β decay of the $T=0$ isomer in the $N=Z$ proton drip-line nucleus ^{70}Br

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We have investigated the β decay of the $T=0$, $T_{1/2}\approx 2.2$ s, isomeric level in the self-conjugate odd-odd nucleus ^{70}Br. The observed β-delayed γ rays in the daughter nucleus ^{70}Se and the deduced decay properties of the isomeric level allow, in conjunction with results from the deformed shell model, a spin and parity assignment of $J^{\pi}=9^{+}$ and suggest a structure of $\{\pi[404]9/2^{+}\nu[404]9/2^{+}\}9^{+}$. The allowed unhindered β decay of the isomer, possibly oblate deformed, proceeds to four-quasiparticle states in ^{70}Se.

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We report the first spectroscopic study of the β-delayed γ ($\beta\gamma$) decay of the $T=0$ isomeric level in the odd-odd, self-conjugate nucleus ^{70}Br, which is the lightest particle-stable isotope of bromine [1]. The study of nuclear $\beta\gamma$ decay provides nuclear structure information on the decaying level and on the final states in the daughter nucleus. In the case of the ^{70m}Br decay, both are of interest: the Nilsson diagram of nuclei in the *fpg* shell is characterized by rapid shape changes as a function of proton and neutron number. The dependence of nuclear deformation on the nucleon number is especially dramatic for self-conjugate nuclei, where the proton and neutron shell gaps reinforce each other. Here, the dependence of the shape of the nucleus as a whole on the shell-model orbitals of the unpaired proton and neutron may be studied. The determination of the microscopic structure is a necessary step towards this goal. The decay daughter, ^{70}Se is located in a region where shape coexistence was first established in the realm of medium-heavy nuclei [2]. However, the exact nature of the coexisting structures is still unknown after almost three decades of research. This $\beta\gamma$ decay study clarifies the microscopic composition of the ^{70}Se daughter levels and provides nuclear structure information exceeding that previously obtained by in-beam studies.

An isomeric level in ^{70}Br was first reported by Vosicki *et al.* [3]. They used a halogenide-selective ion source in conjunction with a mass separator in order to identify products of proton-induced spallation reactions. They observed a β spectrum related to an activity with a half-life of $T_{1/2}=2.2(2)$ s [3] in the mass $A=70$ isobars and attributed it to the decay of an isomeric state in ^{70}Br. Based on the systematics of the odd-odd, self-conjugate nuclides heavier than ^{58}Cu, the isomer was assigned as the lowest $T=0$ level in ^{70}Br. The $T=1$ ground state of ^{70}Br has $J^{\pi}=0^{+}$ and undergoes superallowed β decay with a half-life of $T_{1/2}=78.54(59)$ ms [4]. No additional information was available about the isomeric state or excited levels in ^{70}Br [5].

Bromine-70 and ^{70m}Br were produced in reactions induced by a 110-MeV ^{32}S beam, delivered by the 25-MV tandem accelerator of the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. A 1.19-mg/cm^2 thick ^{40}Ca target was sandwiched between two gold layers of 42.5 μg/cm^2 (exit) and 425 μg/cm^2 (entrance). By gradually increasing the beam intensity on target, we were able to operate at beam currents as high as 36 pnA at the end of the 21 h beam-on-target time. The cross section for the production of ^{70}Br in the ^{40}Ca(^{32}S,pn) reaction was calculated to be 0.54 mb at the midtarget beam energy of 95 MeV by using the fusion-evaporation code HIVAP [6] with the experimental and extrapolated nuclear masses given in [7]. Experimentally, a lower limit in the order of 70 μb was derived for the production of the $T=0$ isomer. We investigated the decay of the $T=0$ isomer at the recoil mass spectrometer (RMS) [8], which was tuned in a charge-state diverging mode to transport mass $A=70$ nuclei in the charge state $Q=15^{+}$ to its final focus. There, the activity was implanted into the transport tape of the moving tape collector (MTC) [9], which was operated with 4-s cycle time to maximize the collection and counting efficiency for the 2.2(2)-s [3] isomer. The short-lived $T=1$, $T_{1/2}=78.54$ ms ^{70}Br activity decayed during the transport time of approximately 0.5 s. The tape carried the isomeric component to a detection station consisting of four segmented clover germanium detectors in a close, crosslike geometry with a γ-photopeak detection efficiency between 6.9% at 100 keV and 2.8% at 1300 keV. Coincidences between signals of two different clover detectors were interpreted as true coincidences and recorded as well as γ-singles events, at a reduced rate, for the purpose of background determination.

