β AND β-DELAYED NEUTRON DECAY STUDIES OF $^{76-79}$Cu AT THE HRIBF

S. V. ILYUSHKIN* AND J. A. WINGER

Dept. of Physics and Astronomy, Mississippi State Univ., Mississippi State, MS 39762, USA *E-mail: svi1@msstate.edu*

C. J. GROSS, K. P. RYKACZEWSKI, AND D. SHAPIRA

Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

R. GRZYWACZ, S. N. LIDDICK, S. PADGETT, AND M. M. RAJABALI

Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

J. C. BATCHELDER

UNIRIB, Oak Ridge Associated Universities, Oak Ridge, TN 37831, USA

A. KORGUL

Institute of Experimental Physics, Warsaw University, Warszawa, PL 00-681, Poland

W. KRÓLAS

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, PL 31-342, Poland

C. MAZZOCCHI

IFGA, University of Milan and INFN, Milano, I-20133, Italy

A. PIECHACZEK AND E. F. ZGANJAR

Dept. of Physics and Astronomy, Louisiana State Univ., Baton Rouge, Louisiana 70803, USA

C. GOODIN AND J. H. HAMILTON

Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA

Isobarically purified and re-accelerated ISOL beams have been used at the Holifield Radioactive Ion Beam Facility (HRIBF) of Oak Ridge National Laboratory to study the β and β-delayed neutron decay properties of $^{76-79}Cu$. The β-delayed neutron probabilities of ^{76}Cu and ^{77}Cu were deduced from comparison of the intensities of γ rays in the Zn daughter isotopes and found to be 6.9(0.4)% and 36(3)%, respectively. For ^{77}Cu we have also identified 14 γ rays associated with this decay and obtained level schemes for the β and βn daughters. For ^{78}Cu, we observe the yrast decay sequence transitions up to the 6^+ state with no population of the 8^+ isomer. In the decay of the r-process critical nuclide ^{79}Cu we observed for the first time a γ ray at 730 keV associated with the known 2_1^+ to ground state transition in ^{78}Zn.

1. Introduction

The study of nuclear structure in the regions near doubly magic nuclides provides information on the strength of the shell closures and details on the interactions between individual nucleons. The structure of these nuclides can usually be well reproduced using shell-model calculations utilizing effective interactions. With a model space consisting of a set of single-particle energies (SPE) and an effective interaction, it is possible to extend the predictions to nuclides much further from stability which are of particular interest. However, these predictions are only as valid as the model space used which is based on known nuclear structure closer to stability. In order to refine the effective interactions, it is necessary to obtain additional experimental information. In addition, the assumption of closed nuclear shells must often be modified as one moves further out from stability since the magic numbers which appear to be valid near stability for some regions fail to hold up in other regions. This complexity is apparent in the new interaction by Lisetskiy *et al.* where the SPE depend on the core which is chosen.[1] Otsuka *et al.* have shown in a theoretical calculation that the tensor interaction between the $\nu g_{9/2}$ state with the proton fp shell states reduces the spin orbit splitting resulting in the $\pi f_{5/2}$ orbital dropping below the $\pi p_{3/2}$ orbital near ^{75}Cu.[2,3] These predictions are complimented by the calculations of Dobaczewski *et al.* which indicate the additional importance of many-body correlations and the inclusion of coupling to continuum states to understand the structure of very neutron-rich nuclei.[4]

The region near ^{78}Ni is also of interest for an understanding of the nucleosynthesis *r-process*. Kratz *et al.* have shown the process passes through a bottle neck near ^{78}Ni and then follows various paths dependent upon the neutron flux.[5] In their predictions, $^{79,80}Cu$ are "waiting-point nuclei", i.e. the lowest-Z member of each isobaric chain at freeze out,[5,6] at two different values of the neutron flux. For this reason, the β-decay half-lives and β-delayed neutron probabilities of the Cu isotopes are of great interest.

