NANO-SECOND ISOMERS IN NEUTRON-RICH Ni REGION PRODUCED BY DEEP-INELASTIC COLLISIONS*

T. Ishii, M. Asai, M. Matsuda, S. Ichikawa

Advanced Science Research Center, Japan Atomic Energy Research Institute
Tokai, Ibaraki 319-1195, Japan

A. Makishima

Department of Liberal Arts and Sciences, National Defence Medical College
Tokorozawa, Saitama 359-8513, Japan

I. Hossain, P. Kleinheinz and M. Ogawa

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
Meguro, Tokyo 152-8550, Japan

(Received January 17, 2001)

Nuclear structure of the doubly magic ^{68}Ni and its neighbors has been studied by spectroscopic techniques. Developing a new instrument isomer-scope, we have measured γ rays from nano-second isomers produced in heavy-ion deep-inelastic collisions with great sensitivity.

PACS numbers: 23.20.–g, 21.60.Cs, 25.70.Lm, 27.50.+e

1. Introduction

Neutron-rich nuclei around ^{68}Ni, which has a magic number of $Z = 28$ and a sub-magic number $N = 40$, provide valuable information about the nuclear shell structure. Recently, γ-ray spectroscopic techniques for studying nuclei in the neutron-rich Ni region have made remarkable progress. A chemically selective isotope separator with a laser ion-source makes it possible to do β-γ study of neutron-rich Co and Ni isotopes separated from fission products [1,2]. Gamma rays emitted from μs-isomers produced in projectile fragmentation have been measured successfully for nuclei far from the line of

* Presented at the XXXV Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 5–13, 2000.

β-stability [3]. High-spin states in neutron-rich nuclei have been studied by in-beam γ-ray spectroscopic experiments through heavy-ion Deep-Inelastic Collisions (DIC) with a large array of Ge detectors [4]. We have also succeeded in measuring γ rays from nano-second isomers produced in DICs using an isomer-scope developed by ourselves [5]. In this paper, we present our experimental setup and some topics of nuclear structure studied with the isomer-scope.

2. Experiments

Experiments have been carried out at the JAERI tandem booster facility [6]. Neutron-rich nuclei were produced by deep-inelastic collisions with ^{70}Zn, ^{76}Ge, and ^{82}Se beams of about 8 MeV/nucleon and a ^{198}Pt target of 4.3 mg/cm^2 thickness. Gamma rays from isomers were measured with the isomer-scope. A schematic picture is shown in Fig. 1. Projectile-Like Fragments (PLF) produced in DICs are detected by four ΔE detectors of 22 μm thickness and of 20 mm diameter and one annular-type Si-E detector of 100 mm diameter. The Si-E detector covers angles of 21–35 degree in the laboratory system, because the PLFs are emitted near or slightly smaller

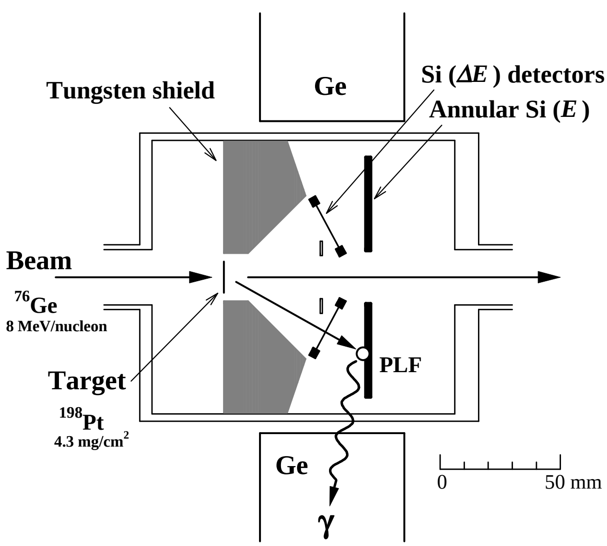

Fig. 1. Isomer-scope: an experimental setup to measure γ rays from isomers with $T_{1/2} > 1$ ns of projectile-like fragments produced in deep-inelastic collisions. It consists of an annular-type Si detector working as a stopper of PLFs, four Si ΔE detectors, four Ge detectors, and a tungsten block to absorb prompt γ rays emitted at the target.

than the grazing angle of about 35 degree. Four Ge detectors surround the Si-E detector and observe γ rays from stopped fragments in the Si-E detector. These Ge detectors are shielded by a tungsten block from prompt γ rays at the target. Taking the ΔE-E-γ-(γ) coincidences, γ rays emitted from isomers can be measured with great sensitivity. A flight time between the target and the Si-E detector is about 1.5 ns, and thus, we can observe isomers with $T_{1/2} > 1$ ns.

