PROTON GROUND-STATE CORRELATIONS IN THE EVEN CALCIUM-ISOTOPES

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The extremely strong selectivity of the (d,α) reaction on 1f-shell target nuclei at 80 MeV bombarding energy for picking up proton-neutron pairs in the completely aligned $(1f_{7/2})^2 7,0$ configuration[1] was used in the $^{even}Ca(d,\alpha)K$ reaction to determine the extend to which proton core excitations exist in the ground states of the even calcium isotopes. Although these proton core excitation components in the ground state wave functions are quite small, the strongest peak in the spin up (d,α) spectrum (the detection system being on the right side of the beam) on each Ca-isotope at Θ_{lab} = 14° belongs to a L = 6, J = 7 transition. This is depicted in Figs. 1 and 2. Transitions to states populated by the pickup of other configuration proton-neutron pairs from the major shell-model components of the target ground state wave function are weaker.

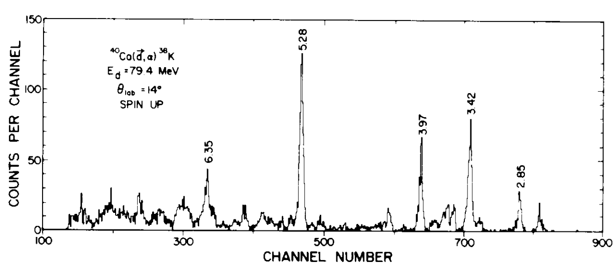

Figure 1. Alpha-particle spectrum of the $^{40}Ca(d,\alpha)^{38}K$ reaction.

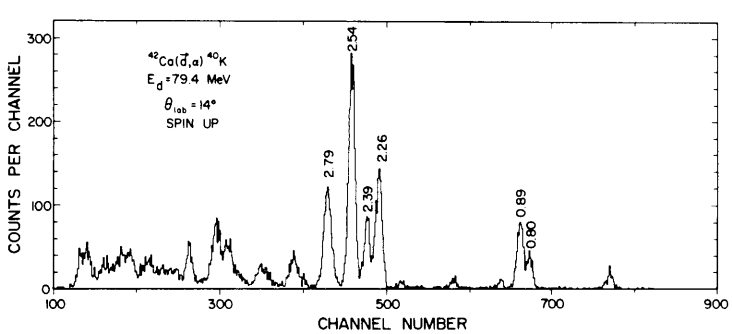

Figure 2. Alpha-particle spectrum of the $^{42}Ca(d,\alpha)^{40}K$ reaction.

Unambiguous L = 6, J = 7 transitions were identified leading to the states at 4.54 and 5.95 MeV in ^{46}K, at 1.91 MeV in ^{42}K, at 2.54 MeV in ^{40}K, and at 5.28 MeV in ^{38}K. Some measured angular distributions of the differential cross section are shown in the left-hand panels of Fig. 3 with the corresponding vector analyzing powers in the right-hand panel. It is interesting to note that in ^{46}K two $J^\pi = 7^+$ states are populated but not in the other K-isotopes. In ^{38}K, there is another 7^+ state known at 3.46 MeV. However, this state is very weakly excited in the $^{40}Ca(d,\alpha)^{38}K$ reaction. This is brought forth only from a channel by channel analysis of the vector analzying power of the peak around 3.4 MeV.

From the expression for the spectroscopic amplitude for the pickup of a proton-neutron pair in the stretched $(1f_{7/2})^2 7,0$ configuration, the proton

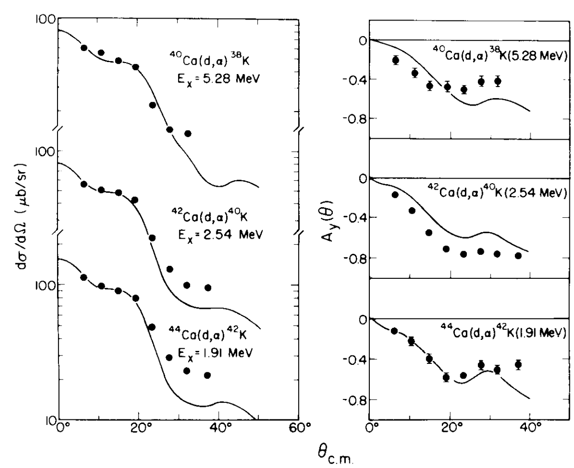

Figure 3. Angular distributions of the differential cross section (left-hand panel) and vector analyzing power (right-hand panel) for L = 6 transitions in the $^{40,42,44}Ca(d,\alpha)$ reactions.

occupation number $n_p(\mathrm{Ca})$ in the ground states of the even Ca-isotopes can be linked to that of ^{50}Ti, $n_p(\mathrm{Ti})$, by the following relation

$$n_p(\mathrm{Ca}) = n_p(\mathrm{Ti}) \frac{n_n(\mathrm{Ti})}{n_n(\mathrm{Ca})} \frac{\sigma_{exp}(\mathrm{Ca})}{\sigma_{exp}(\mathrm{Ti})} \frac{\sigma_{DWBA}(\mathrm{Ti})}{\sigma_{DWBA}(\mathrm{Ca})} \qquad (1)$$

