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# DECAY SPECTROSCOPY OF $^{75-79}$Cu, $^{79-81}$Zn AND $^{83-85}$Ga*

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The $\beta$-decay properties of neutron-rich fission fragments of Cu, Zn, and Ga isotopes were studied at the Holifield Radioactive Ion Beam Facility. Beams of $^{75-79}$Cu, $^{79-81}$Zn, and $^{83-85}$Ga were formed and delivered to two new end-stations at the facility. The Low-energy Radioactive Ion Beam Spectroscopy Station is a traditional on-line low energy (200 keV) beam line with 4 clover Ge detectors, two half-cylindrical plastic $\beta$-detectors, and a moving tape collector. In addition, many of the beams were accelerated to above 2 MeV/u and delivered to a micro-channel plate and transmission ion chamber located just in front of the same detector setup. In both cases, fine adjustment of an isobar separator was used to enhance the isotope of interest. Excited levels in the daughters and $\beta$-delayed neutron branching ratios were measured and used to confirm isotope identification. The decays from $^{79}$Cu and $^{85}$Ga were observed for the first time as was the $^{84}$Ge $2_1^+$ level populated by $\beta$ and $\beta$n decay channels.

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## 1. Introduction

The decay properties of nuclei around doubly magic $^{78}$Ni are an important testing ground for the shell model in regions far from stability. Single particle levels shift as more neutrons are added in isotopic chains. This may be caused by the tensor interaction weakening the spin-orbit splitting and can lead to smaller shell gaps as well as changes in the ground state spin and parities of an isotopic chain. A recent theoretical study by Otsuka *et al.* [1] indicated this change to occur in the copper isotopes around $A = 75$ where the $f_{5/2}$ proton orbital is lowered below the $p_{3/2}$ orbital. In addition, the rising $f_{7/2}$ orbital may cause the reduction of the influence of the $N = 50$ shell gap in heavier Cu isotopes. Other orbitals which may be affected similarly are the neutron orbitals above the $N = 50$ where the $s_{1/2}$ orbital is lowered relative to the $d_{5/2}$ and $g_{7/2}$ orbitals. This region of nuclei also borders the isotopes involved in the astrophysical r-process and their half-lives, masses, and decay properties can influence the rate at which heavier masses are produced.

The isotopes in the present study are indicated in Fig. 1 and some results have been reported [2–5] previously. They are most easily produced through the asymmetric fission of $^{238}$U and separated by the isotope separator online (ISOL) method [6]. These methods are able to produce beams with intensities ranging from less than one to several thousand ions per second from which the decay of these isotopes may be studied.

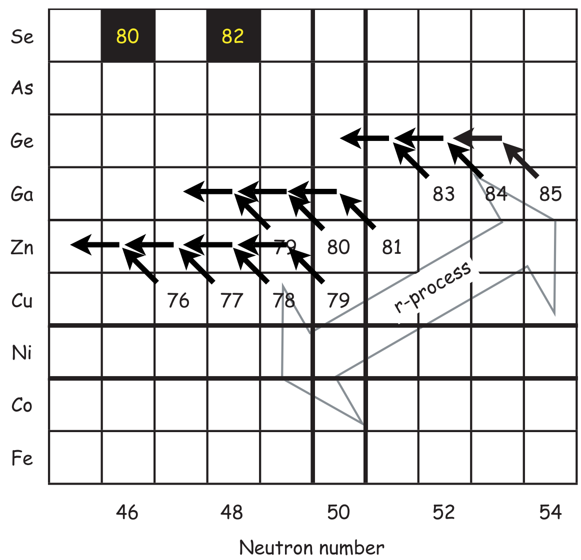


Fig. 1. Chart of nuclei indicating the isotopes studied in this work.

The copper isotopes lie just above the $Z = 28$ closed shell nickel isotopes and can be used to track changes in the proton orbital energy levels. Zinc isotopes lie just above copper and their $2^+$ energies can be used to track nuclear collectivity changes across the isotopic chain. Gallium isotopes lie slightly higher and border the r-process "boulevard" the route of which depends on neutron density. Beta-delayed neutrons provide mass changing decay events and affect the final isotopic mix during the cool-down stage of the r-process as well as in reactors and other fission-process devices. Thus, decay studies of these very neutron-rich nuclei provide information important to a wide range of physical processes.

