New isomeric state in ^{116}Ag

J. C. Batchelder,[1] J.-C. Bilheux,[2] C. R. Bingham,[2,3] H. K. Carter,[1] D. Fong,[4] P. E. Garrett,[6] R. Grzywacz,[2] J. H. Hamilton,[4] D. J. Hartley,[3,5] J. K. Hwang,[4] W. Krolas,[4,7,8] W. D. Kulp,[9] Y. Larochelle,[3] A. Piechaczek,[10] A. V. Ramayya,[4] K. P. Rykaczewski,[2] E. H. Spejewski,[1] D. W. Stracener,[2] M. N. Tantawy,[3] J. A. Winger,[11] J. L. Wood,[9] and E. F. Zganjar[10]

[1]*UNIRIB/Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831, USA*

[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*

[4]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*

[5]*Department of Physics, U.S. Naval Academy, Annapolis, Maryland 21402, USA*

[6]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[7]*Joint Institute for Heavy Ion Physics, Oak Ridge, Tennessee 37831, USA*

[8]*H. Niewodniczanski Institute of Nuclear Physics, PL-31342, Kraków, Poland*

[9]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*

[10]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*

[11]*Department of Physics and Astronomy, Mississippi State University, Mississippi State, Mississippi 39762, USA*

(Received 25 April 2005; published 19 October 2005)

A new isomer in ^{116}Ag with a half-life of 20(1) s has been discovered through the use of conversion electron, β, and γ spectroscopy of on-line mass-separated radioactivities at the Holifield Radioactive Ion Beam Facility at ORNL. The observed electron peaks at 22.5, 44.42, and 47.33 keV were interpreted as the K, L, and M conversion electron lines resulting from a 47.9-keV $E3$ transition associated with the decay of a second isomeric level in ^{116}Ag. A new level structure of ^{116}Ag is proposed, with the levels identified as the 0^- ground-state and isomers at 47.9 and 128.8 keV having spin/parities of 3^+ and 6^- respectively.

DOI: 10.1103/PhysRevC.72.044306 PACS number(s): 27.60.+j, 21.10.Hw, 23.20.Nx

I. INTRODUCTION

Information on the level structure in the neutron-rich Ag isotopes comes mostly from β-decay studies of Ag and the parent Pd isotopes. In the case of ^{116}Ag, the ground state was first suggested to be 1^-, 2^-, or 3^-, based on an 80% β-decay branch to the 0.51-MeV 2^+ state in ^{116}Cd, with a resulting log ft of 6.8 [1]. Later, the spin/parity of (2^-) was assigned to the ground state of ^{116}Ag by Bjørnstad and Alstad [2] based on the argument that the proton is in the $p_{1/2}$ subshell and the neutron in the $d_{3/2}$ state, taking into account a "certain" prolate deformation of ^{116}Ag. They further noted that a spin/parity of 2^- was assigned to the ground state of ^{112}Ag [3], which was based on a measured log ft value of $\approx$10 to the 0^+ ground state of ^{112}Cd. More recent calculations [4], however, indicate that the ground state of ^{116}Ag and other nuclei in the region are strongly oblate deformed. In this article, we report on the structure of the low-energy metastable levels in ^{116}Ag deduced from our measurements, whereas the corresponding results on levels in ^{116}Cd populated in the β decay of ^{116m,gs}Ag will be presented elsewhere [5].

II. EXPERIMENTAL METHOD

Silver-116 was produced at the Holifield Radioactive Ion Beam Facility (HRIBF) via the proton-induced fission of uranium. Forty-mega-electron-volt protons with an intensity of 25 nA bombarded a UC_x target [6] installed at the On-Line Test Facility (OLTF). Proton-induced fission products were then separated by mass at the OLTF and deposited on a moving tape collector (MTC) and subsequently moved to the counting position 30 cm away with a transport time of 700 ms. The counting position was located at the center of an array consisting of three segmented clover Ge detectors (mounted in a close geometry forming three sides of a square $\approx$12 cm per side), plastic scintillators, and a high resolution ($\approx$1 keV at 100 keV) Si(Li) conversion electron spectrometer named BESCA (Bellows Electron Spectrometer for the CARDS Array). BESCA consists of a 5-mm-thick 200-mm^2 liquid nitrogen cooled Si(Li) detector mounted on a movable cold finger. The detector was placed $\approx$2 cm from the moving tape, resulting in an efficiency for conversion electrons of $\approx$2%, whereas the clovers had an efficiency of 5% for 344 keV ^{152}Eu γ rays. The array has been named CARDS (Clover Array for Radioactive Decay Spectroscopy) and was designed for decay studies at the HRIBF (see Ref. [7] for more details).

