Coexisting intruder bands in ^{83}Se and evidence for the role of proton subshell closure in inhibiting formation of odd-neutron intruder bands

R. A. Meyer, O. G. Lien, III, and E. A. Henry
Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550
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Low-lying one-particle, two-hole (1p-2h) intruder bands which coexist with hole states are established in ^{83}Se ($N=49$) and are shown to exhibit properties similar to those of known intruder bands in odd-proton In ($Z=49$) nuclei. Systematics of $N=49$ nuclei show that ^{83}Se ($Z=34$) has the lowest-lying 1p-2h intruder state rather than midshell ^{89}Zr ($Z=40$) as would be expected by comparing with the In isotopes. We discuss the well established occurrence of intruder bands in odd-proton nuclei in contrast to the paucity of such bands in odd-neutron nuclei, and suggest that the $Z=40$ and 64 subshell closures inhibit the core collectivity necessary for the lowering of particle states and formation of intruder bands in odd-neutron nuclei.

RADIOACTIVITY ^{83}As decay measured $E_\gamma, I_\gamma, t_{1/2}$, ^{83}Se deduced levels, J^π. Ge(Li) detectors.

NUCLEAR STRUCTURE Coexistence in odd-neutron nuclei.

A common feature of odd-proton nuclei that lack a few protons to complete shell closure is the occurrence of low-energy particle intruder states as well as the conjugate low-energy hole intruder states in nuclei with a few protons beyond shell closure. For example, in the $Z=82$ region Wood[1] and Zganjar[2] have studied the systematics of coexisting intruder $h_{9/2}$ states and their associated bands in $Z=81$ and 79 (Tl and Au) nuclei. The properties of the conjugate systems with $Z=83$ and 85 (Bi and At) can be found in the recent review of systematics by Schmorak.[3] Similarly, in the $Z=50$ region, one-particle two-hole (1p-2h) states have been studied by many diverse techniques. For example, ^{115}In has been studied by β decay, Coulomb excitation, stripping and pick-up reactions, in-beam γ-ray spectroscopy, and low-temperature perturbed angular correlation techniques (see Ref. 4 and references cited therein). Unified model calculations have been performed for the odd-mass In nuclei and can account for all the properties of the intruder bands observed in In nuclei from $A=107$ to 121. In general these properties include[5]: (1) a set of "extra" low-lying (≤ 1 MeV) $J^\pi=\frac{1}{2}^+,\frac{3}{2}^+, \ldots$ levels in the energy region of the $|1g_{9/2}^{-1}2_1^+\rangle$ multiplet; (2) large spectroscopic factors (S_{ij}) for 1p-2h configurations through the $Z=50$ proton closed shell; (3) strongly-enhanced intraband $E2$ transitions in the particle-core coupled system [$B(E2)\sim 100$ Weisskopf units (W.u.)]; (4) highly retarded $E1$ transitions to the hole and hole-core states [$B(E1)\lesssim 10^{-6}$ W.u.); and (5) rather strong $M1$ transitions from levels in the vicinity of the $|g_{9/2}^{-1}2_1^+\rangle$ multiplet energy to the $J^\pi=\frac{9}{2}^+$ ground state. Also, the excitation energy exhibited by the intruder states in a series of isotopes is the lowest where the core neutrons are at midshell (i.e., where the core nucleus has the highest degree of collectivity). Thus, for the In nuclei the lowest intruder bands are predicted and found experimentally at $^{117}_{49}$In$_{68}$.[4,6]

For odd-neutron nuclei other than light nuclei, little evidence has been found to date for low-lying intruder states with associated bands.[7] A possible explanation may lie in the properties of the underlying even-even core. That is, a proton intruder particle can interact with the core collectivity generated by the complete underlying neutron shell. In contrast, a neutron intruder particle interacts with an underlying core where proton subshell closures block a high degree of collectivity. In odd-proton nuclei near the $Z=50$ shell closure, for example, all the orbitals from $N=50$ to 82 are available to the core, and the lowest-lying intruder states occur at midshell ^{117}In. However, for the $N=49$ nuclei, the $Z=40$ subshell closure effectively blocks all the protons from 28 to 50 from contributing to the core collectivity. Thus, we expect that if proton subshell blocking of core collectivity plays a role in the odd-neutron nuclei, then intruder states and coexisting bands should exist at the lowest energy for mid-subshell $^{83}_{34}$Se$_{49}$ rather than midshell $^{89}_{40}$Zr$_{49}$. An additional difference between the $N=49$ and $Z=49$ nuclear systems is that we expect low-lying $d_{5/2}$ and $s_{1/2}$ intruders and associated bands for $N=49$ rather than the $d_{5/2}$ and $g_{7/2}$ intruders and associated bands found in the In nuclei.

