Is the First Excited 0^+ State in ^{44}Ca of 6p-2h Character?*

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The ^{40}Ar(^{6}Li,d) reaction has been used to investigate the structure of the low-lying states of ^{44}Ca. Cross sections are small (a few μb/sr) but angular-distribution shapes are consistent with a direct process. The results suggest considerable mixing between low-lying four-particle and six-particle–two-hole states in ^{44}Ca.

Sophisticated shell-model calculations[1,2] for the even-even Ca isotopes have consistently failed to reproduce the second 0^+, 2^+ states in these nuclei. In particular, in ^{44}Ca, the 0^+ state at $E_x = 1.90$ MeV and the 2^+ state at 2.67 MeV are apparently not capable of being described within the fp-shell model, even though the 0^+ ground state and the 2^+ state at $E_x = 1.16$ MeV are within the model. One of the more attractive of the possible configurations for the 0_2^+ and 2_2^+ states is that they have a six-particle–two-hole (6p-2h) character.[3] In this description the six particles are in the fp shell and the two holes in the sd shell. Since the ground state of ^{40}Ar is predominantly of the structure $\nu(f_{7/2})^2\pi(d_{3/2})^{-2}$, one would expect that 6p-2h states in ^{44}Ca would be reached strongly by adding 4 fp nucleons, properly coupled, to the ^{40}Ar ground state. Four-particle (4p) states, on the other hand, would be formed in such a process by adding two nucleons to the fp shell and two to the sd shell. These two situations are summarized pictorially in Fig. 1.

Since many more positions are available for adding nucleons into the fp shell (the fp shell is almost empty) than into the sd shell (the sd shell is almost full), one would, in the simplest picture, expect the cross section for adding four nucleons to the fp shell to be much larger than the cross section for adding two fp-shell nucleons and two sd-shell nucleons. If we consider only the $f_{7/2}$ part of the fp shell, and treat neutrons and protons separately, then we can add two fp-shell protons to the ^{40}Ar ground state in $28 = \frac{1}{2}\times 8\times 7$ ways. On the other hand, we can put two protons into the sd shell in just one way – into the $d_{3/2}$ proton holes of the ^{40}Ar ground state. The situation for the neutrons is the same in both cases. One would thus naively expect that the 6p-2h cross section would be about 28 times the 4p cross section. This simple argument ignores the structure factor, which is different in the two cases. However, such overlap factors are not expected to differ by more than a factor of about 2 or 3. Thus, if the ground state has pure 4p character and 0^+ state at 1.90 MeV has pure 6p-2h character, we would expect the cross section for adding four particles to ^{40}Ar to be approximately an order of magnitude stronger for the 1.90-MeV state than for the ground state. Furthermore, for pure configurations, one would expect the same enhancement for the 2.67-MeV 2^+ state over the 1.16-MeV 2^+ state. A similar enhancement effect has been seen previously. For example, in the α-transfer reaction on ^{12}C, [4] the 4p-4h states in ^{16}O were excited much more strongly than was the 0p-0h ground state.

We have investigated the low-lying states of ^{44}Ca using the (^{6}Li, d) reaction to add four nucleons to the ^{40}Ar ground state. The experiment was performed with a 22-MeV ^{6}Li^{+++} beam from the University of Pennsylvania tandem Van de Graaff accelerator. Several previous experiments[4,5] have indicated that at such bombarding energies, the reaction mechanism is dominantly one of direct α transfer.

The target consisted of 25 Torr (53 μg/cm^2) of natural Ar contained in a differentially pumped gas cell.[5] The outgoing deuterons emerged through exit windows of 520-μg/cm^2 Mylar and were momentum-analyzed in the University of Pennsylvania multi-angle magnetic spectrograph. The plates were exposed for a total collected charge of 25 000 μC.

The angular distributions of deuterons leading to the lowest five states of ^{44}Ca are displayed in Fig. 2. Firstly, it is noted that the angular distributions have shapes which are typical of a direct process – even though the cross sections are extremely small (a few μb/sr). The curves are not intended as fits, but *are* the results of distorted-wave calculations using published optical-model parameters.[6,7] The curves tend to emphasize the direct nature of the angular distributions. Secondly, it is noted that the ground state is excited more strongly than is the 0^+ state at 1.90 MeV. The lower 2^+ state at 1.16 MeV is also stronger than the 2^+ state at 2.67 MeV. Thirdly, the ratio of 0^+ cross sections is very nearly the same as the ratio of 2^+ cross sections. This last feature would appear to indicate that the relationship between the first two 2^+ states is similar to that between the first two 0^+ states.

