Magicity of the ^{68}Ni Semidouble-Closed-Shell Nucleus Probed by Gamow-Teller Decay of the Odd-*A* Neighbors

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The particle-hole excitations through the $N = 40$ subshell around ^{68}Ni have been studied by the β decay of ^{69}Co and ^{69}Ni. The half-life of ^{69}Co was measured to be 0.22(2) s, and a new β-decaying isomer with a half-life of 3.5(5) s was identified in ^{69}Ni. From the decay of the ^{69}Ni isomer a 9(4)% mixing of the $\pi p_{3/2}^{+1} \nu p_{1/2}^{-2} \nu g_{9/2}^{+2}$ configuration into the ground state of ^{69}Cu can be deduced. Significant polarization of the ^{68}Ni core nucleus is observed with the coupling of a single nucleon, which implies a rapid decrease in the stabilizing effect of the $N = 40$ semimagic shell gap.

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The suitability of treating $N = 40$ as a subshell closure was initially suggested with the discovery that the first excited state of ^{68}Ni (a closed $Z = 28$ proton shell) has a spin and parity of 0^+ and lies at a higher energy (1770 keV) compared to the first excited states in the even-even neighbors [1,2]. In the shell-model picture, an $N = 40$ closure can be formed by having a large energy gap between the f-p orbitals ($p_{3/2}$, $f_{5/2}$, and $p_{1/2}$) and the $g_{9/2}$ configuration. Additional evidence that ^{68}Ni could be treated as a semidouble-magic nucleus came from results of a deep-inelastic scattering experiment where the first 2^+ state was firmly established at 2033 keV [3]. This value is more than 500 keV higher than corresponding 2^+ states in the even-even neighbors. In addition, these experimenters discovered a 0.86(5) ms 5^- isomeric state at 2849 keV, which was interpreted as a $\nu p_{1/2}^{-1} \nu g_{9/2}^{+1}$ broken pair excitation across the $N = 40$ gap; establishing the size of the energy gap. The size of this gap between the f-p shell and the $g_{9/2}$ orbital is about the order of the pairing energy (Δ) which is $\sim$2 MeV. Conversely, full shell closures have single-particle energy gaps $>$3 MeV, which is well above Δ. To discriminate from a full shell closure, $N = 40$ is described as a subshell closure.

While the existence of the $N = 40$ subshell gap is well established, the persistence of this subshell closure away from ^{68}Ni is not clear. This persistence can be learned by studying nuclei around ^{68}Ni and has been the goal of many recent experimental programs involving in-beam [4–7] as well as β-decay measurements [8–12]. While the results of many of these experiments suggest that the magicity of the $N = 40$ subshell rapidly disappears away from ^{68}Ni, one of the most compelling sets of data to determine the strength of a shell closure is the level structure one observes when a nucleon particle or hole is coupled to the semidouble-magic core. It is also interesting to note that ^{68}Ni closely resembles its valence mirror ^{90}Zr which has a closed $Z = 40$ subshell and a strong $N = 50$ neutron shell closure. Thus it is also possible to learn about the persistence of the $N = 40$ stability by comparison to the ^{90}Zr region.

In this Letter, we address the question whether the level structure of the nuclei ^{69}Ni and ^{69}Cu can be interpreted as the coupling of a particle or hole to the core of ^{68}Ni and probe the strength of the $N = 40$ shell gap. We report the first observation of low-lying particle-hole excitations across the $N = 40$ subshell in ^{69}Ni and ^{69}Cu populated by Gamow-Teller decay. The selective nature of Gamow-Teller decay is used as a spectroscopic tool for clearly identifying specific single-particle components to the wave functions of the states in ^{69}Ni and ^{69}Cu. Crucial to this experiment is the production of isotopically pure sources of ^{69}Co and ^{69}Ni obtained by using resonant laser ionization.

The nuclei in this study were produced in a proton-induced fission reaction of ^{238}U at the LISOL facility at the Louvain-la-Neuve cyclotron laboratory [13]. The resulting fission products were captured and neutralized in an Ar-filled gas cell, and the Co or Ni isotopes were subsequently selectively ionized in a two-resonant-step laser excitation. The ions were extracted from the gas cell and guided to the LISOL mass separator with a sextupole ion guide. The products were then selected by their A/q ratio and transported to the detection point. The resulting β-delayed γ rays were collected in γ-γ and β-γ coincidences using the setup described in Ref. [14].

