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Selective population of maximum-J states in the (d, α) reaction at 80 MeV

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The (d, α) reactions on ^{40,44,48}Ca and ^{58}Ni have been studied using the 80 MeV incident deuteron beam of the Orsay synchrocyclotron. It was found that satisfactory distorted wave Born approximation fits can be obtained. The experimental angular distributions were structured and thus provide minimal ambiguity in the determination of the angular momentum transfer. The angular momentum matching conditions greatly favored large values for the angular momentum transfer. Together with the selectivity of the (d, α) reactions, it allowed the identification of 7^+ states in ^{38,42,46}K and ^{56}Co. The observation of 7^+ levels in ^{38,42,46}K gives a measure of the $f_{7/2}$ proton occupation number in the ground state of the target nuclei ^{40,44,48}Ca. An apparent enhancement of certain of the 3^+ states at high excitation energy was observed in ^{46}K and ^{56}Co and the relative 3^+, 7^+ separation was in qualitative agreement with a simple shell-model picture.

[NUCLEAR REACTIONS ^{40,44,48}Ca(d, α) and ^{58}Ni(d, α), $E = 80.2$ MeV; measured $\sigma(\theta)$; enriched targets, microscopic DWBA analysis, deduced J, π, S.]

I. INTRODUCTION

The (d, α) reaction has been studied extensively in the last few years at low incident energy (<30 MeV). It was shown that this reaction and the inverse (α, d) reaction are highly selective, the proton and neutron picked up from the same shell being preferentially coupled to maximum J. We have investigated (d, α) reactions on ^{40,44,48}Ca and ^{58}Ni targets. An 80 MeV deuteron beam was used in spite of its mediocre energy resolution, for the following reasons:

(i) At this incident energy, the requirement of good angular momentum matching corresponds to an angular momentum of about $6\hbar$ for the transferred pair. This condition favors large angular momentum transfer and should selectively populate the very few high J states. Thus the selectivity of the reaction should be more stringent than at lower energy.

(ii) Higher excitation energy can be reached at larger incident energy.

(iii) Most of the ^{46}K and ^{56}Co levels are not known since it is impossible to produce these residual nuclei through one-nucleon transfer reactions. The low-lying levels of ^{46}K have been investigated with the (d, α) reaction[1-3] at low energy, and some additional information is available from the comparison of the $(p, {}^3\mathrm{He})$ and (p, t) reactions[4,5] on ^{48}Ca. The ^{56}Co low-lying levels have been investigated by $({}^3\mathrm{He}, p)$, $({}^3\mathrm{He}, t)$, and $(p, {}^3\mathrm{He})$ reactions[6-10] and (d, α) reactions[6,7,11,12] at low energy.

II. EXPERIMENTAL METHOD

The (d, α) reactions were induced by the 80.2 MeV deuteron beam from the Orsay synchrocyclotron. An achromatic system improves the experimental energy resolution over the mediocre energy resolution of the extracted beam (1 MeV). It consists essentially[13] of a narrow slit at the first focal point along the beam transport line and of two magnetic spectrometers with matched dispersions. The first one smears the incident beam across the target while the second one analyzes the emitted reaction products. As a result the targets must be large (2.5 cm horizontal dimension) and the focal plane of the second magnet must be equipped with a position-sensitive detector which in the present case is an 80 cm long spark chamber. The resulting energy resolution varied from 160 to 200 keV depending on the beam intensity which varied from 15 to 30 nA. The thickness of the various targets was approximately 1 mg/cm^2.

A few improvements were made to the previously reported[13] method of particle identification and enenergy measurement. For instance, particle identification was considerably improved by using two plastic scintillators (30 cm length, 0.5 and 2 mm thick) perpendicular to the particle path. Coincidences between these two counters were requested before triggering the spark chamber.

Energy calibration was provided mainly by ^{12}C and ^{16}O impurities in the target. The resulting uncertainty on excitation energies varied from 30 to 60 keV. The uncertainty on absolute cross sections is 30%.

