$\pi 7/2[413]$ rotational band and high spin states in odd-mass ^{115,117}Ag

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Twenty four and twenty two new excited states are proposed in neutron-rich ^{115,117}Ag, respectively. These new results came from new works in Gammasphere measuring $\geqslant$ triple- and higher-fold prompt coincidences following the spontaneous fission of ^{252}Cf. The $\pi 7/2[413]$ rotational bands are identified in ^{115,117}Ag, along with higher bands of uncertain structures. A doublet structure in some bands is suggestive of softness toward triaxiality.

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Earlier studies on the odd-Ag isotopes were carried out from the β-decay work of the Pd isotopes [1]. Excited bands with $K^{\pi}=1/2^{+}$ built on the proton $1/2^{+}[431]$ intruder orbital have been observed in odd mass $^{105-115}$Ag and odd mass indium nuclei along with other low spin states in ^{115}Ag [1]. The excitation energy of the intruder bands is minimum in ^{113}Ag with $N=66$. The complicated bands discovered from the β decay [2–4] in odd-A In isotopes have been explained by coupling a hole to their Sn cores and a particle to their Cd cores. These kinds of bands were not observed in the adjacent odd-mass Ag isotopes which were also studied by β decay [1]. Isomeric states with spin and parity of $7/2^{+}$ were observed in ^{115,117}Ag [6]. The Ag isotopes are the partners of Sb in the spontaneous fission (SF) of ^{252}Cf. We have used this relation to identify the levels in ^{115,117}Ag. A 7/2[413] rotational band is identified in both ^{115,117}Ag. High spin states observed in ^{115,117}Ag are interpreted by using the Nilsson deformed shell model, since the rotational band spacings are sufficiently small. We recognize that these Ag nuclei may be in a region of shape coexistence, where the spherical shell model with phonons may be the more appropriate basis for some states and the deformed (Nilsson) shell model for others, especially the yrast and near-yrast levels populated in these fission experiments.

In the present work the high spin states in ^{115,117}Ag are investigated by using the Gammasphere and spontaneous fissioning source ^{252}Cf. The measurements were carried out at the Lawrence Berkeley National Laboratory by using a ^{252}Cf source inside Gammasphere. A ^{252}Cf source of strength ≈ 62 μCi was sandwiched between two Fe foils of thickness 10 mg/cm^2 and was mounted in a 7.62 cm diameter plastic (CH) ball to absorb β rays and conversion electrons. The source was placed at the center of the Gammasphere array which, for this experiment, consisted of 102 Compton suppressed Ge detectors. A total of 5.7×10^{11} triple- and higher-fold coincidence events were collected. The coincidence data were analyzed with the RADWARE software package [7]. The width of the coincidence time window was about 1 μs.

Since the Cf fission partners of the Ag isotopes are Sb isotopes, the transitions belonging to the Ag isotopes are identified in the following way : We compare coincidence spectra obtained by setting double gates on the known transitions in ^{133}Sb as shown in Fig. 1. The double gates used for obtaining these four spectra are 2791.0/1510.5, 2791.0/162.5, 1510.5/162.5, and 2791.0/61.5 keV in ^{133}Sb. A/B means that the double gate is set on two transitions of energies A and B. In Fig. 1 (in all the above gates), we observe two new transitions (118.3 and 223.8 keV) and one transition of energy 147.5 keV which was already assigned to ^{117}Ag from the β decay work of ^{117}Pd [6]. Several γ transitions in ^{117}Ag are further identified from the double-gated coincidence spectrum on the 147.5 keV transition in ^{117}Ag and 2791.0 keV transition in ^{133}Sb as seen in the top spectrum of Fig. 2. All the strong transitions observed in the spectrum are assigned to ^{117}Ag. The level scheme of ^{117}Ag is proposed as shown in Fig. 3, which includes 32 new transitions and 22 new levels. Transition energies and intensities in ^{117}Ag are given in Table I. The intensity errors are thought to be about 5% for the strong transitions and about 30% for the weak transitions.

