formed and axially asymmetric. A calculation of $\langle\sum_i \mathbf{l}_i\cdot\mathbf{s}_i\rangle$ based on their work gives a value of 3.33.[5] However, more recent pairing calculations[27] now favor an axially symmetric shape which is supported by the above experimental results.

[27] A. Goswami, J. Bar-Touv, A. L. Goodman, G. L. Struble, and W. Yucker, Bull. Am. Phys. Soc. **13**, 18 (1968); A. L. Goodman, G. L. Struble, and A. Goswami, Phys. Letters **26B**, 260 (1968).

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Energy Levels of ^{48}Sc†

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The energies of neutrons emitted in the ^{48}Ca$(p,n)^{48}$Sc reaction at proton energies of 4.5 and 5.5 MeV have been determined by a time-of-flight technique. The level structure of ^{48}Sc was deduced up to 4.3-MeV excitation. The Q value determined for the ^{48}Ca$(p,n)^{48}$Sc reaction is -506 ± 7 keV.

I. INTRODUCTION

Energy levels of ^{48}Sc have recently been of interest because many of the low-lying states can be described by the configuration of a $f_{7/2}$ neutron hole coupled to a $f_{7/2}$ proton. They have been studied previously by means of the ^{50}Ti$(d,\alpha)^{48}$Sc, ^{49}Ti$(d,^3$He$)$-^{48}Sc, and ^{49}Ti$(t,\alpha)^{48}$Sc reactions.[1–3] The latter two reactions both tend to populate proton-hole states.

The ^{48}Ca$(p,n)^{48}$Sc reaction is useful as a tool to locate energy levels in ^{48}Sc since the reaction mechanism is not particularly selective of final states. Early work on this reaction includes neutron time-of-flight measurements by Elwyn *et al.*,[4] neutron threshold measurements by Ferguson and Paul,[5] and neutron energy measurement by Chasman *et al.*[6] with the use of a ^{3}He-filled proportional counter. Chasman *et al.*[6] also observed the γ rays from the decay of the excited states with a Ge(Li) γ detector and used the measured γ-ray energies to give accurate energy values for the excited states. Very recently, McMurray *et al.*[7] have carried out a good-resolution time-of-flight measurement and obtained the positions of levels up to 4169 keV.

The present investigation of the ^{48}Ca$(p,n)^{48}$Sc reaction was carried out with several different objectives in mind. We wished to verify directly the existence of an excited state at 131 keV which had been inferred from the γ-ray work of Chasman *et al.*[6] We also wanted to clarify discrepancies in the Q value for the ground-state reaction, to look for the $(1f_{7/2})_p(1f_{7/2})_n^{-1}$ state with $J^\pi=7^+$ observed by Grotowski *et al.*[1] at $E_x=1.06$ MeV and by Schwartz at $E_x=1.17$ MeV, and to search for the $J^\pi=2^+$ state of this configuration which Schwartz predicted at an excitation of about 580 keV. Ohnuma *et al.*[8] have studied the ^{48}Ca$(^3$He$,t)^{48}$Sc reaction and find states strongly excited at excitation energies of 1097 ± 3 and 1150 ± 3 keV. The energy of the 1097-keV state is in good agreement with the energy of 1.06 ± 0.04 MeV given by Grotowski *et al.*[1] for the $J^\pi=7^+$ particle-hole state. The state at 1150 keV has been assigned a probable spin of 1 or 2 by Chasman *et al.*[6] and by McMurray *et al.*[9] and thus maybe the 2^+ particle-hole state. Such an energy for the 2^+ state is in agreement with the earlier calculation of Ball[10] and with the results of a calculation presented by Ohnuma *et al.*,[8] but is in disagreement with the prediction by Schwartz. In addition, it was felt it would be worthwhile to con-

