PHYSICAL REVIEW C VOLUME 42, NUMBER 6 DECEMBER 1990

Intruder states in odd-mass Ag isotopes

J. Rogowski,(1) J. Alstad,(2) S. Brant,(3) W. R. Daniels,(4) D. De Frenne,(5) K. Heyde,(5) E. Jacobs,(5) N. Kaffrell,(1) V. Paar,(3) G. Skarnemark,(6) and N. Trautmann(1)
(1)*Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Federal Republic of Germany*
(2)*Department of Chemistry, University of Oslo, N-0315 Oslo, Norway*
(3)*Prirodoslovno-matematički fakultet, University of Zagreb, 41000 Zagreb, Yugoslavia*
(4)*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
(5)*Laboratorium voor Kernfysica, Proeftuinstraat 86, B-9000 Gent, Belgium*
(6)*Department of Nuclear Chemistry, Chalmers University of Technology, S-41296 Göteborg, Sweden*
(Received 20 August 1990)

The information on the coexistence of deformed intruder states and normal spherical hole-core coupled states in odd-mass Ag nuclei has been extended to the neutron-rich isotopes $^{113}Ag_{66}$ and $^{115}Ag_{68}$. Data have been obtained from an investigation of the γ rays following the β^- decay of the $^{113,115}Pd$ precursors. A minimum for the excitation energy of the intruder states occurs in $^{113}Ag_{66}$, exactly at neutron midshell. The properties of the intruder states in $^{109,111,113,115}Ag$ are discussed and a description in the framework of the interacting-boson-fermion model is presented.

Intruder states have received much attention in recent years, and have been reviewed in detail.[1] For the odd-mass Ag isotopes, up to neutron number $N=64$, it was shown that the $2d_{5/2}$ and $1g_{7/2}$ shell-model states intrude across the $Z=50$ shell closure giving rise to a rotational-like positive-parity band with $J^\pi=\frac{1}{2}^+,\frac{3}{2}^+,\frac{5}{2}^+,\ldots$ (intruder band) coexisting with spherical hole states coupled to the core (normal states). The phenomenon of shape coexistence was investigated in several sequences of isotopes.[1] It was pointed out that the "fingerprints" of shape coexistence are the following: (I) rotational band-like structure of the levels which are assumed to be intruder states having their origin above the $Z=50$ shell closure, (II) enhanced $E2$ transitions within the intruder band, (III) retarded electromagnetic transitions between members of the intruder band and states related to a spherical shape, and (IV) strong excitation of the intruder states as particle states in stripping reactions and no or weak excitation of these states in pickup reactions.

The intruder states in $^{105-111}Ag$ show a decrease in energy with increasing neutron number.[1] According to the present results their energy reaches a minimum in ^{113}Ag at $N=66$, i.e., exactly in the middle of the $N=50$ and $N=82$ shell closures, while in ^{115}Ag their energy increases again.

First results on levels in $^{113,115}Ag$ were presented in Refs. 2 and 3; they are in general agreement with those of Fogelberg *et al.*,[4] who performed a similar study of the β^- decay of $^{113,115}Pd$. While the complete level schemes of $^{113,115}Ag$ together with the information from a study of the $^{114,116}Cd(d,{}^3He)^{113,115}Ag$ reactions will be published elsewhere,[5] we shall concentrate on the intruder states in this report.

The information on levels in $^{113,115}Ag$ has been obtained from the γ rays following the β^- decay of ^{113}Pd with $T_{1/2}=88(2)$ s and two isomers of ^{115}Pd with half-lives of 25(2) and 50(3) s. The Pd activities were produced in the thermal neutron-induced fission of ^{249}Cf and separated chemically from the fission product mixture with the on-line centrifuge system SISAK 2.[6] The γ-ray singles and $\gamma\gamma(t)$ coincidence measurements were performed with three detectors; a 2-cm^3 Ge x-ray detector (energy resolution of 250 eV FWHM at 5.9 keV), a 68-cm^3 HP Ge detector (1.8 keV FWHM at 1333 keV), and a 120-cm^3 Ge(Li) detector (1.9 keV FWHM at 1333 keV). More details concerning the energy and efficiency calibration of the detectors and the experimental procedure can be found in Refs. 7 and 8. As examples, the γ-ray spectra in coincidence with the 222.2- and 280.0-keV transitions from the decay of ^{113}Pd and in coincidence with the 303.9- and 396.5-keV transitions from the decay of ^{115}Pd are shown in Fig. 1. These transitions depopulate the states being candidates for the $\frac{3}{2}^+$ and $\frac{1}{2}^+$ members of the intruder bands in ^{113}Ag and ^{115}Ag, respectively.

