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Hole States of Ca^{43} and Ca^{47}†

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Levels in Ca^{43} and Ca^{47} which can be interpreted as neutron hole states in the $1d_{3/2}$ and $2s_{1/2}$ shells have been observed through the (p,d) reaction. For Ca^{43}, the $1d_{3/2}$ hole state $(T=\frac{3}{2})$ lies at 0.993 MeV, while for Ca^{47}, the indications are that the $2s_{1/2}$ and the $1d_{3/2}$ levels lie very close to 2.60 MeV. Small amounts of p-wave admixtures are found in Ca^{44} and to a much smaller degree in Ca^{48}.

INTRODUCTION

THERE has been considerable theoretical interest in low-lying positive-parity levels in the region of the $1f_{7/2}$ shell, whidh can be interpreted as corresponding to holes in lower shells. Following the investigation by Yntema and Satchler[1] who observed proton hole states in the scandium isotopes through the (d,He^3) reaction on the Ti isotopes and the investigation by Kashy and Conlon[2] of neutron hole states in the Ti isotopes by the (p,d) reaction, Bansal and French[3] have discussed a simple method whereby the approximate energies of these hole states can be calculated. In the present paper, the results of the neutron pickup reactions on Ca^{44} and Ca^{48} by 17.5-MeV protons, in which some of these states are excited, are reported. An additional reason for investigating the $Ca^{44}(p,d)Ca^{43}$ reaction was in order to see whether a similar result would be obtained as was observed in the comparison of the $Ti^{46}(d,p)Ti^{47}$ results[4] with the $Ti^{48}(p,d)Ti^{47}$ results.[2] There it was found that the $1d_{3/2}$ and $2s_{1/2}$ hole states of Ti^{47} were excited in both reactions, indicating the existence of two-hole excitations in the ground-state wave function of Ti^{46}.[2]

Low-lying levels of Ca^{43} have been observed in a number of experiments, including the work of Benczer-Koller *et al.*[5] on the decay of K^{43} which shows that the 0.993-MeV level has positive parity and a probable spin of $\frac{3}{2}+$, and the $Ca^{42}(d,p)Ca^{43}$ results of Bockelman *et al.*[6] where the 0.993-MeV level is shown to be excited in that reaction, with an angular distribution typical of $l_n=2$ stripping. However, in a recent energy-level compilation,[7] the spin of the 0.993-MeV level of Ca^{43} is listed as $\frac{5}{2}+$. For Ca^{47}, in a recent investigation of the $Ca^{48}(p,d)Ca^{47}$ reaction with 40-MeV protons,[8] an $l_n=1$ pickup to a level at 2.7 MeV, with a relatively strong yield, is reported. These latter results, which would indicate strong p-wave admixture in the Ca^{48} ground-state wave function, seemed surprising in view of the good double-shell closure inferred for Ca^{48} from a recent study of the Ca^{49} level structure.[9] Finally, the β-decay work of Kuroyanagi *et al.*[10] on the decay of K^{47} indicated positive parity levels at 2.0 and 2.6 MeV; the 2-MeV level is listed as corresponding to the $1d_{3/2}$ neutron hole state of Ca^{47}. In the present work,[11,12] only a few levels are excited, but their interpretation appears quite unambiguous.

EXPERIMENTAL PROCEDURE AND RESULTS

The identification and measurement of the energy spectra of deuterons resulting from the bombardment of Ca^{44} and Ca^{48} targets with 17.5-MeV protons were carried out by means of a dE/dX-E solid-state detector telescope. The telescope has been described elsewhere.[13] The targets consisted of $CaCO_3$ enriched with either Ca^{44} or Ca^{48} suspended as a slurry in polystyrene.[14] The enrichment of the targets and their calcium content are given in Table I. Since these targets were rather nonuniform, the protons elastically scattered from the target were monitored using a 2-mm-thick solid-state detector with which the protons scattered from calcium

TABLE I. Ca target data.

