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Gamma-ray spectroscopy of the neutron-rich Ni region through heavy-ion deep-inelastic collisions

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Abstract. Nuclei in the neutron-rich Ni region have been studied by γ-ray spectroscopy. Gamma-rays emitted from isomers, with $T_{1/2} > 1$ ns, produced in heavy-ion deep-inelastic collisions were measured with an isomer-scope. The nuclear structure of the doubly magic ^{68}Ni and its neighbor ^{69,71}Cu is discussed on the basis of the shell model. Future experiments for more neutron-rich Ni nuclei are also viewed.

PACS. 23.20.-g Electromagnetic transitions – 21.60.Cs Shell model – 25.70.Lm Strongly damped collisions

1 Introduction

Nuclei in the neutron-rich Ni region provide valuable information about the shell structure far from the line of β stability. It is an interesting subject to investigate whether the numbers of $N = 40, 50$ as well as $Z = 28$ keep the magicity in neutron-rich nuclei. Furthermore, the validity of the shell model can be tested quantitatively by nuclei near the doubly magic ^{68}Ni and ^{78}Ni.

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 β-stability line [3]. High-spin states in neutron-rich nuclei have been studied by in-beam γ-ray spectroscopic experiments through heavy-ion deep-inelastic collisions (DICs) with a large array of Ge detectors [4]. We have also succeeded in measuring γ-rays from ns-isomers produced in DICs using an *isomer-scope* developed by ourselves [5]. In this paper, we present some topics of nuclear structure of the neutron-rich Ni region studied with the isomer-scope.

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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 (PLFs) 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. 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 are 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.

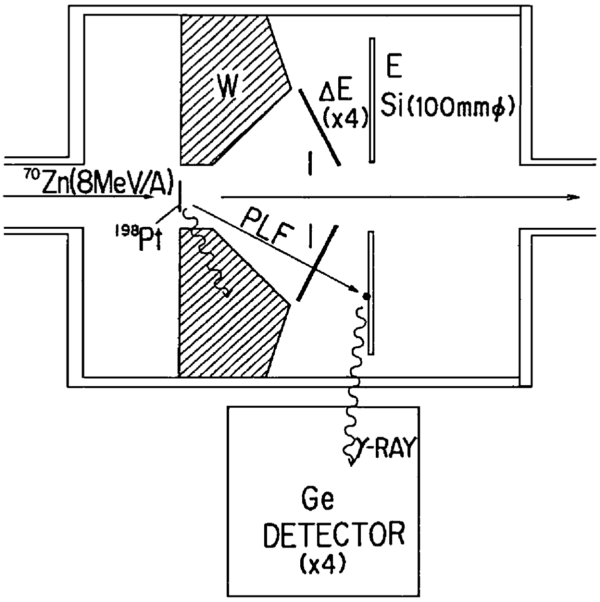

Fig. 1. Isomer-scope: an experimental setup to measure gamma-rays from isomers with $T_{1/2} > 1$ ns of projectile-like fragments produced in deep-inelastic collisions.

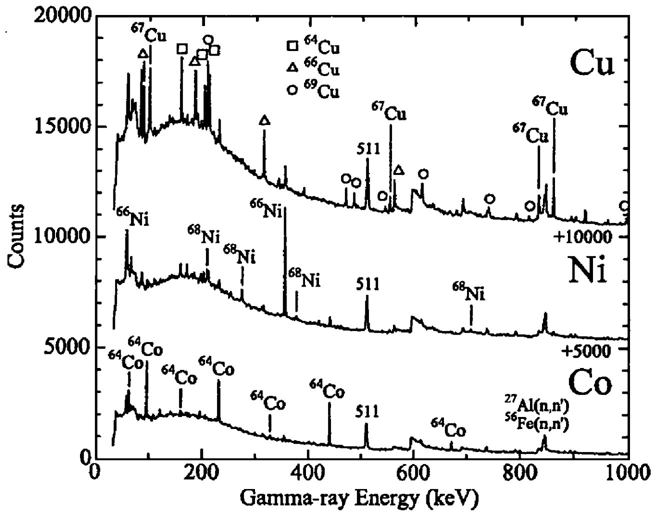

Fig. 2. Gamma-ray spectra measured with the isomer-scope. They are obtained from ΔE-E-γ coincidence data by setting windows on the ΔE-E plot for Co, Ni, and Cu isotopes.