The data acquisition system uses a digital spectroscopy system based on DGF-4C modules (produced by X-ray Instrumentation Associates) [8,9]. These modules incorporate 40-MHz flash ADC's and serve as a replacement for amplifiers, discriminators, and conventional ADCs and TDCs. Signals from the preamps are connected directly into the DGF modules and then analyzed via the on-board processors to determine their amplitude by fitting the waveform and time-stamped by a continuously running clock. These processors can also be programed to reject pileup events, thus allowing a higher count rate to be accepted. Information is then stored in the onboard buffers until readout (which determines the deadtime of the system).

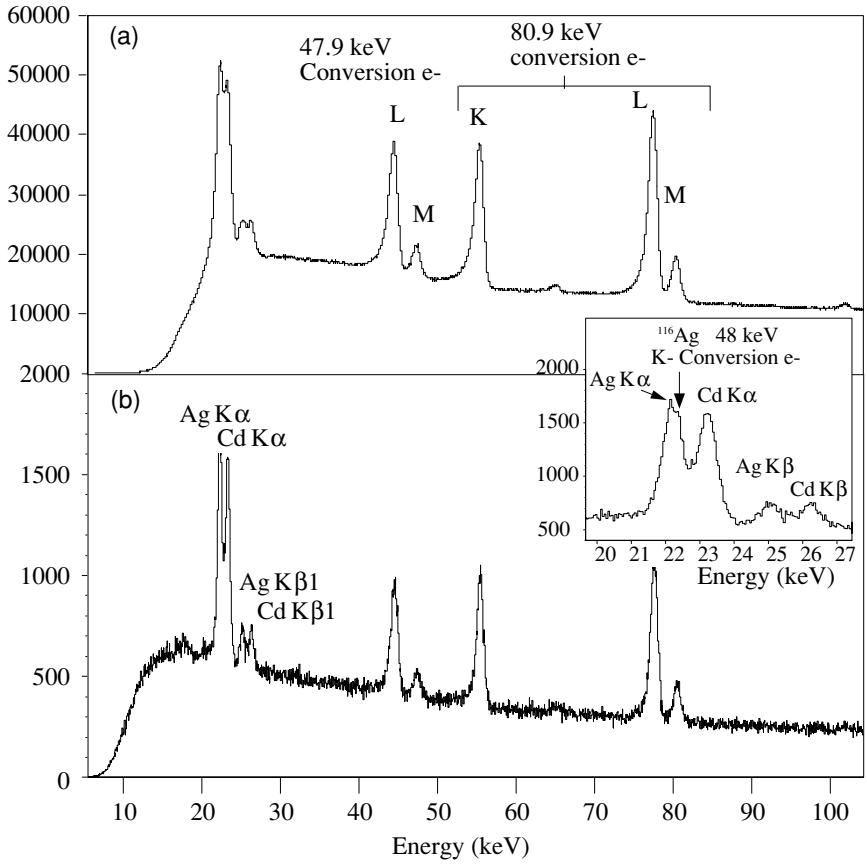

FIG. 1. Energy spectra of conversion electrons of ^{116}Ag observed during two measurements (a) and (b); see the text for details. The conversion electron lines are attributed to the known isomeric transition at 80.9 keV and to the new isomeric transition at 47.9 keV identified in this work.

Three sets of data were taken at tape speeds relevant for the half-lives (previously reported as 8 s and 2.7 min) of the two isomers of ^{116}Ag. These data sets were as follows: (1) ≈20 h of data taken in singles with a tape movement every 15 s, (2) ≈8 h of singles data with a tape cycle of 5 min, and (3) ≈35 h of data taken in coincidence with the BESCA electron spectrometer and a tape cycle of 15 s. γ-γ coincidences were used to construct a level scheme in ^{116}Cd after the β decay of ^{116}Ag, whereas conversion electron data was used to determine the multipolarity of a given γ-ray transition. In addition, the conversion electron spectra contained peaks arising from deexcitation of isomeric levels in ^{116}Ag.

