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Properties of N=84, even-even nuclei populated in the spontaneous fission of ^{248}Cm

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Abstract. Excited states in the neutron-rich, N=84 nuclei ^{134}Sn, ^{136}Te and ^{138}Xe, populated in the spontaneous fission of ^{248}Cm, were studied to medium spins using the EUROGAM2 array. OXBASH code calculations support the experimental identification of maximum aligned configurations in these isotopes. Empirical shell model calculations agree with the proposed excitation energy of the neutron $h_{9/2}$ excitation in the ^{132}Sn region. A discrepancy between the observed and calculated excitation energy of the $I^\pi=12^+$ level in ^{136}Te indicates possible admixtures of collective excitations in this nucleus. Clear signs of collective excitations are observed in ^{138}Xe.

PACS. 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.80.+w $190 \leq A \leq 219$ – 25.70.-z Low and intermediate energy heavy-ion reactions

1 Introduction

Nuclei with a few valence particles outside a doubly-magic core provide useful information on the single-particle excitation energies and nucleon-nucleon effective interactions. In some cases such nuclei can provide information which can not be obtained from studies of nuclei with only a single valence nucleon. The structure of nuclei with just a few valence particle may be simple enough to allow extraction of a precise information on fundamental nuclear properties. This should be especially true for nuclei in the vicinity of ^{132}Sn, which is a good double-closed shell nucleus. A recent study of the ^{134}Sb nucleus [1], provides an example. In ^{134}Sb proton-neutron configurations involving the $i_{13/2}$ neutron level have been identified and give the first estimate of the neutron $i_{13/2}$ excitation energy. Because it is unbound, the $\nu i_{13/2}$ level has not been observed in the single-valence neutron nucleus ^{133}Sn.

Nuclei with a few valence-particles have a reasonably high density of excited states at medium spins and are good subjects for γ-ray spectroscopy measurements. Thanks to recent developments in γ detection techniques [2], nuclei in the ^{132}Sn region can now be studied through prompt-γ spectroscopy of fission fragments. This method allows investigations of excited states up to $\sim 15\hbar$ in spin and $\sim$ 8 MeV in excitation energy and advanced analysis techniques [1] make possible studies of γ-ray yields as small as 10^{-8} of the total intensity.

The present work concerns the N=84 isotones ^{134}Sn, ^{136}Te and ^{138}Xe, which have two valence neutrons outside the ^{132}Sn core. Nuclei close to the ^{132}Sn core are well described by the shell model but there are indications that nucleiwith a few valence particles may acquire collective properties. It is therefore of interest to investigate the N=84 nuclei in order to test the limits of the shell model in this region. Partial results of this work have been recently reported in [3–5].

2 Experiment, data analysis and the results

In the present work, prompt γ radiation following spontaneous fission of ^{248}Cm was measured using the EUROGAM2 array of Ge anti-Compton spectrometers. About 2×10^{10} $\gamma\gamma\gamma$ coincidences were collected. For more details on the experiment and data analysis see [6]).

Partial level schemes of ^{134}Sn, ^{136}Te and ^{138}Xe were obtained from the analysis of triple-γ coincidences. Where possible angular correlations between γ rays in these nu-

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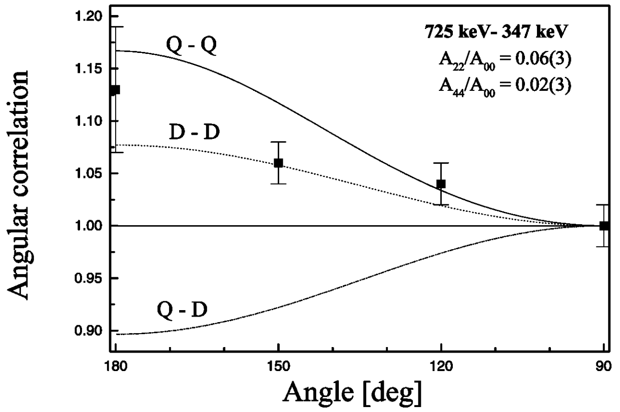

Fig. 1. Angular correlations for gamma transitions in ^{134}Sn. Experimental points are displayed versus the expected quadrupole-quadrupole (Q-Q), dipole-dipole (D-D) and quadrupole-dipole (Q-D) correlations

clei and linear polarisations of γ rays were extracted. The analysis of each nucleus investigated is described in detail below.

2.1 ^{134}Sn

The prompt γ-radiation in fission fragments from ^{248}Cm includes γ-rays from Sn isotopes in coincidence with γ-rays from different Pd isotopes. In a spectrum gated on γ-transitions from ^{112}Pd one may observe γ-lines corresponding to ^{134}Sn. Three transitions with energies 174 keV, 347 keV and 725 keV were identified and assigned to ^{134}Sn [3] using the correlation between masses of complementary fission fragments [7]. The 1247 keV level, depopulated by the cascade of these three transitions, was found to be an isomer with half-life ($T_{1/2}$) of 80(15)ns, determined using the technique described in [8]. The experimental angular correlation between the the 725 keV and 347 keV γ rays, shown in Fig. 1 together with the correlations expected for various transition multipolarities, is consistent with stretched quadrupole character for both transitions. The dipole-dipole assignment, which also agrees with the experiment, is less likely because fission preferably populates yrast states. We assume that the transitions are stretched electric quadrupole (E2). An E2 assignment is also made to the 174 keV transition, in view of the observed lifetime of the 1247 keV level.

