High-resolution study of ^{40}Ca via inelastic proton scattering at 35 MeV*

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Spectra of inelastic proton scattering on ^{40}Ca have been obtained with 4.5 keV resolution at a bombarding energy of 35 MeV. Cross sections for the excitation of several previously unresolved particle-hole states have been measured. Nearly all known energy levels plus nine new levels have been observed up to an excitation energy of 9.3 MeV, slightly above the proton separation energy, and accurate excitation energies have been determined for these states.

[NUCLEAR REACTIONS $^{40}Ca(p,p')$, $E=35.2$ MeV; measured $\sigma(15°, E_p)$, $\sigma(30°, E_p)$; deduced excitation energies; resolution 4.5 keV.]

I. INTRODUCTION

The states in ^{40}Ca which contain large components of the $f_{7/2}-d_{3/2}^{-1}$ shell model particle-hole configuration have been previously identified in $(^3He,d)$,[1] (d,n),[2] and $(^3He,\alpha)$[3] reaction studies. The observation of these same states via inelastic proton scattering is of particular interest because these cross sections provide a good test of the effective interaction used in the microscopic model for this reaction.

A previous study of the $^{40}Ca(p,p')$ reaction by Gruhn *et al.*[4] was the subject of such a microscopic analysis by Petrovich *et al.*[5] That analysis was very promising but there were significant uncertainties because several of the states of interest were unresolved from nearby levels. For example, the 30 keV resolution of Ref. 4 was inadequate to resolve the first 4^- particle-hole state which is a member of a 16 keV doublet. Also all four of the $T=1$ states were either unresolved or incompletely resolved.

In the (p,p') study of Gruhn *et al.*[4] complete angular distributions were measured at four different beam energies from 25 to 40 MeV. The goal of the present experiment was to supplement this comprehensive study with high-resolution spectra (4.5 keV resolution) at one of the same bombarding energies. In this way even without complete angular distributions relative yields within the previously unresolved doublets were obtained, thereby allowing a more detailed test of the microscopic inelastic scattering theory.

A by-product of the present experiment is the determination of very accurate excitation energies for almost all of the levels of ^{40}Ca up to over 9 MeV. The uncertainties assigned to these excitation energies are 0.3–1.2 keV thereby allowing unambiguous comparison of levels seen in this study with previous γ ray measurements.

II. EXPERIMENTAL METHOD

This experiment used a 35.2 MeV proton beam from the Michigan State University cyclotron (references in Ref. 4). The high-resolution spectra were recorded on Kodak NTB 25 μm nuclear track plates in the focal plane of an Enge split-pole magnetic spectrograph.[6] Two exposures were made for an integrated charge of 3000 μC each at laboratory scattering angles of 15.0 and 30.0°.

The experimental resolution of 4.5 keV full width at half-maximum (FWHM) was obtained by using the spectrometer in the energy loss or dispersion matching mode[7] with a solid angle of 0.3 msr. Spectrograph aberrations limit the ultimate resolution if larger solid angles are used. The resolution was measured and optimized using the on-line tuning procedure described in Ref. 7. The linewidth of the energy levels recorded on the nuclear emulsions was 0.15 mm FWHM. This necessitated scanning the plates in 0.05 mm steps, which was very time consuming. The resulting spectra were very clean, however, with an average background of about 2 counts per channel in a spectrum which had an elastic peak with a height of about 2×10^6 counts.

A 40 $\mu g/cm^2$ target of metallic Ca enriched to 99.9% in ^{40}Ca was prepared by vacuum evaporation onto a 25 $\mu g/cm^2$ backing consisting of a thin carbon foil plus two layers of Formvar. A mixture of 5 mg $CaCO_3$ and Zr powder was heated under vacuum in a Ta tube. The tube was crimped at both ends and had a small hole drilled in its side. First CO_2 was driven off by passing current through the tube to heat it to a dull red color and then the resulting CaO was reduced by the Zr with Ca metal simultaneously evaporating through the hole at a much higher temperature. The target was transferred from the evaporator to a vacuum storage chamber and subsequently to the spectrograph scattering chamber via a vacuum lock system without exposure to air. The target withstood the 1 μA proton beam used for this experiment.

