PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Investigation of ^{46}K and ^{46}Ca with (p, ^{3}He) and (p,t) Reactions at 42 MeV†

W. W. Daehnick
Nuclear Physics Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania 15213

and

R. Sherr
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 14 August 1972)

The reactions ^{48}Ca(p, ^{3}He)^{46}K and ^{48}Ca(p,t)^{46}Ca were studied simultaneously with a counter telescope at a beam energy of 41.65 MeV. Experimental resolution for the reaction products was 50 keV for tritons and 90 keV for ^{3}He. Angular distributions from 20 to 60° were obtained for 12 low-lying states in ^{46}K, for 8 of their $T=4$ analogs in ^{46}Ca, and for 14 lower-lying ($T=3$) states in ^{46}Ca. Comparison of the angular distributions with those for known final states and with distorted-wave Born-approximation calculations allowed L assignments for most of the observed transitions. The combination of ^{48}Ca(p,t)^{46}Ca (analog) and ^{48}Ca(p, ^{3}He)^{46}K results helped resolve some divergent J^π suggestions for ^{46}K found in the literature. At least three ^{46}Ca levels at the location of the unnatural-parity $T=4$ analog states for ^{46}K were excited in ^{48}Ca(p,t) with about 10% of the strength of the neighboring natural parity $T=4$ states. This seems to indicate that the familiar one-step zero-range interpretation of (p,t) transfers in this case is less reliable than usual. Another unexpected result was our failure to see a strong 0^+ state in ^{48}Ca(p, ^{3}He)^{46}K.

I. INTRODUCTION

The isotopes ^{46}K and ^{46}Ca are of great interest since their low-lying states may be described by two-hole configurations of a doubly magic ^{48}Ca core. This assumption seems to hold best for the low-lying multiplets of the odd-odd ^{46}K nucleus, since its (2^-) ground state[1] does not appear to be appreciably lowered by pairing admixtures of higher-lying configurations. Some recent studies have attempted to understand the lower levels of ^{46}K in terms of strong mixing of the ($\pi d_{3/2}{}^{-1}\nu f_{7/2}{}^{-1}$) and ($\pi s_{1/2}{}^{-1}\nu f_{7/2}{}^{-1}$) configurations[2, 3] which are nearly degenerate for this isotope, whereas others[4-6] have emphasized the ($d_{3/2}f_{7/2}$) ground-state configuration and looked for a close similarity to ^{38}Cl. References 2, 3, and 6 make specific J^π suggestions for the lowest 4–6 levels of ^{46}K. References 2 and 3 agree in their L assignments and give the same J^π values for the lowest four ^{46}K levels. These p, t (analog), (d, α), and (d, $\alpha\gamma$) studies differ in their interpretation of the 1.37- and 1.94-MeV levels; however, Ref. 6 disagrees in L as well as J^π assignments with all three studies, save for the use of $J^\pi=2^-$ for the ground state[7] and the assumption of two low-lying negative-parity multiplets.

This unusual disagreement could arise, because ^{46}K cannot be studied by single-nucleon transfer or other simple reactions. Two-nucleon transfers for light elements, at low energies in particular, are not accurately predicted by current distorted-wave Born-approximation (DWBA) transfer theories, in part because of their sensitivity to optical-model-parameter ambiguities. In addition, for the case of ^{42}Ca(d, α) and ^{48}Ca(d, α) at 11 MeV the reactions almost certainly have compound nuclear contributions[8, 9] which differ from isotope to isotope and are likely to make empirical L assignment (as in Ref. 6) unreliable.

At 17 MeV it had been found that the ^{48}Ca(d, α) transfer was very predominantly direct, no longer showing any rapid or strong energy dependence of the differential cross section[3]; but a different if less serious problem with the 17-MeV data arises, because the steep fall of $\sigma(\theta)$ towards larger angles and weak oscillations for $L=1$, 2, and 3 produce relatively similar angular distributions, which necessitate a model-dependent choice of the final-state parity before unique L assignments can be made. The (p, t) angular distributions to two of the ^{46}K analog states in ^{46}Ca presented in Ref. 2 point persuasively to $L=3$ and $L=5$ assignments, respectively, but are not backed by DWBA calculations. Hence the strongest J limits to date seem to come from the observed γ transitions in the (d, $\alpha\gamma$) experiment.[3] The observed dominant γ cascade (886 → 691 → 587 keV → ground state) and the 10% branch for a 691 keV → 0 γ ray are fully consistent with the L and J^π assignments of Refs. 3 and 2, but definitely contradict the J^π assignments of Ref. 6.

Apart from Ref. 6, there remains the problem of the different interpretation of the 1.94-MeV level suggested by the $(p, t)^2$ and $(d, \alpha)^3$ experiments, and we must seriously consider the possibility that not all low-lying levels in ^{46}K belong to the $(s_{1/2}f_{7/2})^{-1}$ and $(d_{3/2}f_{7/2})^{-1}$ multiplets, but that one or more may have positive parity. An estimate for the $[d_{3/2}{}^{-2}]$ energies by the method of Bansal and French[10] or Zamick[11] supported this idea. It seemed therefore important to reinvestigate ^{46}K in a manner which would complement existing data.

II. EXPERIMENTAL PROCEDURE

Self-supporting ^{48}Ca targets of 0.5 and 0.9 mg/cm^2 were bombarded with the 41.65 ± 0.08-MeV proton beam of the Princeton cyclotron. The reaction products were detected with a Si surface-barrier telescope consisting of a 100-μ ΔE counter, a 2000-μ E counter, and a 1500-μ veto counter. A fast pileup rejection system permitted counting rates in excess of 15 000 counts/sec. Particle identification and data storage were handled by a Sigma 2 on-line computer, which used tabulated range-energy curves and provided very good particle separation even for deuterons and tritons.

Because of the nature and expense of the targets no attempt was made in this study to verify the nominal thickness of ^{48}Ca foil given by the manufacturer (Oak Ridge National Laboratories). The beam was monitored by charge integration, and dead-time losses were corrected for carefully. In the absence of an independent target-thickness measurement we assign a probable scale uncertainty of ±30% to all absolute cross sections presented in this study.

Figure 1 shows a comparison of (p, t) and $(p, {}^3\text{He})$ spectra for $\theta = 40°$. The ^{48}Ca(p, t) spectrum was taken with the thicker (and cleaner) target, hence groups from ^{12}C and ^{16}O contaminants are quite small. The ^{48}Ca$(p, {}^3\text{He})$ spectrum, obtained with the 0.5-mg/cm^2 target, shows evidence of strong ^{16}O and ^{12}C contaminants (dashed lines) which led to the loss of some data points as the ^{16}O$(p, {}^3\text{He})^{14}$N peaks moved through the spectrum. The solid lines are peak fits obtained with program AUTOFIT.[12] Whereas the thick (0.9-mg/cm^2) target did little harm to the triton resolution (60 versus 50 keV) it prevented the resolution of the first three excited states in ^{46}K (labeled 1, 2, 3); hence almost all runs were taken or repeated with the thin target. In these thin-target runs the doublet nature $(6^+, 2^+)$ of the strong group at 3.0 MeV in ^{46}Ca was apparent; however, the weak (2^+) group rarely amounted to more than 15% of the sum and was not integrated separately. All other ^{46}Ca peaks fitted in Fig. 1 did not show measurable broadening, which implies that they were either singlets or multiplets with a separation of $\lesssim 40$ keV.

