The $(\nu g^2_{9/2}\pi p_{3/2})_{19/2^-}$ Isomer in ^{71}Cu and the Prediction of its $E2$ Decay from the Shell Model

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In deep-inelastic collisions of 8 MeV/nucleon ^{76}Ge projectiles with ^{198}Pt, we have found a $T_{1/2} = 0.25(3)$ μs isomer in ^{71}Cu which decays through a γ-ray cascade of 133-495-939-1189 keV to the $\pi p_{3/2}$ ground state. The detector setup records the γ rays of the isomeric decay as well as data on the fragment which provide its isotopic assignment. The new ^{71}Cu levels are firmly assigned as the five yrast states of the $\nu g^2_{9/2}\pi p_{3/2}$ configuration; a parameter-free shell model calculation using the two-body residual interactions as observed in ^{70}Cu and ^{70}Ni predicts the ^{71}Cu data with excellent accuracy. [S0031-9007(98)07465-1]

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Deep-inelastic collisions are a useful tool to access yrast states of neutron-rich nuclei near nickel [1,2]. The energy spectra of these nuclei give valuable information about the shell structure far from the line of β stability. In particular, nuclei near the doubly closed ^{68}Ni nucleus [3] can provide important quantitative tests for the validity of the shell model. The ^{71}Cu nucleus has one proton and two neutrons outside the ^{68}Ni core. At low excitation these valence particles will occupy the proton $\pi p_{3/2}$ orbital and the neutron $\nu g_{9/2}$ orbital, which are well separated in energy or spin from other single particle states. One therefore expects $\nu g^2_{9/2}\pi p_{3/2}$ character for the low-lying states near the yrast line in ^{71}Cu, and their properties should be calculated quite accurately in a recoupling calculation for their minimum configuration space if experimental two-body residual interactions are used. In the present study we have produced the $(\nu g^2_{9/2}\pi p_{3/2})_{19/2^-}$ isomer of ^{71}Cu in deep-inelastic collisions and have found that its γ-decay cascade differs from the typical decay pattern of analogous $j^2 j'$-type isomers in other heavy three-particle nuclei. We discuss the specific nuclear structure of the $\nu g^2_{9/2}\pi p_{3/2}$ states in ^{71}Cu by comparison with a parameter-free shell model recoupling calculation which employs interaction energies taken as the known excitation energies of the $\nu g^2_{9/2}$ states in ^{70}Ni and of the $\nu g_{9/2}\pi p_{3/2}$ states in ^{70}Cu. We remark here that Rykaczewski *et al.* [4], among more than 50 new isomers produced in fragmentation, also mention a new ^{71}Cu isomer, with a preliminary half-life of 275 ns, but no γ-ray or level energies.

In the present experiment a 4.3 mg/cm^2 thick 96% enriched ^{198}Pt metal foil was bombarded with a 0.2 particle-nA ^{76}Ge beam of 635 MeV from the JAERI tandem booster [5]. The γ decays of isomers in the range of ~1 ns to ~10 μs were measured with the isomer-scope [6], a setup optimized for observation of isomers produced in deep-inelastic collisions (DIC's). The projectilelike fragments (PLF's) are detected in an annular silicon detector placed 6 cm downstream from the target. It covers the angles of 21°–35° from the beam direction, because most PLF's are emitted slightly inside the grazing angle of 35°. Five Ge detectors surround the periphery of the Si detector to observe the γ rays from the stopped fragments. This geometry allows one to shield the γ detectors from the intense γ radiation from the target and thus greatly improves the sensitivity to detect the γ rays from isomers produced with small cross section. Furthermore, as we will discuss below, the data recorded for the fragment give important information on its atomic and its mass number.

In our experiment we observed more than 30 isomers. Half of them were unknown; we have earlier reported our results on isomers in ^{69}Cu and ^{79}As [6,7]. The new isomer decays through a cascade of four intense γ rays with energies of 133, 495, 939, and 1189 keV, giving the isomer excitation as 2756 keV. The 133 and 495 keV lines were found to be also coincident with a much weaker parallel cascade of 342, 1252, and 534 keV γ rays. A $\gamma\gamma$-coincidence sum spectrum for the four intense transitions is displayed in Fig. 1; the inset shows a decay curve derived from the $t_{\gamma\text{-PLF}}$ coincidence data. The four intense γ rays decay with similar rates; the adopted mean value is $T_{1/2} = 0.25(3)$ μs. These results are summarized in Table I and in the isomer decay scheme of Fig. 2. We will return to them after discussion of the isotopic assignment obtained from the data recorded for the fragment.

