MEASUREMENT OF SPINS OF SOME STATES IN Ca^{41}†

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The nucleus Ca^{41} is of particular interest for studies of nuclear structure because its energy levels are expected to follow a rather simple scheme. Since Ca^{40} is generally thought to be a doubly magic closed-shell nucleus with both protons and neutrons filling the $d_{3/2}$ shell and with its first excited state at 3.35 MeV, it might be expected that at least the low-lying energy levels in Ca^{41} would be well described by one neutron placed in various shell-model orbitals. The orbitals available are $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$, in roughly this sequence. One would then expect other states which would include core excitations of Ca^{40} at excitation energies greater than about 3 MeV. Because of the relatively large amount of energy required for such core excitations, one might naively surmise that such excited states of the core would not be mixed strongly with the simple states of Ca^{40} plus a neutron. The results of $Ca^{40}(d,p)Ca^{41}$ experiments,[1] however, did not fulfill this naive expectation. In a (d,p) stripping reaction, the strength with which a given final state is populated is proportional to the extent to which the wave function of the state represents the configuration formed by adding a neutron to the target nucleus in its ground state. The ground state of Ca^{41} was found to conform to this expectation and to have the simple $f_{7/2}$ character. However, the p states were found to be split and, as is shown in Table I, three of the states formed in Ca^{41} (instead of the expected two) have an appreciable intensity in the (d,p) reaction and therefore an appreciable admixture of the single-particle wave function.

Table I.[a] Levels in Ca^{41}, observed in $Ca^{40}(d,p)Ca^{41}$ with reasonable intensity.

Excitation	l_n	$(2J+1)\theta_n^2\times10^3$
0	3	114
1.947	1	80
2.014	2^b	5
2.469	1	27
2.677	0	1
2.967	1	2
3.405	0	1.2
3.619	1^b	5
3.736	1^b	3
3.950	1^b	32

[a] Values taken from P. N. Endt and C. Van der Leun, Phys. 34, 1 (1962). The results of Bockelman and Buechner (reference 1) are normalized to reduced widths by M. H. Macfarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960). Only those levels showing "stripping" angular distributions are listed.

[b] The lesser of two values of l_n permitted by the experiment has been chosen. See Macfarlane and French for details.

The purpose of the present experiment was to determine the spins of these $l=1$ states in Ca^{41} in the hope that this information would lead to a better understanding of the structure of nuclei with $A\approx50$. The situation regarding the splitting of the p states in this region has been rather confusing over the past few years. Earlier measurements of gross structure in (d,p) experiments showed that the $l=1$ strength was, in fact, split into two rough groups which had relative strengths of about 2:1, the more intense group being at lower excitation energy.[2] This led to the conclusion that the lower group corresponded to the $p_{3/2}$ state and the upper to the $p_{1/2}$ state.

However, at least one measurement of the polarization of gamma rays following capture of polarized neutrons in Ti^{48} indicated that a state which is strongly populated in the (d,p) reaction and which would belong to the gross-structure group assigned to the $p_{3/2}$ configuration actually had spin 1/2.[3] Additional measurements on Cr^{53} by inelastic neutron scattering[4] and on Ti^{49}, Cr^{53}, Fe^{55}, Ni^{59}, and Ni^{61} by $(n,\gamma\gamma)$ correlations[5,6] also indicated that spin-1/2 states existed within the "$p_{3/2}$" gross-structure group.

The patterns in all these even-Z, odd-N nuclei with neutron number greater than 26 are almost the same. In most cases, there is a strong p-wave level with angular momentum 3/2; and about 400 keV above there is another $l=1$ state which has about a third of the intensity and for which a spin-1/2 assignment seems likely. Fe^{57} seems to be the only exception to this rule, which is perhaps not surprising in view of the anomalous ground state of this nucleus. This information is tabulated in Table II, which lists only those nuclei for which the assignment of the 3/2 state is definite. The probable assignment of spin 1/2 refers to cases in which the angular distribution of gamma rays was found to be isotropic. Since this is also possible for a 3/2 state with particular

Table II. Systematics of low-lying p states in even-Z, odd-N nuclei for $41 \leq A \leq 61$.

Nucleus	Energy difference	Relative intensities	Spin of upper state	Status of spin assignment
Ca^{41}	0.52	0.3	3/2	definite $(d,p\gamma)$
Ti^{49}	0.34	0.4	1/2	definite $(n,\gamma\gamma)^a$ and γ polarization[b]
Cr^{53}	0.56	0.3	1/2	probable $(n,\gamma\gamma)^c$ and $(n,n'\gamma)^d$
Fe^{55}	0.41	0.35	1/2	probable $(n,\gamma\gamma)^e$
Fe^{57}	0.35	0.5	3/2	definite $(n,\gamma\gamma)^c$
Ni^{59}	0.47	0.5	1/2	probable $(n,\gamma\gamma)^e$
Ni^{61}	0.28	0.2	1/2	definite $(n,\gamma\gamma)^e$ plus lifetime

[a] See reference 5.
[b] See reference 3.
[c] G. Bartholomew (private communication).
[d] See reference 4.
[e] See reference 6.

mixtures of $E2$ and $M1$, the 1/2 assignment can be regarded as definite only in cases in which the mixture is known.