III. THEORY

A. General

In the following analysis we assume that the (d, α) reaction proceeds through the direct pickup of two

TABLE I. Deuteron optical-model parameters used in DWUCK.

	Notation	V_R (MeV)	R_R (fm)	a_R (fm)	W (MeV)	R_I (fm)	a_I (fm)	Ref.
^{40}Ca	d_1	84.6	1.05	0.85	10.75	1.27	0.92	17
	d_2	67.8	1.25	0.71	13.04	1.15	0.94	17
^{58}Ni	d_3	79.3	1.05	0.81	9.03	1.27	0.96	29
	d_4	65.5	1.25	0.69	13.26	1.04	0.98	29

nucleons. The reaction can be described within the microscopic theory of Glendenning.[14]

In the zero range approximation DWBA (distorted wave Born approximation) formalism cross section for a (d, α) reaction for a given ΔT and a set of $NLSJ$ quantum numbers of the transferred pair[14] is

$$\frac{d\sigma}{d\Omega} \sim \sum_{LJM} \left| \sum_{N} G_{NLJ} B_{NL}^{M} \right|^2 ,$$

where the transition amplitude is factorized into a factor G_{NLJ} that depends upon details of the nuclear structure and a kinematic factor B_{NL}^{M} which contains the radial wave function $u_{NL}(R)$ of the center of mass of the transferred pair. The factor G_{NLJ} involves a coherent sum over two-particle configurations and implies that, in general, the structure factors cannot be directly deduced from the experimental data. Only when the quantum numbers of the two transferred nucleons are uniquely determined can G_{NLJ} be factored out. This might occur for configurations such as $[(1f_{7/2})^p(1f_{7/2})^n]_{7^+}$ or $[(1d_{3/2})^p(1d_{3/2})^n]_{3^+}$. The computation of the structure factor is then considerably simplified. The analysis was made using the code DWUCK[15] and for single configurations the structure factors tabulated by Glendenning.[16]

B. Selection rules

For a (d, α) reaction, we have the selection rules

$$\vec{J} = \vec{J}_f - \vec{J}_i, \quad \vec{J} = \vec{j}_n + \vec{j}_p,$$
$$\vec{J} = \vec{L} + \vec{S}, \quad \vec{L} = \vec{l}_n + \vec{l}_p,$$
$$\vec{T} = \vec{T}_f - \vec{T}_i = 0,$$

where $LSJT$ are the transferred pair quantum numbers.[14] Since two nucleons in both the deuteron and α particles are dominantly in a state of relative angular momentum zero we have the additional rules:

$$S + T = 1, \quad S = 1,$$
$$\pi_i \pi_f = (-1)^L = (-1)^{l_n + l_p}.$$

For a zero spin target, the selection rules can be summarized as follows:

(i) When the two nucleons are transferred from different shells:

$$J = L, \quad S = 1, \quad T = 0 \quad \text{if } J \text{ is even},$$
$$J = L \pm 1, \quad S = 1, \quad T = 0 \quad \text{if } J \text{ is odd}.$$

(ii) If the transferred nucleons have the same (nlj) quantum numbers, $J + T$ must be odd and a $(j)_{J=\text{even}}{}^2$ pickup is forbidden.

IV. OPTICAL-MODEL POTENTIALS

Optical potential parameters are listed in Table I. Those corresponding to the incoming channel are taken from Ref. 17. The spin-orbit interaction in the entrance channel was neglected since it does not affect the (d, α) angular distributions very much. Very few optical parameters for 80 MeV α particles are available in the literature at the present time. While the shapes of the angular distributions are not very sensitive to the incoming channel optical parameters, such is not the case for the outgoing channel. It is a well-documented[18] guideline that good DWBA results are obtained with parameters corresponding to the deep wells for which V is close to nV_0 (where V_0 is the proton scattering potential depth and n the number of nucleons in the projectile). This restriction upon the parameters appears necessary for the reliability of the DWBA analysis and minimizes the finite range correction.[18] We have chosen sets of parameters of this type corresponding to α particles near 80 MeV which were checked by reproducing the angular distribution of states of known spin and parity. The best results were obtained for Ca and Ni with Sets d_1 and d_3, respectively (see Table I), and Set α_2 (see Table II). Only the α imaginary well depth W is different between Sets α_2 and α_4; with the last one the calculation poorly reproduces the angular distributions of known ^{56}Co states. Thus a deep α imaginary well seems to be a supplementary condition at our energy. The main effect of this choice of optical parameters is to reduce the contribution from the interior of the nucleus.