III. EXPERIMENTAL RESULTS

Figure 1(a) presents the low-energy portion of the conversion electron spectrum. It clearly shows peaks at 55.32, 77.42, and 80.32 keV arising from the K, L, and M conversion electrons from the previously reported 81-keV transition [10], along with x rays (from Cd and Ag) and intense peaks at 44.42 and 47.33 keV. A comparison of the ratio of counts and the difference in the peak energies between these two peaks and the L and M 81-keV lines suggests that the two new peaks arise from a 48-keV transition with a corresponding K line at 22.5 keV. A comparison of the background subtracted half-lives of these peaks reveals two groups, with the K, L, and M electrons from the 81-keV transition having half-lives of ≈9.8 s and the two new peaks with half-lives of ≈20 s, supporting the assignment of these peaks to a new isomeric transition of 47.9 keV.

The resolution of the BESCA detector was not sufficient in these runs to unambiguously separate 22.5-keV electrons from the Ag K x rays. To resolve this, a second experiment was performed in which an increased resolution and a lower energy threshold in the BESCA detector was achieved. This spectrum is displayed in Fig. 1(b), with an expansion of the low-energy portion of the spectrum shown in the inset. A peak on the shoulder of the Ag K x-ray peak with an energy of 22.5 keV is present. The energies of the conversion electron peaks summed with the binding energies for Ag are 22.5(2) keV + 25.51(K) = 48.0(2) keV, 44.42(10) keV + 3.45(L) = 47.87(10) keV, and 47.33(10) keV + 0.59(M) = 47.92(10) keV. Based on this and the half-life information, we assign these peaks as the K, L, and M conversion electrons of a new 47.9(1)-keV transition. In a similar way, the three peaks assigned to the previously known 81-keV transition are 55.39(10) keV + 25.51(K) = 80.90(10) keV, 77.42(10) keV + 3.45(L) = 80.87(10) keV, and 80.32(10) keV + 0.59(M) = 80.91(10) keV. This gives an improved value for the energy of 80.9(1) keV. The difference in the average binding energy between L and M electrons is 2.86 keV for Ag and 3.01 keV for Cd. For the 47.9-keV transition, the difference is 2.91(6) keV, and the 80.9-keV transition has an energy difference of 2.90(5) keV. This indicates that the 47.9-keV transition arises from a new 20(1)-s isomer in ^{116}Ag. None of these electron peaks are in coincidence with any γ rays

TABLE I. Summary of energies and half-life values of the conversion electrons arising from the decay of the two short-lived isomers of ^{116}Ag.

Energy	B.E.	Transition	$t_{1/2}$(s)	Counts
22.5 keV	+25.51(K)	=48.01 keV		[a]
44.42 keV	+3.45(L)	=47.87 keV	20.3(5) s	562,800(700)
47.33 keV	+0.59(M)	=47.92 keV	19.2(4) s	138,800(400)
		Adopted value	20(1) s	
$K/L = 0.19(4)$*		$M/L = 0.24$		
55.39 keV	+25.51(K)	=80.90 keV	9.8(1) s	703,200(800)
77.42 keV	+3.45(L)	=80.87 keV	9.8(1) s	853,600(900)
80.32 keV	+0.59(M)	=80.91 keV	9.9(1) s	212,500(500)
		Adopted value	9.8(1) s	
$K/L = 0.82$		$M/L = 0.25$		

[a]The value for the K/L ratio of the 48-keV transition is taken from the spectrum shown in Fig. 1(b).

and there is no evidence of contamination from surrounding masses.

A comparison of the rates of K-to-L conversion electrons from a given transition allows one to determine the multipolarity of the transition. For the 80.9-keV transition, the K/L ratio is 0.82, which compares well with the calculated value [11] of 0.80 for a 80.9-keV $E3$ transition. The experimental value for the 47.9-keV K/L electron intensity ratio, from the measurement performed with better energy resolution and low energy threshold, is 0.19(4). Calculated K/L values for this transition are 0.38 for an $M4$ transition, 0.04 for $E4$, and 0.19 for $E3$. We therefore assign the 47.9-keV transition a multipolarity of $E3$. A summary of the energies and half-lives is given in Table I.

Several of the nuclei adjacent to ^{116}Ag have isomeric $E3$ transitions (see Table II). These nuclei are all hindered relative to Weisskopf estimates. The other Ag isotopes have hinderence factors of 10–15, whereas the two ^{116}Ag isotopes at 47.9 and 128.8 keV have values of 62^{+92}_{-25} and 70^{+73}_{-22} respectively. Although in ^{116}Ag these hinderance factors are slightly higher than the other known Ag isotopes, they are of the same order of magnitude and have large error bars (mostly from uncertainty on the IT branching ratio). They are therefore consistent with the other $E3$ transitions in Ag and In in this region.

