Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

STRUCTURE OF NEUTRON-RICH ODD-MASS ^{127,129,131}In POPULATED IN THE DECAY OF ^{127,129,131}Cd*

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(Received October 27, 2008)

New level structures are proposed for neutron-rich ^{127,129,131}In populated in the decay of ^{127,129,131}Cd. No evidence for the presence of 1-particle-2-hole intruder structures in the neutron-rich In isotopes is observed.

PACS numbers: 21.10.–k, 21.10.Pc, 21.10.Tg, 21.60.Cs

Two unexpected systematic features of the structure of even–even neutron-rich Cd and Fe nuclei were identified in the first experiments at ISOLDE in which laser ionization of Ag and Mn, respectively, was used to achieve high selectivity for radioactive decay studies. Kautzsch, Walters and Kratz reported new level structures for ^{126,128}Cd$_{78,80}$ in which the 2^+ and 4^+ energies for ^{128}Cd$_{80}$ were lower than those in ^{126}Cd$_{78}$ which is in sharp contrast with isotonic ^{130,132}Te$_{78,80}$, and also with isotopic ^{100,102}Cd [1]. The 46 ms half-life of the r-process nucleus ^{129}Ag$_{82}$ was also reported in this paper, along with the selective ionization of ^{122}Ag isomers achieved by hyperfine tuning of the laser ion source. At about the same time measurements were

* Presented by W.B. Walters at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

taken and reported by Hannawald *et al.*, showing new level structures in $^{64,66}Fe_{38,40}$ in which the 2^+ level in ^{66}Fe was found at a surprisingly low energy of 574 keV, relative to the 746 keV 2^+ energy of ^{64}Fe, and, also with respect to the 2^+ energies in isotonic $^{66,68}Ni$ [2]. Half-lives for $^{67,68,69}Mn$ were also reported in this paper.

Recent studies of the level structure of neutron-rich ^{64}Fe by Hoteling *et al.* [3], $^{64,66}Fe$ by Lunardi *et al.* [4], and $^{66,68}Fe$ by Adrich *et al.* [5], revealed detailed level structure information for neutron-rich Fe nuclei near the $N = 40$ subshell closure. Subsequently, Pauwels *et al.*, identified a 1-particle-2-hole $1/2^-$ intruder in ^{67}Co [6]. The large cross section for the two-proton knockout reaction from ^{68}Ni to produce ^{66}Fe suggests that the structure of ^{66}Fe is similar to that of ^{68}Ni. Whereas, the much reduced cross section for 2-proton knockout from ^{66}Fe to levels in ^{64}Cr indicates a significant change in structure. Thus, the drop in the 2^+ levels in $^{66,68}Fe$ can now be interpreted as being driven by admixtures of intruder configurations. Combined with the existing data for neutron-rich Cr isotopes [7], the conclusion can be drawn that the ground state of ^{64}Cr is much more deformed than either ^{68}Ni or ^{66}Fe.

Hence, the question can be raised as to whether some form of "intruder" configuration might be responsible for the "^{128}Cd problem", namely, the low 2^+ energy in ^{128}Cd relative to that of ^{126}Cd. Subsequent to the ISOLDE β-decay measurements, additional studies of the low-energy structure of the neutron-rich Cd isotopes have been reported. Stoyer *et al.* [8], have studied the structures of $^{122,124}Cd$, Tomlin, Mantica, and Walters have studied the structures of $^{125,126,127}Cd$ [9], Hoteling *et al.*, have studied the structures of $^{126,128}Cd$ [10], Caceres *et al.*, have reported data for levels in ^{128}Cd and Jungclaus *et al.*, have reported new levels for ^{130}Cd [11, 12]. None of these nuclei have exhibited intruder structures comparable to the well-known intruder levels in the mid-shell $^{114,116}Cd$ nuclei described by Juutinen *et al.* [13], for which proton 1-particle-2-hole intruder structures have been identified in the adjacent $^{115,117}In$ isotopes [14]. Coulomb excitation data for Cd isotopes up through $^{126}Cd_{78}$ show decreased $B(E2)$ values with increasing neutron numbers as N approaches the shell closure at $N = 82$ [15].

