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Two-Particle, Two-Hole States in ^{40}K from the Study of the ^{40}Ar(^{3}He,^{3}H)^{40}K Reaction*

J. J. Wesolowski, Luisa F. Hansen, and M. L. Stelts
University of California, Lawrence Radiation Laboratory, Livermore, California 94550

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Differential cross sections for the ^{40}Ar(^{3}He,^{3}H)^{40}K reaction have been measured for a ^{3}He bombarding energy of 17.9 MeV. A comparison is made between the ^{40}Ar(^{3}He,^{3}H)^{40}K data and the ^{39}K$(d,p)^{40}$K data of Enge *et al.* to determine the location of some of the two-particle, two-hole states in ^{40}K. The angular distributions of 10 triton groups have been obtained. Distorted-wave Born-approximation (DWBA) calculations have been compared with some of these distributions to demonstrate the consistency of spin assignments.

INTRODUCTION

Some time ago Enge *et al.*,[1] using a broad-range spectrograph, studied the energies and angular distributions of protons emitted from the ^{39}K$(d,p)^{40}$K reaction. For many of the levels observed, the orbital angular momentum of the captured neutron in the stripping process was obtained. If the major component of the ground-state wave function of ^{39}K can be taken to be a $(d_{3/2})_p{}^{-1}$ configuration, the simple stripping reaction would be expected to favor states of the one-particle, one-hole type, e.g., $(d_{3/2})_p{}^{-1}(f_{7/2})_n{}^1$ or $(d_{3/2})_p{}^{-1}(p_{3/2})_n{}^1$. If the major component of the ground-state ^{40}Ar wave function is taken to be a $(d_{3/2})_p{}^{-2}(f_{7/2})_n{}^2$ configuration, the ^{40}Ar(^{3}He,^{3}H)^{40}K charge-exchange reaction would favor $(d_{3/2})_p{}^{-2}(f_{7/2})_p{}^1(f_{7/2})_n{}^1$ and $(d_{3/2})_p{}^{-1}(d_{3/2})_n{}^{-1}(f_{7/2})_n{}^2$ configurations, i.e., two-particle, two-hole states. Hence, one anticipates that the ^{40}Ar(^{3}He,^{3}H)^{40}K reaction has strength where the ^{39}K$(d,p)^{40}$K reaction does not, and vice versa. Therefore, the (^{3}He,^{3}H) reaction can be a useful tool for identifying in a given nucleus states which are not easily made in the corresponding (d,p) reaction. The above also applies to the experimentally less tractable (p,n) charge-exchange reaction. The purpose of the ^{40}Ar(^{3}He,^{3}H)^{40}K experiment was to demonstrate that, indeed, this reaction has strength where the ^{39}K$(d,p)^{40}$K reaction does not and vice versa and to determine the location of some of the two-particle, two-hole states in ^{40}K.

EXPERIMENTAL PROCEDURE

Argon gas contained in a 2.5-cm-diam gas cell located in the 102-cm-diam scattering chamber was bombarded by ^{3}He ions accelerated by the Livermore variable-energy cyclotron. The cell has a continuous 290° window made of 0.00254-cm-thick Havar, a cobalt-based alloy. The gas was under a pressure of 0.5 atm. The energy of the ^{3}He beam at the center of the gas cell was 17.9 MeV. The tritons were detected by means of ΔE–E surface-barrier counter telescopes, with appropriate slits and collimators, in conjunction with the mass-identification system of Goulding *et al.*[2] Data collection was speeded by the simultaneous use of three telescope systems mounted at 10° intervals with respect to one another. The total resolution (full width at half-maximum) was 150 keV.

A thin Al target mounted directly beneath the gas cell could be remotely positioned in the beam path. The ^{27}Al(^{3}He,^{3}H)^{27}Si reaction was used to obtain the energy calibration of the system. The experimental errors associated with the energies assigned to the various triton groups were between ± 20 and ± 40 keV.

