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ODD-PARITY ^{100}Sn CORE EXCITATIONS*

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Odd-parity core excited states have been identified in two close neighbors of ^{100}Sn : ^{96}Pd and ^{97}Ag . This was done in an fusion-evaporation experiment, using a ^{58}Ni beam on a ^{45}Sc target. Even-parity core excited states in these nuclei are very well reproduced in large scale (LSSM) calculations in which particle-hole excitations are allowed with up to five $g_{9/2}$ protons and neutrons across the $N = Z = 50$ gap, to the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ orbitals. The odd-parity states can only be qualitatively interpreted though, employing calculations in the full fp_g shell model space, but with just one particle-hole core excitation allowed. A more complete model including odd-parity orbitals is need for the description of core excited states in the region of ^{100}Sn .

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1. Introduction

Nuclei situated in the nuclidic chart close to the heaviest self-conjugate doubly-magic nucleus ^{100}Sn are in focus of many experimental and theoretical studies since decades. They give opportunities to evaluate phenomena which cannot be observed in other regions, like enhanced interactions of protons and neutrons situated in identical shell model orbits. In spite of many experimental and theoretical efforts, a number of issues in the region remains unresolved — see Ref. [1] for a recent review.

Low excitation energy structure of nuclei located immediately below ^{100}Sn is well described in the shell model space consisting of a rigid core at $N = Z = 50$, valence proton or neutron holes located in the $g_{9/2}$, $p_{1/2}$ orbitals, and, for $N > 50$, neutron particles in the $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, $d_{3/2}$ orbitals. This model space should be amended by odd-parity orbitals from below $Z = 38$ in order to reproduce decay properties of the observed spin-gap isomers in ^{94}Pd [2] and ^{96}Ag [3]. In addition, excitations of the $N = Z = 50$ core have been extensively studied in several close lying neighbors of ^{100}Sn with $Z < 50$: ^{101}In [4], ^{102}In [5, 6], ^{98}Cd [7, 8], ^{99}Cd [4], ^{96}Ag [3] and ^{97}Ag [9]. Only even parity core excited states have so far been observed in these nuclei and they are, in general, successfully interpreted in the shell model space consisting of only even parity orbitals, with proton (and neutron) valence holes located in the $g_{9/2}$ orbital and particle-hole excitations across the $N = Z = 50$ gap to the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$ orbitals. In the present paper, we discuss odd-parity $N = Z = 50$ core-excited states identified in two $N = 50$ nuclei below ^{100}Sn : $^{96}_{46}\text{Pd}_{50}$ and $^{97}_{47}\text{Ag}_{50}$. The experimental results for the former nucleus have recently been published [10] and thus related evidence is only briefly summarized here, while the latter case is discussed in more detail.

2. Experiment and data evaluation

Excited states in ^{96}Pd and ^{97}Ag were studied in an experiment which was performed at the Institute de Recherches Subatomiques in Strasbourg, France. A DC beam of ^{58}Ni ions with an energy of 205 MeV and an average intensity of 10 pA was used to bombard a ^{45}Sc target, leading to the compound nucleus (CN) ^{103}In . The ^{96}Pd and ^{97}Ag nuclei were populated in rare events in which 2 neutrons, 1 α particle, 1 proton ($2n1\alpha1p$) and 2 neutrons, 1 α -particle ($2n1\alpha$), were evaporated from the CN, respectively. The EUROBALL γ -ray spectrometer [11, 12] was used in a configuration consisting of 26 Clover [13], 15 Cluster [14] high-purity germanium γ -ray detectors, the Neutron Wall with 50 liquid scintillator neutron detectors [15, 16], and the plastic scintillator charged particle veto detector CUP [17].

In the off-line analysis γ -ray transitions in ^{96}Pd and ^{97}Ag were analyzed in 2 and 3 dimensional γ -coincidence matrices, created with the condition that two neutrons ($2n$) were detected in the Neutron Wall detectors. For this purpose, events with two detected neutrons were distinguished from events in which one neutron interacted in more than one detector by setting gates on the time difference between two interactions and the distance between the involved detectors [16]. In addition, a $\gamma\gamma$ -coincidence matrix gated by the same $2n$ condition and vetoed by the CUP signal was created and used to evaluate transitions in ^{97}Ag . Note that the CUP detector was designed to select events with no charged particles emitted, but it turned out to be also very efficient in enhancing the $2n\alpha$ reaction channel, with respect to channels in which multiple protons were emitted. The efficiency to detect one proton and one α -particle in the CUP detector was estimated at 80% and 63%, respectively.