The three excited states in ^{134}Sn were interpreted as members of the $\nu(f^2_{7/2})_j$ multiplet [3]. The neutron separation energy in ^{134}Sn of 3.74(11) MeV, is higher than the single-particle excitation energies for the $\nu h_{9/2}$ and $\nu i_{13/2}$ neutron levels. Therefore, one may expect bound excited states in ^{134}Sn involving these single-particle levels. In particular, an excited state in ^{134}Sn corresponding to the $\nu(f_{7/2}h_{9/2})_{8^+}$ configuration should be observed in our experiment. One can estimate the $8^+ \rightarrow 6^+$ transition energy using the appropriate data from the ^{208}Pb region. It has been demonstrated [9], that due to the close correspondence of single-particle excitations in the ^{132}Sn and ^{208}Pb regions, properly scaled residual interactions from the ^{208}Pb region may be used in the ^{132}Sn region.

The $(\nu g_{9/2}i_{11/2})_{10^+}$ and $(\nu g_{9/2})^2{}_{8^+}$, levels in ^{210}Pb [10] correspond [9] to the $(\nu f_{7/2}h_{9/2})_{8^+}$ and $(\nu f_{7/2})^2{}_{6^+}$ configurations in ^{134}Sn. The effective residual interactions in ^{210}Pb are -221 keV and +30 keV [10], respectively. After $A^{-1/3}$ scaling (with A the mass number) one obtains values of -257 keV and 35 keV for the interaction between the two neutrons in the $(\nu f_{7/2}h_{9/2})_{8^+}$ and $(\nu f_{7/2})^2{}_{6^+}$ configurations in ^{134}Sn, respectively. Using these interactions and the 1561 keV excitation energy of the $h_{9/2}$ level in ^{133}Sn from [11], the $(\nu f_{7/2}h_{9/2})_{8^+} \rightarrow (\nu f_{7/2})^2{}_{6^+}$ transition energy is calculated to be (1561-257-35) keV = 1269 keV.

The $(\nu f_{7/2}h_{9/2})_{8^+}$ excitation energy can also be estimated using appropriate data from the ^{146}Gd region. Due to the subshell closure at Z=64, the ^{146}Gd nucleus is considered to be doubly magic [12]. ^{148}Gd, having two valence neutrons, is thus an analog of ^{134}Sn. The 8^+, 2693 keV level in ^{148}Gd provides a neutron-neutron interaction strength of -347(12) keV for the $(\nu f_{7/2}h_{9/2})_{8^+}$ configuration. The $A^{-1/3}$ scaling gives -358(12) keV for the interaction between the two neutrons in the $(\nu f_{7/2}h_{9/2})_{8^+}$ configuration in ^{134}Sn. Using this interaction value, the 1561 keV excitation energy for the $h_{9/2}$ level in ^{133}Sn [11] and nuclear masses from the recent compilation [13], the excitation energy of the $(\nu f_{7/2}h_{9/2})_{8^+}$ level in ^{134}Sn is calculated to be 2473 keV. This 8^+ level should decay to the 6^+, 1247 keV level by an E2 transition of about 1230 keV.

Accordingly, we searched for a gamma transition of about 1250 keV in coincidence with the three known transitions in ^{134}Sn (725 keV, 347 keV and 174 keV) and with strong transitions in ^{112}Pd. The relevant double-gated spectra are shown in Fig. 2.

The result of the search is the 1261.5 keV line, which fulfils all the required conditions. In a spectrum gated on the (174+347) keV and the 725 keV lines in ^{134}Sn (the upper panel), besides the known lines in ^{134}Sn and ^{112}Pd, there is a line at 1261.5 keV. In a spectrum gated on the 348 keV and 1261 keV lines (lower panel), known lines in ^{134}Sn and ^{112}Pd appear, which indicate that the 1261.5 keV transition belongs to one of the two nuclei (the 348 keV line, which is also seen in the lower spectrum, is a doublet consisting of the 347.8 keV transition in ^{134}Sn and the 348.7 keV transition in ^{112}Pd).

To assign the 1261.5 keV transition to a particular nucleus, we have analysed coincidence yields in spectra double-gated on lines in the two nuclei. The number of counts in the 1261.5 keV line in the sum of spectra double gated on the 726 keV, 348 keV, and 174 keV lines in ^{134}Sn is 980(70). The corresponding number in the sum of spectra double gated on the 348 keV, 534 keV and 667 keV lines in ^{112}Pd is 620(60). The numbers of counts in both cases were corrected for detector efficiency. The two numbers can be understood if the 1261.5 keV belongs to ^{134}Sn. Besides ^{112}Pd, other Pd isotopes are also produced together with ^{134}Sn in fission of ^{248}Cm. Therefore, not all 1261.5 keV γ-decays are in coincidence with γ-decays in ^{112}Pd. The opposite numerical effect is observed for the