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Representative β-gated γ spectra illustrating the identification of Co and Ni decays in the $A = 69$ mass chain are shown in Fig. 1. These spectra were obtained with lasers set on Co resonance [Fig. 1(a)], Ni resonance [Fig. 1(b)], and lasers off [Fig. 1(c)]. From the comparison of the three spectra one can immediately identify γ rays associated with a particular nucleus. The strongest γ ray in the ^{69}Co decay is the 594-keV and out of its time behavior [see Fig. 1(a) inset] a half-life of 0.22(2) s is determined. This is in agreement with the previously measured half-life of 0.27(5) s [15]. On the basis of the laser selectivity as well as coincidence relationships and half-life behavior, additional γ rays with energies [and intensities relative to the 594-keV transition ($I_\gamma \equiv 100$)] of 303.6 [5.1(7)], 602.4 [15.6(17)], 1128.4 [14.6(19)], 1196.5 [19.7(22)], 1319.5 [16.2(21)], 1342.8 [4.8(11)], 1545.2 [4.8(12)], 1580.6 [4.1(11)], 1641.7 [4.1(12)], 1824.0 [1.6(5)], and 2879.8 keV [6.5(18)] are also assigned to the ^{69}Co decay.

Another line of particular interest is at 1298 keV. This γ ray is clearly observed in the β-gated Co-resonance spectrum; however, unlike other Co lines, it is also observed in the Ni-resonance spectrum. This provides clear evidence that the 1298-keV line is a γ ray associated with ^{69}Ni decay, the daughter of ^{69}Co. The half-life of the 1298-keV line in ^{69}Ni, determined from the weighted average of both the Co-resonance and Ni-resonance experiments, is measured to be 3.5(5) s [Fig. 1(b) inset]. The 1298-keV line has also been observed by Prisciandaro *et al.* [16] from fragmentation of a ^{76}Ge beam, and their half-life measurement is in agreement with ours.

The fact that the 1298-keV transition appears in both Figs. 1(a) and 1(b) with a 3.5(5) s half-life implies that the β decay to the level deexcited by this γ line does not come from the ^{69}Ni ground state, which has a measured half-life of 11.2(9) s [9,17], but results from the decay of an isomer. The location of this isomer has been previously reported by Grzywacz *et al.* [6]. In their paper they reported a 594-keV γ decay to a level at 321(2) keV above the ground state in ^{69}Ni. No γ decay was observed decaying out of this level, thus they suggested that this level was isomeric with an estimated half-life of 3 s.

The partial level scheme showing the ^{69}Co $\rightarrow$ ^{69}Ni $\rightarrow$ ^{69}Cu decay chain is presented in Fig. 2. Included in the scheme of ^{69}Ni are levels that have been identified by Grzywacz *et al.* [6]. While the 594.3-keV transition is a commonly observed γ ray, all other transitions from the β decay are complementary to the isomer work [6]. Three γ rays in addition to the 594-keV transition can be placed unambiguously into the ^{69}Co decay scheme on the basis of coincidence relationships; however, it is not possible to rule out or confirm coincidence relationships

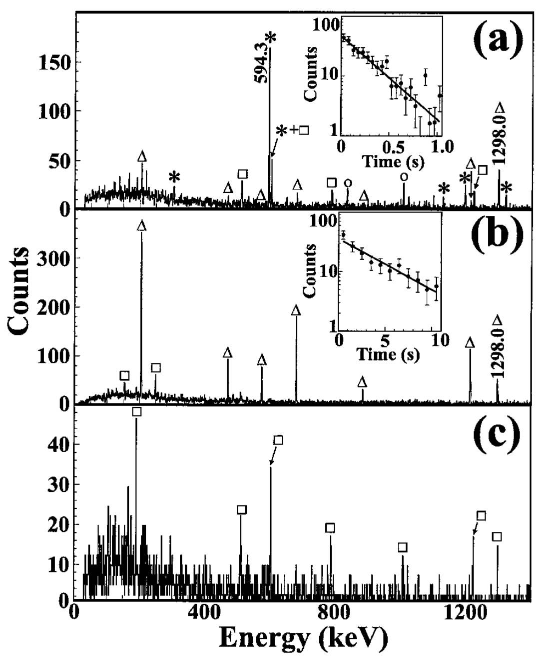

FIG. 1. β-gated γ-ray spectra for mass 69 when (a) lasers are tuned to Co resonance, (b) Ni resonance, and (c) switched off. Asterisks label the energies identified as resulting from ^{69}Co decay, triangles from ^{69}Ni decay, circles from ^{69}Cu decay, and squares as nonresonant background lines. The 594-keV and 1298-keV lines are indicated by their energy, and discussed in the text. The insets in (a) and (b) are the time decay spectra from gates on the 594-keV and 1298-keV γ rays, respectively, with representative exponential fits to the data.