For the determination of multiplicities of transitions, ratios R of intensities measured at two different groups of angles with respect to the beam axis were determined. This was done in spectra gated by a coincident γ ray observed at any direction, in order to obtain sufficiently clean peaks. The R values could be used to distinguish between stretched quadrupole and dipole transitions, for which the expected values are $R \simeq 1.0$ and $R \simeq 0.5$, respectively. Tentative spin assignments were made for most of the observed states, assuming that maximum spin states are preferably populated in a heavy-ion induced reaction, and that prompt transitions of higher multiplicities than 2 were not observed. See Ref. [10] for a more detailed description of the experimental and data analysis procedures.

3. Results

The scheme of excited states in ^{96}Pd nucleus was extended up to an excitation energy of 9707 keV and a tentative spin and parity 19^+ . A rich sequence of yrast and yrare states above the highest possible valence spin 12^+ was established. Among these states, a negative parity isomeric state was identified at the excitation energy of 8384 keV. This state has a spin in the range from 15 to 17, and a half-life of 37.7(11) ns.

Figure 1 shows prompt $\gamma\gamma$ -coincidence spectra gated on known transitions of ^{97}Ag . The spectra were created with the condition that at least two neutrons were detected in the Neutron Wall and no charged particle was registered in the CUP detector. The established level scheme of ^{97}Ag is shown in Fig. 2, and the information about the observed γ -ray transitions is summarized in Table I.

Our results confirm the placement and spin assignment of most of the levels reported in the earlier work on ^{97}Ag [9]. We add to the level scheme three new low energy transitions 61, 74 and 112 keV, linking the 6480 and

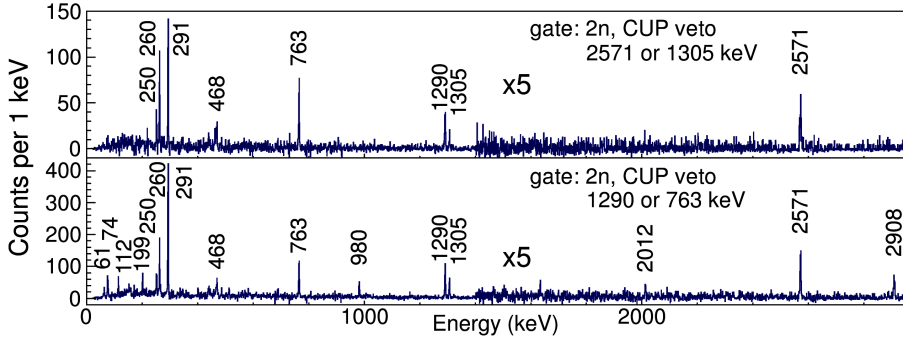


Fig. 1. Prompt $\gamma\gamma$ -coincidence spectra obtained in the $^{58}\text{Ni} + ^{45}\text{Sc}$ reaction, with the condition that 2 neutrons are detected in neutron detectors and no charged particle is registered in the CUP detector. The spectra are gated on the γ -ray lines marked in the plots. Bin contents for energies above 1400 keV are magnified by a factor of 5.

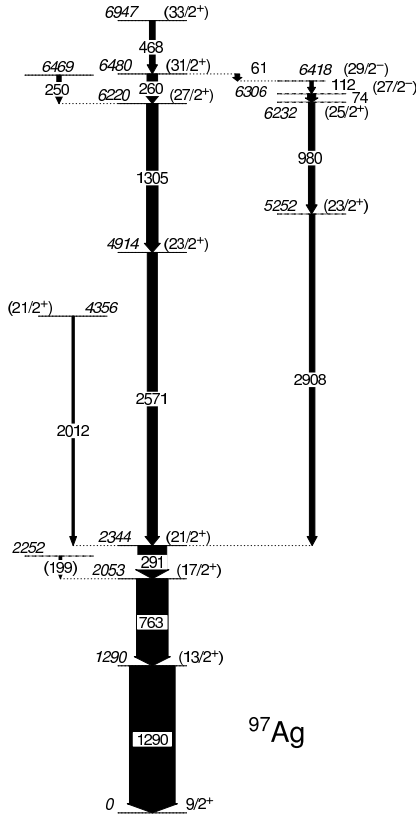


Fig. 2. Level scheme of ^{97}Ag established in this work.