Target \ Atomic percent of target							Target thickness (mg/cm^2)	
	40	42	43	44	46	48	Ca	Polystyrene
Ca^{44}	1.26	0.08	0.06	98.6	<0.02	0.02	0.72	1.1
Ca^{48}	4.1	0.09	<0.05	0.2	0.05	95.6	0.45	0.5

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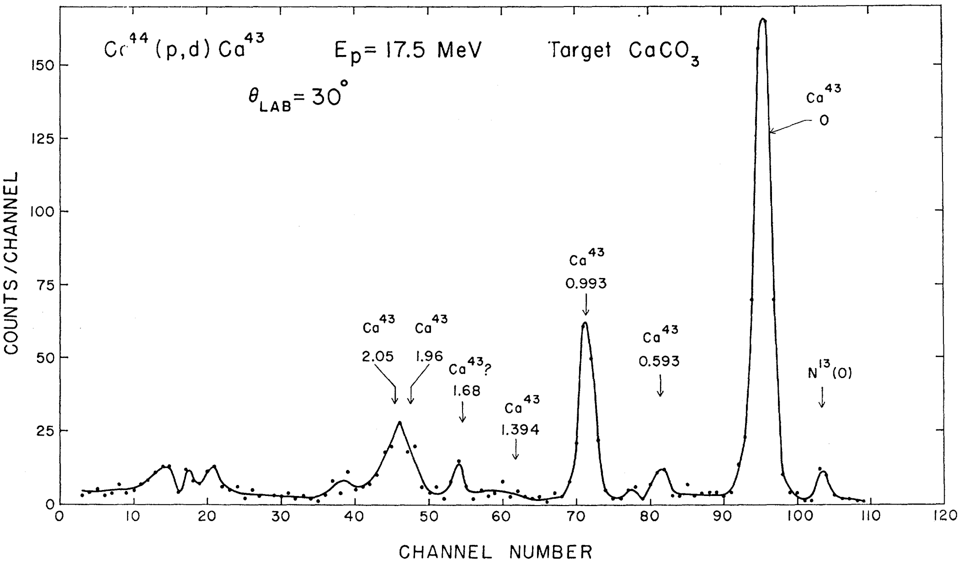

FIG. 1. Energy spectrum of deuterons from the $Ca^{44}(p,d)Ca^{43}$ reaction at a laboratory angle of 30°.

were resolved from those scattered from oxygen and carbon. The $O^{16}(p,p)O^{16}$ cross section measured by Daehnick[15] was then used to obtain an effective target thickness. In this way, values of 9.7 and 12.1 mb/sr were obtained for the elastic-scattering cross sections of 17.5-MeV protons on Ca^{44} and Ca^{48}, respectively, at a laboratory angle of 90°. Considering the various errors, we estimate an uncertainty of ±25% in the absolute values of cross-sections reported here.

The excitation energies of Ca^{43} levels are well known and could not be improved upon in the present investigation; however, our results are consistent with previously measured values.[7] For Ca^{47}, excitation energies and Q values are not well known; they were determined by comparison with the (p,d) spectra from a Ti^{47} target using values of -7.545 and -8.663 MeV as the Q values of the Ti^{46} levels at 0.885 and 2.003 MeV, respectively, and a Q value of -9.533 MeV for the (p,d) transition from Ti^{48}, which was about 20% abundant in the target, to the 0.160-MeV level of Ti^{47}. The excitation energies and Q values thus determined for the $Ca^{48}(p,d)Ca^{47}$ data are listed in Table II.

The deuteron spectrum for the $Ca^{44}(p,d)Ca^{43}$ reaction is shown in Fig. 1 for $\theta_{LAB}=30°$. Two strong peaks are seen, one of which corresponds to the ground level of Ca^{43} and the other to the 0.993-MeV level. The peak corresponding to the 0.593-MeV level ($J^{\pi}=\frac{3}{2}^-$) is relatively weak, but indicates some p-wave admixture.

