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Spin-parity determinations from the $^{48}Ca(\vec{d},\alpha)^{46}K$ reaction near 0°

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The tensor analyzing powers T_{20} have been measured for a number of excited states of ^{46}K following the $^{48}Ca(\vec{d},\alpha)^{46}K$ reaction, leading to the following spin-parity determinations: g.s., 2^-; 0.587 MeV, 3^-; 0.691 MeV, 4^-; 0.886 MeV, N; 1.370 MeV, 3^-; 1.738 MeV, $4^-(0^-)$; and 1.941 MeV, U (where N denotes natural and U, unnatural parity).

[NUCLEAR REACTIONS ^{48}Ca (polarized d, α), $E_d = 7.5$, 8.0, 8.5, and 9.0 MeV; measured tensor analyzing power $T_{20}(\theta_\alpha = 4°)$; ^{46}K levels deduced J^π. Enriched target.]

I. INTRODUCTION

The structure of ^{46}K is interesting from the viewpoint of the shell model since in the most elementary analysis ^{46}K is a proton hole and a neutron hole away from the doubly magic nucleus ^{48}Ca. Unfortunately, due to the lack of appropriate neutron-rich targets (other than ^{48}Ca), ^{46}K is a difficult nucleus to study. Thus, previous investigations of the spins and parities of the levels of ^{46}K consisted mainly of angular distribution measurements following the $^{48}Ca(d,\alpha)$ and $^{48}Ca(p,{}^3He)$ reactions, including a comparison with $T=4$ analog states in ^{46}Ca studied via $^{48}Ca(p,t)$.[1-3] More recently, the $^{48}Ca(d,\alpha\gamma)^{46}K$ reaction has been studied, yielding γ-ray decay schemes and spin limits to a number of bound states.[4] However, the resulting conclusions concerning low-lying levels in ^{46}K are in many cases contradictory, perhaps reflecting the model-dependent nature of the direct reaction work.

In this experiment, α particles from the $^{48}Ca(\vec{d},\alpha)^{46}K$ reaction initiated by a tensor-polarized deuteron beam were observed near $\theta_\alpha = 0°$. As shown by Kuehner and collaborators,[5] a measurement of the tensor analyzing powers T_{20} near 0° allows model-independent natural $[\pi = (-)^J]$ or unnatural $[\pi = (-)^{J+1}]$ parity assignments to be made to nuclear energy levels. Furthermore, it is possible to identify $J^\pi = 0^-$ levels uniquely. Full details have been given in previous papers[5] and will only be alluded to briefly in this work.

Ideally, one would desire a measurement of T_{20} at precisely 0° because of the extreme simplicity of the expressions for T_{20} at that angle. However, the finite size of the detector, and especially the fact that background from deuterons in the beam overwhelm the α particles, makes this condition very difficult to fulfill. Hence, measurements were carried out at small ($\theta = 4°$) angles. Despite the fact that expressions for T_{20} now become model dependent, it is possible to estimate the effects of a nonzero detection angle on T_{20} for natural parity or 0^- levels. The result is a small (~5%) attenuation in the T_{20} value which is quite similar for both compound nuclear[6] and direct reaction[7] models. Thus, one can still readily deduce parities with the resulting measurements.

II. METHOD

A polarized deuteron beam was obtained from the McMaster University Lamb-shift polarized ion source[8] and FN tandem accelerator. The outgoing α particles following the (d,α) reaction were momentum analyzed with an Enge split-pole magnetic spectrograph and detected with a resistive wire gas proportional counter mounted on the focal plane. Measurements were taken at angles of 4° (lab) and incident deuteron energies of 7.5, 8.0, 8.5, and 9.0 MeV.

Targets of enriched (~97%) ^{48}Ca were vacuum evaporated to a thickness of ~40 $\mu g/cm^2$ onto 10 $\mu g/cm^2$ carbon backings. Targets of ^{40}Ca and WO_3 were also used; the former in order to identify and subtract the peaks resulting from the $^{40}Ca(d,\alpha)^{38}K$ reaction in the ^{48}Ca spectra, and the $^{16}O(\vec{d},\alpha)$ reaction on the latter target allowed the fractional beam polarization to be determined from measurements of T_{20} for known natural parity and 0^- states in ^{14}N. In order to prevent excessive oxidation of the Ca targets, they were brought up directly through a vacuum lock system which was then transferred to and fitted over the target chamber. Once the chamber was evacuated, the targets were lowered into it. Thus, they were never allowed to come into contact with air.