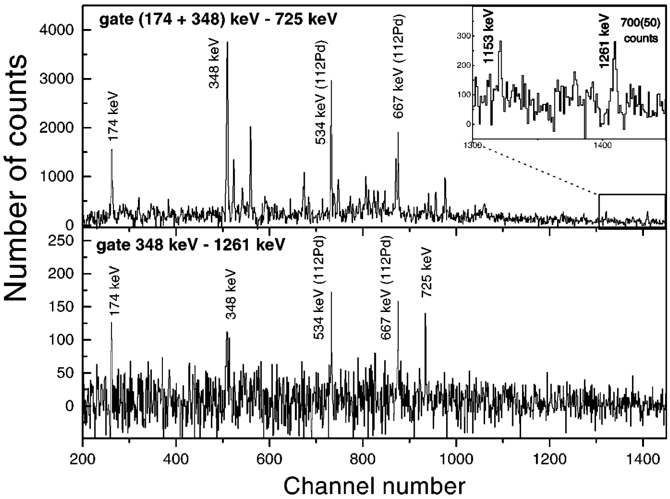

Fig. 2. Fragments of double gated spectra showing γ transitions in ^{134}Sn nucleus

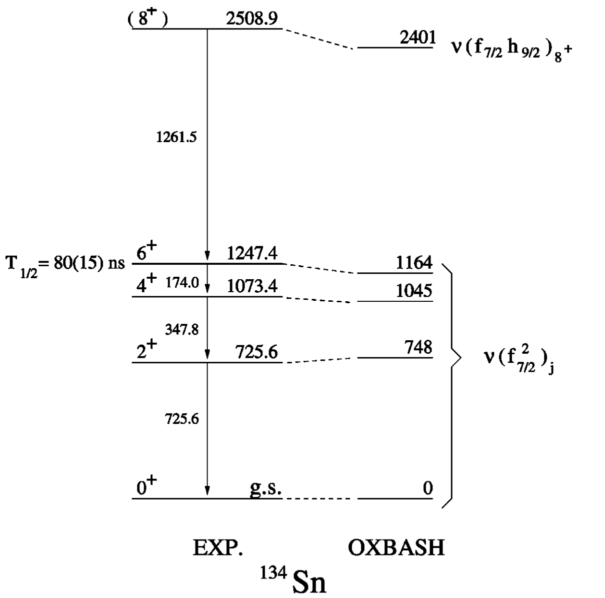

Fig. 3. The partial level scheme of ^{134}Sn obtained in the present work. The right-hand side of the figure shows calculations performed with the code OXBASH [14]

1153.8 keV line in ^{112}Pd, placed on top of the 1550.7 keV level and depopulated by a cascade of the 348.7 keV, 534.4 keV and 667.6 keV transitions. The placement is analogous to the placement of the 1261.5 keV line in ^{134}Sn. The number of counts in the 1153.8 keV line in the sum of spectra double gated on the 726 keV, 348 keV and 174 keV lines in ^{134}Sn is 650(70), while the corresponding number in the sum of spectra double gated on the 348 keV, 534 keV and 667keV lines in ^{112}Pd is 1030(80).

The resulting partial level scheme for ^{134}Sn is shown in Fig. 3. On the right-hand side of Fig. 3, shell-model calculations performed with the OXBASH code [14] are presented. In these calculations, the excitation energy of

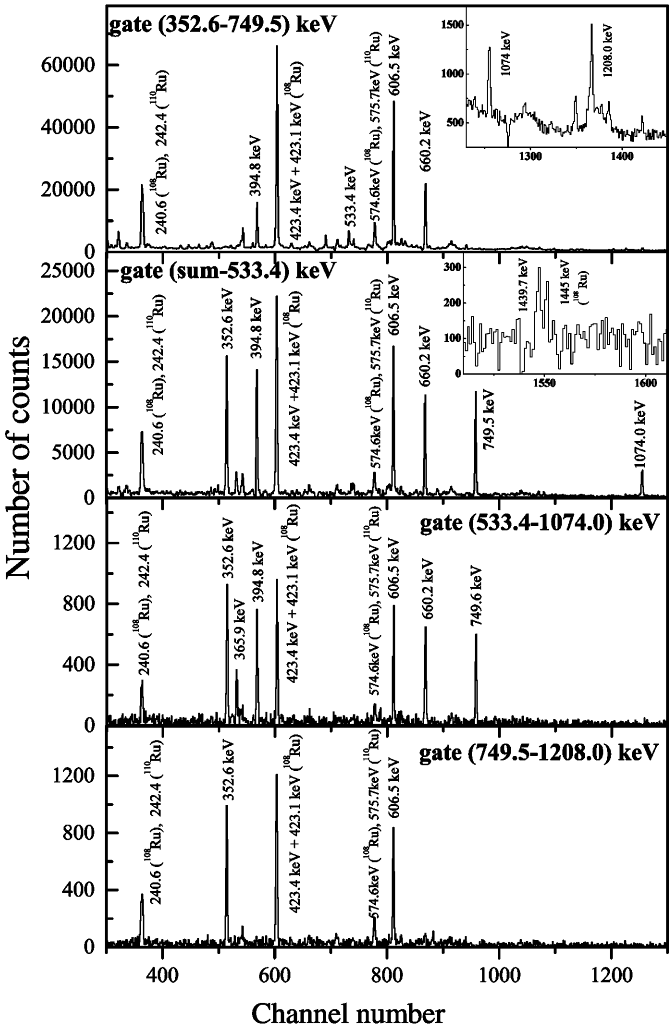

Fig. 4. Fragments of double gated spectra showing γ transitions in the ^{136}Te nucleus. See the text for an explanation of the sum gate

the $h_{9/2}$ level in ^{133}Sn was taken from [11] to be 1561 keV. More details about OXBASH calculations are given in Sect. 3.1.

2.2 ^{136}Te

Prior to this work, yrast excited levels in ^{136}Te have been reported up to 2.8 MeV [15]. We have established the yrast cascade up to 5.1 MeV. Examples of gamma spectra double-gated on lines in ^{136}Te are shown in Fig. 4.