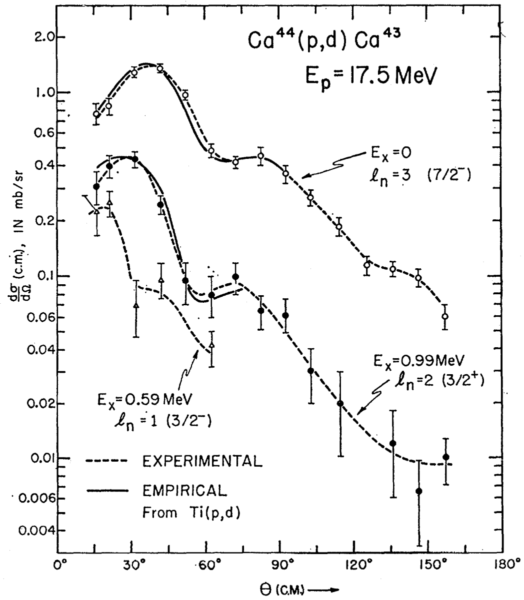

FIG. 2. Angular distributions of deuteron groups resulting from the $Ca^{44}(p,d)Ca^{43}$ reaction. The empirical curves are from Ref. 2.

TABLE II. Summary of results for the (p,d) reaction on Ca^{44} and Ca^{48}.

E_x (MeV)	$-Q$ (MeV)	l_n	σ_{max} (c.m.) (mb/sr)	θ_{max} (deg)	S	J^{π} [a]	J^{π} [b]
			$Ca^{44}(p,d)Ca^{43}$ [c]				
0	8.911	3	1.5	36	2.4	$\frac{7}{2}^-$	$\frac{7}{2}^-$
0.374	9.285	···	<0.05	···	···	···	$\frac{5}{2}^-$
0.594	9.505	1	0.23	19	0.06	$\frac{3}{2}^-$	$\frac{3}{2}^-$
0.993	9.904	2	0.45	28	0.8	$\frac{3}{2}^+$	$(\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+)$
1.389	10.300	···	<0.1	···	···	···	$(\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+)$
			$Ca^{48}(p,d)Ca^{47}$ [d]				
0	7.76	3	5.4	37	6.3	$\frac{7}{2}^-$	$\frac{7}{2}^-$
2.01	9.77	(1)	0.09	(20)	0.02	$(\frac{3}{2}^-)$	$\frac{3}{2}^-$ [e]
2.60	10.36[f]	2	0.3	(28)	0.7	$\frac{3}{2}^+$	$(\frac{5}{2}^+, \frac{3}{2}^-)$
		0	1.2	(43)	···	$\frac{1}{2}^+$	

[a] From present work.
[b] Previously reported.
[c] Excitation energies and Q values are from Ref. 7.
[d] E_x and Q from present work (uncertainty ±25 keV).
[e] Reference 16.
[f] Close-lying doublet (Ref. 16).

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No evidence was found for the excitation of the 1.389-MeV level, and with the present overall resolution full width at half maximum (FWHM) of 80 to 100 keV, not much can be said about higher lying excited levels. The angular distributions of the deuterons leaving Ca^{43} in its ground, 0.593-, and 0.993-MeV levels are shown in Fig. 2, where they are compared with empirical curves taken from the recent (p,d) investigation of the titanium isotopes.[2] It is quite clear from Fig. 2 that the 0.993-MeV level corresponds to the pickup of a neutron from the $1d_{3/2}$ shell $(l_n=2)$ and has therefore spin and parity $J^\pi=\frac{3}{2}+$.