For each incident beam energy, alternate runs were carried out for deuterons polarized predominantly in the $m=0$ and $m=1$ substates, respectively, where the quantization axis is taken to be along the beam direction. This process was carried out for each of the three targets in turn, and the entire cycle was repeated until sufficient events had been accumulated for the ^{46}K peaks of interest. The beam intensities available were ~20 nA, and the fractional beam polarization as determined both by the quench ratio method[9] and the $^{16}O(\vec{d},\alpha)^{14}N$ reaction was $P \sim 0.75 \pm 0.05$.

III. RESULTS

α-particle spectra at $\theta = 4°$ from polarized deuteron bombardment of ^{48}Ca at $E_d = 7.5$ MeV for deuteron substates $m=0$ and $m=1$ are shown in Fig. 1. The excitation energies of peaks corresponding to ^{46}K levels, obtained from Nuclear Data Sheets,[10] are also given. Levels above 2 MeV excitation were very weakly populated and often appeared to be multiplets; since T_{20} measurements of these would be highly unreliable, they are not shown. No new states in ^{46}K below 2 MeV were discovered. The typical resolution of 25 keV full width at half maximum (FWHM) was adequate to resolve all peaks of interest.

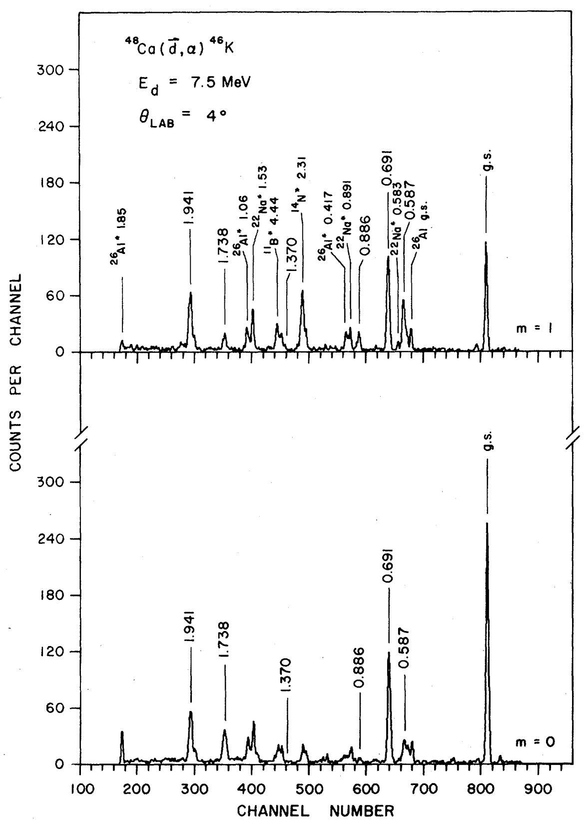

FIG. 1. Energy spectra of α particles from the $^{48}Ca(\vec{d},\alpha)^{46}K$ reaction for substates $m=0$ and $m=1$ at $E_d = 7.5$ MeV. Contaminant peaks shown in the $m=1$ spectrum arise from (d,α) reactions on ^{28}Si, ^{24}Mg, ^{16}O, and ^{12}C and are labeled according to final nucleus and level excitation energy.

A difficulty encountered in the data analysis was interference of impurity peaks arising from the $^{40}Ca(d,\alpha)^{38}K$ reaction. The Q value for this reaction is 4.6 MeV and hence the 3–5 MeV excitation range of ^{38}K is superimposed on the low-lying ^{46}K spectrum. The density of final states at this excitation energy is quite high and therefore a number of peaks of interest are partially obscured. Since these impurity peaks are as intense as the ^{46}K peaks (despite the fact that the target was highly enriched in ^{48}Ca) the cross section for the $^{40}Ca(d,\alpha)$ reaction is at least an order of magnitude larger than for the $^{48}Ca(d,\alpha)$ reaction. This difference can probably be accounted for using a CN fusion-evaporation model for the reaction[11] and results primarily from the different Q values for the competing neutron decay channels in the two cases.

To correct for these impurity peaks, a ^{38}K spectrum using the ^{40}Ca target was taken during each cycle for each of the $m=0$ and $m=1$ deuteron substates, as mentioned in Sec. II. The spectra from the ^{40}Ca and ^{48}Ca targets were normalized using intensities of known peaks corresponding to ^{38}K levels and then subtracted to form a corrected ^{46}K spectrum. An example of this procedure is shown in Fig. 2. The corrected $m=0$ and $m=1$ ^{46}K spectra at a given beam energy were then normalized to the total integrated charge measured in a Faraday cup.

