Discovery of the Missing Two-Particle, Two-Hole 0^+ States in ^{40}Ca

Kamal K. Seth and A. Saha
Northwestern University, Evanston, Illinois 60201

and

W. Benenson, W. A. Lanford,* H. Nann,† and B. H. Wildenthal
Michigan State University,‡ East Lansing, Michigan 48823
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A good-resolution study of the reaction ^{42}Ca$(p,t)^{40}$Ca has revealed the existence of three new 0^+ states in ^{40}Ca at 7698, 8284, and 8438 keV excitation. Arguments are presented to show that these states are indeed the long sought-after 0^+, $T=0$ states with predominantly two-particle, two-hole configurations.

Ever since Gerace and Green[1] identified the 0_2^+ state at 3353 keV in ^{40}Ca as being predominantly four-particle, four-hole (4p-4h) in nature, the most intriguing and challenging question in the spectroscopy of ^{40}Ca has been that relating to the crucially important 0^+ states of the 2p-2h, $T=0$ configuration which have been predicted to lie between 7- and 9-MeV excitation,[1-3] but which have eluded experimental identification so far.[4] In the earlier studies of the reaction ^{42}Ca$(p,t)^{40}$Ca,[4-8] $L=0$ transitions could only be identified to the ground state (g.s.) 0_1^+, the 3353-keV 0_2^+ state, and the 0^+ states with $T=1$ and $T=2$ at about 9.4 and 12.0 MeV, respectively. Further, while the 2p-2h 0^+ states in the 7–9-MeV excitation region were not found, it was noted that the so-called 4p-4h 0_2^+ state at 3353 keV is populated about an order of magnitude more strongly than expected. These observations have led[6-8] to the speculation that perhaps the main part of the 2p-2h, 0^+

