PHYSICAL REVIEW C **78**, 041307(R) (2008)

Shape isomerism at $N = 40$: Discovery of a proton intruder state in ^{67}Co

D. Pauwels,[1,*] O. Ivanov,[1] N. Bree,[1] J. Büscher,[1] T. E. Cocolios,[1] J. Gentens,[1] M. Huyse,[1] A. Korgul,[2] Yu. Kudryavtsev,[1] R. Raabe,[1] M. Sawicka,[1] I. Stefanescu,[1,3] J. Van de Walle,[1] P. Van den Bergh,[1] P. Van Duppen,[1] and W. B. Walters[3]

[1]*Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*

[2]*Institute of Experimental Physics, Warsaw University, ul.Hoża 69, 00-681 Warszawa, Poland*

[3]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*

(Received 16 July 2008; published 29 October 2008)

The nuclear structure of ^{67}Co has been investigated through ^{67}Fe β decay. The ^{67}Fe isotopes were produced at the LISOL facility in proton-induced fission of ^{238}U and selected using resonant laser ionization combined with mass separation. The application of a new correlation technique unambiguously revealed a 496(33) ms isomeric state in ^{67}Co at an unexpected low energy of 492 keV. A ^{67}Co level scheme was deduced. Proposed spin and parities suggest a spherical $(7/2^-)$ ^{67}Co ground state and a deformed first excited $(1/2^-)$ state at 492 keV, interpreted as a proton 1p-2h prolate intruder state.

DOI: 10.1103/PhysRevC.78.041307 PACS number(s): 23.40.−s, 23.20.Lv, 23.35.+g, 27.50.+e

Atomic nuclei in the neighborhood of closed shells often exhibit intriguingly low-energy excitations whereby particle-hole configurations across major shell gaps give rise to so-called intruder states [1,2]. Although expected at an excitation energy of at least the size of the shell gap, the strong energy gain in both pairing and proton-neutron interactions can bring them close to the ground state. In odd-mass nuclei with ± 1 nucleon outside a closed shell, the possible unique spin-parity of the intruder orbitals combined with the difference in deformation compared to the normal states can lead to isomerism. Their excitation energy becomes minimal where the proton-neutron correlations are maximal, typically in the middle of the open shell. Intruder states, through their isomeric character, are excellent experimental and theoretical probes to study the relation between individual and collective excitations in atomic nuclei revealing information on shell gaps, pairing correlations, and proton-neutron interactions. The rich variety in orbitals, shell gaps, and shapes available in exotic nuclei makes intruder states an ideal laboratory for a more general study of mesoscopic systems.

Through the use of a novel correlation technique applied to the β decay of ^{67}Fe, we report on the existence of a proton-intruder isomer in $^{67}Co_{40}$ at an excitation energy of 492 keV. The ^{67}Co nucleus is only one proton-hole separated from the semidoubly magic ^{68}Ni [3] and one proton-particle beyond ^{66}Fe, whose low 2^+ energy hints to a reduced gap at $N = 40$ [4,5]. On the other hand, the nickel and copper nuclear structures adjacent to ^{68}Ni have been successfully interpreted as dominated by particle/hole coupled to the ^{68}Ni core [6–10]. Nevertheless, several examples of low-energy neutron-isomers have been observed arising from excitations across $N = 40$ into the $g_{9/2}$ unique-parity orbital [8,9,11–13], but so far no single low-energy proton-isomer has been reported in this region and in the odd-mass cobalt isotopes up to mass $A = 65$.

In previous ^{67}Fe decay studies the half-life of 470(50) ms was reported [14] and a single γ ray at 189 keV was identified [15]. Low production yields far away from the line of stability and difficulties in producing the short-lived cobalt and iron isotopes using conventional ISOL techniques hamper detailed studies. However, much improved data for the decay of neutron-rich iron and cobalt nuclei can now be obtained with high selectivity using the laser-ion source at the LISOL facility [16]. The ^{67}Fe nuclei were produced in a 30 MeV proton-induced fission reaction on two 10 mg/cm^2 thick ^{238}U targets, placed inside a gas cell. The fission products, recoiling out of the targets, were stopped and thermalized in argon buffer gas at a pressure of 500 mbar. The iron isotopes were selectively laser-ionized by two excimer-pumped dye lasers close to the exit hole of the gas cell. After mass separation the ions were implanted into a movable tape, which was surrounded by three thin plastic β detectors and two MINIBALL γ-detector clusters [17]. This detection setup combined with the laser-ion source offers the possibility of applying a new correlation method [18].