In a spectrum gated on the 352.6 keV and 749.5 keV lines in ^{136}Te reported previously [15] (top panel in Fig. 4), strong lines in ^{136}Te and ^{110}Ru, the main fission partner, are seen. We identified six new lines in ^{136}Te with energies of 365.9, 394.8, 533.4, 1074.0, 1208.0 and 1439.7 keV. The most intense, the 394.8 keV line, is placed on top of the (10$^+$), 2792 keV level proposed in [15]. A spectrum obtained by summing spectra resulting from double gating on the new line at 533.4 keV and the lines of energies

606.5, 423.4, 352.6, 749.5 and 660.2 keV lines is shown in the middle panel of Fig. 4. The intensity of the 394.8 keV line is comparable to the intensities of the lower lying, known transitions (the intensity of the 423.4 keV line is higher than that of the 394.8 keV line because a transition of the same energy is present also in ^{110}Ru). This indicates that the 533.4 keV transition feeds the 3187 keV level, which in turn is depopulated by the 394.8 keV γ ray. In the same spectrum, another new line is observed at 1074.0 keV and we place it on top of the 3720 keV level, depopulated by the 533.4 keV transition. A spectrum double gated on the 1074.0 keV and 533.4 keV lines, shown in the bottom panel of Fig. 4, supports this placement and indicates the presence of the next transition with energy of 365.9 keV. In this spectrum we do not observe the 1439.7 keV line, seen in the middle panel, which suggests that this γ ray is a cross-over transition. A similar argument places the new 1208.0 keV transition, seen in the 352.6 keV - 749.5 keV gate, on top of the 2132.0 keV level. The spectrum obtained by double-gating on the 749.5 keV and 1208.0 keV lines, shown in Fig. 4, confirms this placement.

Spins and parities were assigned to most of the levels observed using angular correlations and linear polarisation measurements. Examples of angular correlations are shown in Fig. 5. The experimental points were fitted to the formula: $W(\Theta) = A_{00} + A_{22}P_2(\cos\Theta) + A_{44}P_4(\cos\Theta)$. The A_{22}/A_{00} and A_{44}/A_{00} coefficients, resulting from the fit are shown in the corresponding panels of Fig. 5. The linear polarisation values, $P(\gamma)$, obtained for γ transitions in ^{136}Te are: P(606 keV)= +0.12(3), P(423 keV)= +0.09(2), P(352 keV)= +0.09(3), P(749 keV)= +0.09(6) and P(660 keV)= +0.19(7). These data and the non-observation of any isomers with lifetimes longer than 10 ns indicate an E2 character for transitions in the yrast cascade up to 3720 keV level.

The partial level scheme of ^{136}Te obtained in the present work is shown on the right-hand side of Fig. 6. The left-hand side of Fig. 6 shows OXBASH calculations for ^{136}Te. The calculations, which will be discussed in detail in the next section, are consistent with the spin and parity assignments proposed for levels in ^{136}Te.

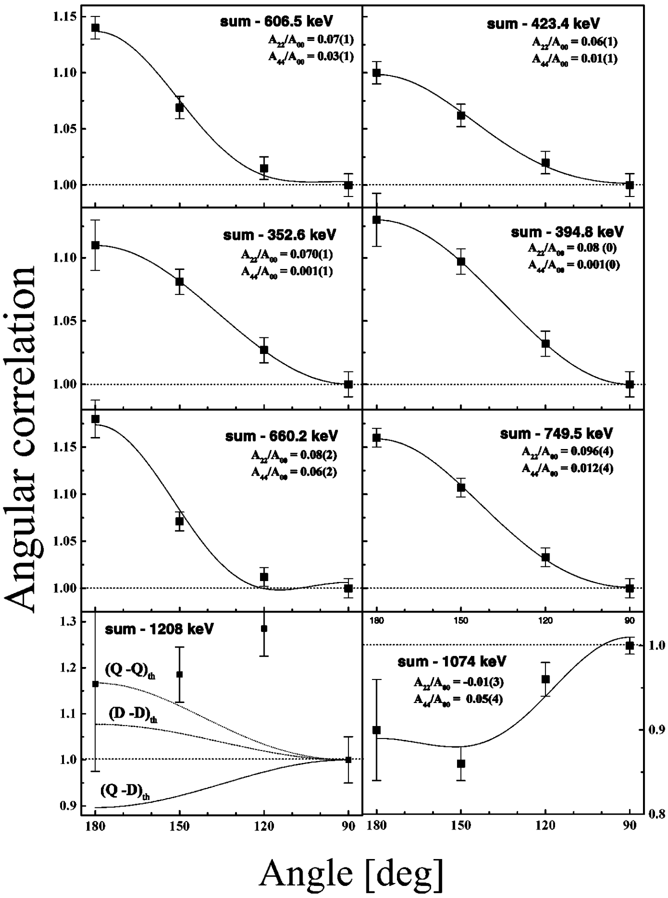

Fig. 5. Examples of angular correlations of γ rays in ^{136}Te. The lines drawn are fits of the data to Legendre polynomial expansions. Fitted coefficients are shown in the panels. Points for the sum-1208 keV correlation are displayed versus the expected quadrupole-quadrupole (Q-Q), dipole-dipole (D-D) and quadrupole-dipole (Q-D) correlations

2.3 ^{138}Xe

The yrast levels in ^{138}Xe up to 5 MeV were studied in [16]. We have extended the yrast sequence up to 5.8 MeV. In addition, 20 non-yrast levels, forming at least two side bands, were found. Examples of double-gated gamma spectra, demonstrating the presence of the new levels above 5 MeV are shown in Fig. 7.