The shapes of the angular distributions characterize the transferred angular momentum L without ambiguity. For a given L value, the detailed

TABLE II. α optical-model parameters used in DWUCK.

	Energy (MeV)	Notation	V (MeV)	R_R (fm)	a_R (fm)	r_c	W (MeV)	R_I (fm)	a_I (fm)	Ref.
$^{40}Ca(\alpha, \alpha)$	104	α_1	219.3	1.21	0.713	1.3	98.77	1.40	0.544	30
$^{40}Ca(\alpha, \alpha)$	86	α_2	200	1.15	0.78	1.4	74	1.7	0.44	31
$^{58}Ni(\alpha, \alpha)$	50	α_3	132.9	1.505	0.518	1.4	20.8	1.67	0.25	32
$^{58}Ni(\alpha, \alpha)$	86	α_4	204	1.15	0.78	1.4	16	1.7	0.44	31
$^{58}Ni(\alpha, \alpha)$	75	α_5	126.9	1.26	0.78	1.4	19.53	1.61	0.537	33
$^{58}Ni(\alpha, \alpha)$	75	α_6	181.1	1.24	0.725	1.3	22.94	1.56	0.592	33

shape of the angular distribution depends on the major shell from which the two nucleons are picked up. The theoretical $L=4$ curves calculated for $d_{3/2}{}^2$ and $f_{7/2}{}^2$ configurations (Fig. 1) demonstrate this effect.

V. SELECTIVITY OF THE (d,α) REACTION AT 80 MeV

A. J selectivity

It is well known that in (α, d)[19,20] and (d, α)[12,21,22] reactions the largest cross sections occur when the proton and neutron are picked up from the same shell and are coupled to maximum J. This effect appears in Fig. 2 where two very predominant peaks are observed. The first peak at 2.28 MeV is the well-known 7^+ state and corresponds to the $(1f_{7/2})^{-2}(2p_{3/2})^2$ configuration in ^{56}Co.

The enhancement of those levels has several origins:

(i) The structure factor G_N is largest for these states. For example, G_N favors $J^\pi=7^+$ over $J^\pi=5^+$ by an order of magnitude in the case of the $L=6$ pickup of two $f_{7/2}$ nucleons.[16]

(ii) When the particles are picked up from the same closed shell, explicit spin effects are unimportant and one has the approximate proportionality $\sigma \sim (2J+1)$. This favors the pickup of high J states.

(iii) At 80 MeV deuteron beam energy angular momentum matching requires that the transferred pair carries an angular momentum of about $6\hbar$. Large values of L transfer imply large values of the spin J of the residual nuclear states for zero spin states.

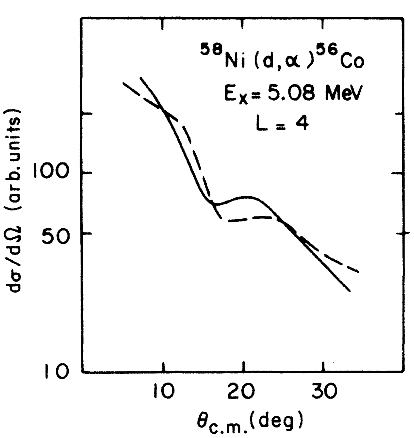

FIG. 1. DWBA calculations for a $L=4$ transfer from $(d_{3/2})^{-2}$ (dashed line) and $(f_{7/2})^{-2}$ (solid line) configurations.

