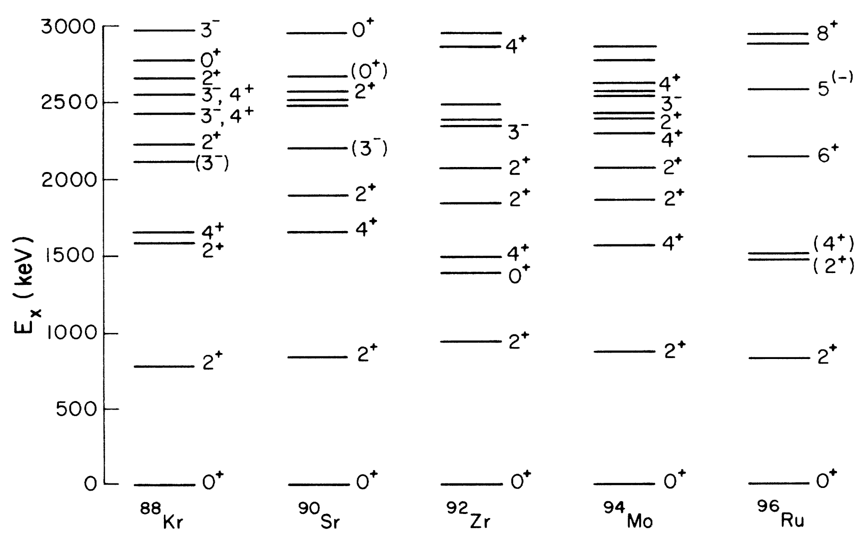

FIG. 6. Spectra of the known energy levels less than 3 MeV in excitation for the $N=52$ nuclei.

B. ^{86}Kr$(t,p)^{88}$Kr reaction

The ^{86}Kr(t,p) reaction yielded the first detailed spectroscopy of the ^{88}Kr level structure and was the subject of an earlier letter.[11] A study of ^{88}Br β^- decay[25] leading to γ rays of ^{88}Kr has also been done. The ^{88}Kr level energies deduced from this work are summarized for comparison with the (t,p) results in Table II. The excitation energies for the low lying states agree within errors; some correspondence among the higher lying levels can be found although there is little overlap between the ^{86}Kr(t,p) and ^{88}Br(β^-) studies, as expected.

The ^{88}Kr nucleus is the most proton deficient of the $N=52$ isotones for which detailed spectroscopic information is available. Figure 6 is a comparison of the ^{88}Kr levels with the levels of other $N=52$ nuclei for $E_x<3$ MeV; our results are summarized in the left hand column. The ^{90}Sr data are taken from the ^{88}Sr$(t,p)^{90}$Sr experiment,[8] and the ^{92}Zr data are from both the ^{90}Zr(t,p)[26] and ^{94}Zr(p,t)[27] reactions. The ^{94}Mo data are taken from the ^{96}Mo(p,t) reactions.[28,29] Finally, data on ^{96}Ru are taken from the ^{94}Mo$(\alpha, 2n\gamma)$[30] reaction. The data in Fig. 6 agree with Nuclear Data sheets wherever comparisons are available.

The ^{88}Kr data may be compared with systematic features observed in the other $N=52$ isotones. The first 4^+ state for all the $Z\geq 38$ nuclei occurs between 1500 and 1700 keV excitation which suggests that the 1654 keV level in ^{88}Kr has a $J^\pi=4^+$; the (t,p) angular distribution was not decisive between a $J^\pi=3^-$ or 4^+ assignment. On the other hand, the next higher state that was ambiguous between 3^- or 4^+ at 2115 keV is a possible candidate for the first 3^- state in ^{88}Kr since it would also be consistent with the trend observed in the neighboring isotones.

