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ELASTIC AND INELASTIC PROTON SCATTERING FROM ^{40}Ca AND TWO-PARTICLE, ONE-HOLE STATES IN ^{41}Sc

A. Marinov, Ch. Drory, E. Navon, J. Burde, and G. Engler
Department of Physics, The Hebrew University, Jerusalem, Israel
(Received 7 May 1969)

The elastic and inelastic scattering of protons by ^{40}Ca were studied at bombarding energies from 4.8 to 6.2 MeV. 60 resonances were identified. The spins of most of them and their partial widths for decay to the ground state and to the first four excited states in ^{40}Ca were determined. Levels in ^{41}Sc having configurations with a large two-particle, one-hole component were identified and compared with similar levels in ^{41}Ca.

According to the simple shell-model theory, ^{40}Ca is a doubly magic nucleus and therefore the reaction ^{40}Ca$(d,p)^{41}$Ca should have only a few strong transitions. However, a study of this reaction[1] yields 120 levels below an excitation energy of 6.83 MeV. The angular distributions of the proton groups leading to most of these levels are isotropic, and further study of their character is desirable.

In order to elucidate the character of the many nonstripping levels in ^{41}Ca and their relation to excited states in ^{40}Ca, it is useful to study their isobaric analogs in the mirror nucleus ^{41}Sc. Study of resonances obtained by the (p,p) and (p,p') reactions on ^{40}Ca could give information about the l value of the captured proton and in many cases about the spins of these states, as well as their reduced widths for decay to the ground state and to excited states of ^{40}Ca. In particular, as the 3^- and 5^- states, at excitation energies of 3.74 and 4.49 MeV, respectively, have strong one-particle, one-hole (1p-1h) components,[2] large reduced widths for inelastic proton scattering leading to these states would indicate large two-particle, one-hole (2p-1h) components for the levels in ^{41}Sc. On the other hand, a large reduced width for the inelastic channels leading to the 0^+ and 2^+ states at 3.35 and 3.91 MeV excitation, respectively, would show that the configuration of the level in ^{41}Sc is more complicated. The results may be compared with those obtained in ^{41}Ca by the (d,p) reaction[1,3] and also by the reaction ^{39}K$(^3$He$,p)^{41}$Ca.[4-6] This last reaction selectively populates 2p-1h states in ^{41}Ca. Such a study has been made previously[7] in the range of excitation energies of 7.5 to 8.3 MeV. However, no spectroscopic information was obtained. The present Letter summarizes the results obtained in ^{41}Sc at the lower excitation energies of between 5.83 and 7.14 MeV.

A natural calcium target of 60 μg/cm^2 was bombarded with 4.8- to 6.2-MeV protons from the tandem Van de Graaff accelerator. Excitation functions of elastic and inelastic proton scattering leading to the ground state and to the 0^+, 3^-, and 2^+ excited states were measured at 90°, 125°, and 160°. Proton spectra were recorded (over most of the energy region) at intervals of 2.4 keV, using surface-barrier silicon detectors. Special precautions have been taken to increase the ratio of peak to background and a ratio of 10 000:1 was obtained for the elastic peaks.

60 resonances were identified. Angular distributions of the inelastically scattered protons leading to the 0^+, 3^-, and 2^+ excited states were measured at backward angles at bombarding energies corresponding to most of the peaks observed in the excitation curves. For some of these resonances the angular distributions were measured in the forward direction as well. Table I summarizes the results. The first column lists the excitation energies of the levels in ^{41}Sc

Table I. Data on levels in ^{41}Sc observed by protons elastic scattering and inelastic scattering leading to the 3.35 MeV(0^+), 3.74 MeV(3^-), and 3.91 MeV(2^+) states in ^{40}Ca.

