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DECAY STUDIES OF VERY NEUTRON RICH NUCLEI NEAR ^{78}Ni*

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The properties of β-γ and β-delayed neutron emission from $^{76-79}$Cu and $^{83-85}$Ga were measured at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. Selected results on the decay properties of copper isotopes are briefly presented and discussed.

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1. Introduction

Nuclei in the vicinity of the doubly magic nucleus $^{78}_{28}$Ni$_{50}$ are among the best candidates to study the evolution of nuclear structure far from the valley of stability. The large neutron to proton ratio, $N/Z \approx 1.8$, is expected to modify the shell structure known for nuclei close to the β stability line. In particular, the spin–orbit splitting for proton orbitals is expected to decrease as the neutron $g_{9/2}$ orbital is filled, causing a migration of the single-particle proton orbitals above the $Z = 28$ shell gap [1–3]. The challenging task for

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experiments is to identify the crossing point of the $\pi p_{3/2}$ and $\pi f_{5/2}$ levels and verify the theoretical predictions for the ground-state configurations of $Z = 29$ neutron-rich copper isotopes. Additional motivation for the studies of very neutron rich nuclei near doubly-magic ^{78}Ni is related to the analysis of the rapid neutron capture process. The β-decay half-lives and β-delayed neutron branching ratios are among the most important input values for simulations of this explosive nucleosynthesis process.

2. Experiment

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory using radioactive beams (RIBs) of $^{76-79}$Cu and $^{83-85}$Ga. These very neutron rich isotopes were produced in a 50 MeV-proton induced fission of a ^{238}U target. The radioactive beams were extracted from the target-ion source system, and on-line mass separated [4]. In general, ion source chemistry has the potential to improve the purity of extracted beams. In our case, the yield of germanium isotopes extracted and separated at the nominal mass number was reduced by adding sulfur. A substantial fraction of $Z = 32$ germanium ions formed ^{A}Ge^{32}S molecules, which were not present in a mass-A separated beam. This helped in the spectroscopy of $Z = 31$ gallium isotopes. A cesium-loaded charge exchange cell was used to produce negative ions for post-acceleration in the Oak Ridge 25-MV Tandem. This charge-exchange process has only a 5% efficiency for gallium and copper, however it also helps to purify radioactive beams. In particular, zinc isotopes do not form negative ions and are removed from the beam after the charge-exchange cell. The HRIBF RIB injector magnet has enough mass resolving power to create beams of high isobaric purity. It was tested using the $A = 76$ beams, of ^{76}Cu and ^{76}Ga. The mass difference to mass ratio ($\Delta M{:}M$) for these isobars is about 1:4600. The yield of ^{76}Ga ions obtained in a magnet setting optimizing the rate of ^{76}Cu was six times larger in comparison to ^{76}Cu. This ^{76}Ga yield was reduced by a factor 100 by increasing the magnetic field by 0.4% and using image slits. Approximately 70% of the ^{76}Cu ions were still transmitted to the detection setup in this setting of our high-resolution mass separator.

The studied nuclei were accelerated to about 2–3 MeV/u in the Tandem and transmitted through a Micro-channel plate detector and mini ionization chamber (mini-IC) [5], filled with a CF_4 gas at 100 to 200 Torr pressure, before implantation into a moving tape collector (MTC). The measurement of six ion energy loss signals in the mini-IC allowed us to identify the atomic number Z of individual mono-energetic isobars. The mini-IC simultaneously acted as an ion energy degrader, allowing for beam purification by increasing the gas pressure and stopping all isobars except the one having the lowest atomic number Z, hence the largest range in matter. More details about this ranging-out method can be found elsewhere [5, 6]. We were able to remove all longer-lived higher-Z contaminants and deposit pure Cu samples on the MTC. The final rates of short-lived Cu isotopes varied from 160 to 320 ions/s for ^{76}Cu($T_{1/2} = 0.64$ s), 15 to 30 ions/s for ^{77}Cu ($T_{1/2} = 0.46$ s), about 2–3 ions/s for ^{78}Cu ($T_{1/2} = 0.3$ s) and about 0.2 ions/s for ^{79}Cu ($T_{1/2} = 0.19$ s). The β and γ radiations following the decays of these nuclei were measured using two plastic β-detectors and four Germanium clover detectors surrounding the collected sample. All signals were recorded using the XIA DGF 4C digital processing modules [7–9].

3. Results

We present here the data leading to the determination of the β-delayed neutron branching ratio $I_{\beta-n}$ for ^{76}Cu decay illustrating the power of a ranging-out method applied to the HRIBF radioactive beams. We performed the measurement in a so-called grow-in mode in which a gas pressure of 100 Torr allowed transmission of the radioactive ions to a collection point at the center of our β–γ detection setup. This particular measurement was run in saturation, while other measurements involved long collection times followed by the tape transport periodically removing the sample. It is important to notice that since zinc ions were removed from the beam by the charge exchange cell, the activities of ^{75}Zn and ^{76}Zn originated only from the β and β-delayed neutron decays of ^{76}Cu. Simultaneously, the number of tape-implanted ^{76}Cu ions was counted in the mini-IC. A section of the γ-ray singles spectrum showing the lines at 228 keV (^{75}Zn $\rightarrow$ ^{75}Ga) and 199 keV (^{76}Zn $\rightarrow$ ^{76}Ga) is given in Fig. 1. One should note that these lines are close in energy, so even a potential inaccuracy in the efficiency calibration has a negligible effect for the determination of the β-delayed branching ratio and only a relative efficiency is needed here. The resulting $I_{\beta-n} = 7(1)\%$ was verified by comparison of the total number of implanted ^{76}Cu ions (1.16×10^6) to the intensity the 228 and 199 keV lines corrected for absolute γ-efficiency giving an identical result. The $I_{\beta-n}$ value measured here is nearly a factor of 3 larger in comparison to the 2.4(5)% reported in [10]. The other recent measurement on ^{76}Cu decay [2] was not sensitive enough to determine the β-delayed branching ratio.

