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Spectroscopy of neutron-rich nuclei produced in ^{14}C induced reactions on ^{48}Ca

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Mass excess values and energies of excited states were determined for the neutron-rich nuclei ^{46}Ar and ^{48}K and tentatively for ^{51}Ca by use of ^{14}C induced transfer reactions on ^{48}Ca.

[NUCLEAR REACTIONS ^{42}Ca(^{14}C, ^{16}O)^{40}Ar, ^{48}Ca(^{14}C, ^{16}O)^{46}Ar, ^{42}Ca(^{14}C, ^{14}N)^{42}K, ^{48}Ca(^{14}C, ^{14}N)^{48}K, ^{48}Ca(^{14}C, ^{11}C)^{51}Ca; E = 67, 75, and 78 MeV; measured mass excess values and excited states in ^{46}Ar, ^{48}K, ^{51}Ca; enriched targets.]

I. INTRODUCTION

Various experimental techniques have been used to study the properties of neutron-rich light- and medium-weight nuclei.[1–5] Most of these methods, however, only prove the stability of these nuclei against particle decay but cannot yield exact values for binding energies or information on excited states. A knowledge of these properties is especially important for nuclei near closed shells where model calculations can be performed. The comparison between calculation and experiment allows us to test the effective nucleon-nucleon interaction in previously unexplored regions of the nuclide chart.

Spectroscopic information on neutron-rich nuclei lighter than those produced in fission has so far been obtained mainly by ^{18}O induced transfer reactions on neutron-rich targets.[6–8] These studies are, however, plagued with a number of problems: Due to the low energies of excited states of nuclei close to ^{18}O, such as ^{17}F or ^{20}Ne, and the limited energy resolution obtainable in such experiments, only a small range of excitation energy of the residual nuclei can be investigated; the spectra from reactions such as (^{18}O, ^{17}F) or (^{18}O, ^{20}Ne) become too complex above 2 MeV excitation energy. Also, only very thin target foils can be used in high-resolution experiments with ^{18}O beams because the energy straggling becomes more and more severe the larger the charge of the particles to be detected. For reactions with low cross sections, and those producing neutron-rich nuclei are of this type, this results in very small counting rates.

Such difficulties can be reduced by the use of ^{14}C ions as projectiles. The emerging ^{14}N and ^{16}O particles produced in the (^{14}C, ^{14}N) and (^{14}C, ^{16}O) reactions, respectively, have excited states at high energies. Thus a larger range of excitation energies in the residual neutron-rich nuclei can be investigated. Furthermore, energy straggling effects are somewhat reduced.

We have investigated ^{14}C induced reactions on ^{48}Ca target nuclei at the Munich MP tandem accelerator. Two experiments were performed: a low-energy-resolution survey investigation employing a ΔE-E time-of-flight telescope with good mass and Z resolution in order to determine energy-averaged cross sections for all direct reaction channels and the average excitation energies of the residual nuclei. The results of this experiment will be discussed elsewhere.[9] The second was a high resolution study employing the quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrograph and a position sensitive ionization chamber in the focal plane. This investigation concentrated on reaction channels with large cross sections at small excitation energies of the residual nuclei, and was designed to determine ground state Q values and the energies of the first few excited states. In this paper we discuss spectroscopic information obtained from the reactions ^{48}Ca(^{14}C, ^{16}O)^{46}Ar, ^{48}Ca(^{14}C, ^{14}N)^{48}K, and ^{48}Ca(^{14}C, ^{11}C)^{51}Ca.

II. EXPERIMENTAL DETAILS

The ^{14}C$^-$ ions were produced in a sputter source from a cone of FeC enriched to 20% in ^{14}C. Detailes of the production of the ^{14}C beam have been published elsewhere.[10] The ^{48}Ca target (100 μg/cm^2) enriched to 97% was evaporated on a carbon backing of 4 μg/cm^2 a real density. The target was transferred immediately after production to the scattering chamber of the QDDD spectrograph with a high vacuum interlock system. The experiments were performed with ^{14}C^{6+} ions of 67, 75, or 78 MeV energy and intensities up to 30 nA. The calibration procedure of magnetic rigidity versus focal plane position has already been described in Ref. 11. The target thickness and beam intensity was monitored by a Si-surface-barrier detector mounted at a scattering angle $\Theta_{lab} = 15°$. Outgoing particles were momentum analyzed and identified with respect to their mass A and Z by means of a 100 cm long position sensitive ionization chamber[12] mounted in the focal plane of the QDDD spectrograph. The detector is similar in design to the one at the Argonne National Laboratory.[13] Figure 1 shows data obtained for the ^{48}Ca + 67 MeV ^{14}C reaction at $\Theta_{lab} = 15°$ which demonstrates the ΔE and E resolution. The magnet setting was chosen for the ^{48}Ca(^{14}C, ^{16}O)^{46}Ar reaction. One observes ejectiles between ^{4}He and ^{18}O which are clearly resolved. Under the assumption that they originate from binary reaction processes one expects that residual nuclei between ^{58}Cr and ^{44}Ar are formed. In the following section we shall concentrate on reactions which exhibit measurable cross sections for resolved low-lying states.

