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MASSES OF NEW ISOTOPES IN THE fp SHELL

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INTRODUCTION

During the past few years there has been a active program at the Argonne FN tandem accelerator aimed at the study of new isotopes far from beta stability. The particular region of the periodic table under investigation has been for $50 < A < 70$, roughly the 1f-2p shell, on both sides of the valley of beta stability. Besides establishing the existence of previously unknown nuclides, the original scope of the program was to obtain information on the spectroscopic properties of parent and daughter for comparison with various nuclear models, and to measure the beta decay energies to compare with various predictions. In addition, calculations of explosive carbon burning during a supernova explosion rely on predicted masses of unknown neutron-rich nuclei in the iron region. Measurements of the masses of experimentally-accessible nuclei can help to decide which predictions are the most reliable to use in the nucleosynthesis calculations.

A total of 4 new neutron-rich isotopes have been studied, all made by heavy-ion-induced reactions on ^{48}Ca targets. These include ^{53}Ti (Ref. 1), ^{57}Cr (Ref. 2), ^{59}Mn (Ref. 3), and ^{60}Mn (Ref. 4). The bombardment of ^{58}Ni by various heavy-ion beams has resulted in the discovery of proton-rich ^{67}As (Ref. 5) and permitted extensive measurements of the superallowed decays of ^{62}Ca , ^{66}As , and ^{70}Br . These latter studies were aimed at extracting accurate ft values for Fermi decays in heavy nuclei.

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EXPERIMENTAL METHODS

The isotopes with half-lives greater than 1 s were studied using the conventional techniques of γ and β spectroscopy. Large Ge(Li) detectors were used for γ singles and γ - γ coincidence measurements, and in conjunction with a plastic scintillator, for β - γ coincidence studies.

In order to perform sensitive studies of short-lived radioactivities it is necessary to transport the active product rapidly from the production region to a low-background counting station. This has been done by either a "rabbit" system to transport a solid target, or using a helium-jet recoil transfer system to transport only radioactive nuclei recoiling from the target.

The rabbit system consists of a chamber holding a carousel upon which are mounted 8 rabbit holders fabricated from rectangular waveguide. The targets are mounted on lightweight rabbits made of delrin plastic. The transfer tube is made of the same waveguide, and the rabbits are propelled out of the bombardment chamber by a burst of helium. At the counting station 3 meters distant the rabbit is stopped by a bumper made of PVC tubing. Typical transit time is ~ 0.4 s. After a suitable counting interval the rabbit is propelled back to the bombardment chamber, and a new target is rotated into position. This allows the background activities on each target to decay in between bombardments, greatly reducing the count rate due to unwanted activities. During transfer and counting periods, the bombardment chamber is isolated from the accelerator vacuum system by a solenoid valve. Figure 1 shows a front view of the rabbit chamber.⁶

The helium-jet system involves transferring recoils from a target through a capillary tube in a stream of helium gas. The recoils, after being thermalized in the gas, are thought to attach themselves to giant ($A \sim 10^7$) clusters. These clusters are presumably formed by the action of the beam on impurities which are added to the helium stream (in the present case, water vapor is used). At the end of the tube the products are collected on a paper tape, while the helium is pumped away. After a suitable collection period, the tape is moved to the detector position for counting. Since a new area of the tape is used for collection, no buildup of long-lived activities takes place.

For half lives less than 1 s, it is not practical to utilize the transfer methods, and the detectors are placed next to the target chamber, which has thin mylar vacuum windows. This configuration is undesirable in that the detectors are thus exposed to intense radiation from the beam during the bombardment.

Fig. 1. Front view of the multiple-rabbit chamber with cover removed. The numbered items are: 1) rabbit holders. One of the holders is removed (bottom position). 2) Rabbit transfer tube. 3) Carrousel disk. 4) Wire for retaining rabbits in their holders. 5) Position-sensing assembly. 6) Helium inlet line.

A crystal-controlled programmable sequence timer is used to time the various events such as bombardment, transfer, and data acquisition. At present a microprocessor-based system is under development to take over this function.

For the study of the Fermi decays along the $N = Z$ line, a ΔE - E plastic scintillator telescope was used to detect high-energy positrons. Half-life and decay energy measurements were obtained simultaneously from data taken in a multispectrum-scaling mode.