III. DWBA CALCULATIONS AND L ASSIGNMENTS

The success of two-nucleon transfer calculations for isotopes as light as Ca has been mixed. Usually qualitative agreement with experiment is found, however, rarely is the agreement for larger L transfers good enough to distinguish with certainty between neighboring L values, especially when angular distributions extend over a limited angular range, or if data and calculations show only moderate structure.[13] A special case exists for $L = 0$ transfers where the structure is so unique that $L = 0$ assignments rarely need buttressing by DWBA. Strong $L = 2$ (p, t) reactions tend to be structured uniquely, but DWBA does not often predict finer details accurately. In addition there is the ambiguity caused by some freedom in the selection of optical-model paremeters. A recent systematic study of deuteron-transfer calculations[14] shows a pronounced superiority of calculations which use "well-matching" (i.e., identical real-well geometries for all potentials) to remove this ambiguity. This approach was chosen for the DW curves shown in Fig. 2. Microscopic calculations were performed with code DWUCK II.[15] The parameters used are given in Table I. The use of other published parameters either produced small changes for the worse or, in the case of the "shallow" triton potentials recommended in Ref. 13, completely unrealistic shapes for $L \geq 2$. Although calculations for Ca(p, t) at proton energies below 30 MeV predict strong energy and configuration dependence no such sensitivity is predicted or seen at 42 MeV. This effect could be a consequence of poor momentum matching which at lower beam energies becomes more critical and results in high sensitivity to the nuclear interior.

At 42 MeV momentum matching for the reactions studied here is best for $L = 3$ and, indeed, agreement for the (p, t) $L = 3$ transfer to the known 3.615-MeV (3^-) state in ^{46}Ca is very good [Figs. 2, 3(a)]. Good agreement is also found for the $L = 3$ transitions in ^{48}Ca$(p, {}^3\text{He})^{46}$K. Because of a very characteristic structure $L = 5$ and $L = 6$ transitions are also uniquely selected by DWBA curves [See Figs. 2, 3, and 4(a)]. Our data and calculations could not be compared for previously *known* pure $L = 0$, 1, 2, and 4 transfers; and Fig. 2 should be used as a guide in judging to which extent the proposed L assignments are compelling.

In making L assignments we have used the following procedure: All (p, t) transitions were assumed to proceed by a single L transfer and were grouped according to shape (compare Fig. 3). We needed six different empirical curves to fit all levels between 3 and 6 MeV excitation within error bars. Some known states provided us with empirical $L=3$, 5, and 6 curves which furthermore showed very good qualitative agreement with DWBA predictions (Figs. 2 and 3). Hence on the basis of good agreement with empirical as well as DWBA curves all new $L=3$ and $L=5$ assignments are considered reliable. A comparison with DWBA curves suggests that the remaining curves of Figs. 2 and 3 are $L=2$ and $L=4$, although there seem to be two types of empirical $L=4$ curves. The $L=2$ and $L=4$ assignments must be considered as tentative.

For the natural-parity (p,t) analog states (Fig. 5) the DWBA fits are good, but less unique (by

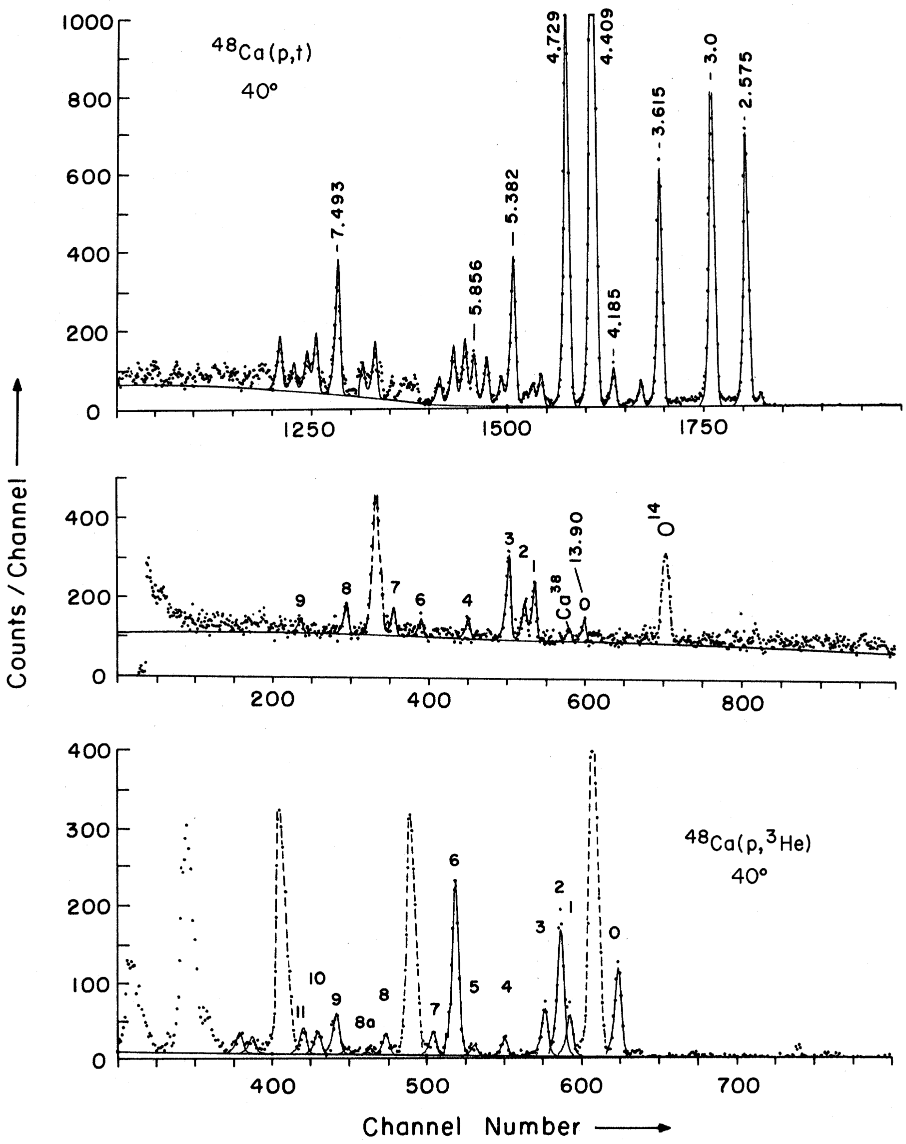

FIG. 1. Pulse-height spectra for the ^{48}Ca$(p,t)^{46}$Ca and ^{48}Ca$(p,{}^3\mathrm{He})^{46}$K reactions. In both spectra, channel 0 corresponds to ~13.1 MeV (lab). The high energy cutoff due to the finite detector depth is 29.5 MeV (channel 1825) in the triton spectrum. Dispersion in the (p,t) spectrum is 9.05 keV/channel and in the $(p,{}^3\mathrm{He})$ spectrum 18.1 keV/channel. The experimental resolution is $\lesssim 50$ keV for tritons and 90 keV for ^{3}He, respectively. Selected triton peaks are labeled by excitation energy in MeV. ^{3}He peaks and their (p,t) analogs are labeled by level order (compare Table III). Solid lines show fits by program AUTOFIT with a standard peak shape. Dashed lines indicate peaks resulting from ^{16}O and ^{12}C target impurities.