2. Experimental Results

Beams of $^{76-79}$Cu ions were produced by the proton-induced fission of a UC_x target and then accelerated to 2–3 MeV/u by the ORNL Tandem. The ions were then time tagged using an MCP detector, passed through a six segment miniature ion chamber (mini-IC), and implanted onto the tape of a Moving Tape Collector (MTC). By passing through the mini-IC, the ions could be clearly identified by energy loss in the six segments. In addition, the gas pressure could be adjusted to a high pressure for the "ranging-out mode" in order to achieve a nearly pure beam.[7] The ranging-out mode works by taking advantage of the different stopping powers for the components of the mass separated beam delivered by the Tandem. This is further enhanced in the case of Cu ions since negative Zn ions do not form in the charge exchange cell and are removed from the beam before postacceleration. In addition to ranging out, the mini-IC allowed for a pass-through mode in which the mini-IC is operated at a low pressure to identify the ions with the deposition point placed in the middle of the detector array. This allows a correlation between ion implantation and subsequent decays to be established, i.e. ion-tagged γ ray spectra. The detector array consisted of four Ge clover detectors and two plastic scintillator β detectors, with the signals from all the detectors read out using digital electronics. In addition, the mini-IC made it much easier to tune the high-resolution injector (isobar) magnet for the Tandem to select the ions of interest.

The β decay of ^{76}Cu served as a test case for the ranging-out technique[7] since the half-lives within the $A=76$ and $A=75$ decay chains were short enough to remove built up residual activity in a span of only a few minutes. The objectives of the experiment were to measure the β-delayed neutron probability and to look for a possible second β-decaying isomeric state. These two topics are related since an interpretation of the first measurement can depend on the second as discussed below. The first experimental study of ^{76}Cu indicated the possibility for a second β-decaying isomer based on a difference in the apparent half-lives of the two strongest γ rays (598 and 697 keV) observed in the decay.[8] A measurement of the β-delayed neutrons from this decay only showed evidence for a single β-decaying state with a half-life of 641(6) *ms*.[9] More recently, Van Roosbroeck *et al.* remeasured the decay using a laser ion source and observed only a single β-decaying state with a half-life in agreement with Kratz *et al.*.[9,10] Both Ref. 8 and Ref. 10 are in basic agreement on the observed γ rays and the inferred excited states in ^{76}Zn. In our measurement, a nearly pure beam ($>99\%$) was obtained using the ranging-out mode, while data were also obtained using the pass-through mode. A comparison of the relative intensities of the 228-keV γ ray from ^{75}Zn decay to the 199-keV γ ray from ^{76}Zn decay was used to determine the β-delayed neutron probability since we could easily determine the effective decay probabilities based on the MTC cycle and the known half-lives. However, the determination of the decay probabilities is dependent on the half-life of ^{76}Cu. We observed that the intensity of the 598-keV γ ray would require a branching ratio of 138(10)% in comparison to the known branching ratio for the 563-keV γ ray (66(3)%[11]) if a half-life of 641 ms is used for ^{76}Cu. Therefore, a longer-lived β-decaying isomer of ^{76}Cu must exist. Consequently, a saturation spectrum in pass-through mode was obtained with a beam purity of 76%. A comparison of the relative intensities of γ rays from the β and βn branchings for all members of the decay chain originating from ^{76}Cu as well as absolute measurements relative to the measured number of ^{76}Cu ions were used to determine a β-delayed neutron branching probability of 6.9(4)% for the studied ^{76}Cu activity. This is a much more precise value than obtained previously (3(2)%[12] and 2.4(5)%[13]) as well as larger by about a factor of two.

The β decay of ^{77}Cu was also performed in both the ranging-out and pass-through modes. The objectives were to measure the β-delayed neutron probability, by comparison of the 199-keV γ ray from ^{76}Zn to the 189-keV γ ray from ^{77}Zn decay, while also obtaining information on γ rays from the decay. Prior to this experiment the only information on states in ^{77}Zn was a 1.05 s E3 isomer at 772 keV and states at 114 and 803 keV observed in the β-delayed neutron branch of ^{78}Cu.[10,14] We were able to observe 14 γ rays associated with the β decay of ^{77}Cu and produce the decay scheme shown in Fig. 1. It wasn't realized until the analysis phase the difficulty presented by the $1/2^-$ ^{77}Zn isomer. Extracting the intensity of the 772 keV IT γ ray was hindered by its overlap with a γ ray from the room background which had a nearly identical intensity. The observed intensity of the 772-keV γ ray indicates of minimum of 54(4)% β-decay branch from the $(1/2^-)$ isomer for which nearly 100% will directly feed the ground state of ^{77}Ga thereby bypassing the 189-keV level. Therefore, we could not use the measured branching ratio for the 189-keV γ ray. Instead, we used the absolute branching through the 199-keV γ ray compared to the number of ^{77}Cu ions measured by the mini-IC to obtain a value of 36(3)% for the β-delayed neutron probability for the studied ^{77}Cu activity. This is more than a factor of two higher than the previously reported value of 15^{+10}_{-5}%.[13] One very interesting aspect of this decay is observed in the feeding of the excited states where we observe no connecting γ rays between the states

