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Systematic study of β-decay properties in the vicinity of ^{78}Ni

Z. Y. Xu[1], S. Nishimura[2], G. Lorusso[2], P. Doornenbal[2], M. Niikura[1], T. Sumikama[3], P.-A. Söderström[2], H. Watanabe[4], H. Baba[2], F. Browne[2,5], S. Franchoo[6], G. Gey[2,7,8], T. Isobe[2], P. R. John[9], H.-S. Jung[10], S. Kubono[2], Z. Li[11], I. Matea[6], K. Matsui[1], D. Mengoni[9], P. Morfouace[6], D. R. Napoli[12], F. Naqvi[13], H. Nishibata[14], A. Odahara[14], E. Sahin[15], H. Sakurai[1,2], D. Sohler[16], I. G. Stefan[6], D. Suzuki[6], R. Taniuchi[1], J. Taprogge[2,17,18], Zs. Vajta[2,16], V. Werner[13], J. Wu[2,11], A. Yagi[14], and K. Yoshinaga[19]

[1]*Department of Physics, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, 113-0033 Tokyo, Japan*
[2]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Department of Physics, Tohoku University, 6-3 Aramaki-Aoba, Aoba, Sendai, Miyagi 980-8578, Japan*
[4]*IRCNPC, School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[5]*School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom*
[6]*Institut de Physique Nucléaire, CNRS/IN2P3 and Université Paris-Sud, Orsay, France*
[7]*LPSC, Université Grenoble-Alpes, CNRS/IN2P3, F-38026 Grenoble Cedex, France*
[8]*ILL, 38042 Grenoble Cedex, France*
[9]*Dipartimento di Fisica e Astronomia, Università di Padova and INFN Sezione di Padova, I-35131, Padova, Italy*
10*Department of Physics, University of Notre Dame, Notre Dame, Indiana, USA*
[11]*Department of Physics, Peking University, Beijing 100871, China*
[12]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020, Legnaro, Italy*
[13]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511, USA*
[14]*Department of Physics, Osaka University, Machikaneyama 1-1, Toyonaka, Osaka 560-0043, Japan*
[15]*Department of Physics, University of Oslo, Oslo, Norway*
[16]*Institute for Nuclear Research, Hungarian Academy of Sciences, P.O. Box 51, Debrecen H-4001, Hungary*
[17]*Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[18]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[19]*Department of Physics, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan*

E-mail: xuzy@ribf.riken.jp

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An experiment studying β-decay properties of neutron-rich nuclei in the vicinity of ^{78}Ni was performed at the RIBF facility in 2012. The half-lives of 20 neutron-rich nuclei in Co–Zn isotopic chains were measured, including five new half-lives of ^{76}Co, ^{77}Co, ^{79}Ni, ^{80}Ni, and ^{81}Cu. These new results extend the systematic study of β-decay half-life beyond ^{78}Ni, and they suggest a doubly magic character of ^{78}Ni.

KEYWORDS: β-decay half-life, shell structure, ^{78}Ni

1. Introduction

Analogous to atomic physics, the concept of nuclear shell structure was triggered by the discovery of particularly stable nuclei with specific proton and neutron numbers such as 2, 8, 20, 28, 50, 82, and 126 along the β-stability line [1]. With a strong spin-orbit interaction plus a mean field potential, these magic numbers were correctly interpreted by M. Goeppert-Mayer and O. Haxel *et al.* in 1949 [2, 3]. More recently, with the development of experimental techniques exploiting radioactive ion beams, many nuclei with extreme neutron-to-proton ratios (N/Z), so-called exotic nuclei, have been produced and studied. The results obtained in the last few decades have demonstrated that the shell structure may change dramatically as a function of proton or neutron number [4–9]. To address the origins of shell evolution comprehensively, it is of particular interest to investigate the properties of nuclei in the vicinity of ^{78}Ni (Z = 28 and N = 50), which have a large neutron excess $N/Z \approx 1.8$.

The first half-life measurement for ^{78}Ni was performed in 2005 [10], and several half-lives have been reported on the lower N/Z side of ^{78}Ni [11–15]. This contribution discusses the half-lives beyond ^{78}Ni, which were recently measured and published by the RIKEN -decay group [16].

2. Experiment

The experiment was performed at the RIBF facility in RIKEN. A 5-pnA ^{238}U beam was accelerated up to an energy of 345A MeV by the RIKEN cyclotron accelerator complex before impinging on a 3-mm-thick beryllium target to produce secondary beams via in-flight fission. The fission products were separated based on their momenta and mass-to-charge ratios (A/Q) by the first half of BigRIPS [17]. Then, an event-by-event particle identification (PID) was carried out via the ΔE-$B\rho$-TOF method, in which the energy loss, the magnetic rigidity and the time of flight were measured, giving Z and A/Q information for all the fragments transported through the spectrometer [18]. The resultant PID plot is presented in Fig. 1. The highly segmented beam stopper, Wide-range Active Silicon Strip Stopper Array for Beta and ion detection (WAS3ABi), was composed of eight double-sided silicon strip detectors (DSSSDs) and dedicated to the implantation of heavy ions and the detection of their β decays [19]. Each silicon detector had a 1-mm thickness and an active area of 60×40 mm^2 , which was segmented into 60 strips horizontally and 40 strips vertically. The γ-ray detector, EUROBALL-RIKEN Cluster Array (EURICA) [20, 21], was placed around WAS3ABi to detect β-delayed γ rays as well as γ rays emitted by implanted isomers.