The tensor analyzing powers T_{20} for each level in ^{46}K were calculated from the corrected $m=0$ and $m=1$ peak intensities according to the formulas given in Ref. 5 and are presented in Fig. 3. For each state in ^{46}K, the values of T_{20} at beam energies of 7.5, 8.0, 8.5, and 9.0 MeV are presented from left to right. The error bars shown for each point reflect uncertainties in the fractional beam polarization, statistical uncertainties in the peak intensities, and the estimated uncertainty in normalization to the ^{38}K impurity spectra.

The results of the measurements for each level in ^{46}K are summarized in Table I, and each state is discussed in turn below.

The ground state. The experiment demands unnatural parity for this level, and this is consistent with the 2^- assignment.[3,10] Such a spin and parity is also predicted by the Nordheim "strong rule" for a $\pi d_{3/2}^{-1} \nu f_{7/2}^{-1}$ configuration.

0.587 MeV level. A $J^\pi = 4^-$ assignment to this state was made by Paul *et al.*[2] on the basis of a

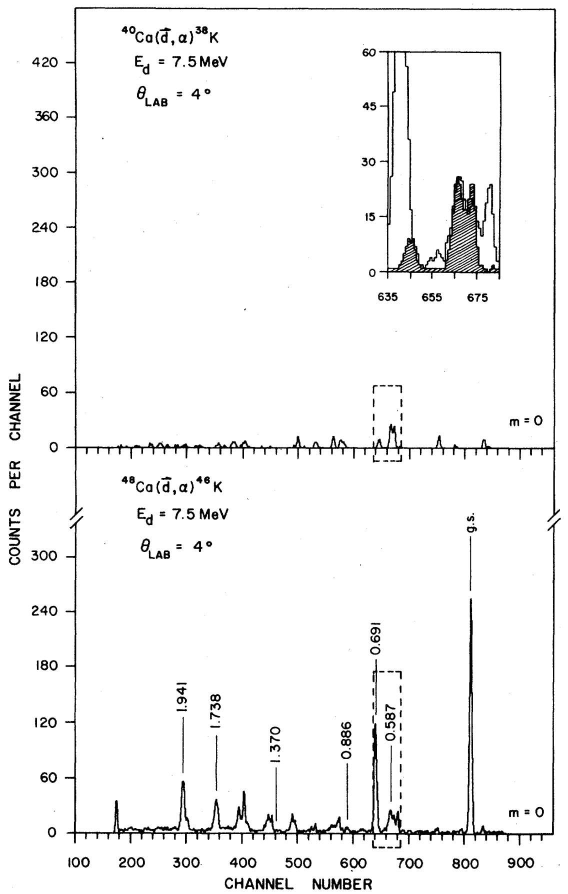

FIG. 2. A normalized ^{38}K spectrum is compared with an uncorrected ^{46}K spectrum for 7.5 MeV deuterons and $m=1$. The insert gives an expanded view of the two dotted regions, superimposed; the ^{38}K spectrum is shown shaded for greater clarity.

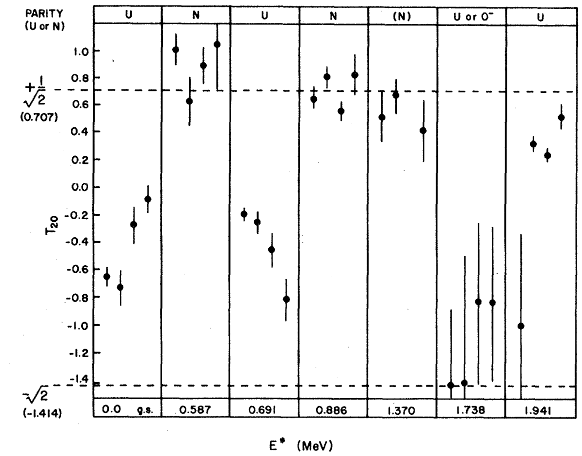

FIG. 3. Tensor analyzing powers, T_{20}. For each state of interest in ^{46}K, T_{20} is presented (left to right) for beam energies of 7.5, 8.0, 8.5, and 9.0 MeV, respectively. The limits for natural parity ($T_{20}=1/\sqrt{2}$) and $J^{\pi}=0^-$ ($T_{20}=-\sqrt{2}$) are indicated by the dashed lines. Note that some attenuation (~5%) of these values would be expected as a result of the nonzero detection angle. The parities (N or U, denoting natural or unnatural parity, respectively) deduced are given at the top of the figure. There is no 8.5 MeV measurement for the 1.370 MeV level.

comparison of L values from the ^{48}Ca(d,α) and ^{48}Ca($p,{}^3$He) reactions. However, it has been suggested[3] that at the beam energy used (11 MeV), CN contributions to the cross sections were significant and may have been different for the two reactions, thereby invalidating these results. Indeed all other experiments[3,4] suggest $J^{\pi}=3^-$ for this state, consistent with the natural parity assignment of the present work. This level had a small cross section in the (d,α) reaction and suffered considerable interference from a ^{38}K contaminant peak, reflected in the rather large error bars in Fig. 3.