## 2. Experimental setup

Beams of neutron-rich fission fragments were provided by the Holifield Radioactive Ion Beam Facility. A 54 MeV beam of protons with intensity of 10–15 $\mu$A bombarded a pressed-powdered uranium carbide target. Fission products were released from the target, positively ionized, and formed into a beam which was subsequently passed through two-stages of magnetic mass filtration and an optional charge exchange cell located between the two stages. The last stage is a two-sector dipole magnet (isobar separator) with nominal resolving power of 20,000. In practice, beam emittance limits its mass resolution to $M/\Delta M = 5000$–10000.

Two different experimental set-ups were used and are illustrated in the sketches of Fig. 2. In the Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) set-up [7], a 200 keV mixed isotope beam, enhanced in purity by the upstream isobar separator, is implanted into a moving tape (MTC) which is used to transport the activity to and/or from the measuring station which is comprised of Ge detectors and plastic $\beta$-counters. In the

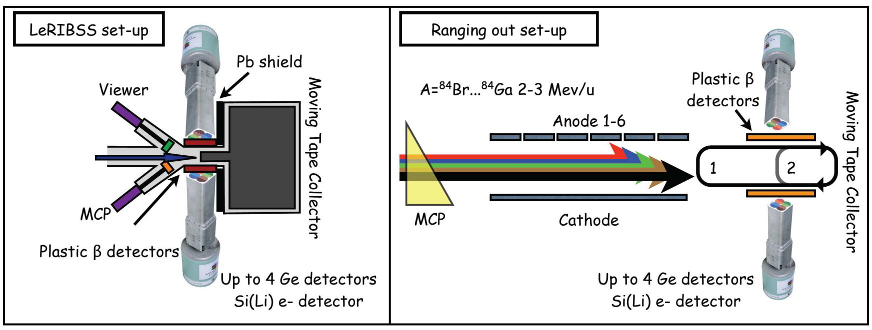


Fig. 2. Sketches of the experimental set-ups for LeRIBSS (left) and ranging out (right). Two of the four clover Ge are not shown. The MCP was not used in the LeRIBSS data. See text for details.

ranging out data, the negatively charged beam is accelerated to 2–3 MeV/$u$ by the HRIBF tandem accelerator, passed through a microchannel-plate-plus-thin-foil detector (MCP) and a transmission ion chamber (IC) [8]. If the moving tape is in position 1, the gas pressure in the IC is adjusted to range out heavier $Z$ components of the beam. The lower $Z$ components pass though the detector and are implanted on the tape which transports them to the Ge measuring station. In position 2, the pressure is lower and all components are tagged and identified by their energy-loss signals. For very short-lived decay events ($T_{1/2} < 200$ ms), implantation rates can be low enough that time correlations with the MCP may be used to enhance identification of events. Note that the MCP was not used in the LeRIBSS data.

The two set-ups each have advantages over the other. LeRIBSS can make use of positive ions and hence, does not require charge exchange or acceleration by the tandem. Both processes can cause large losses of intensity. Charge exchange, while helpful in some cases for isotope selectivity, also increases emittance and degrades the performance of the isobar separator. Thus, the highest beam intensities are available at LeRIBSS. The advantage of ranging out is the higher energy of the beam which allows techniques such as individual beam particle tagging and identification. This is difficult, if not impossible, at 200 keV. Thus, despite the overall lower intensity of the beam and poorer isobar separator performance, essentially pure and counted samples of the desired neutron-rich isotope are possible. The sample is then transported to the measuring station where its decay and that of its daughters can be observed. In both techniques, we can measure absolute $\beta$-delayed neutron branching ratios by detecting $\gamma$ transitions in the $A-1$ daughters, knowing the $\gamma$-ray efficiency of our experiment, tracking the subsequent daughter decays in order to correct any direct $\beta$ feeding (unobserved) to the ground state, and knowing an absolute decay branch/intensity in a daughter. Ranging-out allows a consistency check as one knows the number of ions deposited in the sample.

This paper reports on data collected with both set-ups. LeRIBSS was used to study $^{75-77,79}$Cu and $^{79-81}$Zn. Ranging out was used to study $^{76-79}$Cu and $^{83-85}$Ga. In this report, we confine ourselves to presenting data only on the most neutron-rich isotopes.