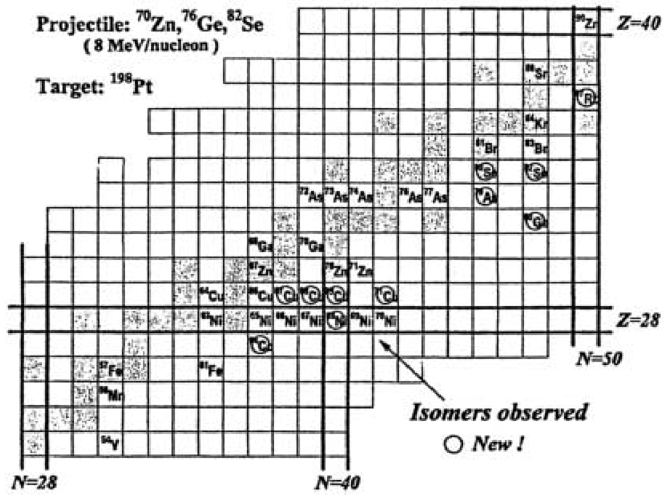

Fig. 3. Distribution of isomers measured with the isomer-scope. Stable isotopes are shown as dark squares. The nuclei depicted in this chart are those whose isomers were observed by the isomer-scope. The new isomers we have found are marked with circles.

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.

3 Doubly magic ^{68}Ni

The $^{68}_{28}$Ni$_{40}$ nucleus has properties of doubly magic nuclei as a valence mirror nucleus $^{90}_{40}$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 long lifetime. We have found an 8^+ isomer at 4208 keV with a half-life of 23(1) ns [8]. Figure 4 shows the decay scheme of this 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}Ni$_{38}$ core from the $B(E2; 8^+ \to 6^+)$ 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 $B(E2; 8^+ \to 6^+)$ value is determined as 26(4) e^2fm^4. Assuming the $g_{9/2}$ orbital is occupied by two neutrons, an effective charge was 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 $e_{\text{eff}}(\pi g_{9/2}) = 2.0e$ ($e_{\text{pol}} = 1.0e$) from the $B(E2; 8^+ \to 6^+)$ 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 spacing between the 6^+ and 4^+ levels in ^{68}Ni is wider than that in ^{70}Ni. This fact suggests that the 4^+ state has a significant admixture of other components, *e.g.*, $\nu g^2_{9/2}\nu f^{-2}_{5/2}$ and $\pi p_{3/2}\pi f^{-1}_{7/2}$, as well as $\nu g^2_{9/2}\nu p^{-2}_{1/2}$. 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 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

We have made a parameter-free shell model calculation for the decay data of the $19/2^-$ isomer in ^{71}Cu [9]. We take a

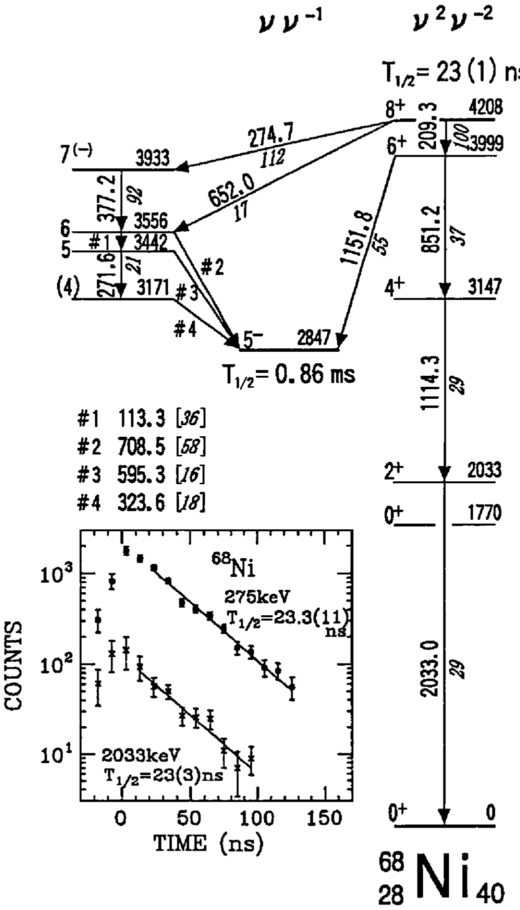

Fig. 4. Decay scheme of the 8^+ isomer in ^{68}Ni. The relative γ-ray intensities are depicted in italics. Decay curves of this isomer are also shown.

core to be ^{68}Ni and a minimum model space of $\pi p_{3/2}\nu g_{9/2}^2$. The relative residual interactions of $(\nu g_{9/2}^2)_{0^+,2^+,4^+,6^+,8^+}$ and $(\pi p_{3/2}\nu g_{9/2})_{3^-,4^-,5^-,6^-}$ are taken from the experimental energy levels in ^{70}Ni [3] and ^{70}Cu [14], respectively. The result of the calculation is shown in fig. 5. The calculated energies are normalized at the ground state, because nuclear masses of the neighboring nuclei are not known accurately enough to predict the ground-state energy in ^{71}Cu.

