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EXPERIMENTAL LEVEL SCHEME OF ^{78}Cu*

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Excited states in ^{78}Cu were observed for the first time following the β decay of ^{78}Ni created by in-flight fission of ^{238}U. Based on the coincidence relationships between the observed γ-ray transitions, it was possible to construct a level scheme comprising eight excited states with tentative spin assignments for 5 of them. In addition to the γ-decaying states, an isomeric state with a lifetime of 3.8(4) ms was found to decay by internal conversion.

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1. Introduction

The doubly magic ^{78}Ni represents an important benchmark for nuclear structure studies, providing information on the consequences of a large neutron excess. The properties of nuclei in the region of ^{78}Ni are furthermore important for the understanding of the astrophysical r-process. With one additional proton and one neutron hole relative to ^{78}Ni, ^{78}Cu is an ideal nucleus to study the proton–neutron interaction in this region of the nuclear chart. Probing the structure of ^{78}Cu can therefore reveal important aspects of nuclear structure beyond ^{78}Ni. Previous studies of odd–even $^{69-79}$Cu have shown that the proton $p_{3/2}$ and $f_{5/2}$ orbitals shift in energy and cross when moving away from stability and approaching $N = 50$ [1–3]. Low-energy states in ^{78}Cu are therefore expected to form a multiplet based on the coupling of the $\pi f_{5/2}$ and $\nu g_{9/2}^{-1}$ orbitals. Given the large spin differences that may arise from the multiplet structure in odd–odd nuclei, isomeric states are common and may also be expected in ^{78}Cu.

2. Experimental details and results

The experiment took place at the RIKEN Nishina Center, Saitama, Japan, during the EURICA campaign [4]. A beam of ^{238}U at 345 MeV/u was incident on a ^{9}Be target, producing a wide range of fission fragments, which were separated and identified in the BigRIPS fragment separator. The separator was optimized for the transmission of nuclei in the vicinity of ^{78}Ni, and ions of interest were implanted into the WAS3ABi array of DSSSD detectors, which was surrounded by the EURICA array of HPGe detectors.

In the first step of the analysis procedure, the β-decay half-life of ^{78}Ni was determined. Figure 1 shows the total decay curve for ^{78}Ni, corresponding to the time difference between ion implantation and detection of β-decay electrons within the same or neighboring pixel of WAS3ABi. The decay curve contains not only β-decay events from ^{78}Ni, but also subsequent daughter decays, including those populated by beta-delayed neutron emission. The known half-lives and probabilities for neutron emission P_n [5] for the daughter decays were fixed in the fitting procedure, leaving only the half-life of

^{78}Ni and the total number of decay events as free parameters. The latter can be used to determine the detector efficiency and is needed to determine decay intensities. The half-life of ^{78}Ni was found to be 122.2(51) ms [6]. Details of the procedure can be found in Ref. [7].

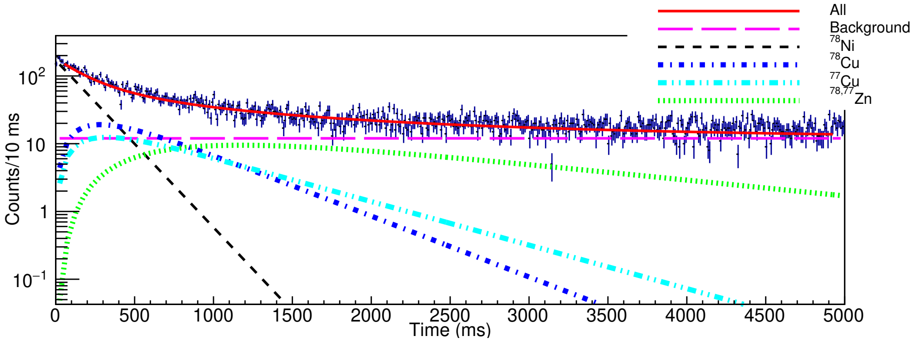

Fig. 1. Total observed number of detected beta decays fitted with the corresponding number of decays from implanted ^{78}Ni and its daughters and grand-daughters.