## 3. Experimental results

### *3.1. Decay of $^{75-79}$Cu isotopes*

The decays of $^{75-77}$Cu were studied at LeRIBSS primarily with negative ions in order to suppress the nearby Zn isotopes as they do not form negative ions. Positive ions of $^{79}$Cu were attempted but the much larger yield of $^{79}$Zn dominated the spectrum. This was the first attempt at using positive ion beams at 200 keV and illustrates that we must better understand what is coming out of the ion source with positive charge, as well as the tune through the isobar separator as we explore these new capabilities. The ranging out set-up was used to study $^{76-79}$Cu.

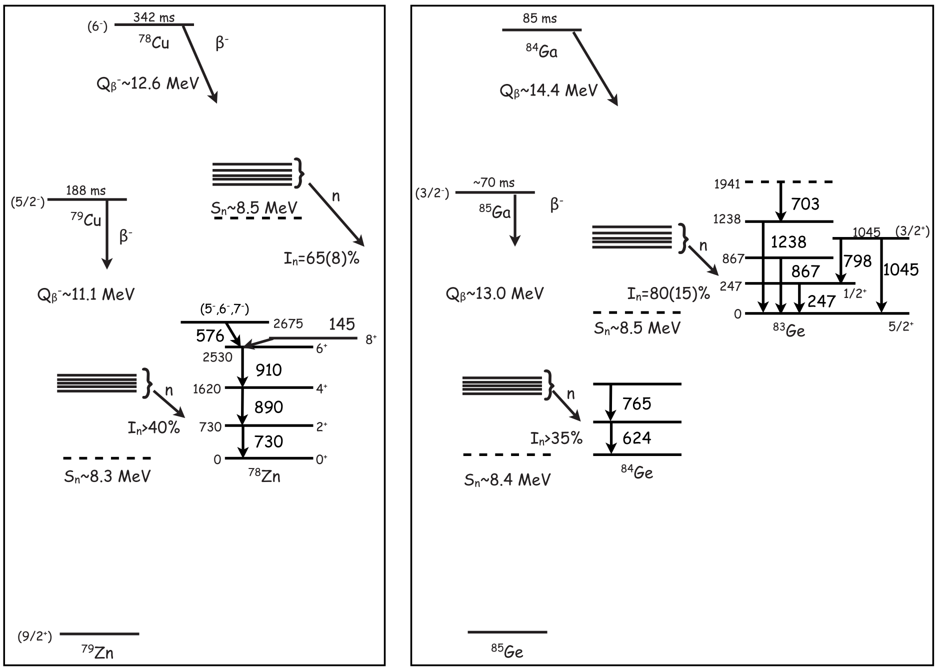


Fig. 3. Partial decay schemes deduced in the present work. Separation energies and $Q_\beta$-values are from [9]. Not all states indicated in the neutron-branch daughters were necessarily observed via $\beta$-delayed neutron decay.

The decay of $^{79}$Cu, shown in Fig. 3, was only observed through the $\beta$-delayed neutron branch which must be large. The 730 keV $2^+$ state in $^{78}$Zn was the only state observed. The beam rate was on the order of 0.1–0.2 per second. The limit on the branching ratio is determined by the number of Cu ions observed in the ionization chamber and the $\gamma$-ray efficiency as determined by calibration sources. We cannot accurately determine any direct ground state feeding in this decay because of low statistics.

The decay of $^{78}$Cu was observed through both $\beta$ and the large $\beta_n$ decay channels. Our data confirm the level scheme proposed by Daugas *et al.*, [10] although we did not populate the $8^+$ state. However, we do observe an additional state at 2.675 MeV. Previous $\beta$-decay studies [11] reported only the $4^+$ and $2^+$ states and as a result, proposed a $5^-$ ground state for $^{78}$Cu. Our data coupled with the theoretical analysis from Ref. [11] suggest a $6^-$ ground state arising from the coupling of $\pi f_{5/2} \otimes \nu g_{9/2}$. This coupling indicates that in the very neutron-rich Cu isotopes the $\pi f_{5/2}$ level has moved below the $\pi p_{3/2}$ level. Otsuka predicts [1] this to occur at $^{75}$Cu. The prediction was reportedly confirmed a week after this conference in a talk on ground state magnetic moments [12] measured with $\beta$-NMR. In light of this confirmation, a suggested second $\beta$-decaying state in $^{77}$Cu which decays strongly to the positive parity states in $^{77}$Zn is doubtful. The data could be explained by a large first-forbidden decay branch from a $5/2^-$ ground state to the levels feeding the low-energy $9/2^+$ and $7/2^+$ states.