† Work supported in part by the Atomic Energy Control Board of Canada and the U. S. Atomic Energy Commission.
[1] K. Grotowski, S. Wiktor, and F. Pellegrini, Nuovo Cimento **47B**, 255 (1967).
[2] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).
[3] J. J. Schwartz, Phys. Rev. Letters **18**, 174 (1967).
[4] A. J. Elwyn, H. H. Landon, S. Oleska, and G. N. Glasoe, Phys. Rev. **112**, 1200 (1958).
[5] A. T. G. Ferguson and E. B. Paul, Nucl. Phys. **12**, 426 (1959).
[6] C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. **140**, B212 (1965).
[7] W. R. McMurray, M. Peisach, R. Pretorius, P. van der Merwe, and I. J. van Heerden, Nucl. Phys. **A99**, 6 (1967).
[8] H. Ohnuma, J. R. Erskine, J. A. Nolen, Jr., J. P. Schiffer, and N. Williams, in International Conference on Nuclear Structure, Tokyo, Japan, 1967 (unpublished), contribution 4.74.
[9] W. R. McMurray, M. Peisach, R. Pretorius, P. van der Merwe, and I. J. van Heerden, Nucl. Phys. **A99**, 17 (1967).
[10] J. B. Ball, Bull. Am. Phys. Soc. **11**, 349 (1966).

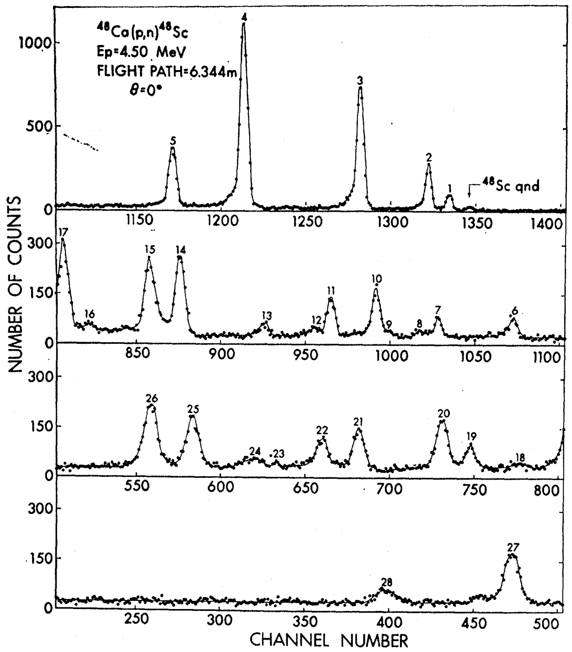

FIG. 1. Time-of-flight spectrum obtained at $E_p=4.50$ MeV and $\theta=0°$ with a 50-μg/cm² calcium target enriched to 84.6% ^{48}Ca. The flight path was 6.344 m and the time calibration is 0.32 nsec channel.

firm the results of McMurray *et al.*[7] on the energies of the excited states.

II. EXPERIMENTAL TECHNIQUE

Neutron spectra for the ^{48}Ca$(p,n)^{48}$Sc reaction were obtained using the University of Alberta pulsed-beam time-of-flight facility. The system includes terminal pulsing and a Mobley compression system, and yields a 0.4-nsec beam pulse at a repetition rate of 1 MHz. For the present experiment, average beam currents of approximately 1 μA were used.

A scintillation detector consisting of an 8.9-cm-diam by 1.9-cm-thick NE 213 scintillator coupled to a XP1040 photomultiplier tube operated a constant fraction of pulse-height trigger[11] to provide the start signal for a time-to-amplitude converter. The stop signal was derived from a cylindrical capacitive time pick-off placed in the beam tube immediately ahead of the target. The remaining circuitry was similar to that described by Fife *et al.*[12] Modifications, which have been described elsewhere,[13] improved the dynamic range and time resolution of the system.

The target was a 50-μg/cm² layer of 84.6% enriched ^{48}Ca on a gold backing. Runs were made at $\theta=0°$ with a 6.344-m flight path for proton energies of 4.5 and 5.5 MeV. At these energies, the target thickness was equivalent to approximately 2.4 and 2.1 keV,[14] respectively.

The differential linearity of the time-to-pulse height converter was checked by a measurement with uncorrelated start and stop signals, and was found better than 2% over a 1500-channel range. A time calibration

TABLE I. Energy levels of ^{48}Sc.

