Core-Excited States in the Doubly Magic ^{68}Ni and its Neighbor ^{69}Cu

T. Ishii,[1] M. Asai,[1] A. Makishima,[2] I. Hossain,[3] M. Ogawa,[3] J. Hasegawa,[3] M. Matsuda,[1] and S. Ichikawa[1]

[1]*Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan*

[2]*Department of Liberal Arts and Sciences, National Defense Medical College, Tokorozawa, Saitama 359-8513, Japan*

[3]*Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Meguro, Tokyo 152-8550, Japan*

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In deep-inelastic collisions of 8 MeV/nucleon ^{70}Zn projectiles with ^{198}Pt, we have found an 8^+ isomer with $T_{1/2} = 23(1)$ ns at 4208 keV in ^{68}Ni; the $\nu g_{9/2}$ $E2$ effective charge was determined to be $1.5(1)e$. In ^{69}Cu, a $19/2^-$ isomer with $T_{1/2} = 22(1)$ ns at 3691 keV was identified and its decay data were calculated quite accurately by a parameter-free shell model calculation using empirical input parameters. Proton $2p$-$1h$ excitation, fed by another $T_{1/2} = 39(6)$ ns isomer at 3827 keV, induces large collectivity in ^{69}Cu.

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The neutron-rich nucleus $^{68}_{28}$Ni$_{40}$ is known to have the properties of doubly closed shells [1,2], and its core excited states can provide valuable information on the nuclear shell structure around this nucleus. This shell structure is important as a base to extend the knowledge of more neutron-rich nuclei towards another doubly magic ^{78}Ni, which is also relevant to astrophysics. Until now, however, only a few excited states, e.g., 0^+ at 1770 keV [1], 2^+ at 2033 keV, and 5^- at 2847 keV [2], have been identified, because in-beam spectroscopic techniques with fusion reactions cannot be applied to such a neutron-rich nucleus.

At the $N = 40$ shell closure in ^{68}Ni, the $\nu p_{1/2}$ and $\nu g_{9/2}$ orbitals lie below and above its Fermi surface, with a smaller energy gap than those at other magic numbers. Thus, the neutron core-excited states of the $\nu g_{9/2} \nu p_{1/2}^{-1}$ and $\nu g_{9/2}^2 \nu p_{1/2}^{-2}$ configurations will appear at low excitation energies. Among these excitations, the $(\nu g_{9/2}^2 \nu p_{1/2}^{-2})_{8^+}$ state is of particular interest. This state is expected to be an isomer, and from its lifetime we can derive a $\nu g_{9/2}$ effective charge, which is a measure of core polarizability. Furthermore, the levels descended from this isomer provide neutron-neutron two-body residual interaction energies. On the other hand, the neutron number 40 is known to lose magicity at $Z = 26$ and 30 [3,4]. This $N = 40$ property can be tested by the excited states in $^{69}_{29}$Cu$_{40}$, especially by the proton two-particle one-hole ($2p$-$1h$) excitation. In the present study, we have found the $(\nu g_{9/2}^2 \nu p_{1/2}^{-2})_{8^+}$ isomer in ^{68}Ni by deep-inelastic collisions. The $\nu g_{9/2}^2$ levels and the $\nu g_{9/2}$ $E2$ effective charge in ^{68}Ni are discussed by comparing with those for $\pi g_{9/2}$ in a valence mirror nucleus $^{90}_{40}$Zr$_{50}$. Using these experimental levels in ^{68}Ni and the $\nu g_{9/2}$ effective charge, we show that a shell model calculation accurately predicts the experimental data obtained from a new isomer of $(\pi p_{3/2} \nu g_{9/2}^2 \nu p_{1/2}^{-2})_{19/2^-}$ in ^{69}Cu. We discuss the collectivity of the proton $2p$-$1h$ states observed in ^{69}Cu.

