Investigation of the i_{13/2} neutron orbital in the ^{132}Sn region: New excited levels in ^{135}Sb

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The $i_{13/2}$ neutron orbital in the ^{132}Sn region – new excited levels in ^{135}Sb

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Excited states in ^{135}Sb, populated in spontaneous fission of ^{248}Cm have been studied by means of prompt γ spectroscopy, using the EUROGAM2 detector array. New excited states containing the neutron $i_{13/2}$ orbital in their wave functions have been proposed. More accurate value of the $i_{13/2}$ neutron single-particle energy in the ^{132}Sn core potential has been determined.

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The experimental knowledge of single-particle (s.p.) energies is crucial for studying nucleon-nucleon residual interactions and associated phenomena, like the role of tensor forces and the monopole shifts in the evolution of s.p. energies when departing from a doubly-magic core. Around the ^{132}Sn core one encounters a rare opportunity to study such an evolution for the high-l neutron orbital, $i_{13/2}$ as discussed in Ref. [1]. The situation here is particularly interesting, because the $\nu i_{13/2}$ orbital is expected to lie just above the neutron separation energy. While in the $N = 83$ isotones, ^{135}Te and ^{137}Xe, the $i_{13/2}$ neutron is bound [2, 3] in ^{133}Sn it is most likely unbound [4]. An interesting question is how high above the neutron separation energy the $13/2^+$ level built on the $\nu i_{13/2}$ is located in ^{133}Sn, and whether it will be possible to observe it experimentally. The answer depends on the precise determination of the $\nu i_{13/2}$ s.p. energy in ^{133}Sn. The energy $\epsilon_{i_{13/2}} = 2694(200)$ keV reported in [4], the only value available to date, has rather large uncertainty, which should be decreased. It is also important to find further excitations, close to the ^{132}Sn core, containing the $\nu i_{13/2}$ orbital. After observing the evolution of the $\nu i_{13/2}$ energy with increasing proton number [1] it is now of interest to study this effect as a function of the increasing neutron number, e.g. in the Sb isotopes.

In this work we report on new excited levels in ^{135}Sb and discuss their connection to the $\nu i_{13/2}$ excitation. In the second part of the work we use new experimental knowledge gained in recent years to improve the $\nu i_{13/2}$ s.p. energy both, its value and precision. The new value is then used to estimate the position of the first $13/2^+$ level in ^{133}Sn, which should help its experimental identification.

Excited states in ^{135}Sb were populated in spontaneous fission of ^{248}Cm. The measurement of high-fold coincidences of prompt γ rays following fission was performed with the EUROGAM2 array (see Ref. [5] for detailed description of the experiment and data analysis). Since our previous study of ^{135}Sb [6] we have improved the analysis technique [7], which has allowed for the observation of additional excited states in ^{135}Sb above spin I^π=23/2$^+$ reported in Ref. [6].

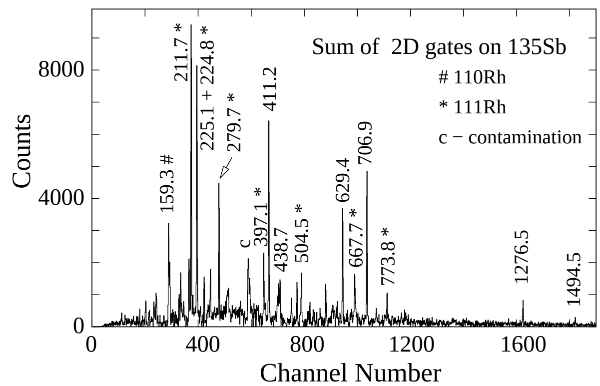

FIG. 1. A summed γ ray spectrum doubly gated on all pairs of 225.1, 411.2 and 706.9 keV γ lines in ^{135}Sb. Lines in the spectrum are labeled in keV.

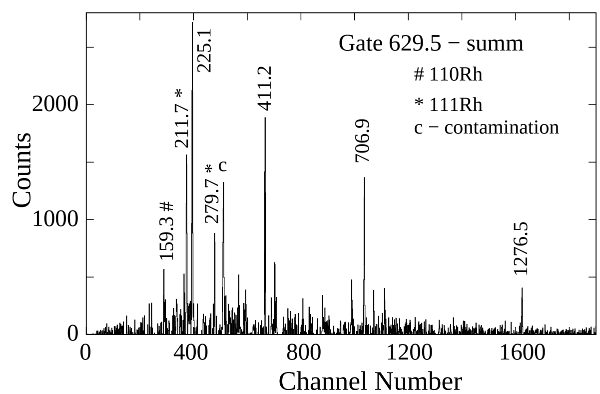

FIG. 2. A summed, doubly gated γ ray spectrum with the first gate set on the 629.5 keV line the second gate on the 225.1, 411.2 and 706.9 keV lines of ^{135}Sb. Lines in the spectrum are labeled in keV.