In order to study the deexcitation properties of possible intruder levels in ^{83}Se we have isolated short-lived arsenic nuclei from fission products by fast automated chemistry and spectroscopy techniques (FACTS).[8] The LLNL FACTS system and its operation is described in detail elsewhere[9] as are the details of the highly automated arsenic chemistry.[8] For the ^{83}As studies, spectroscopy included low as well as high gain Ge(Li) singles spectra, time multiscaled singles spectra, and three-parameter $(\gamma\gamma t)$ coincidence spectra. In all, approximately 5000 separate chemical separations and subsequent spectroscopy measurements were required to obtain 25×10^6 coincidence events and simultaneous singles measurements.

In Fig. 1 we present a partial decay scheme for 13.4-s ^{83}As. Included in the figure are the values of $(2J+1)S$ determined for each level by $(\vec{d},p)$ reactions.[10] The 1p-2h nature of the band members are reflected in the large $(2J+1)S$ values. The extent of mixing between the intruder $\frac{5}{2}^+$ level and the $\frac{5}{2}^+$ member of the $|g_{9/2}^{-1}2_1^+\rangle$ multiplet is reflected both in their observation by (d,p) reactions and in their γ-branching ratios. Such a feature is found in the studies of the odd-mass In nuclei such as ^{115}In and can be accounted for only in the framework of the unified model.[4] Another feature of the ^{83}Se intruder states which is also observed in the In nuclei is that the lowest-energy intruder levels have a measurable lifetime. From our three-parameter coincidence data, we estimate that the 582-keV level has a half-life of 3 ns, consistent with a preliminary result cited by Hoff *et al.*,[11] and consistent with that found for ^{115}In band members by Bäcklin *et al.*[12] Also, as in In nuclei, strong intraband transitions occur while out-of-band transitions are weak or not detected. Thus, the intruder band members in ^{83}Se have properties similar to those found in the $Z=49$ In nuclei such as ^{115}In except for the difference resulting from having an $s_{1/2}$ rather than a $g_{7/2}$ orbital available.

In Fig. 2 we show levels of other $N=49$ nuclei that can be associated with the intruder band members we observe in ^{83}Se. The systematics show that the intruder band occurs at the lowest energy at mid-subshell ^{83}Se and increases in energy as pairs of protons are added to the core and ^{89}Zr is approached.[13,14] This trend is expected if the $Z=40$ subshell closure is blocking the full collectivity of the core (i.e., the "effective" mid-subshell nucleus is ^{83}Se). Preliminary results of Hoff *et al.*[11] for the de-

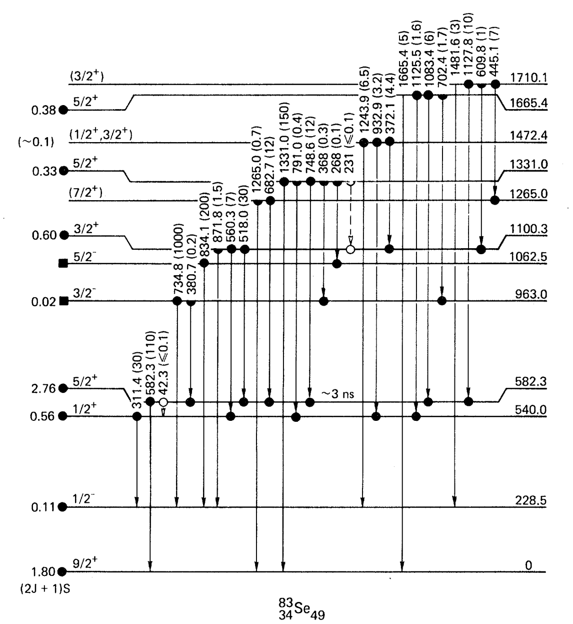

FIG. 1. Partial level scheme of ^{83}Se derived from 13.4-s ^{83}As decay data. We place on the left side of each level the value of $(2J+1)S$ determined by Montestruque *et al.* (Ref. 10). A dot (●) at the left of the level indicates the value of J^π was determined by $(\vec{d},p)$ studies while a square indicates the J^π value resulted from decay data and systematics. A dot at the top of the arrow indicates a gate was set for the transition while a dot at the bottom signifies that the transition was observed in at least one gate (n.b. gates set on transitions from levels with $E>1750$ keV are not shown).