The results for the $Ca^{48}(p,d)Ca^{47}$ reaction are shown in Figs. 3 and 4, where the overall resolution (FWHM) is again 80 to 100 keV. The spectra of Fig. 3 show that below 4.5-MeV excitation in Ca^{47} only the ground and 2.60-MeV groups have large yields. There is also an indication of a weak transition to a level at 2.01 MeV with possibly $l_n=1$ pickup. The work of Gelote and Rapaport[16] on $Ca^{46}(d,p)Ca^{47}$ does indeed prove this weakly excited state to be the expected $2p_{3/2}$ single-particle level. The angular distributions are shown in Fig. 4 where they are compared, as in the previous case, to empirical curves. The ground-state angular distribution is seen to correspond to the pickup of a neutron from the $1f_{7/2}$ shell. The 2.60-MeV distribution is rather interesting. It appears that one can rule out pure $l_n=1$, 2, or 3, and that $l_n=0$ is the closest assignment. Recent results on $Ca^{46}(d,p)Ca^{47}$ indicate that there are two weakly excited levels only a few keV apart at about this energy,[16] the higher energy peak showing $l=0$ stripping.[17] And, on the basis of the Ti(p,d) data where it is found that the $l_n=2$ in Ti^{45}, Ti^{47}, and Ti^{47} lie at approximately the same Q value, -11.2 MeV, one might expect a similar correlation here, especially since there is no other candidate for $l_n=2$ in the Ca^{47} spectrum. Hence various admixtures of l values were tried for the 2.60-MeV distribution (see Fig. 5), and it appears that a combination of $l_n=0$ with $l_n=2$ does indeed give the best fit to the data, indicating that the $2s_{1/2}$ and $1d_{3/2}$ neutron hole states both lie at approximately 2.60 MeV. However, since the empiirical $l_n=3$ curve does not fit the ground-state transition too well, it is questionable how much one can trust the empricial $l_n=0$ to fit the 2.60-MeV state, and hence with what certainty one can extract the $l_n=2$ contribution in the angular distribution of this state.

It has been predicted by Bansal and French[3] that the $d_{3/2}$ state lies very low in excitation and hence may not be resolved from the ground-state transition. But if the strength of the transition is similar to that of the $d_{3/2}$ state in Ca^{43}, it would clearly modify the angular distribution of the ground-state transition; this is not observed.

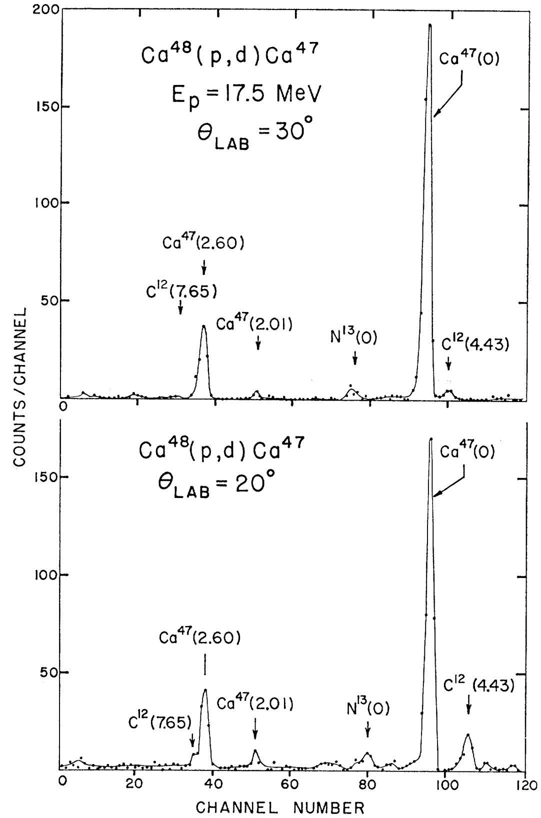

FIG. 3. Energy spectra of deuterons from the $Ca^{48}(p,d)Ca^{47}$ reaction at angles of 20° and 30°.

Finally, no pickup characteristic of $l_n=0$ was observed in the $Ca^{44}(p,d)Ca^{43}$ reaction. On the basis of the expected strength of the transition, the members of the doublet at 2 MeV which were unresolved in this experiment could certainly be candidates.