In this paper, new results are reported for the level structures of $^{127,129,131}In_{78,80,82}$ observed in the β decay of $^{127,129,131}Cd$, respectively. The parent Cd nuclei were selectively ionized using the ISOLDE Resonance Ionization Laser Ion Source (RILIS) as described by Dillmann *et al.* and Erdmann *et al.* [16, 17]. The aim of this paper is to provide data that can be compared to various calculations for nuclei in this mass region, and to explore the possibility that intruder structures might exist in these nuclei that would represent configuration admixtures from across the $N = 82$ and $Z = 50$ closed shells.

Levels in ^{123,125,127}In populated in the decay of ^{123,125,127}Cd were identified by Hoff *et al.*, and provide the data for establishing the systematic behavior of the neutron-rich In nuclei [18]. Additional data for ^{123,125}Cd decay to levels of ^{123,125}In were provided by Huck *et al.* [19]. High-spin isomers in ^{123,125,127,128,129,130}In have been observed by Scherillo *et al.* [20].

The γ rays observed in the decay of expected $h_{11/2}$ and $d_{3/2}$ ^{127}Cd isomers are consistent with the gamma rays proposed by Hoff *et al.* The energies of the $1/2^-$ and $21/2^-$ beta-decaying isomers in ^{127}In have been determined by Gausemel *et al.*, to be 420(65) keV and 1863(58) keV, respectively [21]. It is possible to propose a more precise value for the position of the $1/2^-$ level by noting that Hoff *et al.*, observed gamma rays at 1744.7(2) and 1755.4(4) keV to be in coincidence with the 523 keV $3/2^-$ to $1/2^-$ transition. They also observed two additional gamma rays that showed no coincidences at 2677.4(3) and 2688.6(10) keV. As the former γ rays decay to the $3/2^-$ level, it is possible to place the latter γ rays as decaying to the ground state and obtain an energy of 408 keV for the $1/2^-$ isomer and 933 keV for the $3/2^-$ level.

A weak peak is observed at 270.2(4) keV, shown in Fig. 1, that could be placed as the transition from the $5/2^+$ level at 1202.3 keV to the $3/2^-$ level at 933 keV that provides additional support for the 408 keV position of the $1/2^-$ isomer in ^{127}In.

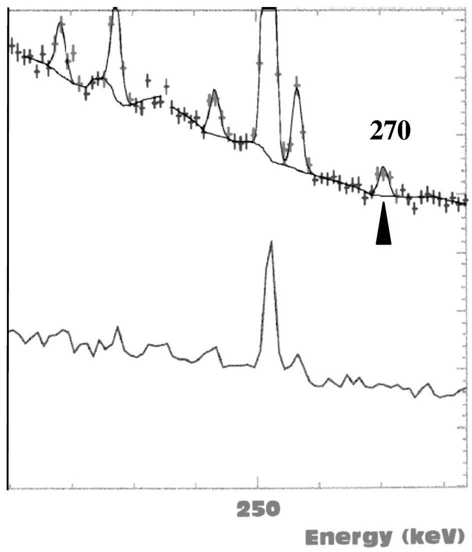

Fig. 1. Portion of the spectrum of γ rays following the decay of ^{127}Cd to levels of ^{127}In. The upper spectrum was taken with the lasers on and the lower spectrum was taken with the lasers off.

No γ rays for the decay of the 104(6) and 242(8) ms isomers of ^{129}Cd isomers to levels of ^{129}In have been previously reported [22]. However, Gausemel *et al.*, placed the positions of the $1/2^-$ and $23/2^-$ β decaying isomers at 369(46) keV, and 1630(56) keV, respectively, from Q_β measurements, and Scherillo *et al.*, reported a $17/2^-$ 8.5 μs isomer at 1633 keV that cascades to the ground state through the proposed $13/2^+$ and $11/2^+$ levels at 1395 and 995 keV, respectively [19]. Earlier, Fogelberg *et al.*, identified a $29/2^+$ isomer whose decay populated the $23/2^-$ β-decaying isomer [23].

The energies and relative intensities for the γ rays that were observed in this study for the decay of ^{129}Cd isomers to levels in ^{129}In are shown in Table I. These γ rays are assigned by comparing spectra taken with the lasers on with spectra taken with the lasers off. Portions of those spectra are shown in Figs. 2 and 3, and a partial decay scheme is shown in Fig. 4. Only limited coincidence data are available, and have been used to place the γ rays at 542, 1760, and 1796 keV. The strong γ rays at 632, 1423, and 1586 keV were placed as the $3/2^-$ to $1/2^-$, $5/2^+$ to $9/2^+$, and $9/2^+_2$ to $9/2^+$ transitions, respectively. No coincidence data were obtained for the other transitions. Only the γ rays at 400 and 440 keV could be placed as the $5/2^+$ to $3/2^-$ transition and keep the $1/2^-$ isomer within a 1σ range indicated by the beta decay data. As no basis exists for choosing which transition is correct, if either, we have shown the position of the $1/2^-$ isomer and the $3/2^-$ excited level as bars with a width of 40 keV. Both values for the position of the $1/2^-$ isomer are well within the uncertainty of the Q_β measurement.