Peak centroids and areas were extracted from the spectra via a Gaussian peak fitting program. The width of each peak was determined independently and not from calibration peaks. In this way impurities which have different linewidths can be identified in addition to the normal kinematics method. Also unresolved close spaced doublets show up in this method as wider than normal lines. Cross sections from Ref. 4 have been used for two or three of the ^{40}Ca states which were unscannable due to their very large yields. Peaks with up to about 5000 counts were scanned with the centroids of the unscannable peaks being determined by visual estimation through the microscope. The present absolute cross sections were obtained by normalizing to the 5^- 4.491 MeV level of Ref. 4.

The energy levels with the most accurate excitation energies listed in the recent Endt and van der Leun compilation[8] were used as calibration lines to assign more accurate energies to the less well known levels. The lines which were used in the calibration as well as the new results are given in the next section. A check on the ^{40}Ca calibration lines is the consistency of the values found here for the ^{12}C 4.439 MeV level and the ^{16}O 6.131 MeV level compared with the values in Refs. 9 and 10, the maximum deviation being 0.5 keV. The scattering angle measurement which was necessary to this comparison was provided by the kinematic position of the broad peak from the ^{1}H(p,p) scattering. Detailed discussion of the calibration procedure used here is given in Ref. 9.

III. RESULTS

The ^{40}Ca(p,p') spectrum recorded at the 15° scattering angle is shown in Fig. 1. The spectrum begins with the first excited state of ^{40}Ca at 3.352 MeV and extends to an excitation energy of 9.3 MeV. The very strong 3^- and 2^+ states at 3.736 and 3.904 MeV, respectively, were not scannable, the strongest scannable state being the 5^- 4.491 MeV level. Impurity lines, some of which are indicated in Fig. 1, have been identified as well known states of ^{12}C, ^{13}C, ^{16}O, and ^{28}Si.

Energy calibration

Eight of the levels of ^{40}Ca which have the most accurately known excitation energies have been used to establish the energy scale for these (p,p') spectra. The excitation energy uncertainties associated with these calibration lines increase from 0.2 keV for the low lying levels to 1.1 keV for a resonance state at 9.136 MeV.[8] The line corresponding to the ^{28}Si first excited state was also used in the calibration procedure. Using these calibration lines a quadratic momentum vs plate position calibration curve was established via the least squares fitting procedure described in Ref. 9. A list of previously known levels in ^{40}Ca from the compilation of Endt and van der Leun[8] is compared with those seen in the present experiment in Table I.