The ordering of transitions in the bands is generally based on relative intensities, coincidence relationships, and the

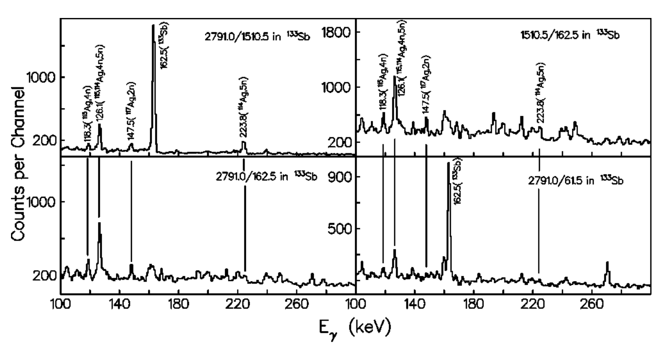

FIG. 1. Coincidence spectra with double gates set on 2791.0/1510.5, 1510.5/162.5, 2791.0/162.5, and 2791.0/61.5 keV in ^{133}Sb. A/B means that the double gate is set on A and B transitions.

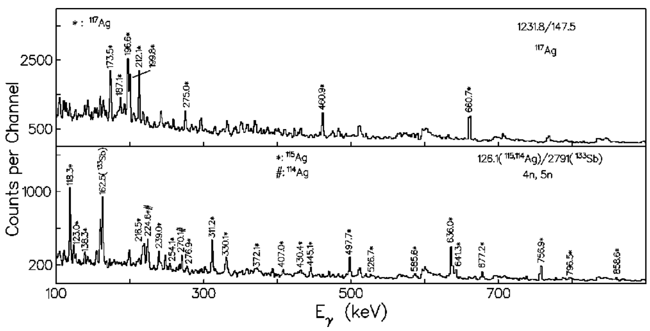

FIG. 2. Coincidence spectra with double gates set on 1231.8/147.5(^{117}Ag) and 126.1(^{115,114}Ag)/2791(^{133}Sb).

feeding and decaying balances for levels. The spin-parity assignments are all tentative, as indicated by the parentheses about all but the $7/2^+$ and $9/2^+$ states in ^{115}Ag and $7/2^+$ state in ^{117}Ag. However, the fact that the fission products are formed with an average of six or more units of angular momentum greatly simplifies the construction of bands and assignments of spins, because only yrast or near-yrast states are observed. We are further helped by the fact that the bands are interlaced with each other. Thus spin and parity assignments are quite constrained, since only $E2$, $M1$, and $E1$ multipolarities are expected to compete. Ideally, one would like to have internal conversion coefficients (ICCs) or directional γ-γ correlation measurements to confirm multipolarity assignments. Measurement of ICCs for prompt fission γ radiation is not feasible due to complexity of the large mix of fission product activities. The Eurogam collaboration has made a few angular correlation measurements [8,9]. In their case the fission fragments were stopped in a KCl salt pill, a diamagnetic medium in which the perturbing magnetic or electic fields at the stopped fission nuclei should be small. In all our Gammasphere experiments, we have stopped in metallic stoppers such as Fe and Ni, which could leave large residual perturbing fields. We certainly reconize that the tenative spins and parities we propose on the level schemes are not proven to the standards usually applied to radioactive decay schemes. The inherent difficulties in fission γ work preclude our measuring internal conversion coefficents and γ-γ or fragment-γ angular corrrelation data. For publication we thus have only the alternatives of (1) presenting tables of γ transition energies and relaive intensities, (2) presenting these along with proposed level scheme without spin-parity values, or (3) putting in the features of the preceding alternatives along with our best estimate of spins and parities and a sketch of the reasoning behind the choices. In following alternative (3) we make use of analogies and trends with nearby isotopes and isotones and to the constraints of the appropriate shell model for the region.