The mass number of the 2756 keV isomer was deduced from the kinetic energy of the PLF. Figure 3 shows the yields of isomers in different copper isotopes as a function of the PLF energy, extracted from the γ-PLF coincidence data. This figure illustrates useful properties of DIC's for the identification of nuclei. First, the energy distribution of an individual isotope has a narrow width. Second, the PLF energy increases with the mass number. From our data (Fig. 3) the former is determined as 332(4), 367(3), and 402(2) MeV for ^{64,66,69}Cu, respectively. The

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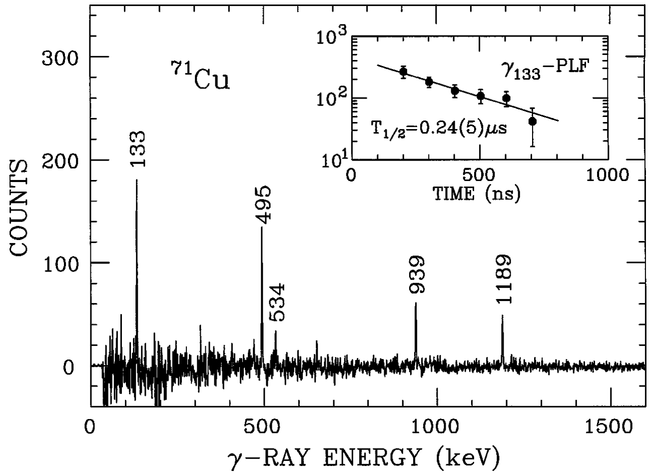

FIG. 1. A γ-γ coincidence spectrum representing the sum of coincidence gates on the 133, 495, 939, and 1189 keV transitions. The inset shows the decay curve for the 133 keV γ ray.

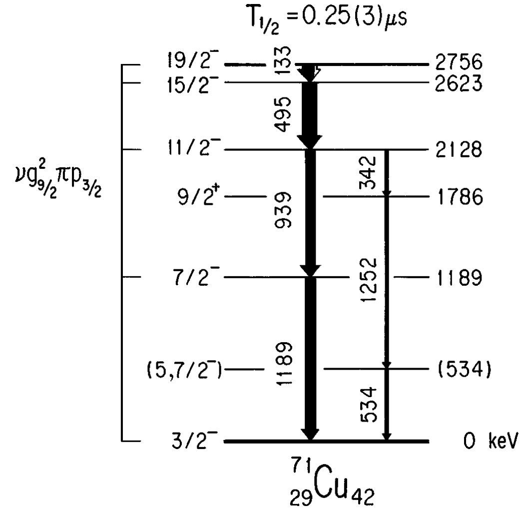

FIG. 2. Decay scheme of the isomer in ^{71}Cu.

2756 keV isomer, denoted by 71 in Fig. 3, has the energy of 412(6) MeV. From this value, its mass number can be estimated by extrapolation of the data of Fig. 3 to be 70 $\pm$ 1, if it is a copper isotope.

Furthermore, the neutron number of the PLF was estimated from the population yields in the reaction using a different germanium isotope as a projectile. We compared the isotopic yields in the reaction of ^{74}Ge + ^{198}Pt with those in the reaction of ^{76}Ge + ^{198}Pt with the same beam energy. In the reaction with the ^{74}Ge projectile, the integral yield distribution shifted toward neutron-deficient nuclei. The ratios of the yields, $I(^{74}\mathrm{Ge})/I(^{76}\mathrm{Ge})$, were 2.4(5), 1.2(1), 0.40(3), and 0.25(5) for the ^{64}Cu, ^{66}Cu, ^{69}Cu, and the 2756 keV isomer, respectively. These ratios indicate that the 2756 keV isomer belongs to a more neutron-rich nucleus than ^{69}Cu.