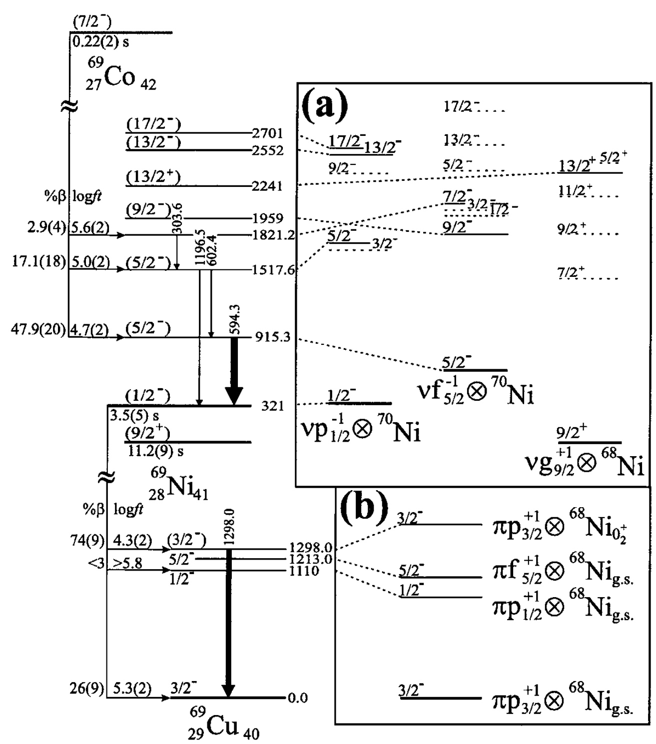

FIG. 2. The experimental decay scheme of ^{69}Co and ^{69}Ni, with comparative shell-model calculations for (a) ^{69}Ni and (b) ^{69}Cu. Theoretical levels that can be associated with experimental levels are indicated by solid levels and larger fonts. Details are provided in the text.

of the other γ-ray transitions. A total of 71(7)% of the γ-ray intensity could be placed in the level scheme and the β-decay branching ratios labeled in Fig. 2 for ^{69}Co are deduced assuming that all unplaced γ rays are not in coincidence and feed either the isomer or ground state. From the comparison of the intensity feeding into the 321-keV isomeric level in ^{69}Ni with γ rays observed from the ground-state decay of ^{69}Ni [17], it is possible to conclude that 30(4)% of the β decay of ^{69}Co proceeds to the $9/2^+$ ground state of ^{69}Ni either directly or through excited levels. The amount of ground-state to ground-state feeding can be inferred by comparison with the forbidden $7/2^- \rightarrow 9/2^+$ decay observed in ^{67}Co [11]. Assuming the same $\log ft$ for the ^{69}Co decay to the ^{69}Ni ground state (i.e., 6.3) the β-branching ratio would be $\approx$2%; however, it is likely that this β feeding would be somewhat larger due to the increased occupation of the $g_{9/2}$ orbital [11]. Still most of the unplaced γ-ray intensity can feed the ground state of ^{69}Ni.

Included in the inset of Fig. 2(a) are results from a shell-model calculation using the interaction presented in Ref. [18] with modified single-particle energies [19]. These calculated levels are organized on the basis of their leading configurations in the wave function, and those which can be positively associated with an experimental level are indicated with a dashed line to that state.

With regard to the decay of ^{69}Ni, the ground-state decay was originally studied by Bosch *et al.* [17] and later by Jokinen *et al.* [20]. This decay scheme is confirmed in our study. From both studies [17,20], the decay of the low-spin isomer of ^{69}Ni was not observed which is likely due to the specific reactions used and the characteristics of their respective ion sources. In addition, earlier work from $(d, ^3\text{He})$ transfer studies establishes many low-energy levels in ^{69}Cu [21]. For clarity, we show only the first few excited states in ^{69}Cu in Fig. 2. Presented in Fig. 2(b) are the calculated low-lying states in ^{69}Cu using the same interaction discussed above in both the proton and neutron subspaces.