In Fig. 1 γ spectra are shown, detected in prompt coincidence (350-ns time window) with β particles ["β-gated" (a)] or without any coincidence ["singles" (b)]. The *upper* black spectra were acquired over 11 h with the lasers tuned to the resonance frequency for iron, while the lower red spectra were acquired over 6 h with the lasers off, both in a 1.4 s-1.6 s implantation-decay cycle. By comparing both β-gated spectra, a number of ^{67}Fe decay lines could be identified, among them the 189-keV line, observed already in Ref. [15], and the 680-keV line. The ground-state half-life of ^{67}Fe was remeasured from the time dependence of the β-gated 189-keV γ ray during decay as shown by the inset in Fig. 1(a) and the value $T_{1/2} = 416(29)$ ms was obtained. The intense line at 694 keV originates from the decay of ^{67}Co ($T_{1/2} = 425(25)$ ms), as reported in Ref. [10]. A laser-enhanced 492-keV transition is observed in the singles γ spectrum of Fig. 1(b); its absence in the β-gated spectrum of Fig. 1(a) indicates the presence of an isomeric transition beyond the 350-ns time window of the β-γ gate. Its similar half-life behavior compared to the 189-keV line (^{67}Fe decay) and the 694-keV line (^{67}Co decay), all about 0.5 s, did not allow us to conclude in which nucleus this transition occurs. However, because the transition