Based on the time correlations between ion implantation and β decay, it was possible to associate γ-ray transitions with the decay of excited states in ^{78}Cu. A γ-ray spectrum showing the four strongest transitions in ^{78}Cu is shown in Fig. 2 (a). Despite limited statistics, it was possible to analyze γ–γ

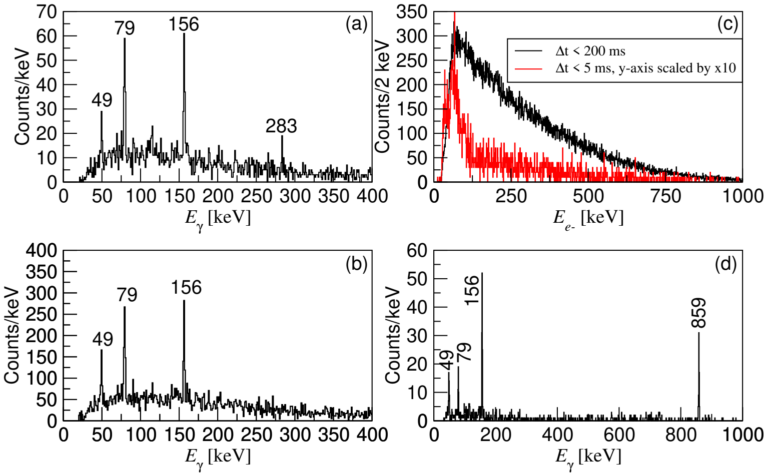

Fig. 2. (Color online) (a) Single γ-ray spectrum. Peaks are marked by their energy in keV. (b) Total projection γ–γ coincidence spectrum. (c) DSSSD signals for 200 ms (black) and 5 ms (red/gray, and scaled by a factor of 10 to clearly be seen in the figure). (d) γ-ray spectrum gated on low-energy DSSSD events below 200 keV and using a short time-gate of 5 ms.

coincidences and place several of the observed transitions in a level scheme for ^{78}Cu, which is shown in Fig. 3. The three low-energy transitions at 49, 79, and 156 keV are in prompt mutual coincidence with each other, and in coincidence with the 859, 985, and 1503 keV transitions. Being by far the strongest transitions, it is reasonable to assume that the cascade of low-energy transitions is feeding the ground state, which has been tentatively assigned as $I^{\pi} = (6^{-})$ in a previous experiment [8]. The three low-energy transitions have comparable intensities when correcting for detector efficiency and electron conversion for M1 multipolarity. Other multipolarities for any of the low-energy transitions would result in long lifetimes of the states and much higher conversion coefficients, requiring a significant imbalance in either β or γ feeding, for which there is no evidence in the data. It is, therefore, concluded that the three low-energy transitions form a cascade of M1 transitions from a (3^{-}) state at 284 keV to the (6^{-}) ground state. Although there is no experimental indication for the ordering of the three transitions, the empiric parabolic rule for proton–neutron multiplets [9] suggests an ordering as shown in Fig. 3. These negative-parity states are interpreted as members of the $\pi f_{5/2} \times \nu g_{9/2}^{-1}$ multiplet. The remaining 2^{-} and 7^{-} members of the multiplet are unobserved and expected to lie at higher excitation energy. The 859 and 985 keV transitions are in mutual coincidence and therefore placed as a cascade feeding the (3^{-}) state. Besides the three low-energy transitions, no coincident γ rays were observed for the 1503 keV transition, which is consequently also assumed to be feeding the (3^{-}) state. Due to the lack of further coincidence relations and the resulting incompleteness of the level scheme, it would be highly speculative to attempt spin assignments for the higher-lying states.

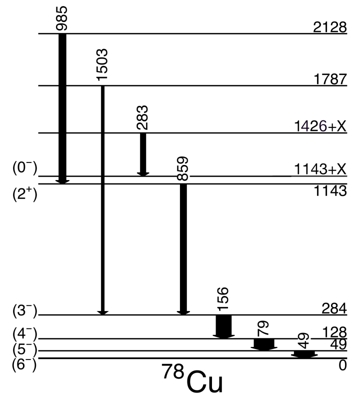

Fig. 3. Experimentally obtained level scheme.