No additional γ rays were observed with a 3.5 s half-life or in coincidence with the 1298.0-keV line. In particular, no γ ray from the 1110-keV level reported by Zeidman and Nolan [21] could be observed, thus leading to an upper limit of 3% β-decay feeding from the $(1/2^-)$ isomer in ^{69}Ni. The ground-state feeding can be determined by comparing the γ-ray intensity feeding into the 321-keV level in ^{69}Ni to the intensity of the 1298.0-keV γ line. From this comparison, one can conclude that 26(9)% of the ^{69}Ni isomer decay feeds the ^{69}Cu ground state; however, this value may increase if there is additional intensity feeding the ^{69}Ni isomer. This possibility of missed intensity has been taken into account in the uncertainty of the deduced $\log ft$ values, which are 4.3(2) and 5.3(2) for the excited and ground-state decays, respectively.

The positive parity levels observed and calculated in ^{69}Ni$_{41}$ (see Fig. 2) can be interpreted as arising from the coupling of a single $g_{9/2}$ neutron to excitations of the ^{68}Ni core, whereas the negative-parity levels can be viewed as $2p$-$1h$ states arising from coupling a $p_{1/2}$ or $f_{5/2}$ hole to the core of $^{70}_{28}$Ni$_{42}$ which has two $g_{9/2}$ neutrons beyond ^{68}Ni. A similar interpretation has been presented by Brown *et al.* for the odd-proton structure in $^{91}_{41}$Nb$_{50}$ [22].

The unique features of the decay sequence arise from the structure of $^{69}_{27}$Co$_{42}$ which consists of a single $f_{7/2}$ proton hole coupled to two $g_{9/2}$ neutrons beyond the $N = 40$ subshell closure. While forbidden decay is possible (as stated earlier) the major decay path is the Gamow-Teller decay of an $f_{5/2}$ core neutron to fill the last $f_{7/2}$ proton orbital leaving behind one-neutron hole $(f_{5/2})$ and two-neutron $(g^2_{9/2})$ structures. Hence, it is possible to assign the level we observe most strongly in β decay at 915 keV as the $2p$-$1h$ state $(\nu f^{-1}_{5/2} \otimes {}^{70}\text{Ni})$. The level at 1518 keV can be identified as a $5/2^-$ level whose principal configuration is the $p_{1/2}$ hole coupled to the 2^+ core excitation of ^{70}Ni; however, the low $\log ft$ value of 5.0(5) for this level suggests that the two observed $5/2^-$ levels are strongly mixed. The level at 1821 keV is likely the $7/2^-$ state originating from the coupling of an $f_{5/2}$ hole to the 2^+ state in ^{70}Ni. Thus all the negative parity states in ^{69}Ni can be interpreted as the coupling of a hole to a ^{70}Ni core.

The core polarization, which depends on the mixing of the neutron $(p_{1/2})^2_{0^+}$ and $(g_{9/2})^2_{0^+}$ content in the wave functions, is conclusively seen from the results observed in the $1/2^-$ isomer decay of ^{69}Ni. The decay of the $2p$-$1h$ state can proceed either by forbidden decay of one of the $g_{9/2}$ neutrons or by Gamow-Teller decay of the $p_{1/2}$ particle to the empty $p_{3/2}$ proton orbital in $^{69}_{29}$Cu$_{40}$ leaving behind the two $g_{9/2}$ neutron particles and a completely vacant $p_{1/2}$ orbital. It is the latter path that is uniquely observed in this decay sequence leading to population of a newly identified $3/2^-$ level at 1298 keV that can be viewed as the $p_{3/2}$ proton coupled to the $2p$-$2h$ state at 1770 keV in ^{68}Ni. This level is quite comparable to the $5/2^+$ level at 1466 keV in $^{91}_{40}$Zr$_{51}$ [23] which can be viewed as a $d_{5/2}$ neutron coupled to the $2p$-$2h$ state at 1761 keV in ^{90}Zr. It should be noted that while this state has been observed, its unique character has not been specifically identified or discussed. For the 1298-keV level in ^{69}Cu, the selectivity of the Gamow-Teller decay leaves little doubt about its configuration. This selectivity is further illustrated by the nonobservation of feeding of the $p_{1/2}$ state identified from particle-transfer reactions at 1110 keV [21] which sets a limiting $\log ft$ to this state of >5.8.