IV. DISCUSSION AND CONCLUSIONS

There are two possibilities for the placement of these transitions: either they both decay to the ground state of ^{116}Ag or one of the isomers decays into the other, which then decays into the ground state. If both of these isomers decayed directly to the ground state of ^{116}Ag, a 33-keV transition between the two isomers (with the same spin/parity) would be much faster than a 80.9-keV $E3$ transition and would be expected to be highly converted. Although the K electron for this transition would be too low in energy to observe, the L electron would be at 29.2 keV. No evidence of this transition has been observed in the data. Therefore, the level scheme must contain a higher energy isomer decaying into a lower energy isomer, which then decays to the ground state. The α_κ values for a 47.9- and 80.9-keV transition are calculated to be 76.2 and 15.2 respectively. A 47.9-keV γ ray is effectively below the threshold of the clover detectors used in this experiment, but a small γ peak at 81 keV is observed the raw γ spectrum that is absent in the γ-γ coincidence matrix. This peak gives an experimental $\alpha_\kappa = 11(5)$, which is consistent with the expected value of 15.2.

γ rays following the β decay of ^{116}Ag provide evidence for the assignment of the spin/parities of the β-decaying states. If the ground state of ^{116}Ag is taken to be 2^-, the isomeric states depopulated via $E3$ transitions would be 5^+ and 8^-. As such,

TABLE II. $E3$ isomeric transitions in nuclei near ^{116}Ag.

Isomer	E (keV)	$t_{1/2}$(s)	BR(I.T.)	α_{tot}	W.u.	Hind
^{115m}Pd [12]	89.3	50	8%	22.7	0.0022	440
^{115m}Ag [4]	41.1	18.0	21.0%	1349	0.067	15
^{117m}Ag [12]	28.6	5.34	6.0%	11063	0.097	10
^{118m}Ag [10]	127.6	2.0	41%	4.52	0.111	9
^{114m}In [13]	311.7	0.043	100%	0.11	0.115	9
^{116m}In [14]	162.4	2.18	100%	1.67	0.086	12
^{118m}In [15]	140	8.5	98.6%	3.43	0.037	27
^{116m2}Ag	80.9(1)	9.8(1)	8(4)%	38.3	0.014(7)	70^{+73}_{-22}
^{116m1}Ag	47.9(1)	20(1)	7(4)%	571	0.016(7)	62^{+92}_{-25}

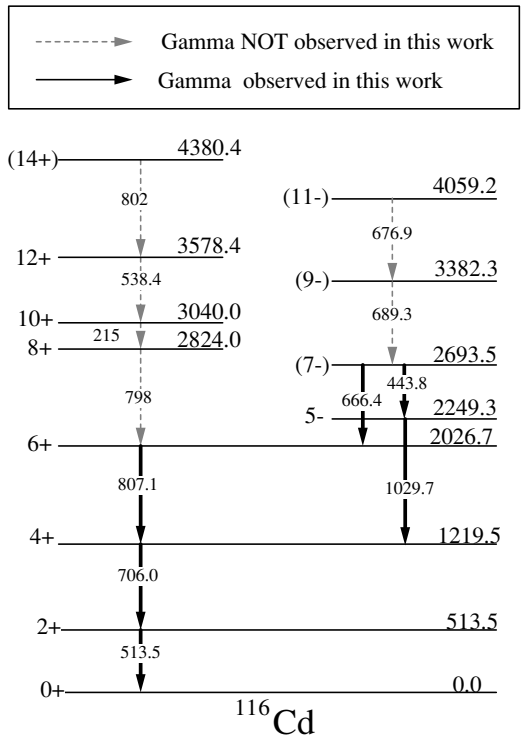

FIG. 2. Levels fed via the ^{176}Yb(^{28}Si, Fγ) reaction [15]. Those γs deexciting these levels observed in the β decay of ^{116}Ag are shown as solid black lines, and those that are not observed are shown as dashed gray lines. This evidence supports the conclusion that the decaying states in ^{116}Ag have spins of 6 or less.