Analysis of the β^{+}/EC decay of the $T=0$ isomer in ^{70}Br is based on the γ-γ coincidence and γ-singles data obtained in this experiment as well as on the in-beam level scheme of ^{70}Se ($T_{1/2}=41.1$ m [10]), which has been repeatedly investigated [11–15]. The level scheme of ^{70}Se adopted in this paper (see Fig. 1) was obtained in the ^{40}Ca(^{36}Ar,$\alpha 2p$) reaction by using the OSIRIS spectrometer in a thick-target experiment [15]. It comprises all transitions so far observed in ^{70}Se except the deexcitation of a tentative 0_2^{+} level at 2012 keV by a 1067-keV γ ray [13,14]. This level was neither confirmed nor rejected in the present work. Figure 2(a) dis-

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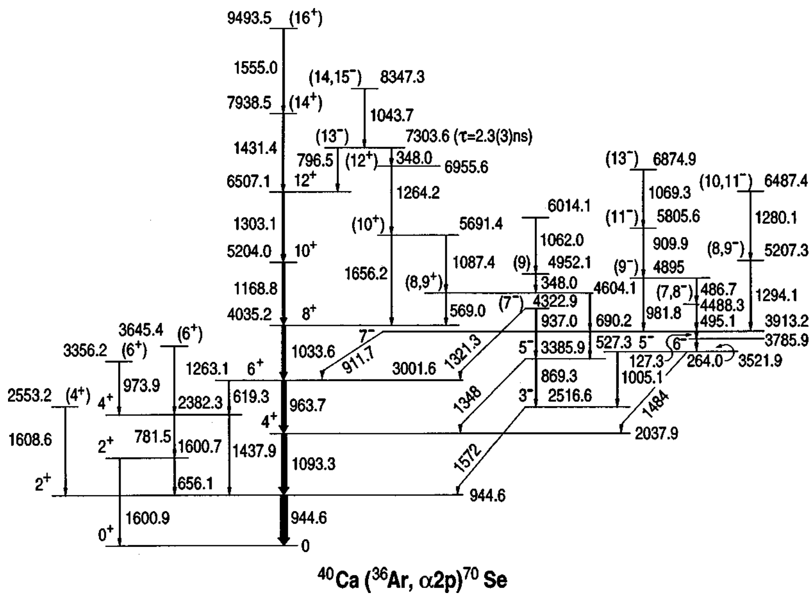

FIG. 1. In-beam level scheme of ^{70}Se from the ^{40}Ca(^{36}Ar,$\alpha 2p$) reaction [15].

plays part of the total projection of the γ-γ coincidence matrix [$TP(\gamma\gamma)$] obtained in the present experiment. Five γ rays can be identified as depopulating levels in ^{70}Se, namely those at 911.7, 944.6, 963.7, 1033.6, and 1093.3 keV. The γ line at 1039.25 keV originates from the $\beta\gamma$ decay of the ^{70}Br grand-daughter ^{70}As ($T_{1/2}=53$ m) and the γ line at 1016.04 keV stems most probably from the $\beta\gamma$ decay of the charge-state contaminant ^{68}As, which is produced in the strong ^{40}Ca(^{32}S,α) channel. The background line at 1120.3 keV is populated by the ^{214}Bi $\beta\gamma$ decay in the ^{238}U natural decay chain. The γ rays in ^{70}Se do not originate from an isomeric state with a half-life sufficiently long to survive the time of flight through the RMS of 2.7 μs. Such an isomer had been observed in the thick-target in-beam experiment [15], where ungated γ-γ coincidences and beam-gated γ-singles data were recorded. Furthermore, the decay behavior of the ^{70}Se γ lines as a function of the time elapsed since tape transport is compatible with a half-life of $T_{1/2}\approx 2$ s. Observation of the selenium γ rays in the $A=70$ nuclides confirms the existence of the isomeric level and places it through the observed characteristic γ rays firmly in ^{70}Br. The partial β-decay scheme of the $T=0$ isomer, derived in this experiment, is shown in Fig. 3. Gamma-ray and level energies were adopted from [15]. Gamma-ray intensities, relative to the intensity of the $2_1^+ \rightarrow 0_1^+$ transition, and their combined statistical and dominating systematic uncertainties were determined from $TP(\gamma\gamma)$ and are displayed in Fig. 3. The observation of the γ rays of 569.0 and 690.2 keV, which are obscured by background activity in $TP(\gamma\gamma)$, was confirmed by gating simultaneously on the four lowest transitions of the yrast band and subtracting the background. The resulting spectrum, displayed in Fig. 2(b), shows those γ rays in coincidence with the yrast transitions. Their intensity agrees very well with the expected number of photopeak events based on the decay scheme of Fig. 3 and the experimental γ-ray detection efficiencies. The relative intensities I_γ of the four γ rays of 348.0, 1062.0, 1168.8, and 1656.2 keV, which are located above the 8_1^+, 7_1^-, and $(8,9)^+$ levels are crucial for establishing β-decay intensities I_β. Upper γ-ray intensity limits were determined, which are compatible with zero intensity for all four transitions. The upper limit for the 348.0 keV transition is relatively high due to the intense background of the 511-keV annihilation radiation Compton events, $I_\gamma(348.0)<10$, therefore also $I_\gamma(1062.0)<5$ has been in-