*Dieter.Pauwels@fys.kuleuven.be

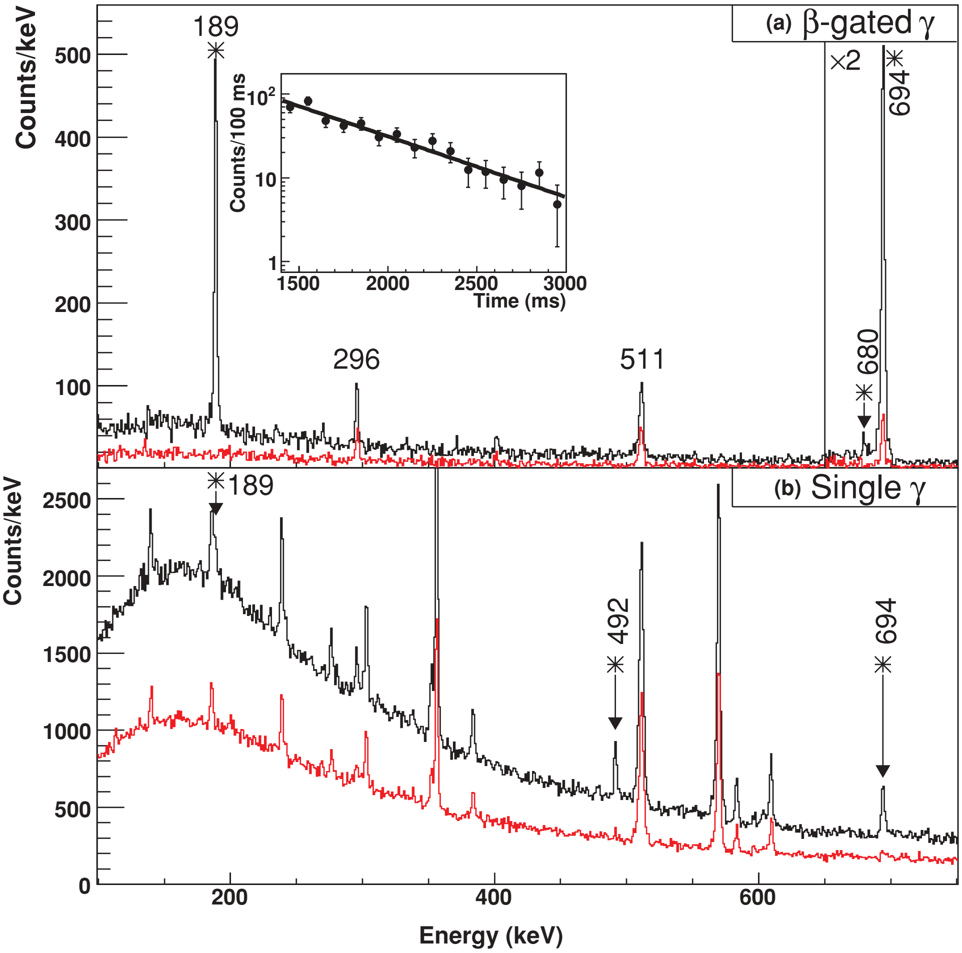

FIG. 1. (Color online) γ-ray spectra at $A = 67$. (a) β-gated spectra with the laser-on (upper black online) and laser-off (lower red online). (b) Singles γ-ray spectra with the laser-on (upper black online) and the laser-off (lower red online). Lines marked by a star are laser-enhanced lines and the 296-keV line is from ^{102}Nb β decay reaching the detection setup in the doubly charged molecular form $^{102}NbO_2^{++}$. The lines that are not marked are background lines. The upper insert in (a) is the fitted decay behavior of the 189-keV line.

is also observed when the lasers are tuned to ionize cobalt, it cannot be placed in ^{67}Fe.

To determine the placement of these newly identified γ rays, a new correlation technique [18] was developed that is applicable for weakly produced exotic nuclei through the ISOL scheme. By using the free-running digital electronics, all required ingredients are available at the LISOL facility to satisfy the two conditions presented in Ref. [18]: data-acquisition in cycles (i.e., implantation-decay cycles), low background conditions, and weak but high-purity beams. While correlation techniques at In-Flight separators make use of unambiguous implantation triggers, long-time-range correlations at ISOL separators are forced to run in cycles to accurately estimate the random correlations.

The isomeric 492-keV transition can be correlated in time with respect to well-established γ transitions, like the 189-keV transition in ^{67}Co and the 694-keV transition in ^{67}Ni. Figure 2(a) shows all correlated single γ events in a time window from 1 μs to 200 ms *after* a β-gated 189-keV event from data taken in cycles of 10-s implantation, after which the detection tape was immediately moved. The randomly correlated events present in the spectrum can be estimated by taking all statistics in the specific time windows over all 19,409 implantation-decay cycles, normalized to this number of cycles, see Fig. 2(b). In Fig. 2(c) the estimated randomly correlated events are subtracted leaving only the 492-keV peak present, indicating that the transition takes place after the β-gated 189-keV transition. Combined with the presence of the 492-keV line in Fig. 2(d), showing all the events correlated in a time window from 1 μs to 200 ms *before* a β-gated 694-keV event after subtraction of random correlations, the isomeric transition can firmly be placed in ^{67}Co.

The half-life of this newly established isomeric state in ^{67}Co was determined by two independent methods: the 492-keV γ-ray decay behavior in a data set with the lasers tuned on cobalt, revealing a half-life of 503(42) ms, and by fitting the decay behavior of correlated 492-keV events after β-gated 189-keV trigger events in the iron data set, revealing a half-life of 483(56) ms. These results indicate the reliability of the half-life values obtained from the correlation technique [18]. The half-life value of 496 (33) ms, shown in Fig. 3, is the weighted average of the two methods. Additionally, from the correlated 492-keV events after β-gated 189-keV trigger events, the isomeric state at 492 keV is found to decay by a lower limit of 80% through the 492-keV γ-transition, leaving room for at maximum 20% β decay. The half-life of the ^{67}Co ground state was obtained with the same correlation technique as described in Ref. [18].