	Excitation (keV)		
Level[a]	This experiment	McMurray *et al.*[b]	Chasman *et al.*[c]
1	131±7	151±20	131± 2
2	258±7	237±20	253± 2
3	624±5	628± 6	624± 3
4	1140±5	1139± 7	1144± 3
5	1403±5	1397± 7	1406± 3
6	1892±5	1883± 6	1877±20
7	2059±5	2080± 7	2077±20
8	2104±4		
9	(2165±4)		
10	2192±4	2175± 5	2192± 3
11	2276±4	2267± 6	2276± 3
12	(2303±5)		
13	2392±4	2380± 5	
14	2518±4	2508± 4	2519± 5
15	2560±4	2548± 4	
16	2639±5	2630±10	
17	2669±4	2661±10	
18	2730±4	2725±10	
19	2784±4	2776± 6	
20	2810±4	2800± 6	
21	2893±4	2885± 6	
22	2921±4	2920± 4	
23	(2960±7)		
24	2978±4	2969± 4	
25	3025±4	3021± 6	
26	3053±4	3050± 6	
27	3152±4	3146± 4	
28	3221±4	3208± 4	
		3258± 6	
29	3289±5		
30	3303±5	3292± 6	
31	3333±5	3322± 6	
		3353±10	
32	3372±5	3370±10	
33	3481±5	3479± 5	
34	3526±5	3515± 5	
35	3564±5	3557±10	
36	3620±5	3617±10	
37	(3659±5)	3640±10	
38	3675±5	3667± 5	
39	3709±5	3705±10	
40	3743±4		
41	3774±5		
42	3806±5	3805± 5	
		3862±10	
		3919±10	
43	(3957±5)		
44	(3974±5)		
45	3988±5	3975±10	
46	4026±5	4017±10	
47	4062±5	4060±10	
48	4092±5	4086±10	
49	4141±5	4139±10	
50	4174±5	4169±10	
51	4290±5		

[a] Level numbers correspond to those in Figs. 1 and 2.
[b] Reference 7.
[c] Reference 6.

[11] D. A. Gedcke and W. J. McDonald, Nucl. Instr. Methods **55**, 377 (1967).
[12] A. A. Fife, G. C. Neilson, and W. K. Dawson, Nucl. Phys. **A91**, 164 (1967).
[13] W. J. McDonald and D. A. Gedcke, University of Alberta Nuclear Research Center Internal Report, 1967 (unpublished).
[14] Natl. Acad. Sci.—Nat. Res. Council Publ. **1133** (1964).

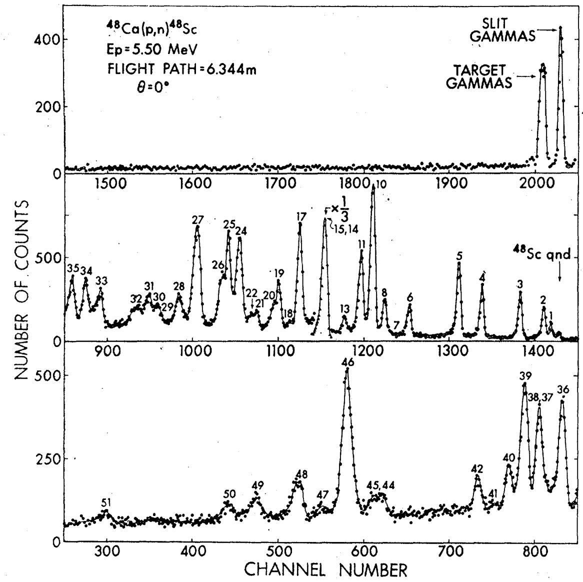

FIG. 2. Time-of-flight spectrum obtained at $E_p=5.50$ MeV. γ-ray peaks are observed from defining slits located 23 cm before the target, as well as from reactions in the target.

was obtained from a ^{9}Be$(d,n)^{10}$B spectrum and was checked using the method of Hatcher,[15] which results in absolute time markers every 50 nsec across the whole time range. By combining the calibration data with the results of the differential linearity measurement, a time calibration accurate to better than 0.3 nsec was obtained.