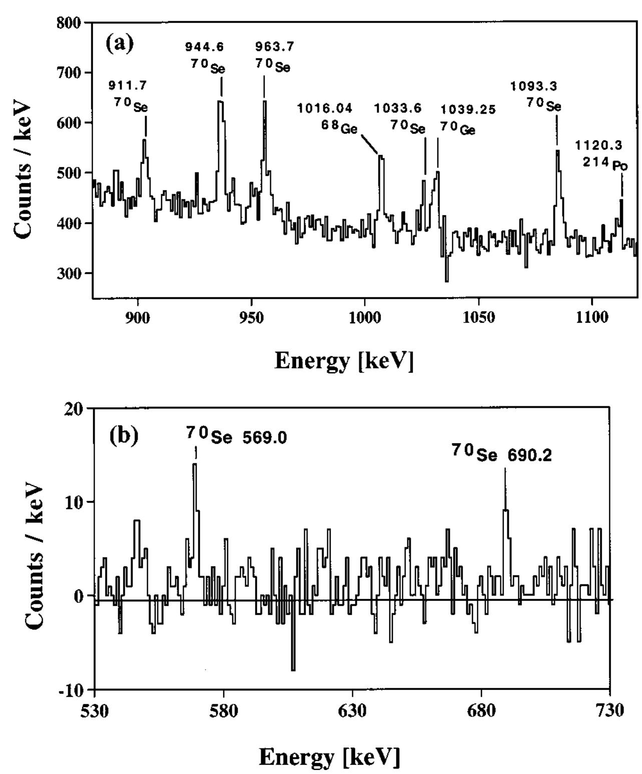

FIG. 2. (a) Part of a total projection of the γ-γ coincidence matrix. Transitions in ^{70}Se from the ^{70m}Br decay as well as from background activity are indicated. (b) Background subtracted projection of the γ-γ coincidence matrix, gated on the four lowest yrast transitions. The previously known 569.0- and 690.2-keV transitions in ^{70}Se can be recognized in addition to other, unidentified lines.