For the states which were well resolved and had

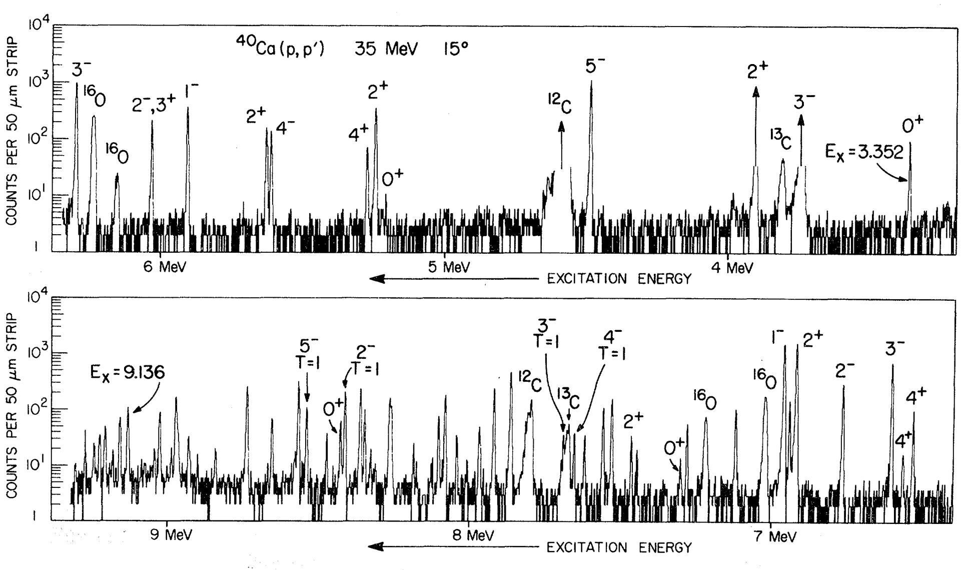

FIG. 1. Spectrum of ^{40}Ca(p,p') at a scattering angle of 15° and a bombarding energy of 35.2 MeV.

TABLE I. Excitation energies and cross sections for levels of ^{40}Ca seen in the (p, p') reaction at 35.2 MeV.

J^{π}; T [a]	E_x [a] (keV)	E_x [b] (keV)	$\sigma_{c.m.}(15.4°)$ [c] (μb/sr)	$\sigma_{c.m.}(30.7°)$ [c] (μb/sr)
0^+	3352.9± 1.3	3352.1± 0.3	126	45
3^-	3736.8± 0.2 [d]	(3736.4)	(11 300)	(13 000)
2^+	3904.4± 0.2 [d]	(3904.1)	(2240)	1536
5^-	4491.5± 0.2 [d]	(4491.5)	1560 [c]	1911 [c]
0^+	5212.2± 0.5	5213.8± 0.5 [e]	13± 30%	<10
2^+	5249.0± 0.3 [d]	(5249.5)	575	162
4^+	5278.9± 0.6	5279.3± 0.3	122	93
4^-	5614.3± 0.3 [d]	(5614.3)	194	286
2^+	5627.9± 0.8	5630.1± 0.3	248	140
1^-	5902.5± 1.3	5903.3± 0.3	503	211
2^-	6025.2± 0.4	6026.2± 0.3 [f]	268	225
3^+	6029.0± 0.5			
3^-	6285.1± 0.3 [d]	(6285.8)	1471	1165
4^+	6509 ±10	6508.4± 0.3	114	131
4^+	6544 ±10	6543.6± 0.4 [e]	32	g
3^-	6581 ± 3	6583.3± 0.3	975	755
2^-	6750.5± 1.5	6750.9± 0.3	410	301
2^+	6909.8± 1.0	6909.1± 0.3	2316	1362
	6930 ±10 [h]	6931.8± 0.3 [i]	190	178
1^-	6951 ± 2	6950.9± 0.4	2457	1106
$(3^-, 6^+)$ [j]	7113.5± 0.4 [h]	7113.9± 0.4	164	312
	7240 ±10	k	<10	<10
	7280 ±10	7278.0± 0.4	76	53
0^+	7300 ±10	7300.7± 0.5	25± 15%	19± 15%
	7399 ±10	k	<10	<5
	7426 ±10	(7425 ±1) [l]	<10	8±40%
	7447.1± 1.4	7447.1± 0.6 [e]	33± 15%	g
2^+	7467.1± 1.7	7466.2± 0.6 [e]	46	g
$(1-3)^-$	7532.6± 1.1	7532.5± 0.5	221	220
	7561.8± 0.6	7561.6± 0.5	146	173
	7625.7± 1.4	7623.5± 0.5	49	70
4^-; 1	7658.8± 0.5 [d]	(7658.5)	59	86
	7676 ±10	7676.4± 0.6 [e]	g	34
3^-; 1	7695.8± 1.4	7694.4± 0.6 [e]	(50) [m]	44
(0^+) [j]		7701.2± 0.6 [e]	g	42
	7768 ±10	(7769.4± 1) [n]	8± 25%	6±25%
	7811 ±10	7814.7± 0.6 [e]	g	15± 15%
	7867 ±10	7871.7± 0.5	696	541
	7928 ±10	7927.9± 0.5	333	394
	7972 ±10	7976.3± 0.6 [o]	92	82
	8016 ±10	(8018.8± 1) [l]	15± 25%	g
		8051.8± 0.6	52	22± 15%
	8092 ±10	8091.2± 0.6	269	340
	8113 ±10	8113.1± 0.6	115	100
	8133 ±10	(8138.1± 1) [l]	≲20	<5
	8186 ±10	(8186.8± 1) [l]	15± 25%	g
		8195.9± 0.6 [e]	33± 15%	g
(0^+) [j]		8271 ±1 [p]	170± 20%	65± 20%
$(0-3)^-$	8275 ± 3	8276 ±1 [p]	250± 20%	72± 20%
	8321 ±10	8323.1± 0.6	23± 20%	44