In Fig. 2 partial level schemes for $^{113,115}Ag$ are presented showing only the members of the intruder bands and some lower-lying levels populated by transitions deexciting these members. In order to check the rotational character, the rotational formula for $K=\frac{1}{2}$ bands has been applied to the energy values of the intruder band members. Best agreement with the experimental values has been obtained with the parameter sets of $A=17.23$ keV, $a=-1.92$, and $E_0=228.9$ keV for ^{113}Ag and $A=15.56$ keV, $a=-2.73$, and $E_0=336.4$ keV for ^{115}Ag. The calculated energy values are also given in Fig. 2.

In Table I the energies and electromagnetic properties of the intruder states in odd-mass $^{109-115}Ag$ are compared. Unfortunately, for the lighter isotopes $^{109,111}Ag$ no lifetimes are known except for the $\frac{3}{2}^+$ states and therefore, the occurrence of enhanced intraband $E2$ transitions cannot be tested. For the state at 370 keV in ^{113}Ag, being a candidate for the $\frac{7}{2}^+$ band member, an upper limit for the lifetime of ≤ 0.8 ns has been determined by Fogelberg *et al.*[4] This corresponds to an enhancement factor of

≥ 140 Weisskopf units (W.u.) for the possible 147.8-keV $E2$ intraband transition. For ^{115}Ag the two possible $E2$ transitions have enhancement factors of 121 and 89 W.u. (see Table I). Both values correspond within the uncertainties determined by the γ-branching ratios to a value for the quadrupole moment $Q_0 = 3.3$ b and a deformation parameter $\beta = 0.26$.

Concerning the retardation of electromagnetic transitions between members of the intruder band and states related to a more spherical shape, it has to be taken into account that in this mass region all $E1$ transitions are well known to be strongly hindered, and therefore this cannot be used as a signature for shape coexistence. A better argument comes from the hindrance of $E2$ transitions for which values between 1.3×10^{-2} and 4.7×10^{-2} W.u. have been found in the four Ag isotopes (see Table I).

For ^{109,111}Ag both transfer (pickup and stripping) reactions could be performed with the result of a strong excitation of the intruder states in the stripping reaction,[1] as expected from the "fingerprints" of shape coexistence. For ^{113,115}Ag, due to the lack of stable target material, only the $(d,{}^3\text{He})$ pickup reaction has been accessible with the result that the intruder states are not at all or only weakly excited.[5,7]

In the adjacent odd-mass In nuclei, particle-core coupling calculations have been carried out[13–15] that contain, besides the hole-core (Sn) coupled configurations, also the 2h-1p core [or particle-core (Cd)] coupled configurations. Within this extended model space, both the behavior of the regular $J^\pi = \frac{9}{2}^+, \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ states (mainly single hole in character), the hole-core coupled configurations $|1g_{9/2}^{-1}\otimes \text{Sn}(2_1^+)$; $J^\pi > (J^\pi = \frac{5}{2}^+, \ldots, \frac{13}{2}^+)$, and the low-lying 2h-1p shell-model intruder $J^\pi = \frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+, \frac{9}{2}^+$ states could be quite well described. The occurrence of low-lying intruder excitations has been observed in the $^{107-121}$In nuclei. Nearby the closed shell, in odd-mass $_{51}$Sb nuclei, but also further away from the closed shell in the, e.g., $_{47}$Ag and $_{53}$I nuclei, similar shell-model intruder excitations were observed. They are shown to present a general feature near single-closed shells when the other nucleon type (here the neutrons) has a maximal number of valence nucleons. The observation of a quite regular band structure on top of the $\frac{1}{2}^+$ level could also be interpreted as the observation of a $K^\pi = \frac{1}{2}^+[431]$ rotational-like band, perturbed via the nearby $K^\pi = \frac{3}{2}^+[422]$ band through Coriolis mixing. Here too, a quite consistent picture is obtained with an increasing quadrupole deformed shape [equilibrium deformation ϵ_2(equi.)] in the deformed intrinsic band, reaching a maximal value of $\epsilon_2(\text{equi.}) \approx 0.175$ at $N = 66, 68$