Previously, two transitions of energies 126.1 and 125.8 keV were known in ^{115}Ag and ^{114}Ag, respectively [6]. In the coincidence spectrum with the double gate set on the 126.1 (in both ^{115,114}Ag) and 2791 keV transitions (^{133}Sb) as shown in the bottom spectrum of Fig. 2, the strongest γ transition is at 118.3 keV. According to Wahl's fission-yield table [10], ^{133,132}Sb and ^{116,115}Ag of the Sb and Ag isotopes produced in the SF of ^{252}Cf have the strongest yields. The ^{114}Ag has a much weaker yield than ^{115}Ag in SF of ^{252}Cf.

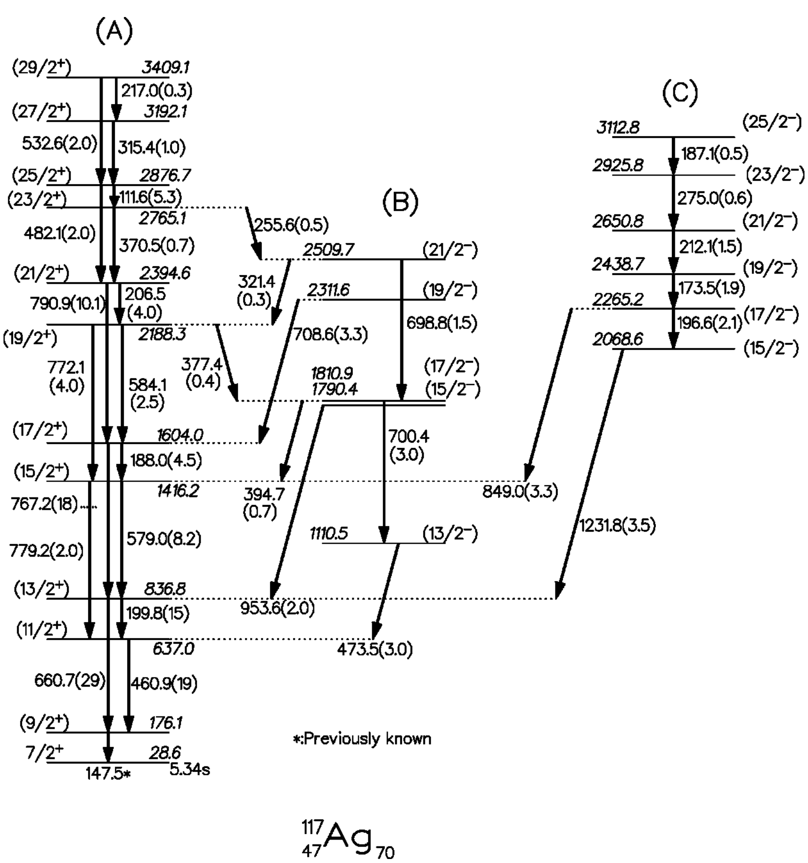

FIG. 3. Partial level schemes of ^{117}Ag. An asterisk means the only previously observed transition. We show only those prompt transitions and derived levels in spontaneous fission γ-γ coincidences between light and heavy fragments. That is, transitions and levels seen in β decay or other reactions are emitted to avoid confusion. Thus, the $1/2^-$ ground states and many low spin states are not shown here. Prompt fission γ's mainly populate yrast and near yrast states.

TABLE I. Transition energies and intensities in ^{117}Ag. The intensity errors are thought to be about 5% for the strong transitions and about 30% for the weak transitions. All of spins and parities except $7/2^+$ are tentatively assigned in the present work.