In Fig. 1 we display a sum of γ ray spectra doubly gated on pairs of 225.1, 411.2 and 706.9 keV lines in ^{135}Sb [6]. Three new lines are identified at energies of 438.7, 1276.5 and 1494.5 keV. Fig. 2 shows a sum of doubly gated γ ray spectra with the first gate set on the 629.4 keV line and the second gate on the 225.1, 411.2 and 706.9 keV lines of

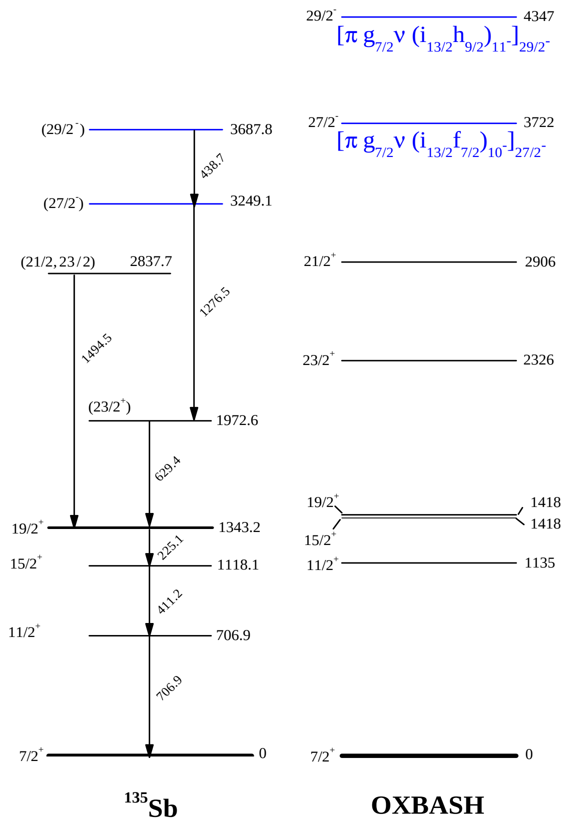

FIG. 3. (Color online) Partial level scheme of ^{135}Sb as obtained in the present work in comparison with the shell model predictions. See text for details.

^{135}Sb. In the spectrum the 438.7 and 1276.5 keV lines are present but the 1494.5 keV is not seen. This suggests that the 1494.5 keV transition feeds the 1343.2 keV level and the 1276.5 438.7 keV cascade populates the 1972.6 keV level. The 438.7 keV transition, which has lower intensity than the 1276.5 keV transition should be placed higher in the cascade. Based on the present coincidence data we propose three new excited states in ^{135}Sb at 2837.7, 3249.1 and 3687.8 keV, as shown in Fig. 3. In Tab. I properties of the γ lines of ^{135}Sb, observed in the present work are listed.

To propose spins of excited levels in ^{135}Sb we analysed angular correlations between transitions in ^{135}Sb seen in this work. The results are listed in Tab. I. The A_2^{exp} and A_4^{exp} values should be compared against theoretical values of $A_2^{th} = 0.102$, $A_4^{th} = 0.009$ for the quadrupole-quadrupole cascade and $A_2^{th} = -0.071$, $A_4^{th} = 0.000$ for the quadrupole-dipole cascade. The results are consistent with the stretched quadrupole character of the 225.1, 411.2, 629.4 and 706.9 keV transitions. Their prompt characters indicates that these are E2 rather than M2 transitions and confirm spins and parities $11/2^+$, $15/2^+$, $19/2^+$ and $23/2^+$, for the 706.9, 1118.1, 1343.2 and 1972.6 keV levels in ^{135}Sb suggested earlier [6].

TABLE I. Properties of γ transitions in ^{135}Sb, populated in spontaneous fission of ^{248}Cm, as observed in the present work. Intensities of γ lines are in relative units.