virtue of the larger experimental error bars and the shallower angular distributions). The empirical curves have identical shapes, but are shifted by ±2° with respect to DWBA predictions. In Fig. 5(a) we give empirical curves to emphasize the constancy of $L = 3$ and 5 shapes. The $L = 0$ and $L = 2$ DWBA fits in Fig. 5(b) are acceptable, but not unique. The data would also be reasonably consistent with $L = 3$. The even-parity assignments are strengthened by the observation that the natural-parity angular distributions are identical with their ^{46}K analog $(p, {}^3\mathrm{He})$ transitions as expected, save for a small Q-value effect which leads to stronger forward peaking in $(p, {}^3\mathrm{He})$; however, the $(p, {}^3\mathrm{He})$ analogs have smaller error bars and are no longer consistent with $L = 3$.

The curves drawn for the forbidden analog states (2^-, 4^-, 1^+ in Fig. 5), of course, do not imply natural-parity assignments, but are meant to show that their excitation would be consistent with a two-step process which does not wipe out the dominant L dependence in its transfer step.

In the $^{48}\mathrm{Ca}(p, t)^{46}\mathrm{Ca}$ analysis we have relied as much as possible on empirical angular distributions taken from known transitions. This approach is not practical for $^{48}\mathrm{Ca}(p, {}^3\mathrm{He})^{46}\mathrm{K}$; hence the curves in Fig. 4 are generally based on DWBA predictions.

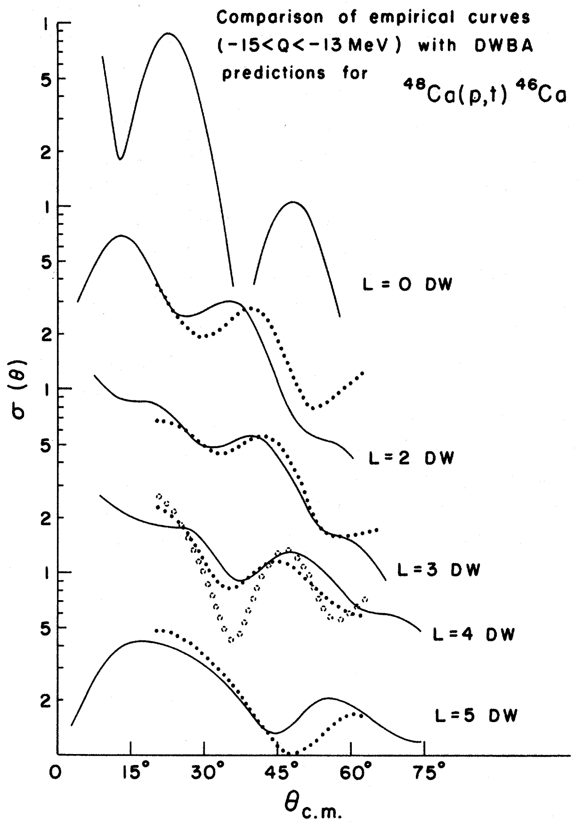

FIG. 2. Comparison of DWBA predictions for (p,t) transitions (solid lines) with the empirical curves (dotted lines) used in Fig. 3. Two types of empirical curves are classified as $L = 4$. Systematics in this mass region (Refs. 2, 19) suggest that the more structured empirical curve is more typical of $L = 4$ than the shallower one which happens to agree better with the DWBA prediction (see text). Other empirical curves show good correspondence to DWBA curves of their known or suggested L transfer although phase shifts of ±2–5° are typical. Disagreements of this order must also be expected for DWBA fits to $(p, {}^3\mathrm{He})$ data.

IV. RESULTS OF THE $^{48}\mathrm{Ca}(p, t)^{46}\mathrm{Ca}$ EXPERIMENT

Attention is directed to the almost perfect energy correspondence of the lowest ten ^{46}K states to a group of ^{46}Ca peaks beginning at 13.895 ± 0.030 MeV (level 0 in Fig. 1) which were seen at all angles. Some of these states have previously been identified as $T = 4$ ^{46}K analogs.[2] The present study, with much better statistics and improved energy resolution, confirms and extends the as-

TABLE I. Parameters used for the DWBA calculations with microscopic ($d_{3/2}$, $s_{1/2}$, $f_{7/2}$) form factors. The nonlocality parameters for the scattered waves were $\beta = 0.85$ for protons and 0.25 for tritons and helions. Finite-range-correction parameters were $R = 0.4$ for (p, t) and $R = 1.0$ for (p, He^3). Curves for $R = 0$ (zero range) differed only in slope.

	V (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	$4\,W_d$ (MeV)	r_i (fm)	a_i (fm)	r_c (fm)	$\lambda_{\mathrm{s.o.}}$
Protons [a]	46.7	1.17	0.75	6.53	13.2	1.32	0.62	1.25	
Tritons [b] and ^{3}He	166.0	1.16	0.75	16.7	⋯	1.498	0.817	1.25	
Bound neutrons and protons	c	1.25	0.65	⋯	⋯	⋯	⋯	1.25	25

[a] Taken from F. D. Becchetti and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
[b] Taken from E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, Phys. Rev. 182, 1113 (1969).
[c] Adjusted to give the correct separation energy.

signments by Dupont, Martin, and Chabre of natural or unnatural parity to this group of ^{46}Ca states. Apart from Q-value effects the (p, t) and $(p, {}^3\mathrm{He})$ cross sections for analog states should show a predictable (upper) ratio.[16,17] It can be seen in Fig. 2 that the peak areas for the natural-parity pairs labeled 1, 3, 4, 7, and 8 are almost identical, whereas the (p, t) cross section for levels 0, 2, 5, 6, 9, 10, 11 are roughly an order-of-magnitude smaller (or else indistinguishable from the $T = 3$ "continuum"). The area for the small L forbidden groups is difficult to measure since the $T_<$ background is not as smooth as assumed in the peak-fitting routine; nevertheless, at least two forbidden levels (0 and 2) definitely appear well above background with a strength of 15 and 7%, respectively, of their $(p, {}^3\mathrm{He})$ counterparts. Unless future studies show that these "analog" peaks do not correspond to single $T = 4$ levels we observe here one of the largest violations of zero-range one-step DWBA selection rules for (p, t) reported to date.

