dence experiment, in which the prompt-fission fragments are identified with respect to their A and Z.

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Study of the Reactions ^{46,48}Ti(^{14}C,^{16}O)^{44,46}Ca and ^{50,52}Cr(^{14}C,^{16}O)^{48,50}Ti at 51 MeV

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The first measurements are reported for (^{14}C,^{16}O) two-proton pickup reactions. Angular distributions for transitions up to ~3.5 MeV excitation in ^{44,46}Ca and ^{48,50}Ti were obtained with a 51-MeV ^{14}C beam. The angular distributions exhibit a characteristic l dependence. Significant two-proton-hole configurations are found in the first excited 0^+ states of ^{44}Ca(1.88 MeV) and ^{46}Ca(2.42 MeV). Evidence is presented for multistep excitation of the first 2^+ states, especially in ^{44}Ca and ^{46}Ca where one-step transitions are expected to be inhibited.

Two-nucleon transfer reactions provide a basic experimental method for studying pairing correlations in nuclei.[1,2] A large amount of data already exists for the stripping and pickup of two neutrons by use of (t,p) and (p,t) reactions, and some very limited data are also available on two-proton stripping by the (^{3}He, n) reactions. However, there are almost no data of spectroscopic usefulness for two-proton pickup, because of the experimental difficulties of the (n, ^{3}He) reaction, which is the obvious light-ion reaction to perform. The (^{18}O, ^{20}Ne) reaction[3,4] has been investigated as a possible alternative to the (n, ^{3}He) reaction, but unfortunately, the strong excitation of low-lying states of ^{20}Ne often prevents clean separation of excited states of the final nuclei under study. In addition, strong coupling between the ground and low-lying collective states in both ^{18}O and ^{20}Ne increases the likelihood of complicated multistep processes in the (^{18}O, ^{20}Ne) reactions, thereby making the extraction of spectroscopic information difficult.

Since the first excited states in both ^{14}C and ^{16}O occur above 6 MeV excitation, the principal difficulties encountered with (^{18}O, ^{20}Ne) are not expected in the (^{14}C, ^{16}O) reaction, or at least they should be greatly reduced. In addition, this reaction possesses high positive Q values that are kinematically very favorable. For these reasons, it is of interest to explore experimentally the properties of the (^{14}C, ^{16}O) reaction and to determine its usefulness as a source of proton-pairing information.

To perform the experiment, ^{14}C ions were produced[5] in a sputter source and then accelerated to an energy of 51 MeV in a Van de Graaff accelerator. Self-supporting targets of ^{46,48}Ti and ^{50,52}Cr of approximately 100-μg/cm^2 thickness were bombarded with a beam intensity of 200 nA. The ^{16}O reaction products were detected and iden-

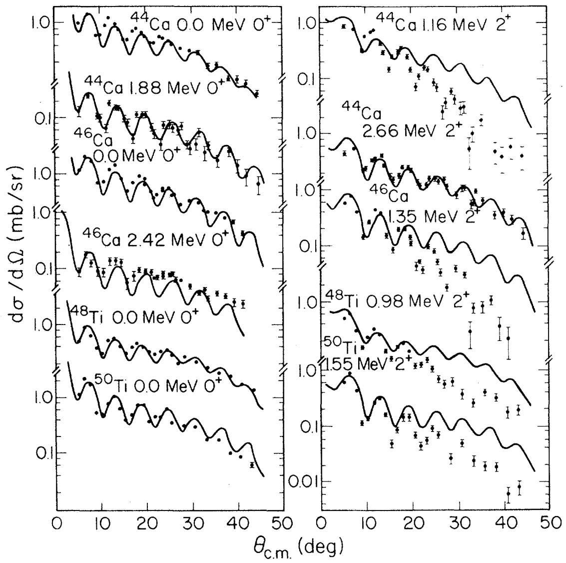

FIG. 1. Angular distributions for translations to the 0^+ and 2^+ states in ^{44,46}Ca and ^{48,50}Ti populated by the (^{14}C, ^{16}O) reaction. The solid curves are DWBA calculations using the program LOLA.

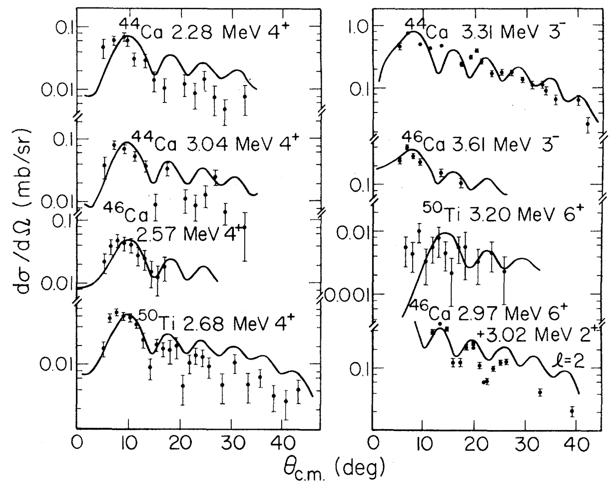

FIG. 2. Angular distributions for transitions to higher-spin states ($J \geq 3$) in ^{44,46}Ca and ^{50}Ti populated by the (^{14}C, ^{16}O) reaction. The solid curves are DWBA calculations using the program LOLA.

tified in a quadrupole-triple-dipole magnetic spectrograph with a focal-plane detector consisting of a helical-cathode proportional chamber[6] for position measurements and an ionization chamber for energy signals.