In order to define the atomic number, we carried out an experiment with a Si $\Delta E - E$ telescope, placed at 28°, instead of the annular Si detector. As an example, Fig. 4(a) shows a diagram of the energy loss ΔE vs the total energy $E + \Delta E$ for the 0.6 μs 6^- isomer in ^{66}Cu [6]. Also displayed are the gate contours chosen for the analysis of the data. They are obtained from a stopping power calculation where the apparent slope, in addition to the dependence on the fragment energy, also accounts for the variation of the fragment mass with energy as displayed in the lower part of Fig. 4(a). Figure 4(b) shows the yields for several isomers obtained with these gate windows. The atomic numbers are clearly identified from these data, and they firmly classify the 2756 keV isomer as a copper isotope.

TABLE I. Gamma rays in decay of the ^{71}Cu $19/2^-$ isomer.

No.	E_γ (keV)	I_γ	$T_{1/2}$ (μs)	Coincident γ rays
1	133.0(3)	78(9)	0.24(5)	*3, 4, 5, 6, 7*
2	342.4(9)	13(6)		*1, 3, 4, 7*
3	494.7(3)	100(8)	0.30(6)	*1, 2, 4, 5, 6*
4	534.4(6)	21(7)		*1, 2, 3, 7*
5	939.1(4)	81(8)	0.24(6)	*1, 3, 6*
6	1189.1(4)	75(7)	0.23(6)	*1, 3, 5*
7	1251.6(9)	12(9)		*2, 3, 4*

The above experimental evidence confines the 2756 keV isomer to ^{70}Cu or ^{71}Cu. Although nothing is known on the ^{70}Cu yrast cascade, it is very unlikely that it would have a sequence as the γ-ray cascade from the 2756 keV isomer. On the other hand, γ rays of 534.1(5) keV ($I_\gamma = 100$) and 1251.7(5) keV ($I_\gamma = 40$) were recently found in 1.9 s ^{71}Ni β decay [8], and thus we definitely conclude that the 2756 keV isomer belongs to ^{71}Cu.

In the isomer decay scheme of Fig. 2 it is assumed that the 133-495-939-1189 keV cascade defines the $19/2^- \rightarrow 15/2^- \rightarrow 11/2^- \rightarrow 7/2^- \rightarrow 3/2^-$ yrast level sequence, consistent with $E2$ character for the 133 keV isomeric transition. The 1786 keV state fed in ^{71}Ni β decay and from the $11/2^-$ yrast state is probably $I^\pi = 9/2^+$, which would favor a $\nu g_{9/2}$ assignment for the 1.9 s ^{71}Ni β

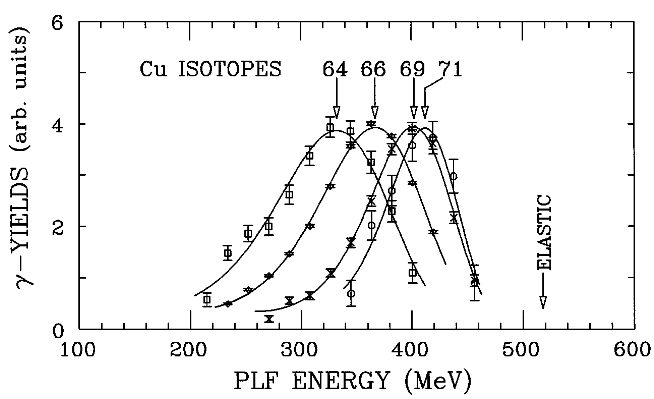

FIG. 3. Gamma-ray yields for isomers in different copper isotopes as a function of the PLF energy as marked by arrows with mass number. The 2756 keV isomer is denoted by "71." The mean energy of elastically scattered projectiles is also shown.