III. RESULTS

A. The ^{48}Ca(^{14}C, ^{16}O)^{46}Ar reaction

Figure 2(a) shows a position spectrum obtained at an incident energy $E = 75$ MeV and a scattering angle $\Theta_{lab} = 15°$. The magnetic field was set for the ^{48}Ca(^{14}C, ^{16}O)^{46}Ar reaction, with a solid angle of 9 msr. The main background arises from the ^{16}O(^{14}C, ^{16}O)^{14}C reaction due to a small ^{16}O contamination in the ^{48}Ca target. At the magnet setting chosen the spectrograph does not correct for the kinematic

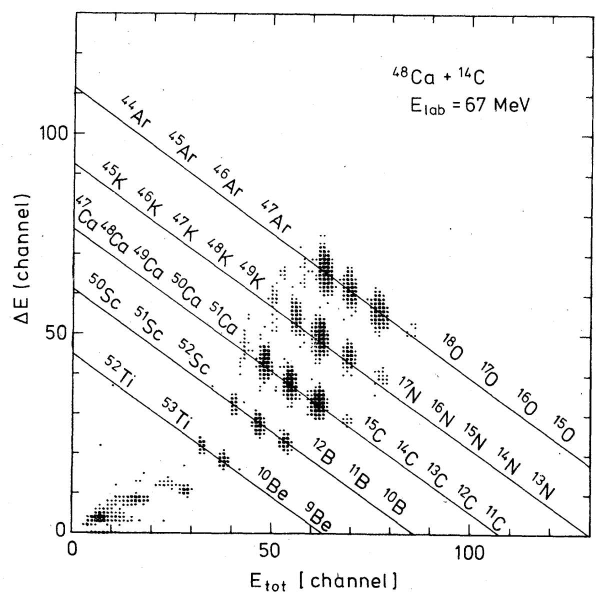

FIG. 1. ΔE-E spectrum obtained for the reaction ^{14}C + ^{48}Ca. The observed ejectiles are labeled in the lower right part of the figure; the residual nuclei are indicated in the upper left part.

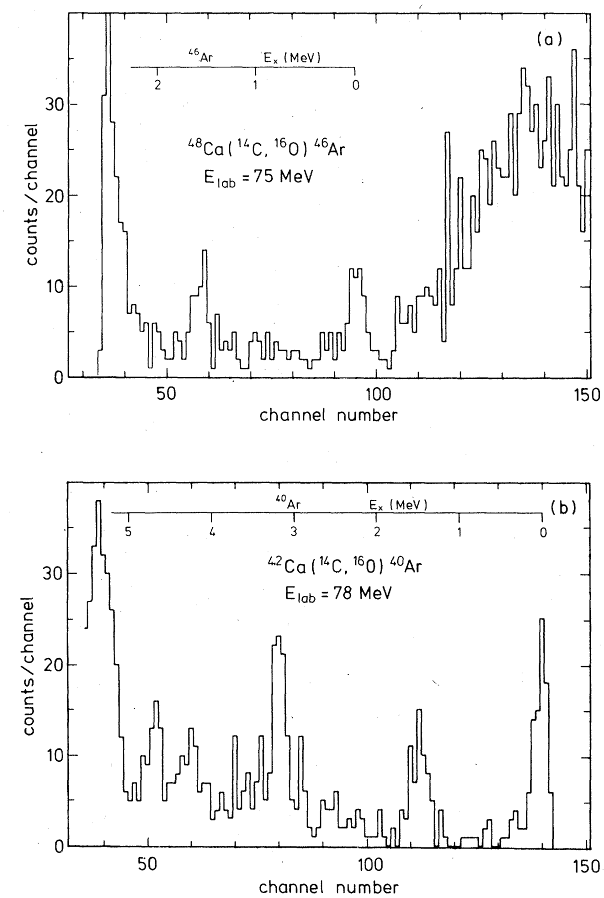

FIG. 2. Position spectra obtained for the reactions ^{48}Ca(^{14}C, ^{16}O)^{46}Ar (top) and ^{42}Ca(^{14}C, ^{16}O)^{40}Ar (bottom).