TABLE I

Gamma-ray transitions assigned to ^{97}Ag . The following quantities are listed: γ -ray energy (E_γ), relative γ -ray intensity (I_γ), excitation energy of the initial state (E_i), angular distribution ratio (R) and the spin and parity assignments of the initial (J_i^π) and the final (J_f^π) state. The R values were obtained from spectra gated on the 763, 1290 and 1305 keV transitions.

E_γ [keV]	I_γ	E_i [keV]	R	J_i^π	\rightarrow	J_f^π
61.3(4)	6(2)	6480		(31/2 ⁺)	\rightarrow	(29/2 ⁻)
73.8(3)	13(4)	6306	0.56(15)	(27/2 ⁻)	\rightarrow	(25/2 ⁺)
112.4(3)	6(2)	6418	0.50(14)	(29/2 ⁻)	\rightarrow	(27/2 ⁻)
199.3(4)	6(1)	2252	0.93(29)			
249.8(3)	9(1)	6469	0.62(15)		\rightarrow	(27/2 ⁺)
260.3(3)	22(2)	6480	1.10(12)	(31/2 ⁺)	\rightarrow	(27/2 ⁺)
291.1(3)	61(3)	2344	1.00(9)	(21/2 ⁺)	\rightarrow	(17/2 ⁺)
467.6(3)	12(1)	6947	0.52(11)	(33/2 ⁺)	\rightarrow	(31/2 ⁺)
763.1(3)	69(8)	2053	1.00(13)	(17/2 ⁺)	\rightarrow	(13/2 ⁺)
980.2(3)	14(2)	6232	0.78(17)	(25/2 ⁺)	\rightarrow	(23/2 ⁺)
1289.7(3)	100(10)	1290	0.91(12)	(13/2 ⁺)	\rightarrow	(9/2 ⁺)
1305.4(3)	25(2)	6220	1.04(18)	(27/2 ⁺)	\rightarrow	(23/2 ⁺)
2011.9(7)	5(1)	4356		(21/2 ⁺)	\rightarrow	(21/2 ⁺)
2570.6(3)	22(3)	4914	0.49(12)	(23/2 ⁺)	\rightarrow	(21/2 ⁺)
2907.5(4)	12(2)	5252	0.32(12)	(23/2 ⁺)	\rightarrow	(21/2 ⁺)

6232 keV levels. The values of the angular distribution ratio R of the 74 and 112 keV transitions suggest their dipole character, while the R value for the 61 keV transition could not be determined. Additional constraints on the character of these low-energy transitions are provided by the intensity balance for the involved levels, including internal conversion. The total relative intensities of the three transitions are listed in Table II. These should be compared to the intensity of the 980 keV transition, which depopulates the 6232 keV level. The intensity balance excludes the $E2$ character for the 61 and 74 keV transitions. Most likely they are both $E1$ transition, as this assignment brings their intensities closer to the intensity of the 112 keV transition, which is the weakest one of the three.

A half-life of the 6480 keV level was established to be 3.7(1) ns in the work of Ref. [9]. One of the new low-energy transitions discussed above is now a second primary transition of the isomer, competing with the 260 keV $E2$ transition. The new primary transition carries 37% of the isomer depopulation intensity, assuming that the entire intensity of the new decay branch is represented by the intensity of the 980 keV transition. We thus calculate reduced transition strengths for the three possible low energy primary transitions and for different assumptions on their character — see Table II.

TABLE II

Total relative transition intensities, including internal conversion, and reduced strengths of the new primary transition, assuming $E2$, $M1$ and $E1$ characters of the three newly observed low energy γ -ray transitions. The intensity units are the same as in Table I. The transition strengths were calculated assuming that each of the transitions is the primary one, and the isomer branching ratio was determined from the intensities of the 260 and 980 keV transitions.