### *3.2. Decay of $^{79-81}$Zn isotopes*

The decays of $^{79-81}$Zn were studied at LeRIBSS with positive ions only one month prior to this conference. As such, we only present an on-line spectrum to illustrate the capabilities of our LeRIBSS beam line. Yields were large and data on all isotopes were taken in less than 24 hours. Fig. 4 illustrates the power of the high resolution isobar separator. The majority of counts in the transitions from $^{81}$Ga are attributed to the decay of $^{81}$Zn even though the mass difference is expected to be only one part in 6300. The expected beam intensity of $^{81}$Ga on the LeRIBSS beam line is expected [13] to be on the order of $10^6$ ions per second while that of $^{81}$Zn is on the order of 10 ions per second. We can conclude therefore, that the isobar separator is suppressing the neighboring $^{81}$Ga by about $10^5$. We have observed many new transitions in the decays of $^{79,80,81}$Zn and are able to confirm the 351 and 452 keV transitions assigned [14] to $^{81}$Zn decay.

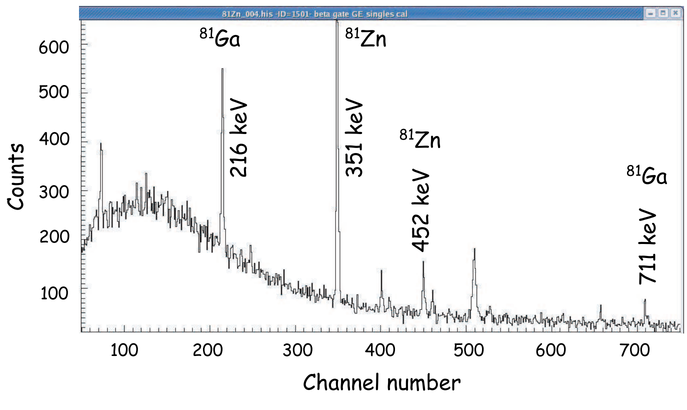


Fig. 4. On-line spectrum from the decay of $^{81}$Zn taken in about 5 hours. The $^{81}$Ga transitions are mostly from the decay of $^{81}$Zn and illustrate an estimated $10^5$ suppression factor attributed to the isobar separator. The mass difference between $^{81}$Zn and $^{81}$Ga is estimated [9] to be of the order of 1 part in 4600.

### *3.3. Decay of $^{83-85}$Ga isotopes*

The decays of $^{83-85}$Ga were studied using the ranging out set-up at low pressure. This allowed the tagging of each individual beam ion, and through time correlations with the MCP, enhanced decays associated with short-lived (70-80 ms) $^{84,85}$Ga. Partial decay schemes of $^{84,85}$Ga are shown in Fig. 3 and time-correlated $\gamma$-ray spectra of $^{84}$Ga decays are shown in Fig. 5. The overlap of the two time-correlated spectra reveal an excess of counts at 248, 624, 765 and 1045 keV. The 1045 keV transition has not been placed in the level schemes shown in Fig. 3. The 624 keV transition is assigned to the first $2^+$ state in $^{84}$Ge and is the first time any excited state has been observed in this nucleus.

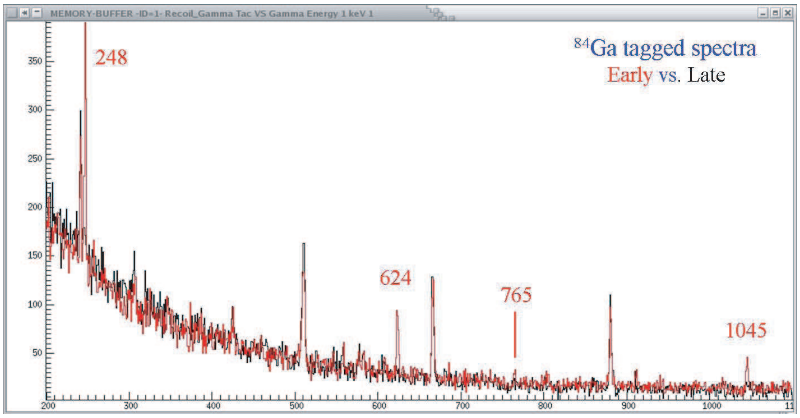


Fig. 5. Two time-correlated $\gamma$-ray spectra overlaid on each other. Peaks labeled by energy are enhanced in the "early" ($<$ 300 ms after implantation) spectrum and are assigned to the decay of $^{84}$Ga. The "late" spectra are those decays recorded in the 300-900 ms time interval after implantation. The 624 keV $\gamma$-ray is assigned to the $2^+ \to 0^+$ transition in $^{84}$Ge. The 248 keV transition is the $1/2^+ \to 5/2^+$ transition in $^{83}$Ga populated by $\beta$-delayed neutrons.