broadening of this reaction; thus the events corresponding to ^{16}O nuclei in their ground or 6.1 MeV 3^- excited state, respectively, show up as broad structures at the lower and upper end in the position spectrum. The two sharp lines in between are attributed to the ^{48}Ca(^{14}C, ^{16}O)^{46}Ar reaction, with ^{46}Ar in its ground and first excited state, respectively. This assignment is substantiated by the correct kinematical behavior: the same two lines are seen at 67 MeV incident energy. The cross section for the production of the ^{46}Ar ground state is ~20 μb/sr at 67 MeV incident energy, and ~40 μb/sr at 75 MeV. No other ^{46}Ar states are populated with appreciable cross section up to an excitation energy of 2.2 MeV.

The state at $E^* = 1.55$ MeV is thought to be the 2^+ first excited state in ^{46}Ar; this assignment is made in analogy to the spectrum [Fig. 2(b)] obtained for the ^{42}Ca(^{14}C, ^{16}O) ^{40}Ar reaction. Apart from the ground state, mostly 2^+ excited states are populated, whereas the 0^+ state in ^{40}Ar at 2.13 MeV excitation energy is very weak.

B. The $^{48}Ca(^{14}C, ^{14}N)^{48}K$ reaction

Figure 3 presents data obtained at $\Theta_{lab} = 15°$ for the $^{48}Ca(^{14}C, ^{14}N)^{48}K$ charge exchange reaction at 75 and 78 MeV incident energy, respectively. In addition we show a spectrum obtained for the $^{42}Ca(^{14}C, ^{14}N)^{42}K$ reaction. The individual states are not well resolved in this latter case. However, the multiplet resulting from the $(\pi d_{3/2}^{-1}, \nu f_{7/2}^{3})$ coupling can be identified at low excitation energy; in addition several excited states, around 1 MeV and 1.5 MeV excitation energy are also populated. Moreover, via the ^{40}Ca impurity in the ^{42}Ca target the lowest energy particle-hole configurations in ^{40}K are produced with appreciable cross section. These data demonstrate that low-lying simple particle-hole configurations are formed as final states in the $(^{14}C, ^{14}N)$ charge exchange reaction. For the ^{48}K nucleus we expect six low-lying states originating from the coupling of the $(2s_{1/2}^{-1})$ and $(1d_{3/2}^{-1})$ proton hole and $(2p_{3/2}^{1})$ neutron particle orbitals. In the spectra shown in Fig. 3 we identify the transition to the ground of ^{48}K, and to two excited states with energies around 0.8 and 2.1 MeV, respectively. The spectrum for 75 MeV incident energy has somewhat better resolution, and indicates some additional strength around 0.35 MeV excitation energy. The cross section for the ^{40}K ground state transition is ~80 $\mu b/sr$ at 75 MeV incident energy.