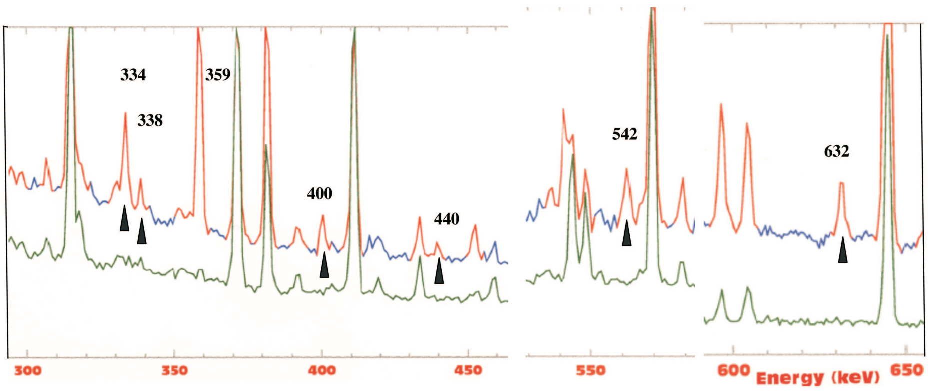

Fig. 2. Portions of the spectrum of gamma rays following the decay of ^{129}Cd to levels of ^{129}In. The upper spectrum was taken with the lasers on and the lower spectrum was taken with the lasers off.

TABLE I

Energies (in keV) and relative intensities for the γ rays in ^{129}Cd decay to levels of ^{129}In. Uncertainties in the energy values are $\approx$ 0.5 keV. Uncertainties in the intensity values are $\approx$ 10% for the stronger peaks and $\approx$ 20% for the weaker peaks.

Energy	Intensity	from	to	Energy	Intensity	from	to
333.5	13.0	1687	1354	1585.7	12.0	1586	0
338.2	6.0			1689.9	6.0		
358.8	50.0	1354	995	1755.3	4.0		
400.5	7.0	1423	(1023)	1760.9	19.0	3184	1423
439.7	4.0	1423	(983)	1763.3	5.0		
537.2	2.0			1770.9	3.0		
541.8	11.0	1525	(983)	1796.1	32.0	3150.2	1354
561.7	8.0			2087.9	5.5		
589.1	5.2			2155.1	9.0	3150.1	995
618.3	4.3			2216.7	8.0		
631.9	30.0	(983)	(351)	2330.9	5.0		
731.1	8.5	2419	1687	2460.2	6.0		
839.8	6.0			2628.5	4.0		
858.1	3.3			2838.4	2.0		
863.1	5.5			2879.9	2.5		
995.0	100.0	995	0	2918.5	1.0		
1020.3	8.5			2999.0	2.0		
1065.2	8.0	2419	1354	3184.1	3.0	3184	0
1103.4	5.0			3348.0	4.0		
1234.1	5.0			3388.9	2.0		
1354.1	21.0	1354	0	3487.8	1.0	4471	(983)
1422.6	20.0	1423	0	3701.9	6.0		
1462.2	11.0	3150	1687	3888.2	2.0		
1499.4	7.0			3914.7	3.0		
1554.8	5.0			3967.5	4.0		
1557.9	5.0			4119.9	2.0	4471	(351)
1561.5	5.0						

Portions of the γ-ray spectrum observed in the decay of 68 ms ^{131}Cd to levels of ^{131}In are shown in Figs. 5 and 6 and the possible single-proton hole levels included in Fig. 7. The position of the $1/2^-$ isomer is taken from Q_β measurements reported by Fogelberg *et al.* [24]. Owing to the short half-life and low relative yield, the statistics are poor. These data were taken using a special UC_x target / RILIS system with a temperature-controlled quartz transfer line in between which served as thermochromatography column to chemically suppress the high In and Cs isobaric contaminations of ^{131}Cd [25].