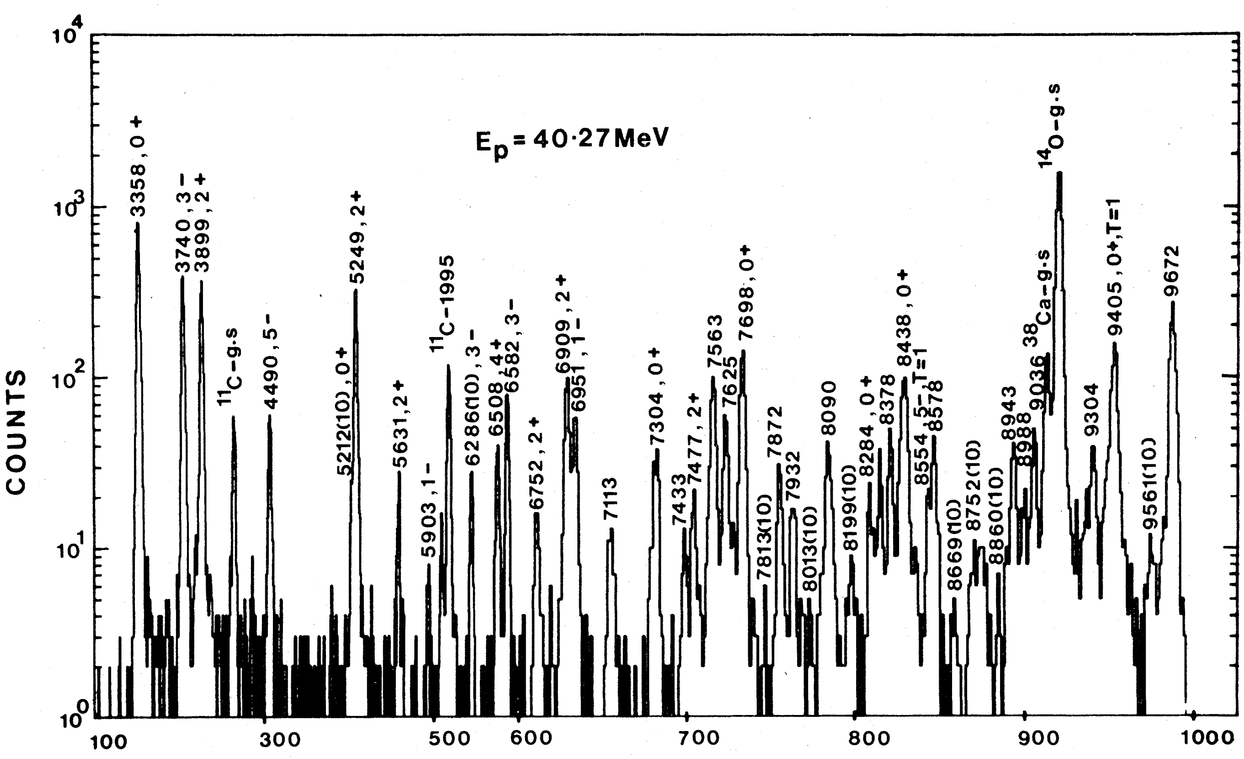

FIG. 1. Spectrum at θ(lab) = 6° for the reaction ^{42}Ca$(p,t)^{40}$Ca. The g.s. transition is not displayed. Excitation energies (in keV) are from the present experiment. Errors are ±5 keV unless otherwise specified. The abscissa has been expanded by a factor of 2 beyond channel number 600.

strength does indeed lie in the 3353-keV state, in contradiction to the theoretical calculations. Before accepting such drastic conclusions, it is necessary to reexamine the situation critically. The unexpectedly strong excitation of the 3353-keV state poses a serious problem, but the problem of the missing 0^+ states in the 7–9-MeV excitation region is even more serious. Several rather dissimilar calculations[1,2] predict two or three 0^+, $T=0$ states in this energy region. It does not appear very likely that extending the configuration space used in these calculations or modifying the interaction will drastically alter the predictions about their existence. It is therefore of crucial importance to make a concerted effort to find the missing 0^+ states. In this Letter we report on just such an experiment, and on our success in finding three "new" 0^+ states at 7698(5), 8284(10), and 8438(5) keV in ^{40}Ca.

The reaction ^{42}Ca$(p,t)^{40}$Ca was studied using the 40.27-MeV proton beam from the Michigan State University cyclotron and an Enge split-pole spectrograph equipped with a single-wire proportional counter in its focal plane. An overall energy resolution of about 22 keV (full width at half-maximum) was achieved. Figure 1 shows a typical spectrum. Most of the known states in ^{40}Ca up to 9.5 MeV were excited. Energy calibration, expected to be accurate to ± 5 keV, was based on the accurately known energies[4,9] of several strong states in ^{40}Ca up to 8.5-MeV excitation and the accurately known Q value for the ^{16}O$(p,t)^{14}$O(g.s.) transition. One significant result of the accurate energy calibration is that for the reaction ^{40}Ca$(p,t)^{38}$Ca we find $Q_0 = -20\,452(5)$ keV. The 1971 mass tables give $Q_0 = -20\,484(16)$ keV.

Absolute cross-section normalization, expected to be accurate to within ± 10%, was based on the known thickness and isotopic analysis of a self-supporting rolled target. Our cross sections are in excellent agreement with those reported by Bayman and Hintz[5] and Schapira *et al.*[6] at $E_p = 40$ MeV. The absolute cross sections recently reported by Debevec[7,8] at $E_p = 41.7$ MeV are about 30% smaller than ours.

In Fig. 2 we show angular distributions for all $L=0$ transitions. The 3353-keV transition shows a first minimum which is displaced by about 2° from that for the g.s. This feature was observed earlier[10] and was attributed to a predominantly d^2 pickup as opposed to the mainly f^2 pickup for the ground state.