The top panel, labelled “sum-599 keV” shows a double-gated spectrum obtained by summing spectra produced by setting one gate on the 599.0 keV line [16] and the other on the yrast transitions [16] below the 599.0 keV transition. Strong transitions in ^{138}Xe and in ^{104,106}Mo nuclei, which are fission partners to ^{138}Xe, are present, including the 570.6 keV line placed at the top of the scheme in [16]. The high intensity of the 847.8 keV line indicates that this transition feeds the 3571 keV level, which decays with emission of the 599.0 keV line.

The spectrum double-gated on the 599.0 keV and 847.8 keV lines, shows that the next γ ray in the yrast cascade has energy 570.6 keV. In this spectrum we have identified new lines at 530.3 keV, 545.9 keV and 824.3 keV. Analysis of spectra obtained by gating on these lines shows that they belong to ^{138}Xe. The 1118.6 keV γ ray, seen in the 599.0-847.8 keV spectrum, is not present in this second set. This suggests that the 1118.6 keV γ ray may link a non-yrast, side-band level with the 3571 keV yrast level. A spectrum double-gated on the 729 keV and 1118 keV lines, shown in the bottom panel of Fig. 7, confirms that the 1118.6 keV transition populates the 3571 keV level.

Other new lines appear in the “sum-729” spectrum shown on Fig. 7, where “sum” means that the spectrum is the sum of spectra obtained by setting gates on the 729 keV γ ray and γ rays in the yrast sequence below that line. The spectra given with gates set on the lines

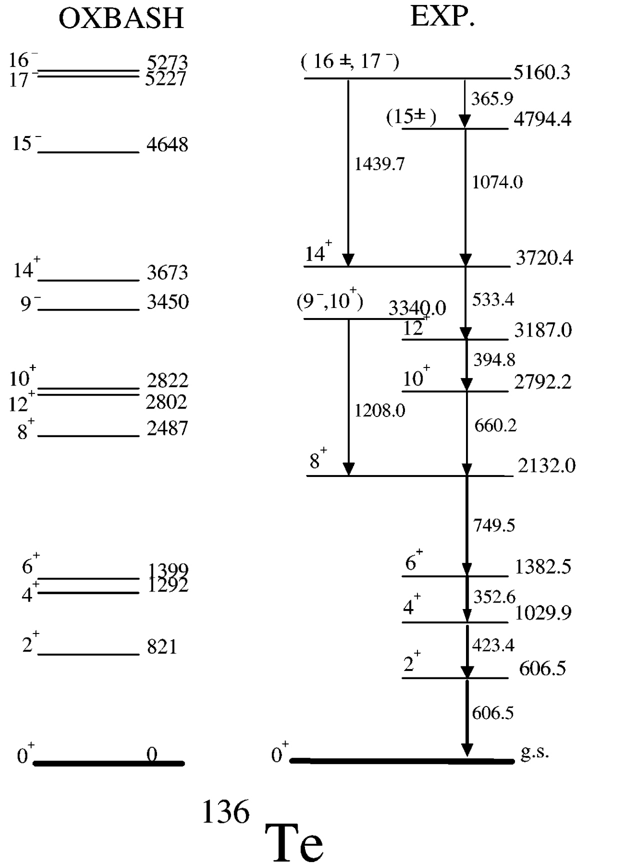

Fig. 6. The partial level scheme of ^{136}Te obtained in the present work and OXBASH calculations for ^{136}Te with Kuo-Herling interactions. See text for more comments about the calculations