E_γ (keV)	Relative I_γ	$I_i^\pi \rightarrow I_f^\pi$
111.6	5.3	$(25/2^+)\rightarrow(23/2^+)$
147.5		$(9/2^+)\rightarrow 7/2^+$
173.5	1.9	$(19/2^-)\rightarrow(17/2^-)$
187.1	0.5	$(25/2^-)\rightarrow(23/2^-)$
188.0	4.5	$(17/2^+)\rightarrow(15/2^+)$
196.6	2.1	$(17/2^-)\rightarrow(15/2^-)$
199.8	15	$(13/2^+)\rightarrow(11/2^+)$
206.5	4.0	$(21/2^+)\rightarrow(19/2^+)$
212.1	1.5	$(21/2^-)\rightarrow(19/2^-)$
217.0	0.3	$(29/2^+)\rightarrow(27/2^+)$
255.6	0.5	$(23/2^+)\rightarrow(21/2^-)$
275.0	0.6	$(23/2^-)\rightarrow(21/2^-)$
315.4	1.0	$(27/2^+)\rightarrow(25/2^+)$
321.4	0.3	$(21/2^-)\rightarrow(19/2^+)$
370.5	0.7	$(23/2^+)\rightarrow(21/2^+)$
377.4	0.4	$(19/2^+)\rightarrow(17/2^-)$
394.7	0.7	$(17/2^-)\rightarrow(15/2^+)$
473.5	3.0	$(13/2^-)\rightarrow(11/2^+)$
460.9	19	$(11/2^+)\rightarrow(9/2^+)$
482.1	2.0	$(25/2^+)\rightarrow(21/2^+)$
532.6	2.0	$(29/2^+)\rightarrow(25/2^+)$
579.0	8.2	$(15/2^+)\rightarrow(13/2^+)$
584.1	0.4	$(19/2^+)\rightarrow(17/2^+)$
660.7	29	$(11/2^+)\rightarrow 7/2^+$
698.8	1.5	$(21/2^-)\rightarrow(17/2^-)$
700.4	3.0	$(17/2^-)\rightarrow(13/2^-)$
708.6	3.3	$(19/2^-)\rightarrow(17/2^+)$
772.1	4.0	$(19/2^+)\rightarrow(17/2^+)$
779.2	2.0	$(15/2^+)\rightarrow(11/2^+)$
790.9	10.1	$(21/2^+)\rightarrow(19/2^+)$
849.0	3.3	$(17/2^-)\rightarrow(15/2^+)$
953.6	2.0	$(15/2^-)\rightarrow(13/2^+)$
1231.8	3.5	$(15/2^-)\rightarrow(13^+)$

This means that the fragment pair of ^{133}Sb-^{115}Ag with four neutrons emitted is more strongly populated than the fragment pair of ^{133}Sb-^{114}Ag with five neutrons emitted. The average neutron multiplicity in the spontaneous fission of ^{252}Cf is about 3.5 [11,12]. Therefore the new 118.3 keV transition is assigned to the $4n$ channel of ^{115}Ag rather than to the 5n channel of ^{114}Ag. By double gating on the 118.3 and 126.1 keV transitions, we found several new transitions such as 311.2, 330.1, 526.7, 641.3, 796.5, and 911.0 keV in the coincidence spectrum. By double gating on these transitions, the level scheme of ^{115}Ag is proposed as shown in Fig. 4 which includes 34 new transitions and 24 new levels. Transition energies and intensities in ^{115}Ag are given in Table II. The intensity errors are thought to be about 5% for the strong transitions and about 30% for the weak transitions.