The level scheme for ^{67}Co, shown in Fig. 4, has been constructed from $\beta\gamma\gamma$ coincidences. The γ-ray intensities in ^{67}Co are relative to the 189-keV transition ($I_\gamma = 100$). Assigned spins and parities are based on a $7/2^-$ ground state of ^{67}Co [10]. Weisskopf estimates for the half-life of an $E3$, $M3$,

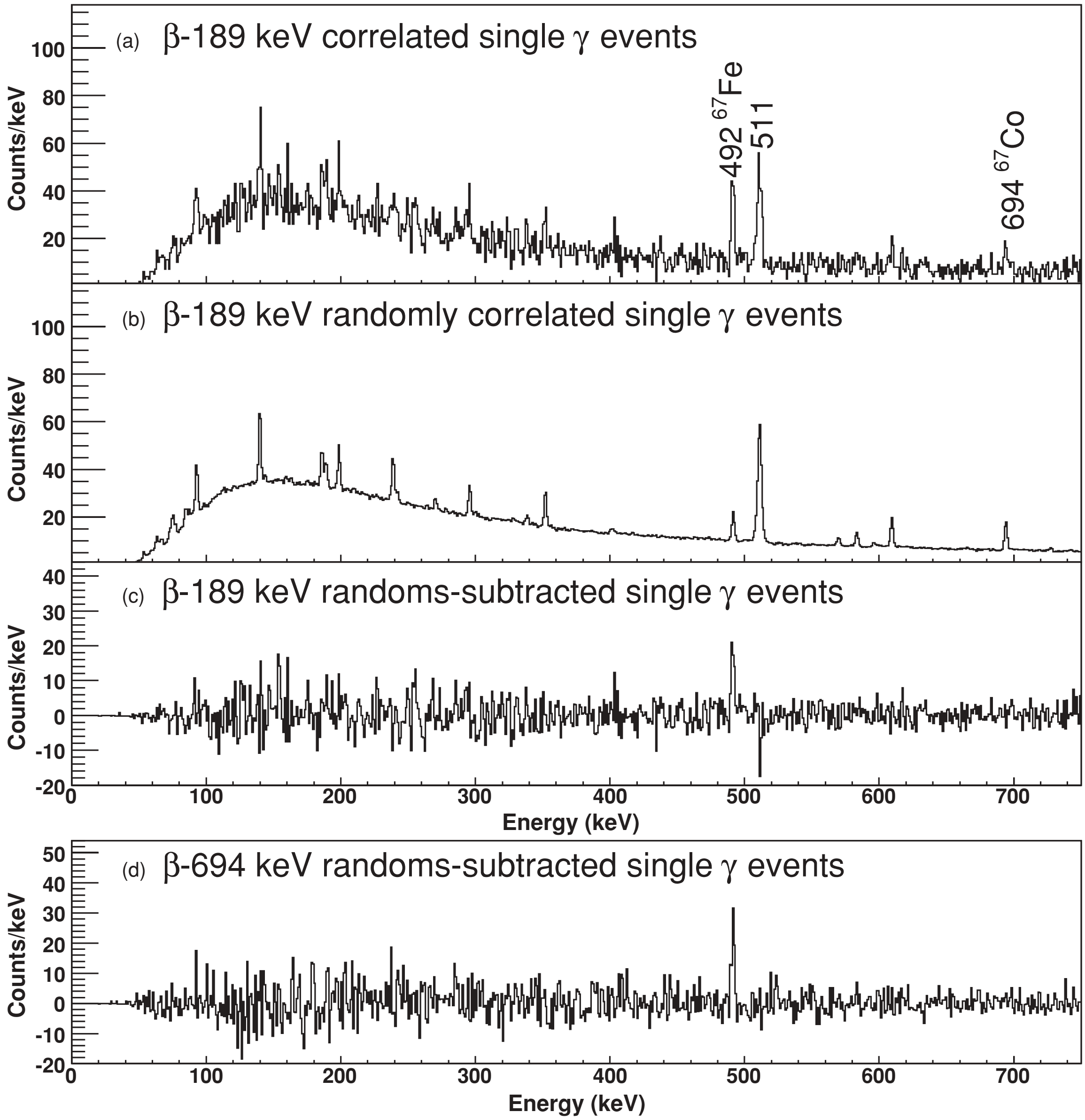

FIG. 2. Single γ events coming *after*β-gated 189-keV events in a 1 μs to 200 ms window (a), the corresponding randomly correlated events (b), and randoms-subtracted histogram (c). The randoms-subtracted histogram in (d) corresponds to single γ events *before*β-gated 694-keV events in a 1 μs to 200 ms window.