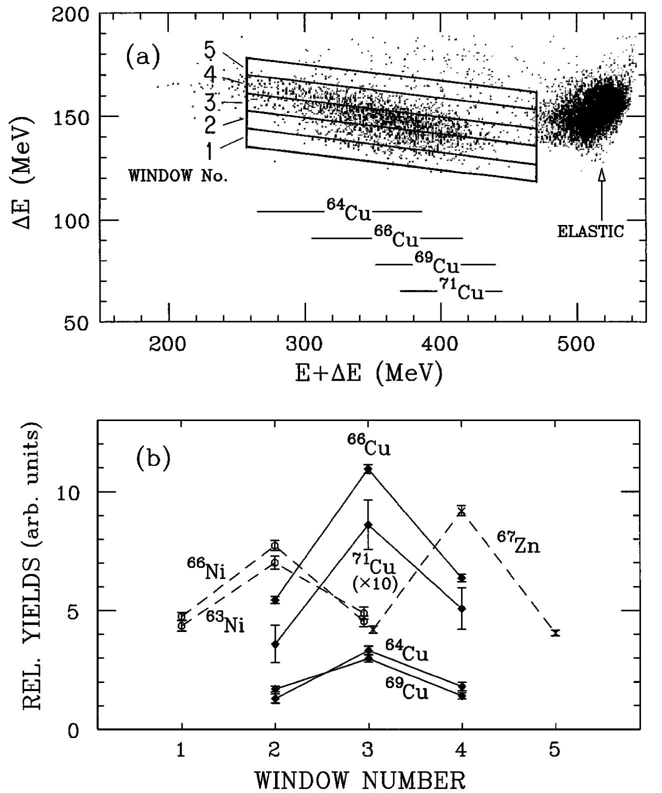

FIG. 4. (a) The energy loss ΔE vs total energy $E + \Delta E$, measured with the telescope in coincidence with the 315 keV $4^+ \rightarrow 3^+$ γ ray in ^{66}Cu 0.6 μs isomer decay. Gate windows to define the atomic numbers are shown. The FWHM values for the PLF energy distributions of ^{64,66,69,71}Cu are drawn in the lower part. (b) Yields of isomers in coincidence with the gate windows displayed in (a).

parent. We place the 534 keV line lowest in the scheme due to its large intensity in β decay, indicative of higher-lying β-fed $\pi g_{9/2}$ strength not populated in decay of the $19/2^-$ isomer.

As mentioned before, the ^{71}Cu $19/2^-$ isomer decay through a four-transition $E2$ cascade as in its even two-particle neighbor ^{70}Ni is different from the typical decay pattern of analogous $j^2 j'$ three-particle isomers with $j > 7/2$. In these isomers the multipolarity of the isomeric transition is higher than $E2$. For example, in the classical case of ^{93}Mo [9] the $(\pi g_{9/2}^2 \nu d_{5/2})_{21/2^+}$ isomer has 6.9 h half-life and decays through $E4$-$E2$-$E2$ to the $\nu d_{5/2}$ ground state, and in ^{211}Po the decay cascade for the 25 s $(\pi h_{9/2}^2 \nu g_{9/2})_{25/2^+}$ isomer [10] is $E4$-$E1$-$E3$. The 0.5 s $(\pi h_{11/2}^2 \nu f_{7/2})_{27/2^-}$ isomer of ^{149}Dy [11] deexcites through $E3$-$E2$-$E2$-$E3$, exploiting the odd-parity 7^- and 5^- two-proton couplings of the ^{148}Dy neighbor. Also, in ^{53}Co [12], where the three particles are holes in ^{56}Ni, the $(\nu f_{7/2}^{-2} \pi f_{7/2}^{-1})_{19/2^-}$ state undergoes 247 ms Fermi decay to its mirror $19/2^-$ configuration in ^{53}Fe, which in turn connects with $T_{1/2} = 2.6$ min via $E4$-$E2$ to the $\nu f_{7/2}^{-1}$ ground state. However, in the analogous three-particle nuclei ^{43}Sc and ^{43}Ti the decays of the $(f_{7/2}^2 f_{7/2})_{19/2^-}$ states proceed as triple-$E2$ cascades to the $f_{7/2}$ ground states.