						Mode of Decay: 0^+ at 3.35 MeV					3^- at 3.74 MeV					2^+ at 3.91 MeV				
E_x (MeV)	l	J^π	Γ (keV)	Γ_p (keV)	$\Gamma_p/\Gamma_p(s.p.)$	l	j	σ_{in} (mb)	Γ_p' (keV)	$\Gamma_p'/\Gamma_p'(s.p.)$	l	j	σ_{in} (mb)	Γ_p' (keV)	$\Gamma_p'/\Gamma_p'(s.p.)$	l	j	σ_{in} (mb)	Γ_p' (keV)	$\Gamma_p'/\Gamma_p'(s.p.)$
5.834	2		8.7	8.7	0.010															
5.867	3		12.3	12.3	0.12															
5.969	3		6.6	6.6	0.060															
5.981	1	$3/2^-$	8.7	8.7	0.0044	1	3/2	41.3	0.30	0.043										
6.011	0	$1/2^+$	26.7	26.7	0.0060															
6.045	1	$3/2^-$	12.1	12.1	0.0060	1	3/2	63.5	0.72	0.077										
6.083													X[a]							
6.129	2		2.9	2.9	0.0030															
6.145	2	$5/2^+$	2.9	0.58[b]	0.00055						1		41.5	0.37[b]	0.19[b]					
6.201	1	$3/2^-$	6.5	6.5	0.0030	1	3/2	19.3	0.12	0.0073										
6.234	3		8.3	8.3	0.058															
6.257				X																
6.312								X												
6.324								X					X							
6.333}	0	$1/2^+$}	27.9	27.9	0.0055	0	1/2	X												
6.359}	2	$5/2^+$}	2.8	0.196	0.00016	2	5/2	63.5	1.7	0.28			X			0	1/2	32.6	0.86	0.07
6.397	2	$(3/2^+)$	8.1	0.31	0.00024						1	3/2	37.1	7.8	1.0					
6.410	2	$5/2^+$	6.0	6.0	0.0047	2	5/2	47.6	0.185	0.026			X			0	1/2	36.4	0.141	0.0085
6.434	3	$5/2^-$	10.4	10.4	0.060						2 0	}(5/2) } 1/2	22.4	0.149 0.007	0.096 0.00018	1		37.3	0.262	0.064
6.456	(1)	$(3/2^-)$	4.9	4.9	0.0020											(1)		9.8	0.048	0.011
6.468	3		12.1	12.1	0.067								X					X		
6.474								X												
6.504																		X		
6.512	2	$5/2^+$	18.8	18.8	0.014	2	5/2	16.1	0.206	0.021						0	1/2	24.1	0.308	0.012
6.520								X												
6.532	2	$5/2^+$	1.3	0.03	0.000023						1	1/2[c]	28.1	1.27	0.10					
6.570	3	$5/2^-$	4.5	4.5	0.023											1		47.6	0.143	0.017
6.580}	(0;2)		4.5	4.5		(0;2)		X}												
6.589}	(1)					(1)		X}												
6.608}	0	$1/2^+$	9.5	9.5	0.0017	0	1/2	X}												
6.621}	2	$5/2^+$	3.2	3.2	0.0022	2	5/2	X}								0	1/2	87.6	0.193	0.0048
6.641								X										X		
6.650[d]	4	$9/2^+$	4.0	0.040	0.0012						1	3/2	21.4	3.57	0.15					
6.691	1	$3/2^-$	3.2	0.18	0.000066	1	3/2	6.9	0.42	0.0049						1	(1/2)[c]	42.5	2.6	0.20
6.700	2	$5/2^+$	6.2	0.58	0.00038	2	5/2	33.9	1.57	0.088	1	1/2[c]	26.7	1.23	0.046	0	1/2	59.5	2.76	0.047
6.728																		X		
6.741	2	$5/2^+$	7.2	7.2	0.0046						1	1/2[c]	47.8	0.243	0.0077	0		23.8	0.121	0.0018
6.750													X					X		
6.783	3	$5/2^-$	10.4	10.4	0.044			28.6								1		32.4	0.240	0.013
6.825	2	$5/2^+$	4.1	4.1	0.0024	2	5/2	10.1	0.030	0.0011	1		26.3	0.078	0.0020	0	1/2	25.8	0.077	0.00078
6.840	3	$5/2^-$	6.3	0.63	0.0026						0	1/2	29.9	1.36	0.0080	1		93.6	4.25	0.17
6.851	1	$3/2^-$	9.6	9.6	0.0033											1	3/2[c]	53.1	0.55	0.022
6.870	1			X																
6.879[e]	4	$9/2^+$	1.3	0.15	0.0041								58.5			2	5/2	154	0.79	0.16
6.894[f]			3.4																	
6.905	3		6.9	6.9	0.027															
6.920	(3)		4.5	4.5	0.017						(0)	(1/2)	21.8	0.072	0.00035	(1)		61.9	0.203	0.0063
6.955	(2)		1.3	0.026	0.000015						(1)		28.1	1.28	0.023					
6.966	2	$5/2^+$	6.9	6.0	0.0033						1	1/2[c]	152	0.88	0.015					
6.995	4	$9/2^+$	1.3	0.024	0.0006						1	3/2	27.3	0.88	0.014	2	5/2	13.3	0.427	0.055
7.000	1		<1.0	<1.0														X		
7.020																		X		
7.028	2	$5/2^+$	3.2	0.26	0.00014						1		99.3	2.94	0.041					
7.066	3	$5/2^-$	9.3	2.8	0.0095											1		122	2.8	0.056
7.076																		X		
7.104	2	$5/2^+$	19.8	5.5	0.0029						1		264	14.3	0.16					
7.104[g]	(4;2)	$(7/2^+,5/2^+)$	3.4																	
7.110	(1;3)	$(3/2^-,5/2^-)$	14.0													1		25.7		
7.121	2} 1}	$3/2^+$} $1/2^-$}	7.7					51.5												
7.140	2	$5/2^+$	12.0	1.3	0.00066						1	3/2[c]	109	9.0	0.095	0	1/2	22.9	1.9	0.0081