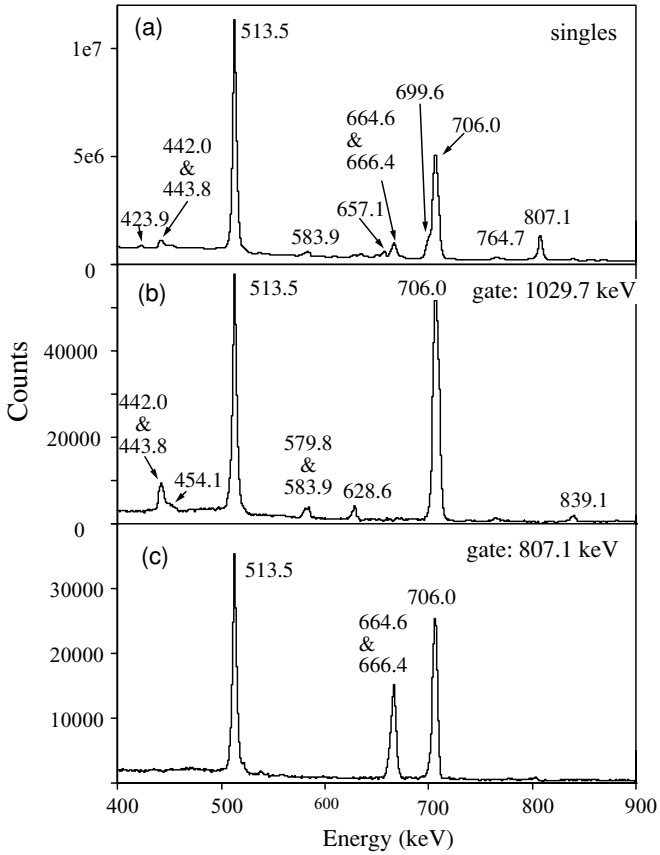

FIG. 3. γ spectra arising from the decay of ^{116}Ag, showing singles (a), γ's in coincidence with the 1029.7-keV $5^- \rightarrow 4^+$ transition (b), and γ s in coincidence with the 807.1-keV $6^+ \rightarrow 4^+$ transition (c).

one would expect to populate the known 8^+ and 9^- states in ^{116}Cd, which have been studied via the fusion-fission reaction $^{28}\mathrm{Si} + {}^{176}\mathrm{Yb}$ [16]. In Ref. [16] the authors report levels in the ground-state band up to (14^+), and a band based on 5^- up to (11^-) (see Fig. 2). In the present work, no evidence for the known 798-keV γs deexciting the 8^+ state at 2824.0 keV or the 689.3-keV γs arising from the 3382.3-keV 9^- level were observed (see Fig. 3). All of the other γs observed in Ref. [16] arising from states with spin 7 and smaller were observed in the present work. This can be explained if the ground state of ^{116}Ag is 0^-, which would give J^π for the two isomers of 3^+ and 6^-. In previous β-decay studies of ^{116m}Ag [2,17], the observation was made that there is direct β decay of ^{116m}Ag to 2^+ and 3^+ states, which is not consistent with a β decay of a 5^+ isomer. However, a 3^+ isomer will exhibit decay to these states, thus solving this discrepancy.

The original assignment of the ground state of ^{116}Ag as 2^- [2] was based on the log ft value of the β decay to the first excited 2^+ state in ^{116}Cd [1] and the assumption of prolate deformation [2] of the ground state. Deformation calculations by Möller-Nix [4], however, indicate that the ground state of ^{116}Ag and other nuclei in the region are strongly oblate deformed with a $\beta_2 = -0.258$ predicted for the ^{116}Ag ground state. At this deformation, one would expect that the 47th proton would be in either the $1/2^+[440]$ from the $\pi 1g_{9/2}$ state or $1/2^-[301]$ from the $\pi 2p_{1/2}$ state. The 69th neutron would be expected to be in $7/2^-[523]$ from the $\nu 1h_{11/2}$ state or $1/2^+[420]$ from the $\nu 1g_{7/2}$ state. Two 1^+ excited states in ^{116}Ag were identified as being populated directly by the allowed Gamow-Teller β transition from the 0^+ ground state of ^{116}Pd [12,18]. The $E1$ decay from these 1^+ states indicate that the ground state of ^{116}Ag could be 0^-,1^-, or 2^-. The only combination of the above neutron and proton states that give a value consistent with this picture is $\pi p_{1/2}1/2^-[301] \otimes \nu g_{7/2}1/2^+[420]$, which gives possible spin/parities of 0^- and 1^-. Nordheim's rule [19] favors a spin/parity of 0^-.