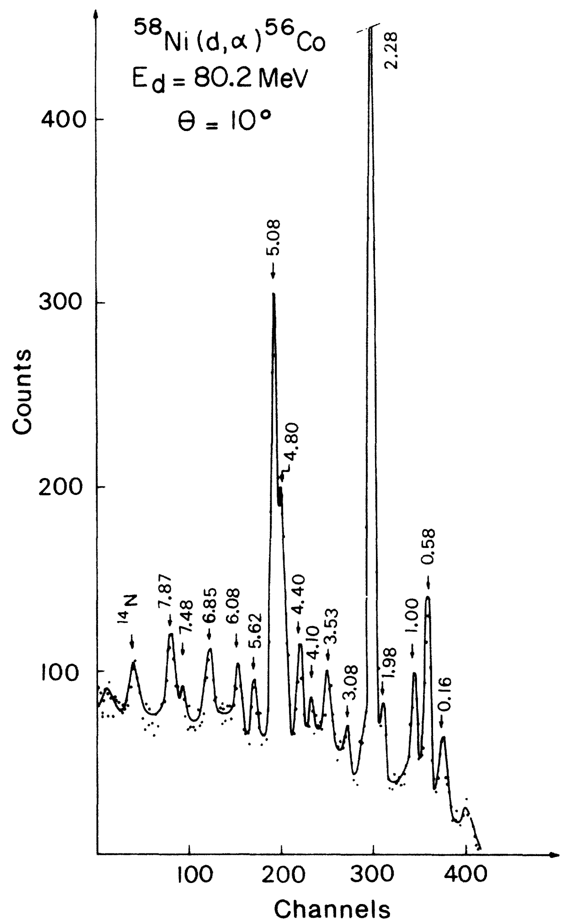

FIG. 2. Energy spectra of α particles from the $^{58}Ni+d$ reaction at 80.2 MeV.

B. L transfer selectivity

We notice (Fig. 3) that when there are two allowed values for the transferred angular momentum L, the contribution of the higher L value to the transition appears to be the most important one. In our case at 80 MeV, the higher angular momentum value is favored by the angular momentum matching condition. For example in the ^{38}K (3^+) ground state the $L=4$ transfer is dominant. The same situation occurs for ^{38}K 1.7 MeV (1^+) and ^{42}K (2^-) ground states for which the best fits are obtained with $L=2$ and $L=3$ transfers, respectively. For the ^{42}K (2^-) ground state which has a dominant $(\pi 1d_{3/2})^{-1}(\nu 1f_{7/2})^3$ configuration, the structure factor[16] calculation predicts that the $L=1$ transition should dominate in contrast to the experimental result. Therefore the dominance of the $L=J+1$ rule observed at high incident energy must be due to the dynamics of the reaction (the requirement of large L transfer to conserve good momentum matching). By contrast, at lower energy the $L=J-1$ transfer tends to dominate.[21,22]

VI. EXPERIMENTAL RESULTS AND DISCUSSION

Typical energy spectra of α particles appear in Figs. 2 and 4. Differential cross sections were measured between 7 and 33°. The angular distributions are shown in Figs. 5 and 6. The assigned error bars are the standard errors due to counting statistics and background subtraction.

The analysis will concentrate only on those states which are strongly populated in ^{38,42,46}K and ^{56}Co and are dominated by $L=4$ or $L=6$ transfers. To populate ^{38,42,46}K states by $L=6$ transfer would be impossible if the (sd) proton shell of the Ca isotopes were closed. The strong excitation of these states provides evidence for the occurrence of $f_{7/2}$ proton configurations. Furthermore the observation of levels at high excitation energy may allow

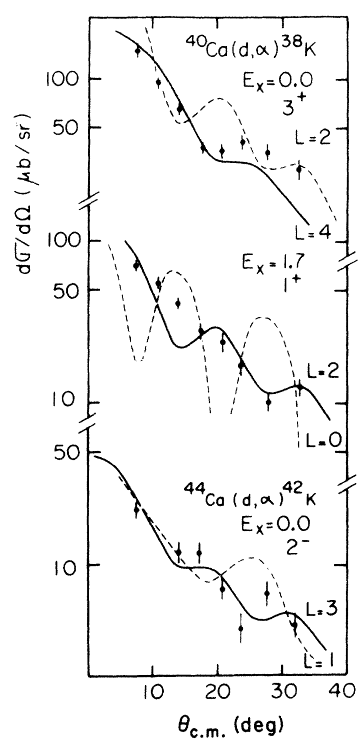

FIG. 3. Comparison of experimental angular distributions for known spin levels and DWBA calculations for the two L values allowed $L=J+1$.