and $E4$ 492-keV transition are 0.63 ms, 33 ms, and 500 s, respectively. Hence, the extracted half-life indicates an $M3$ multipolarity for the 492-keV transition, which, in turn, leads to $(1/2^-)$ proposed spin and parity values for the 492-keV isomer in ^{67}Co. The expected probability ratio for an $M1$ 189-keV to an $E2$ 680-keV transition is the only possible match that is of the same order of magnitude as their intensity ratio. Hence, $(3/2^-)$ spin and parity values are proposed for the 680-keV level and $(5/2^-)$ values are proposed for the 1252-keV level on the basis of the observed decay to both the $(7/2^-)$ ground state and $(3/2^-)$ level at 680 keV. The ^{67}Fe decay pattern supports a low spin and negative parity for its ground state.

The level structures for the ground state and low-energy $1/2^-$, $3/2^-$, and $9/2^-$ levels in odd-mass $^{57-67}$Co nuclei are shown in Fig. 5, along with the energy of the 2_1^+ level in the adjacent even-even nickel core nucleus. The data on mass 65 were obtained from another experiment at LISOL [19] and the results are consistent with those of previous studies [20,21]. Higher spin levels in ^{65}Co were deduced using the same data set and the methods of Ref. [22].

As can be seen, the energies of the $9/2^-$ levels, representative also for the $11/2^-$ levels that are not shown in the figure, follow the energies of the core 2^+ levels quite closely. This behavior provides strong support for the description of these nuclei as a single $\pi f_{7/2}^{-1}$ hole in the $Z = 28$ closed shell coupled to excited levels that arise from excitations in the adjacent even-even nickel core nucleus [23]. Two $3/2^-$ levels and a single $1/2^-$ level are also shown that have both core-coupled and $\pi p_{3/2}^{+1}$ and $\pi p_{1/2}^{+1}$ configurations, respectively, as deduced

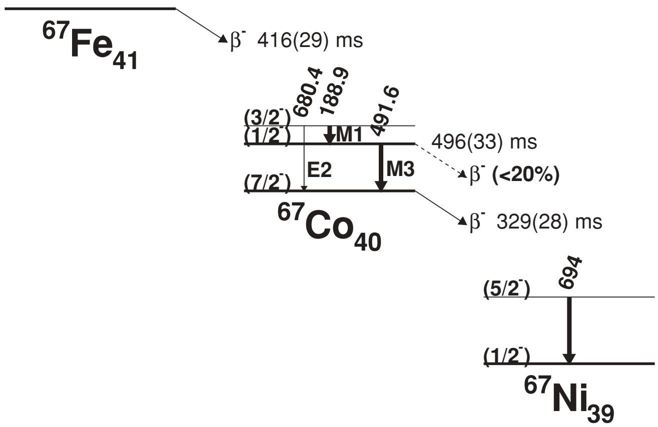

FIG. 3. Partial $A = 67$ β-decay chain.

from proton transfer [24–26] and Coulomb excitation studies [27,28]. Note that a $1/2^-$ core-coupled state can only be obtained by coupling a $\pi f_{7/2}^{-1}$ hole to a 4^+ state.