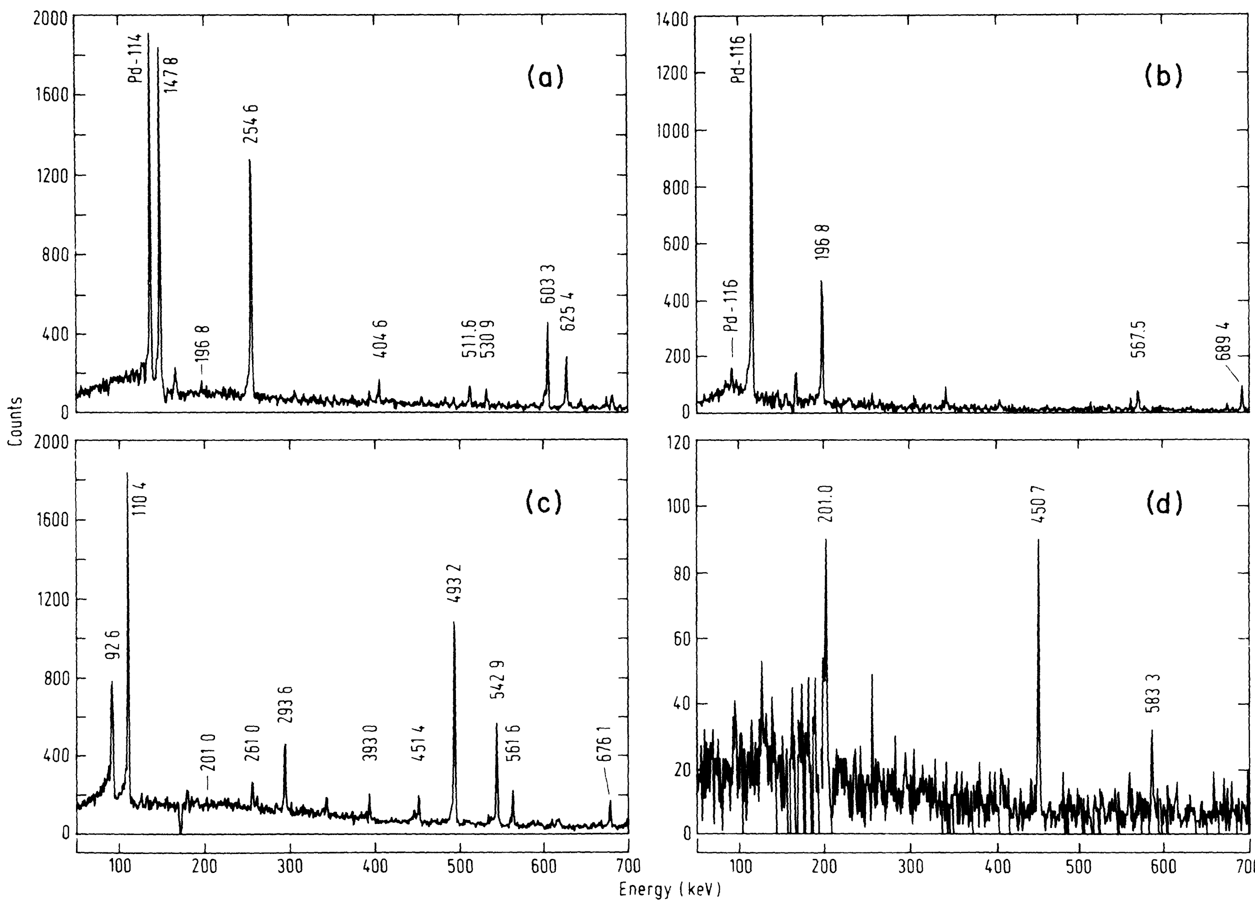

FIG. 1. The γ-ray spectra in coincidence with the 222.2- (a) and 280.0-keV (b) transitions from the decay of ^{113}Pd, and in coincidence with the 303.9- (c) and 396.5-keV (d) transitions from the decay of ^{115}Pd.

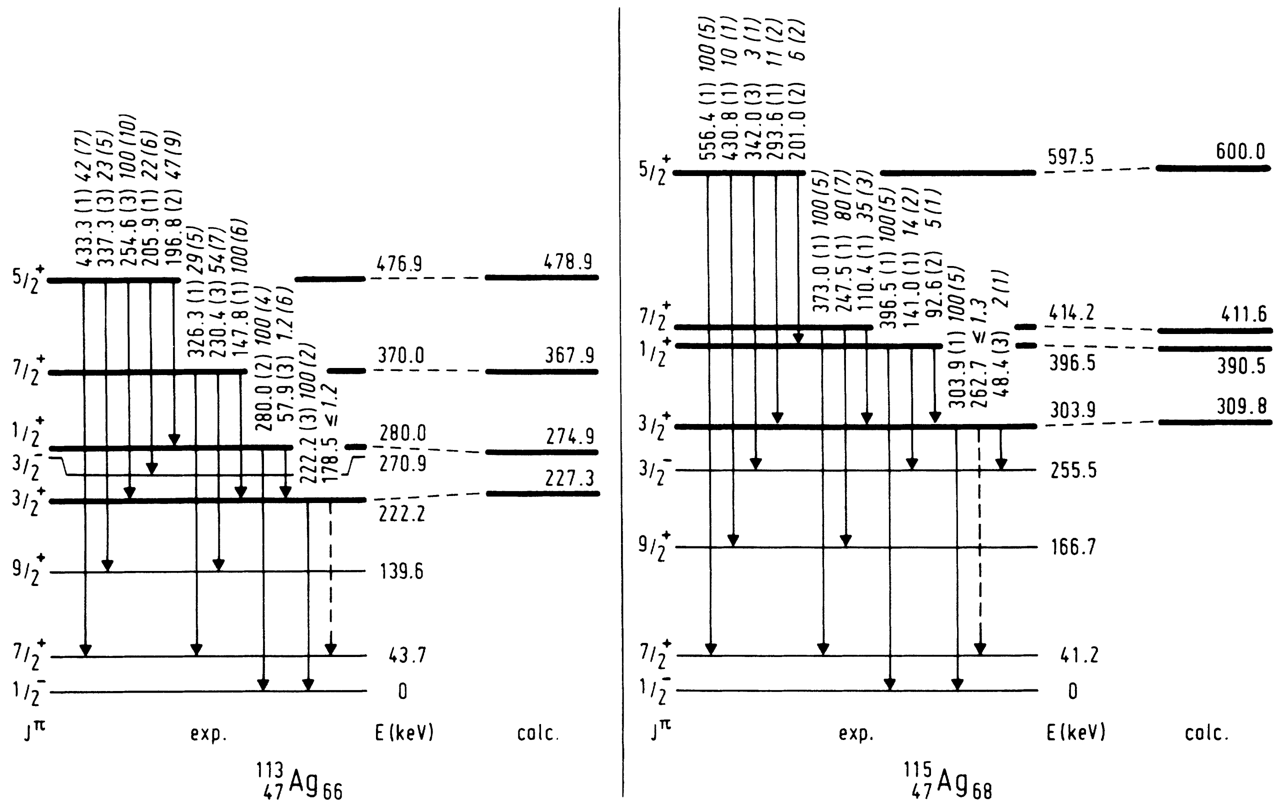

FIG. 2. Partial level schemes of ^{113}Ag and ^{115}Ag. Energies and relative intensities of γ rays are given with their uncertainties in parentheses. The energies of the intruder band members are compared to the values calculated with the rotational formula for $K=\frac{1}{2}$ bands (for details see text).