Recently, we fabricated ΔE detectors from a Si wafer of 20 μm thickness bought from the Virginia Semiconductor Inc. The energy resolution of the hand-made ΔE detectors is better than the commercially available ones used before. This is probably caused by a good uniformity of the thickness of the Si wafer.

Examples of γ-ray spectra measured with the isomer-scope are shown in Fig. 2. These spectra were obtained from the ^{76}Ge (8 MeV/nucleon) + ^{198}Pt reaction by setting windows on the E-ΔE distribution for Co, Ni, and Cu isotopes. The time window was set on the PLF-γ time spectrum at the range of $\pm$60 ns around the prompt peak. The γ rays from DIC products are clearly observed and selected by each element.

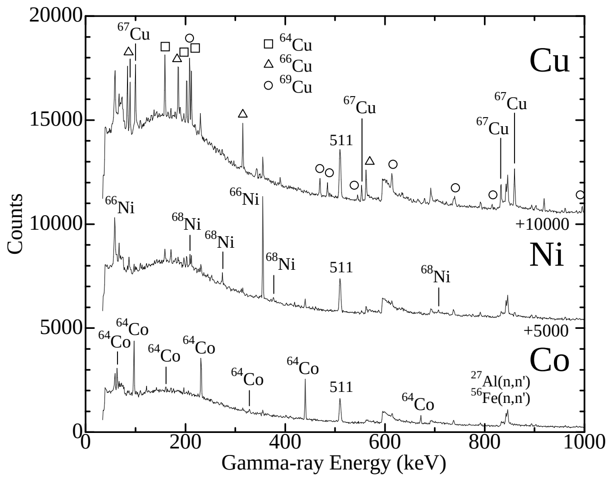

Fig. 2. Gamma-ray spectra measured with the isomer-scope. They were obtained from ΔE-E-γ coincidence data by setting windows on the ΔE-E plot for Cu, Ni, and Co isotopes, respectively.

Many isomers in the neutron-rich Ni region were observed using the isomer-scope as shown in Fig. 3. In these nuclei, we have found new isomers in ^{64}Co [7], ^{68}Ni [8], ^{67,68,69,71}Cu [7–9], ^{80}Ge [10], ^{79}As [11], ^{80,82}Se [10], and ^{87}Rb.

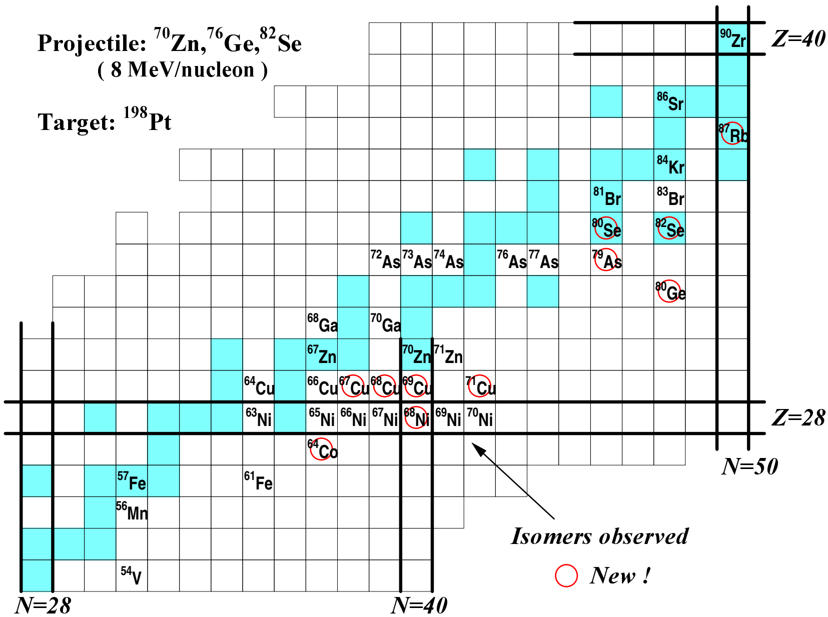

Fig. 3. Distribution of isomers measured with the isomer-scope. Stable isotopes are shown as dark squares. The nuclei depicted in this chart are those whose isomers were observed by the isomer-scope. New isomers we have found are marked with circles.