COMPARISON OF ^{40}Ar(^{3}He,^{3}H)^{40}K RESULTS WITH ^{39}K$(d,p)^{40}$K DATA

The triton energy spectrum obtained at 30° is shown in Fig. 1. The excitation energies corresponding to the more prominent peaks are listed in the figure. The ground and first excited states were too close in energy to be resolved in this experiment, and similarly for the second and third excited states. The measured energies of the fourth and fifth excited states are 1.65 ± 0.02 and 1.96 ± 0.02 MeV, which are in good agreement with the values of 1.639 and 1.954 quoted by Enge *et al.* For higher excitation energies the density of levels is sufficiently large, as shown in the (d,p) work, that individual levels cannot be unambiguously assigned to any of the peaks in the spectrum. However, the peak at 4.38 ± 0.02 MeV can be identified as primarily representing the ground-state analog transition for several reasons. First, the measured excitation energy is in close agreement with the value of 4.40 MeV, calculated using the semiempirical Coulomb displacement energy formula of Anderson *et al.*[3] and the Q value of Ashby and Catron.[4] Secondly, the triton angular distribution which we observe can be adequately described by an $l=0$ angular-momentum transfer, and the cross section is quite large. Last, Anderson *et al.*, studying the ^{40}Ar$(p,n)^{40}$K reaction, also identified a prominent level

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[1] H. A. Enge, E. J. Irwin, Jr., and D. H. Weaner, Phys. Rev. **115**, 949 (1959).

[2] F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pell, IEEE Trans. Nucl. Sci. **11**, 388 (1964).

[3] J. D. Anderson, C. Wong, and J. W. McClure, University of California Radiation Laboratory Report No. UCRL-12178, 1964 (unpublished).

[4] Val J. Ashby and Henry C. Catron, University of California Radiation Laboratory Report No. UCRL-5419, 1959 (unpublished).

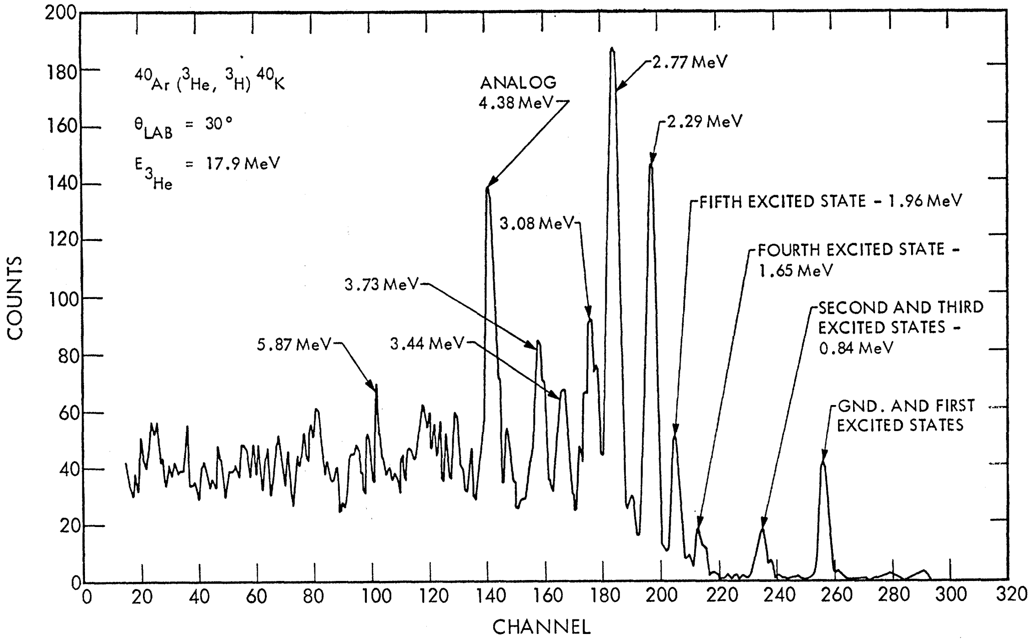

FIG. 1. Triton energy spectrum at $\theta_{\text{lab}}=30°$.

observed at an excitation energy of 4.26±0.2 MeV as the analog state.[5]

The peak at 5.87-MeV excitation energy is 1.49 MeV above the ground-state analog, and hence probably corresponds to the analog of the first excited 2+ level at 1.460 MeV in ^{40}Ar. Statistics and background made it difficult to obtain an angular distribution in order to verify this. The ^{40}Ar$(p,n)^{40}$K work of Anderson *et al.* also showed a peak at 1.50 MeV above the ground-state analog which was identified as the first-excited-state analog. The measured angular distributions for 10 of the most prominent peaks observed are shown in Fig. 2.