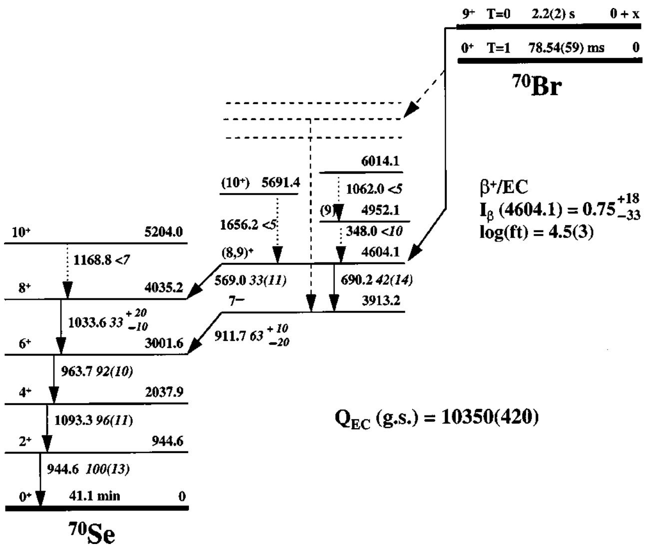

FIG. 3. Partial β-decay scheme of the $T=0$ isomer in ^{70}Br, derived in this experiment. Observed γ rays are indicated by full arrows, their energy and their relative intensity. Dotted arrows indicate weak transitions whose intensity is compatible with zero. I_β denotes the absolute β-branching ratio relative to one ^{70m}Br decay and x is the excitation energy of the isomer. The log (ft) value of 4.5(3) assumes $I_\beta=0.75(+18-33)$, 0.5 MeV$<x<$1.0 MeV and takes into account the uncertainties in $T_{1/2}=2.2(2)$ s [3] and $Q_{\rm EC}=10350(420)$ keV [7]. The dashed arrows indicate a tentative decay path through the 7_1^- level.

cluded in Fig. 3. In order to investigate if the lines at 569.0 and 911.7 keV are caused by background radiation at 569.7 keV (^{207}Bi β^- decay) and 911.7 keV (^{228}Ac β^- decay), we generated gated, background subtracted γ-ray spectra by projecting a gate—identical to that used in generating the spectrum of Fig. 2(b)—at various places in the γ-γ coincidence matrix. We did not find evidence that background activities contaminate the background subtracted gated coincidence spectra. Furthermore, the 1063.66 keV γ ray ($I_\gamma=84.18\%$) from the ^{207}Bi decay which accompanies the 569.7 keV γ ray ($I_\gamma=8.79\%$) is not visible in $TP(\gamma\gamma)$. Likewise, the 911.7 keV γ ray ($I_\gamma=100\%$) from the ^{228}Ac decay should be observed together with a 968.97 keV γ ray ($I_\gamma=60.8\%$), which is also absent in $TP(\gamma\gamma)$. Therefore, we conclude that the γ rays of 569.0 and 911.7 keV indeed originate from the ^{70m}Br decay. Note that all singly or multiply gated spectra contain γ rays which could not be placed in the decay scheme. The ^{70m}Br source strength was not measured in the present experiment. Instead, it was determined from the number of $2_1^+\to 0_1^+$ γ transitions, since the intensity by-passing the $2_1^+\to 0_1^+$ transition is small, approximately (5–10) % [14]. Hence, the relative γ-ray intensities of Fig. 3 correspond to absolute γ-ray intensities per 100 ^{70m}Br decays. From these γ-ray intensities, a β-decay intensity $I_\beta=0.75$ $(+18\ -33)$ per ^{70m}Br decay to the $(8,9)^+$ level at 4604.1 keV was deduced. The uncertainties were obtained by adding the errors of $I_\gamma(569.0)$ and $I_\gamma(690.2)$ in quadrature and allowing for a possible feeding of the 4604.1 keV level through higher lying states of up to 0.15 units. The remaining β-decay feeding proceeds most probably through unidentified levels into the 7_1^- state at 3913.2 keV, which is yrast, and channels away γ-ray flux from the ground-state band, see Ref. [12]. Note that there is no β-decay feeding to levels of the yrast band and the γ-vibrational states on the left-hand side of the in-beam level scheme. Due to the high multipolarity of a possible internal transition deexciting the isomer, which will be shown to have $J^\pi=9^+$, into the ^{70}Br ground state, no useful upper limit for its excitation energy could be established based on the experimental half-life of 2.2(2) s [3]. Instead, the excitation energy of the isomer was estimated from the energy systematics of other lowest $T=0$ levels in the odd-odd, self-conjugate nuclides, which is summarized in Fig. 4. In the nearly spherical nuclei ^{62}Ga and ^{66}As, those $T=0$ levels are found at 571 keV $[J^\pi=(1^+)]$ [16] and at 837.1 or 394.2 keV $[J^\pi=(1^+)]$ [17]. In the