In previous (p,t) experiments no clear evidence

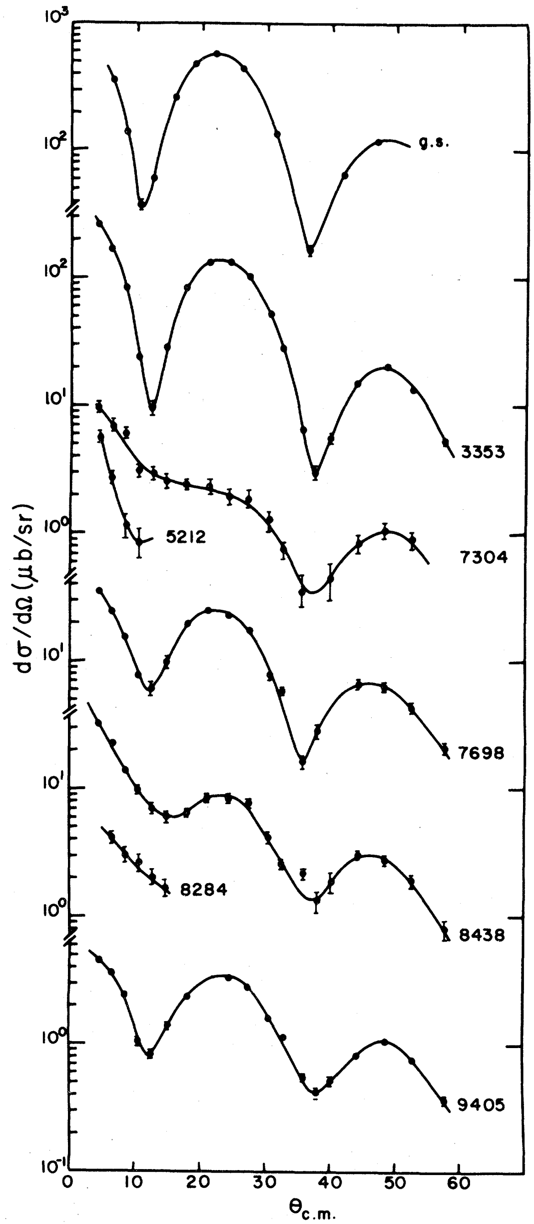

FIG. 2. Measured differential cross sections for all $L=0$ transitions observed in the present experiment. The curves through the points have been drawn only to guide the eye; they have no theoretical significance.

for excitation of the known 0^+ states at 5.2 and 7.3 MeV could be obtained. In the present experiment the weakly excited state at 5212(10) keV could be successfully resolved from the strong 2^+ state at 5249(5) keV at the most forward angles. The expected $L=0$ nature of the transition is confirmed and it is estimated that the strength of this state is ~ 0.5% that of the ground state. The state at 7304(5) keV is found to be weak though clearly identifiable at all angles. The unambiguous $L=0$ transitions to states 7698(5) and 8438(5) keV have not been identified previously. The 7698-keV state was actually observed in earlier (p,t) experiments,[6-8] but since the data were limited to $\theta \geq 12°$, it was misidentified as the 3^- state seen at 7695 keV in $(^3He, d)$ experiments.[11] Nolen[9] has verified that indeed there is a 7-keV doublet at this energy.

In a recent $^{36}Ar(^6Li, d)^{40}Ca$ experiment strong excitation of a 0^+ state at 8280(20) keV has been reported.[12] In our experiment the transition to the state at 8284(10) keV is very weak but can be identified clearly at the most forward angles where it displays $L=0$ behavior. We estimate that this state is populated with a strength about 0.3% of the g.s. A strongly excited 0^+ state has been reported at 8.28 ± 0.1 MeV in a recent $^{38}Ar(^3He, n)$ experiment[13] with 0.4-MeV energy resolution. It most likely corresponds to our weakly excited state at 8284(10) keV but may also include contributions from the 0^+ states at 7698(5) and 8438(5) keV.