The (d,p) work of Enge *et al.* lists the maximum cross sections measured for proton groups corresponding to various excitation energies in ^{40}K. Figure 3 shows a comparison between these (d,p) maximum cross sections and those obtained from the (^{3}He,^{3}H) measurements. For the latter case, only those cross sections for triton groups whose angular distributions were measured are plotted. However, reference to the spectrum shown in Fig. 1, as well as spectra taken at other angles, shows that other triton groups, if present at all, have cross sections smaller than the smallest shown in Fig. 3. Two general statements can be made with reference to Fig. 3. First, the (^{3}He,^{3}H) cross sections are less than the (d,p) cross sections by about a factor of 50. Secondly, the graph clearly demonstrates, as was anticipated, that the (^{3}He,^{3}H) reaction has strength where the (d,p) reaction does not and vice versa. This is particularly noticeable for the 0^-, 1^-, 2^-, and 3^- quadruplet of levels at about 2-MeV excitation energy[6] and also for the analog state. In the latter case, the (d,p) reaction data showed no strength at all. The various levels near 4.38-MeV excitation (4.017–4.538 MeV) seen in the (d,p) work were all populated by $l_n=1$ transitions and thus were assigned negative parity. The triton groups corresponding to the $(d_{3/2})_p^{-1}(f_{7/2})_n^{1}$ quadruplet of levels are also of interest since they give an indication of the difficulty in populating states by the (^{3}He,^{3}H) reaction when this requires moving an $f_{7/2}$ neutron to the $(d_{3/2})$ shell as well as charge exchanging. The maximum cross section observed for the 3^-, 4^- doublet is 23 μb/sr and that of the 2^-, 5^- doublet is 13 μb/sr. On the other hand, the analog transition which only requires a charge-exchange mechanism has a maximum observed cross section of 220 μb/sr.

One notes from Fig. 3 that between the analog and ground state there are six observed triton groups of various excitation energies which have cross sections which are much larger than those corresponding to the $(d_{3/2})^{-1}(f_{7/2})^{1}$ quadruplet. This fact, coupled with the observation that in each case the corresponding (d,p) reaction showed little strength, leads one to surmise that these states were made by a simple charge exchange in the $(d_{3/2})$ or $(f_{7/2})$ shells, i.e., are two-particle, two-hole states. They would have $(d_{3/2})_p^{-2}(f_{7/2})_p^{1}(f_{7/2})_n^{1}$ and $(d_{3/2})_p^{-1}(d_{3/2})_n^{-1}(f_{7/2})_n^{2}$ configurations. Since the analog is the first $T_>$ state, i.e., the first state