Because the energy spacing and relative intensity of the first two $l = 1$ states in Ca^{41} are closely similar to those in the somewhat heavier nuclei, one would perhaps expect that the states arise from similar configurations. In the present experiment we have measured the proton-gamma angular correlation following the $Ca^{40}(d,p)$ reaction going to the 2.47-MeV and 3.95-MeV excited states. The spin of the state at 1.95-MeV excitation is established as 3/2 by the polarization work of Trumpy[3] and the (p,γ) angular correlation work by Taylor.[7] The present results are shown in Fig. 1. It is clear that the 2.47-MeV state decaying through the 1.95-MeV states shows a strong anisotropy and therefore must have spin $3/2^-$.

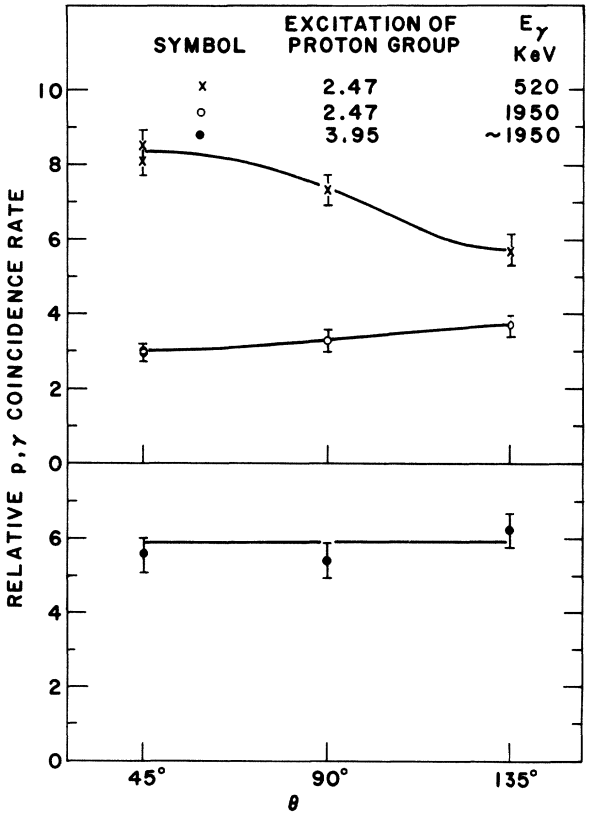

FIG. 1. Angular distribution of gamma rays in coincidence with proton groups from the $Ca^{40}(d,p)Ca^{41}$ reaction leading to the 2.47-MeV and 3.95-MeV excited states of Ca^{41}. The proton counter was placed at 80° with respect to the incident beam. The angles shown for the gamma detector are also with respect to the incident beam. The point at 45° was repeated by making the measurement at 180° from this point (-135°). Both these points are shown at 45°; their agreement is a test of the symmetry and reproducibility of the experiment. The solid lines are drawn through the points for the gamma rays in coincidence with the protons from the 2.47-MeV level and do not represent any theoretical fit.

The 3.95-MeV state also seems to decay predominantly through the 1.95-MeV state and is isotropic within experimental error. The fact that no other strong $l=1$ states are observed in Ca^{41} makes the assignment of $1/2^-$ extremely likely.

This result, then, is contrary to what one might have expected naively on the basis of a mainly qualitative analogy with heavier nuclei. The source of the 2.47-MeV state remains somewhat of a mystery, since it is difficult to see how two $3/2^-$ states could occur at such a low excitation energy.[8] This state might be suspected of being the 3/2 state formed by an $f_{7/2}$ neutron coupled to the 2^+ excited state (at 3.90 MeV) of the Ca^{40} core. This possibility seems to be ruled out, however, by the fact that the ground-state transition from this state is very weak, less than 3% of the transition to the 1.95-MeV state. This $E2$ strength is not as strong as one might expect from a state whose parentage is in a 2^+ state. Alternatively, one might expect this to be a $p_{3/2}$ neutron coupled to the 0^+ first excited state of Ca^{40} at 3.35 MeV. The problem would then be to explain why such a state should occur at such a low excitation energy.

It is hoped that this additional information will encourage some theoretical calculations of the structure of these nuclei.

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[8] M. H. Macfarlane (private communication).

THREE EXAMPLES OF THE $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ DECAY MODE*

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To study K^+ decay modes, we took 30 000 pictures of the CERN slow K^+ beam, stopping in the Ecole Polytechnique 80-cm liquid hydrogen bubble chamber. In the first scan we have found 3 decays consistent with scheme $K^+ \to \pi^+ + \pi^- + e^+ + \nu$. Another example of this decay mode in emulsion has already been reported.[1]

The characteristics of the three events are given in Table I and reproductions in Fig. 1.

In the table, P is the momentum, θ and ϕ are the azimuthal and dip angle in the chamber system, and R is the visible track length. For dip-angle error, we give $\Delta \sin\phi$ which is more nearly linear in the larger Z measurement error than $\Delta\phi$.

Table I. Track parameters.

Event No.	Ident.	R (cm)	P (MeV/c)	$\Delta P/P$	θ	$\Delta\theta$	ϕ	$\Delta\sin\phi$
1	π^+	17.41	81	···	337.6	0.6	-28.4	0.019
	π^-	0.38	27	0.04	13.5	2.4	59.5	0.100
	e^+	25.70	68	0.04	265.5	0.0	3.5	0.011
2	π^+	13.80	92	0.09	190.8	0.6	44.5	0.0175
	π^-	15.18	78	···	342.8	0.6	48.9	0.0188
	e^+	10.16	88	0.07	312.0	0.6	-63.9	0.0096
3	π^+	7.85	112	0.06	196.4	0.6	-13.1	0.013
	π^-	3.8	72	0.10	5.5	0.9	6.3	0.029
	e^+	26.8	81	0.06	325.6	0.6	38.3	0.020