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 $\beta$ decay of $^{69}$Co and $^{68}$Ni. The half-life of $^{69}$Co was measured to be 0.22(2) s, and a new $\beta$-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 $\pi p_{1/2}^+\nu g_{9/2}$ 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 $\nu p_{1/2}^+\nu g_{9/2}$ 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 ($\Delta$) which is ~2 MeV. Conversely, full shell closures have single-particle energy gaps $>3$ MeV, which is well above $\Delta$. 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 $\beta$-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 $\beta$-delayed $\gamma$ rays were collected in $\gamma-\gamma$ and $\beta-\gamma$ coincidences using the setup described in Ref. [14].
Representative $\beta$-gated $\gamma$ 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 $\gamma$ rays associated with a particular nucleus. The strongest $\gamma$ ray in the $^{69}\text{Co}$ 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 $\gamma$ rays with energies [and intensities relative to the 594-keV transition ($I_{\gamma}/I_{100}$)] 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 $^{69}\text{Co}$ decay.

Another line of particular interest is at 1298 keV. This $\gamma$ ray is clearly observed in the $\beta$-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 transition in $^{69}\text{Ni}$, determined from the weighted average of both 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 $^{76}\text{Ge}$ 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 $\beta$ decay to the level deexcited by this $\gamma$ line does not come from the $^{69}\text{Ni}$ 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 $\gamma$ decay to a level at 321(2) keV above the ground state in $^{69}\text{Ni}$. No $\gamma$ 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 $^{69}\text{Co} \rightarrow ^{69}\text{Ni} \rightarrow ^{69}\text{Cu}$ decay chain is presented in Fig. 2. Included in the scheme of $^{69}\text{Ni}$ are levels that have been identified by Grzywacz et al. [6]. While the 594.3-keV transition is a commonly observed $\gamma$ ray, all other transitions from the $\beta$ decay are complementary to the isomer work [6]. Three $\gamma$ rays in addition to the 594-keV transition can be placed unambiguously into the $^{69}\text{Co}$ decay scheme on the basis of coincidence relationships; however, it is not possible to rule out or confirm coincidence relationships.
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 69Co 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 69Ni with γ rays observed from the ground-state decay of 69Ni [17], it is possible to conclude that 30(4)% of the β decay of 69Co proceeds to the 9/2− ground state of 69Ni 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− → 9/2+ decay observed in 67Co [11]. Assuming the same log ft for the 69Co decay to the 69Ni ground state (i.e., 6.3) the β-branching ratio would be ≈2%; however, it is likely that this β feeding would be somewhat larger due to the increased occupation of the g9/2 orbital [11]. Still most of the unplaced γ-ray intensity can feed the ground state of 69Ni.

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 69Ni, 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 69Ni 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,3He) transfer studies establishes many low-energy levels in 69Cu [21]. For clarity, we show only the first few excited states in 69Cu in Fig. 2. Presented in Fig. 2(b) are the calculated low-lying states in 69Cu 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 68Ni. The ground-state feeding can be determined by comparing the γ-ray intensity feeding into the 321-keV level in 68Ni to the intensity of the 1298.0-keV γ line. From this comparison, one can conclude that 26(9)% of the 68Ni isomer decay feeds the 69Cu ground state; however, this value may increase if there is additional intensity feeding the 69Ni 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 68Ni (see Fig. 2) can be interpreted as arising from the coupling of a single g9/2 neutron to excitations of the 68Ni core, whereas the negative-parity levels can be viewed as 2p-1h states arising from coupling a p1/2 or f5/2 hole to the core of 68Ni, which has two g9/2 neutrons beyond 68Ni. A similar interpretation has been presented by Brown et al. for the odd-proton structure in 49Nb [22].

The unique features of the decay sequence arise from the structure of 69Co which consists of a single f7/2 proton hole coupled to two g9/2 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 f5/2 core neutron to fill the last f7/2 proton orbital leaving behind one-neutron hole (f5/2) and two-neutron (g9/2) structures. Hence, it is possible to assign the level we observe most strongly in β decay at 915 keV as the 2p-1h state (l=−1 f5/2 ⊗ 70Ni). The level at 1518 keV can be identified as a 5/2− level whose principal configuration is the p1/2 hole coupled to the 2+ core excitation of 70Ni; 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 f5/2 hole to the 2+ state in 70Ni. Thus all the negative parity states in 69Ni can be interpreted as the coupling of a hole to a 70Ni core.