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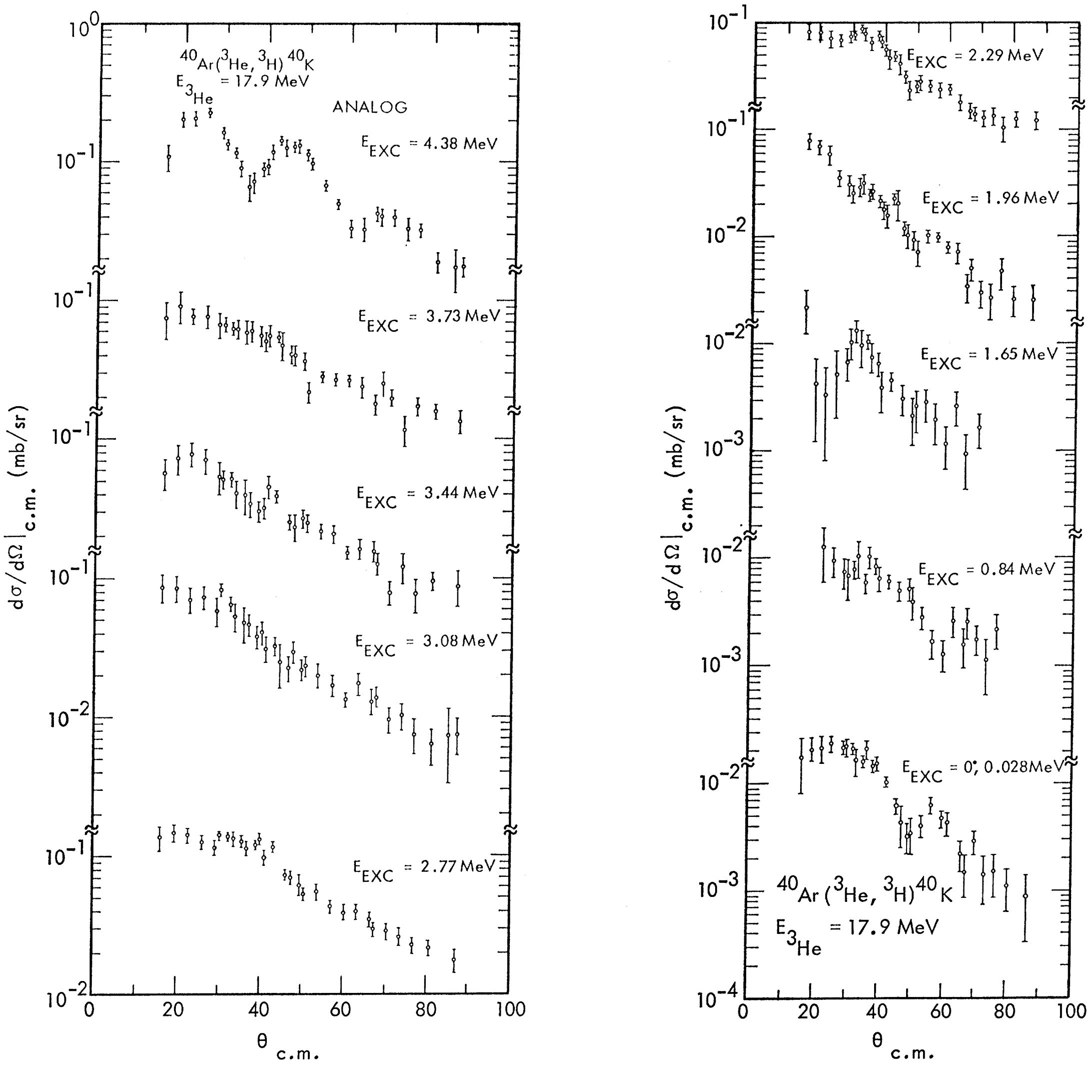
[5] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. **129**, 2718 (1963).

[6] The large displacement towards higher excitation energy of the 0^- state may be due in part, according to Enge *et al.* (Ref. 1), to $f_{\frac{5}{2}}$ admixtures in the spin 1, 2, and 3 states.



(a) (b)

FIG. 2. Measured triton angular distributions for various excitation energies E in ^{40}K. The indicated errors refer to the absolute errors.

with an isospin one unit greater than that of the ground state (in this case $T_>=2$), these states have $T=1$, and because they have the same configuration as the analog but a lower T value they are sometimes referred to as configuration states. If one allows for a recoupling of the spin in either the $(d_{3/2})$ or $(f_{7/2})$ shells, then for spin values J equal to 1, 2, or 3, one can generate two states of different energy, given by