0.691 MeV level. The $J^{\pi}=5^-$ assignment to this state by Paul *et al.*[2] is inconsistent with the present work, which demands unnatural parity. In fact, other measurements, notably the γ-ray

TABLE I. Spin-parity assignments to levels in ^{46}K.

E^* (MeV)	J^{π} a	b	c	d	$\langle T_{20}\rangle$ at 4°	Parity	J^{π} (adopted)
0.0[e]	(2⁻)	(2⁻)	(2⁻)	2⁻	−0.44	U	2⁻
0.587	(4⁻)	3⁻	3⁻	3⁻	+0.89±0.11	N	3⁻
0.691	(5⁻)	(4⁻)	(4⁻)	4⁻	−0.43	U	4⁻
0.886	(3⁻)	5⁻	5⁻	5⁻	+0.71±0.05	N	5⁻
1.370		(3⁻, 4⁻)	3⁻	3⁻	+0.54±0.12	(N)	(3⁻)
1.738				4⁻	−1.12	U or 0⁻	0⁻, 4⁻
1.941			1⁺	1⁺	+0.03	U	1⁺

[a] Reference 2.
[b] Reference 1.
[c] Reference 3.
[d] Reference 4.
[e] Excitation energies from Ref. 9.

decay scheme,[4] strongly suggest $J^\pi = 4^-$ for this level, in agreement with our conclusions.

0.886 MeV level. The natural parity assignment of this experiment cannot distinguish between the 3^{-2} and 5^{-3} assignments made to this level. The $J^\pi = 5^-$ assignment, however, appears to be favored by other measurements.[4]

1.370 MeV level. Dupont *et al.*[1] were unable to distinguish between 3^- and 4^- possible spin-parity assignments for this state while Daehnick *et al.*[3,4] suggest a 3^- assignment by comparing angular distributions from the $(p, {}^3He)$ and (d, α) reactions. Our results (see Fig. 3) suggest natural parity (and hence 3^-), but due to the large uncertainties this assignment remains tentative.

1.738 MeV level. This level has been assigned[4] $J^\pi = 4^-$ on the basis of (d, α) angular distributions and shell-model arguments. The present experiment also implies unnatural parity but a $J^\pi = 0^-$ assignment is possible as well. A 0^- state in ^{46}K could be formed by excitation of a $f_{7/2}$ shell neutron to the $p_{3/2}$ shell; the resulting $\pi d_{3/2} \nu p_{3/2}$ configuration can then couple to spins 0^-, 1^-, 2^-, and 3^-. The centroid of such a configuration is predicted to lie near 2 MeV excitation since this is the excitation energy of the $p_{3/2}$ state in ^{47}Ca. Such configurations have not been considered by earlier workers and their identification in ^{46}K would be of considerable interest. However, γ-ray data[4] appear to rule out a 0^- assignment to this level since a fast transition has been observed to the 0.587 $(J^\pi = 3^-)$ MeV level. It is unlikely that the $M3$ transition required for $J^\pi = 0^-$ could compete with γ-ray decay to lower spin states in ^{46}K. Thus, the 0^- assignment can probably be ruled out and one must look elsewhere for the $d_{3/2} p_{3/2}$ states.

1.941 MeV level. This level has been assigned $J^\pi = 4^-$ by Dupont *et al.*, and $J^\pi = 3^-$ and 1^+ in two separate experiments by Daehnick *et al.*[4,12] The 3^- assignment[12] can be ruled out by the unnatural parity required by the present experiment. The most recent experiment[4] yields $L = 0 + 2$ in the (d, α) reaction; this, together with the fact that the γ-ray decay of this level proceeds exclusively to the 2^- ground state,[4] strongly supports the $J^\pi = 1^+$ assignment. The positive parity assignment suggests that this is a hole state based on a neutron excitation from the $d_{3/2}$ to the $f_{7/2}$ shell. Such a state should indeed lie at low excitation because of the favorable $\nu f_{7/2}^8$ configuration which results, despite the ~7 MeV energy gap between the $d_{3/2}$ and $f_{7/2}$ shell-model orbitals.