All four of these levels follow the energy trend of the core levels up through $N = 34$. As additional neutrons are added, first the $3/2^-$ level drops in energy for $N = 36$ and beyond and the $(1/2^-)$ level for $N = 38$ and particularly $N = 40$ where the core 2^+ and 4^+ energies are 2.033 and 3.149 MeV, respectively. Hence, particularly for the $(1/2^-)$ level, core-coupled configuration admixtures should be negligible for ^{67}Co, leaving proton π(1p-2h) excitations across $Z = 28$ as the only possible configuration. The strong decrease in excitation energy of the $(1/2^-)$ state can be described by strong proton-neutron correlations inducing deformation [1]. According to calculated Nilsson orbitals presented in Ref. [29], a prolate-deformed ^{67}Co nucleus with a quadrupole deformation value of $0.25 < \varepsilon_2 < 0.4$ leads in a very natural way to a first excited $[321]1/2^-$ state obtained by promoting one proton particle from the $f_{7/2}$ into the $p_{3/2}$ orbital. Also the neutrons favor this configuration because of the sharply downsloping $1/2^+[440]$ and $3/2^+[431]$ orbitals. It is tempting to assign the $(3/2^-)$ and $(5/2^-)$ states at 680 and 1252 keV as the first members of a rotational band built on the $(1/2^-)$ state. Such a rotational band occurs in the indium isotopes [1], where the Coriolis decoupling is even strong enough to bring the $3/2^+$ state below the $\pi[431]1/2^+$ band head. Figure 5 also indicates that already in ^{65}Co the $(1/2^-)$ intruder level sets in at 1095 keV [19], 482 keV lower in energy than the first excited $(1/2^-)$ level in ^{63}Co, while the corresponding Ni 4_1^+ state goes up by 575 keV.

In the $N = 49$ isotones counterpart, the neutron-intruder configuration can be followed as a function of the filling of the proton orbitals, showing a maximum excitation energy toward $_{40}$Zr, consistent with a subshell closure at $Z = 40$ [1,30]. The situation is completely different in the odd-mass cobalt isotopes as the $(1/2^-)$ proton-intruder state is up till now lowest at $N = 40$, evidencing that for the $Z = 27$ isotopes the $N = 40$ subshell gap is washed out, as is the case in the iron [4] and chromium isotopes [31]. In the lighter odd-mass cobalt isotopes the intruder configuration is more difficult to localize because of the strong fragmentation of its strength over different states. It is, remarkably enough, the semimagic behavior of the ^{68}Ni core that allows a pure character of the intruder state not mixed up with core-coupled configurations. The rapid onset of deformation below $Z = 28$ can thus be explained by the strong proton-neutron residual interactions between the protons in the $\pi f_{7/2}$ orbital and neutrons in the $\nu f_{5/2}$ and $\nu g_{9/2}$ orbitals [4,31].

Combining the energy measured for this newly identified proton intruder in ^{67}Co with that of the previously known $7/2^-$ π(2p-1h) intruder state in ^{69}Cu at 1711 keV [6,7], allows us to estimate the energy of the 0^+ π(2p-2h) intruder state in ^{68}Ni using the prescription of Ref. [33]. At $Z = 50$ and $Z = 82$ the estimated 0_2^+ energies from summing the intruder excitation energies of the $Z \pm 1$ isotones are reproduced on average