Recently, experimental techniques for studying neutron-rich nuclei near ^{68}Ni have made remarkable progress. Grzywacz *et al.* [5] found μs isomers around this nucleus by identifying a mass and an atomic number of the nucleus produced in projectile fragmentation. Franchoo *et al.* [6] observed excited states in $^{68-74}$Cu by β decay of nickel isotopes separated from fission products using an isotope separator with a laser ion source. Broda *et al.* [2,7] measured in-beam γ rays of $^{64-68}$Ni produced in heavy-ion deep-inelastic collisions (DIC's) with a large array of γ detectors. We also succeeded [8,9] in measuring in-beam γ rays from isomers, with $T_{1/2} \gtrsim 1$ ns, produced in DIC's using an isomer-scope developed by ourselves [8].

In the present experiment, a ^{198}Pt foil, 4.3 mg/cm^2 in thickness, was bombarded with a 0.1 particle-nA ^{70}Zn beam of 566 MeV from the JAERI tandem booster [10]. The γ rays from isomers were measured with an improved isomer-scope which detects projectile-like fragments (PLF's) with ΔE-E telescopes. Four Si ΔE detectors, each of diameter 20 mm and thickness 22 μm, were arranged symmetrically around the beam axis and were placed in front of a Si E detector of an annular shape, 100 mm in outer diameter and 22 mm in inner diameter; each ΔE detector was inclined at 28° to the beam axis so that the PLF's are incident on this detector perpendicularly. Four Ge detectors, with 30% efficiency, surrounded the periphery of the Si E detector to observe the γ rays from the stopped fragments; these Ge detectors were placed in a cross geometry and each Ge detector was adjacent to each ΔE detector. A tungsten block shields these Ge detectors from the intense γ radiation from the target. Sorting the γ emitters by atomic numbers from the ΔE-E-γ(-γ) coincidence data, we have greatly improved the sensitivity to detect the γ rays of interest. Furthermore, as we will discuss below, this geometry allows us to measure in-plane to out-of-plane ratios of γ rays emitted by PLF's.

Gamma-ray spectra of nickel and copper isotopes are shown in Figs. 1(a) and 1(b). These spectra are obtained not only by setting a window in the ΔE-E diagram but also setting a $t_{\mathrm{PLF}\text{-}\gamma}$ window of 20–100 ns to reduce the γ rays from short-lived isomers and from backgrounds

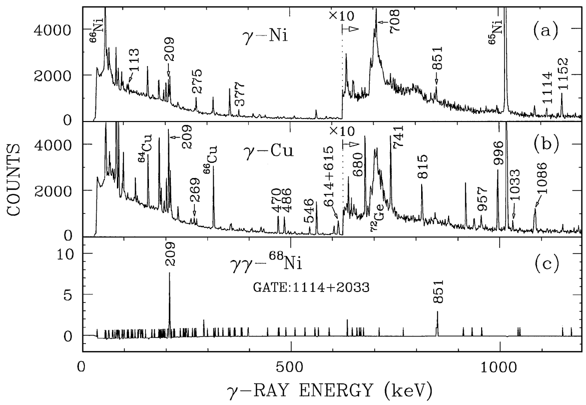

FIG. 1. (a) A γ-ray spectrum of Ni isotopes. The γ-ray energies are depicted for ^{68}Ni. (b) A γ-ray spectrum of Cu isotopes. The γ-ray energies are depicted for ^{69}Cu. (c) A γ-γ spectrum in coincidence with the 1114-keV and 2033-keV γ rays in ^{68}Ni. These three spectra were obtained from the ΔE-E-$\gamma(-\gamma)$ coincidence data, by setting a $t_{\mathrm{PLF}\text{-}\gamma}$ window of 20−100 ns and sorting by atomic numbers.