Detailed angular distributions were measured between 4° and 36° for final states with excitation energies up to about 3.5 MeV. Angular distributions for transitions to 0^+ and 2^+ states are shown in Fig. 1, while angular distributions for states with higher spins are shown in Fig. 2. Results of finite-range distorted-wave Born-approximation (DWBA) calculations using the code LOLA[7] with the optical potential from Lemaire *et al.*[8] and a cluster form factor are shown as the solid curves in the figures. The DWBA curves have been averaged over $\theta_{\rm lab} = \pm 1.15°$ to correspond to the experimental angular acceptance. The products of the spectroscopic factors, defined as

$$NC^2S_1C^2S_2 = \sigma_{\rm exp}/\sigma_{\rm LOLA}(2l+1)W^2(l_1 j_1 l_2 j_2; S_x l),$$

were extracted, and the results are listed in Table I.

The DWBA calculations show excellent agreement with experiment for the six 0^+ transitions shown in Fig. 1. The four ground-state transitions are the most strongly populated in each spectrum, a situation well known in other neutron- and proton-pair transfer reactions.[1,2]

TABLE I. Spectroscopic factors for transitions in the (^{14}C, ^{16}O) reactions.

E_x (MeV)	J^π	$NC^2S_1C^2S_2$
	^{46}Ti(^{14}C, ^{16}O)^{44}Ca	
0.00	0^+	0.84
1.16	2^+	0.76
1.88	0^+	0.34
2.28	4^+	0.88
2.66	2^+	0.70
3.04	4^+	0.80
3.31	3^-	3.88
	^{48}Ti(^{14}C, ^{16}O)^{46}Ca	
0.00	0^+	1.14
1.35	2^+	1.12
2.42	0^+	0.28
2.58	4^+	0.86
3.02	2^+	2.86
3.61	3^-	6.0
	^{50}Cr(^{14}C, ^{16}O)^{48}Ti	
0.00	0^+	0.92
0.98	2^+	0.60
	^{52}Cr(^{14}C, ^{16}O)^{50}Ti	
0.00	0^+	1.44
1.55	2^+	1.24
2.68	4^+	1.10
3.20	6^+	3.60

Of special interest are the first excited 0^+ states which are appreciably populated in ^{44}Ca at 1.88 MeV and ^{46}Ca at 2.42 MeV. Previous experimental and theoretical work has indicated the complexity of the structure of the low-lying states of the Ca isotopes.[9-15] In particular, ^{40}Ca does not form a good closed core, and the existence of excited rotational bands has been proposed in which multiparticle, multihole configurations are expected to play an important role for some low-lying states. The 1.88-MeV, 0^+ state of ^{44}Ca was found to be weakly excited in the ^{42}Ca(t,p) reaction[11] but strongly populated in the ^{40}Ar(^{6}Li, d) reaction.[10] A dominant six-particle, two-hole (6p-2h) configuration was suggested earlier for this 0^+ state to explain the large α-transfer strength. The fact that this state is also strongly populated in the present (^{14}C, ^{16}O) reaction is consistent with the (t,p) and (^{6}Li, d) results and demonstrates explicitly the importance of the two-proton-hole component in the overall configuration. The spectroscopic factor ratio of 0.41 that is given in Table I for $C^2S(1.88\text{ MeV}, 0^+)/C^2S(\text{g.s.}, 0^+)$ is very large for an excited 0^+ state in a two-proton pickup reaction, implying that the proton-pairing vibration of ^{44}Ca resides dominantly in the 1.88-MeV 0^+ state. In fact, it is the proton-pairing vibration substructure within the 6p-2h configuration which provides the unusually large strength in the α-transfer as well as the two-proton-pickup reaction.

The 2.42-MeV 0^+ state of ^{46}Ca is also strongly populated in the present reaction, ^{48}Ti(^{14}C, ^{16}O)^{46}Ca, with significant strength. There exists no other experimental datum concerning the proton configurations of the low-lying states of ^{46}Ca, since ^{46}Ca can not be reached by (^{3}He, n) or (^{6}Li, d) reactions, and the reaction ^{50}Ti(d, ^{6}Li)^{46}Ca has not yet been reported. However, both (p,t) (Ref. 14) and (t,p) (Ref. 15) reactions have been performed and the ratios of excited to ground-state strengths are 0.1 for (p,t) and in the range of 0.13–0.2 for (t,p). Thus the present results suggest the importance of two-proton-hole configurations in the 2.42-MeV level, but the two-neutron transfer strengths indicate that neutral excitations are also significant. Clearly, the 2.42-MeV state is of a complex multiparticle, multihole nature that would be consistent with a rotational structure such as found in a number of low-lying states of the calcium isotopes.