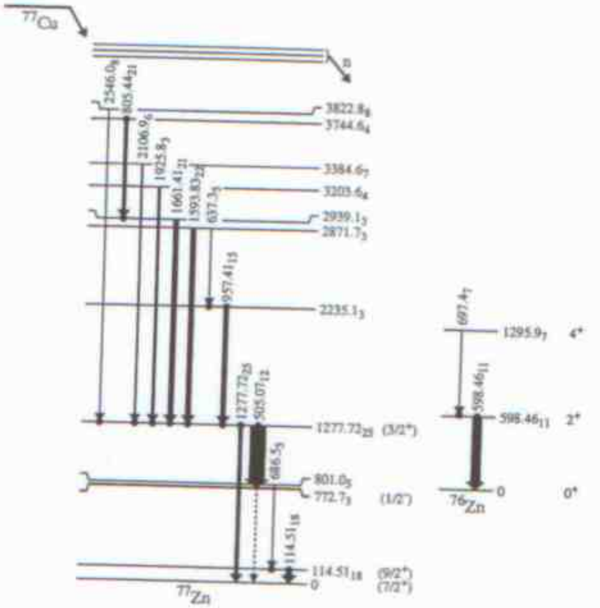

Fig. 1. Proposed decay scheme for ^{77}Cu showing population of excited states in both ^{77}Zn and ^{76}Zn.

above the isomer and the first excited $(9/2^+)$ state except for the 801-keV level which is probably of higher spin. In fact, there is no direct feeding to the 1277-keV level in the decay which, based on the observed intensities of the 505 and 1277-keV γ rays, is assumed to be a $(3/2^+)$ state. This indicates that most of the feeding is by allowed transitions to higher-lying negative parity states. The apparent direct population of the 114-keV $(9/2^+)$ state suggests the presence of a high-spin β-decaying isomer, however we did not observe any apparent difference in the time behavior of the 114 and 505-keV γ rays.

The β decays of ^{78,79}Cu were also measured using the pass-through mode using both a saturation measurement and a MTC cycle. The resultant decay schemes based on our data are shown in Fig. 2. Excited states in ^{78}Zn were first identified in the decay of the (8^+) isomeric state (shown as a dashed level in Fig. 2).[15] Subsequently, ^{78}Cu β decay[10] and ^{78}Zn Coulomb Excitation[16] measurements have confirmed the yrast sequence.[15] In our measurement, we observed a level feeding somewhat different from that proposed by Van Roosbroeck *et al.*, who observed feeding only to the

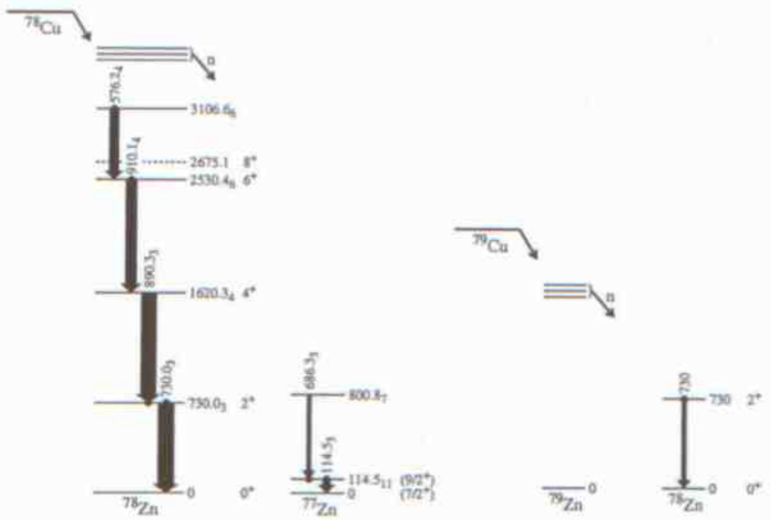

Fig. 2. Proposed decay schemes for ^{78}Cu and ^{79}Cu.