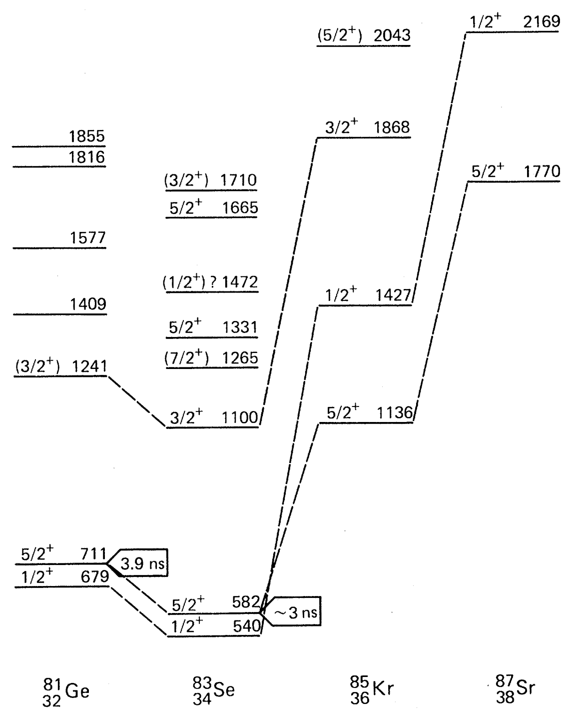

FIG. 2. Systematics of intruder levels in $N=49$ nuclei. These data are taken from Refs. 9–11, 13, and 14. All nuclei but ^{81}Ge have both supporting reaction spectroscopy and γ-ray level decay data. Levels of ^{81}Ge are selected from those observed in the decay of 1.23-s ^{81}Ga [Hoff *et al.* (Ref. 11)] which have γ-ray deexcitation properties similar to those in ^{83}Se.

cay of ^{81}Ga to levels of $^{81}_{32}$Ge$_{49}$ show a $\frac{1}{2}^+$ level at 679 keV and a $\frac{5}{2}^+$ level at 711 keV that has a 3.9-ns half-life, similar to the 540- and 582-keV levels in ^{83}Se. Here, as a pair of protons are taken away from the ^{83}Se nucleus, the energy of the intruder levels increase. Although no transfer data are available to definitely establish the intruder levels in ^{81}Ge, the band members can be identified by comparison to ^{83}Se. This comparison shows that the intruder band members in ^{81}Ge and ^{83}Se agree remarkably well in energy. If we normalize to the lowest-energy intruder level in each nucleus, the average energy difference between comparable levels in the two nuclei is 10 keV. Also, the branching ratio out of the 1241-keV level in ^{81}Ge is similar to that of the $\frac{3}{2}^+$ 1100-keV level in ^{83}Se as are those from ^{85}Kr.[13]

If conjugate 2p-1h intruder bands occur for $N=51$ nuclei similar to those obtained in $Z=51$ Sb nuclei,[15] one of the most likely nuclei to possess such bands should be $^{95}_{44}$Ru$_{51}$. The core for this nucleus is the mid-subshell nucleus $^{94}_{44}$Ru$_{50}$. The $1g_{9/2}$ hole strength in ^{95}Ru has been observed in transfer reaction studies.[16] However, other than the $(\alpha, 2n\gamma)$ work of Lederer *et al.*,[17] no in-beam γ-ray experiments capable of observing 2p-1h band members have been reported. Hole states built on the $p_{3/2}$ have not been reported in ^{95}Ru; however, some evidence does exist for low-lying $p_{3/2}$ hole strength in other related odd-neutron nuclei.[18]

Recent evidence of a $Z=64$ subshell closure[19] could explain why no intruder bands have been found for the odd-neutron nuclei near $N=82$. Transfer reaction studies of the $N=83$ odd-mass nuclei[20] have found large fractions of the $3s_{1/2}$, $2d_{3/2}$, and $h_{11/2}$ cross shell hole-state strength. However, the strength is fragmented and at approximately 1600 keV. Also, no bands built on these hole states have been found in decay or in-beam γ-ray spectroscopy studies. For the conjugate $N=81$ nuclei no neutron stripping studies have been performed and decay scheme studies exhibit scant evidence for intruder states or bands built on them.[21] A lack of intruder states and associated bands at low energies could be expected if the $Z=64$ subshell closure is effective in blocking the full degree of collectivity necessary to allow lowering of the intruder states and development of their associated bands. An indication that this may be the case can be gained by noting that for the $N=84$ even-even nuclei, no minimum occurs for the first excited collective state (2_1^+). Rather 2_1^+ level energies exhibit a steady rise as $Z=64$ is approached.[22]

Using data from β-decay and reaction experiments, we have been able to establish for the first time 1p-2h intruder states and associated bands in an $N=49$ nucleus which coexist with the expected hole states and hole-core coupled states. We have used systematics to suggest that for odd-neutron nuclei, the existence of proton subshell closure in the underlying core blocks the collectivity necessary for formation of low-lying intruder bands. This is indicated by the occurrence of the lowest-lying intruder band for mid-subshell ^{83}Se rather than midshell ^{89}Zr. We extend this idea to suggest that the recently discovered $Z=64$ subshell closure plays an important role in inhibiting the occurrence of low-energy intruder 1p-2h or 2p-1h states and associated bands in the odd-neutron nuclei around $N=82$ and $Z<64$.[19]

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