Here the n_n are the neutron occupation numbers and σ_{exp} and σ_{DWBA} are the experimental and calculated (d,α) differential cross sections, respectively. It should be noted that $n_p(\mathrm{Ca})$ extracted from Eq. (1) does not depend on the absolute normalization of the distorted-wave Born approximation (DWBA) cross section for the (d,α) reaction. Furthermore, the dependence on optical-model parameters is greatly reduced as long as they are very nearly the same for all nuclei. In the analysis the following values were used: $n_p(\mathrm{Ti}) = 1.85$ and $n_n(\mathrm{Ti}) = 6.7$, $n_n(^{48}\mathrm{Ca}) = 6.8$ $n_n(^{44}\mathrm{Ca}) = 2.9$, $n_n(^{42}\mathrm{Ca}) = 1.7$ and $n_n(^{40}\mathrm{Ca}) = n_p(^{40}\mathrm{Ca})$.

Microscopic DWBA calculations were performed with the code DWUCK4 using optical model parameters from the literature,[2] and standard nonlocality and finite range corrections were applied. These parameters have been used successfully in an extensive series of (d,α) analysis of 80 MeV incident energy for nuclei between ^{50}Ti and ^{64}Ni.

There remains the question of what form factors for the transferred proton-neutron pair to use in this comparison between pickup from the Ca-isotopes and ^{50}Ti, since for the Ca-isotopes it involves not only "small" components of the ground state wave functions but also the final states are very far away from the $1f_{7/2}$ proton centroid. The shell-model $1f_{7/2}$ orbital lies about 6 to 7 MeV above the $1d_{3/2}$ orbital.

According to the standard prescription one uses a separation energy for each nucleon equal to one-half the deuteron separation energy for that particular transition. One then generates a radial wave function from a standard Woods-Saxon well (r_0 = 1.25 fm, a = 0.65 fm, λ = 25) with the depth adjusted to match the separation energy. This prescription yields $1f_{7/2}$ proton occupation numbers of 1.8, 1.5, 1.9, and 1.6 for the masses 40, 42, 44, and 48, respectively. These values are clearly too large showing the deficiency of the standard form factor prescription.

As a first step toward a more realistic form factor, the prescription was modified in the following way. Recently Sick et al.[3] have shown that, for a few special cases, precise valence- nucleon radial wave functions can be obtained by combining information at large radii from low energy "sub-Coulomb" transfer reactions and at smaller radii from measurements of the highest allowed multipolarity nuclear magnetization density by elastic electron scattering. In a procedure which incorporates both informations, the magnetic form factors are fitted using phenomenological radial wave functions computed from a Woods-Saxon potential with its depth adjusted to the separation energy of the unpaired nucleon. The results of this analysis are then represented by the root-mean-square radius of the valence nucleon wave function.[4] It has been demonstrated[5] that the use of such radial wavefunctions in analyses of single-nucleon transfer reactions leads to a more realistic determination of absolute spectroscopic factors. If one uses the $1f_{7/2}$ rms radii[4] of 4.08 for neutrons (extracted from ^{49}Ti) and 4.10 for protons (extracted from ^{51}V), the proton occupation numbers reduce to 1.1, 1.0, 1.4 and 1.0 for the calcium isotopes 40, 42, 44 and 48 respectively. These numbers are still uncomfortably large indicating that the form factor is probably still not correctly described.

If an effective one-body potential well is used for generating a more realistic form factor, it is probably not only sufficient to change the radius but also to vary its depth. This means that the transferred nucleon is no longer bound by the observed separation energy. From a comparison of the proton separation energies of ^{A}Ca and $^{A+1}$Sc one deduces that the shell-model $1f_{7/2}$ orbital in the calcium-isotopes lies about 6 to 7 MeV above the $1d_{3/2}$-$2s_{1/2}$ orbitals. Use of an effective binding energy for a $1f_{7/2}$ proton, which is smaller by this amount than the actual separation energy, yields $1f_{7/2}$ proton occupation numbers of 0.9 ± 0.2, 0.9 ± 0.2, 1.2 ± 0.3, and 0.7 ± 0.2 for the Ca-isotopes 40, 42, 44, and 48, respectively.

These last occupation numbers are believed to be the most realistic ones that presently can be derived from the (d,α) data at 80 MeV bombarding energy. In Fig. 4 they are compared to results from single-nucleon stripping and pickup reactions.[6] The agreement is quite good with exception of the results from the ^{48}Ca(d,^{3}He)^{47}K reaction[7] which yield a very small $1f_{7/2}$ proton occupancy in the ground state wave function of ^{48}Ca. At present, it is unclear how to explain it.