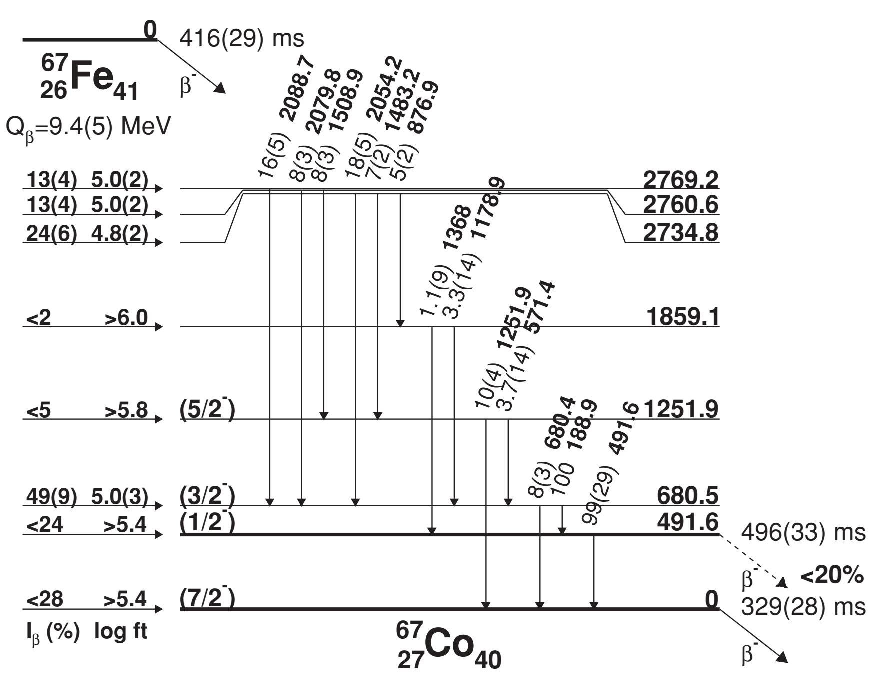

FIG. 4. ^{67}Fe β-decay scheme. The γ-ray intensities are indicated relative to the 189-keV transition ($I_\gamma = 100$). The upper limits of the β-decay feeding (^{67}Fe to ^{67}Co) are 1σ limits on the missed γ-ray intensities. The log ft values are lower limits due to possibly missed γ rays. The upper limit of β-decay out of the 492-keV isomer is deduced from the correlations.

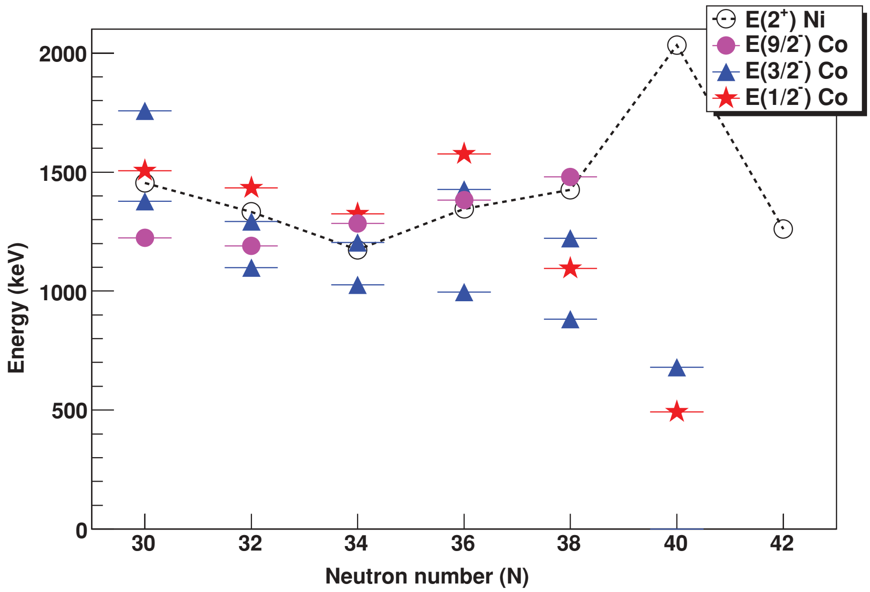

FIG. 5. (Color online) Odd-mass cobalt systematics of low-lying $1/2^-, 3/2^-$, and $9/2^-$ states relative to the $7/2^-$ ground state [32]. The 2^+ energy in the even nickel isotones are indicated by open circles [32].

within ~200 keV. The 2.2 MeV estimate for ^{68}Ni makes the (0_3^+) state at 2.511 MeV, therefore, a good candidate for the π(2p-2h) configuration. This state was observed in β-decay work and could not be described by shell model calculations not allowing excitations across $Z = 28$ [13], while it was properly predicted by Hartree-Fock-Bogoliubov calculations from collective excitations [34]. The low-lying ^{68}Ni structure is thus dominated by excitations across the $N = 40$ (0_2^+ state at 1770 keV) [35] and the $Z = 28$ (0_3^+ state at 2511 keV) (sub)shell gap.

In conclusion, a ($1/2^-$) isomeric state with a half-life of 496(33) ms has been identified in ^{67}Co using a new correlation technique. This newly established isomer has been interpreted as a prolate ([321]$1/2^-$) proton intruder state coexisting with a spherical ($7/2^-$) ground state. Taking away only one proton from ^{68}Ni already induces the obliteration of the $N = 40$ subshell gap and sets in a region of deformation below $Z = 28$. The identification and further study of intruder states in heavier cobalt, nickel, and copper isotopes beyond $N = 40$ will deliver crucial information on the $Z = 28$ gap toward ^{78}Ni.