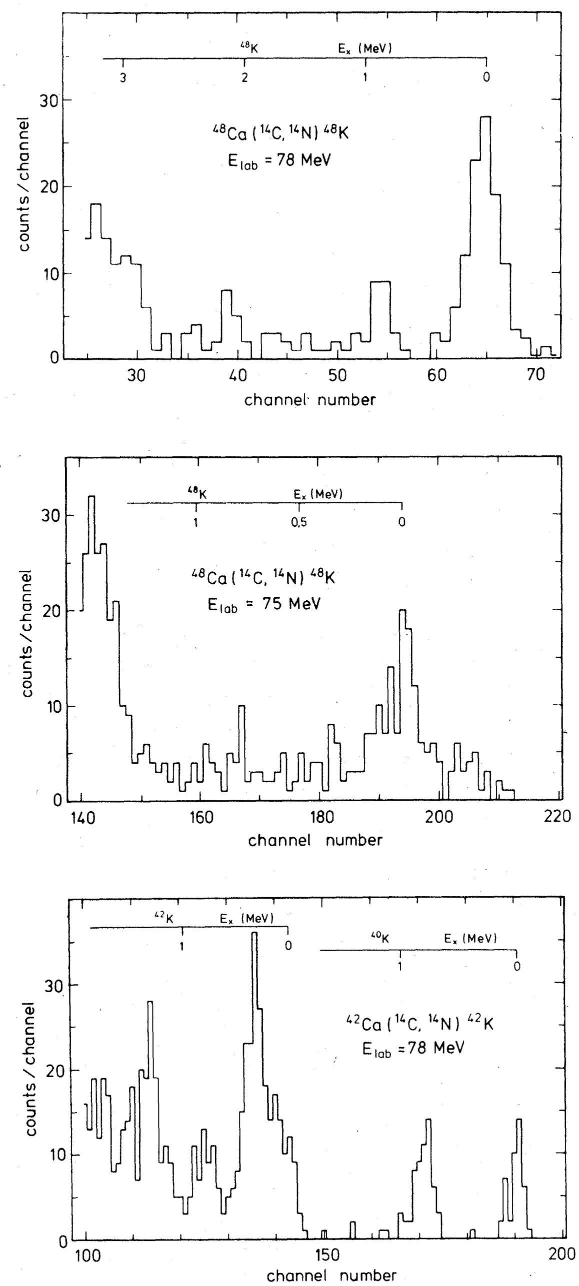

FIG. 3. Position spectra obtained for the reaction $^{48}Ca(^{14}C, ^{14}N)^{48}K$ at $E_{lab} = 78$ MeV (top), $E_{lab} = 75$ MeV (center), and for the reaction $^{42}Ca(^{14}C, ^{14}N)^{42}K$ (bottom).

C. The $^{48}Ca(^{14}C, ^{11}C)^{51}Ca$ reaction

In addition to the ejectiles heavier than or equal to ^{14}C in mass we observe neutron deficient nuclei lighter than ^{14}C, for example ^{11}C (see Fig. 1). ^{11}C events were observed at 67, 75, and 78 MeV incident energy, respectively. At 67 MeV bombarding energy the statistic is too low to draw any conclusion. At 75 MeV the ^{11}C events obtained at a scattering angle of 17.5° are attributed to the $^{48}Ca(^{14}C, ^{11}C)^{51}Ca$ reaction. ^{11}C ions originating from light target impurities would have a much lower magnetic rigidity. At 78 MeV incident energy under a smaller scattering angle of 10° the ^{11}C spectrum could be contaminated by reaction products from the lighter target impur-

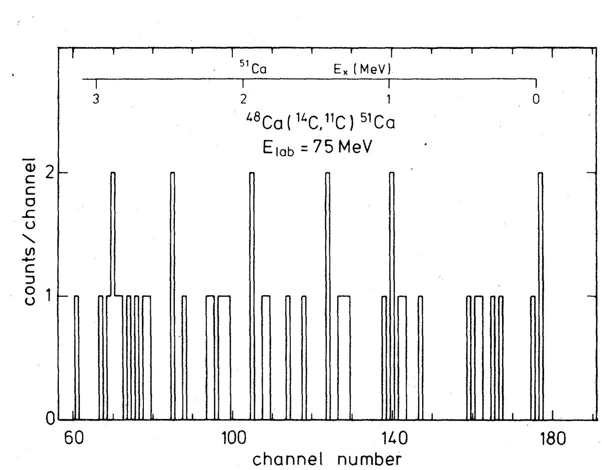

FIG. 4. Position spectrum for the reaction $^{48}Ca(^{14}C, ^{11}C)^{51}Ca$.

ities. Figure 4 shows a position spectrum obtained at 75 MeV incident energy. The cross section corresponding to the events with the largest Q value is ~3 μb/sr. If we associate these events tentatively with the ground state transition to ^{51}Ca we deduce an upper limit for the mass excess of the Ca isotope ^{51}Ca to be $M_{exc}(^{51}\text{Ca}) = -35.94 \pm 0.05$ MeV.

IV. DISCUSSION

Table I summarizes the mass excess values obtained in the present experiment. The error bars are mainly determined by the low statistical accuracy of the data which is due to the small cross sections and low beam intensity. Corrections for the energy loss in the target for particles like ^{11}C, not tabulated in data tables, are believed to be accurate to better than 20 keV; uncertainties arising from hysteresis effects in the magnetic field are smaller than 6×10^{-4}.

Also shown in Table I are mass excess values derived for ^{46}Ar and ^{48}K from other experiments, and the values predicted by various mass formulas.[14] The different experimental data agree within the error bars. Large deviations are noted between experiments and the mass formula by Myers, whereas there is remarkable good agreement with the predictions of Comay and Kelson, and also of Jänecke *et al.* In the following paragraphs, the experimental results will be discussed in greater detail.