In Table I we summarize our results for all the $L=0$ transitions observed. Since the 9405(5)-keV state is the known $T=1$ analog of the lowest 0^+ state in ^{40}K, all the other states are expected to be $T=0$.

We now refer to the two kinds of theoretical calculations which are available. In the "coexistence model" calculations, the states of ^{40}Ca are described as arising from a mixing of the spherical shell-model states and the deformed states constructed by promoting pairs of particles from the filled $d_{3/2}$ shell to the unfilled f-p shells.[1] It has been shown that[7,8,3] these calculations lead to predictions of a completely washed out angular distribution and to an *underestimate* of the cross section to the $0_2{}^+$, 3353-keV state by almost an order of magnitude and an equally

TABLE I. Summary of results.

EXPERIMENT			THEORETICAL CALCULATIONS							
			NEW FP CALCULATIONS[b]						COEXISTENCE CALCULATIONS[a,c]	
J,T	E^*(±keV)	σ(rel)	E^*	σ(rel)	Overlaps $f^2 \pm d^2$	% Components 0p-0h	2p-2h	4p-4h	E^*	σ(rel)
0_1^+,0	0	100.	0	100.	0.973-0.371	56.6	33.7	9.7	0	100
0_2^+	3358(5)	24.0	3525	3.4	0.105+0.405	22.6	11.0	66.4	3500	2.7(6.6)
0_3^+	5212(10)	0.5	5457	2.5	0.031-0.246	11.8	20.2	68.0	5100	(6.2)
0_4^+	7304(5)	0.6	8160	1.4	0.135+0.036	0.1	75.6	24.3	7200	5.1
0_5^+	7698(5)	5.3	8610	1.32	0.109-0.032	3.3	17.6	79.1	7800	
0_6^+	8284(10)	0.3	9637	0.54	0.059-0.046	0.8	26.0	73.2		
0_7^+	8438(5)	2.6	10173	0.08	0.035+0.066	0.5	4.4	95.1		
			10311	0.08	0.037+0.033	0.3	42.3	57.4		
0_8^+,1	9405(5)	7.9	6835	29.	0.167-0.887		69.2	30.8		99
0_9^+,2	11970[a]	12.[a]	11440	58.	0.390-1.133		52.1	47.9		50
0_1^+	0(^{38}Ca)	101.								
0_1^+	0(^{42}Ca)					54.5	44.9	0.6		
						2p-0h	4p-2h	6p-4h		

[a]From Debevec (Ref. 7) and Adelberger *et al*. (Ref. 8).

[b]These results are from the new calculations using the interaction of Federman and Pittel (Ref. 2) (see text). For the calculation of σ(rel) optical-model parameters used by Schapira *et al*. (Ref. 6) were employed.

[c]These numbers are due to Debevec (Ref. 7) and Adelberger *et al*. (Ref. 8) and for $T=0$ states are based on wave functions of Gerace and Green (Ref. 1). The numbers in parentheses are due to Erikson, Horsfjord, and Nilsson (Ref. 3), obtained by introducing triaxial deformations.

large *overestimate* of the cross section to the 0_3^+, 5212-keV state. Recently Erikson, Horsfjord, and Nilsson[3] have tried to improve on this situation by introducing triaxially deformed components which contain admixtures of the $s_{1/2}$ hole state, but have achieved only nominal success.