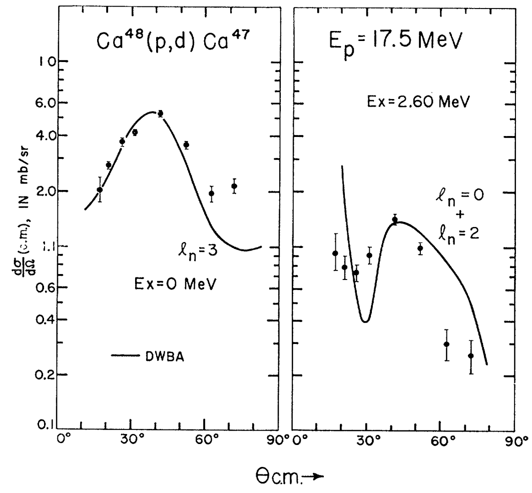

FIG. 4. Angular distribution of deuteron groups resulting from the $Ca^{44}(p,d)Ca^{43}$ reaction. The curves are empirical curves taken from Ref. 2.

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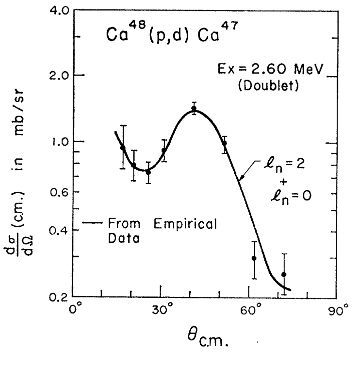

FIG. 5. Angular distribution of deuterons to the 2.60-MeV group in Ca^{44}. The curve represents a combination of $l_n=0$ and $l_n=2$.

ANALYSIS AND DISCUSSION

In order to extract the spectroscopic factors for the (*p,d*) reaction, distorted-wave Born-approximation calculations[18] were carried out using the Oak Ridge code JULIE. The optical parameters used were taken from investigations by Perey[19] for the protons and by Perey and Perey[20] for the deuterons and are similar to those used for Ref. 2. The calculations are in good agreement with the l_n values assigned except for the 2.60-MeV "doublet" in Ca^{47} where even after adding both $l_n=0$ and $l_n=2$ contributions, the fit is not expecially good.

It is interesting to note that the spectroscopic factors for $l_n=1$ pickup are much smaller for Ca^{44} and Ca^{48} than they are for the Ti^{46} and Ti^{50} nuclei.[2] In the $Ca^{48}(p,d)Ca^{47}$ reaction, the weak excitation of the 2.01-MeV level with a value $S(2p_{3/2})=0.02$ shows an admixture of $2p_{3/2}$ in Ca^{48} three times smaller than in Ca^{44}, testifying to the especially strong shell closure in Ca^{48}, inferred from other data.[9]

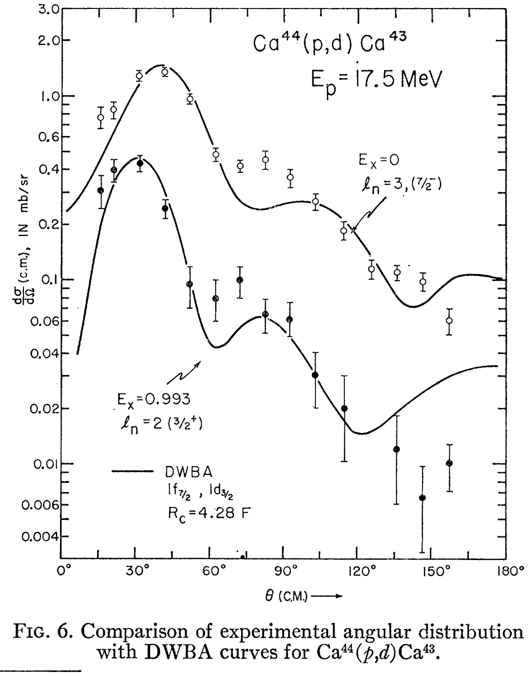

FIG. 6. Comparison of experimental angular distribution with DWBA curves for $Ca^{44}(p,d)Ca^{43}$.