Much of the early heavy-ion transfer data were obtained with energies near the Coulomb barrier, and they showed the same bell-shaped angular distributions[16,17] for all transferred l. For this reason it was supposed that such reactions could only be of limited value in spectroscopic studies. However, Henning *et al.*[18] studied the reaction ^{48}Ca(^{16}O, ^{14}C)^{50}Ti and concluded that under certain favorable kinematic conditions the small-angle cross sections do exhibit a definite l dependence. The present data along with the DWBA calculations also show the existence of some l dependence in the angular distributions at the most forward angles, in which the first maximum broadens and the position shifts to larger angles as the transferred l increases. As shown in Fig. 2, the angular distributions of the 4^+ states all have wide maxima at $\theta_{\text{c.m.}} = 10°$, which in fact correspond to minima in the 0^+ angular distributions.

The l dependence exhibited by the (^{14}C, ^{16}O) reaction could prove especially valuable for investigating closely spaced levels at higher excitation energies. An example is shown in Fig. 2, where the angular distribution for the unresolved 2.97-MeV 6^+ and 3.02-MeV 2^+ doublet of ^{46}Ca is well described by $l=2$ but not by $l=6$; hence it is concluded that the transition is predominantly to the 3.02-MeV 2^+ state.

The occurrence of multistep processes in heavy-ion–induced transfer reactions has been well established for two-neutron stripping and pickup reactions[19] and hence would be expected in two-proton transfer as well. Data for such reactions as (^{16}O, ^{14}C) and (^{12}C, ^{10}Be), however, are more scarce and the systematics are less well understood. The reaction ^{48}Ca(^{16}O, ^{14}C)^{50}Ti,[18] in particular, showed no evidence of multistep processes, as indicated by the good agreement with DWBA calculations based on a direct two-proton transfer process.

The situation seems to be different for the (^{14}C, ^{16}O) reactions to the 2^+ states shown in Fig. 1. The angular distributions to the first 2^+ states at 1.16 MeV in ^{44}Ca and 1.35 MeV in ^{46}Ca have very steep slopes that can not be described by the DWBA calculations which fall off more slowly. This discrepancy is probably not due to an improper choice of optical potentials in the DWBA analysis, since all of the 0^+ states as well as the 2.66-MeV second excited 2^+ state of ^{44}Ca are very well reproduced by the DWBA calculation. A plausible explanation for these anomalous angular distributions is that the first 2^+ states of ^{44}Ca and ^{46}Ca have predominantly neutron configurations, and hence are inhibited in the Ti(^{14}C, ^{16}O) reactions by a one-step transition. On the other hand, these 2^+ states could be populated by twostep processes in which, for example, the g.s.-to-g.s. transition is followed by a strong inelastic excitation. In fact, previous coupled-channels analyses[19] have shown that a falloff of the angular distribution more rapid than the DWBA prediction, such as observed for the first 2^+ states of ^{44}Ca and ^{46}Ca in the present experiment, is a clear signature of the presence of multistep processes in a heavy-ion transfer reaction.

The agreement with the DWBA calculations is somewhat better for the first 2^+ states of ^{48,50}Ti than for ^{44,46}Ca, although there is still evidence of multistep excitation. The improvement could reflect the presence of the two valence protons in the 2^+ states of ^{48,50}Ti, which can be populated by direct transfer in the (^{14}C, ^{16}O) reaction. Finally the excellent fit to the 2.66-MeV second 2^+ state of ^{44}Ca is probably due to one-step excitation of proton-hole configurations in the core, along with the reduced likelihood of inelastic excitation of this state.

The transitions to states other than the first 2^+ states do not appear to be strongly affected by multistep processes (see Fig. 2), presumably because of the weaker coupling between these states and the g.s. Hence the spectroscopic factors extracted from the DWBA for these levels should be more reliable than for the first 2^+ states.

In conclusion, (^{14}C, ^{16}O) appears to be the most promising reaction reported thus far for studying proton correlations in nuclei by two-proton pickup. In the present work, the reaction was tested on four nuclei in the Ca–Ti region, and strengths were deduced for numerous transitions including six $l=0$ states. Strong proton 2p-2h correlations are found in the first excited 0^+ states of ^{44}Ca and ^{46}Ca. There is evidence for multistep processes in the transition to the first 2^+ states, especially in ^{44,46}Ca where one-step pickup of a proton pair is expected to be inhibited to these states. The angular distribution shapes are found to be sensitive to the transferred angular momenta over a range of at least $l=0$ to $l=6$. Thus the (^{14}C, ^{16}O) reaction offers the possibility of studying proton correlations over a wide range of nuclei.

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