TABLE I *(Continued)*

J^{π}; T [a]	E_x [a] (keV)	E_x [b] (keV)	$\sigma_{c.m.}(15.4°)$ [c] (μb/sr)	$\sigma_{c.m.}(30.7°)$ [c] (μb/sr)
		8339.1 ± 0.6	36	15 ± 25%
	8357 ± 2	8358.9 ± 0.6	121	50 ± 50%
	8371 ± 10	8373.3 ± 0.6	348	450 ± 20%
2^-; 1	8424 ± 2	8424.2 ± 0.7 [e]	279	g
(0^+) [j]		8439.0 ± 0.7 [e]	100	g
	8481 ± 10 [q]	8484.3 ± 0.7 [e]	50	g
	8535 ± 10	k	<8	g
5^-; 1	8551 ± 2	8551.1 ± 0.7 [e]	169	g
	8578 ± 10 [q]	8578.2 ± 0.7 [e]	439	g
	8626 ± 10 [q]	k	<8	g
	8664 ± 10 [q]	8665.3 ± 0.8 [e]	112	g
	8743 ± 10 [q]	8747.7 ± 0.8 [e]	392	g
	8757 ± 10 [q]	k	<8	g
	8805 ± 10 [q]	k	<8	g
	8848 ± 10 [q]	8850.6 ± 0.9 [e]	42	g
	8904 ± 10 [q]	8909.0 ± 0.9 [e]	24	g
	8931 ± 10 [q]	8938.4 ± 0.9 [e]	66	g
	8977 ± 10 [q]	···	g	g
	8993 ± 10 [q]	8995.0 ± 1.0 [e]	50	g
	9028 ± 10 [q]	9032.7 ± 1.0	177	86 ± 20%
		9050.1 ± 1.0	47	25 ± 40%
	9075 ± 10 [q]	9080.3 ± 1.1	20 ± 25%	15 ± 20%
	9093 ± 1.1 [r]	9093.0 ± 1.1	32 ± 20%	23 ± 15%
	9136 ± 1.1 [r,d]	(9136.1)	177	230
	9158 ± 10 [q]	9162.1 ± 1.1	131	142
	9171 ± 10 [q]	k	<10	<5
		9185.3 ± 1.2	30 ± 15%	25
	9197 ± 10 [q]	k	<12	<5
	9211 ± 10 [q]	9209.9 ± 1.2 [e]	317	g
	9228 ± 12 [s]	9227.5 ± 1.2	75	20 ± 25%
		9246.0 ± 1.2	40 ± 30%	54
	9267 ± 10 [q]	9274.5 ± 1.2	38	33

[a] J^{π}, T, and E_x values from Endt and van der Leun (Ref. 8) compilation unless otherwise indicated.

[b] Excitation energies determined in the present experiment.

[c] Relative cross section uncertainties ±10% limited by plate scanning accuracy. Absolute cross sections normalized to the 5^- 4.491 MeV cross sections of Gruhn *et al.* (Ref. 4). The values used from that work are $\sigma_{c.m.}(15.4°) = 1560$ μb/sr ±6% and $\sigma_{c.m.}(30.7°) = 1911$ μb/sr ±2% for the 5^- state. The values in parenthesis for unscannable states are also from Ref. 4.