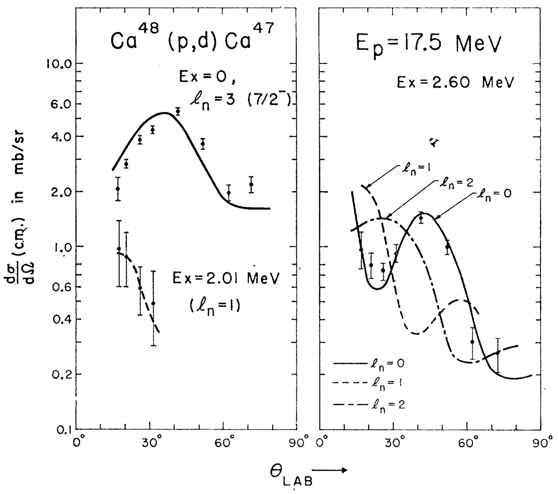

FIG. 7. Comparison of experimental angular distribution with DWBA curves for $Ca^{48}(p,d)Ca^{47}$.

The lowest expected $\frac{3}{2}^+$, $T=\frac{3}{2}$ state in Ca^{43} would appear to be formed by coupling a $1d_{3/2}$ hole to a $(1f_{7/2}{}^4, T=1)$ wave function. This could not be strongly excited by $l_n=2$ pickup from the Ca^{44} ground state, in which the four $1f_{7/2}$ nucleons are mostly in a state with $T=2$ (and $T_z=2$). A different $\frac{3}{2}^+$, $T=\frac{3}{2}$ state in Ca^{43} that we could easily reach from this Ca^{44} ground state is

$$\begin{aligned}\psi_{1,\,T_z=3/2}{}^{T=3/2}=(\tfrac{4}{5})^{1/2}&\{d_{3/2}{}^{-1},\,{}_{T_z=-1/2}{}^{T=1/2}\}\\&\times\{[f_{7/2}]^4,\,{}_{T_z=2}{}^{T=2}\}-(\tfrac{1}{5})^{1/2}\\&\times\{d_{3/2}{}^{-1},\,{}_{T_z=1/2}{}^{T=1/2}\{\}[f_{7/2}]^4,\,{}_{T_z=1}{}^{T=2}\}.\end{aligned}$$

The strong excitation of the 0.993 MeV level in Ca^{43} by the (*p,d*) reaction suggests that ψ_1 makes an appreciable contribution to it. If ψ_1 described all of this level, then the (*p,d*) spectroscopic factor would be 3.2. It is observed to be 0.8. Thus the 0.993-MeV level probably contains other components such as $[d_{3/2}{}^{-1}f_{7/2}{}^4(T=1)]$ or $[d_{3/2}{}^{-1}f_{7/2}{}^4(T=2, L=2)]$. If this were the case, one would expect that ψ_1 would be shared by other states in Ca^{43}. However, there is no evidence for the (*p,d*) excitation of other $\frac{3}{2}^+$ states up to about 4 MeV. The observed spectroscopic factor is similar to values found for the levels which have been described as $1d_{3/2}$ hole states in the Ti isotopes.[2] The state orthogonal to ψ_1 is, of course, the analog to K^{43} which should lie around 8 MeV.

For Ca^{47}, the $d_{3/2}$ wave function can be written as

$$\begin{aligned}\psi_1=(8/9)^{1/2}&\{d_{3/2}{}^{-1},\,{}_{T_z=-1/2}{}^{T=1/2}\}\{[f_{7/2}]^8{}_{J=0,\,T_z=4}{}^{T=4}\}\\&-(\tfrac{1}{9})^{1/2}\{d_{3/2}{}^{-1},\,{}_{T_z=1/2}{}^{T=1/2}\}\{[f_{7/2}]^8,\,{}_{T_z=3}{}^{T=4}\}.\end{aligned}$$

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[18] The optical parameters used were for the neutron, $r_0=1.25$ F, $a=0.65$ F, $\Delta=27$ MeV; for the protons, $V=48$ MeV, $W=0$, $r_0=r_c=1.25$ F, $a=0.65$ F, $V_{so}=8.5$ MeV, $r_0'=1.25$ F, $a'=0.47$ F, $W'=44$ MeV; for the deuterons, $V=112.8$ MeV, $W-0$, $r_0=r_c=1.021$ F, $a=0.846$ F, $r_0'=1.471$ F, $a'=0.444$ F, $W'=79$ MeV.