In Fig. 5, we compare two coincidence spectra (middle and bottom panels) with the double gates on 118.3/311.2 in ^{115}Ag and 762.7/147.5 in ^{117}Ag. The 1226.0 keV transition in ^{131}Sb, 2791.0 and 1510.5 keV transitions in ^{133}Sb are shown along with the number of neutrons evaporated. In the coincidence spectrum double gated on 767.2/147.5 in ^{117}Ag, the 1226.0 keV transition in ^{131}Sb with four neutrons evaporated is very strong when compared with the 2791.0 keV transition in ^{133}Sb with two neutrons evaporated. The intensity ratio of the 1226.0 keV transition in ^{131}Sb $(4n)$ and 2791.0 keV transition in ^{133}Sb $(2n)$ is $R(1226.0/2791.0) = 1.2(4)$. In the coincidence spectrum with double gates on 118.3/311.2, 126.1/497.7, and 126.1/636.0 keV transitions in ^{115}Ag, the intensity ratios of 1226.0 keV transition in ^{131}Sb $(6n)$ and 2791.0 keV transition in ^{133}Sb $(4n)$ are R(1226.0/2791.0)=0.32(10), 0.25(8), and 0.31(10), respectively. Therefore, the 311.2, 497.7, and 636.0 keV transitions are assigned to ^{115}Ag. Several other new transitions in ^{115}Ag are identified by gating on the 126.1/636.0 and 126.1/497.7 keV transitions. The coincidence spectrum with a double gate on the 636.0/756.9 keV transitions in ^{115}Ag is shown in Fig. 6. Thirteen of the new transitions in ^{115}Ag are shown in Fig. 6.

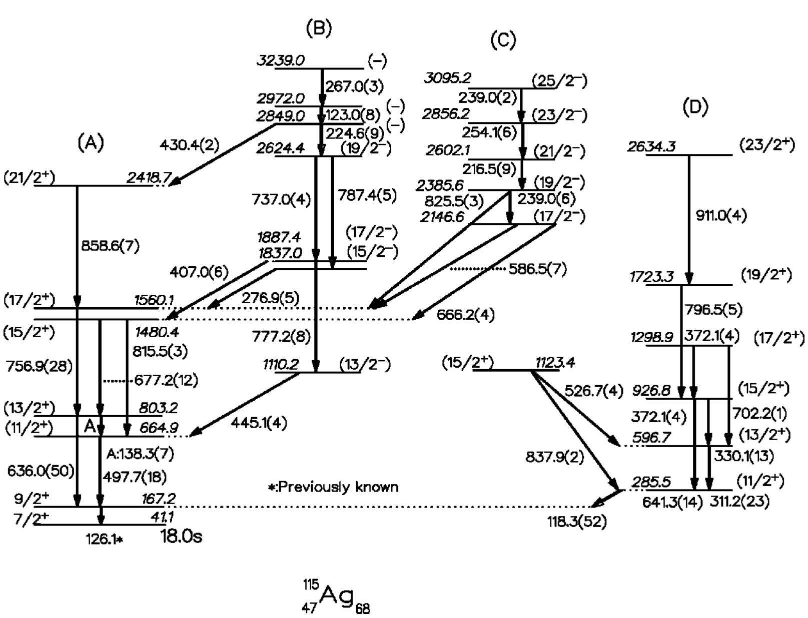

FIG. 4. Partial level scheme of ^{115}Ag. An asterisk means the only previously observed transition. See marks for Fig. 3 above.

TABLE II. Transition energies and intensities in ^{115}Ag. The intensity errors are thought to be about 5% for the strong transitions and about 30% for the weak transitions. All of spins and parities except $9/2^+$ and $7/2^+$ are tentatively assigned in the present work.