The $\beta$-delayed neutron branches in these nuclei are large and dominate the decays observed in the present data. In Fig. 6 we present the energy level systematics of the $\nu s_{1/2}$ state as a function of atomic number. As the $Z = 28$ shell closure is approached, this level is approaching the ground state and is found at 248 keV in $^{83}$Ge. Note that the present study has more precisely determined this energy which was previously reported to be 280(20) keV [15]. One possible explanation for the large variation in energy is the changing proton–neutron tensor interaction pushing the $\nu d_{5/2}$ and $\nu g_{7/2}$ levels above the $\nu s_{1/2}$ state.

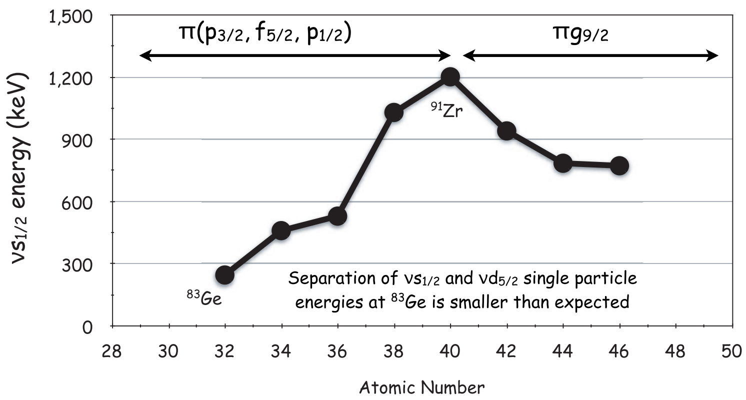


Fig. 6. The energy of the $\nu s_{1/2}$ level relative to the $N = 51$ ground state as a function of atomic number. The large energy dependence might be attributed to the tensor interaction [1]. The data are from the ENSDF database at `http://www.nndc.bnl.gov/ensdf/`

## 4. Summary and conclusions

The neutron-rich Cu, Zn, and Ga isotopes have been studied through their $\beta$-decays. These nuclei lie near the doubly closed nucleus $^{78}$Ni and their nuclear structures provide data to better constrain shell model calculations. Decays from several of these isotopes have been observed for the first time. Our data on the Cu isotopes support a recent study at ISOLDE that the ground state spins of these nuclei change from $\pi p_{3/2}$ to $\pi f_{5/2}$ in the heavier isotopes. The data in neutron-rich Ga isotopes have been used to identified the first $2^+$ state in $^{84}$Ge and have better established the energy of the $\nu s_{1/2}$ state in $^{83}$Ge. We have measured $\beta$-delayed neutron branching ratios by observing the population of excited states in the $A - 1$ daughter nuclei.

Two measurement techniques have been used to take these data. Traditional low-energy implantation-and-measure techniques are used on the new HRIBF LeRIBSS end station. This addition to the facility allows us to use positively charged beams and take advantage of the increased yields by not requiring charge exchange and the resulting better beam emittance results in improved isobar separation provided by our high-resolution magnet. However, by using acceleration (negatively charged ions only) we are able to use an ionization chamber to tag and identify isotopes by their differing loss of energy. In addition, time correlations can be used to improve our identification for very short-lived decay events. The ionization chamber can also be operated at high pressure which results in the ranging-out of high-$Z$ isotopes and we are able to produce pure samples of neutron-rich isotopes. These samples are then transported to a traditional $\beta$-decay measurement station.

We wish to acknowledge the facility and staff for their help and excellent quality of the neutron-rich beams. In addition, the engineering staff at HRIBF deserves our thanks for their help in constructing the LeRIBSS beam line. The Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. This work was also supported by U.S. DOE contracts DE-FG02-96ER41006, DE-FG02-96ER40983, DE-AC05-06OR23100, DE-FG02-96ER40978, DE-FG05-88ER40407, and DE-FC03-03NA00143, the Foundation for Polish Science, and by the Polish Ministry of Science contract NN202103333.

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