The experiments involving heavy-ion bombardments produce a large number of known radioactivities whose β - γ coincidence spectra can be used to calibrate the energy scale of the β detector. Choosing one as a standard spectrum, it is compressed or stretched to fit as many known spectra as possible, and the linearity of the procedure is checked by plotting the stretch factors so obtained as a function of β endpoint energy. Stretch factors are obtained for the unknown β spectra, and, after adding the appropriate excitation energies, total decay energies and therefore mass excesses are

Fig. 2. Endpoint energy calibration for the known β spectra obtained in the β - γ coincidence experiment. The straight line is a linear least-squares fit to the data points. Also shown are the positions of the 2 ^{57}Cr endpoints.

extracted with typical uncertainties of ± 100 keV. Allowance can also be made in the computer fits for inner β branches as well as coincident γ rays.

Using the empirical shapes from the detector system corrects for systematic effects such as detector resolution, backscattering, energy loss in intervening materials, and edge losses, which are the same to first order for all β groups. The shape method also uses nearly all of the data, instead of just the high-energy portion. An example of the system linearity is shown in Fig. 2, taken from the ^{57}Cr experiment.

RESULTS FOR NEUTRON-RICH NUCLEI IN THE f-p SHELL

Using 1.1 mg/cm² enriched ^{48}Ca metal foil targets, the nuclides ^{53}Ti , ^{57}Cr , ^{59}Mn , and ^{60}Co were produced using the $^{48}\text{Ca}(^7\text{Li}, \text{pn})^{57}\text{Ti}$, $^{48}\text{Ca}(^{11}\text{B}, \text{pn})^{57}\text{Cr}$, $^{48}\text{Ca}(^{13}\text{C}, \text{pn})^{59}\text{Mn}$ and $^{48}\text{Ca}(^{18}\text{O}, \alpha \text{pn})^{60}\text{Co}$ reactions. The measured half lives and mass excesses for these nuclides are shown in Table I, along with mass excess predictions. Also included are data on ^{55}V from the Brookhaven group⁷ and J^π values measured for the ground states.

An example of the spectroscopic information obtained from these studies is the decay scheme for ^{57}Cr (Ref. 2) shown in Fig. 3.

TABLE I. Results for neutron-rich isotopes in the 1f-2p shell.

Nuclide	Ground State J^π	Half-Life ^a (seconds)	(M-A) ^a _{exp} (MeV)	(M-A) predicted (MeV)			
				MSMME ^b	JCK ^c	LZ ^d	SH ^e
⁵³ Ti	(3/2) ⁻	32.7 ± 0.9	-46.84 ± 0.10	-46.50	-46.53	-46.33	-46.4
⁵⁵ V	(3/2, 5/2, 7/2) ^{-f}	6.54 ± 0.15 ^f	-49.15 ± 0.10 ^f	-49.15	-49.41	-49.37	-49.4
⁵⁷ Cr	3/2 ⁻	21.1 ± 1.0	-52.39 ± 0.10	-52.12 ± E _x ^g	-52.67	-52.62	-52.3
⁵⁹ Mn	(5/2) ⁻	4.61 ± 0.15	-55.5 ± 0.11 -55.49 ± 0.04 ^h	-55.35	-55.94	-56.08	-55.6
⁶⁰ Mn	3 ⁺	1.79 ± 0.10	-52.89 ± 0.10	-	-53.01	-53.37	-52.2

^aPresent work unless otherwise noted.

^bReference 12.

^cJ. Jänecke, At. Data Nucl. Data Tables 17, 455 (1976).

^dS. Liran and N. Zeldes, At. Data Nucl. Data Tables 17, 431 (1976).

^eP. A. Seeger and W. M. Howard, At. Data Nucl. Data Tables 17, 428 (1976).

^fReference 7.

^gThe modified shell model mass equation (MSMME) used in Ref. 12 predicts the mass excess of the lowest $J = 5/2^-$ state, not the $3/2^-$ ground state. A linear extrapolation from ⁵³Cr and ⁵⁵Cr puts the $J = 5/2^-$ state at $E_x = 0.036$ MeV.