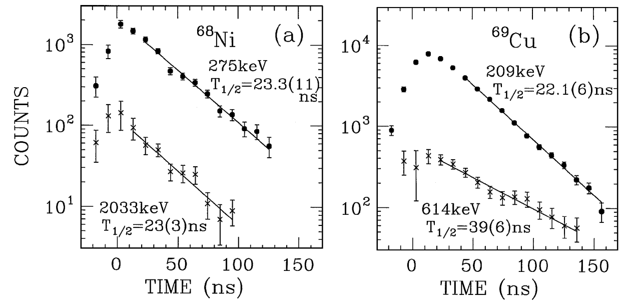

FIG. 2. Decay curves (a) for the 275-keV and 2033-keV γ rays in ^{68}Ni, and (b) for the 209-keV and 614-keV γ rays in ^{69}Cu.

mainly induced by neutrons. In these spectra, we have found γ rays from new isomers in ^{68}Ni and ^{69}Cu. The isomer in ^{68}Ni at the excitation energy of 4208 keV decays through a cascade of four γ rays of 209, 851, 1114, and 2033 keV. Figure 1(c) shows a $\gamma\gamma$ spectrum in coincidence with the latter two γ rays identified previously [2]. This isomer also decays to the long-lived 5^- isomer [2] through several paths of γ transitions. New γ rays in ^{69}Cu are found to be coincident with the low-lying known transitions [8]. Two new isomers were identified at the excitation energies of 3691 and 3827 keV. Decay curves derived from the $t_{\mathrm{PLF}\text{-}\gamma}$ coincidence data are displayed in Figs. 2(a) and 2(b) for some γ rays in ^{68}Ni and ^{69}Cu, respectively. The adopted half-life of the 4208 keV isomer in ^{68}Ni is 23(1) ns, and those of the 3691-keV and 3827-keV isomers in ^{69}Cu are 22(1) and 39(6) ns, respectively. The decay schemes established by the $\gamma\gamma$ coincidence relationships are shown in Fig. 3. The present results are summarized in these schemes, including the γ-ray intensities.

According to a simple picture of DIC's, the angular momentum of the PLF is aligned perpendicular to the reaction plane defined by the beam axis and a ΔE detector. Thus, the anisotropies of γ rays from the PLF's can be measured with the Ge detectors placed in and out of the reaction plane [11]. For example, a stretched quadrupole γ ray has an anisotropy of $W(\mathrm{in})/W(\mathrm{out}) > 1$, while a stretched dipole one has $W(\mathrm{in})/W(\mathrm{out}) < 1$, where the $W(\mathrm{in})$ and $W(\mathrm{out})$ are the γ-ray intensities measured at in plane ($\phi = 90°$) and out of plane ($\phi = 0°$), respectively. In the present setup, the $W(\mathrm{in})$ was measured by the Ge detector adjacent to a ΔE detector and the $W(\mathrm{out})$ was measured by the other two Ge detectors at both sides of the in-plane Ge detector. Figure 4 shows the results for the γ rays in ^{68}Ni and ^{69}Cu, together with those for known ^{65,66}Ni transitions. These results were obtained from the data within the time range of $t_{\mathrm{PLF}\text{-}\gamma} < 100$ ns. Although the anisotropies decrease with time of an order of 10 ns, the anisotropies for the new isomers in ^{68}Ni and ^{69}Cu still remain and allow us to determine the multipolarities of the γ rays. The anisotropy of the 190-keV γ ray with a long lifetime, however, seems too large. The details of this method will be described in another paper.

On the basis of these γ-ray anisotropies, we have determined the spins of the excited states in ^{68}Ni and ^{69}Cu as shown in Fig. 3. For the γ rays of the 209-851-1114-2033 keV cascade in ^{68}Ni, we assigned their spin sequence as $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$. This assignment is consistent with the anisotropy result of $\Delta I = 2$ for the 209-keV γ ray. This spin sequence is also consistent with the lifetime results; we have determined the 851-keV and 1114-keV γ rays to be $\Delta I \leq 2$, because no retardation was observed in this cascade, as shown by the decay curve of the 2033-keV γ ray in Fig. 2(a). For the parity assignment of the ^{69}Cu levels, we referred to the reaction data [12,13] and the β decay data [14]. We also took account of the present lifetime data to distinguish between an $E2$ and an $M2$ transition.