$$\psi_1=\alpha\phi_f+\beta\phi_d, \quad \psi_2=\beta\phi_f-\alpha\phi_d,$$

where ϕ_d and ϕ_f are wave functions for the d and f shells, respectively. It is not difficult to show that for certain reasonable assumptions, one state for each of these J values will have very little strength. These assumptions are that the charge exchange occurs mainly in the shell in which the recoupling takes place, that the probability for charge exchanging in either shell is approximately equal, and that α and β are about equal.[7] Then there are eight $T=1$ states with spins 0^+ to 7^+. The cross section to the 0^+, $T=1$ state is expected to be very small for reasons to be discussed later. This leaves seven $T=1$ states which could be populated. These qualitative results are simply meant to show that our assertion that the (^{3}He,^{3}H) reaction preferentially populates the two-particle, two-hole configuration states is not inconsistent with the fact that only six triton groups of large strength were observed between the analog and ground states. One also expects the (p,n) reaction to preferentially populate such two-particle, two-hole states. The ^{40}Ar$(p,n)^{40}$K data of Anderson *et al.*[5] also displayed peaks between the

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[7] A. Kerman (private communication).

analog and ground states which could be interpreted as configuration states. At a proton bombarding energy of 17.8 MeV, a group at (2.28±0.20)-MeV excitation energy was observed, while at a bombarding energy of 13.0 MeV, possibly as many as three groups were observed. The excitation energies were 2.36±0.20, 3.06±0.20, and 3.76±0.20 MeV. These could easily be interpreted as corresponding to the 2.29-, 3.08-, and 3.73-MeV levels observed in the (^{3}He,^{3}H) data. The background and resolution problems inherent in the (p,n) measurement make this reaction less tractable to the study of these states than the (^{3}He,^{3}H) reaction. Probably this is the reason that the Anderson *et al.* data did not show more configuration states.

DWBA CALCULATIONS

Most of the angular distributions shown in Fig. 2 are rather washed out. Thus one expects it will be rather difficult to assign possible spin values to the various groups based on a study of the angular-momentum transfers necessary to fit the data. Nevertheless, DWBA calculations were carried out to show the consistency, at least qualitatively, of the data with the interpretation given above. The calculations were made with the code JULIE.[8] The parameters used to generate the incoming-channel distorted waves were those obtained from optical-model fits to ^{40}Ca(^{3}He,^{3}He)^{40}Ca elastic scattering data at 22 MeV.[9] Gibson *et al.*[10] have pointed out that energy dependence of the ^{3}He optical potential appears to be quite small. Both the real and imaginary parts were Woods-Saxon shapes. The real part had a depth of 159 MeV, a radius of $1.24A^{1/3}$ F, and a diffuseness of 0.686 F, while for the imaginary part these parameters were 12.9 MeV, $1.70A^{1/3}$ F, and 0.81 F, respectively. Because no pertinent triton elastic scattering data were available, the outgoing-channel optical parameters were taken to be the same as those used in the incident channel. The choice for the shape of the symmetry term, i.e., the $\mathbf{T}\cdot\mathbf{t}$ interaction causing the transition, was prompted by the results of an earlier study of the ^{48}Ti(^{3}He,^{3}H)^{48}V "quasielastic" reaction which demonstrated that good fits could be obtained using a surface-symmetry term with geometrical parameters equal to those of the imaginary part of the optical potential.[11] Thus for the ^{40}Ar(^{3}He,^{3}H)^{40}K case, the symmetry term had a derivative Woods-Saxon shape with a radius of $1.70A^{1/3}$ F and a diffuseness of 0.81 F. A comparison between a calculation for $l=0$ angular-momentum transfer and the data for the analog state is shown in Fig. 4. Since it is not the purpose of

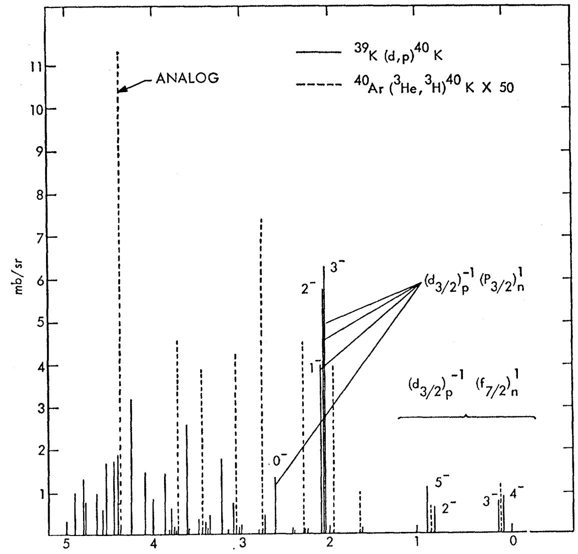

FIG. 3. Comparison of maximum cross sections measured in the (d,p) experiments with those obtained in the (^{3}He,^{3}H) experiment.