^hE. Kashy, W. Benenson, D. Mueller, H. Nann, and L. Robinson, Phys. Rev. C 14, 1773 (1976).

A large number of spin and parity restrictions have been made in ⁵⁷Mn, and the correspondence with levels in the daughter nucleus observed by charged-particle reactions is excellent. The ground-state spin and parity of ⁵⁷Cr turns out to be $3/2^-$, the same as for all other known $N = 33$ odd-A nuclides. The simplest shell model would predict $J^\pi = 5/2^-$, but at $N = 33$ the binding energy gained by pairing 2 1f_{5/2} neutrons is greater than that obtained from filling the 2p_{3/2} orbital and allowing the 33rd neutron to reside in the 1f_{5/2} orbital. Figure 4 shows the β -delayed spectrum from ⁴⁸Ca + ¹¹B and Fig. 5 shows the β spectra used to obtain the ⁵⁷Cr mass excess.

In general the production cross sections for the isotopes of interest range from 0.6 mb to ~8 mb, as predicted by the evaporation code Alice,⁸ making them always less than 1% of the total reaction cross section. The sensitivity of the detection system is such that isotopes with production cross sections in the few hundred μ b region are still amenable to investigation.

Fig. 3. β -decay scheme for ^{57}Cr . Also shown are levels in ^{57}Mn from the $^{54}\text{Cr}(\alpha, p)^{57}\text{Mn}$ and $^{55}\text{Mn}(t, p)^{57}\text{Mn}$ reactions.

RESULTS FOR PROTON-RICH NUCLIDES ON THE $N=Z$ LINE

The nuclides ^{62}Ga , (Ref. 9) ^{66}As , and ^{70}Br have been produced via the $^{58}\text{Ni}(^6\text{Li}, 2n)^{62}\text{Ga}$, $^{58}\text{Ni}(^{10}\text{B}, 2n)^{66}\text{As}$, and $^{58}\text{Ni}(^{14}\text{N}, 2n)^{70}\text{Br}$ reactions. A decay curve for high-energy positrons from ^{62}Ga is shown in Fig. 6. The positron spectrum obtained in the same experiment is shown in Fig. 7. The energy calibration was accomplished by measuring the decays of ^{46}V , ^{50}Mn , ^{54}Co , ^{58}Cu , and ^{28}P , with Q_{EC} values ranging from 7.05 to 12.55 MeV. These isotopes were produced by the (p,n) reaction on appropriate targets.

Fig. 4. Singles γ -ray spectrum from $^{48}\text{Ca} + ^{11}\text{B}$ during the first 40 s following bombardment. The vertical scale is in square-root format.

Preliminary values for the half-lives and decay energy Q_{EC} of ^{62}Ga , ^{66}As , and ^{70}Br are given in Table II. The resulting ft values have been corrected for charge-dependent and radiative effects of the order of 1–2%, and are listed in Table II. The prediction of the conserved vector current (CVC) hypothesis is that the ft values for all Fermi decays will be equal. Careful evaluations of the well-studied Fermi decays between 140 and ^{54}Co by Towner and Hardy¹⁰ and by Raman, Walkiewicz and Behrens¹¹ yield an average corrected ft value of 3085.5 ± 3 sec. Higher precision in the Q_{EC} measurements is required before the present experiments will be sensitive to any systematic deviations from the predicted value.

Fig. 5. Background-corrected ^{57}Cr β spectra feeding the 1535.0- and 1835.4-keV states in ^{57}Mn . Solid line indicates fit of standard shape to each spectrum.

RESULTS FOR PROTON-RICH As and Ge NUCLIDES

In addition to ^{66}As , the β^+ decays of the light As isotopes ^{67}As and ^{68}As have been studied. They were produced via the $^{58}\text{Ni}(^{14}\text{N}, \alpha n)^{67}\text{As}$ and $^{58}\text{Ni}(^{12}\text{C}, pn)^{68}\text{As}$ reactions. ^{67}As was previously unknown, as were the states of the daughter nucleus ^{67}Ge . An extensive spectroscopic study of ^{67}Ge has been completed, with early results reported in Ref. 13. The mass of ^{67}Ge was measured using the threshold of the $^{64}\text{Zn}(\alpha, n\gamma)^{67}\text{Ge}$ reaction, and differs by

Fig. 6. Time behavior of high-energy positrons from the decay of ^{62}Ga . The solid curve is a fit to the data using an exponential decay plus a constant background.