Compared to the $2p$-$2h$ state in ^{68}Ni a 472-keV downward shift of the $3/2^-_2$ state in ^{69}Cu is observed which can be attributed to the proton-neutron interaction. To estimate the shift we have applied the effective shell model (ESM) approach, which neglects configuration mixing [24]. Using ^{66}Ni as an effective core, relative single-particle energies (SPE) and two-body matrix elements (TBME) were determined from excitation energies.

SPE were taken from ^{67}Cu, ^{67}Ni, and TBME from ^{68,70}Cu ($[\pi p_{3/2}\nu p_{1/2}]_{1,2}, [\pi p_{3/2}\nu g_{9/2}]_{3-6}$) and ^{68,70}Ni ($[\nu p_{1/2}]_0^2, [\nu g_{9/2}]_{0,2}^2$), which results in a shift of 540 keV. The corresponding shift for the $5/2_2^+$ state in ^{91}Zr is only 295 keV, which is to be compared to 340 keV calculated in the ESM using input data from ^{88,89}Sr, ^{89,90}Y, and ^{90}Zr, respectively. The larger shift in ^{69}Cu implies that the ^{68}Ni core is more easily polarized. The theoretical overestimation in the shift indicates configuration mixing, which is neglected in the ESM.

It is also possible to deduce the mixing of the $\pi p_{3/2}^{+1}\nu p_{1/2}^{-2}\nu g_{9/2}^{+2}$ configuration into the $\pi p_{3/2}^{+1}$ ground state of ^{69}Cu. The factor of 10 difference in the ft values for Gamow-Teller population of the ground and 1298-keV levels in ^{69}Cu can be used to determine that there is a 9(4)% mixture of these states. From the shell-model calculations presented in Fig. 2 the mixing of the $\pi p_{3/2}^{+1}\nu p_{1/2}^{-2}\nu g_{9/2}^{+2}$ configuration into the ground state is predicted to be 6% which is in good agreement with the observed mixing. For comparison, the $L = 2$ strength for the population of the 1466-keV $5/2^+$ level in ^{91}Zr is $\sim 2\%$ of the population of the ground state [23].

In summary, the β-delayed γ decay of ^{69}Co was measured for the first time. The Gamow-Teller decay of the $\pi f_{7/2}^{-1}\nu g_{9/2}^{+2}$ ^{69}Co ground state is observed to populate neutron $2p$-$1h$ states in ^{69}Ni that subsequently feed a $1/2^-$ isomer at 321 keV which can be interpreted as the $\nu p_{1/2}^{-1}\nu g_{9/2}^{+2}$ configuration. From the deduced $\log ft$ values, it can be seen that the wave functions of the observed $5/2^-$ states are heavily mixed. From the comparison of the calculated ^{69}Ni scheme to the experimental levels, it is possible to interpret all negative parity levels as couplings of single-hole states to the core of ^{70}Ni.

The decay of the $1/2^-$ isomer in ^{69}Ni is observed to strongly populate a level at 1298 keV while only relatively weakly feeding the ^{69}Cu ground state. This is an illustration of the selectivity of the Gamow-Teller decay where the $\nu p_{1/2} \rightarrow \pi p_{3/2}$ conversion necessitates that the "spectator" $\nu g_{9/2}$ pair remains. The 1298-keV level in ^{69}Cu is interpreted as a $p_{3/2}$ proton particle coupled to the neutron $2p$-$2h$ excitation. Direct β feeding to the ground state is the result of a 9(4)% mixing of the $\pi p_{3/2}^{+1}\nu p_{1/2}^{-2}\nu g_{9/2}^{+2}$ configuration into the wave function which is larger than the $\sim 2\%$ mixing observed in ^{91}Zr. Thus, while ^{68}Ni has features consistent with other doubly magic nuclei, the $N = 40$ subshell closure is even weaker than the corresponding $Z = 40$ gap, and its stabilizing effect disappears already with the coupling of a single nucleon.

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