These results were all to be expected, *except* for the larger cross section to the 0_1^+ and 2_1^+ states than to the 0_2^+ and 2_2^+ states. Without strong mixing of the 4p and 6p-2h states, it is difficult to see how one could have a larger cross section for the lower states. If the 4p and 6p-2h states do mix to form the 0_1^+, 0_2^+, 2_1^+, and 2_2^+ states, then we may write

$$|0_1^+\rangle = \alpha|4p\rangle + \beta|6p\text{-}2h\rangle,$$
$$|0_2^+\rangle = -\beta|4p\rangle + \alpha|6p\text{-}2h\rangle,$$
$$\alpha^2 + \beta^2 = 1,$$

and similarly for the 2^+ states.

If one then makes some assumption concerning the ratio of 4p cross sections and 6p-2h cross sections to be expected on theoretical grounds, then the observed ratio of cross sections $\sigma(0_1^+)/\sigma(0_2^+) \approx 2$ can be used to estimate the values of α and β. For example, if $\sigma(6p\text{-}2h) = \sigma(4p)$, then we obtain $\beta^2 \approx 0.03$, $\alpha^2 \approx 0.97$; whereas if $\sigma(6p\text{-}2h) = 10\sigma(4p)$, we get $\beta^2 \approx 0.38$, $\alpha^2 \approx 0.62$. The actual situation probably lies between these two extremes.

Further indication concerning the possible mixing of these states comes from the neutron stripping reaction on ^{43}Ca.[8] There, the 0^+ state at 1.90 MeV was observed to have a spectroscopic factor roughly 20% of the value for the ground state. The sum of these two spectroscopic factors is only slightly less than the theoretical value[1,2] for the ground state. Thus, the indication is that the shell-model ground state is mixing with some other state which is not in the model calculations in order to produce the two low-lying 0^+ states. Furthermore, the $l = 3$ spectroscopic factor for the 2^+ state at 2.67 MeV is slightly larger than the value observed for the 2^+ state at 1.16 MeV. Again the summed spectroscopic factors roughly give the theoretical value.

In conclusion, the weak cross section observed in the $^{40}Ar(^6Li, d)^{44}Ca$ reaction to the 0^+ and 2^+ states at 1.90 and 2.67 MeV, respectively, is difficult to reconcile with the suggestion that these states have pure 6p-2h character. The weak cross section can be explained if the 4p states and 6p-2h states mix strongly. Single-nucleon spectroscopic strengths are not in disagreement with such mixing. If such mixing is not the explanation, it would appear that the only remaining possibility is that the 6p-2h states lie at a much higher excitation energy in ^{44}Ca.

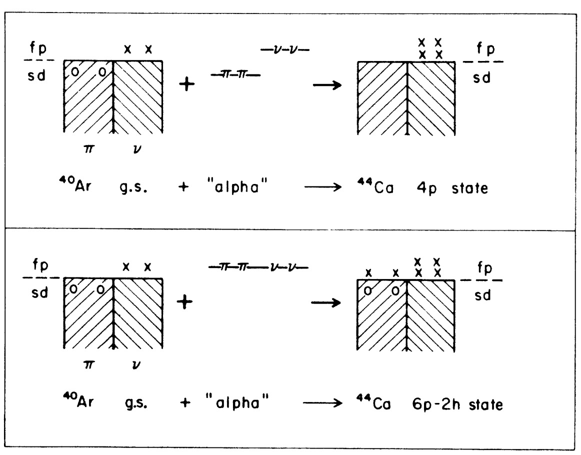

FIG. 1. Pictorial representation of an α-transfer reaction on the ^{40}Ar ground state leading to four-particle (top) and six-particle–two-hole (bottom) states in ^{44}Ca.