E_γ (keV)	Relative I_γ	$I_i^\pi \rightarrow I_f^\pi$
118.3	52	$(11/2^+) \rightarrow 9/2^+$
123.0	8	
126.1		$9/2^+ \rightarrow 7/2^+$
138.3	7	$(13/2^+) \rightarrow (11/2^+)$
216.5	9	$(21/2^-) \rightarrow (19/2^-)$
224.6	9	
239.0	6	$(19/2^-) \rightarrow (17/2^-)$
239.0	2	$(25/2^-) \rightarrow (23/2^-)$
254.1	6	$(23/2^-) \rightarrow (21/2^-)$
267.0	3	
276.9	5	$(15/2^-) \rightarrow (17/2^+)$
311.2	23	$(13/2^+) \rightarrow (11/2^+)$
330.1	13	$(15/2^+) \rightarrow (13/2^+)$
372.1	4	$(15/2^+) \rightarrow (11/2^+)$
407.0	6	$(17/2^-) \rightarrow (15/2^+)$
430.4	2	
445.1	4	$(13/2^-) \rightarrow (11/2^+)$
497.7	18	$(11/2^+) \rightarrow 9/2^+$
526.7	4	$(15/2^+) \rightarrow (13/2^+)$
586.5	7	$(17/2^-) \rightarrow (17/2^+)$
636.0	50	$(13/2^+) \rightarrow 9/2^+$
641.3	3	$(15/2^+) \rightarrow (11/2^+)$
666.2	4	$(17/2^-) \rightarrow (15/2^+)$
677.2	12	$(15/2^+) \rightarrow (11/2^+)$
702.2	1	$(17/2^+) \rightarrow (13/2^+)$
737.0	4	$(19/2^-) \rightarrow (17/2^-)$
756.9	28	$(17/2^+) \rightarrow (13^+)$
777.2	8	$(17/2^-) \rightarrow (13/2^-)$
787.4	5	$(19/2^-) \rightarrow (15/2^-)$
796.5	5	$(19/2^+) \rightarrow (15/2^+)$
815.5	3	$(15/2^+) \rightarrow (11/2^+)$
825.5	3	$(19/2^-) \rightarrow (17/2^+)$
837.9	2	$(15/2^+) \rightarrow (11/2^+)$
858.6	7	$(21/2^+) \rightarrow (17/2^+)$
911.0	4	$(23/2^+) \rightarrow (19/2^+)$

The coincidence spectrum obtained by double gating on the 223.8/178.3 keV transitions is shown in the top spectrum of Fig. 5. The 1226.0 keV transition in ^{131}Sb is nearly zero, as it should be if the gate transitions are in ^{114}Ag ($7n$). The

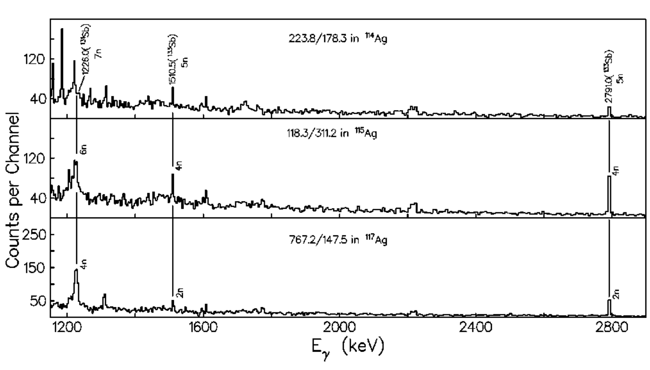

FIG. 5. Coincidence spectra with double gates set on 223.8/178.3 in ^{114}Ag, 118.3/311.2 in ^{115}Ag, and 147.5/767.2 in ^{117}Ag.

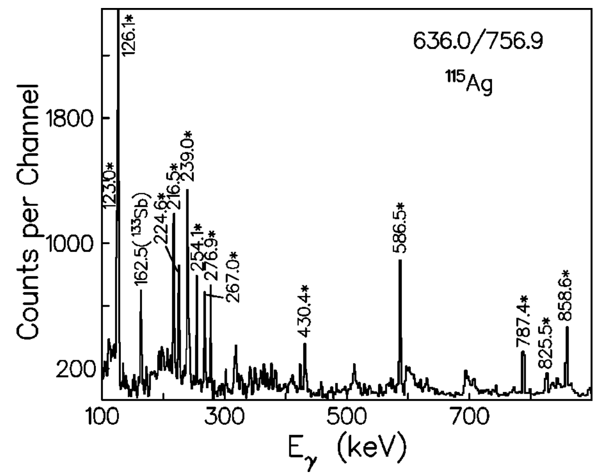

FIG. 6. Coincidence spectrum with double gate set on 636.0/756.9 in ^{115}Ag. An asterisk means γ transitions belonging to ^{115}Ag.

yield ratio would be $R(1226.0,7n/2791.0,5n) \approx 0$. Therefore, the 178.3, 223.8, and 270.1 keV transitions are assigned to ^{114}Ag.