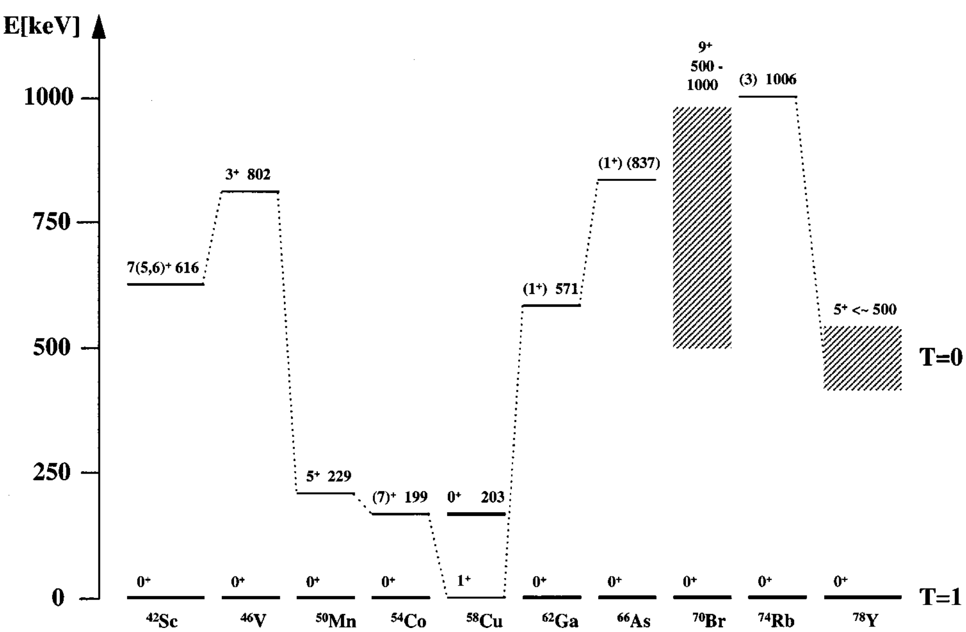

FIG. 4. The known lowest $T=1$ and $T=0$ states in the self-conjugate, odd-odd nuclei of the *fpg* shell. For the $T=0$ levels, several J^π assignments are uncertain as indicated by parentheses. The placement of the lowest $T=0$ level in ^{66}As at 837 keV is not unambiguous [17]. For ^{78}Y, the hatched area indicates the possible excitation energy of the 5^+ isomer as deduced by its β-decay properties [19]. For ^{70}Br, the hatched area indicates the presumed excitation energy of the 9^+ isomer as used in the text.

moderately deformed ^{74}Rb the lowest $T=0$ level is at 1006 keV $[J^{\pi}=(3^{+})]$ [18], and it is located below 500 keV ($J^{\pi}=5^{+}$) in the strongly deformed ^{78}Y [19]. The data in Fig. 4 suggest a placement of the ^{70}Br isomer between 800 keV and 1 MeV. However, the $J^{\pi}=9^{+}$ multiplet may be spread in energy considerably more than its (1^{+}) and (3^{+}) neighbors in ^{66}As and ^{74}Rb and we assume therefore that the isomer is located between 0.5 and 1.0 MeV. The Q_{EC} value of the isomeric decay was not measured in the present experiment. Instead, the Q_{EC} (g.s.) value for the ^{70}Br ground state β^{+}/EC decay was taken as 10 350(420) keV from the compilation of experimental and extrapolated masses [7]. Adding the estimated excitation energy of the isomer to Q_{EC} (g.s.), and combining the result with I_{β} and $T_{1/2}$ [3], one obtains $\log(ft)=4.5(3)$ for the transition to the 4604.1 keV level. The uncertainty of the log(*ft*) value includes the experimental and systematical errors of the energy of the isomer, Q_{EC} (g.s.), I_{β} and $T_{1/2}$.