The absence of the main decay peak for ^{131}In at 2434 keV in the spectrum taken with the lasers turned off is an indication of the success of this technology. That same peak's presence in the spectrum taken with the lasers-turned on is an indication that ^{131}Cd was, indeed, successfully ionized.

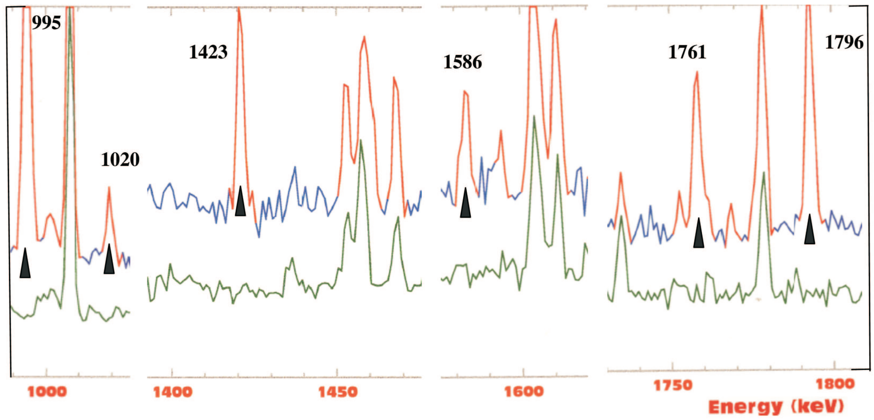

Fig. 3. Portions of the spectrum of γ rays following the decay of ^{129}Cd to levels of ^{129}In. The upper spectrum was taken with the lasers on and the lower spectrum was taken with the lasers off.

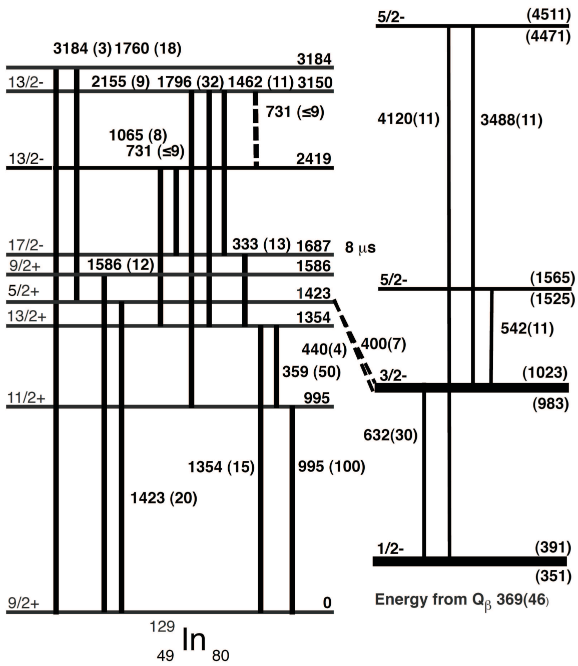

Fig. 4. Proposed partial level scheme for ^{129}In populated in the decay of ^{129}Cd isomers. The energies are in keV. The energy for the $1/2^-$ level is taken from the Q_β measurements reported by Gausemel *et al.* [20].

Seven rays can be assigned to the decay of ^{131}Cd, with energies at 844, 988, 2428, 3556, 3866, 4403, and 6039 keV. As can be seen, any of the three lower-energy gamma rays could be attributed to statistical fluctuations in the data. The lines at 988 and 2428 are the most "durable" in all of the analyses and are placed as the transition between the $p_{3/2}$ and $p_{1/2}$, and $f_{5/2}$ and $p_{1/2}$ single proton hole levels, respectively. We cannot, however, rule out the possibility that the 844 keV transition is the $f_{5/2}$ to $p_{3/2}$ single proton transition, with the 2428 keV transition joining the other high-energy lines in decaying from levels arising from coupling to the 4 MeV ^{132}Sn core to the $g_{9/2}$ ground state, $p_{1/2}$ isomer or other levels. The positions of the rays at 3556, 3866, 4403, and 6039 keV likely represent decay from levels with configurations involving a broken ^{132}Sn core.

Fogelberg *et al.*, identified a proposed $21/2^+$ β-decaying isomer in ^{131}In at 3764 (88) keV [24] and Gorska *et al.*, have recently reported the presence of a proposed γ-decaying $17/2^+$ isomeric level at 3782(2) keV with a half-life of 630(60) ns [26]. If the ray observed in this study at 3556 keV populates the 1^- level at 332 keV, then it would originate from a level at 3888 keV, quite close to the previously reported isomers.