[d] States used as calibration lines in present work. Also used was the $^{28}Si(2^+)$ state with $E_x = 1778.7 \pm 0.1$ keV (Ref. 8) which was in the spectrum as an impurity. The values listed for the calibration lines in the present results column are the values obtained in the fitting procedure.

[e] State observed at only one angle.

[f] Excitation energies extracted for this state are 6026.1 and 6026.3 keV at 15° and 30°, respectively. There is no indication of broadening of this line within the 4.5 keV experimental resolution of this experiment.

[g] Obscured by an impurity.

[h] Probably a doublet.

[i] Excitation energies extracted for this state are 6931.9 and 6931.7 keV at 15° and 30°, respectively. There is no indication of broadening of this line within the present experimental resolution.

[j] See text for discussion of these states.

[k] This state not observed at either angle with cross section upper limits as indicated.

[l] Very weak state seen at one angle only. Assignment tentative.

TABLE I *(Continued)*

[m]Estimated cross section for a state partially obscured by an impurity.

[n] This state is very weak at both angles. Assignment tentative.

[o] Probably a doublet with separation ~4 keV.

[p] Incompletely resolved doublet with average centroid energy of 8274.5± 0.8 keV. The summed cross sections at each angle are accurate to ±10%.

[q] Excitation energy from Grace and Poletti (Ref. 12).

[r] Excitation energy derived from (p,γ) resonance energy of Leenhouts and Endt (Ref. 11) and the ^{39}K(p,γ) Q value.

[s] Excitation energy from Fuchs, Grabisch, and Roschert (Ref. 2).

cross sections ≳50 μb/sr in the present experiment the average deviation in excitation energies extracted from the 15° and 30° spectra was 0.1–0.2 keV. Hence the new uncertainties on the excitation energies indicated in Table I are in most cases just slightly larger than those on the nearby calibration lines. Levels which are particularly weak, partially obscured, or seen at only one angle have larger uncertainties indicated.

The identification of all of the calibration lines were unambiguous with the possible exception of the resonance level at 9.136 MeV. Below 9.3 MeV excitation only two resonance levels have been observed,[11] at 9093± 1.1 and 9136± 1.1 keV, respectively. The location of either of these in the present experiment was desirable to provide an accurate calibration energy at high excitation in ^{40}Ca. A preliminary calibration which used no input energies above 7.659 MeV yielded excitation energies of 9094 and 9138 keV for two states in the region of interest with uncertainties of ~5 keV due to the large extrapolation. Since there were no nearby states with which these states could be confused the calibration was rerun using the stronger of the two, the 9136± 1.1 keV level, as a calibration line thereby greatly improving the accuracy of the excitation energy assignments in the region above 8 MeV. Since the (p,γ) reaction tends to locate states which look like ^{39}K$+p$ it is not surprising that these states would be seen in the direct (p,p') reaction. Some states of complex structure which are populated via the compound nucleus in low energy (p,p') spectra, however, may not be seen in either the (p,γ) resonance work or the higher energy (p,p') spectra.

Of the 70 levels in Table I for which there is a comparison with previous energy assignments only 3 disagree by more than the combined errors indicated and none disagree by more than twice the combined errors indicated. The previous measurements of Grace and Poletti[12] listed in Table I as those levels with uncertainties of 10 keV are in much better agreement with the present results than their error bars indicate, the average agreement being within 2 keV.