It is well known that the isomerism of these aligned three-particle states is caused by the strongly attractive $\pi\nu$ two-body residual interaction for the maximum-spin coupling, whereas the couplings with spins one or two units less have significantly smaller attraction. As a consequence, e.g., the fully aligned $(\pi g_{9/2}^2 \nu d_{5/2})_{21/2^+}$ state in ^{93}Mo, where the $(\pi g_{9/2} \nu d_{5/2})_{7^+}$ coupling strongly contributes, is lowered in energy below the $(\pi g_{9/2}^2 \nu d_{5/2})_{17/2_1^+}$ level, and analogous in other cases.

To elucidate the isomer decay cascade of ^{71}Cu, its energy spectrum was calculated from the shell model in the minimum model space $\nu g_{9/2}^2 \pi p_{3/2}$ using two-nucleon residual interactions from experimental energy levels. The relative residual interactions of $(\nu g_{9/2}^2)0^+, 2^+, 4^+, 6^+, 8^+$ and of $(\nu g_{9/2} \pi p_{3/2})3^-, 4^-, 5^-, 6^-$ are taken from the excitation energies in the two-particle nuclei ^{70}Ni [13] and ^{70}Cu [14] (see *note added* at the end of this Letter). These nine energies fully specify the model space for our calculation. Although in ^{70}Cu four levels observed in ^{70}Zn$(t, {}^3$He) experiments are conclusively characterized as the $\nu g_{9/2} \pi p_{3/2}$ quartet [14], their spins could not be assigned from the reaction data. The nuclide ^{70}Cu has two β-decaying isomers [15,16], suggested to be, e.g., (1^+) and (5^-) or $3^-, 4^-, 5^-$. The latter is almost certainly a quartet member, but its spin remains unclear since the ^{70}Zn levels populated in its decay were not established in γ-ray measurements, despite the fact that pure ^{70}Cu activity was available [17] from an on-line mass separator. We therefore suggest quartet spin assignments based on the systematics of $\pi\nu$ two-particle multiplets. It is generally observed that the $I_{\max} - 1$ coupling lies significantly above the $I_{\max}$ state, and that the two extreme spin couplings occur lowest in energy. This assigns the 5^- and 4^- states of ^{70}Cu and leaves two alternatives for the 3^- and 6^- energies. We choose the assignments as shown in Fig. 5(a), in accord with the expectation for a $\pi\nu$ multiplet that the triplet spin coupling is more attractive than the singlet one, which also is observed for the $\pi\nu$ two-particle multiplets pertinent in the heavier nuclei quoted above, as well as for the firmly established $\pi f_{7/2} \nu p_{3/2}$ energies of ^{50}Sc. Moreover, the neighboring ^{68}Cu nucleus has a firm 6^- lowest lying quartet member [18]. The resulting 6^- assignment for the ^{70}Cu high-spin β activity, finally, is well in accord with the current prevailing rudimentary knowledge on its decay [17].

The energy spectrum calculated for ^{71}Cu is illustrated and compared to experiment in Fig. 5(b). The ^{71}Cu ground state excitation energy is calculated as $-133(480)$ keV, where the large error stems from essentially two of the six ground state masses (^{69,70}Ni) required for this three-particle calculation. We took them from the 1997 mass table [19] except for ^{70}Cu, where we assign the measured mass [14] to the lowest $\nu g_{9/2} \pi p_{3/2}$ quartet member as concluded in Ref. [14]. Because of the ± 480 keV error in the ground state energy, we show in Fig. 5(b) the calculated level energies normalized at the ground state.