E_γ [keV]	Relative intensity			Transition strength [W.u.]		
	$M1$	$E2$	$E1$	$M1$	$E2$	$E1$
61.3	17(6)	58(21)	10(3)	3.6×10^{-3}	270	8.6×10^{-5}
73.8	25(8)	67(22)	18(6)	2.8×10^{-3}	190	5.9×10^{-5}
112.4	7(3)	11(4)	6(2)	1.2×10^{-3}	64	2.1×10^{-5}

An $E2$ assignment for the new primary transition can be excluded. The strength of the 260 keV $E2$ transition is 3.0 W.u. and a competition of two such $E2$ transitions is not possible. A strong $M1$ hindrance on the level of 10^{-3} W.u. is unlikely. In turn, an $E1$ strength of 10^{-5} W.u. is much more likely — compare for example ^{96}Pd , where the high spin isomer decays by a primary $E1$ transition of 2.7×10^{-8} W.u. [10].

We conclude that all the three low-energy transitions are dipoles and that the primary transition depopulating the 6480 keV isomer, either 61 or 74 keV, should be a parity changing $E1$. The other of the two transitions is probably also an $E1$, linking the sequence back to even parity levels. The 112 keV is probably an $M1$ and we place it between the 61 and 74 keV transitions, with the more intense $E1$ located at the bottom of this low-energy cascade. However, the intensities of these transitions are determined with large error bars, and, in fact, the 112 keV transition appears too weak, so other orderings and parity assignments are possible, including the possibility that the parity change back to positive may happen only in the lower lying high-energy transitions. A different order of the entire cascade of the five transitions, including 980 keV and 2908 keV cannot be excluded, either, thus the levels at 5252 and 6232 keV are considered tentative. In any case, the $E1$ character of the new primary transition is supported both by the transition intensity and strength arguments, so at least one of the states involved should have odd-parity.

In addition, we observe a new 250 keV transition feeding the 6220 keV level, and a tentative 199 keV transition feeding the 2053 keV level. We support the placement of the 4356 keV level deexcited by the 2012 keV transition. The transitions 559 keV, 907 keV and 399 keV, placed in the work of Ref. [9] above the 4356 keV level, could not be identified in our data. We note, however, that intensity balance of the 6220 keV level indeed indicates existence of an unobserved decay path of this level.

4. Discussion and shell model calculations

In order to interpret states in ^{96}Pd and ^{97}Ag , four different shell model calculations were performed and the results are presented in Figs. 3 and 4. Calculations marked GF were performed in the standard $(p_{1/2}, g_{9/2})$ proton (π) space, assuming a $^{88}_{38}\text{Sr}_{50}$ core, with the empirical interactions of Ref. [18]. For the FPG calculations, this model space was extended by adding the $\pi(f_{5/2}, p_{3/2})$ orbitals with realistic interactions derived from the CD-Bonn nucleon–nucleon potential [2, 3]. In turn, the large scale LSSM calculations, performed with a $^{80}_{40}\text{Zr}_{40}$ core, allow for up to 5 particle–hole excitations of $g_{9/2}$ protons and neutrons across the $N = Z = 50$ gap to the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ orbitals. The LSSM space does not include any odd-parity orbitals, though. Calculations marked as FPGNDG were done by implementing the FPG model space by single $g_{9/2}$ neutron particle–hole core excitations to the $d_{5/2}, g_{7/2}$ orbitals. See Ref. [10] for more details on the performed calculations.

The valence states of ^{96}Pd and ^{97}Ag are, in general, rather well reproduced even in the most restricted GF calculations. Opening up the entire fpg shell (FPG) improves the agreement, except for the lowest spin states, which are calculated too low, and this is understood as a result of a deficiency in the determination of empirical interactions. All the even parity states, including core-excited states, are well reproduced in the LSSM model, up to the highest states observed in the two nuclei.