Cross sections

In addition to the excitation energies there are also listed in Table I the cross sections for the population of the various excited states of ^{40}Ca via the (p,p') reaction at 35.2 MeV at scattering angles of 15° and 30°. As explained earlier the present data were normalized to the cross sections for the 5^- state at 4.491 MeV obtained by Gruhn *et al.*[4] The uncertainties in the cross sections for states with yields ≳30 μb/sr are ±10%, limited by plate scanning reliability. Weaker and partially obscured states have larger percentage uncertainties as indicated in the table. The lower limit in cross section for observable states was 5–10 μb/sr and at this limit eight previously reported levels[8] were not observed whereas nine new states were seen. The eight states not seen here were all seen previously only by Grace and Poletti[12] in a (p,p') experiment at 13 MeV beam energy. It appears, therefore, that there is a slightly different selectivity between the (p,p') reactions at the two different energies, scattering at the low one being dominated by compound nucleus effects while direct processes dominate at the higher energy. The cross sections of states excited in this experiment vary by more than a factor of 2000 : 1, from a cross section of 13 000 μb/sr for the 3^- 3.736 MeV state down to ~6 μb/sr for some of the barely discernable states.

IV. DISCUSSION

The main purpose of the present experiment was to measure the cross sections for population via the (p,p') reaction of several previously unresolved particle-hole states in ^{40}Ca. While the $f_{7/2}$-$d_{3/2}^{-1}$ states were the main ones of interest new information on possible $p_{3/2}$-$d_{3/2}^{-1}$ and other states was also obtained.

$f_{7/2}$-$d_{3/2}^{-1}$ particle-hole states

The energy levels which are believed to contain large components of the $f_{7/2}$-$d_{3/2}^{-1}$ configuration

TABLE II. States of ^{40}Ca which are believed to contain large components of the $f_{7/2}$-$d_{3/2}^{-1}$ configuration and their cross sections in the (p, p') reaction at 35 MeV.

J^{π}; T	E_x (keV)	$\sigma_{c.m.}(15.4°)$ (μb/sr)	$\sigma_{c.m.}(30.7°)$ (μb/sr)
3^-; 0	3737	11 300	13 000
5^-; 0	4492	1560	1911
4^-; 0	5614	194	286
2^-; 0	6026	≲268	≲225
2^-; 0	6751	410	301
4^-; 1	7659	59	86
3^-; 1	7694	~50	44
2^-; 1	8424	279	···
5^-; 1	8551	169	···

are listed separately in Table II and the cross sections are repeated there also. Many of these states were unresolved from nearby levels in previous (p, p') measurements. Portions of the spectra in the regions of some of these states are displayed in Fig. 2. The first 4^- state is 16 keV from a 2^+ state of comparable strength, while the 3^-, $T=1$ and 2^-, $T=1$ states are only 7 and 15 keV, respectively, from previously unknown levels.

The states listed in Table II were chosen because of their large $l=3$ spectroscopic factors in ^{39}K(^{3}He, d)[1] and ^{39}K(d, n)[2] stripping reactions as well as their large $l=2$ transition strengths in the ^{41}Ca(^{3}He, α) pickup reaction.[3] The stripping and pickup yields to the two 2^- states indicated are divided, with the state at 6.751 MeV being stronger than the lower state. According to the wave functions of Gerace and Green[13] this splitting is due to mixing with a 3p-3h deformed state. The same

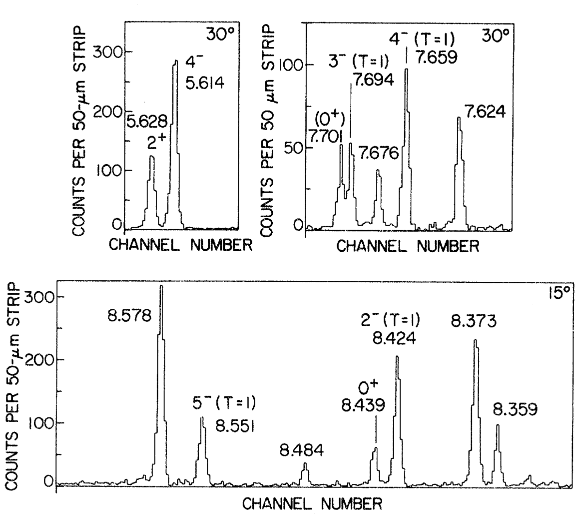

FIG. 2. Spectra of ^{40}Ca(p, p') in the regions of some of the $f_{7/2}$-$d_{3/2}^{-1}$ particle-hole states.

model also predicts the other 1p-1h states to remain relatively free from mixing with deformed states.