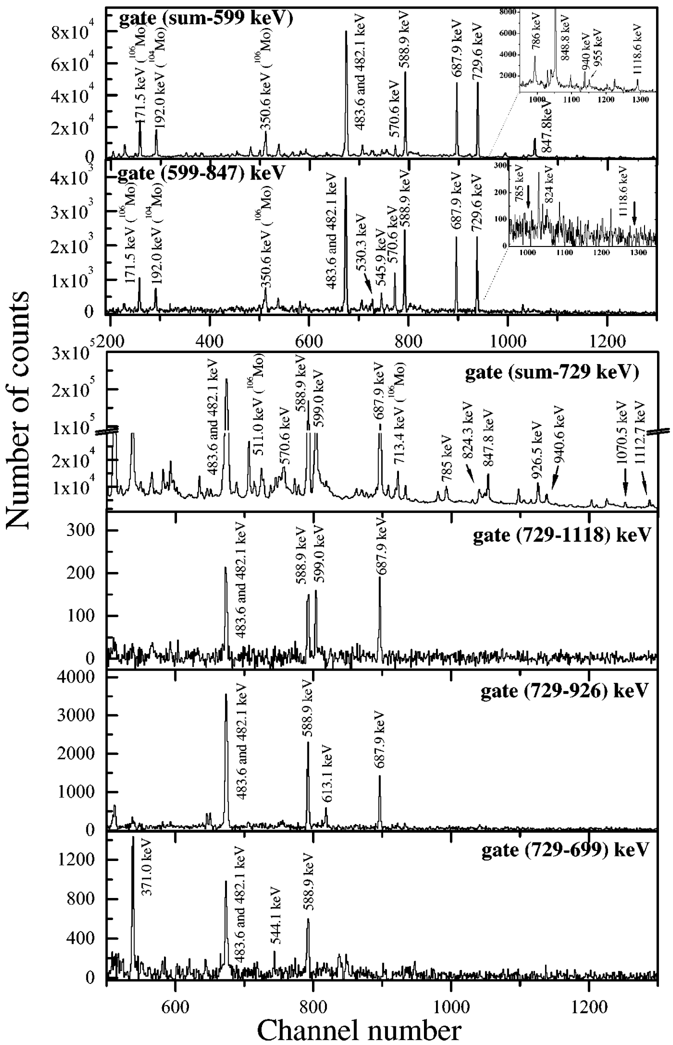

Fig. 7. Fragments of double gated spectra showing γ transitions in the ^{138}Xe nucleus. See the text for an explanation of the sum gate

at 729.6 and 926.5 keV, and on those at 729.6 and 699.9 keV are also shown on Fig. 7. These lines and a number of other, newly identified transitions, were placed in the partial level scheme shown in Fig. 8.

The spins and parities shown in Fig. 8 were assigned using angular correlation and linear polarisation measurements. Examples of angular correlations between transitions in ^{138}Xe are shown in Fig. 9. These are the sums of angular correlations between the named transition and transitions placed below the named one.

The measured linear polarisation values, P(γ), obtained for certain γ rays are: P(589keV) = +0.13(2), P(483keV) = +0.10(2), P(729keV) = +0.11(3), P(688keV) = +0.16(4) and P(599keV) = +0.23(7).

3 Discussion

^{132}Sn is a doubly magic nucleus and the spectroscopy of nuclei surrounding the ^{132}Sn core is a source of information on fundamental nuclear properties. In particular the properties of a few valence-quasiparticle excitations provide information in a direct way on the single particle energies and the effective nuclear residual interactions. Also, the structural studies of nuclei in the vicinity of the magic shell closure allow for the precise testing of nuclear models.

Many interesting questions can be adddressed when discussing the N=84 isotones. Nuclei close to the Z=50 magic number are expected to behave as closed-shell nuclei. On the other hand, it is expected that when departing from the Z=50 proton shell, the increasing number of valence protons will soften the underlying ^{132}Sn core. Where this happens and how strongly the shell-model description is violated are important questions for the model. The present systematic study of the N=84 isotopes close to the Z=50 line provides an experimental background for such a discussion.