Two pieces of evidence indicate that the 9.8-s isomer is the 6^- state that decays into the 3^+ 20-s isomer. A close inspection of the half-life curves of the background subtracted conversion electron lines in Fig. 4 reveals that the 80.9-keV lines can be fitted well with a straight line on a log plot and the 47.9-keV lines exhibit a small "grow-in" curve, indicating that the 80.9-keV transition decays into the 47.9-keV state. The measurements of this work show that both isomers decay primarily by β decay to ^{116}Cd, with $I_\beta = 93(4)\%$ for the 20-s activity and $I_\beta = 92(4)\%$ for the 9.8-s activity [5]. Therefore, the effect on the shape of the decay curve would be expected to be small. In addition, both isomers and the longer-lived ground state will be produced directly in the proton induced fission of UC_x.

The measured half-life of a given γ-line is primarily because of the β decay feeding the state, with some contribution from higher states decaying to the state. By measuring the

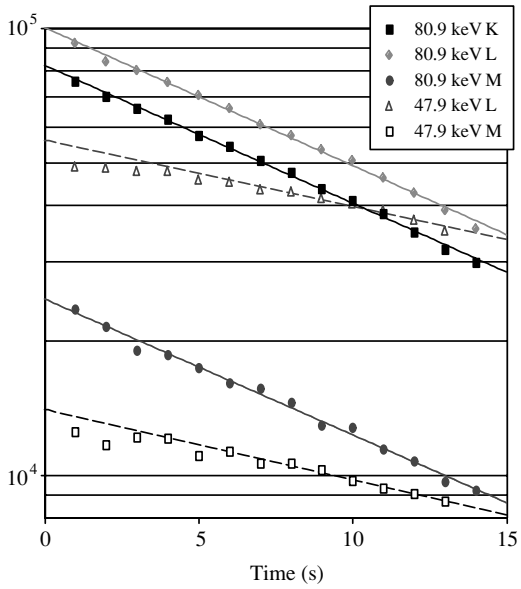

FIG. 4. Background separated half-life curves of the labeled conversion electron peaks displayed in Fig. 1(a). The K, L, and M lines arising from the 80.9-keV isomer are fitted well with an exponential curve. The L and M lines from the 47.9-keV transition exhibit a small "grow-in" pattern at the beginning of the measurement time.

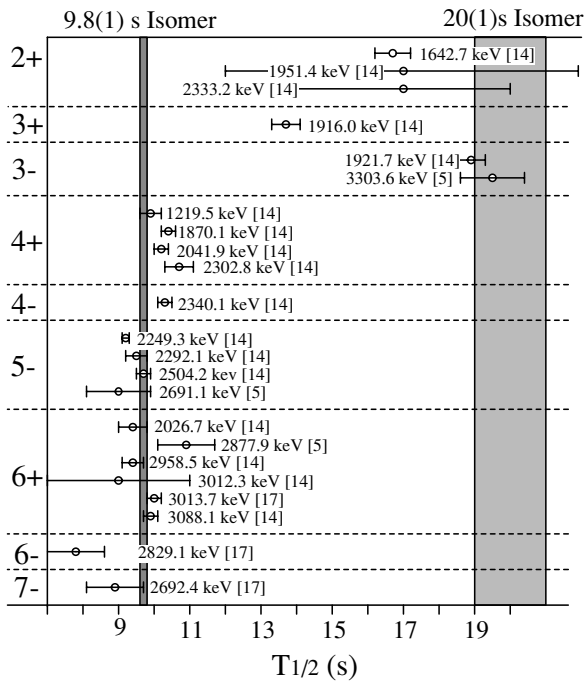

FIG. 5. Half-life of the states with known spin/parity in ^{116}Cd that are fed by the β decay of the two short-lived isomers. The measured half-life of the state is weighted average of the observed γ rays that depopulate that state with the long-lived components subtracted out. The reference number refers to the publication that assigned the spin/parity of the state.

half-lives of the β decays to known spin/parity states in ^{116}Cd, one can determine which isomer is feeding them. Figure 5 shows the measured half-lives of the states with measured spin/parity in ^{116}Cd that are fed by the β decay of the two short lived isomers. The measured half-life of the state is the weighted average of the observed γ rays that depopulate that state with the long-lived components subtracted out. The 513.5-keV (2_1^+) and 1213.1-keV (2_2^+) levels are fed via γs from many higher energy states in ^{116}Cd, and, as such, the measured half-life would be expected to a combination of the two ^{116}Ag isomer's half-lives and are not included in the figure. The figure clearly shows that the states in ^{116}Cd with spins of 2 and 3 have half-lives that cluster around the half-life of the longer lived 20(1)-s isomer, and the states with spins of 4 or greater have half-lives near the value of the shorter-lived 9.8(1)-s isomer. This indicates that the shorter-lived isomer is the higher spin and vice versa. We therefore conclude that the three isomers of ^{116}Ag are (a) a 0^- ground state(this work), with $T_{1/2} = 230(5)$s [5], and $I_\beta - = 100\%$; (b) a 3^+, 47.9-keV isomer, with $T_{1/2} = 20(1)$ s and $I_\beta - = 93(4)\%$; and (c) a 6^-, 128.8-keV isomer, with $T_{1/2} = 9.8(1)$ s, and $I_\beta - = 92(4)\%$.