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)	Ang. Correlations A_2^{exp}, A_4^{exp}	Initial level E_{exc}(keV)	I^π
225.1(1)	31(3)	0.074(16), -0.018(28)	1343.2	$(19/2^+)$
438.7(3)	3(1)		3687.8	$(29/2^-)$
411.2(1)	57(4)	0.090(23), -0.009(37)	1118.1	$(15/2^+)$
629.5(2)	12(2)	0.060(53), -0.139(89)	1972.9	$(23/2^+)$
706.9(1)	100(5)	0.090(23), -0.009(37)	706.9	$(11/2^+)$
1276.5(2)	5(1)		3249.1	$(27/2^-)$
1494.5(3)	1.5(5)		2837.7	

The yrast excitations in ^{135}Sb should correspond to maximum-aligned, proton-neutron configurations: proton in the $\pi g_{7/2}$ or $\pi h_{11/2}$ orbitals and two neutrons in the $\nu f_{7/2}$, $\nu h_{9/2}$ or $\nu i_{13/2}$ orbitals. The odd proton in the $\pi g_{7/2}$ orbital coupled to the $[(\nu f_{7/2})^2]_{0^+,2^+,4^+,6^+}$ multiplet of the ^{134}Sn core forms a sequence of $[\pi g_{7/2}(\nu f_{7/2})^2]_{7/2^+,11/2^+,15/2^+,19/2^+}$ levels corresponding to the ground state and the 706.9, 1118.1 and 1343.2 keV excited states [6]. After promoting one neutron to the $\nu h_{9/2}$ orbital, the $[\pi g_{7/2}(\nu f_{7/2} h_{9/2})]_{23/2^+}$ configuration is formed, seen at 1972 keV [6]. The promotion of the odd proton from the $\pi g_{7/2}$ orbital to the $\pi h_{11/2}$ orbital will create the $[\pi h_{11/2}(\nu f_{7/2})^2_{6^+}]_{23/2^-}$ configuration, which may explain the 2837.7 keV level. The last excitation corresponding to a single-nucleon promotion is the $[\pi g_{7/2}(\nu f_{7/2} i_{13/2})]_{27/2^-}$ configuration, which could explain the 3249.1 keV level in ^{135}Sb.

Higher-lying excitations in ^{135}Sb are obtained by promoting two nucleons. The $[\pi h_{11/2}(\nu f_{7/2} h_{9/2})]_{27/2^-}$ configuration is another possibility to explain the 3249.1 keV level in ^{135}Sb, although it is expected at higher excitation than the $[\pi g_{7/2}(\nu f_{7/2} i_{13/2})]_{27/2^-}$ configuration. Finally, the $[\pi g_{7/2}(\nu h_{9/2} i_{13/2})]_{29/2^-}$ configuration could explain the 3687.8 keV level in ^{135}Sb.

To verify these suggestions we have performed shell model calculations using the OXBASH code, with the same interactions as described in Ref. [8]. In Tab. II the s.p. energies used in the calculations are shown. The level scheme of ^{135}Sb, observed in the present work is compared in Fig. 3 to the shell model predictions. The comparison supports the proposed interpretation of the 3249.1 and 3687.8 keV levels as dominated by simple, maximum-aligned configurations containing the $\nu i_{13/2}$ orbital. In the calculations the second $27/2^-$ excitation is predicted at high energy, 4.5 MeV. The observation of new levels in ^{135}Sb containing the $\nu i_{13/2}$ orbital, further confirms the identification of this orbital proposed in Ref. [4].

The $\epsilon_{i_{13/2}} = 2694(200)$ keV s.p. energy in the ^{132}Sn core potential was estimated from the energy of the $(\pi g_{7/2} \nu i_{13/2})_{10^+}$ proton-neutron excitation in ^{134}Sb [4].

TABLE II. Experimental single-particle energies used in the OXBASH calculation.

Experimental single-particle energies					
protons	E(MeV)	Ref.	neutrons	E(MeV)	Ref.
$1g_{7/2}$	-9.653	[9, 10]	$2f_{7/2}$	-2.445	[9]
$2d_{5/2}$	-8.691	[11]	$3p_{3/2}$	-1.591	[13]
$2d_{3/2}$	-7.185	[12]	$1h_{9/2}$	-0.884	[13]
$3s_{1/2}$	(-6.631)*		$3p_{1/2}$	-0.789	[13]
$1h_{11/2}$	-6.833	[11]	$2f_{5/2}$	-0.440	[13]
			$1i_{13/2}$	+0.250	[4]

* tentative experimental value

TABLE III. Energy of the residual interactions, V_0, V_1, V_2, between valence nucleons outside the ^{208}Pb and ^{132}Sn cores. Comparison of the interactions calculated in the ^{132}Sn region (V_2) and interaction from the ^{208}Pb region (V_0) scaled to the ^{132}Sn region (V_1) is done. The difference, $\Delta V = V_2$ - V_1, is shown in the last column. All values are in keV.