[a]The letter "X" in a particular channel indicates that de-excitation via this channel has been observed, however, the cross section is low and the parameters of the level have not been determined.

[b]The fits of the elastic excitation curves give $\Gamma_p/\Gamma \cong 0.2$. However, in this case the sum of Γ_p and Γ_p' as quoted in the Table is not equal to Γ, and the reason for this is not known. From the inelastic results alone, assuming $\Gamma_p + \Gamma_p' = \Gamma$, one gets either $\Gamma_p/\Gamma = 0.975$ or $\Gamma_p/\Gamma = 0.025$ and vice versa for Γ_p'/Γ.

[c]The angular distribution can be explained if assuming the above spin of the outgoing protons. However, the possibility of a particular interference between $j_{out} = 1/2^-$ and $j_{out} = 3/2^-$, althouth unlikely, cannot be completely excluded.

[d]This level de-excites also via the 5^- state in ^{40}Ca. The following parameters have been determined. $l_{out} = 1$; $\sigma_{in} = 2.9$mb; $\Gamma_p' = 0.48$ keV; $\Gamma_p'/\Gamma_p'(s.p.) = 1.4$.

[e]This level de-excites also via the 5^- state in ^{40}Ca. The following parameters have been determined. $l_{out} = 1$ and 3; $\sigma_{in} = 9.0$mb; $\Gamma_p' = 0.046$ keV; $\Gamma_p'/\Gamma_p'(s.p.) = 0.026$ (if only $l_{out} = 1$ contributes); $\Gamma_p'/\Gamma_p'(s.p.) = 5.5$ (if only $l_{out} = 3$ contributes).

[f]This level decays via the 5^- state in ^{40}Ca with a cross-section of about 5.6 mb.