The assignment of 0^- to the ground state of ^{116}Ag is consistent with previously reported results from the β decay of ^{116}Pd and high-spin studies of ^{116}Ag. The high spin levels of ^{116}Ag were studied via the ^{28}Si(^{176}Yb,γF) reaction [20].

The authors built a level scheme on a $\pi g_{9/2} \otimes \nu h_{11/2}$ band head that was previously reported as a 5^+ state [10]. In the present work this state is identified as the 6^- state, which is consistent with a $\pi g_{9/2} \otimes \nu h_{11/2}$ interpretation. β decay of the 0^+ ground state of ^{116}Pd would not directly populate a 3^+ or 6^- state in ^{116}Ag and has been reported [12,18] only to strongly populate two 1^+ states at 394 keV (22%) and 115 keV (78%). The 394-keV state decays by $E1$ or $M1$ transitions of 302.6, 278.3, and 178.0 keV. Through the use of Weisskopf estimates [21], the decay of this level to the 47.9-keV level via an $E2$ transition is expected to be slower than the three known transitions by a factor of $\approx 10^5$. A similar situation exists for the 115-keV state, where an $E2$ transition to the 47.9-keV state would be a factor of $\approx 10^6$ slower. As such, the levels in ^{116}Ag known from the β decay of ^{116}Pd have no observable connection to the 3^+ and 6^- states in ^{116}Ag reported herein. The decay of the 91-keV state in ^{116}Ag to the ground state was previously reported to be an $M1$ transition [18]. Because we have given the new assignment of 0^- to the ground state, we therefore propose a spin/parity of 1^- for the 91-keV level of ^{116}Ag. Figure 6 shows the low-energy states in ^{116}Ag from the β decay of ^{116}Pd [18] along with the two new states (47.9 and 128.8 keV) from this work.

An examination of the nuclei neighboring ^{116}Ag reveals that for $N = 69$, the ground state of ^{117}Cd [22] and ^{115}Pd [23] is $1/2^+$. Both of these isotopes have low-energy $11/2^-$ isomers (136.4 and 177.0 keV, respectively). For $Z = 47$, both ^{117}Ag and ^{115}Ag have ground states of $1/2^-$ and low-lying $7/2^+$ isomers (arising from $\pi g_{9/2}$ [24]) of 28.6 and 41.2 keV, respectively.

Therefore, the interpretation of the 0^- ground state and the 1^- 91-keV state arising from the coupling of the $1/2^- p_{1/2}$ proton and the $1/2^+$ neutron (split from the $\nu g_{7/2}$ orbital) is consistent with a level systematic of neighboring nuclei. The 3^+ isomer is composed of the $1/2^+$ neutron coupled to the $7/2^+$ proton state, and we assign the 6^- isomer to the $\pi g_{9/2} \otimes \nu h_{11/2}$

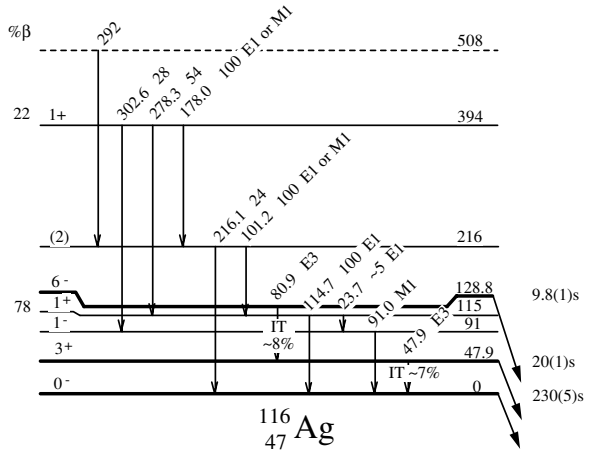

FIG. 6. Low-energy states in ^{116}Ag from the β decay of ^{116}Pd [18] along with the two long-lived isomeric states discussed in this work. According to the Weisskopf estimates [21], the levels populated in the β decay of ^{116}Pd would not exhibit any substantial deexcitations to the 3^+ and 6^- isomers.

band head that has been observed in the high spin levels of ^{110,112,114,116}Ag [20,25]. The $E3$ $3^+ \rightarrow 0^-$ transition in ^{116}Ag is similair to the $7/2^+$ to $1/2^-$ $E3$ proton transition in ^{115}Ag with a spectator neutron, whereas the $6^- \rightarrow 3^+$ transition involves the neutron undergoing a transition with a spectator proton.