^{208}Pb $\to$ ^{132}Sn			^{132}Sn		
configuration	V_0	V_1	configuration	V_2	ΔV
$(\pi h_{9/2}\nu j_{15/2})_{12+}$	-621	-723	$(\pi g_{7/2}\nu i_{13/2})_{10+}$		
$(\pi h_{9/2}\nu g_{9/2})_{9-}$	-396	-461	$(\pi g_{7/2}\nu f_{7/2})_{7-}$	-488	-27
$(\pi h_{9/2}\nu i_{11/2})_{10-}$	-776	-903	$(\pi g_{7/2}\nu h_{9/2})_{8-}$	-976	-73
$(\pi i_{13/2}\nu g_{9/2})_{11+}$	-960	-1117	$(\pi h_{11/2}\nu f_{7/2})_{9+}$	-1154	-37
$(\nu g_{9/2}\nu i_{11/2})_{10+}$	-221	-257	$(\nu f_{7/2}\nu h_{9/2})_{8+}$	-280	-23
$(\pi h_{9/2}\pi f_{7/2})_{8+}$	+107	+125	$(\pi g_{7/2}\pi d_{5/2})_{6+}$	+201	+76

The main contribution to the large uncertainty was the unknown energy of the 7^- isomeric state in ^{134}Sb, which, at that time, had to be estimated using data from the ^{208}Pb region (see further in text). Recently, the energy of this isomer has been measured to be 279(1) keV [14] and it is now possible to determine energies of excited states in ^{134}Sb relative to the ground state without scaling from the ^{208}Pb region.

To determine the $\nu i_{13/2}$ s.p. energy in ^{132}Sn potential the proton-neutron residual interaction within the $(\pi g_{7/2}\nu i_{13/2})_{10^+}$ configuration is required. At present there is no sufficient data in the ^{132}Sn region to calculate this particular interaction. However, one may estimate it basing on the well known correspondence between excitations in the ^{132}Sn region and in the ^{208}Pb region [15], applying the $A^{-1/3}$ scaling to the relevant interaction from the ^{208}Pb region. The result, V_1, of such scaling for the $(\pi g_{7/2}\nu i_{13/2})_{10^+}$ coupling is presented in the first row of Tab. III.

The uncertainty of a scaled interaction energy has been estimated before to be about 100 keV [4]. The new experimental data obtained recently allows now more nucleon-nucleon interactions to be calculated in the ^{132}Sn region (V_2 values in Tab. III). They can be compared with energies scaled from the ^{208}Pb region – V_1 values in Tab. III (column V_0 shows the original values in the ^{208}Pb region). The difference between them, $\Delta V = V_2$ - V_1, shown in the last column of Tab. III, suggests the maximum uncertainty of 70 keV for the scaling procedure. Therefore,

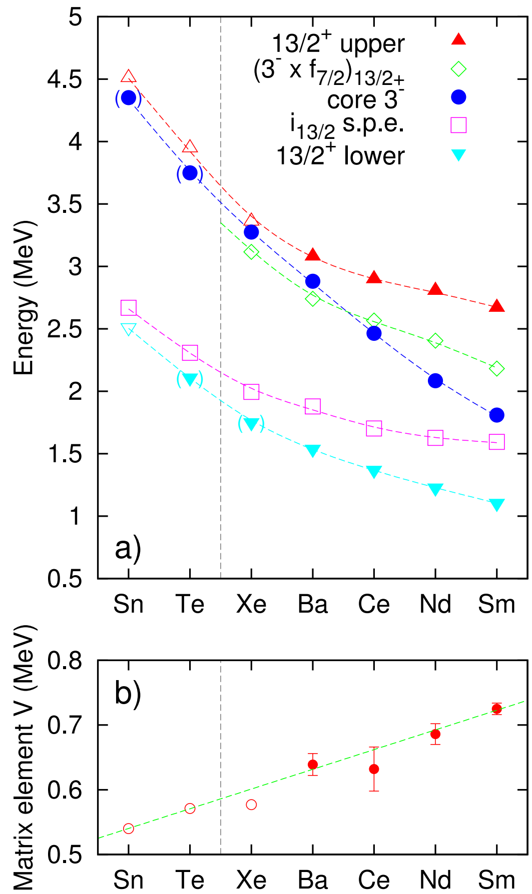

FIG. 4. (Color on-line) a) Systematics of excitation energy of various $13/2^+$ states in Sn-to-Sm, $N = 83$ isotones and 3^- excitations in their respective $N = 82$ cores. Filled symbols denote experimental values and empty symbols denote estimated energies. b) Systematics of the energy of the residual interaction with linear extrapolation. Filled symbols are calculated using experimental data and empty ones are estimated. One can note that the systematics is well described by linear trend. Results obtained in [2, 28] are presented to the right of the dashed line. The data are taken from Refs. [2, 16–28]. See text for more details.

we assume the interaction energy for the $(\pi g_{7/2}\nu i_{13/2})_{10^+}$ coupling to be -723(70) keV. The experimental s.p. energies relevant for this calculations are given below for completeness: 0, 962 and 2792 keV for the $g_{7/2}$, $d_{5/2}$ and $h_{11/2}$ protons, and 0 and 1561 keV for the $f_{7/2}$ and $h_{9/2}$ neutrons, respectively [9, 11, 13].