The odd-odd, self-conjugate nuclei ^{42}Sc, ^{50}Mn, ^{54}Co [10], ^{66}As [17], and ^{78}Y [19] have low-lying, isomeric $T=0$ states with an aligned proton-neutron pair in identical Nilsson orbitals. The Nilsson orbitals at and above the Fermi surface at $N=Z=35$ are $[301]1/2^{-}$, $[301]3/2^{-}$, $[303]5/2^{-}$, and the low-spin, positive parity $g_{9/2}$ orbitals for prolate and $[310]1/2^{-}$, $[301]3/2^{-}$, and the high-spin positive-parity $g_{9/2}$ orbitals for oblate deformation, with $|\beta_2|$ around 0.2–0.3; see, e.g., [20] for the Nilsson diagram of the *fpg* shell. The presence of $1/2^{-}$, $3/2^{-}$, $5/2^{-}$, and $9/2^{+}$ orbitals at low excitation energies was experimentally verified in the prolate deformed $N=35$ isotones ^{65}Zn, ^{67}Ge, and ^{69}Se, where the three odd parity levels are located within 125 keV above the ground state and the $9/2^{+}$ level descends from 1065.5 to 574 keV with increasing proton number [21–23]. Also, the low-energy structure of the light odd-even bromine isotopes is characterized by low-lying $1/2^{-}$, $3/2^{-}$, and $5/2^{-}$ levels and a $9/2^{+}$ state at somewhat higher excitation energy [24,25]. This suggests a configuration space allowing 1^{+}, 3^{+}, 5^{+}, or 9^{+} levels for the two unpaired nucleons outside the ^{68}Se core, and the respective J^{π} assignments for ^{70m}Br. Since the decay populates the $J^{\pi}=(8,9)^{+}$ level in ^{70}Se, Gamow-Teller selection rules indicate that $7^{+}\leqslant J^{\pi}\leqslant 10^{+}$. Thus, ^{70m}Br must have $J^{\pi}=9^{+}$ and a $\{\pi[404]9/2^{+}\nu[404]9/2^{+}\}9^{+}$ configuration. Independent evidence for the $J^{\pi}=9^{+}$ assignment within the given configuration space is the absence of direct β-decay feeding to the known 2_1^{+}, 4_1^{+}, or 6_1^{+} levels in ^{70}Se, which should occur if the isomer had $1^{+}\leqslant J^{\pi}\leqslant 5^{+}$.

The log(*ft*) value for the decay to the 4601.4-keV level of 4.5(3) indicates an allowed unhindered transition with $|\Delta K|=1$, $\Delta\Lambda=0$, $\Delta n_z=0$, $\Delta n=0$. See, e.g., [26] for a compilation of data on allowed unhindered transitions from the rare-earth region. For example, the β^{+}/EC decay of ^{160}Ho ($J^{\pi}=5^{+}$) to the $J^{\pi}=4^{+}$, 1694.37 keV level in ^{160}Dy has a log(ft) value of 4.7. It is interpreted as a spin-flip transition $\pi\,7/2^{-}[523]\,\nu 3/2^{-}[521]\rightarrow\nu\,5/2^{-}[523]\,\nu 3/2^{-}[521]$. The decay of the 9^{+} isomer does not proceed via the transformation of the "valence" proton $\pi 9/2^{-}[404]\rightarrow\nu 7/2^{-}[404]$, since the expected large splitting between the $g_{9/2}$ and $g_{7/2}$ spin-orbit partners together with the pairing gap in the even-even daughter is incompatible with the location of the $(8,9)^{+}$ state at 4604.1 keV. Instead, the experimental log(ft) value can be explained by assuming a spin-isospin flip decay of the ^{68}Se core $\pi\,3/2^{-}[301]\rightarrow\nu\,1/2^{-}[301]$, and a four-quasiparticle (4-qp) configuration $[\{\pi^{-1}\,3/2^{-}[301],\ \nu\,1/2^{-}[301]\}1^{+},\ \{\pi 9/2^{+}[404],\ \nu\,9/2^{+}[404]\}9^{+}]8^{+}$ for the 4604.1 keV daughter level. This suggests a J^{π} assignment of 8^{+} for the 4604.1 keV state.

The $J^{\pi}=9^{+}$ assignment for ^{70m}Br indicates that the isomer may carry an oblate deformed component in its wave function. The Nilsson diagram shows the high-*K*, $[404]9/2^{+}$ orbital downsloping with decreasing quadrupole deformation β_2, favored by an oblate deformed shape of the mean field. Total Routhian surface calculations for ^{70}Se [15] suggest the presence of a collective oblate component in the low-spin region below the 8_1^{+} level. This component disappears near the 8_1^{+} level as a function of rotational frequency and a noncollective oblate structure emerges, which competes at higher spins with a prolate collective structure. The prolate collective structure was interpreted as the upper portion of the ground-state band. The noncollective oblate structure was identified with the levels on the right-hand side of the in-beam level scheme of Fig. 1. Evidence for the latter assignment was the existence of a $J^{\pi}=(13^{-})$, $\tau=2.3(3)$ ns, isomer at 7303.6 keV, which is not a member of a collective band and is assumed to have a 4-qp structure. Our finding that the ^{70m}Br β decay populates the 4-qp level at 4604.1 keV confirms this interpretation and is experimental evidence that the oblate deformed structure is related to two unlike nucleons in the high-*K* $[404]9/2^{+}$ Nilsson orbitals.