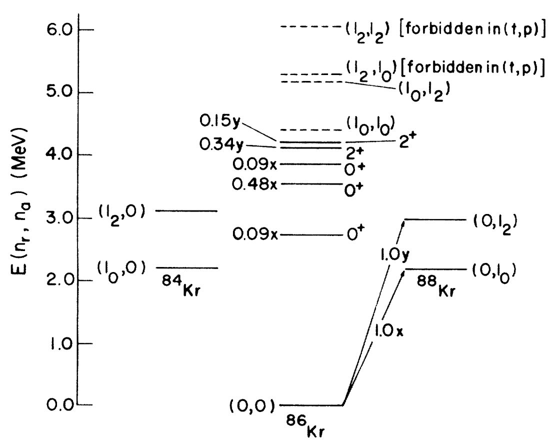

FIG. 7. A summary of the monopole and quadrupole states in the Kr nuclei. The solid lines are experimental energy levels; the slashed lines are the predicted 2p-2h pv states in ^{86}Kr. The x and y notation indicates the fraction of monopole and quadrupole strength, respectively, observed experimentally.

TABLE IV. A summary of information on excited 0^+ and 2^+ levels in ^{86}Kr attributed to pairing monopole and quadrupole states. See text for further discussion.

E_x (^{86}Kr) (keV)	J^π	ϵ	R	$\sum$	$\bar{E}_x$ (keV)
0.0	0^+	0.38			
2733	0^+	0.092	0.091		
3542	0^+	0.48	0.48	0.66	3468
3832	0^+	0.087	0.086		
4111	2^+	0.47	0.34		
4194	2^+	0.21	0.15	0.49	4136
4826	(2^+)	(0.14)	(0.10)	(0.78)	(4422)
4948	(2^+)	(0.26)	(0.19)		

C. Pairing monopoles and quadrupoles in the ^{86}Kr and ^{88}Kr nuclei

We now discuss the pairing vibrational aspects of the ^{84,86}Kr(t,p) reactions. The notation used is that of Ref. 1; the quantities (n_r,n_a) refer to the number of particle pairs removed or added to the vacuum which occurs at the closed neutron shell (^{86}Kr). The vacuum itself is represented as $(0,0)$. The n_r and n_a are subscripted with $\underline{0}$ and $\underline{2}$ indicating a monopole or quadrupole pairing phonon.

A summary of the harmonic model predictions is given by the dashed lines in Fig. 7. The known experimental facts are given by the solid lines. These data are from the present (t,p) experiments except for the excitation of the first 2^+ state in ^{84}Kr which occurs at 882 keV.[21] The energies have been scaled according to neutron number[1] in order to give the $(0,1_0)$ and $(1_0,0)$ quanta the same energy — which is the harmonic vibrational quantum energy for the Kr isotopes. The ordinate of Fig. 7 is thus labeled with $E(n_r,n_a)$ which shows the vacuum at zero energy and $E(1_0,0)=E(0,1_0)=\hbar\omega$. The $(1_0,1_0)$ pv state is comprised of two such quanta, and is predicted to be at 4398 keV [cf. Eq. (3) and Fig. 7]. The energies of the pairing quadrupole quanta are given by $E(1_2,0)=E(1_0,0)+882$ keV, and $E(0,1_2)=E(0,1_0)+779$ keV. The $(1_0,1_2)$ 2^+ and $(1_2,1_0)$ 2^+ states should be directly populated in the ^{84}Kr(t,p) and ^{88}Kr(p,t) reactions, respectively. The harmonic model further predicts[1-3] that the transition strengths $(0,0)$ to $(0,1_0)$ and $(0,1_2)$ should equal the transition strengths from $(1_0,0)$ to $(1_0,1_0)$ and $(1_0,1_2)$, respectively.