TABLE I. Comparison of the energies and reduced transition probabilities (RTP) in Weisskopf units for the intruder states in ^{109,111,113,115}Ag.

Nucleus	Initial state E_i (keV)	Initial state J^π	Initial state $T_{1/2}$ (ns)	Final state E_f (keV)	Final state J^π	$T_{1/2}^{\text{partial}}$ (ns)	Transition Multipolarity	RTP
^{109}Ag[a]	724.3	$\frac{3}{2}^+$	3.2(8)	415.2	$\frac{5}{2}^-$	14.2(57)	$E1$	7.1×10^{-7}
				311.3	$\frac{3}{2}^-$	10.6(32)	$E1$	4.0×10^{-7}
				88.0	$\frac{7}{2}^+$	7.0(19)	$E2$	2.5×10^{-2}
				0	$\frac{1}{2}^-$	370(140)	$E1$	2.1×10^{-9}
^{111}Ag[b]	376.7	$\frac{3}{2}^+$	16(1)	289.7	$\frac{3}{2}^-$	513(71)	$E1$	8.7×10^{-7}
				59.9	$\frac{7}{2}^+$	420(51)	$E2$	1.3×10^{-2}
				0	$\frac{1}{2}^-$	17.4(17)	$E1$	3.1×10^{-7}
^{113}Ag	222.2	$\frac{3}{2}^+$	24(1)	43.7	$\frac{7}{2}^+$	≥ 2062	$E2$	$\leq 4.7\times10^{-2}$
				0	$\frac{1}{2}^-$	24.7(12)	$E1$	1.1×10^{-6}
	370.0	$\frac{7}{2}^+$	≤ 0.8[c]	222.2	$\frac{3}{2}^+$	≤ 1.8	$E2$	≥ 140
^{115}Ag	303.9	$\frac{3}{2}^+$	5.2(3)[c]	255.5	$\frac{3}{2}^-$	280(140)	$E1$	9.1×10^{-6}
				41.2	$\frac{7}{2}^+$	≥ 426	$E2$	$\leq 3.2\times10^{-2}$
				0	$\frac{1}{2}^-$	5.5(5)	$E1$	1.8×10^{-6}
	396.5	$\frac{1}{2}^+$	0.8(3)[c]	303.9	$\frac{3}{2}^+$	20.8(89)	$E2$	121
				255.5	$\frac{3}{2}^-$	7.4(30)	$E1$	1.4×10^{-5}
				0	$\frac{1}{2}^-$	1.0(4)	$E1$	4.4×10^{-6}
	414.2	$\frac{7}{2}^+$	1.6(3)[c]	303.9	$\frac{3}{2}^+$	11.6(24)	$E2$	89

[a]References 9 and 10.
[b]References 11 and 12.
[c]Reference 4.

for the odd-mass In nuclei. (More details will be discussed in Ref. 5.)