Apart from differential cross sections for the low-lying ^{46}K levels and their ^{46}Ca analogs this experiment[18] yielded about 14 useful (p, t) angular distributions to $T = 3$ states between 2.6 and 7.5 MeV in ^{46}Ca which are shown in Fig. 3, and compared to empirical L curves. A comparison of our $^{48}\mathrm{Ca}(p, t)^{46}\mathrm{Ca}$ level scheme with the compilation in *Nuclear Data Sheets*[1] shows several energy and L disagreements with adopted levels in the region of 4 to 6 MeV of excitation which are outside the experimental uncertainties. Recent high resolution $^{48}\mathrm{Ca}(p, t)$ work by Crawley *et al.*[19] in fact shows that the majority of peaks in the 3- to 6-MeV region consists of close multiplets. Fortunately, the member favored in (p, t) tends to stand out by about an order of magnitude so that

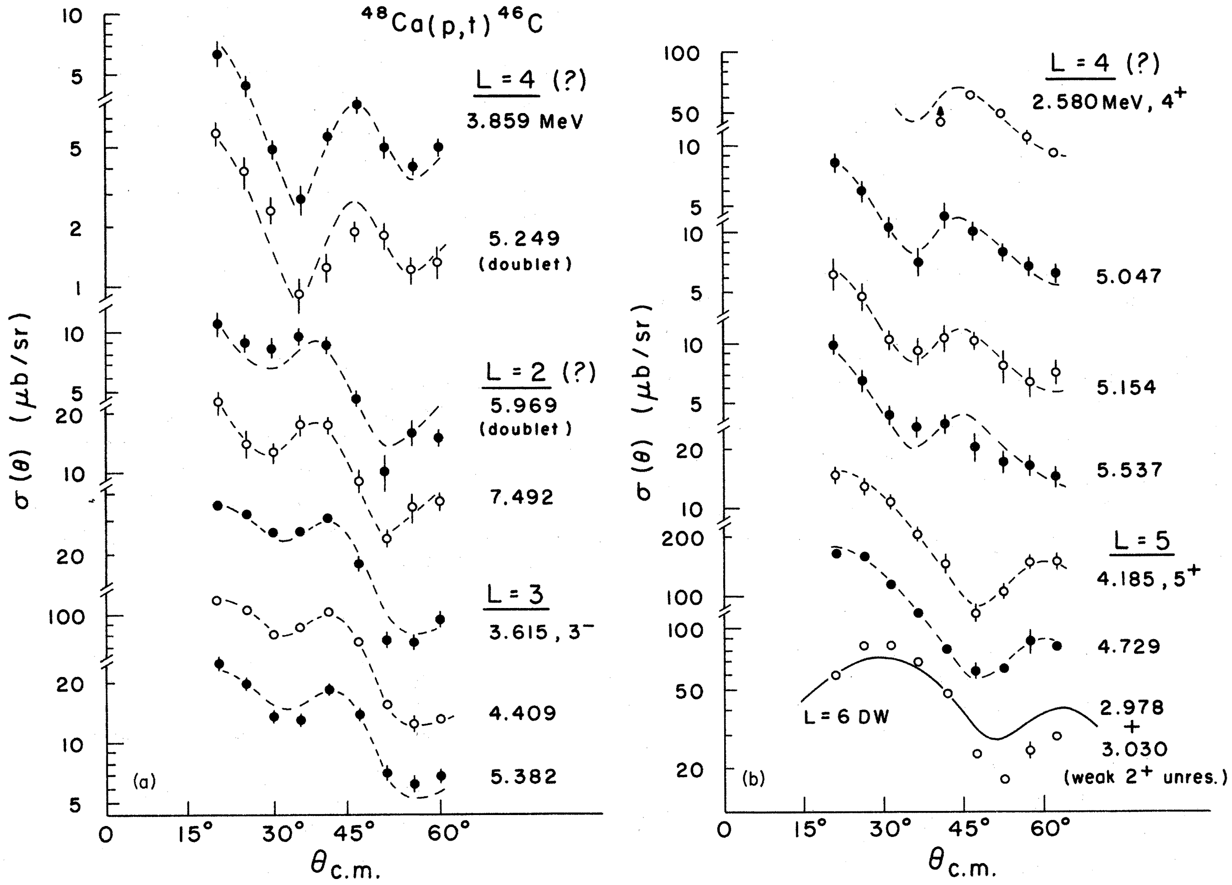

FIG. 3. (a), (b) Experimental angular distribution for $^{48}\mathrm{Ca}(p,t)$ to ^{46}Ca states between 2.5 and 7.5 MeV in excitation. Data believed to belong to the same L transfer are grouped together. Each group is compared to a single empirical curve (dashed line) which for $L = 3$ and 5 is derived from a known transition. $L = 2$ and 4 assignments are tentative. Error bars include statistics as well as estimated uncertainties for background subtraction. 50% of the points are the result of more than one measurement. (DWBA calculations show no significant Q value or configuration dependence in this energy region.)