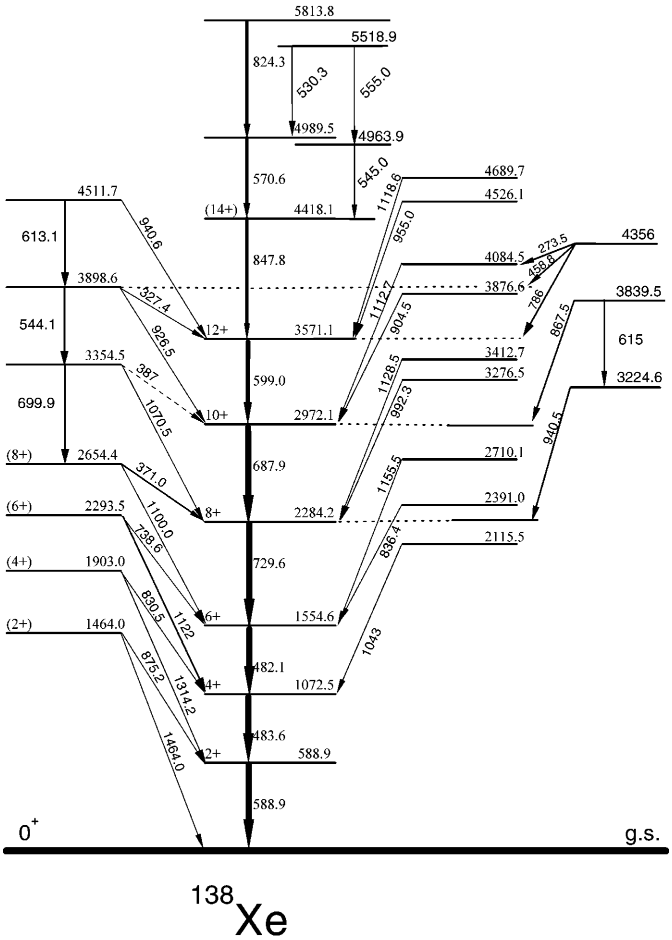

Fig. 8. The partial level scheme of ^{138}Xe obtained in this work

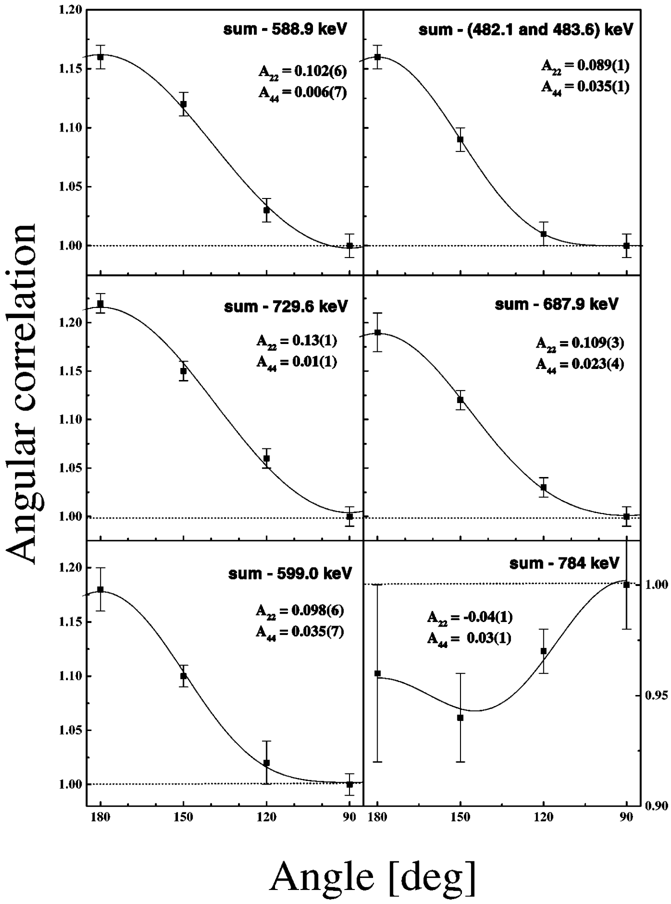

Fig. 9. Examples of angular correlations for gamma transitions in ^{138}Xe. "Sum" denotes a sum of yrast transitions below the studied transition. The lines represent fits to the data in terms of Legendre polynomial expansions. The coefficients of the fits are shown in the panels

3.1 OXBASH calculations

Shell model calculations for the ^{134}Sn and ^{136}Te nuclei have been performed using the code OXBASH [14]. The calculations included single particle orbitals $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ for protons and $f_{7/2}$, $h_{9/2}$, $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $i_{13/2}$ for neutrons. The single particle energies used, given relative to ^{132}Sn, are presented in Table 1.

We have used the realistic residual interaction derived by Kuo and Herling for ^{208}Pb region from the measured interaction between free nucleons [20,21] and assumed that it scales with mass number A as $A^{-1/3}$. The residual interaction was derived from the free nucleon-nucleon potential of Hamada and Jonston [22] using reaction matrix techniques as in [23] with renormalizations to account for the truncated model space. This interaction reproduced well many properties of nuclei in the region of ^{208}Pb [24,25]. For our calculations we have taken the original matrix elements of Kuo and Herling [20] for $g_{7/2}, d_{5/2}, d_{/2}, s_{1/2}$ and $h_{11/2}$ protons and for $f_{7/2}, h_{9/2}, f_{5/2}, p_{3/2}, p_{1/2}$ and $i_{13/2}$ neutrons in the form

$$\langle j_1 j_2|V|j_3 j_4\rangle = \langle j_1 j_2|V|j_3 j_4\rangle_{bare} + \langle j_1 j_2|V|j_3 j_4\rangle_{1p-1h} ,$$

Table 1. The energies of sigle-particle states in the ^{132}Sn region used in the present OXABASH calculation

Neutron level	$E_{exc}(keV)$	Comments
$\nu h_{9/2}$	-0.884	from [11]
$\nu f_{7/2}$	-2.445	from [17]
$\nu f_{5/2}$	-0.440	from [11]
$\nu p_{3/2}$	-1.591	from [11]
$\nu p_{1/2}$	-0.789	from [11]
$\nu i_{13/2}$	+0.250	from [1]
Proton level	$E_{exc}(keV)$	**Comments**
$\pi g_{7/2}$	-9.625	from [13]
$\pi d_{5/2}$	-8.663	from [18]
$\pi d_{3/2}$	-7.185	from [19]
$\pi h_{11/2}$	-6.833	from [18]

where the second term on the right hand side is due to the core polarisation effects. All the matrix elements were scaled with the mass factor of $(208/132)^{1/3}$ and additionally six diagonal matrix elements for paired neutrons have

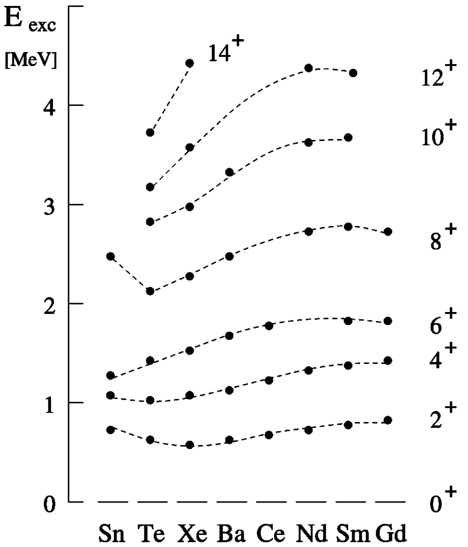

Fig. 10. The positive-parity levels in the even-even, N=84 isotones. Data are from this work and [27–29]. Dashed lines are drawn to guide the eye

been multiplied by 0.6 to reduce the overbinding of the 0^+ ground states.

The need to reduce diagonal matrix elements has been noticed already in [26], where a factor of 0.6 was introduced. There, the 2^+, 4^+ and 6^+ excited levels in ^{134}Sn were predicted, using OXBASH, at 1245 keV, 1731 keV and 1924 keV, respectively (see Fig. 3 in [26]). Comparison with the present experiment shows that these predictions are too high. Our OXBASH calculations, which use the same program and input data with the 0.6 factor, reproduce experiment quite well, as shown in Fig. 3. While we are not able to explain this difference, we note that if the energies calculated in [26] are multiplied by 0.6, they agree within few keV with our calculations.