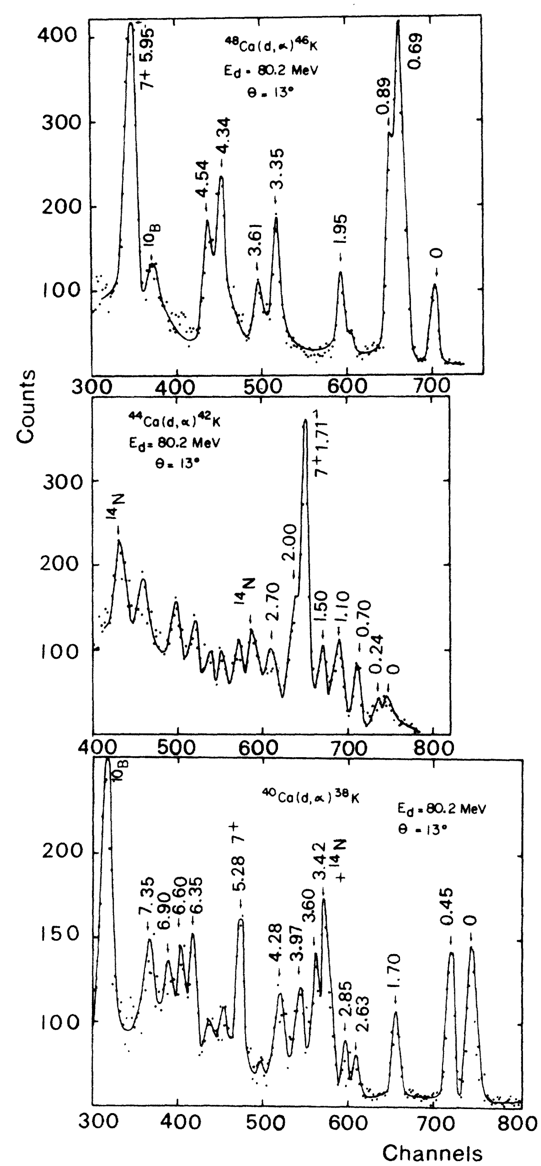

FIG. 4. Energy spectra of α particles from ^{40,44,48}Ca + d reactions at 80.2 MeV.

the location of "deeper" configurations such as $(d_{3/2})^{-2}$ which provides information on the location of the $d_{3/2}$ shell in ^{46}K and ^{56}Co.

A. Observation of 7^+ states in ^{38,42,46}K and proton configuration mixing in ^{40,44,48}Ca

Three particular states at 5.28 MeV in ^{38}K, 1.91 MeV in ^{42}K, and 5.95 MeV in ^{46}K strongly populated in this reaction (Fig. 4) have very similar angular distributions (Fig. 5). The DWBA calculated angular distributions with $L=4$, 5, 6, and 7 angular momentum transfer have been compared (Fig. 5) and the diffraction pattern is seen to be shifted by about 4° when L changes by one unit. Only the $L=6$ calculation correctly fits the experimental angular distribution for these levels. The corresponding states of the residual nuclei must have either $J^\pi=7^+$ or 5^+ since the $T=0$ coupling of two nucleons from the same shell can only result in odd-J positive-parity states. The only state with a large $L=6$ contribution is $J^\pi=7^+$ because of the structure factor discussed above. The $J^\pi=7^+$ assignment is also consistent with the systematic observation[19,20] that the most strongly populated high-spin states in the time-reversed (α, d) reaction do have $J=L+1$. Furthermore, the 1.91 MeV state of ^{42}K is already known to be a 7^+ state.[20] Hence, the three states at 5.28 MeV in ^{38}K, 1.91 MeV in ^{42}K, and 5.95 MeV in ^{46}K are assigned $J^\pi=7^+$.