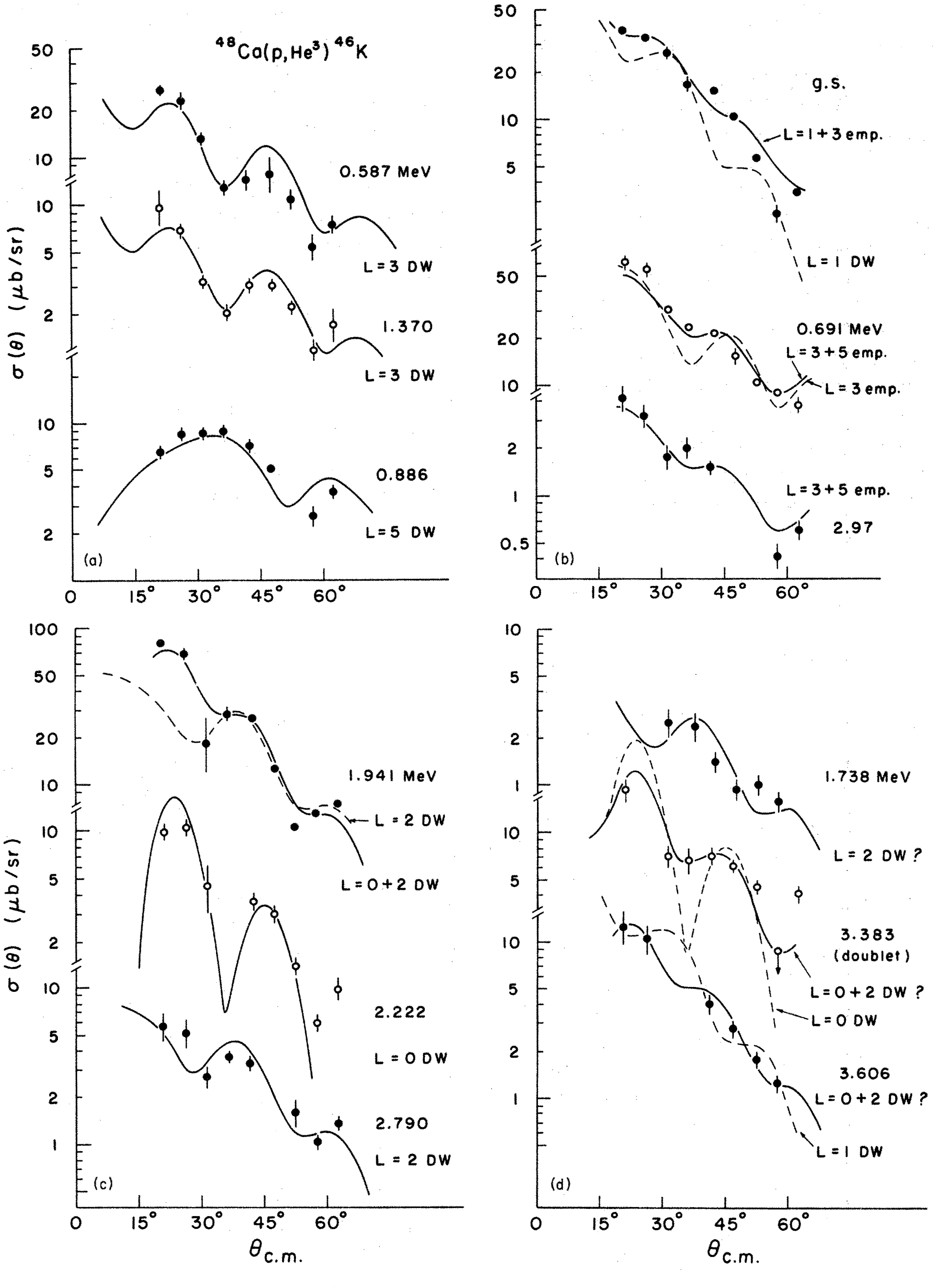

FIG. 4. (a)–(d) Comparison of ^{48}Ca(p, ^{3}He)^{46}K data with DWBA calculations for states between 0 and 3.6 MeV in excitation. DWBA curves are for the nearest MeV in excitation, and show no significant configuration dependence. Nonlocality and finite-range corrections were used (Table I), but had only a very minor effect on the angular distributions. Experimental error bars include statistics and background uncertainties. The larger errors generally stem from uncertainties in the separation of close-lying levels or interfering impurity peaks. (a) shows transitions to levels of natural parity which must have pure L transfers. The negative-parity $L = 3$, 5 fits are unique. (b) shows transitions to unnatural-parity states believed to belong to the $(d_{3/2}f_{7/2})$ and $(s_{1/2}f_{7/2})$ multiplets. The data are not consistent with any pure L curves, but agree well with (1+3) and (3+5) mixtures, especially if the empirical curves of Fig. 4(a) are used. The fits suggest 2^- and 4^- assignments, respectively. (c) shows transition to states believed to have positive parity. The 1.941-MeV transition has unnatural parity and does not agree with any 0^-, 2^-, or 4^- curves that can be constructed. However, $L = 0 + 2$ gives a good fit. The 2.222- and 2.790-MeV transitions have natural parity. They disagree significantly with $L = 1$, 3, or 5, but agree rather well with $L = 0$ and 2, respectively. (d) shows the remaining (p, ^{3}He) transitions compared with possible fits; however, lack of supporting information discourages tentative assignments.

with very few exceptions data with 50-keV resolution are useful up to about 5.6 MeV in ^{46}Ca, provided excitation energies are carefully measured.

We agree with Dupont, Martin, and Chabre[2] that the (p, t) transitions *near* 4.43 and 4.75 MeV are $L = 3$ and $L = 5$, respectively, but we do not draw their conclusion that there is a disagreement with (t, p) results. Our exact energies are 4.409 and 4.729 ± 0.003 MeV, i.e., $\gtrsim$20 keV lower than the known (t, p) states,[1, 20] whereas, e.g., for the nearby 3.858-MeV (t, p) level we obtain 3.859 MeV. About half of the states for which transitions are shown in Fig. 3 have not been seen in ^{44}Ca(t, p) and these data give J^{π} suggestions for new states (See Table II.)

Our $L = 2$ and $L = 4$ data generally have less pronounced minima than found in Ref. 2 (at 40 MeV) for the $L = 2$ and $L = 4$ transitions to lower-lying states. Since the 3.859- and 5.249-MeV transitions do have deep minima at 35°, but agree very poorly with $L = 0$, we assume that our DWBA calculations produce too weak an $L = 4$ minimum and that these two states show cleaner angular distributions than the 5.047-, 5.158-, and 5.537-MeV ($L = 4$) transitions. The latter as well as the tentative $L = 2$ curves may be flattened out by unresolved neighbors of different L or unsubtracted background.

V. RESULTS FOR ^{46}K AND COMPARISON WITH OTHER WORK

A summary of our information on ^{46}K is given in Table III. We believe that our J^{π} assignments for the 0.587- (3^-), 1.370-(3^-), and 0.886-MeV (5^-) states are unique for the following reasons:

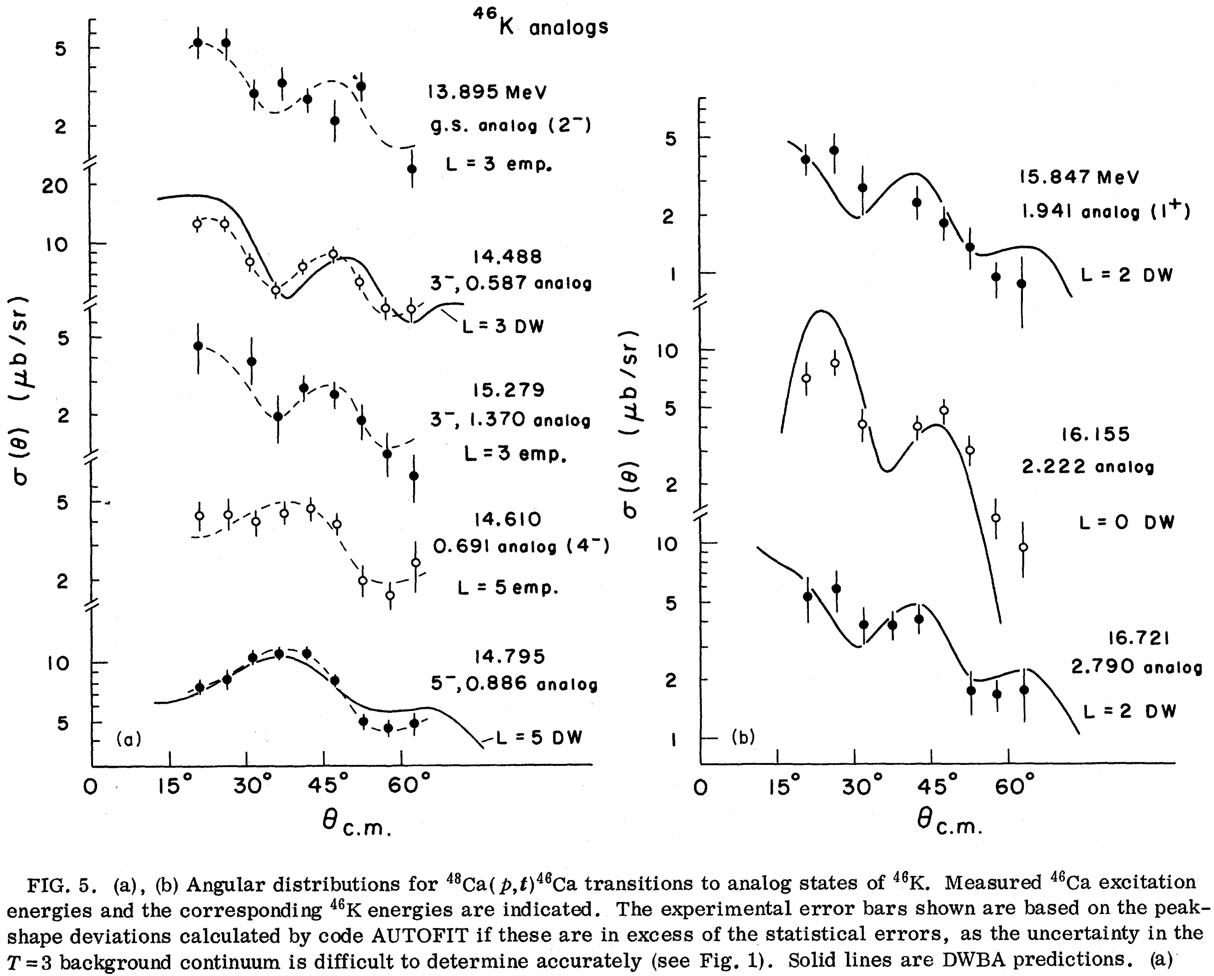

FIG. 5. (a), (b) Angular distributions for ^{48}Ca$(p,t)^{46}$Ca transitions to analog states of ^{46}K. Measured ^{46}Ca excitation energies and the corresponding ^{46}K energies are indicated. The experimental error bars shown are based on the peak-shape deviations calculated by code AUTOFIT if these are in excess of the statistical errors, as the uncertainty in the $T = 3$ background continuum is difficult to determine accurately (see Fig. 1). Solid lines are DWBA predictions. (a) shows transitions to negative-parity states. The previously assigned 3^- and 5^- levels (Ref. 2) are compared with DWBA predictions, while the other levels are only compared with empirical curves. The relatively good $L = 3$ and $L = 5$ fits to the 2^- and 4^- analogs were not expected. (b) shows a comparison of positive-parity transitions with DWBA curves for L values needed for the $(p, {}^3$He) data. Data and calculations differ slightly in phase (≈3°) and slope, as seen before.

from comparison with the (p, t) analog states one knows that these states are natural-parity levels. Pure $L=3$ and $L=5$ DWBA predictions, respectively, [Fig. 4(a)] give good fits, but all other pure L curves are inconsistent with the data. Similar arguments hold for the 2.222-MeV (0^+) and 2.790-MeV (2^+) assignments, with the reservation that the data are less complete and the fits somewhat less compelling. Finally, the L values needed for $(p, {}^3\mathrm{He})$ also give good fits to the (p, t) transitions to the natural-parity analog states (Fig. 5).

TABLE II. Summary of ^{48}Ca$(p, t)^{46}$Ca results and comparison with earlier ^{46}Ca assignments as given by Refs. 1, 2, and 20. The energy uncertainties given assume that the 3.615-MeV level is known to ±2 keV. $\sigma_{\max}$ refers to the largest measured cross section (between 20 and 30°). See Table III for analog states $E^* > 13.9$ MeV.

Previous work (Refs. 1, 2, 20)				Present work			
E^* (MeV)	J^π	$L(t,p)$	$L(p,t)$	E^* (MeV)	$L(p,t)$	$\sigma_{\max}$ (μb/sr)	J^π assignment
0	0^+	0	0	...	...	...	...
1.347	2^+	2	2	...	...	...	...
2.424	0^+	0	(0)	2.424±0.003	a	a	...
2.575	$(4)^+$	4	4	2.578±0.003	a	>60	...
2.975	...	...	...	2.978±0.004	6	≤85	6^+
3.021	2^+	2	...	3.030±0.008	a	a	...
3.615	3^-	3	3	3.615[b]	3	35	3^-
3.642	$(2)^+$	2	...	c, d	...	...	...
3.780	...	...	...	e	...	...	...
3.858	...	...	...	3.859±0.003	(4)	6	...
...	...	...	...	(3.97)[c]	...	...	...
4.23	...	...	...	4.185±0.003	5	15	5^-
4.28	...	...	...	b, c	...	...	...
...	...	...	3	4.409±0.003	3	121	3^-
4.432	$(2)^+$	2	...	c, d	...	...	...
...	...	...	5	4.729±0.003	5	162	5^-
4.749	$(4)^+$	4	...	c, d	...	...	...
5.003	...	2?	...	c, d	...	...	...
5.047	...	...	...	5.047±0.004	(4)	8	...
...	...	...	...	5.154±0.006	(4)	6	...
...	...	...	...	5.249±0.006[f]	(4)	6	...
5.324	0^+	0	...	c, d	...	...	...
...	...	...	...	5.382±0.004	3	25	3^-
5.397	...	...	...	c, d	...	...	...
5.537	...	...	...	5.537±0.004	(4)	10	...
5.607	0^+	0	...	c, d	...	...	...
5.636	0^+	0	...	c,d	...	...	...
5.690	...	...	...	c,d	...	...	...
...	...	...	...	5.712±0.004[f]	...	...	...
5.858	...	...	...	5.857±0.004[f]	...	8	...
5.962	...	...	...	5.969±0.005[f]	(2)	11	...
6.055	...	0?	...	d	...	...	...
...	...	...	...	6.097±0.005[f]	...	7	...
6.271	$(2)^+$	2	...	d	...	...	...
6.380	...	...	...	d	...	...	...
...				...			
...				...			
...				7.055±0.007[f]	...	...	...
7.498	...	2?	...	7.492±0.007[f]	(2)	23	...
7.511	...	...	...				

[a] Incomplete angular distribution.
[b] Taken from Ref. 1 as calibration point.
[c] Very weak in (p, t).
[d] Not resolved.
[e] Not seen.
[f] Probable doublet or multiplet.

L assignments for the unnatural-parity states are much more difficult, since (in principle) two L values will contribute and tend to wash out any characteristic structure. This is, indeed, the case for the transitions shown in Fig. 4(b). The ground-state (2^-) angular distribution does not agree with a pure $L=1$ DW curve, but is reasonably well fitted by an arbitrary mixture of $L=1$ (DW) and $L=3$ (empirical). Summing of empirical $L=3$ and $L=5$ angular distributions also gives good fits to the 0.691- and 2.97-MeV transitions.

Of particular interest is the strong 1.941-MeV state [Fig. 4(c)]. It is readily seen that it is not fitted by any pure L curve. The steep falloff between 20 and 35° requires an $L=0$ contribution; on the other hand the typical deep $L=0$ minima are absent. An $L=0+2$ mixture gave the only acceptable fit. Too little is known for the remaining states [Fig. 4(d)] to suggest specific assignments.