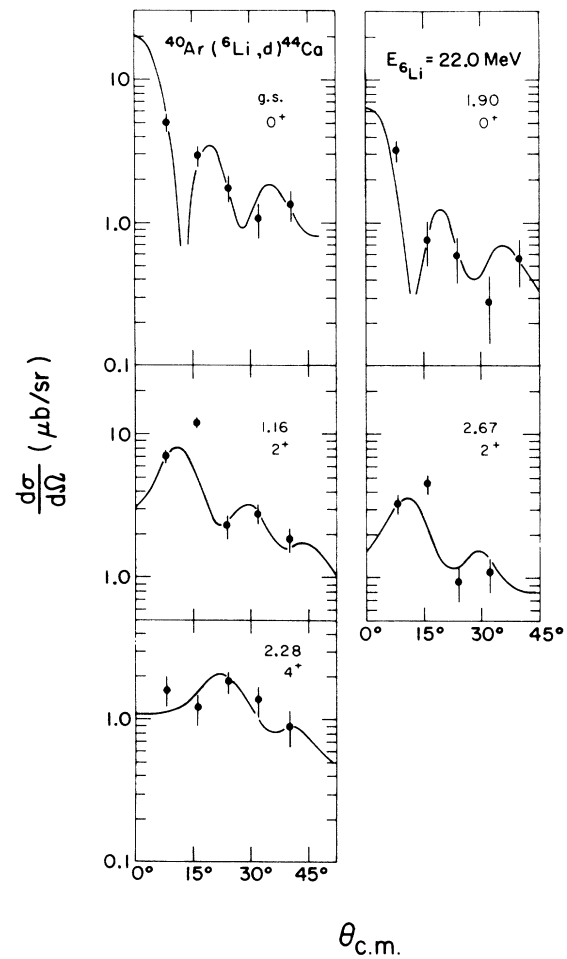

FIG. 2. Angular distributions for the reaction $^{40}Ar(^6Li, d)^{44}Ca$ at a bombarding energy of 22 MeV. The curves are the results of distorted-wave Born-approximation calculations, as discussed in the text.

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Distorted-Wave Born-Approximation Analysis of the ^{90}Zr(d, α)^{88}Y and ^{89}Y(^{3}He, α)^{88}Y Reactions

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The levels of ^{88}Y have been studied with the ^{90}Zr(d,α) and ^{89}Y(^{3}He, α) reactions with 30- to 40-keV resolution at 15-MeV incident energy. The (d,α) angular distributions for transitions to eight prominent levels below 2.2 MeV have been measured over $15° \le \theta \le 150°$. The reliability of parameters entering distorted-wave Born-approximation calculations was checked in detail. The (d,α) calculations include the finite-range correction of Chant and Mangelson. The two-nucleon form factors (f.f.) were generated by the oscillator-expansion technique of Drisko and Rybicki, and the effect of residual interaction on the f.f. and angular distributions was studied. An attempt has been made to determine the (d,α) absolute normalization constant based on local zero-range calculations, and limits of $20 \le D_0^2 \le 30$ have been set. Two-nucleon f.f. generated by the Bayman-Kallio method were compared with the Drisko-Rybicki f.f. The (^{3}He, α) angular distributions for eight strongly populated levels below 1.7 MeV were measured over $20° \le \theta \le 125°$. Spectroscopic factors and l_n transfers have been extracted with both local zero-range and nonlocal finite-range calculations. The (^{3}He, α) results were compared with (d,α) results to determine unique parities and narrow J^π limits for the levels studied. ^{3}He and α elastic scattering on ^{89}Y have also been measured and optical-model potentials have been determined. Good agreement between this work and the recently reported ^{85}Rb($\alpha, n\gamma$)^{88}Y results is seen for the level energy and J^π assignments made.

I. INTRODUCTION

Direct (d, α) reactions on 0^+ targets have proved to be powerful tools with which to investigate the spectroscopy of odd-odd nuclei when the reactions are compared with single-particle-transfer reactions feeding the same final nucleus.[1] The reliability of spectroscopic information extracted from the measured (d, α) angular distributions depends largely on parameters entering in the current distorted-wave Born-approximation (DWBA) calculations of two-nucleon-transfer reactions.[2,3] The inclusion of the nonlocality and finite-range corrections into the conventional local zero-range DWBA calculations for (d, α) transitions has helped to bring the calculations into closer agree-