The neutron-rich, Ar isotope ^{46}Ar has so far been produced only in the ^{48}Ca(^{6}Li, ^{8}B) ^{46}Ar reaction,[5] and a mass excess of -29.73 ± 0.01 MeV was obtained. Our experimental result agrees with this value within the error bars. Of specific interest in connection with shell model calculations is the energy of the first excited state in ^{46}Ar. Since the first excited 2^+ state is strongly populated in the ^{42}Ca(^{14}C, ^{16}O) ^{40}Ar reaction, we believe that the state seen at 1.55 MeV excitation in the ^{48}Ca(^{14}C, ^{16}O) ^{40}Ar reaction is the first excited 2^+ state in ^{46}Ar. This state should be of a mixed $(2s_{1/2}^{-1}, 1d_{3/2}^{-1}) - (d_{3/2}^{-2})$ configuration.

Only one shell model calculation has been performed for the neutron-rich Argon nuclei.[15] The first excited state is predicted to be a 0^+ state lying above 2 MeV excitation energy, which is at variance with our experimental data. We have recalculated the energies of the lowest-lying states in ^{46}Ar using the effective nucleon-nucleon interactions of Glaudemans.[16] The single particle states considered are the $2s_{1/2}^{-1}$ and $1d_{3/2}^{-1}$ hole states in ^{47}K, the latter lying at 0.36 MeV excitation energy. The first excited state is predicted to be 2^+ at 2.27 MeV excitation. The mass excess is predicted to be -29.01 MeV, in good agreement with the experiment.

Two groups have reported on the production of ^{48}K. In an (n,p) experiment the mass excess of ^{48}K was determined form β^- measurements, with an uncertainty of 0.5 MeV.[17] Recently, in a study of the ^{48}Ca(^{7}Li, ^{7}Be)^{48}K reaction[18] the mass excess was redetermined to be -32.117 ± 0.027 MeV and an excited state was identified at 0.583 MeV. No additional states could be identified because the spectra are too complex due to the excitation of the ^{7}Be ejectiles. Our value for the mass excess of ^{48}K is in good agreement with the results from the (^{7}Li, ^{7}Be) data. The excited states seen in the two experiments are, however, different. We observe two states at 0.8 MeV and 2.1 MeV excitation which are not seen in the (^{7}Li, ^{7}Be) experiment. On the other hand, the state at $E^* = 0.58$ MeV is not observed in our data. The reason for this behavior is not clear but could be connected with the different Q and l matching of the two reactions.

No spectroscopic information exists on the neutron-rich nucleus ^{51}Ca. If we associate the events with the highest energy with the ground state transition of the reaction ^{48}Ca(^{14}C, ^{11}C) ^{51}Ca we calculate a mass excess value $M_{exc} = -35.94 \pm 0.05$ MeV for ^{51}Ca. In addition we observe some strength to "states" around 0.4, 1.0, 1.4, and 2.0 MeV excitation energy. This spacing is similar to the one known for the nucleus $^{59}_{28}$Ni$_{31}$, which also has 3 neutrons outside the closed $N = 28$ con-

TABLE I. Mass excess values predicted by various mass formulas and comparison with the experimental results. The predictions are taken from Ref. 14.

					M_{exc} (MeV)			
Nucleus	Myers	Groote *et al.*	Liran Zeldes	Beiner *et al.*	Janecke *et al.*	Comay Kelson	Wapstra	This work
^{46}Ar	−31.31	−31.26	−27.96	−28.7	−29.98	−29.76	−29.73 ± 0.01 [a]	−29.72 ± 0.05
^{48}K	−31.33	−32.27			−32.92	−32.76	−32.117 ± 0.027 [b]	−32.15 ± 0.05
^{51}Ca	−32.39	−34.48	−34.69	−35.1	−35.15	−35.24		−35.94 ± 0.05

[a]Reference 5.
[b]Reference 18.

figuration. The statistical accuracy of our data is, however, too poor to allow any definite conclusions about ^{51}Ca.

V. CONCLUSIONS

We have demonstrated that spectroscoptic information on neutron-rich nuclei can be obtained by the use of ^{14}C ions and a high-resolution magnetic spectrograph. This information is especially interesting in the region of closed shell nuclei where model calculations can be performed. In our case we obtain information on the nuclei ^{46}Ar, ^{48}K, and ^{51}Ca. Similar studies of ^{14}C induced reactions on heavier target nuclei are in progress.

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