With this interaction energy the value of the $\nu i_{13/2}$ s.p. energy can now be determined more precisely. We consider only the 10^+ level in ^{134}Sb at 2713 keV, which corresponds to the $(\pi g_{7/2}\nu i_{13/2})_{10^+}$ maximum aligned configuration and leads to $\epsilon_{\nu i_{13/2}} = 2669(70)$ keV. The new value is close to the previous value of 2694(200) keV [4], while its uncertainty is estimated to be nearly three times lower.

In the ^{132}Sn region in $N = 83$ isotones two $13/2^+$

levels are expected, originating either from a s.p. $\nu i_{13/2}$ excitation or an octupole excitation coupled to the $\nu f_{7/2}$ ground state, $\left(3^- \times \nu f_{7/2}\right)_{13/2^+}$. However, if these two excitations lie close in energy, they mix together to form the $13/2^+$ levels. This mixing has been investigated in Ref. [2, 28] and is the subject of the last part of this work.

For isotones with $Z \geq 56$, the authors of Ref. [28] used the energies of two experimentally measured $13/2^+$ levels ($13/2^+$ lower and $13/2^+$ upper) and their spectroscopic factors to disentangle the energies of pure states, the s.p. $\nu i_{13/2}$ and the $\left(3^- \times \nu f_{5/2}\right)_{13/2^+}$ configuration. In addition, they estimated matrix elements describing the interaction between the two pure states. Furthermore in [2], using these results and the energy and spectroscopic factor of the lower $13/2^+$ level in ^{137}Xe, they estimated the properties of the upper $13/2^+$ level in this nucleus. All their results are presented in Fig. 4, to the right of the dashed line. In this paper we employ the same two level mixing model and make predictions for the lower $13/2^+$ level in ^{133}Sn, to help its experimental search (see Ref. [29]).

The experimental information available for this estimate, the energies of the lower $13/2^+$ level in ^{135}Te and the 3^- excitation in the ^{134}Te and ^{132}Sn cores, are insufficient and some assumptions have to be done.

As to the energy of the pure wave functions, the new value $\epsilon_{\nu i_{13/2}} = 2669(70)$ keV can be taken for ^{133}Sn and the $\epsilon_{\left(3^- \times \nu f_{5/2}\right)_{13/2^+}}$ can be assumed equal to the 3^- excitation energy in the core. The latter assumption is supported by the observation that the $\left(3^- \times \nu f_{5/2}\right)_{13/2^+}$ energy approaches the 3^- core excitation energy when the proton number decreases, as seen in Fig. 4(a). In fact, we note that for one valence proton nucleus, ^{133}Sb, the energy of an octupole excitation is 4297 keV [30], which is very close to the 4352 keV octupole excitation in ^{132}Sn. Moreover, the uncertainty associated with this assumption, estimated to be about 200 keV, has small influence on the final numerical result.

Another value missing is the interaction matrix element between the two $13/2^+$ pure states in ^{133}Sn. It is estimated at 540 keV using a linear extrapolation, as shown in Fig. 4(b). The uncertainty of the extrapolated value is assumed to be 50 keV.

With this input we deduced the value of 2511(80) keV for the lower $13/2^+$ level in ^{133}Sn. This energy is rather close to the neutron separation energy ($S_n = 2402(4)$ keV [31]) and might be accessible experimentally. We note that the 2792 keV value discussed recently (but not accepted) in Ref. [29] is not consistent with the above prediction.

In summary, we have determined more accurately the energy of the $i_{13/2}$ neutron s.p. orbital in the ^{132}Sn core potential, which is now $\epsilon_{\nu i_{13/2}} = 2669(70)$ keV. With this value we estimated the excitation energy of the first $13/2^+$ level in ^{133}Sn to be 2511(80) keV. In ^{135}Sb we have proposed two new states, which may contain the $\nu i_{13/2}$ in their configurations. Identification of further excited states comprising this orbital is required for the study of the evolution of the $\nu i_{13/2}$ s.p. energy with the increasing neutron number.

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