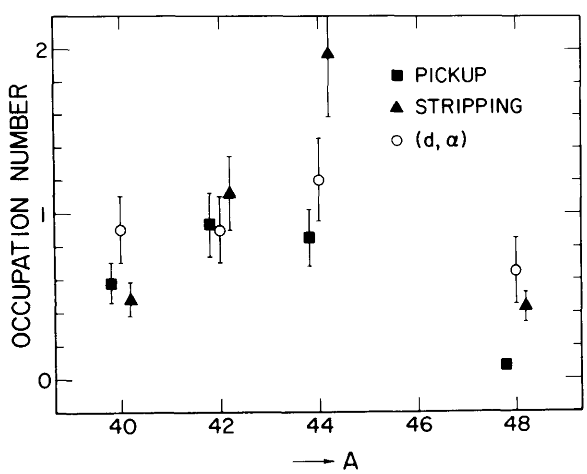

Figure 4. Number of $1f_{7/2}$ protons in the ground states of the even calcium isotopes.

One possiblity is that the $1f_{7/2}$ proton pickup strength in the ^{48}Ca(d,^{3}He)^{47}K reaction is much more fragmented than the $(1f_{7/2})^{2}{}_{7,0}$ proton-neutron pickup strength in the (d,α) reaction and has therefore escaped detection. This is corraborated by the fact that in the ^{48}Ca(d,^{3}He) study both the $2s_{1/2}$ and the $1d_{3/2}$ pickup strength were observed to be fragmented. It may be relevant that in a weak coupling picture $7/2^{-}$ states in ^{47}K can be constructed by coupling a $2s_{1/2}$ or $1d_{3/2}$ proton hole to the collective 3^{-} state in ^{48}Ca, while in ^{46}K one cannot make a 7^{+} state by coupling a proton-neutron pair in the $2s_{1/2}$ and $1d_{3/2}$ orbitals to any low-lying collective state in ^{48}Ca. On the other hand, if a solution for this discrepancy is sought in terms of an interference between one- and two-step processes, it would have to be constructive in the (d,α) case and destructive for (d,^{3}He). Moreover, this interference could not alter the shape of the one-step (d,α) VAP angular distributions, experimentally observed to be stable for the transitions to both 4.54 and 5.95 MeV states in ^{46}K and all other 7^{+} transitions studied across the $1f_{7/2}$ shell (up to ^{64}Ni). Unfortunately, absolute multi-step calculations of this kind are presently not feasible.

These proton occupation numbers for the $1f_{7/2}$ orbital agree quite well with the results of shell-model calculations by Zucker[8] who obtains 0.57, 0.72, 0.83 and 0.64 for the calcium-isotopes 40,42,44 and 48, respectively. The agreement for ^{48}Ca is astonishing.

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STUDY OF THE $^{12}C(^7Li,t)^{16}O$ α-TRANSFER REACTION AT HIGH ENERGIES

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A study of $^{12}C(^7Li,t)^{16}O$ at $E(^7Li)$ = 101 MeV was completed at IUCF using two Si ΔE detectors backed by thick intrinsic Ge E detectors. Also, α-particles were observed in coincidence at back angles to identify decay from high spin states in ^{16}O. This utilized a 600 mm^2 Si E detector with time-of-flight used for identification.

In addition to the well-known levels at $E_x < 20$ MeV, we may have observed new levels at $E_x > 20$ MeV to 30 MeV and possibly some at $E_x \gg 30$ MeV (see Figure 1). The analysis of the coincidence α-particle decay data from specific levels has just begun.

A related high-resolution study of $^{12}C(^7Li,t)$ for the region in ^{16}O, $E_x < 10$ MeV was started at NSCL (MSU) using $E(^7Li)$ = 80 MeV with the k = 320 spectrometer. An initial run resolved both the 7.12/6.92 MeV $1^-/2^+$ doublet and the 9.6 MeV 1^-level in ^{16}O which are of interest in astrophysics (helium burning). A second run is scheduled for Spring 1986. This work will be continued and may be extended to higher energies at IUCF using the new k = 600 spectrometer.

The high energy $^{12}C(^7Li,t)^{16}O$ data should provide new information on high-spin α-cluster levels in ^{16}O, $E_x > 10$ MeV. It will also permit comparisons with our earlier[1] data and analysis of $^{12}C(^6Li,d)^{16}O$ done at IUCF with $E(^6Li)$ = 90 MeV. These data can be used to

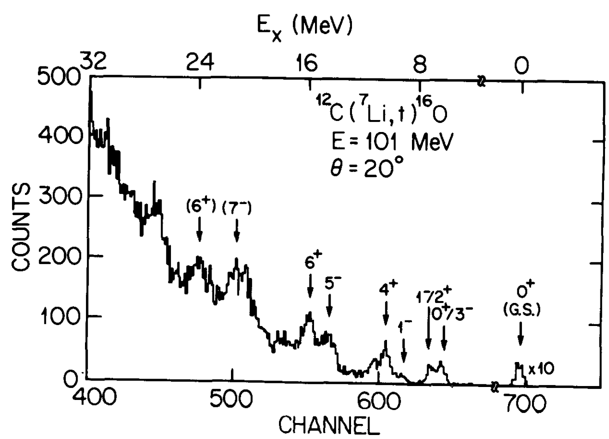

Figure 1. A triton energy spectrum and corresponding levels in ^{16}O observed in $^{12}C(^7Li,t)$ at $E(^7Li)$ = 101 MeV.