[g]This level, which has the same energy as the previous one, de-excites via the 5^- state in ^{40}Ca and has an entirely different width. σ_{in} (to 5^-) is 26.0 mb. As it is impossible to know if it also de-excites via the 3^- state in ^{40}Ca it is difficult to deduce the other parameters.

assuming that the Q value of the reaction ^{40}Ca(p, γ)^{41}Sc is 1.082 MeV.[8] The l values of the captured protons were obtained from the shape of the resonances in the elastic scattering excitation curves. The spins of the states were obtained from the angular distributions of the inelastically scattered protons leading to the 0^+, 3^-, and 2^+ excited states in ^{40}Ca. In a few cases de-excitation to the 5^- state at 4.49 MeV was also observed. The angular distributions of most of the resonances were analyzed, assuming isolated resonances and that only the lowest possible outgoing waves contribute to the reactions. Because of the low energies of the outgoing protons, there is about a factor of 100 between the penetrabilities of the p and f waves and similarly a factor of 20 for the s and d waves. Therefore, the above assumption is justified, and it is also consistent with the data. In some cases the angular distributions could be fitted only by assuming two overlapping resonances, and in a few other cases the assumption of interference between two outgoing waves of different l values was necessary. The width of the resonance Γ was taken in most cases as the full width at half-maximum of the inelastic peaks corrected for target thickness and spreading of the beam. For those resonances where no measurements in the forward direction were made, the inelastic cross sections were calculated assuming symmetry around 90°. $\Gamma_{p'}$ was found using the Breit-Wigner single-resonance formula and assuming $\Gamma = \Gamma_p + \sum \Gamma_{p'}$. This yields two possible solutions for Γ_p/Γ and for $\Gamma_{p'}/\Gamma$. Usually these solutions are of the form $\Gamma_p/\Gamma \cong 1$ and $\Gamma_p/\Gamma \ll 1$ and the choice between these two solutions was made by comparison with the elastic proton scattering, taking into account interference from neighboring resonances.[9] Listed in Table I are the values of Γ, Γ_p, and the ratios of Γ_p to the single-particle widths Γ_p(s.p.) for the elastic channel. The single-particle widths are calculated using a real potential of Saxon-Woods shape[10] with reasonable parameters.[11] The widths were calculated with an optical model program for each value of l, at low energy, and then corrected for the true energies by the penetrability factors. Table I also gives the l values and where possible, the j values of the outgoing waves leading to the 0^+, 3^-, and 2^+ excited states, together with σ_{in}, $\Gamma_{p'}$, and $\Gamma_{p'}/\Gamma_{p'}$(s.p.), the inelastic cross sections, partial widths, and the ratios of the partial widths to the single particle widths, respectively. Four levels at excitation energies of 6.650, 6.879, 6.894, and 7.104 MeV showed significant widths for the inelastic channel leading to the 5^- state and the results are given in the comments of Table I.

It may be seen from Table I that, though in most cases the values of $\Gamma_{p'}/\Gamma_{p'}$(s.p.) are quite small, they are usually larger than the corresponding values of Γ_p/Γ_p(s.p.). Also, for exit channels with $l_{\text{out}} = 1$, a small value of $\Gamma_{p'}(l_{\text{out}} = 3)$ which would hardly affect the angular distribution, would yield a large value of $\Gamma_{p'}(l_{\text{out}} = 3)/\Gamma_{p'}$(s.p.). The results show that, in addition to the large number of resonances decaying to the 0^+ and 2^+ excited states of ^{40}Ca, a number of the resonances clearly decay predominantly to the 3^- state and some also decay to the 5^- state. These states of ^{41}Sc may be identified as having configurations with a large 2p-1h component. The states at 6.145, 6.397, and 6.532 MeV may be identified as the analogs of the states at 6.091, 6.338, and 6.488 MeV, respectively, found in ^{41}Ca via the reaction ^{49}K(^{3}He, p)^{41}Ca by Belote et al.[6] and that at 7.026 MeV with the level at 6.990 MeV in ^{41}Ca found by Seth et al.[5] In addition we observed several further levels which de-excite via the 3^- state and also via the 5^- state. The analogs of most of them are beyond the range of energy studied in Ref. 6, and although they are not quoted by Seth et al.[5] they may be seen in their results. In the region of excitation between 5.83 to 6.88 MeV, we identify a total of 44 levels; in the equivalent region in ^{41}Ca 50 levels have been found by Belote, Sperduto, and Buechner.[1] However, as there is no spectroscopic information available for the levels in ^{41}Ca, detailed correspondence is not possible. Bolsterli et al.[3] suggest intermediate structure of 2p-1h character in ^{41}Ca at $E_x = 4.8$, 5.1, 6.0, 6.3, 6.4, and 6.6 MeV. No simple correlation could be found between their results and the states with significant component of 2p-1h configuration identified in ^{41}Sc. Although one may argue that the structure at $E_x = 6.0$, 6.4, and 6.6 MeV corresponds to the states at 6.145, 6.397-6.434, and 6.650 MeV, respectively, there are other levels in the vicinity of these states which have different spins and parities and significant reduced width for decay to the 0^+ and 2^+ excited states. The only indication of intermediate structure may perhaps be seen in the vicinity of $E_x = 7.1$ MeV where there are three $\frac{5}{2}^+$ states which de-excite via the 3^- state in ^{40}Ca. No data exist for the corresponding region of excitation in ^{41}Ca.