III. EXPERIMENTAL RESULTS

Figure 1 shows a portion of the time-of-flight spectrum obtained at a bombarding energy of 4.50 MeV. A similar spectrum observed at a proton energy of 5.50 is shown in Fig. 2. Data for both spectra were obtained at an angle of 0° and with a flight path of 6.344 m.

The excitation energies of ^{48}Sc derived from this experiment are listed in Table I. For comparison, the values obtained by Chasman *et al.*[6] and by McMurray *et al.*[7] are also tabulated. The agreement between the three experiments is seen to be generally very good.

Our excitation energies are based upon our ground-state Q value of -506 ± 7 keV and the weighted means of the Q values deduced from the measurements shown in Figs. 1 and 2. A 1-keV target-thickness correction is included. The errors were calculated from the estimated uncertainties in the peak positions and time calibration. The existence of levels was confirmed using other measurements of lower precision at 4.5 MeV (0°, 45°, and 135°) and 5.5 MeV (0° and 135°). Levels without parentheses in Table I were seen in all spectra with the exception of those levels above 3221 keV, which could only be seen in the 5.5-MeV spectra. For levels with $E_x\leq3221$ keV, parentheses indicate observation in at least half of the spectra at each bombarding energy. Above that excitation energy parentheses indicate observation in two of the three spectra.

No evidence of carbon or oxygen contamination on the target or collimation slits was seen, nor was there any evidence of (p,n) reactions from other isotopes in the target.

IV. DISCUSSION OF RESULTS

The excitation energies obtained in our experiment and those of Chasman *et al.*[6] and of McMurray *et al.*[7] agree very well in general except for the following discrepancies.

The state seen by Chasman *et al.*[6] at 1592 ± 20 keV by use of a ^{3}He spectrometer is not confirmed in the time-of-flight experiments. Also we do not observe the states at 3258, 3353, 3862, and 3919 keV which were reported by McMurray *et al.*[7] On the other hand, we do observe states at excitations of 3289, 3743, and 3774 keV and possible states at excitations of 2303, 2960, 3957, and 3974 keV which they did not see. Our results show that the state reported by Chasman *et al.*[6] and McMurray *et al.*[7] at about 2080 keV is actually two states at excitations of 2059 and 2104 keV. It is also possible, though unlikely, that our level at 3289 keV corresponds to that of McMurray *et al.*[7] at 3258 keV. Our level energies tend to be systematically higher than those of McMurray *et al.*[7] by an average of about 5 keV.

The existence of excited states at 131 and 253 keV, which had been inferred by Chasman *et al.*[6] from a high-precision study of the ^{48}Ca$(p,n\gamma)^{48}$Sc reaction, is confirmed by direct observation of the neutron groups. Evidence for those states can be clearly seen in Figs. 1 and 2. The $J^\pi=7^+$ state would presumably not be produced in any more abundance than the $J^\pi=6^+$ ground state and, hence, could have been obscured by the strong peak from the 1140-keV state. On the other hand, the $J^\pi=2^+$ state predicted by Schwartz[3] at an excitation energy of about 580 keV should probably have been excited as strongly as the 624-keV state, which has a probable $J^\pi=3^+$ assignment. It is possible that a weak neutron group to this level could have been obscured by neutrons from the 624-keV state. It should also be noted that the γ-ray work of Chasman *et al.*[6] also gave no evidence for this state. There is no evidence in our work for a state at 580 keV. The $J^\pi=1^+$ state found by Schwartz[3] at 2700 ± 20 keV could not be clearly identified with any of the states we observed in that region of excitation.

The Q value for the ground-state reaction was derived as follows. A value of $Q_0=-511\pm7$ keV was found from a direct measurement of the energy of the ground-state neutron group. Excitation energies of 131, 253, 624, 1144, 1406, 2172, 2276, and 2519 keV obtained by Chasman *et al.*[6] were combined with our Q values for these states and the above value of Q_0 to give an average

[15] C. Hatcher, Edgerton, Germeshausen and Grier, Inc., Salem, Mass., Nanonotes, Vol. I, No. 2, 1964 (unpublished).