The core polarization, which depends on the mixing of the neutron (p1/2)0 2 and (g9/2)0 2 content in the wave functions, is conclusively seen from the results observed in the 1/2− isomer decay of 69Ni. The decay of the 2p-1h state can proceed either by forbidden decay of one of the g9/2 neutrons or by Gamow-Teller decay of the p1/2 particle to the empty p3/2 proton orbital in 69Cu leaving behind the two g9/2 neutron particles and a completely vacant p1/2 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 p3/2 proton coupled to the 2p-2h state at 1770 keV in 68Ni. This level is quite comparable to the 5/2+ level at 1466 keV in 68Cu [23] which can be viewed as a d5/2 neutron coupled to the 2p-2h state at 1761 keV in 68Zr. 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 69Cu, 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 p1/2 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 68Ni a 472-keV downward shift of the 3/2− state in 69Cu 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 66Ni as an effective core, relative single-particle energies (SPE) and two-body matrix elements (TBME) were determined from excitation energies.
SPE were taken from \( ^{67}\text{Cu} \), \( ^{67}\text{Ni} \), and TBME from \( ^{68,70}\text{Cu} \left[ \left\{ \pi p_{3/2} \nu p_{1/2} \right\}_{1,2}\right] , \left[ \pi p_{3/2} \nu g_{9/2} \right]_{3,6} \) and \( ^{68,70}\text{Ni} \left( \left\{ \nu p_{1/2} \right\}_{0,2} , \left\{ \nu g_{9/2} \right\}_{0,2} \right) \), which results in a shift of 540 keV. The corresponding shift for the 5/2\(^+\) state in \( ^{91}\text{Zr} \) is only 295 keV, which is to be compared to 340 keV calculated in the ESM using input data from \( ^{88,89}\text{Sr} \), \( ^{89,90}\text{Y} \), and \( ^{90}\text{Zr} \), respectively. The larger shift in \( ^{68}\text{Cu} \) implies that the \( ^{68}\text{Ni} \) 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 \( \pi p_{3/2} \nu p_{1/2} \nu g_{9/2} \) configuration into the \( \pi p_{3} \) ground state of \( ^{69}\text{Cu} \). The factor of 10 difference in the \( ft \) values for Gamow-Teller population of the ground and 1298-keV levels in \( ^{69}\text{Cu} \) 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 \( \pi p_{3/2} \nu p_{1/2} \nu g_{9/2} \) 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 \( ^{91}\text{Zr} \) is \( \sim 2\% \) of the population of the ground state [23].

In summary, the \( \beta \)-delayed \( \gamma \) decay of \( ^{69}\text{Co} \) was measured for the first time. The Gamow-Teller decay of the \( \pi f_{7/2} \nu g_{9/2} \) \( ^{69}\text{Co} \) ground state is observed to populate neutron 2\( p \)-1\( h \) states in \( ^{69}\text{Ni} \) that subsequently feed a 1/2\(^-\) isomer at 321 keV which can be interpreted as the \( \nu p_{1/2} \nu g_{9/2} \) 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 \( ^{69}\text{Ni} \) scheme to the experimental levels, it is possible to interpret all negative parity levels as couplings of single-hole states to the core of \( ^{70}\text{Ni} \).

The decay of the 1/2\(^-\) isomer in \( ^{69}\text{Ni} \) is observed to strongly populate a level at 1298 keV while only relatively weakly feeding the \( ^{69}\text{Cu} \) 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 \( ^{69}\text{Cu} \) is interpreted as a \( p_{3/2} \) proton particle coupled to the neutron 2\( p \)-2\( h \) excitation. Direct \( \beta \) feeding to the ground state is the result of a 9(4)\% mixing of the \( \pi p_{3/2} \nu p_{1/2} \nu g_{9/2} \) configuration into the wave function which is larger than the \( \sim 2\% \) mixing observed in \( ^{91}\text{Zr} \). Thus, while \( ^{68}\text{Ni} \) 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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\[ \text{References} \]