The FPGNDG model space is certainly too much truncated for the core excitations. The FPGND calculations overestimate even parity core-excited states in ^{96}Pd on average by about 560 keV. In ^{97}Ag the average discrepancy is slightly larger: about 720 keV, for the $23/2^+$ to $33/2^+$ states of the main yrast cascade. The FPGNDG calculations were also run for ^{94}Ru , and in this nucleus the core-excited states are overestimated by about 270 keV and 580 keV [10], for even and odd-parity, respectively. We notice that the discrepancy tends to be larger in ^{96}Pd than in ^{94}Ru and also larger for the odd-parity than for the even-parity. In ^{96}Pd the 15^- state is calculated 1108 keV higher than the observed odd-parity isomer. In ^{97}Ag close lying odd-parity states, $27/2^-$ and $29/2^-$, are calculated at the excitation energy of about 7400 keV, *i.e.* about 1 MeV above the corresponding experimental states, and in calculations they are located very close to the yrast $31/2^+$ and $33/2^+$ states. We conclude that the odd-parity core-excited states in the FPGNDG model are, in general, calculated about 1 MeV too high. Apart from this main shift, the relative positions of the odd-parity states with respect to even-parity states are rather consistently reproduced in calculations for both ^{96}Pd and ^{97}Ag .

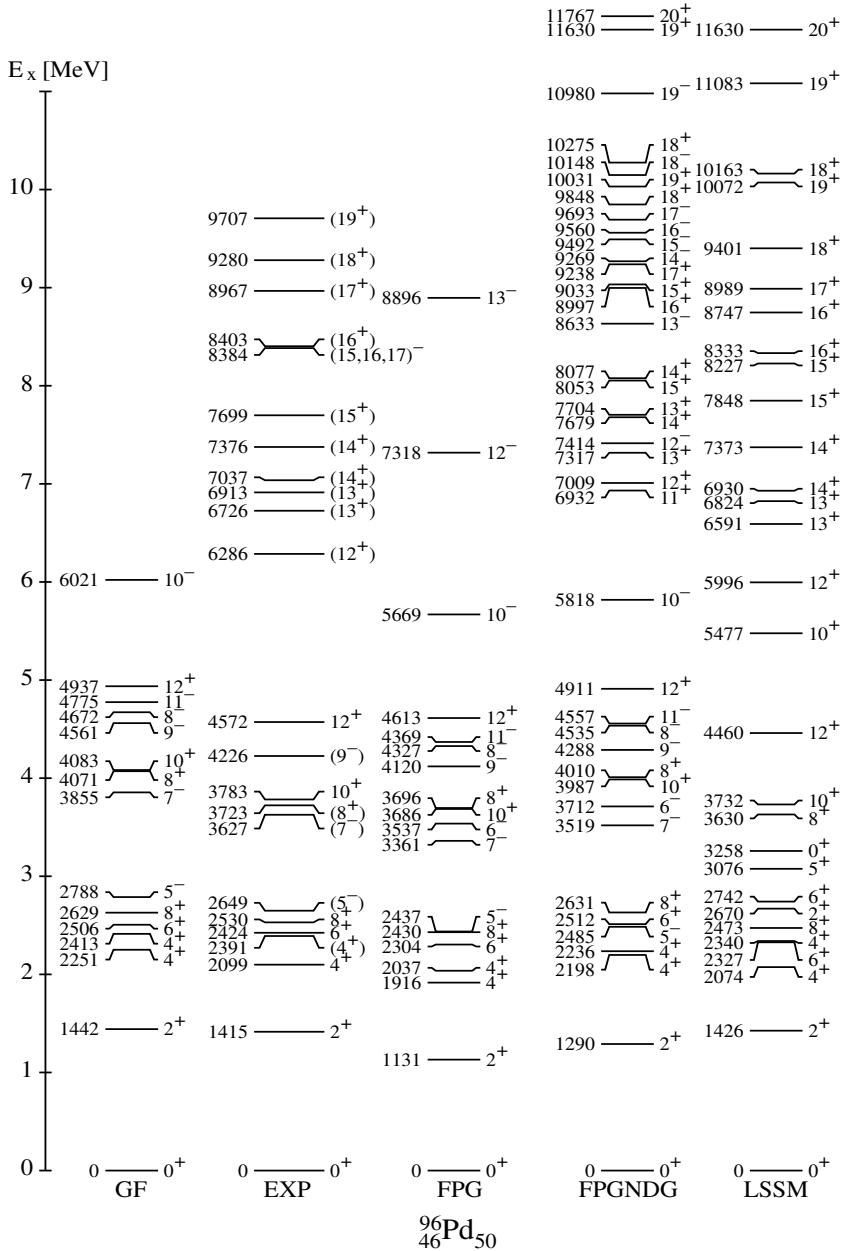


Fig. 3. Experimental and shell model states for ^{96}Pd . See the text and Ref. [10] for the description of the shell model calculations.