The experimental results are given in Fig. 7

and Table IV. Table IV is a summary of the 0^+ and 2^+ transition strength to ^{86}Kr in the excitation region where the pairing monopole $(1_0, 1_0)$ and pairing quadrupole $(1_0, 1_2)$ vibrations are expected to occur. The 0^+ and 2^+ strength is split into several components with the centroid of 0^+ and 2^+ strength at 3468 keV and 4136 (4422) keV, respectively. [The quantity in parenthesis includes the (2^+) assignments at 4826 and 4948 keV while the first number is based only on the 4111 and 4194 keV 2^+ states.] The centroids represent a weighted average of the excitation energies, the weights being the enhancement factors summarized in Table IV. The centroids are 930 keV and 1041 (755) keV lower, respectively, than the harmonic predictions for the $(1_0, 1_0)$ and $(1_0, 1_2)$ states.

In Table IV the ratio R was calculated by dividing the ϵ of the 0^+ and 2^+ levels in ^{86}Kr by the ϵ derived for the ground state and 779 keV levels in ^{88}Kr. The sums of these ratios are 0.66 and 0.49 (0.78) for the 0^+ and 2^+ transitions, and are less than the value 1.0 predicted on the basis of the harmonic model. These results are summarized in Fig. 7 where the fractions of the $(0, 1_0)$ and $(0, 1_2)$ strengths are labeled x and y, respectively, for the residual levels in ^{86}Kr. There is considerable strength observed in the ^{84}Kr (t,p) reaction with $E_x > 5.0$ MeV (see Fig. 1), but the resolution was not sufficient to obtain angular distributions and hence ϵ values for this excitation region. Some undetected 0^+ or 2^+ levels at these excitations could correspond to pair vibration fragments and would tend to move the ^{86}Kr energy centroids and strengths into better agreement with the harmonic model.

The fragmentation of pairing vibration strength observed in ^{86}Kr is similar to what has been reported in the other $N = 50$ nuclei. The experiments appropriate for comparison are ^{86,88}Sr(t,p),[7,8] the ^{90,92}Zr(p,t),[27] and the ^{92,94}Mo(p,t) reactions.[31,32] In each case there is a principal fragment of the 2p-2h 0^+ and 2^+ pairing vibration states in the $N = 50$ nucleus together with several small fragments with the total strength amounting to about $\frac{1}{2}$ to $\frac{2}{3}$ of the prediction, excluding any unresolved strength. Thus, despite the fragmenting of the basic pairing vibration strength, the simple harmonic model provides a reasonable guide to understanding the spectra produced by two-neutron transfer reactions in the region of $N = 50$. The fractionation of the multipole pairing states is likely a result of coupling to other nuclear degrees of freedom possessing the same J^π. For the monopole case, such degrees of freedom would include proton configurations coupled to 0^+ and two phonon surface vibrations such as $(2^+ \otimes 2^+)_{0^+}$ and $(3^- \otimes 3^-)_{0^+}$.[33] This latter configuration, for example, could produce $L = 0$ strength at about 6 MeV in ^{86}Kr where considerable (t,p) cross section exists to many unresolved levels.

V. SUMMARY

The ^{84,86}Kr(t,p) reactions have been studied with a 17 MeV triton beam with 45–50 keV energy resolution. Many new levels in ^{86}Kr have been found, and it was possible to make J^π assignments based on proton angular distributions to several states. The experimental results on ^{88}Kr represent the first spectroscopic information[11] (energy levels, J^π values) available on the excited states of this nucleus. The ^{84,86}Kr(t,p) reactions have been compared to predictions of the pairing vibrational model. The excited 2p-2h monopole and quadrupole pairing strength in ^{86}Kr is fractionated, but when summed, $\frac{2}{3}$ and $\frac{1}{2}$ to $\frac{2}{3}$, respectively, of the ^{88}Kr$(0^+)_{g.s.}$ and ^{88}Kr(2^+) transitions are located in levels of ^{86}Kr that could be resolved. These results are qualitatively similar to the pv effects observed in two-neutron transfer reactions performed on other nuclei near $N = 50$ and help establish the systematics of the neutron pairing in this region.

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