Of the states listed in Table II one remains a member of the unresolved doublet consisting of the 2^- and 3^+ states at 6.0252 and 6.0290 MeV,[8] respectively. The 3^+ state, believed to be a member of a 2^+, 3^+, 4^+ $K=2$ rotational band[13] beginning with the 2^+ state at 5.249 MeV, should not be populated in a one-step (p, p') reaction. However, its possible yield via a two-step or coupled channels mechanism is unknown. The centroid of the state seen in the present experiment is closer to that of the 2^- than the 3^+ state. Furthermore this state is not wider than isolated states in the present spectra. With the 4.5 keV resolution of this experiment, the 4 keV doublet would form a noticeably broadened line if the two states had comparable yields. Hence, it is believed that the yield to the 3^+ state in these data is less by a factor of 3 or more than that to the 2^- state of this doublet.

Microscopic (p, p') calculations are currently being carried out[14] in an attempt to properly predict the absolute cross sections to all of these states with realistic nuclear wave functions and an effective nucleon-nucleon interaction derived from the two body data.

$p_{3/2}$-$d_{3/2}^{-1}$ particle-hole states

It is also of interest to try to identify those states in the ^{40}Ca spectrum which are dominantly of the $p_{3/2}$-$d_{3/2}^{-1}$ configuration. These states should have large $l=1$ strength in proton stripping reactions[1,2] and should be seen weakly in the neutron pickup reaction from ^{41}Ca.[3] There are several candidates for the $T=0$ members of this configuration but there are very few spins known in the region of the expected $T=1$ members.

The best candidates for the $T=0$ $p_{3/2}$-$d_{3/2}^{-1}$ states have been selected and listed in Table III with the selections being based on comparisons of stripping and pickup data. There are currently no definitely known 0^- states in ^{40}Ca; the two candidates in the table were chosen based on the work of Tellez, Delaunay, and Ronsin[15] and Fuchs, Grabisch, and Roschert.[2] The tentative 0^- assignments to these states by Tellez *et al.*[15] is based on their primary decay to the 6.95 MeV 1^- state. The present work shows that the state which Tellez saw at 8275 ± 3 keV is a member of a 5 keV doublet (see Table I), the other member probably being a 0^+ state.[16] The 8276 keV level listed in Table III is ~50% stronger in (p, p') than the other member of the doublet at 8271 keV with the higher member of the doublet being listed in the table mainly because it is slightly closer in energy to the 8275

TABLE III. States of ^{40}Ca which are believed to contain large components of the $p_{3/2}d_{3/2}^{-1}$ configuration and their cross sections in the (p,p') reaction at 35 MeV.

J^{π}; T	E_x (keV)	$\sigma_{c.m.}(15.4°)$ (μb/sr)	$\sigma_{c.m.}(30.7°)$ (μb/sr)
(0^-; 0)	8276	~250	~70
(0^-; 0)	8359	121	~50
1^-; 0	6951	2457	1106
$(2)^-$; 0	7533	221	220
3^-; 0	6285	1471	1165
3^-; 0	6583	975	755

keV level of Tellez *et al.*[15]

The spin of the 7533 keV level has not been established definitely, either, but it is the best candidate for the 2^- member of this configuration, based on its $l=1$ stripping strength.[1,2] There are two known 3^- states included in Table III, both probably containing appreciable $p_{3/2}$-$d_{3/2}^{-1}$ components. The lower of these two states has an $l=1$ spectroscopic factor about twice as large in stripping experiments[1,2] and it is also weaker in the pickup experiment[3] than the other 3^- state. Hence the 3^- state at 6285 keV seems to have the largest component of the $p_{3/2}$-$d_{3/2}^{-1}$ configuration.