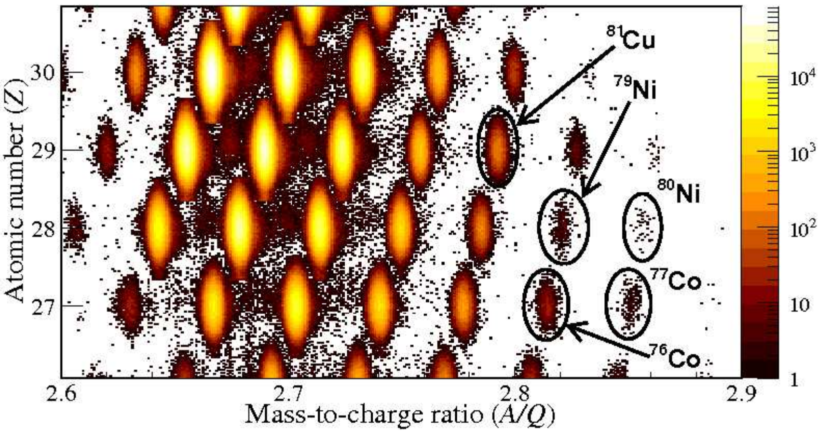

Fig. 1. Particle-identification (PID) plot of the experiment. Half-lives were measured for the first time for nuclei highlighted by black circles [16].

3. Results and discussion

Decay events were associated to heavy-ion implantations based on position and time information from the active stopper, and decay curves of different nuclei were constructed as a time difference between implantation and correlated β decays. The resulting half-lives, together with a few literature values, are presented in Fig. 2.

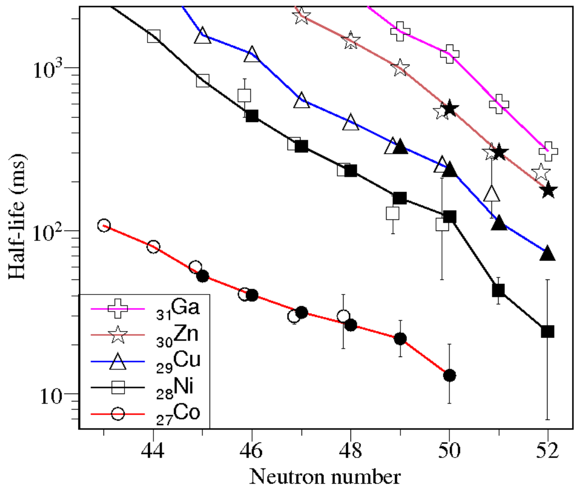

Fig. 2. Experimental half-lives as a function of neutron number for isotopes with $Z = 27 - 31$. All the solid symbols represent the half-lives determined in Ref. [16] while the open symbols are half-lives taken from literature [11, 13, 14, 22]. The systematic trends in different isotopic chains are highlighted by lines connecting the data points with a smaller uncertainty.

Figure 2 shows the systematic trend of -decay half-lives for the nuclei around ^{78}Ni as a function of neutron number. Experimentally, a strong linearity emerges in Fig. 2 below $N = 50$. Beyond that, a sudden reduction manifests in the $Z = 28$ isotopic chain due to the shorter half-lives of ^{79,80}Ni with reference to the systematics at $N \leq 50$. The fast β-decay processes in ^{79,80}Ni could be attributed to the first neutron outside the $N = 50$ shell as follows. If a large shell gap existed, the neutron outside the shell can dramatically increase the Q_β values and consequently the β-decay rates of ^{79,80}Ni compared to that of ^{78}Ni due to the fifth-power dependence between half-life and Q_β value. Note that this sudden reduction of the half-lives beyond $N = 50$ is not clearly observed in the Zn and Ga isotopic chains, and the kink shown by the half-lives of $^{78-81}$Cu is much weaker than the Ni isotopes. Since the Q_β variation crossing the $N = 50$ shell is determined by the strength of neutron shell gap, the stronger kink shown in the Ni isotopic chain is in compliance with the predicted enhancement of the $N = 50$ shell at $Z = 28$ [23]. This behavior is referred to as the concept of mutual support of magicities [24].

Besides the kink along the Ni isotopic chain, a large gap can be noticed in Fig. 2 between the half-lives of Co and Ni isotopes from $N = 44$ to $N = 50$. According to shell model calculations from Ref. [25], the main contribution to the $^{27}\mathrm{Co} \to ^{28}\mathrm{Ni}$ decay is either the Gamow-Teller (GT) transition $\nu f_{5/2} \to \pi f_{7/2}$ or the first-forbidden transition $\nu g_{9/2} \to \pi f_{7/2}$. These transitions, however, are greatly hindered in the β decay $_{28}\mathrm{Ni} \to _{29}\mathrm{Cu}$ because of the fully occupied $\pi f_{7/2}$ single-particle orbit (SPO). In the latter case, the proton produced in a β decay probably fills the $\pi f_{5/2}$ SPO above $\pi f_{7/2}$, leading to a reduction of Q_β value with a magnitude equal to the $Z = 28$ shell-gap energy. Due to the fifth-power relation, a gap is expected between the half-lives of Co and Ni isotopes, which agrees with the observation in Fig. 2. The new half-lives of ^{76,77}Co therefore indicate an almost constant $Z = 28$ shell gap without significant quenching up to $N = 50$.

4. Summary

The β-decay half-lives of ^{76,77}Co, ^{79,80}Ni, and ^{81}Cu were measured recently at RIBF, RIKEN. A sudden decrease of half-lives of the nickel isotopes is noticed beyond $N = 50$, more pronounced than other isotopic chains from Cu to Ga. Besides, the half-life gap between corresponding Co and Ni isotopes, which was previously observed at $N \leq 48$, is found to persist up to $N = 50$. These observations suggest a doubly magic character of the neutron-rich nucleus ^{78}Ni.

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