IV. DISCUSSION

It is known that the separation between the $d_{3/2}$ and $s_{1/2}$ proton single particle states steadily decreases with increasing atomic number for the potassium isotopes; indeed, the order of these states is reversed in ^{47}K. As pointed out by Sartoris and Zamick,[13] this effect can be understood as arising from the much stronger interaction of a $d_{3/2}$ particle with the eight $f_{7/2}$ neutrons than that of a $s_{1/2}$ particle. In ^{47}K, the $s_{1/2}$-$d_{3/2}$ splitting is only about 360 keV. The proximity of these two states leads to the possibility of large configuration mixing in the ^{46}K states, especially between the pairs of 3^- and 4^- levels arising from the $\pi d_{3/2}^{-1} \nu f_{7/2}^{-1}$ and $\pi s_{1/2}^{-1} \nu f_{7/2}^{-1}$ configurations.

To demonstrate the importance of this mixing, we compare in Fig. 4 the ^{46}K spectrum as deduced in this work with the conjugate ^{38}Cl level scheme, described by the $\pi d_{3/2} \nu f_{7/2}$ configuration. One observes that it is precisely the 3^- and 4^- levels of ^{46}K which appear to be displaced, since the 2^- $\rightarrow 5^-$ spacing is nearly the same in both nuclei.

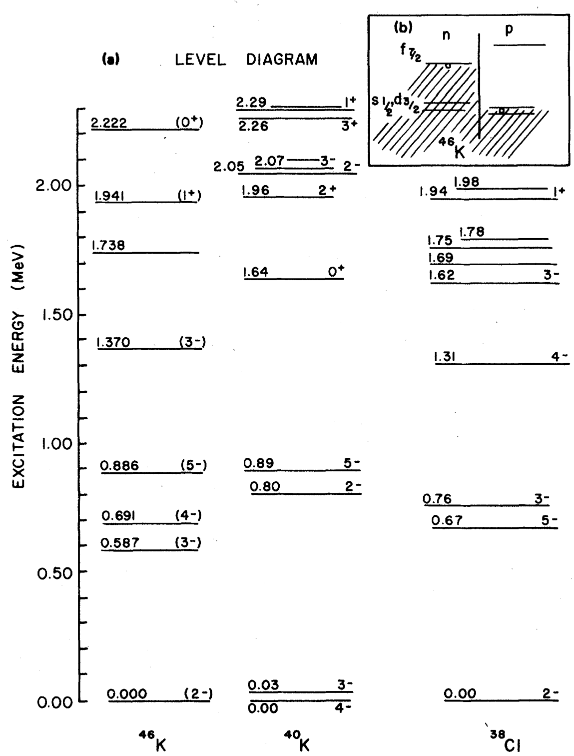

FIG. 4. (a) Energy level diagrams of ^{46}K, ^{40}K, and ^{38}Cl. The lowest ^{38}Cl states may be described as pure $\pi d_{3/2} \nu f_{7/2}$ configurations. The importance of configuration mixing in ^{46}K is illustrated by the fact that the spacing of the 2^- and 5^- levels in ^{38}Cl corresponds rather well to the spacing of the $(\pi d_{3/2}^{-1} \nu f_{7/2}^{-1})$ 2^- and 5^- levels in ^{46}K, while the 3^-, 4^- pair do not. This is attributed to the importance of $s_{1/2}^{-1} f_{7/2}^{-1}$ configurations in ^{46}K. The conjugate ^{40}K spectrum $\pi d_{3/2}^{-1} \nu f_{7/2}$ may be obtained from the ^{38}Cl levels by means of the Pandya particle-hole transformation, but not from ^{46}K. (b) Lowest shell-model configurations for ^{46}K.

Daehnick and Sherr[3] have given an extensive discussion of the low-lying ^{46}K spectrum based on the simplest shell-model configurations which need not be repeated here. Suffice it to emphasize, however, that such shell-model calculations have not considered the $p_{3/2}$ neutron excitations which could well be important in the structure of certain low-lying states.

V. CONCLUSIONS

The present T_{20} measurements have led to model-independent spin-parity assignments to low-lying levels of ^{46}K which, by confirming the most recent measurements of Daehnick *et al.*[4], have removed a good deal of uncertainty resulting from previous conflicting J^{π} assignments.

It would be interesting to extend the measurements to higher states, in particular to search for the negative parity multiplets resulting from the $\nu p_{3/2}$ configuration, including a 0^- state which has a particular signature ($T_{20} = -\sqrt{2}$) in the ($\vec{d}$, α) reaction.

ACKNOWLEDGMENTS

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