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TABLE III. Comparison of (d,p) and (p,d) spectroscopic factors.

Reaction	E_x (MeV)	l_n	S	E_x (MeV)	l_n	S
$Ca^{44}(p,d)Ca^{43}$	0	3	2.4	0.993	2	0.8
$Ca^{42}(d,p)Ca^{43}$	0	3	0.75[a]	0.993	2	0.08
$Ti^{48}(p,d)Ti^{47}$	0.160	3	3.80	1.81	2	0.7
$Ti^{46}(d,p)Ti^{47}$	0.160	3	0.50[a]	1.816	(2)	0.04

[a] Assumed values for $S(d,p)$.

In this case, the spectroscopic factor $S(p,d)=3.55$. The experimental value measured, is $S=0.7$, similar to the value for Ca^{43}.

Since the 0.993-MeV $\frac{3}{2}^{+}$ level of Ca^{43} is excited by the $Ca^{42}(d,p)Ca^{43}$ reaction, it appears that we have here a situation very similar to that found for the 1.81-MeV level of Ti^{47} which is also excited by both the (p,d) pickup and the (d,p) stripping processes. A comparison of these two states is shown in Table III, where the (d,p) spectroscopic factors for the $\frac{3}{2}^{+}$ levels have been obtained by normalizing the $l_n=3$ spectroscopic factors in the reactions $Ca^{42}(d,p)Ca^{43}$ and $Ti^{46}(d,p)Ti^{47}$ to their predicted values of 0.75 and 0.50, respectively. It appears that the wave functions of the Ca^{42} and Ti^{46} ground states must have a component with two neutrons or a neutron and proton missing from the $1d_{3/2}$ shell, that is, promoted to the $1f$ shell for sizeable portion of the time.[21] Evidence of such excitations in Ca^{40} has recently been reported.[22]

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Decay of 54-sec Br^{86} and 55-sec Br^{87}†

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The decay of Br^{86} and Br^{87}, produced by fission of U^{235}, has been studied with β- and γ-ray scintillation spectrometers in singles and coincidence operation. Rapid chemical techniques taking advantage of the difference in half-lives of the selenium precursors were used to produce samples having different proportions of Br^{86} and Br^{87}, and the radiations following the decay of these two isotopes were resolved in this way. A decay scheme is proposed for Br^{86}, with $Q_\beta=7.5\pm0.5$ MeV.

I. INTRODUCTION

THE 1-min bromine fission-product activity was discovered by Hahn and Strassman[1] shortly after they discovered nuclear fission. Various workers have studied this activity and it has been identified with the 55-sec delayed-neutron activity in fission. Our work dealing with this aspect of the activity will be published elsewhere.[2] Until recently, the activity was thought to be Br^{87} and a study of the decay was made.[3] The discovery of 54±2-sec Br^{86} by Stehney and Steinberg[4], however, showed that the 55-sec bromine activity found in fission is actually a mixture of Br^{86} and Br^{87} (55.4±0.7 sec, Ref. 2). Our study of the activity was carried out in the light of this recent result.

Since it was not feasible to use the Stehney-Steinberg method[4] $[Kr^{86}(n,p)Br^{86}]$ to produce sufficiently large quantities of Br^{86} to study the decay, and because it was possible to obtain large quantities of 55-sec bromine activity from fission, the problem was approached using samples produced by the latter source. This method has a serious disadvantage in that both isotopes have essentially the same half-life, thereby rendering it impossible to distinguish between the two by observing the decay at successive intervals. The predicted independent fission yields[5] of Br^{86} and Br^{87} indicate that approximately 75 and 50%, respectively, of the activity of these isotopes result from precursor decay. This means that it would be possible to make samples having various Br^{86}/Br^{87} ratios provided that the selenium precursors have appropriately different half-lives and that at least one of the half-lives is not short compared to the chemical separation time. As these conditions were met, it was possible to study the decay of both isotopes using sources activated in the thermal-neutron fission of U^{235}. The ~16-sec selenium precursor of the 1-min bromine activity studied by Sattizahn *et al.*[6] seems to be

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