The three low-energy transitions and the 859 keV transition are seen as weak lines in the decay following the implantation of ^{78}Cu, which suggests that they depopulate an isomeric state in ^{78}Cu. Figure 2 (c) shows the energy signals in WAS3ABi during the first 5 ms after implantation (red/gray) and during the first 200 ms after implantation (black). The low-energy signal in the spectrum for short correlation time is consistent with the detection of conversion electrons from a low-energy transition, whereas the spectrum for the longer correlation time is characteristic for β-decay electrons. Gating on the low-energy electron signal and short correlation times below 5 ms results in a very clean γ-ray spectrum showing the 49, 79, 156, and 859 keV transitions in ^{78}Cu, as shown in Fig. 2 (d). This is a clear proof of an isomeric state at a small energy above the state at 1143 keV excitation energy, and it determines the ordering of the 859 and 985 keV transitions. With a clean tag on γ rays and electron energy, the lifetime of the isomeric state was found to be 3.8(4) ms. Based on the lifetime of the isomeric state, together with the observation of conversion electrons and the non-observation of γ rays, the transition that depopulates the isomer is most likely of M2 multipolarity. The isomeric state is therefore interpreted as a (0^-) state based on the $\pi f_{5/2} \times \nu d^{-1}_{5/2}$ configuration, with the state at 1143 keV excitation energy assigned as (2^+). This interpretation is supported by shell model calculations [10].

The γ-ray singles spectrum shows a clear peak at 283 keV, as can be seen in Fig. 2 (a). One could be tempted to place the transition in parallel to the cascade of three low-energy transitions, as it corresponds approximately to the energy sum of the three transitions. However, the 283 keV transition has no coincidence relation with any other transition. This can be seen from its absence in the total projection of the γ–γ coincidence matrix, which is shown in Fig. 2 (b). Given the strength of the 283 and 859 keV transitions in the singles spectrum, any coincidence relation between them should have been observed. The absence of coincidences suggests that the 283 keV transition is feeding the isomeric state. More details and evidence will be presented in a forthcoming publication, together with a comparison to shell model calculations [10].

3. Conclusions

To summarize, ^{78}Cu has been studied by analyzing γ rays following the β decay of ^{78}Ni, produced by in-flight fission. A γ–γ coincidence analysis allowed constructing a partial level scheme for ^{78}Cu, comprising eight excited states. A sequence of low-lying states is interpreted as members of the $\pi f_{5/2} \times \nu g^{-1}_{9/2}$ multiplet. The energies of these states provide direct information on the proton–neutron interaction outside ^{78}Ni. In addition, an isomeric state with a half-life of 3.8(4) ms has been observed to decay by electron conversion. This state is tentatively assigned as (0^-) and interpreted as based on the $\pi f_{5/2} \times \nu d_{5/2}^{-1}$ configuration, providing information on the size of the $N = 50$ shell gap.

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REFERENCES

[1] K.T. Flanagan *et al.*, *Phys. Rev. Lett.* **103**, 142501 (2009).

[2] E. Sahin *et al.*, *Phys. Rev. Lett.* **118**, 242502 (2017).

[3] L. Olivier *et al.*, *Phys. Rev. Lett.* **119**, 192501 (2017).

[4] P.-A. Söderström *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **317**, 649 (2013).

[5] A. Tolosa Delgado, «Study of beta-delayed neutron emitters in the region of ^{78}Ni and its impact on r-process nucleosynthesis», Ph.D. Thesis, Universitat de València (main), 2020.

[6] Z.Y. Xu *et al.*, *Phys. Rev. Lett.* **113**, 032505 (2014).

[7] Z.Y. Xu, «Beta-decay spectroscopy on neutron-rich nuclei in a range of $Z = 26$–32», Ph.D. Thesis, Department of Physics, University of Tokyo, 2014, `http://hdl.handle.net/2261/57714`

[8] R.P. de Groote *et al.*, *Phys. Rev. C* **96**, 041302 (2017).

[9] V. Paar *et al.*, *Nucl. Phys. A* **331**, 16 (1979).

[10] L.G. Pedersen *et al.*, accepted for publication in *Phys. Rev. C*.