Inspection of the wave functions leads to the observation that the dominating components of the core-excited states in the LSSM calculations include one $g_{9/2}$ neutron excitations across the $N = 50$ gap to the $d_{5/2}$ and $g_{7/2}$ orbitals. In the FPGNDG calculations, the odd-parity states 15^- , 16^- , 17^- in ^{96}Pd as well as $27/2^-$, $29/2^-$ in ^{97}Ag , are also dominated by the $g_{9/2}$ neutron particle-hole excitation — in these cases to the $d_{5/2}$ orbital — coupled to odd-parity valence configurations.

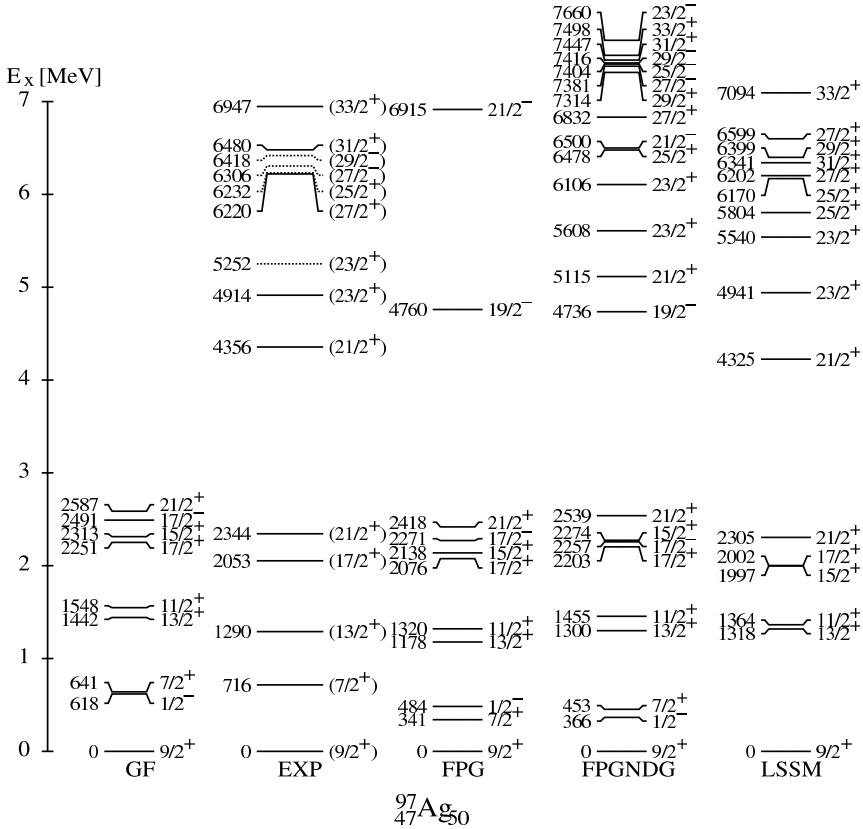


Fig. 4. Experimental and shell model states for ^{97}Ag . See the text and Ref. [10] for the description of the shell model calculations. The experimental $(7/2^+)$ state at 716 keV was reported in the work of Ref. [19].

5. Summary and conclusions

Odd-parity $N = Z = 50$ core-excited states were observed in the ^{96}Pd and ^{97}Ag nuclei. Shell model calculations in the full fpg shell with just one particle-hole excitation across the magic $N = 50$ gap provide a qualitative description of these states. A more complete and consistent model is, how-

ever, needed to quantitatively describe the odd-parity states, with larger model space, improved interactions, which are consistent for odd- and even-parity orbitals, and particle-hole excitations allowed. In addition, further experimental work is required to make firm spin and parity assignments of states in ^{96}Pd and ^{97}Ag . The role of odd-parity orbitals in the core excitations in other close neighbors of ^{100}Sn remains an open question.

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