Let us now discuss the nuclear structure of ^{68}Ni. If the 8^+, 6^+, 4^+, and 2^+ states in ^{68}Ni had a pure $\nu g_{9/2}^2 \nu p_{1/2}^{-2}$ configuration, the level spacings between these states should be the same as those in $^{70}\mathrm{Ni}_{42}$ because of the presumable conservation of seniority [15]. In fact, in valence mirror nuclei $^{90}_{40}$Zr and $^{92}_{42}$Mo, these level spacings are almost the same; 141, 371, and 891 keV for ^{90}Zr, and 148, 330, and 773 keV for ^{92}Mo [4]. In ^{70}Ni, their spacings are 183, 448, and 970 keV [5]. Apparently, the spacing between the 6^+ and 4^+ states in ^{68}Ni is much wider than that in ^{70}Ni, while the spacing between the 8^+ and 6^+ states is nearly the same. This fact suggests that the 4^+ state in ^{68}Ni has a significant admixture of other components, while the 8^+ and 6^+ states have a very pure $\nu g_{9/2}^2 \nu p_{1/2}^{-2}$ configuration. In the ^{68}Ni region, the energy difference between the $\nu f_{5/2}^{-1}$ and the $\nu p_{1/2}^{-1}$ states is smaller than that between the analogous proton states in the ^{90}Zr region; $\epsilon(f_{5/2}^{-1}) - \epsilon(p_{1/2}^{-1}) = 694$ and 1745 keV in $^{67}\mathrm{Ni}_{39}$ [7] and $^{89}_{39}$Y [4], respectively. Thus, the $(\nu g_{9/2}^2 \nu f_{5/2}^{-2})_{4^+}$ component contributes significantly to the 4^+ state in ^{68}Ni and would lower this state.