A similar calculation was done for the levels in ^{69}Cu by taking the core to be ^{66}Ni [8]. In this calculation, the absolute-energy levels in ^{69}Cu were also calculated, using the $\nu g_{9/2}$ single-particle energy in ^{67}Ni [15] and the relevant six ground-state masses [16]. In both calculations for ^{69,71}Cu, the excellent agreement between the experiment and calculation is obtained. This fact suggests the shell model calculation using experimental energy levels as input parameters has a predictive power.

It is worth mentioning that j^2j' aligned states tend to lower in energy and to become a long-lived isomer decaying through $E3$ or $E4$ transitions, *e.g.*, ^{93}Mo, ^{149}Dy, and ^{211}Po [17]. This is caused by the nature of neutron-proton residual interactions; a maximum-spin coupling is most attractive, whereas the couplings with one or two units less have significantly smaller attractions. The $19/2^-$ isomer in ^{69,71}Cu, however, decays to the $15/2^-$ state through the $E2$ transition. This normal sequence results mainly from the following two input quantities; one is the spacing between the two highest j^2 levels, that is, the 8^+-6^+ spacing in ^{68,70}Ni, and the other is the attraction in the $(jj')_{I_{\max}-2}$ coupling, which is much larger in ^{68,70}Cu than in heavier nuclei and contributes to push down the $15/2^-_1$ states through diagonalization.

We have also applied such a recoupling calculation to other j^2j'-type nuclei known over the nuclear chart, using experimental level energies in the neighboring nuclei as two-body residual interactions. For almost all j^2j' three-particle nuclei, this shell model calculation gives a quite accurate result and explains whether the inversion of the $(j^2j')_{I_{\max}}$ and $(j^2j')_{I_{\max}-2}$ levels is realized [18].

5 $(\nu g_{9/2}^{-2})8^+$ isomers in N = 48 nuclei

The $(\nu g_{9/2}^{-2})8^+$ isomers are known in stable or proton-rich $N = 48$ nuclei. We have found the 8^+ isomers in neutron-rich ^{80}Ge and ^{82}Se nuclei [10]. The level spectra of $N = 48$ nuclei are shown in fig. 6. The nuclei of ^{82}Se and ^{80}Ge have a wide spacing between the 8^+ and 6^+ states, while ^{84}Kr-^{92}Ru nuclei have a narrow space, less than 100 keV. Moreover, the 2^+ levels in ^{82}Se and ^{80}Ge lie at lower energies compared to the other $N = 48$ nuclei. Thus, ^{80}Ge and ^{82}Se nuclei are considered to have large collectivity. In fact, the energy levels of these nuclei are rather similar to collective bands backbending at the 8^+ states. The ^{78}Zn nucleus, observed recently by projectile fragmentation experiments [19], has a smaller 8^+-6^+ space again and the 8^+ isomer has a half-life of 319 ns. The collectivity seems to be reduced toward $Z = 28$. The nucleus with two less protons than ^{78}Zn is ^{76}Ni, a two-hole nucleus of $^{78}_{28}$Ni$_{50}$. It is promising to observe the 8^+ isomer in ^{76}Ni by projectile fragmentation experiments, and to obtain important information about the magicity of $Z = 28$ and $N = 50$.

6 Missing μs-isomers 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 $B(E2) \propto (\langle n\rangle - 5)^2$, where $\langle n\rangle$ is an expectation value of neutrons occupied in the $\nu g_{9/2}$ orbital [20]. In fact, an analogous nucleus $^{94}_{44}$Ru has the $B(E2; 8^+ \to 6^+)$ 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 [21] 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^+