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[1] B. Blank *et al.*, Phys. Rev. Lett. **74**, 4611 (1995); R. Pfaff *et al.*, Phys. Rev. C **53**, 1753 (1996).
[2] J. H. Hamilton, A. V. Ramayya, W. T. Pingston, R. M. Ronningen, G. Garcia-Bermudez, H. K. Carter, R. L. Robinson, H. J. Kim, and R. O. Sayer, Phys. Rev. Lett. **32**, 239 (1974).
[3] B. Vosicki, T. Björnstad, L. C. Carraz, J. Heinemeier, and H. L. Ravn, Nucl. Instrum. Methods **186**, 307 (1981).
[4] R. H. Burch, Jr., C. A. Gagliardi, and R. E. Tribble, Phys. Rev. C **38**, 1365 (1988).
[5] C. Borcan *et al.*, Eur. Phys. J. A **5**, 243 (1999); **6**, 481 (1999).
[6] W. Reisdorf, Z. Phys. A **300**, 227 (1981).
[7] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[8] C. J. Gross *et al.*, Nucl. Instrum. Methods Phys. Res. A (in press).

[9] E. F. Zganjar, A. Piechaczek, J. C. Batchelder, and C. J. Gross, in *Proceedings of the International Conference on Perspectives in Nuclear Physics*, Paradise Island, Nassau, 1998, edited by K. Carter, R. Piercey, and J. Hamilton (World Scientific, Singapore, 1999).
[10] *Table of Isotopes*, edited by R. B. Firestone, V. S. Shirley, C. M. Baglin, S. Y. Frank Chu, and Jean Zipkin (Wiley, New York, 1996).
[11] E. Nolte, Y. Shida, W. Kutschera, R. Prestele, and H. Morinaga, Z. Phys. **268**, 267 (1974).
[12] R. Wadsworth, L. P. Ekström, G. D. Jones, F. Kearns, T. P. Morrison, P. J. Twin, and N. J. Ward, J. Phys. G **6**, 1403 (1980).
[13] A. Ahmed *et al.*, Phys. Rev. C **24**, 1486 (1981).
[14] J. Heese, K. P. Lieb, L. Lühmann, F. Raether, B. Wörmann, D. Alber, H. Grawe, J. Eberth, and T. Mylaeus, Z. Phys. **325**, 45 (1986).
[15] T. Mylaeus *et al.*, J. Phys. G **15**, L135 (1989).
[16] S. M. Vincent *et al.*, Phys. Lett. B **437**, 264 (1998).
[17] R. Grzywacz *et al.*, Phys. Lett. B **429**, 247 (1998).
[18] D. Rudolph *et al.*, Phys. Rev. Lett. **76**, 376 (1996).
[19] J. Uusitalo *et al.*, Phys. Rev. C **57**, 2259 (1998).
[20] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).
[21] K. R. Pohl, D. F. Winchell, J. W. Arrison, and D. P. Balamuth, Phys. Rev. C **51**, 519 (1995).
[22] J. W. Arrison, D. P. Balamuth, T. Chapuran, D. G. Popescu, J. Görres, and U. Hüttmeier, Phys. Rev. C **40**, 2010 (1989).
[23] M. Wiosna, J. Busch, J. Eberth, M. Liebchen, T. Mylaeus, N. Schmal, R. Sefzig, S. Skoda, and W. Teichert, Phys. Lett. B **200**, 255 (1988).
[24] A. G. Griffiths, C. J. Ashworth, J. Rikovska, N. J. Stone, J. P. White, I. S. Grant, P. M. Walker, and W. B. Walters, Phys. Rev. C **46**, 2228 (1992).
[25] J. W. Arrison, T. Chapuran, U. J. Hüttmeier, and D. P. Balamuth, Phys. Lett. B **248**, 39 (1990).
[26] P. C. Sood and R. K. Sheline, Mod. Phys. Lett. A **18**, 1711 (1989).