The studied decays of ^{77}Cu, ^{78}Cu and ^{79}Cu do not offer an unambiguous conclusion about the lowest energy proton orbital in these nuclei. For ^{78}Cu we observed a direct beta feeding to two levels in ^{78}Zn [11], to the new level at 3.106 MeV (I_β about 35%) and to the known 4^+ state at 1.62 MeV (I_β about 65%). This indicates that the spin of decaying ^{78}Cu state is most likely 4 or 5. A comparison to the shell model analysis [2, 12] suggests

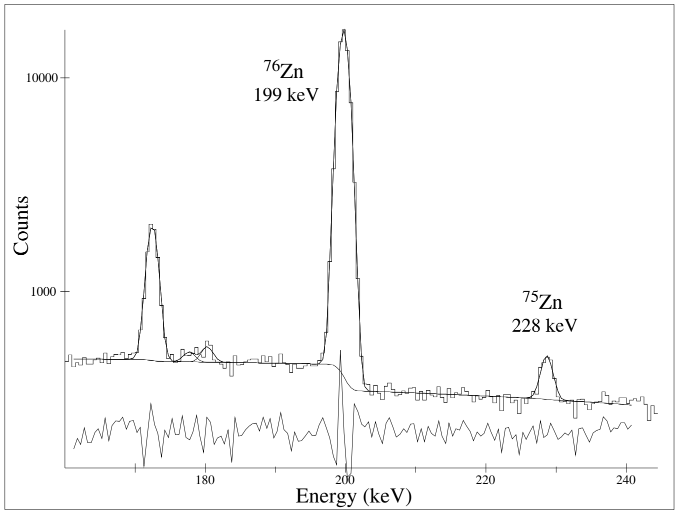

Fig. 1. The energy spectrum of gamma radiation following the decays of ^{76}Zn and ^{75}Zn. These zinc isotopes were populated in the decay of ^{76}Cu (see text for details).

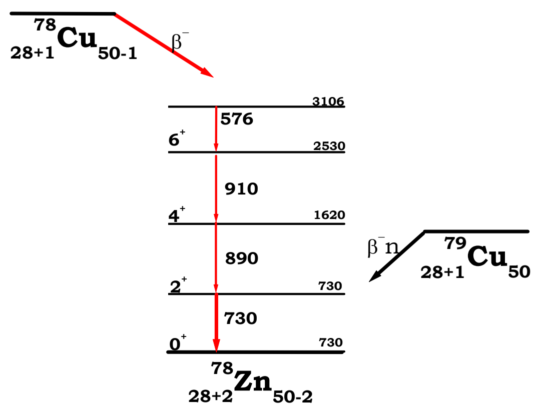

Fig. 2. Partial decay schemes of ^{78}Cu and ^{79}Cu activities studied at the HRIBF.

that indeed the configuration $(4^-,5^-)[\pi p^1_{3/2},\nu g^{-1}_{9/2}]$ is possible for the studied ^{78}Cu activity, see Fig. 2. However, an occupation of the $\pi f_{5/2}$ orbital by the 29th proton in very neutron rich copper isotopes is suggested by the measured properties of ^{79}Cu decay. A large branching ratio, about 25%, for β-n transition to the 2^+ state at 0.73 MeV in ^{78}Zn [11, 13] was deduced from the observed intensity of 730 keV line, see Fig. 2. The lower spin $\pi p_{3/2}$ configuration for ^{79}Cu ground-state would rather trigger a dominating β–n transition to the lowest 0^+ ground-state.

4. Summary

The β and β-delayed neutron decay properties of post-accelerated $^{76-79}$Cu and $^{83-85}$Ga radioactive ions were studied at HRIBF using ranging-out method [5, 6]. The β-delayed neutron probabilities were obtained using the observed relative yields of the daughter zinc activities as well as by a direct comparison of the observed γ intensities to the measured number of implanted copper ions. The $I_{\beta-n}$ yields deduced in this work for ^{76}Cu and ^{77}Cu, of 7(1)% and 36(3)%, respectively, are a factor of two to three larger in comparison to earlier reported values [10].

We have observed a γ-ray cascade following the direct β decay from ^{78}Cu to the new level at 3.11 MeV in ^{78}Zn. We have identified for the first time a γ transition following ^{79}Cu decay. The measured intensity of the 730 keV line indicates about 25% β-delayed neutron branching ratio to the 2^+ state in ^{78}Zn. These decay properties and shell model calculations [2, 12] suggest that the $\pi f_{5/2}$ is the ground-state proton configuration for ^{79}Cu — an $N = 50$ copper isotope with a filled $\nu g_{9/2}$ orbital.

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