The cross section for the observed 7^+ states gives a measure of the proton and neutron occupation numbers in the $f_{7/2}$ shell. The experimental cross section, once corrected for kinematical dependence by means of a DWBA calculation, is proportional to the product of the $f_{7/2}$ proton and neu-

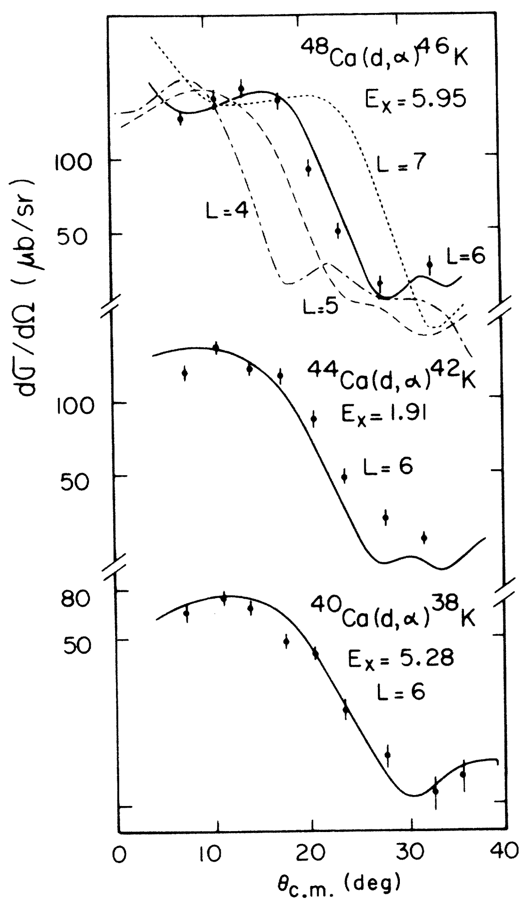

FIG. 5. Comparison of experimental angular distributions for the 7^+ levels and DWBA calculations for $L=6$ (solid line) and $L=4$, 5, 7 (dashed lines) transfers.

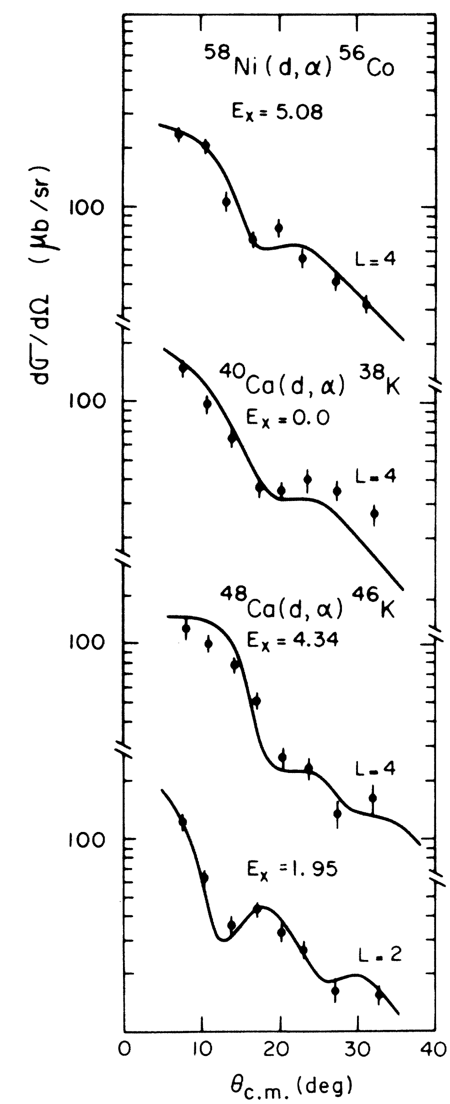

FIG. 6. Comparison of experimental angular distributions for the levels studied (see text) and DWBA calculations.