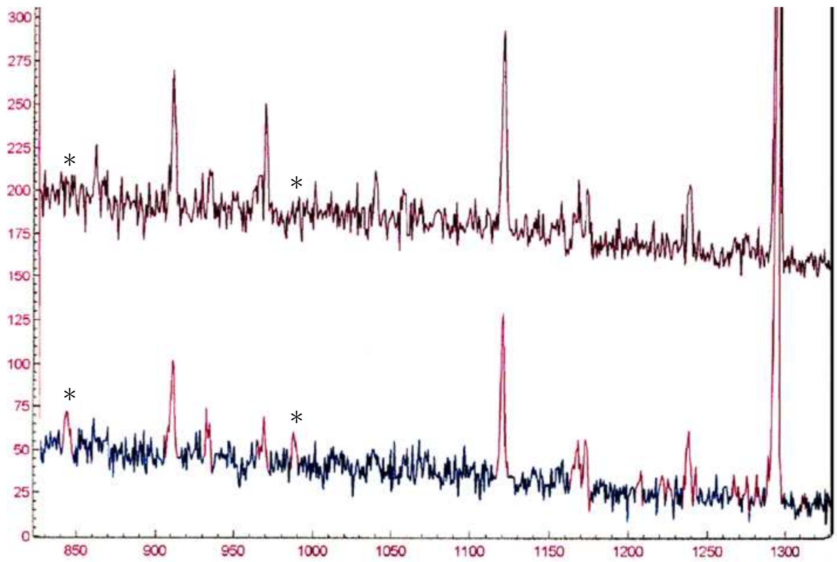

Fig. 5. Portion of the spectrum of γ rays near 1 MeV following the decay of ^{131}Cd to levels of ^{131}In. The upper spectrum was taken with the lasers turned off and the lower spectrum was taken with the lasers turned on. The asterisks ($*$) are shown over the rays at 844 and 988 keV that appear to disappear when the lasers are turned off.

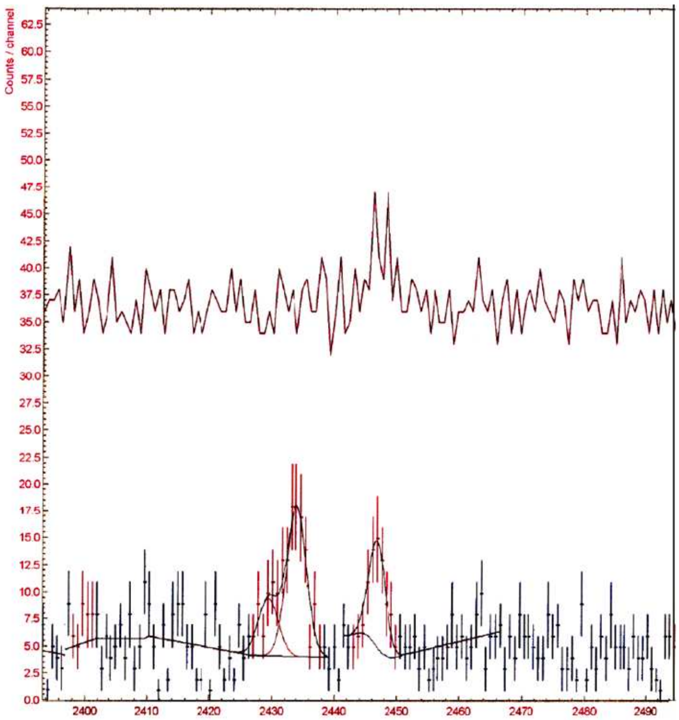

Fig. 6. Portion of the spectrum of γ rays near 2.4 MeV following the decay of ^{131}Cd to levels of ^{131}In. The upper spectrum was taken with the lasers turned off and the lower spectrum was taken with the lasers turned on. The right side of the doublet seen in the lower spectrum taken with the lasers on lies at 2434 keV and is well known from the decay of the $9/2^+$ ground state of ^{131}In to levels in ^{131}Sn [24]. The less intense left hand side is the proposed 2428 keV transition arising from decay of ^{131}Cd, as neither peak appears in the upper spectrum taken with the lasers turned off, and no peak at that energy was observed by Fogelberg *et al.*, in their study of the decay of ^{131}In.