For many ^{46}K levels information on their natural or unnatural parity tends to compensate for the lack of simple reactions that reliably distinguish between even and odd parities. This information alone suffices to show that the 5^- assignment to the 0.691-MeV level in Ref. 6 must be incorrect, independent of the weight that one might attach to our (p, ^{3}He) DWBA fits and specific L assignments. On the other hand, this study is fully consistent with the *data* of Refs. 1, 2, and 3, and confirms the previous assignments for the lowest four ^{46}K levels. Only weak additional support is found for the (2^-) ground-state assignment, as all available data merely require that it be a low-spin (≤ 3) unnatural-parity state. The exclusion of 0^-, 1^+, and 3^+ relies heavily on the relative quality of DWBA fits and the β-decay data.[7] The 2^- assignment is, of course, strongly favored by empirical and shell-model systematics.[21]

Our (p, ^{3}He) data provide an easy and natural way to explain the divergent J^π suggestions for the 1.370- and 1.941-MeV levels in Refs. 2 and 3. In both studies both of these levels were assumed to belong to the low negative-parity multiplets. It turns out that this (stated) assumption must be in error. Our study agrees with Ref. 2 in the assignment of unnatural parity to the 1.941-MeV level, ruling out 3^-; but it also agrees with Ref. 3 which ruled out 4^- [because sum rules for deuteron transfers show that this level is far too strong for a second 4^- level in (d, α) and because it seems to γ decay exclusively to the 2^- ground state]. The 1^+ assignment from ^{48}Ca(p, ^{3}He)^{46}K obviously fulfills both conditions. The 3^- assignment for the weak level at 1.370 MeV is now well supported by the good $L=3$ fit to the (p, ^{3}He) transitions as well as to its (p, t) analog transition.

VI. DISCUSSION

The customary shell-model interpretation of ^{46}K suggests similarity to ^{38}Cl, provided explicit consideration is given to the near degeneracy of the $2s_{1/2}$-$1d_{3/2}$ orbits. Mixing for close-lying shell-model configurations typically results in a significant lowering of one level of a given J^π (the lowering increasing with the number of configurations contributing) and comparatively smaller

TABLE III. ^{48}Ca(p, ^{3}He)^{46}K results shown in comparison with their ^{48}Ca(p, t) analog transitions and the ^{48}Ca(d, α)^{46}K data of Ref. 3. The symbols n and u stand for natural [$\pi=(-1)^L$] and unnatural parity, respectively. Excitation energies for (p, ^{3}He) and (d, α) are uncertain to 0.2% of E^* or ±1.5 keV, whichever is larger. The relative (p, t) energies are usually uncertain by about ±5 keV.

		^{48}Ca(d, α)		^{48}Ca(p, ^{3}He)		^{48}Ca(p, t)				
Level no.	E^* (MeV)	L	σ_{max} (μb/sr)	L	σ_{max} (μb/sr)	E^* -13.905	L	σ_{max} (μb/sr)	Parity	J^π
0	0.0	(1+3)	280	(1+3)	37	−0.10	(3?)	5	u	(2^-)
1	0.587	3	90	3	27	0.584	3	12	n	3^-
2	0.691	(3+5)	650	(3+5)	63	0.705	(5?)	4	u	(4^-)
3	0.886	5	75	5	9	0.891	5	11	n	5^-
4	1.370	3	35	3	9	1.374	3	4	n	3^-
5	1.738	...	~12[a]	...	2	...	...	<2[b]	(u)	...
6	1.941	(2, 3)	300	2+0	80	1.942	(2?)	4	u	1^+
7	2.222		<5[b]	0	11	2.24	(0)	8	n	(0^+)
8	2.790		<5[b]	(2)	7	2.81	(2)	7	n	(2^+)
8a	2.969		<5[b]	(3+5)	4	...	...	<2[b]	(u)	(4^-?)
9[c]	3.383[c]		<5[b]	(0+?)	18	3.39	...	~2	u	...
10	3.606		~5	...	12	...	...	<2[b]	(u)	...

[a] Not excited by direct (d, α) transfer.

[b] Not distinguishable from background.

[c] Doublet, not resolved.

changes from the zero-order energies for the other states of the same J^π. In agreement with this interpretation the rather pure $(d_{3/2}f_{7/2})$ 2^- and 5^- levels of ^{46}K are split by roughly the amount found in ^{38}Cl. For the mixed 3^- and 4^- states we find that one J^π each is lowered below the 5^- level, whereas the two remaining levels go up somewhat in energy, i.e., they are found near or above 1.3 MeV. Hence, shell-model expectations agree with the results presented in Table III, although one tentative candidate for the second 4^- level at 2.969 MeV appears to lie somewhat too high in excitation.

The occurrence of a strong 1^+ state at 1.941 MeV justifies the idea mentioned in the Introduction that some positive-parity levels might be appreciably lowered by residual interactions from their zero-order shell-model location derived from ^{47}K and ^{47}Ca single-hole energies (2.6 MeV above the centroid of the negative-parity multiplets). In ^{38}Cl a 1^+ state is found at 1.942 MeV,[22] but the similarity in excitation energy is fortuitous since the centroid of the $d_{3/2}{}^2$ configuration should lie considerably higher in ^{46}K than in ^{38}Cl. The considerable lowering of the known 1^+ state in ^{46}K may result from the mixing of the $d_{3/2}{}^2$, $s_{1/2}d_{3/2}$, and $s_{1/2}{}^2$ configurations. The 0^+ and 2^+ states should have comparable contributions of two configurations, while the $[d_{3/2}{}^{-2}]_{3+}$ state is expected to remain rather pure and near its zero-order shell-model energy. Obviously, a detailed shell-model calculation for positive-parity states of ^{46}K is called for and feasible, but none has been published to date.

A different prediction for positive-parity states in ^{46}K can be obtained by the method of Bansal and French[10] and Zamick.[11] With the parameters for the $d_{3/2}f_{7/2}$ interaction normally used for estimating excitation energies of particle-hole states the value of 1.94 MeV for the $[f_{7/2}{}^8 d_{3/2}{}^{-2}]_{1+}$ state is reasonable while a value of 2.22 MeV for the 0^+ state is 2 or 3 MeV too high. On the other hand, if Kuo and Brown's[23] matrix elements are used the 0^+ energy is reasonable, but the 1^+ energy is about 3 MeV too low. Similar results are found for ^{40}K and ^{56}Co particle-hole states.

A question arises about the possibility that there is a lower 0^+ state as predicted by normal parameters. The latter always predict it to be appreciably below the 1^+ and if this were the case one should expect to see a strong $M1$ $(1^+ \rightarrow 0^+)$ transition, similar to results[24] in ^{40}K. No such branch is seen in $(d, \alpha\gamma)$ from the 1.94-MeV state. It is therefore reasonably certain that the 2.22-MeV state is the lowest candidate for the 8p-2h $T = 4$ state.

If this assignment is correct, its yield is considerably reduced from expectations based on the simplest model of this state. It may be that we have here another example in which a $\Delta T = 0$, 0^+ to 0^+ transition is inhibited in $(p, {}^3\text{He})$ reactions.[25]

A comparison of the relative $(p, {}^3\text{He})$ cross sections for the low-lying states of ^{46}K with DWBA predictions for pure $(s_{1/2}f_{7/2})$, $(d_{3/2}f_{7/2})$, and $d_{3/2}{}^2$ configurations indicates the need for significant configuration mixing. Only strong coherence effects would explain the enhancement of the 0.691-MeV (4^-) and the 1.941-MeV (1^+) states, and the reduced cross sections seen for the weak 3^- state at 1.370 MeV and the even weaker higher 4^- level (presumably at 2.969 MeV). At present the unexpectedly large contribution of $L = J + 1$ terms in transitions to some unnatural-parity states (levels 0, 2, 8a) is not understood. Population of their analogs in ^{46}Ca also appears to proceed by $L = J + 1$, and one is tempted to speculate that a two-step process may be responsible for both effects.