TABLE II. Preliminary half-lives and Q_{EC} values for odd-odd $N = Z$ nuclides in the $1f-2p$ shell.

Nuclide	Half-life ^a (ms)	Q_{EC} (keV)	$\mathcal{F}t$ (sec)
^{62}Ga	116.34 ± 0.35	9171 ± 26	3081.2 ± 47.1
	115.95 ± 0.30^b		
	116.4 ± 1.5^c		
^{66}As	96.37 ± 0.46	9550 ± 50	3062 ± 90
	95.78 ± 0.39^b		
^{70}Br	80.2 ± 0.8^b	9970 ± 170	3118 ± 295

^aPresent work, unless otherwise noted.

^bD. E. Alburger, Phys. Rev. C 18, 1875 (1978).

^cR. Chiba et al., Phys. Rev. C 17, 2219 (1978).

Fig. 7. Background-corrected positron spectrum of ^{62}Ga decay. The solid curve is a fit obtained by stretching a standard shape (in this case ^{54}Co) to fit the data.

more than 200 keV from the previous value. Our work has confirmed a spin of $1/2^-$ for the ^{67}Ge ground state. No mass has been reported for ^{68}As , and our work has established its ground-state spin to be $3(+)$. Table III summarizes the results obtained for these nuclides.

DISCUSSION

As can be seen from Table 1, the modified shell model mass equation¹² does well in predicting the masses of the $T_z = 9/2$ nuclei in the f-p shell. Most of the other formulations seem to overestimate the binding energy of these nuclides. A possible exception is for ^{53}Ti , where all predictions yield a less tightly bound nucleus than is observed. An independent measurement of the ^{53}Ti mass, possibly via the $^{48}\text{Ca}(^{18}\text{O}, ^{13}\text{C})^{53}\text{Ti}$ reaction, would help to clear up this point.

TABLE III. Results for proton-rich As and Ge isotopes.

Nuclide	Ground state $J\pi^a$	Half-life ^a (seconds)	(M-A) _{exp} ^a (MeV)
⁶⁷ Ge	1/2 ⁻	1140 ± 18 ^f	-62.666 ± 0.012
⁶⁶ As	0 ⁺	0.0964 ± 0.0005	-52.07 ± 0.05
⁶⁷ As	(5/2 ⁻)	42.4 ± 1.2	-56.66 ± 0.10
⁶⁸ As	3(+)	151.5 ± 0.9	-58.9 ± 0.1
(M-A) predicted (MeV)			
MSSME ^b	JGC ^c	LZ ^d	SH ^e
-62.70	-62.76	-62.71	-61.9
--	--	-51.80	-50.9
--	-56.54	-56.33	-56.2
--	-58.74	-58.95	-58.0

^aPresent work unless otherwise noted.

^bReference 12.

^cJ. Jänecke, At. Data Nucl. Data Tables 17, 455 (1976).

^dS. Liran and N. Zeldes, At. Data Nucl. Data Tables 17, 431 (1976).

^eP. A. Seeger and W. M. Howard, At. Data Nucl. Data Tables 17, 428 (1976).

^fTable of Isotopes, 7th Edition, Ed. C. M. Lederer et al., John Wiley and Sons, 1978, p. 214.

Large-basis shell-model calculations in the 1f-2p shell have had reasonable success in explaining low-lying levels in this group of nuclei. It is hoped that new data being provided will stimulate further calculation, especially on the nuclides lying off the stability line.

Precise measurements of the Q_{EC} values for the decay of ⁶²Ga, ⁶⁶As, and ⁷⁰Br are of interest because of the possibility of observing systematic deviations from the CVC predictions for the decay rate due to charge-dependent effects. The ability to measure the deviations caused by charge-dependent effects, which have a Z^2 dependence, would allow calculations of these effects to be checked. However, the outlook for significantly increased precision is clouded by the fact that the statistical rate function f has an E^5 dependence, making a reduction of the uncertainty in the ft value very difficult.

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