3. Doubly magic ^{68}Ni

The $^{68}_{28}\mathrm{Ni}_{40}$ nucleus has properties of doubly magic nuclei as a valence mirror nucleus $^{90}_{40}\mathrm{Zr}_{50}$; the first excited state is 0^+ at 1770 keV [12], and the 2^+_1 level lies at 2033 keV [4]. Broda *et al.* [4] also identified the $(\nu g_{9/2}\nu p^{-1}_{1/2})5^-$ isomer with a half-life of 0.86 ms. We have found an 8^+ isomer at 4208 keV with a half-life of 23(1) ns [8]. Figure 4 shows a partial decay scheme of the 8^+ isomer. This isomer decays to the ground state through the E2 cascade and also decays to the long-lived 5^- isomer through several paths of γ transitions.

We can derive the $\nu g_{9/2}$ E2 effective charge for the $^{66}\mathrm{Ni}_{38}$ core from the $B(\mathrm{E2}; 8^+ \to 6^+)$ value in ^{68}Ni, because the 8^+ and 6^+ states should have a pure $\nu g^2_{9/2}\nu p^{-2}_{1/2}$ configuration. From the partial half-life of the 209 keV γ ray, the $B(\mathrm{E2}; 8^+ \to 6^+)$ value is determined as 26(4) $e^2\mathrm{fm}^4$. Assuming the $g_{9/2}$ orbital is occupied by two neutrons, an effective charge is obtained to be 1.5(1) e, where $\langle r^2\rangle = 22$ fm^2 is used. For analogous core of $^{88}_{38}$Sr, an effective charge is calculated to be $e_{\mathrm{eff}}(\pi g_{9/2}) = 2.0\ e$ ($e_{\mathrm{pol}} = 1.0\ e$) from the $B(\mathrm{E2};8^+ \rightarrow 6^+)$ value in ^{90}Zr. Compared with this value, the effective charge obtained from the present ^{68}Ni data is of a reasonable magnitude.

The energy levels in ^{68}Ni were calculated by a shell model using S3V interaction by taking the core to be ^{56}Ni [4, 13]. This calculation gives the 6^+ and 8^+ level energies lower than the experimental values by about 400 keV, although it reproduces the 2^+, 4^+, and 5^- levels in ^{68}Ni. We expect a modern shell model calculation to be able to reproduce the experimental data of ^{68}Ni and to give an insight into the nuclear structure of neutron-rich Ni nuclei.

4. Shell model calculation

The experimental data of the $19/2^-$ isomer decay in ^{69}Cu are compared to a shell model calculation. We take a minimum model space of $\pi p_{3/2}\nu g^2_{9/2}$ by taking the core to be ^{66}Ni. The relative residual interactions of $(\nu g^2_{9/2})0^+, 2^+, 4^+, 6^+, 8^+$ and $(\pi p_{3/2}\nu g_{9/2})3^-, 4^-, 5^-, 6^-$ are taken from the experimental levels in ^{68}Ni [8] and ^{68}Cu [14], respectively. Using the $\nu g_{9/2}$ single particle energy in ^{67}Ni [15] and the relevant six ground state masses [16], we can calculate the energy levels in ^{69}Cu with no free parameters. The results are shown in Fig. 4. The $3/2^-$ ground level calculated within the $\pi p_{3/2}\nu p^2_{1/2}$ model space is also shown. Excellent agreements between calculation and experiment are found. This fact indicates that shell model calculation using experimental levels as input parameters has predictive power. The $B(\mathrm{E2};19/2^- \rightarrow 15/2^-)$ value in ^{69}Cu, 63(3) $e^2\mathrm{fm}^4$, is also well reproduced. Using $e_\nu = 1.5\ e$ obtained from our data in ^{68}Ni and $e_\pi = 2.0\ e$ of an assumed value, this shell model calculation gives 56 $e^2\mathrm{fm}^4$, in good agreement with the experiment.

It is worth mentioning that the $19/2^-$ level in ^{69}Cu is lower than the 8^+ level in ^{68}Ni by about 500 keV. This downward shift originates from the difference between the $\pi p_{3/2}\nu g_{9/2}$ and the $\pi p_{3/2}\nu p_{1/2}$ interaction energies. The $19/2^-$ level relates to the former interaction, while the $3/2^-$ ground state relates to the latter. Because the former interactions, particularly 6^- maximum-spin coupling interaction, are more attractive than the latter, this downward shift is realized. Similar downward shift is also observed of the $21/2^+$ state in a valence mirror nucleus ^{91}Zr. As shown in Fig. 4, the levels in ^{91}Zr are also accurately calculated by a shell model calculation using experimental energy levels of ^{90}Zr and ^{90}Y [17] and nuclear masses.

A similar three-particle calculation was applied to the $19/2^-$ isomer decay in ^{71}Cu, taking the core to be ^{68}Ni and using the energy levels in ^{70}Ni [3] and ^{70}Cu [14] as residual interactions. This calculation also gives an excellent agreement between experiment and calculation [9].