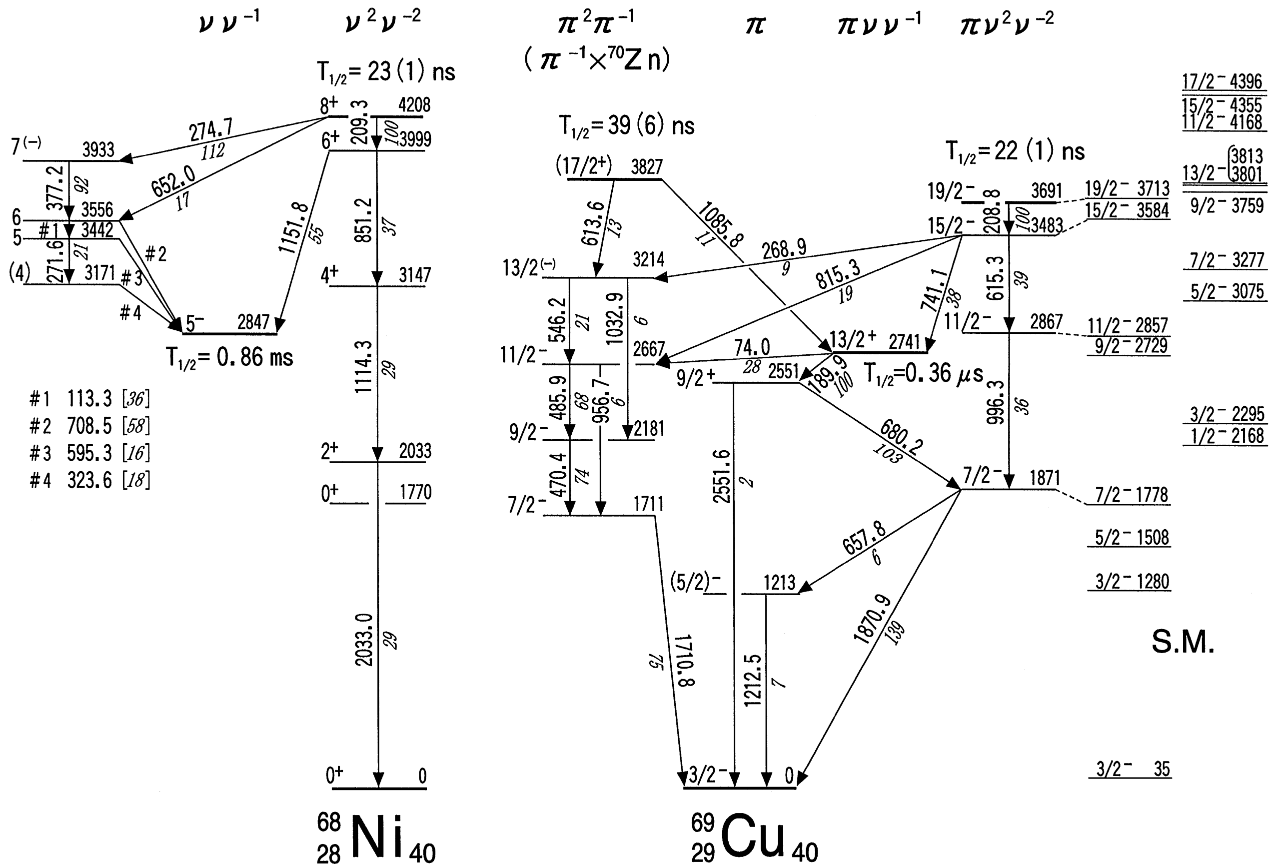

FIG. 3. Decay schemes of the isomers in ^{68}Ni and ^{69}Cu. The relative γ-ray intensities are depicted in italics. The experimental levels in ^{69}Cu denoted by $\pi\nu^2\nu^{-2}$ are compared to the shell model calculation (see text); the calculated yrast levels are shown next to the experimental ones.

As discussed above, the 8^+ and 6^+ states in ^{68}Ni have a pure configuration of two neutrons in the $\nu g_{9/2}$ orbital. Therefore, we can derive the $\nu g_{9/2}$ $E2$ effective charge for the ^{66}Ni$_{38}$ core from the $B(E2; 8^+ \rightarrow 6^+)$ value in ^{68}Ni. From the partial half-life of the 209-keV γ ray, the $B(E2; 8^+ \rightarrow 6^+)$ value is determined as 26(4) e^2 fm^4, corresponding to $e_{\mathrm{eff}}/e = 1.5(1)$. In this Letter, a radial matrix element is evaluated by $\langle r^2 \rangle = (N + 3/2)A^{1/3}$ fm^2, derived from a harmonic oscillator potential. For the analogous core of $^{88}_{38}$Sr, effective charges are calculated to be $e_{\mathrm{eff}}(\pi g_{9/2}) = 2.0e$ ($e_{\mathrm{pol}} = 1.0e$) and $e_{\mathrm{eff}}(\nu g_{9/2}^{-1}) = 2.1e$ from the $B(E2; 8^+ \rightarrow 6^+)$ values in ^{90}Zr and ^{86}Sr, respectively [4]. Compared with these values, the effective charge obtained from the present ^{68}Ni data is of a reasonable magnitude.

The other new states in ^{68}Ni with spins of $7^{(-)}$, 6, and 5 can be formed by the neutron $1p$-$1h$ excitation of $(\nu g_{9/2} \nu f_{5/2}^{-1})_{7^-,6^-,5^-}$. These states lie above the $(\nu g_{9/2} \nu p_{1/2}^{-1})_{5^-}$ isomer by 600–1100 keV. This separation is consistent with the energy difference between the $\nu f_{5/2}^{-1}$ and $\nu p_{1/2}^{-1}$ states. However, we also point out the possibility of proton $1p$-$1h$ excitations such as $(\pi g_{9/2} \pi f_{7/2}^{-1})_{7^-}$ and $[\pi(f_{5/2}, p_{3/2}) \pi f_{7/2}^{-1}]_{6^+,5^+}$ for these states, because these excitations may lie around at 4 MeV. Beta-decay studies of ^{68}Co would give a clue to their configurations.