The spins and parities of band *A* built on the $7/2^+$ isomeric state with a half-life of 18.0 s in ^{115}Ag are assigned based on the first two states having known spins and parities of $9/2^+$ and $7/2^+$ [5]. The spins and parities of band *A* in ^{117}Ag built on the $7/2^+$ isomeric state with a half-life of 5.34 s [5] are, also, assigned by its similarity to band *A* in ^{115}Ag. Band *A* is probably from the $7/2^+[413]$ Nilsson state split from the $g_{9/2}$ orbital in the prolate deformed well in $Z=47$.

Band *B* is similar to the $1/2^-[301]$ yrast band in ^{111}Ag [6]. Band *B* may likely be the yrast portion of the ground band $1/2^-[301]$, Coriolis mixed with the $3/2^-[301]$. Perhaps the triaxiality is quenching the orbital angular momentum, so as to produce some doublet bunching, as in band *A*. The interconnecting $E1$ transitions between bands *A* and *B* in both nuclei are a hint that the centers of mass and charge of the nuclear systems in these bands are separating, though we would need lifetime measurements of levels to draw conclusions about any degree of quadrupole-octupole collectivity.

Band *C* is quite similar to the negative parity band built on the 2235.42 keV state in ^{111}In [6]. Band *C* may be an yrast portion of a gamma band ($K=2$) built on band *B*, the extension of the ground band. Its regular spacing and lack of observable crossover transitions are notable features. The γ band designation implies microscopically admixing with the ground band a dominant component of the $5/2^-[303]$ band. In the table of Isotopes [6] for isotope ^{111}Ag this $5/2^-$ assignment is given to an excited band 808.9 keV above the $1/2^-$ ground band but could as well be considered a γ band built on the ground band.

Band *D* was identified only in ^{115}Ag and not in ^{117} Ag. It lies quite low, showing rather regular spacing with cascade and crossover transitions. There are no interconnecting transitions with bands *A*, *B*, and *C*, except for decay out into the $9/2^+$ member of band *A*. We regard both parity and the spins as uncertain. It could be the $5/2^+[422]$ split out from the $g_{9/2}$ proton family, though this band would not be expected to appear so low unless the quadrupole deformation is much smaller for this band, in a case of shape coexistence. As the neutron filling goes past half filling of the $h_{11/2}$ subshell we can expect the quadrupole deformation to begin to decrease.

The remarkable bunching of levels into doublets may be a consequence of a softness for triaxiality, or breaking of cylindrical symmetry of the well. The level schemes of the even-even palladium neighbors show the second 2^+ excited states to be fairly low, an indicator of triaxiality, which could well be accentuated in the odd neighbors by mixing of nearby Nilsson states differing in projection K by two units; such mixing does not require breaking of pairs in odd-A nuclei. The triaxial field, in turn, may be thought of as partially quenching the orbital motion of the odd nucleon, leaving only its intrinsic spin of 1/2 to couple to excited rotational states of an even-even palladium rotor. The doublet bunching may also be derived by second-order band mixing extending to the anomalously spaced $K=1/2$ Nilsson state of the $g_{9/2}$ orbital. The paper of Skalski, Mizutori, and Nazarewicz [5] explores triaxial tendency in this region and gives a good Nilsson level diagram for the $A\approx 100$ region.

In summary, the 34 new transitions with 24 new derived levels in ^{115}Ag are identified based on the 18.0 sec $E3$ isomeric state. The 32 new transitions with 22 new derived levels in ^{117}Ag are identified based on the 5.34 sec $E3$ isomeric state. The band built on the $7/2^+$ state is proposed to be a $\pi 7/2[413]$ rotational band. There is evidence from doublet structure in bands for softness toward triaxiality.

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