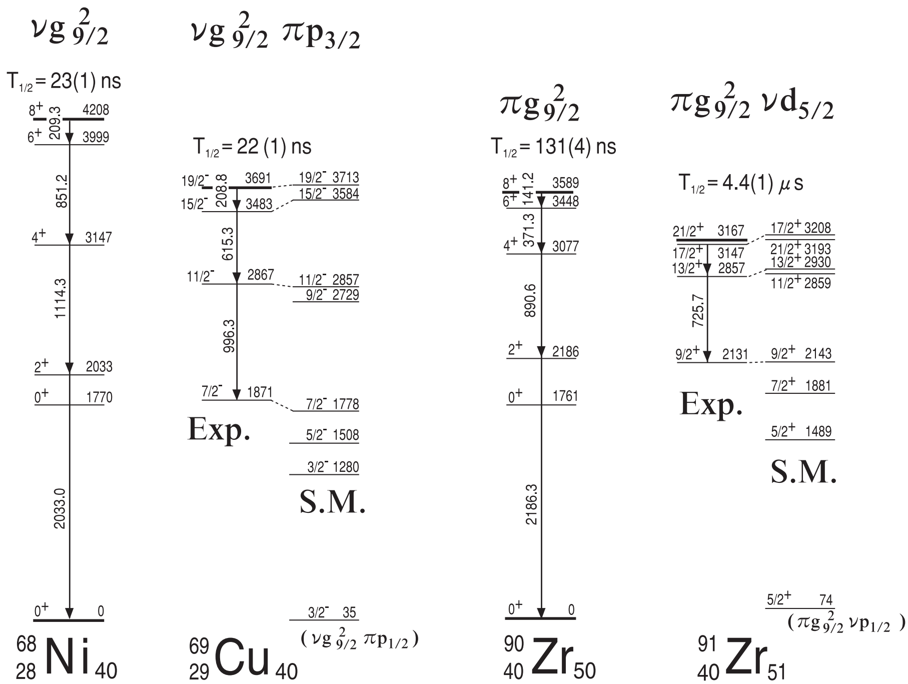

Fig. 4. Decay schemes of the isomers in ^{68}Ni and ^{69}Cu as well as their analogous nuclei ^{90}Zr and ^{91}Zr. The experimental levels in ^{69}Cu and ^{91}Zr are compared to the shell model calculation.

5. Missing μs-isomer in ^{72}Ni

The 8^+ isomer in ^{72}Ni is expected to have a long lifetime from the following reason. First, the energy spacing between the 8^+ and 6^+ states in ^{72}Ni should be similar to those in ^{68}Ni and ^{70}Ni, that is, about 200 keV, as far as the seniority number is conserved. Second, the B(E2) value in ^{72}N$_{44}$ should be very small, because $B(\mathrm{E2}) \propto (\langle n\rangle - 5)^2$, where $\langle n\rangle$ is an expectation value of neutrons occupied in the $\nu g_{9/2}$ orbital [18]. In fact, an analogous nucleus $^{94}_{44}$Ru has the $B(\mathrm{E2}; 8^+ \to 6^+)$ value of 0.0036 W.u. and the half-life of 71 μs. However, the isomer in ^{72}Ni was not found by projectile-fragmentation experiments [19] and the lower and upper limits of its half-life were given to be $T_{1/2} > 1.5$ ms or < 26 ns. A longer lifetime than 1.5 ms would be acceptable from the above shell model picture. But, if this 8^+ isomer had such a long lifetime, the 6^+ level would also have a long lifetime enough to be detected by fragmentation experiments. On the other hand, if this isomer had a short lifetime, very interesting physics would be involved; *e.g.*, the $Z = 28$ shell closure is broken, the seniority number is not conserved, or the 7^- energy level decreases steeply in neutron-rich Ni nuclei. Since our experimental setup covers nano-second region, we will search for this isomer with the isomer-scope. We also expect a modern shell model calculation to predict the structure of these neutron-rich Ni nuclei.

6. Conclusion

Developing the isomer-scope to measure γ rays from nano-second isomers produced in DICs, we have found new isomers in the neutron-rich Ni region and studied their nuclear structures. The $(\nu g_{9/2}^2 \nu p_{1/2}^{-2})8^+$ isomer was found in the doubly-magic ^{68}Ni and the $\nu g_{9/2}$ E2 effective charge was obtained. Shell model calculation using empirical input parameters accurately predicts the decay data of the $(\pi p_{3/2} \nu g_{9/2}^2)19/2^-$ isomers in ^{69,71}Cu. The missing 8^+ μs-isomer in ^{72}Ni suggests interesting physics would appear in neutron-rich Ni nuclei.

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