Let us turn to the discussion on ^{69}Cu. The levels denoted by $\pi\nu^2\nu^{-2}$ in Fig. 3 are considered to have main configurations of $\pi p_{3/2} \nu g_{9/2}^2 \nu p_{1/2}^{-2}$ by a shell model calculation discussed below. Our previous Letter on the $19/2^-$ isomer in ^{71}Cu [9] showed that the observed levels in ^{71}Cu were calculated accurately by a shell model with the $\pi p_{3/2} \nu g_{9/2}^2$ model space, using experimental energy levels as two-body residual interactions. A similar three-particle calculation can be applied to the decay of the $19/2^-$ isomer in ^{69}Cu by taking the core to be ^{66}Ni instead of ^{68}Ni. The relative residual interactions of $(\nu g_{9/2}^2)_{0^+,2^+,4^+,6^+,8^+}$ are taken from the levels in ^{68}Ni. Those of $(\pi p_{3/2} \nu g_{9/2})_{3^-,4^-,5^-,6^-}$ are taken from the levels in ^{68}Cu obtained by the ^{68}Zn$(t, {}^3$He) reaction [16]; the 772, 950, 1350, and 716 keV levels are assigned as 3^-, 4^-, 5^-, and 6^-, respectively, by the systematics of $\pi\nu$ two-particle multiplets [9]. The excitation energy of the $19/2^-$ state in ^{69}Cu is calculated as 3713(110) keV, using the $\nu g_{9/2}$ single particle energy in ^{67}Ni [7] and the relevant six ground state masses [17]. Note that no free parameters are used in the present calculation. The calculated levels are illustrated on the right-hand side in Fig. 3. The $3/2^-$ ground level calculated within the $\pi p_{3/2} \nu p_{1/2}^2$ model space is also shown. The excellent agreement between calculation and experiment indicates

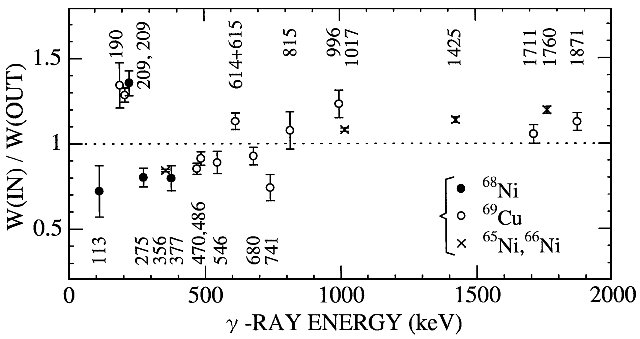

FIG. 4. In-plane to out-of-plane ratios for the γ rays in ^{68}Ni and ^{69}Cu. Those for the γ rays in ^{65,66}Ni are also shown; 1017 keV ($9/2^+ \rightarrow 5/2^-$), 356 keV [$(5^-) \rightarrow (4^+)$], 1425 keV [$(4^+) \rightarrow 2^+$], and 1760 keV ($2^+ \rightarrow 0^+$) [7].

that the input parameters taken from the level energies well absorb the effect of the configuration mixing which cannot be treated within the small model space. The $B(E2; 19/2^- \rightarrow 15/2^-)$ value in ^{69}Cu, 63(3) e^2 fm^4, can be also explained. Using $e_\nu = 1.5e$ obtained from the present work and $e_\pi = 2.0e$ of an assumed value, this shell model calculation gives 56 e^2 fm^4, in good agreement with the experiment.