The first of the "shell-model" type of calculations was done by Federman and Pittel[2] (FP) in the $f_{7/2}d_{3/2}$ basis. To clear up some ambiguities and to remove some unnecessary approximations we have repeated their calculations with the Oak Ridge National Laboratory–Rochester University code using the FP interaction and considering configurations up to 4p-4h in ^{40}Ca and up to 6p-4h in ^{42}Ca. The results in Table I are from these "new" FP calculations. As can be seen, in these "shell-model" calculations also the problems with the 0_2^+ and 0_3^+ states persist, and almost equally serious problems surface for other excited states. We have tried several other interactions which have been used in this mass region but with no improvement in the situation. Within the limited $f_{7/2}d_{3/2}$ basis we have been able to search an interaction for the $A = 38-42$ nuclei which leads to predictions of strong excitation of the 3353-keV 0_2^+ state (26.1% g.s. with well-structured angular distribution) and weak excitation of the 5212- and 7304-keV states (3.3 and 1.2%, respectively). However, such an interaction makes the 0_2^+ state mostly (70%) 2p-2h and the 0_3^+ and 0_4^+ states mostly (72 and 97%, respectively) 4p-4h. It also predicts strong excitation of the 0_2^+ state in the (^{3}He, n) experiment which is contrary to the experiment,[13] and has several other unpalatable consequences for other nuclei in the $A = 38-42$ region. If we consider the 4p-4h nature of the 0_2^+ state as being experimentally established by its very strong population (70% of g.s.) in the reaction ^{36}Ar(^{6}Li, d), we have to conclude that the problems with the (p,t) results reflect either the basic inadequacies of the reaction theory which takes no account of correlations between the two picked-up particles or the basic inadequacy of the $f_{7/2}d_{3/2}$ space.

A clue to the nature of the configuration space required to explain the data is provided by a comparison of the results of our (p,t) pickup experiment and the two stripping experiments. Strong pickup takes place *from* filled orbits and strong stripping takes place *to* empty orbits. The 3353-keV state is populated with appreciable strength (24% of g.s.) by the (p,t) reaction, but only weakly (~ 5% of g.s.) by the (^{3}He, n) reaction. This suggests that this state has an appreciable component of the f^2s^{-2} type. Similarly the very weak population of the 8284-keV state (~ 0.3% of g.s.) in our (p,t) experiment and its strong population (~ 40% of g.s.) in the two stripping experiments would suggest that this state contains appreciable amount of p^2 particles in it. These considerations would suggest that a comprehensive attempt to explain these data requires a configuration space which includes at least $s_{1/2}d_{3/2}f_{7/2}p_{3/2}$ shells. This is much too large a space for the extended shell-model calculations possible at present.

*Now at Yale University, New Haven, Conn. 06520.
†On leave of absence from Institut für Kernphysik der J. W. Goethe Universität, Frankfurt am Main, Germany.
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[1] W. J. Gerace and A. M. Green, Nucl. Phys. A93, 110 (1967), and A123, 241 (1968).
[2] P. Federman and S. Pittel, Phys. Rev. 186, 1106 (1969), also private communication.
[3] T. Erikson, V. Horsfjord, and B. Nilsson, Phys. Lett. 46B, 173 (1973).
[4] P. M. Endt and C. Van der Leun, Nucl. Phys. A214, 1 (1973).
[5] B. F. Bayman and N. M. Hintz, Phys. Rev. 172, 1113 (1968).
[6] J. P. Schapira, M. Chabre, Y. Dupont, and P. Martin, Phys. Rev. C 5, 1593 (197).
[7] P. T. Debevec, Ph.D. dissertation, Princeton University, 1972 (unpublished).
[8] E. G. Adelberger, P. T. Debevec, G. T. Garvey, and R. Ohanian, Phys. Rev. Lett. 29, 883 (1972).
[9] J. A. Nolen, Jr., to be published.
[10] K. K. Seth, H. Ohnuma, T. Suehiro, S. Yamada, and S. Takeda, Phys. Rev. Lett. 30, 132, 250(E) (1973).
[11] K. K. Seth, J. A. Biggerstaff, P. D. Miller, and G. R. Satchler, Phys. Rev. 164, 1450 (1967).
[12] H. T. Fortune, R. R. Betts, J. N. Bishop, M. N. I. Al-Jadir, and R. Middelton, Bull. Amer. Phys. Soc. 18, 1399 (1973), also private communication.
[13] W. P. Alford, R. A. Lindgren, D. Elmore, and R. N. Boyd, Phys. Lett. 46B, 356 (1973).