The above type of particle-core coupling calculations cannot be carried out for the odd-mass Ag nuclei since the full 3h plus 4h-1p core coupling calculations exhaust very large model spaces. Concentrating though on the intruder states, the 4h-1p core coupled states can be studied to a good approximation from coupling of the particle states above $Z=50$ ($1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2}$) to a collective core, using the interacting-boson-fermion model (IBFM).[16-18] Even though the shell-model space is mapped onto a collective boson model space, both the truncated model space and the IBFM Hamiltonian allow a quite accurate description of the shell-model intruder states. In the odd-mass $^{109-115}$Ag nuclei, similarly as in the odd-mass In nuclei, the lowest intruder states ($J^{\pi}=\frac{1}{2}^+, \frac{3}{2}^+$) show a decrease in energy with increasing neutron number exhibiting a minimum at $N=66$, i.e., exactly at the midshell configuration between $N=50$ and $N=82$. In the present IBFM calculations, we use a SU(3) parametrization of the underlying core with collective inertia as discussed in Refs. 19 and 20 and the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, and $3s_{1/2}$ one quasiparticle excitations with occupation probabilities $v^2(1g_{7/2})=0.05$, $v^2(2d_{5/2}) = v^2(2d_{3/2}) = v^2(3s_{1/2}) = 0.01$, and relative energies $\epsilon(2d_{5/2})-\epsilon(1g_{7/2})=0.4$ MeV, $\epsilon(3s_{1/2})-\epsilon(1g_{7/2})=0.7$ MeV, and $\epsilon(2d_{3/2})-\epsilon(1g_{7/2})=1.3$ MeV. The boson-fermion interaction[16] adjusted to ^{109}Ag results in the values $\Gamma_0=0.25$ MeV, $\Lambda_0=0$ MeV, $A_0=-0.08$ MeV, and $\chi=-\sqrt{7}/2$, respectively. The calculated spectra for $^{109-115}$Ag are shown in Fig. 3. Here, the change in the energy spectra occurs through a slight change in the monopole strength A_0 (see Ref. 5 for more details). In particular, the changing band structure from a $(\frac{1}{2}^+,\frac{3}{2}^+),(\frac{5}{2}^+,\frac{7}{2}^+),\ldots$ staggering into a situation with large negative decoupling coefficient $a \approx -2$ and a $(\frac{3}{2}^+)$, $(\frac{1}{2}^+,\frac{7}{2}^+)$, $(\frac{5}{2}^+,\ldots)$ pattern is well reproduced. This situation is almost identical with the changing band structure in going from ^{113}In towards ^{119}In. The interpretation in the odd-mass In nuclei was given through the changing relative position of the $1g_{7/2}$ and $2d_{5/2}$ orbitals with the

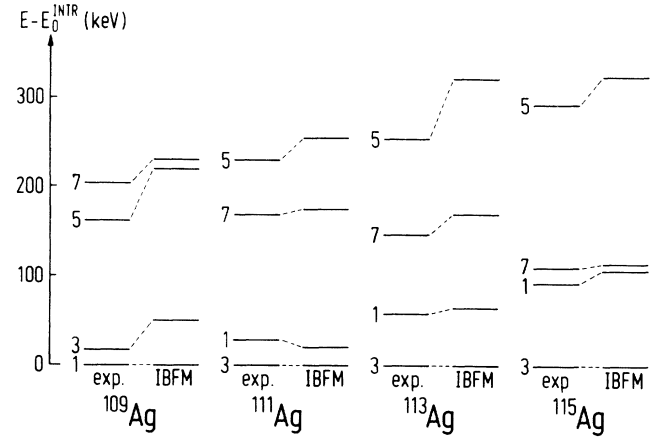

FIG. 3. Intruder positive-parity states of ^{109,111,113,115}Ag in comparison to IBFM calculations. The indicated spin values are twice the actual values.

$1g_{7/2}$ becoming the lowest-lying orbital in ^{115}In. In the IBFM calculation, on the other hand, the variation in monopole strength implies an effective modification of the average field that the bosons constitute for the single-particle motion and quite closely simulate this changing single-particle ordering. Calculations for the lighter nuclei ^{105,107}Ag as well as for the regular 3h (or 1h-Cd core coupled) configurations will be discussed in more detail in Ref. 5.

The authors would like to thank the U.S. Transplutonium Research Committee for making the ^{249}Cf available. This work was supported by the Bundesministerium für Forschung und Technologie (Federal Republic of Germany) under Contract No. 06 MZ 552, the Research Council for Science and Humanities (Norway), the Department of Energy, the National Fund for Scientific Research–Interuniversity Institute for Nuclear Sciences (Belgium), and the Natural Science Research Council (Sweden). One of the authors (K.H.) is grateful for a research grant NATO RG-86/0452.

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