$Q_0 = -506$ keV with a standard deviation of 3 keV. Since the average value for Q_0 may still contain systematic uncertainties such as flight path, the position of the γ-ray peak for the determination of zero time in the flight-time measurements, proton energy, and target thickness, we have adopted an error for Q_0 which is typical of that for an individual determination. Thus we deduce $Q_0 = -506 \pm 7$ keV. However, the errors in the excitation energies of Table I are smaller because certain systematic errors tend to cancel.

Our value for Q_0 disagrees with that of -529 ± 10 keV quoted by Chasman *et al.*[6] Their value was derived from the Q value for the first excited state ($Q = -660 \pm 10$ keV) which was measured by Johnson and quoted by Mattauch *et al.*[16] and from the measurement of the energy of the first excited state by a Ge(Li) γ-ray detector. Since our excitation energies agree with those of Chasman *et al.*,[6] the disagreement then arises from the Q-value measurement of Johnson. We also disagree with the value of -534 ± 15 keV given by McMurray *et al.*[7] The value given by Mattauch *et al.*[17] in their systematic analysis of nuclear-reaction energies for the determination of masses ($Q_0 = -493 \pm 12$ keV) is in good agreement with the present determination.

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[16] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 73 (1965).

[17] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

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Nuclear Resonance Fluorescence in Cu^{65}†

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The Coulomb fragmentation of $Zn^{65}I_2$ molecules was utilized as the means of producing γ rays which are resonant with the 1.116-MeV level in Cu^{65}. A study of the resonant self-absorption led to a mean lifetime $\tau = (3.80 \pm 0.25) \times 10^{-13}$ sec for this level. From the angular distribution of the resonant radiation, the mixing amplitude δ for the $M1+E2$ 1.116-MeV ground-state transition was determined as $\delta = -0.437 \pm 0.015$.

I. INTRODUCTION

THE situation with regard to the lifetime of the 1.116-MeV level in Cu^{65} and the multipole mixing of the 1.116-MeV ground-state transition has been summarized in a paper[1] which reported resonance-fluorescence results obtained through the use of gaseous sources of Ni^{65}. A disturbing aspect brought out by that summary was the discrepancy between the $E2/M1$ mixing amplitudes reported on the basis of the angular distribution of γ rays following Coulomb excitation[2,3] and the mixing amplitudes obtained from studies of the angular distribution of resonant γ rays[1] or from a comparison[1] of the best $B(E2)$ and $B(M1)$ values. The Coulomb-excitation angular distribution measurements[2,3] led to an average $\delta = -0.22 \pm 0.06$. The other experiments combined to give $\delta = -0.51 \pm 0.03$. The ratios δ^2 of the $E2$ and $M1$ transition rates, derived from the two sets of experiments, thus differed by a factor of about 5. This difference, in turn, made the total lifetime deduced from the Coulomb-excitation experiments[3] approximately 5 times shorter than the lifetime estimated on the basis of Doppler shift[4] and resonance-fluorescence[1] studies.

The short half-life (2.56 h) of the radioisotope Ni^{65} made it difficult to improve over the accuracy obtained in the previous resonance-fluorescence experiment[1] as long as this isotope had to be used. However, a marked improvement appeared to be feasible if an efficient way of obtaining resonant 1.116-MeV γ rays from the long-lived (245-day) isotope Zn^{65} could be found. The recent observation[5] of the large velocities resulting from the Coulomb fragmentation of the $Cu^{65}Cl_2$ molecule following K capture in Zn^{65} indicated a way of producing resonant γ rays from gaseous Zn^{65} compounds. The suggested analysis[5] of the $Zn^{65}Cl_2$ experiments made it probable that $Zn^{65}I_2$ sources would provide an even larger fraction of resonant γ rays. It was, therefore,

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[1] G. B. Beard, Phys. Rev. **135**, B577 (1964).

[2] B. Elbeck, H. E. Gove, and B. Herskind, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **34**, No. 8 (1964).

[3] R. L. Robinson, F. K. McGowan, and P. H. Stelson, Phys. Rev. **134**, B567 (1964).

[4] M. A. Eswaran, H. E. Gove, A. E. Litherland, and C. Broude, Nucl. Phys. **66**, 401 (1965).

[5] F. R. Metzger, Phys. Rev. Letters **18**, 434 (1967).