Microscopic (p,p') calculations similar to those being done for the $f_{7/2}$-$d_{3/2}^{-1}$ particle-hole states are also being done for the $p_{3/2}$-$d_{3/2}^{-1}$ states.[14]

0^+ states in ^{40}Ca

New results from the present experiment and a recent ^{42}Ca(p,t) study[16] have increased the number of known 0^+ excited states in ^{40}Ca to nine. There is a variation in cross section of ~20× from the weakest to the strongest 0^+ seen in the (p,p') reaction. (There are currently no measured cross sections to the 0^+ states above 9.3 MeV in ^{40}Ca.) A complete understanding of the structure of all these 0^+ states and their relative yields in various direct nuclear reactions does not currently exist. Adelberger *et al.*,[17] for example, have recently pointed out some anomalies in the $l=0$ transitions from the ^{42}Ca(p,t) reaction.

In Table IV are the currently known 0^+ states in ^{40}Ca and their approximate yields relative to the ground state transitions in various nuclear reactions. The table also includes the (p,p') cross sections measured in the present experiment. Weak 0^+ transitions in the ^{42}Ca(p,t) reaction[16] were observed to states at 7698 ± 5, 8284 ± 10, and 8438 ± 5 keV, but there were no previously known energy levels in ^{40}Ca near these energies to which these spin assignments could be made. The present (p,p') spectra show each of these states as new energy levels near previously known states with spin assignments other than 0^+. Previously 0^+ states were seen at 8280 ± 20 keV in the $(^6\text{Li},d)$ experiment[18] and at 8280 ± 100 keV in $(^3\text{He},n)$.[19] This state is now seen to be a member of a 5 keV doublet with the nearby state probably being a 0^- state as discussed in the previous section. The 0^+ member of this doublet has a cross section larger than the other 0^+ states seen in this experiment.

6^+ states in ^{40}Ca

In contrast to the large number of known 0^+ states in ^{40}Ca there are currently no 6^+ states listed in this nucleus,[8] even though there are shell model predictions[20] for such states below 8 MeV

TABLE IV. The 0^+ states in ^{40}Ca and their yields in various nuclear reactions.

E_x (MeV)	Relative Yields (p,t) [a]	$(^3\text{He},n)$ [b]	$(^6\text{Li},d)$ [c]	Cross sections in (p,p') at 35 MeV 15.4° (μb/sr)	30.7 (μb/sr)	Primary Structure
0.0	1.00	1.00	1.00	Elastic		0p-0h
3.352	0.21	0.06	0.70	126	45	4p-4h
5.214	0.005	<0.03		13	10	
7.301	<0.01	···		25	19	(8p-8h)
(7.701)	~0.04	···		···	42 }	
(8.271)	0.003	0.40		170	65 }	(2p-2h)
(8.439)	0.02	···		100	··· }	
9.38	0.06	0.26				$T=1$, 2p-2h
10.65	···	0.10				?
11.98	0.10	0.18				$T=2$, 2p-2h

[a] References 16 and 17.
[b] Reference 19.
[c] Reference 18.

excitation. The present cross section ratio between 15° and 30° gives evidence for the possible existence of a 6^+ state at 7114 keV. There was previous evidence[21] that this state may be a doublet, but the spins proposed at that time were 2 and 3. The state was seen via $l=1$ in proton stripping experiments[1,2] and a mixture of $l=0$ and 2 in the neutron pickup experiment,[3] with 3^- being the only spin assignment consistent with these results. A (6^+) state was reported at 7.12 MeV by Bauer *et al.*[22] in a low-resolution (α, α') experiment and an $l=5$ transition was seen to a state at 7.114 MeV in (p, p') by Gruhn *et al.*[4] Considering that a weak yield to the 3^- member of this doublet could have shifted an $l=6$ angular distribution to look more like an $l=5$ in the (p, p') experiment, there does now seem to be relatively consistent evidence for a 3^-, 6^+ doublet with ~1 keV spacing at 7114 keV excitation in ^{40}Ca.

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