The levels of ^{57}Cu (inverted) are also included in Fig. 7 for comparison with the proposed levels for ^{131}In. The spin-orbit splitting between the $3/2^-$ and $1/2^-$ levels can be seen to have changed by only $\approx$ 125 keV, in spite of the large increase in the size of the nucleus. Likewise, the separation between the higher-L $9/2^+$ and $5/2^-$ levels is also changed only of the order of $\approx$ 300 keV. The large change is the relative tighter binding of the two high-L orbitals relative to the $L = 1$ orbitals.

It can also be seen that the calculated levels for ^{129}In are in reasonable agreement with the observed levels, including the high-spin isomers. The calculated levels are quite consistent with the observed isomers. The calculated position of the $25/2^+$ level is seen to be well above the calculated

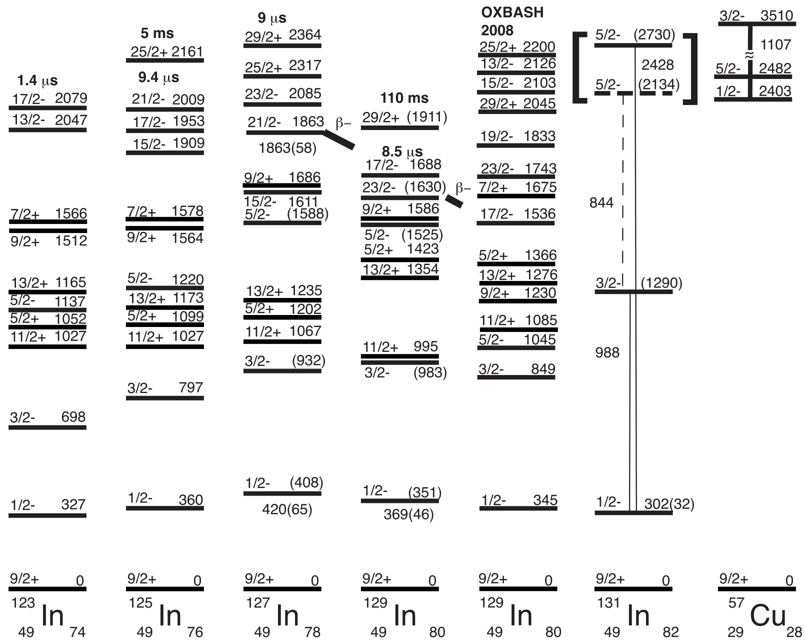

Fig. 7. Levels in the odd-mass In isotopes along with calculated levels for ^{129}In. The energies are in keV. The energies for the $1/2^-$ levels in ^{127,129}In shown below the levels are taken from the Q_β measurements reported by Gausemel *et al.* [20].

position of the $29/2^+$ isomer, the calculated position of the $19/2^-$ level is seen to be well above the calculated position of the $17/2^-$ beta-decaying isomer, and the calculated positions of the $13/2^-$ and $15/2^-$ levels are well above the calculated position of the $17/2^-$ isomer. However, the large drops of $\approx$ 400 keV in the positions of the $29/2^+$ and $23/2^-$ levels are somewhat surprising. It can also be noted that the calculated positions of the $11/2^+$ and $13/2^+$ levels for ^{129}In are closer to the observed positions of those two levels in ^{127}In than in ^{129}In. Indeed, it is not clear what curious feature of nuclear structure is revealed by the sudden widening of this splitting from 168 keV in ^{127}In to 359 keV ^{129}In. Taken together, it can be noted that reducing the neutron valence space from four neutrons to two neutrons seems to have a strong effect on the positions of the proton-hole core-coupled levels. Stated another way, as the neutron valence space shrinks from 8 holes in ^{123}In to 4 holes in ^{127}In, the movements of the levels appear to be quite systematic and predictable, whereas sudden rather large shifts appear with the reduction of the neutron valence space to only 2 neutron holes. Neither in ^{129}In itself, nor in the systematic movements of the levels is there a suggestion that the onset of intruder configurations could be taking place.

The authors wish to express their appreciation to the ISOLDE Collaboration, the US DOE, the US NSF, Deutsche Froschungsgemeinschaft (DFG) KR 806/13-1, the Helmholtz Gemeinschaft under grant VH-VI-o61, and the Alexander von Humboldt Foundation for support of this work.

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