In conclusion, we have discovered a new $I^\pi = 3^+$ isomeric state at 47.9 keV in ^{116m}Ag, with a half-life of 20(1) s. We have shown that the ground state of ^{116}Ag has a spin/parity of 0^- rather than 2^- as reported previously. New spin/parity assignments of 3^+, 1^-, and 6^- have been proposed for the levels at 47.9, 91, and 128.8 keV.

This work demonstrates how modern spectroscopy techniques dedicated to β-decay studies can help to verify and correct the long-adopted properties of nuclear levels. The spin and parity adopted for the ground states of ^{112}Ag, ^{114}Ag, and ^{116}Ag were derived from the estimated comparative half-life (log ft) values. However, arguments based on log ft values often suffer from a relatively incomplete decay scheme, which results in the wrong estimation of "apparent β feeding" of a given level. This is especially important because the spin/parity assignments of levels in more exotic nuclei is often based on systematics. More complete spectroscopy of isomeric and β decays involving the determination of spins and parities can indicate different level properties and trigger a change in our extrapolation in nuclear states of more exotic nuclei.

ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy under contracts DE-AC05-76OR00033 (UNIRIB), DOE-AC05-00OR22725 (ORNL), DE-FG05-88ER40330 (JIHIR), DE-FG02-96ER40958 (Georgia Institute of Technology), DE-FG02-96ER41006 (Mississippi State University), DE-FG05-88ER40407 (Vanderbilt University), DE-FG02-96ER40983 (University of Tennessee), DE-FG02-96ER40978 (Louisiana State University), and W-7405-ENG-48 (LLNL).

[1] J. M. Alexander *et al.*, Phys. Rev. **111**, 228 (1958).
[2] T. Bjørnstad, J. Alstad, and J. Inorg. Nucl. Chem. **36**, 2159 (1974).
[3] R. H. Nussbaum *et al.*, Physica **19**, 385 (1953).
[4] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[5] J. C. Batchelder *et al.* (to be published).
[6] D. W. Stracener, in *Proceedings of the Sixteenth International Conference on the Application of Accelerators in Research and Industry*, edited by J. L. Duggan and I. L. Morgan (AIP Press, New York, 2000), p. 257.
[7] J. C. Batchelder *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 625 (2003).
[8] B. Hubbard-Nelson *et al.*, Nucl. Instrum. Methods Phys. Res. A **422**, 411 (1999).
[9] R. Grzywacz, Nucl. Instrum. Methods Phys. Res. B **204**, 649 (2003).
[10] B. Fogelberg, A. Bäcklin, and T. Nagarajan, Phys. Lett. **B36**, 334 (1971).
[11] HISSC program at http://www.nndc.bnl.gov/nndc/physco
[12] B. Fogelberg *et al.*, Z. Phys. A **337**, 251 (1990).
[13] J. Blachot, Nucl. Data Sheets **97**, 593 (2002).
[14] J. Blachot Nucl. Data Sheets **92**, 455 (2001).
[15] J. Hattula *et al.*, Z. Phys. **231**, 203 (1970).
[16] N. Buforn *et al.*, Eur. Phys. J. A **7**, 347 (2000).
[17] Y. Wang *et al.*, Phys. Rev. C **64**, 054315 (2001).
[18] V. Koponen *et al.*, Z. Phys. A **333**, 339 (1989).
[19] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).
[20] M.-G. Porquet *et al.*, Eur. Phys. J. A **18**, 25 (2003).
[21] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952), p. 627.
[22] B. Fogelberg *et al.*, Nucl. Phys. **A267**, 317 (1976).
[23] D. Fong *et al.*, Phys. Rev. C **72**, 014315 (2005).
[24] H. Penttila *et al.*, Z. Phys. A **338**, 291 (1991).
[25] M.-G. Porquet *et al.*, Eur. Phys. J. A **15**, 463 (2002).