VII. ACKNOWLEDGMENTS

The authors are indebted to P. Debevec and W. Braithwaithe for assistance in the data acquisition, and to J. Comfort and R. Gibson for help in formatting the data for analysis at the University of Pittsburgh computer.

[†] Work supported by the National Science Foundation and the U. S. Atomic Energy Commission.

[1] R. L. Auble, Nucl. Data B4, 269 (1970), ($A = 46$).

[2] Y. Dupont, P. Martin, and M. Chabre, Phys. Letters 31B, 68 (1970).

[3] J. H. Orloff and W. W. Daehnick, Bull. Am. Phys. Soc. 15, 47 (1970); W. W. Daehnick, J. Orloff, T. Canada and T. S. Bhatia, *ibid.* 16, 555 (1971).

[4] A. Marinov and J. R. Erskine, Phys. Letters 14, 46 (1965).

[5] A. E. L. Dieperinck and P. J. Brussaard, Nucl. Phys. A106, 177 (1968); F. C. Erné, *ibid.* 84, 91 (1966).

[6] M. Paul, A. Marinov, Ch. Drory, J. Burde, E. Navon, and Sh. Morderchai, Nucl. Phys. A168, 267 (1971).

[7] B. Parsa and G. E. Gordon, Phys. Letters 23, 269 (1966).

[8] J. Jänecke, Nucl. Phys. 48, 129 (1963).

[9] J. H. Orloff, Excitation Functions for ^{48,40}Ca$(d,\alpha)^{46,38}$K 12–17 MeV (unpublished).

[10] R. K. Bansal and J. B. French, Phys. Letters 11, 145 (1964).

[11] L. Zamick, Phys. Letters 19, 580 (1965); however,

see also L. Zamick, in Proceedings of the 1971 Gull Lake Conference (to be published).

[12] J. R. Comfort, Argonne National Laboratory Informal Report PHY 1970 B, 1970 (unpublished).

[13] H. W. Baer, J. J. Kraushaar, C. E. Moss, N. S. P. King, R. E. L. Green, P. D. Kunz, and E. Rost, Ann. Phys. (to be published).

[14] R. DelVecchio and W. W. Daehnick, Bull. Am. Phys. Soc. 17, 509 (1972); Phys. Rev. C 6, 2095 (1972).

[15] P. D. Kunz, University of Colorado, 1969 (unpublished); See also Ref. 13.

[16] J. C. Hardy, H. Brunnader, and J. Cerny, Phys. Rev. Letters 22, 1439 (1969). It is found that for $T_i = T_f = 4$ in (^{48}Ca + p) the ratio $\sigma(p,t)/\sigma(p, {}^3\mathrm{He})$ is nearly constant, as expected for allowed transfers; however, its value $R_{\mathrm{exp}} = 0.8 \pm 0.2$ lies considerably above the value $R_{\mathrm{th}} \leq 0.42$ that would be predicted from Eqs. (4) and (5) of the reference cited.

[17] J. Cerny, R. H. Pehl, and G. T. Garvey, Phys. Letters 12, 234 (1964).

[18] The experimental data were previously presented by W. W. Daehnick and R. Sherr, Bull. Am. Phys. Soc. 17, 535 (1972).

[19] G. M. Crawley, P. S. Miller, G. Igo, and J. Kulleck, Bull. Am. Phys. Soc. 17, 535 (1972); and G. M. Crawley, private communication.

[20] D. C. Williams, J. D. Knight, and W. T. Leland, Phys. Rev. 164, 1419 (1967); J. H. Bjerregaard *et al.*, Nucl. Phys. A103, 33 (1967).

[21] M. H. Brennan and A. M. Bernstein, Phys. Rev. 120, 927 (1960).

[22] G. H. Wedberg, Ph.D. thesis and Argonne Informal Report Phys.-1971 C, 1971 (unpublished). See also G. A. P. Engelbertink and J. W. Olness, Phys. Rev. C 5, 431 (1971).

[23] T. T. S. Kuo and G. Brown, Nucl. Phys. A114, 241 (1968).

[24] P. J. Twin, W. C. Olsen, and D. M. Sheppard, Nucl. Phys. A143, 481 (1970).

[25] P. Debevec and G. Garvey, Bull. Am. Phys. Soc. 17, 91 (1972).

PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Beta Spectrum of ^{87}Kr

F. K. Wohn, J. K. Halbig, W. L. Talbert, Jr., and J. R. McConnell

Ames Laboratory USAEC and Department of Physics, Iowa State University, Ames, Iowa 50010

(Received 21 August 1972)

A measurement of the β spectrum of ^{87}Kr was undertaken to resolve some discrepancies in recently reported values of the branching of the β decay to the ground state of ^{87}Rb. Sources of mass-separated ^{87}Kr, provided by the TRISTAN on-line isotope separator, were investigated with a high-resolution $\pi\sqrt{2}$ magnetic spectrometer. Using constraints based on previous γ-ray decay schemes, the measurement yielded a Q value of 3.888 ± 0.007 MeV and a ground-state β intensity of $(30.5 \pm 2.2)\%$. In addition, the intensity ratio for an unresolved γ-ray doublet at 2555 keV was independently determined on the basis of β-branch intensities to the levels at 2555 and 2960 keV.

I. INTRODUCTION

There have been five recent measurements[1-5] of the level structure of ^{87}Rb populated from the decay of ^{87}Kr. The most recent work by Shihab-Eldin *et al.*[1] (referred to subsequently as SPBR), contains a brief summary of the earlier γ-ray studies. The level scheme reported by SPBR is shown in Fig. 1; 28 transitions have been placed in this level scheme, which proposes the existence of three new levels not reported previously. A major discrepancy in these recent γ-ray studies involves the relative intensities of the two components of a γ-ray doublet, consisting of a 2554.5-keV transition from the 2555-keV level and a 2557.7-keV transition from the 2960-keV level. The intensity ratio of the 2554.5- to the 2557.7-keV transition was reported as 2.01 in SPBR, 1.0 in the work of Bocquet *et al.*[2] (BBCPSM), 0 by Onega and Carpenter[3] (OC), 1.88 by Lycklama, Archer, and Kennett[4] (LAK), and ∞ by Holm[5] (H). The doublet was unresolved in all five of these measurements; the intensity ratio was determined either by fitting the observed doublet to two components or by the intensity of the doublet in coincidence with the 402.7-keV transition. The ^{87}Kr β-spectrum measurement reported here is sufficiently sensitive to the relative β feeding to the two levels depopulated by the doublet to allow a choice to be made among the different reported intensity ratios of the two γ rays.

Four of the five γ-ray studies also reported measurements of the β spectrum of ^{87}Kr.[2-5] With the intensity of the ground-state β decay designated as β_0, BBCPSM reported $\beta_0 = 32\%$ with $Q = 3.95 \pm 0.05$ MeV, OC found $\beta_0 = 13.6\%$ with $Q = 3.85 \pm 0.04$