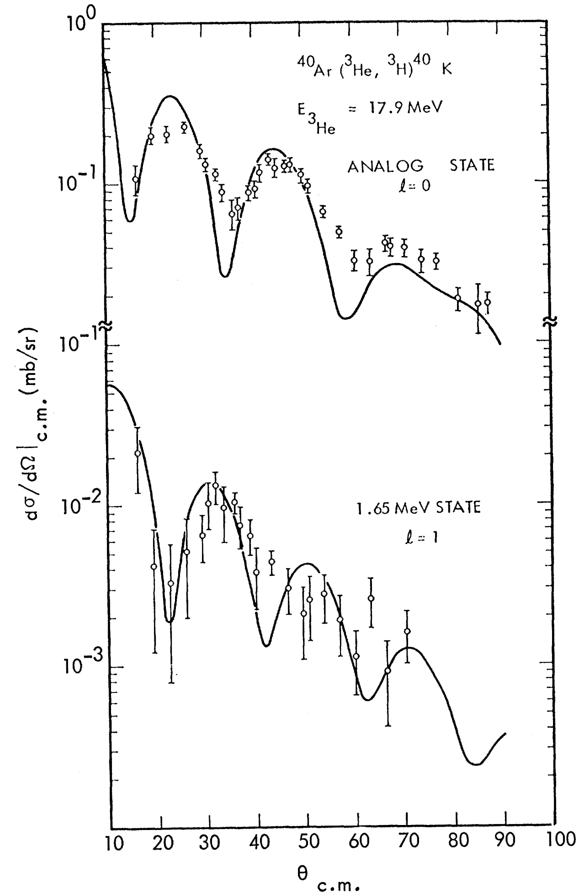

FIG. 4. Comparisons of DWBA calculations with ^{40}Ar(^{3}He,^{3}H)^{40}K analog-state and 1.65-MeV-state data.

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[8] R. M. Drisko, code JULIE (unpublished). The calculations were carried out by P. G. Roos.

[9] P. G. Roos (private communication).

[10] E. F. Gibson, B. W. Ridley, J. J. Kraushaar, M. E. Rickey, and R. H. Bassel, Phys. Rev. **155**, 1194 (1967).

[11] J. J. Wesolowski, E. H. Schwarcz, P. G. Roos, and C. A Ludemann, Phys. Rev. **169**, 878 (1968).

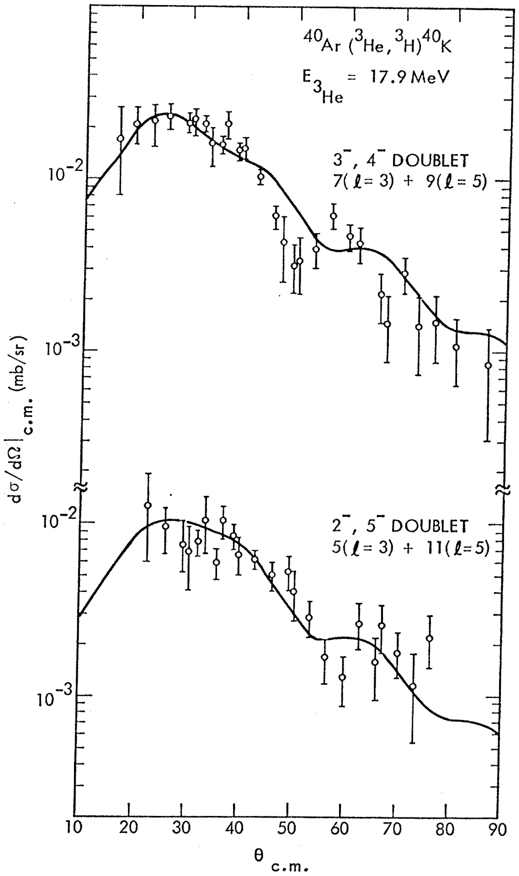

FIG. 5. Comparison of DWBA calculations with triton angular distributions corresponding to ground-state doublet and 0.84-MeV doublet.