We acknowledge the support by the European Commission within the Sixth Framework Programme through I3-EURONS (Contract RII3-CT-2004-506065), BriX-IUAP P6/23, FWO-Vlaanderen (Belgium), GOA/2004/03, the Foundation for Polish Science (A.K.), the US Department of Energy, and the Alexander von Humboldt Foundation (W.B.W.).

[1] K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Rep. **102**, 291 (1983).
[2] J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. Van Duppen, Phys. Rep. **215**, 101 (1992).
[3] R. Broda *et al.*, Phys. Rev. Lett. **74**, 868 (1995).
[4] M. Hannawald *et al.*, Phys. Rev. Lett. **82**, 1391 (1999).
[5] P. Adrich *et al.*, Phys. Rev. C **77**, 054306 (2008).
[6] A. M. Oros-Peusquens and P. F. Mantica, Nucl. Phys. **A669**, 81 (2000).
[7] I. Stefanescu *et al.*, Phys. Rev. Lett. **100**, 112502 (2008).
[8] J. Van Roosbroeck *et al.*, Phys. Rev. C **69**, 034313 (2004).
[9] W. F. Mueller *et al.*, Phys. Rev. Lett. **83**, 3613 (1999).
[10] L. Weissman *et al.*, Phys. Rev. C **59**, 2004 (1999).
[11] R. Grzywacz *et al.*, Phys. Rev. Lett. **81**, 766 (1998).
[12] J. Prisciandaro *et al.*, Phys. Rev. C **60**, 054307 (1999).
[13] W. F. Mueller *et al.*, Phys. Rev. C **61**, 054308 (2000).
[14] F. Ameil *et al.*, Eur. Phys. J. A **1**, 275 (1998).
[15] O. Sorlin *et al.*, Nucl. Phys. **A669**, 351 (2000).
[16] M. Facina *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **226**, 401 (2004).
[17] J. Eberth *et al.*, Prog. Part. Nucl. Phys. **46**, 389 (2001).
[18] D. Pauwels *et al.*, Nucl. Instr. Methods Phys. Res. Sect. B **266**, 4600 (2008).
[19] D. Pauwels *et al.* (to be published).
[20] L. Gaudefroy, Ph.D. thesis, Université de Paris XI Orsay, 2005.
[21] M. Block *et al.*, Phys. Rev. Lett. **100**, 132501 (2008).
[22] N. Hoteling *et al.*, Phys. Rev. C **74**, 064313 (2006).
[23] P. H. Regan, J. W. Arrison, U. J. Hüttmeier, and D. P. Balamuth, Phys. Rev. C **54**, 1084 (1996).
[24] B. Rosner and C. H. Holbrow, Phys. Rev. **154**, 1080 (1967).
[25] A. G. Blair and D. D. Armstrong, Phys. Rev. **140**, B1567 (1965).
[26] K. W. C. Stewart, B. Castel, and B. P. Singh, Phys. Rev. C **4**, 2131 (1971).
[27] R. Nordhagen, B. Elbek, and B. Herskind, Nucl. Phys. **A104**, 353 (1967).
[28] J. M. G. Gómez, Phys. Rev. C **6**, 149 (1972).
[29] P. Möller *et al.*, At. Data Nucl. Data Tables **66**, 131 (1997).
[30] R. A. Meyer, O. G. Lien, and E. A. Henry, Phys. Rev. C **25**, 682 (1982).
[31] O. Sorlin *et al.*, Eur. Phys. J. A **16**, 55 (2003).
[32] URL: http://www.nndc.bnl.gov/ensdf/.
[33] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse, K. Heyde, and P. Van Isacker, Phys. Rev. Lett. **52**, 1974 (1984).
[34] M. Girod, P. Dessagne, M. Bernas, M. Langevin, F. Pougheon, and P. Roussel, Phys. Rev. C **37**, 2600 (1988).
[35] K. Kaneko, M. Hasegawa, T. Mizusaki, and Y. Sun, Phys. Rev. C **74**, 024321 (2006).