tron spectroscopic factors:

$$\left(\frac{d\sigma}{d\Omega}\right)_{7^+}(\exp)\bigg/\left(\frac{d\sigma}{d\Omega}\right)_{7^+}(\mathrm{DWBA})\sim C^2S_n(f_{7/2})C^2S_p(f_{7/2})\,. \tag{1}$$

The spectroscopic factors already known from the analysis of one-particle transfer reactions on calcium isotopes appear in Table III. In that table, the product of the known spectroscopic factors is compared to a normalized value of the cross section for the 7^+ states. The excellent agreement obtained for ^{44}Ca supports the validity of relation (1). The unknown value of $C^2S_p(f_{7/2})$ for ^{48}Ca can then be extracted yielding $C^2S_p(f_{7/2})=0.068$. The occupation numbers S_p are 0.46, 0.48, and 0.61 for ^{40}Ca, ^{44}Ca, and ^{48}Ca, respectively. Although this method of measuring C^2S_p is indirect and approximate, it is worth noting that it indicates a rather constant proton $f_{7/2}$ strength for the three Ca isotopes under study.

B. States excited by predominant $(d_{3/2})^{-2}$ transfer in ^{46}K and ^{56}Co

1. ^{46}K

Two positive-parity states have been observed at 1.95 and 4.34 MeV in ^{46}K where the low-lying states have $(\pi 1d_{3/2}{}^{-1}\nu 1f_{7/2}{}^{-1})$ and $(\pi 1s_{1/2}{}^{-1}\nu 1f_{7/2}{}^{-1})$ configurations and thus negative parity.[4,24] The 4.34 MeV angular distribution is well reproduced by an $L=4$ transfer (Fig. 6). An $L=4$ transition is likely to result from $[\pi 1d_{3/2}{}^{-1},\nu 1f_{7/2}{}^{8}1d_{3/2}{}^{-1}]_{3^+}$ or $[\pi 1d_{3/2}{}^{-2}1f_{7/2},\nu 1f_{7/2}{}^{7}]_{3^+}$ configurations of ^{46}K. The latter term is expected to be very small since the proton occupation number in the $f_{7/2}$ shell is small. Furthermore, the best DWBA fit is obtained by a pure $L=4$ calculation as expected from the first configuration. Therefore with the assumption that there is little configuration mixing in ^{46}K since most strongly excited states in a (d,α) reaction result from the pickup of a nucleon pair coupled to maximum J, the 4.34 MeV level is suggested to have $J^\pi=3^+$.

The 1.95 MeV angular distribution is well reproduced by an $L=2$ calculation (Fig. 6). This is in good agreement with the result obtained by Daehnick and Sherr[4] who suggested a 1^+ assignment and a $(sd)^{-2}+(ss)^{-2}$ configuration mixture for this state. As discussed above the $[\pi 1d_{3/2}{}^{-2}1f_{7/2}{}^{1}\nu 1f_{7/2}{}^{7}]$ configuration is unlikely. The dominant configurations are probably $(\pi 1d_{3/2}{}^{-1},\nu 1f_{7/2}{}^{8}1d_{3/2}{}^{-1})$ and $(\pi 1s_{1/2}{}^{-1},\nu 1f_{7/2}{}^{8}1d_{3/2}{}^{-1})$.

TABLE III. Comparison of the experimental 7^+ cross section to the product of the neutron and proton strengths.

	C^2S_n [a]	C^2S_p	$C^2S_n\times C^2S_p$	Experimental cross section for 7^+ states [b]
^{40}Ca	0.42 [c]	0.46 [d]	0.19	0.19
^{44}Ca	3.5 [e]	0.096 [f]	0.34	0.36
^{48}Ca	7 [g]	(0.068) [h]		0.48

[a] Arithmetic average of experimental values from the listed references.
[b] Normalized to $C^2S_n\times C^2S_p$ for ^{40}Ca.
[c] References 34–37.
[d] Reference 37.
[e] References 34, 38, and 39.
[f] Reference 42.
[g] References 34 and 39–41.
[h] Deduced from this work as explained in the text.