this paper to discuss DWBA charge-exchange calculations as such, no attempts were made to generate better fits by adjusting the values of the parameters. Suffice to note that the values used, including (in the case of the analog transition) the strength of the symmetry term, were compatible with those found in the more exhaustive study of the Ti data mentioned earlier, and, as can be seen from Fig. 4, give agreement with the data. This agreement for the analog state made it reasonable to attempt to fit the shapes of the angular distributions of other states to ascertain something about their spins. DWBA calculations were carried out for $l=0$ to 6. The calculations were run only at several representative excitation energies rather than at the exact excitation energy of each triton group to be studied. The shapes of the calculated distributions vary sufficiently smoothly and slowly with energy that within the context of this paper such a small approximation is reasonable.

The 1.65-MeV state is well resolved from neighboring states. The (d,p) angular distribution required an $l=1$ angular-momentum transfer, thus yielding a spin assignment $J \leq 3^-$. The agreement between the DWBA calculation and the (^{3}He,^{3}H) data for this state was much better for an $l=1$ transfer than for any other value of l. This is shown in Fig. 4. Thus the (^{3}He,^{3}H) reaction would also assign a negative parity to the 1.65-MeV level, but would limit the spin value to $\leq 2^-$.

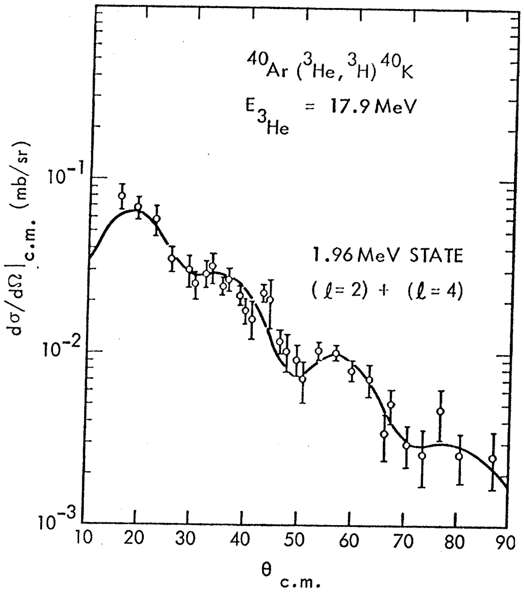

FIG. 6. Comparison of DWBA calculations with triton angular distributions for the 1.96-MeV state.

The 4^- ground state can be populated via the (^{3}He,^{3}H) reaction by $l=3$ and $l=5$ transfers, while the 3^- first excited state requires $l=3$. An attempt to fit the shape of the angular distribution of the triton group corresponding to this doublet was made for a combination of $l=3$ and $l=5$. This is shown in Fig. 5. The theoretical calculation carried out for the $2^-(l=1, 3)$, $5^-(l=5)$ doublet using a combination of $l=3$ and 5 is also shown in Fig. 5. The agreement with the data, although not exceptionally good, is sufficient to demonstrate the consistency of the spin assignments with the calculations.

Having thus demonstrated that the DWBA calculations give reasonable agreement with the data for levels of known spin, we may now apply it to other levels in the hope of extracting some information about their spins.

The level at 1.96 MeV was resolved from neighboring levels, but, as can be seen in Fig. 2, the angular distribution is somewhat washed out. Thus one expects that the spin is such that several l transfers are possible. A combination of $l=2$ and $l=4$ gave good agreement with experiment, as can be seen in Fig. 6. In the (d,p) experiment, a level at 1.954 MeV was observed but with a very low cross section and an "isotropic" distribution. These facts are consistent with a 3^+ assignment to this state.