2_1^+ and 4_1^+ states. Our placement of the γ rays is firmly established by $\gamma\gamma$ coincidence data with no observation of the 145-keV transition depopulating the (8^+) isomeric state. We observe a split in the feeding with $\approx 35\%$ feeding to the 4_1^+ state and $\approx 65\%$ feeding the 3106-keV level. Determination of the β-delayed neutron probability was again hampered by the presence of the isomeric state in ^{77}Zn. Although the 114-keV γ ray is clearly seen in the data, there is no clear evidence for the 189-keV γ ray (^{77gs}Zn$\rightarrow$^{77}Ga*) which is surprising since we would expect as many counts as are observed in the 224-keV peak from the decay of ^{78}Zn. The β branching probability based on the 224-keV γ ray is 37(12)% yielding a 63(12)% β-delayed neutron probability which is consistent with the minimum value of 65(20)% reported by Van Roosbroeck *et al.*[10] but significantly higher than the value of 15^{+10}_{-5} reported by Pfeiffer and Kratz.[13] For ^{79}Cu, with a rate of only $\approx 0.1 - 0.2$ ions per second, identification of the 730-keV γ ray in the β-delayed neutron branch required the use of ion tagging. Using particle identification in the mini-IC and the timing signal from the MCP, we were able to generate spectra within a few half-lives of the implantation of a ^{79}Cu ion. Comparison of this spectrum to one gated at a later time relative to the implantation allows easy identification of the γ rays associated with a particular decay. We have yet to clearly associate any γ rays with states in ^{79}Zn.

3. Conclusions

Using recently developed beam purification and ion tagging methods, we have made measurements of the β and β-delayed neutron properties of $^{76-79}$Cu. Results indicate the possibility of β-decaying isomers in ^{76}Cu and ^{77}Cu, with the measured β-delayed neutron probabilities for $^{76-78}$Cu being much higher than previously reported. We report for the first time on a γ ray from the βn decay of ^{79}Cu.

Acknowledgment

This work was supported under US DOE grants DE-FG02-96ER41006, DE-AC05-00OR22725, DE-FG02-96ER40983, DE-AC05-06OR23100, DE-FG02-96ER40978, and DE-FG05-88ER40407, through NNSA grant DEFC03-03NA00143, through the Polish Ministry of Science and Higher Education grant N N202 1033 33, and the Foundation for Polish Science.

References

1. A. F. Lisetskiy *et al.*, Phys. Rev. C**70**, 044314 (2004).
2. T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).
3. T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).
4. J. Dobaczewski *et al.*, Prog. Part. Nucl. Phys. **59**, 432 (2007).
5. K.-L. Kratz *et al.*, Prog. Nucl. Part. Phys. **59**, 147 (2007).
6. F.-K. Thielemann *et al.*, Prog. Nucl. Part. Phys. **59** 74 (2007).
7. C. J. Gross *et al.*, Eur. Phys. J. A**25**, **S01**, 115 (2005)
8. J. A. Winger *et al.*, Phys. Rev. C**42**, 954 (1990).
9. K.-L. Kratz *et al.*, Z. Phys. A**340**, 419 (1991).
10. J. Van Roosbroeck *et al.*, Phys. Rev. C**71**, 054307 (2005).
11. ENDSF Database at the National Nuclear Data Center, http://www.nndc.bnl.gov.
12. G. Rudstam *et al.* Atom. Data Nucl. Data Tab. **53**, 1 (1993).
13. B. Pfeiffer and K.-L. Kratz, *Prog. Nucl. Energy*, 41/1-4,39 (2002).
14. B.Ekström *et al.*, Phys.Scr. **34**, 614 (1986)
15. J. M. Daugas *et al.*, Phys. Lett. B**476** 213 (2000).
16. J. Van de Walle *et al.*, Phys. Rev. Lett. **99**, 142501 (2007).