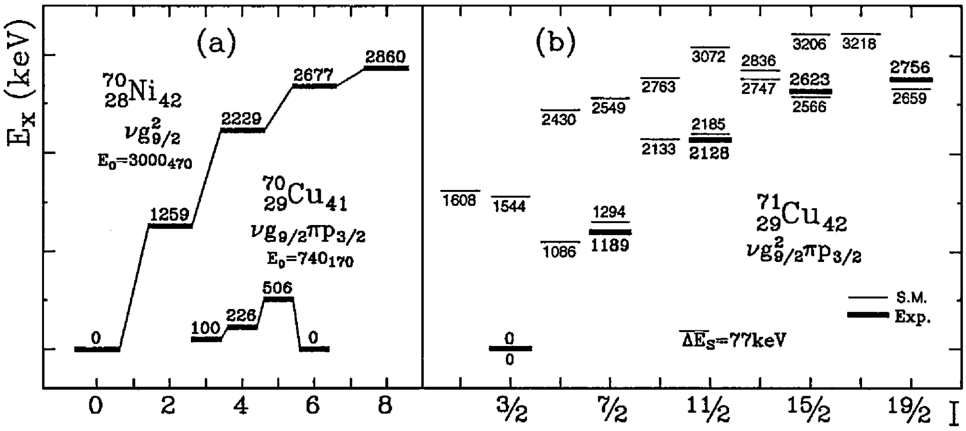

Fig. 5. (a) Interaction energies used in the shell model calculation for ^{71}Cu. E_0 specifies the E_x value for zero residual interaction. (b) Experimental levels of ^{71}Cu compared to calculated values normalized at the ground state.

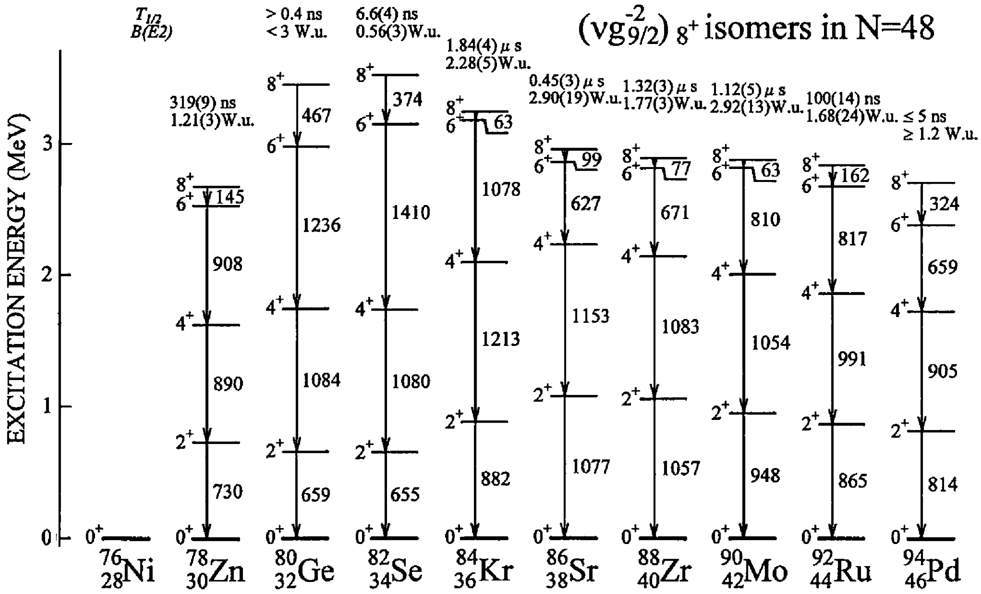

Fig. 6. Decay schemes of the 8^+ isomers in $N = 48$ isotones from ^{78}Zn to ^{94}Pd. Transition energies are given in units of keV. The $B(E2; 8^+ \to 6^+)$ values are also shown.

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 the isomer-scope covers ns-isomers, we will search for this isomer with the isomer-scope after improving its detection sensitivity. We also expect a modern shell model calculation to predict the structure of these neutron-rich Ni nuclei.

7 Conclusion

Developing the isomer-scope to measure γ-rays from ns-isomers produced in DICs, we have found new isomers in the neutron-rich Ni region and studied their nuclear structures. The $(\nu g^2_{9/2} \nu p^{-2}_{1/2})8^+$ 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 predicts the decay data of the $(\pi p_{3/2} \nu g^2_{9/2})19/2^-$ isomers in ^{69,71}Cu. From the systematics of energy levels in $N = 48$ nuclei, the 8^+ isomer in ^{76}Ni would have a long lifetime to be detected by projectile fragmentation experiments. The missing 8^+ μs-isomer suggests interesting physics would appear in neutron-rich Ni nuclei.

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