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PARITY-FORBIDDEN ALPHA DECAY OF SOME O^{16} LEVELS

M. Gari and H. Kümmel*
Max-Planck-Institut für Chemie (Otto-Hahn-Institut), Mainz, Germany
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The theory of the parity-nonconserving alpha decays from the 2^- (8.88 MeV), 0^- (10.937 MeV), and 3^+ (11.05 MeV) O^{16} levels is developed. Using the weak nucleon-nucleon interaction of Blin-Stoyle and Herczeg and known O^{16} wave functions modified by short-range correlations via the Bethe-Goldstone equation, the irregular alpha widths have been related to known regular widths. The influence by the hard core of the strong interaction has been studied.

Measurements of alpha particles produced by the parity-nonconserving weak interaction are under way.[1] Although having the disadvantage of being second order in the weak-coupling constant G, there are also some advantages over the polarization measurements,[2-4] which are of first order in G. Some of the corresponding irregular widths are as small as 10^{-13} keV. Yet with experimental techniques presently available one is able to measure this small quantity with reasonable accuracy—better than just the order of magnitude. The theory is relatively simple and reliable, since the irregular widths Γ_{irr} can be related to known regular widths Γ_{reg}. Also, the proportionality to G^2 yields a stronger dependence of the result on the details of the weak interaction, such that one possibly can decide whether the conserved-vector-current (CVC) theory is valid or not.

We have computed the admixtures of "wrong parity" to the O^{16} states 2^- at 8.88 MeV and 0^- at 10.937 MeV (and estimated the same for the 3^+ state at 11.05 MeV). This admixture, e.g., to the state 8.88, is given by

$$|8.88, 2^+\rangle_{adm} = \sum_i F_i |i, 2^+\rangle \tag{1}$$

with

$$F_i = \frac{\langle i, 2^+ | V_{weak} | 8.88, 2^-\rangle}{E_i - E(8.8)}. \tag{2}$$

Now, using the basic formula[5] for the α-decay width

$$\Gamma = P_L (2MR)^{-1} |\langle \text{daughter} + \alpha | \text{parent} \rangle_R|^2 = P_L \gamma_L^2 \tag{3}$$

[with $R \approx$ sum of daughter and α-particle radii, $P_L(E, R)$ = penetrability for angular momentum L], one obtains the irregular width

$$\Gamma_{irr} = \frac{P_L}{2MR} |\sum_i F_i \langle \text{daughter} + \alpha | i, 2^+ \rangle|^2. \tag{4}$$

In the case of the 8.88 level, to a very good approximation only the 6.9, 9.843, and 11.5 states contribute, since other states have a large energy denominator and/or small experimental reduced widths γ_L^2. For the 0^- (10.9-MeV) level the only contribution comes from 0^+ (11.25 MeV). In the latter case, thus,

$$\Gamma_{irr}^{10.9} = \frac{P(10.9, R)}{P(11.25, R)} |F_{11.25}|^2 \Gamma_{reg}^{11.25}, \tag{5}$$

where $\Gamma_{reg}^{11.25}$ is the experimental width of the α