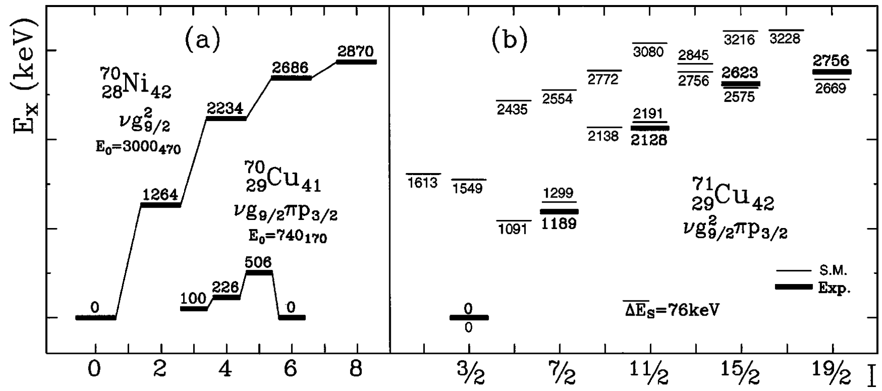

FIG. 5. (a) Interaction energies used in the shell model calculation for ^{71}Cu. E_0 specifies the E_x value for zero residual interaction. (b) Experimental levels of ^{71}Cu compared to calculated values (see *note added* at the end of this Letter) normalized at the ground state. The calculated ground state energy is $-133(480)$ keV. The mean deviation for the four level spacings is 76 keV.

The agreement between calculation and experiment is excellent. Most significantly, theory correctly predicts the monotonic spin sequence, similar as in the ^{70}Ni neighbor, and not observed in analogous j^2j' three-particle isomers in heavier nuclei. It is also obvious that the configurations of the five ^{71}Cu states must be quite pure in terms of the model space as specified above.

The monotonic spin sequence of ^{71}Cu is not in a simple manner related to a specific cause. But it is clear that two input quantities are of significance, namely, the spacing of the two highest levels in the j^2 spectrum and the attraction in the $jj'_{I_{\max}-2}$ coupling, which is much larger in ^{70}Cu than in heavier nuclei and contributes to push the $(j^2j')I_{\max}$ and $I_{\max}-2$ states apart.

Finally, we discuss the $B(E2; 19/2^- \to 15/2^-)$ value in ^{71}Cu obtained from the present experiment. This value, 45(5) $e^2\,\mathrm{fm}^4$, is much larger than the preliminary $8^+ \to 6^+ B(E2)$ value of 13 $e^2\,\mathrm{fm}^4$ in ^{70}Ni [13]. This difference can be explained within the $\nu g^2_{9/2}\pi p_{3/2}$ model space. The $19/2^- \to 15/2^-$ $E2$ transition in ^{71}Cu is induced not only by $|8^+ \times \pi p_{3/2}; 19/2^-\rangle \to \sqrt{1-a^2}\,|6^+ \times \pi p_{3/2}; 15/2^-\rangle$ but also by $|8^+ \times \pi p_{3/2}; 19/2^-\rangle \to a|8^+ \times \pi p_{3/2}; 15/2^-\rangle$; here a is a mixing amplitude. The latter transition proceeds by both the neutrons and the proton. With the mixing amplitude of $a^2 = 0.16$ from the above calculation, the $B(E2; 19/2^- \to 15/2^-)$ results as 34 $e^2\,\mathrm{fm}^4$, in near agreement with experiment. Here, the effective charges are assumed to be $e_\nu = 1.0e$ and $e_\pi = 2.0e$, and $\langle r^2\rangle = 23$ and 19 fm^2 are used for the $0g_{9/2}$ and $1p_{3/2}$ orbitals, respectively.

In conclusion, we have found the $(\nu g^2_{9/2}\pi p_{3/2})_{19/2^-}$ isomer of ^{71}Cu produced in deep-inelastic collisions, where the isotopic assignment was derived from data taken on the fragment properties. For the first time in the neutron-rich nickel region a shell model calculation with predictive power is presented, using the nine two-body levels from ^{70}Ni and ^{70}Cu which fully specify the $\nu g^2_{9/2}\pi p_{3/2}$ minimum model space. Theory is in excellent agreement with experiment and readily explains the $E2$ decay of the ^{71}Cu three-particle isomer.

Note added.—After submission of this manuscript a Letter appeared, by Grzywacz *et al.* [20], which again reports their ^{70}Ni energies but now differing by up to 10 keV from [13] which we have used in our calculation. In ^{71m}Cu decay Grzywacz *et al.* assign the 981 keV γ ray known from β decay of ^{71}Ni [8] as ground state transition, providing a good candidate for the predicted $5/2^-$ state of our Fig. 5. Their assignment of a 471 keV transition to the $15/2^-$ state cannot be correct since it would imply a long half-life for the intermediate 2151 keV level, but a 471 keV ^{71}Cu γ line is known from Ref. [8].

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