The remaining five angular distributions show much less structure than one would anticipate. For example, none shows a structure corresponding to a large or a combination of large angular-momentum transfers. Some attempts were made to fit the distributions using various combinations of l values, but met with insufficient success to warrant even tentative spin assignments. Of course, in each case the observed triton group is in a region where the density of levels is sufficiently high, as shown by the (d,p) work, that more than one state may be contributing to the cross section. A higher-resolution experiment would resolve this point.

"ANTIANALOG" STATE

The ground-state isobaric analog has been readily identified in this experiment. Another state of interest is the "antianalog," i.e., the state which has the same configuration as the analog, the same spin and parity, but an isotopic spin $T_f=T_T-1$, where T_T is the isotopic spin of the analog. In our case, $T_T=2$. Such a state exists only if the configuration which represents the analog contains two or more orbits which are not fully closed for both neutrons and protons. In the case of two subshells not fully closed, with separate isobaric spins $T^{(1)}$ and $T^{(2)}$, the effective transition operator becomes

$$[\alpha_1\mathbf{T}^{(1)}+\alpha_2\mathbf{T}^{(2)}]\cdot\mathbf{t}_0,$$

where $\mathbf{t}_0$ refers to the incident nucleon. If there is only one subshell not fully closed, $\alpha_1=\alpha_2=\alpha$ and the operator becomes the familiar

$$\alpha\mathbf{T}\cdot\mathbf{t}_0.$$

French and MacFarlane[12] have calculated the square of the charge-exchange interaction matrix element for a target state $T^{(1)}$, $T^{(2)}$, $T_T=T^{(1)}+T^{(2)}$ and the results are

$$\langle H\rangle^2(T_f=T_T-1)=[T^{(1)}T^{(2)}/2T_T](\alpha_1-\alpha_2)^2,$$
$$\langle H\rangle^2(T_f=T_T)=(1/2T_T)[\alpha_1T^{(1)}+\alpha_2T^{(2)}]^2.$$

Thus, a measure of the ratio of the analog to antianalog cross sections yields the ratio of α_2 to α_1. Since one expects the ratio to be close to unity, the difficulty lies in measuring the small cross section to the antianalog state. In the ^{40}Ar(^{3}He,^{3}H)^{40}K experiment, no $l=0$ transition was observed between the analog and the ground state. It is estimated that the antianalog should be several MeV above the ground state.[7] If it were low enough, say between the 0.84-MeV doublet and the 1.65-MeV state and resolved from these states, then a lower limit for α_2/α_1 would be approximately 0.98. Although the (d,p) reaction is not expected to populate this state well, the work of Enge *et al.* showed no indication at all of a state in this region. The work did, however, show a weakly populated $l_n=2$ or 3 state at 2.256-MeV excitation. An $l_n=2$ transfer would be consistent with the 0^+ assignment. If this were the location of the 0^+, $T=1$ state it would be too close to the 2.29-MeV state which was well populated in the (^{3}He,^{3}H) experiment to make it possible for us to obtain a useful lower limit for α_2/α_1. Clearly, a theoretical calculation of the excitation energy of the 0^+, $T=1$ state would be of value.

CONCLUSIONS

The experiment has, indeed, shown that the distribution of transition strengths is markedly different for the ^{40}Ar(^{3}He,^{3}H)^{40}K and ^{39}K$(d,p)^{40}$K reactions. Thus, the charge-exchange reaction can be a useful tool for studying states which are not well populated in the stripping reaction. In particular, the analysis of the data has determined the location of some of the two-particle, two-hole states in ^{40}K and, in fact, for the 1.96-MeV level, a DWBA analysis has allowed us to make a tentative spin and parity assignment of 3^+. It should be noted that because of the large density of levels in most of the region of interest it would be worthwhile to repeat and expand upon this work, using higher-resolution equipment.

ACKNOWLEDGMENTS

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[12] J. B. French and M. H. MacFarlane, Phys. Letters **2**, 255 (1962).