2. ^{56}Co

The low-lying ^{56}Co levels are expected to be a mixture of one-particle–one-hole and two-particle–two-hole states. Fifty states of this type up to 5 MeV excitation have been calculated by McGrory[23] and qualitative agreement with the experiment has been found.[24,12] The most strongly populated state in the low energy spectrum at 2.28 MeV (7^+) corresponds to a $(1f_{7/2}{}^{-2}2p_{3/2}{}^{2})$ configuration. Its relative strength and energy compare well[24] with McGrory's calculation.

The 5.08 MeV level is also very strongly populated in this reaction.[12] The strength of this level (Fig. 2) and the good fit (Fig. 6) obtained between the experimental and the DWBA $L=4$ angular distributions suggest that it might result from the pickup of a $d_{3/2}{}^2$ nucleon pair leading to a state with $J^\pi=3^+$ and a dominant $(1d_{3/2}{}^{-2}2p_{3/2}{}^{2})$ configuration.

C. Comment on energy separation between 7^+ and 3^+ levels

The energy difference between the 3^+ and 7^+ states in ^{38}K, ^{46}K, and ^{56}Co can be estimated as $\Delta E=\epsilon_p+\epsilon_n+M_1-M_2$, where ϵ_p and ϵ_n are the proton and neutron single-particle energy differences between the $1f_{7/2}$ and $1d_{3/2}$ shells, respectively. M_1 and M_2 are the residual interaction matrix elements between two $f_{7/2}$ holes coupled to $(7^+,0)$ and two $d_{3/2}$ holes coupled to $(3^+,0)$, respectively. This calculation was performed[10] for the 3^+ level in ^{56}Co. The values $\epsilon_p=\epsilon_n=2.1$ MeV were taken from the work of Gillet *et al.*,[25] M_1 was calculated[10] in ^{38}K as $M_1=-2.4$ MeV, and $M_2=-2.6$ MeV was deduced from an experimental result.[19] In that way the 3^+ state was expected to be at 6.3 MeV. The agreement with our experimental result is reasonable.

The same relation can be applied to the case of ^{38}K and ^{46}K. In ^{38}K, the calculated energy difference between the 3^+ ground state and the 7^+ state is $\Delta E = 4.5$ MeV instead of 5.28 MeV. The 7^+ state must lie at the same excitation energy in ^{38}K as in ^{34}Cl according to the Pandhya theorem[26] and indeed the location of the ^{34}Cl, 7^+ state at 5.23 MeV[27] is in good agreement with the 5.28 MeV value found for ^{38}K. Finally, the calculated energy difference between the 3^+ and 7^+ states in ^{46}K is $\Delta E = 2.9$ MeV instead of 2 MeV.

One should notice that the theoretical calculation of the wave functions of those 7^+ and 3^+ states is impeded by the large size of the configuration space to be included.[28] No result has been reported so far.

VII. CONCLUSION

It is shown that the (d, α) reaction at 80 MeV has a high degree of selectivity for maximum J coupling of the transferred proton and neutron pair and that the range of excitation energies which can be reached in the residual nucleus is large. It was found that satisfactory DWBA fits can be obtained at 80 MeV if the sets of optical parameters follow the empirical rule $V_n \sim n V_{\text{nucleon}}$ (as at lower energy[18]) and are furthermore restricted to deep imaginary wells ($W \sim 80$ MeV) for the outgoing particle; also that shallow potentials do not work at all. The angular distributions are structured and provide minimal ambiguity in the determination of the angular momentum transfer.

Good angular momentum matching requires large values of the transferred angular momentum. Together with the documented selectivity of the (d, α) reactions, it allows identification of 7^+ states in ^{38,42,46}K and ^{56}Co and probably of some 3^+ states in ^{38,46}K and ^{56}Co. The observation of 7^+ levels in ^{38,42,46}K gives a measure of the $f_{7/2}$ proton occupation number in the ground state of the target nuclei ^{40,44,48}Ca. The presence of 3^+ states at high excitation energy allows the localization of the $d_{3/2}$ shell in ^{46}K and ^{56}Co. The results are in qualitative agreement with a simple shell-model picture.

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