The $19/2^-$ level in ^{69}Cu is lower than the 8^+ level in ^{68}Ni by 517 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 the 6^- maximum-spin coupling interaction, are more attractive than the latter, this downward shift realizes. Similar downward shift is also observed of the $21/2^+$ state in a valence mirror nucleus ^{91}Zr [4]. The experimental energies of the 8^+ level in ^{68}Ni and the $19/2^-$ level in ^{69}Cu can be explained consistently by our calculation, although previous calculations using a larger model space [2,18] gave a lower 8^+ excitation at about 3800 keV.

The $7/2^-$ to $13/2^{(-)}$ levels depicted on the left-hand side in the ^{69}Cu decay scheme, named the $\pi^2\pi^{-1}$ band, are considered as proton $2p$-$1h$ excitation with the $\pi(p_{3/2}^2, p_{3/2}f_{5/2}, f_{5/2}^2)\pi f_{7/2}^{-1}$ configurations, as also suggested by Broda *et al.* [19]. This is because the $7/2^-$ level at 1711 keV has a large spectroscopic factor of $C^2S = 2.7$ and 1.8 in the ^{70}Zn$(d, {}^3$He) [12] and ^{70}Zn$(\vec{t}, \alpha)$ proton pickup reactions [13], respectively. This $\pi^2\pi^{-1}$ band is similar to a collective band: regular level spacings and competition between the $\Delta I = 1$ and $\Delta I = 2$ transitions. This competition indicates that the $E2$ strengths in this band are significantly large, because the $M1$ strengths dominated by the large g factor of $\pi f_{7/2}^{-1}$ should have an order of magnitude of the Weisskopf estimate, namely, 1.8 μ_N^2. Using this $B(M1)$ value, the $B(E2)$ values are obtained as $3(1) \times 10^2$ and $10(3) \times 10^2$ e^2 fm^4 for the $11/2^- \rightarrow 7/2^-$ and the $13/2^{(-)} \rightarrow 9/2^-$ transition, respectively. These $B(E2)$ values are comparable to the $B(E2; 2^+ \rightarrow 0^+)$ value of $3.6(4) \times 10^2$ e^2 fm^4 in $^{70}_{30}$Zn$_{40}$ [4]. Furthermore, the $\Delta I = 2$ spacings in this band are close to those in ^{70}Zn; the 2^+-0^+ and 4^+-2^+ spacings in ^{70}Zn are 885 and 902 keV, respectively [4]. Thus, we have concluded that the states in the $\pi^2\pi^{-1}$ band have large collectivity as the two-valence-proton nucleus ^{70}Zn. From this point of view, the $\pi^2\pi^{-1}$ band may be represented as $\pi f_{7/2}^{-1} \times {}^{70}$Zn.

The 3827-keV isomer in ^{69}Cu can be assigned as the $(\pi p_{3/2}\pi g_{9/2}\pi f_{7/2}^{-1})_{17/2^+}$ state, decaying to the $(\pi p_{3/2}\pi f_{5/2}\pi f_{7/2}^{-1})_{13/2^-}$ state through the 614 keV $M2$ transition with 0.3(1) W.u. However, this assignment results in the 1086-keV γ ray as an $E2$ transition with large hindrance. This hindrance would suggest that this isomer has a different shape from the $13/2^+$ state at 2741 keV. Further theoretical and experimental study is required for understanding the structure of this isomer.

In conclusion, we have found the $(\nu g_{9/2}^2 \nu p_{1/2}^{-2})_{8^+}$ isomer in ^{68}Ni by deep-inelastic collisions and determined the $E2$ effective charge for the $g_{9/2}$ neutrons. Using the energy levels in ^{68}Ni and this $\nu g_{9/2}$ effective charge, we have shown that a shell model calculation predicts the decay data of the $(\pi p_{3/2} \nu g_{9/2}^2 \nu p_{1/2}^{-2})_{19/2^-}$ isomer in ^{69}Cu with excellent accuracy. The proton $2p$-$1h$ excitation induces large collectivity in ^{69}Cu.

Note added.—Broda *et al.* [20] also found the $19/2^-$ isomer decay in ^{69}Cu independently; their data are similar to ours.

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