The results of OXBASH calculations are discussed for each of the studied nuclei in the following sections.

3.2 Structure of yrast levels in even-even, N=84 isotones

Figure 10 shows the systematic trends of yrast excitations in the even-even, N=84 nuclei from the semi-magic ^{134}Sn (Z=50) to the ^{148}Gd nucleus, in which a distinct subshell closure has been identified [12]. The new data obtained in the present work are included in the diagram. The smooth dependence of the excitation energies as a function of proton number supports the spin and parity assignments to levels in ^{134}Sn, ^{136}Te and ^{138}Xe, made in the present work.

The 2^+, 4^+ and 6^+ excitation energies show a regular behaviour suggesting that these excitations are composed mainly of the $\nu(f^2_{7/2})_j$ configuration present in all the N=84 isotones. However, the systematic behaviour of higher spin levels shows a distinct discontinuity between the Sn and Te isotones. This can be explained by the lack of valence protons in ^{134}Sn. While in ^{136}Te and ^{138}Xe isotones the 8^+, 10^+ and 12^+ excitations can be attributed to the $(\nu^2\pi^2)_j$ configuration, in the ^{134}Sn nucleus the 8^+ level has the $\nu(f_{7/2}h_{9/2})_j$ configuration and the corresponding 10^+ and 12^+ levels are not present. The lowest 10^+ and 12^+ excitations in ^{134}Sn, corresponding to the $\nu(i^2_{13/2})_j$ configuration, are expected at 6.8 MeV and 6.9 MeV, respectively, according to OXBASH calculations.

It is worth noting that in both ^{134}Sn and ^{148}Gd, the pattern of excitation energies is characteristic of closed-shell nuclei. In particular, the excitation energies of the 8^+ levels, which in both nuclei correspond to the same $\nu(f_{7/2}h_{9/2})_j$ configuration, are very similar. In the middle of the chain (Xe - Nd nuclei), however, the excitation energies are approximately equidistant, as observed in vibrational systems. This may indicate the presence of collective effects in the Xe - Nd, N=84 isotones. The excitation scheme of ^{138}Xe shown in Fig. 8 is characteristic of a collective nuclear motion with a vibrational-type yrast cascade and well developed side bands. One should however remember that in the Ce - Sm isotones, the $\pi g_{7/2}$ subshell is filled and the $\pi d_{5/2}$ subshell is active. Consequently, excitation patterns in those nuclei may be different from those in the Xe and Ba isotones. It is interesting to determine if the lack of the 8^+, 10^+ and 12^+ excitations in ^{142}Ce is due to experimental limitations or to the closure of the $\pi g_{7/2}$ subshell. If such excitations can be found where Fig. 10 suggests, then one has to consider the collective nature for these levels or assume that the $\pi g_{7/2}$ subshell closure is not important.

The yrast, $I^\pi=14^+$ excitation in ^{136}Te corresponds to the $\nu(h_{9/2}f_{7/2}) \otimes \pi g^2_{7/2}$, maximum aligned configuration. The OXBASH estimate of this excitation energy agrees remarkably well with experiment. In [4] it was suggested that the excitation energy of the $I^\pi=14^+$ level in ^{136}Te indicates that the mass of ^{134}Te is lower by 200(80) keV than the adopted value [13]. This has been recently confirmed in a Q_β measurement for the A=134 chain [30], where the mass of ^{134}Te was found to be 160(30) keV lower than the adopted value [13].

The yrast, $I^\pi=14^+$ excitation in ^{138}Xe may have significant contributions from both the $\nu(h_{9/2}f_{7/2}) \otimes \pi g^2_{7/2}$ and $\nu f^2_{7/2} \otimes \pi g^4_{7/2}$ configurations, while in ^{140}Ba the $I^\pi=14^+$ excitation should correspond to the $\nu(h_{9/2}f_{7/2}) \otimes \pi g^{-2}_{7/2}$ configuration. This level has not so far been identified in ^{140}Ba. It is even more interesting to look for a $I^\pi=14^+$ excitation in ^{142}Ce. With the $\pi g_{7/2}$ shell closed, ^{142}Ce should behave similarly to ^{134}Sn, where the low lying $I^\pi=14^+$ excitation is not expected.

For the yrast states with spins higher than $14\hbar$ the data are too incomplete to give any systematic guidance, though the calculated energies for levels with spins I=15,16 and 17 in ^{136}Te agree very well with experiment. In particular, OXBASH calculations strongly suggest negative parity for the 3720.4 keV, $I=15\hbar$ level in ^{136}Te, which should correspond to the $\nu(f^2_{7/2})\pi(h_{11/2}g_{7/2})$ maximum aligned configuration. The lowest I=15$\hbar$ level with positive parity is predicted above 7.5 MeV.

3.3 The $\nu(h_{9/2}f_{7/2})_{8+}$ configuration in ^{134}Sn and the excitation energy of the $\nu h_{9/2}$ single-particle level

In recent years significant progress has been made in studies of the doubly closed shell nucleus ^{132}Sn and its neighbours [11,31–33]. The key elements of such studies are measurements of single-particle energies, which provide a fundamental input to accurate theoretical calculations.

In the ^{133}Sn nucleus, which gives the most direct data on the single-neutron energies, the neutron separation energy, S_n, is merely 2.45 MeV. At present the only way to populate excited states in ^{133}Sn is either directly in fission or in β^--decay of fission fragments. Both processes predominantly populate states in ^{133}Sn at energies higher than the neutron separation energy. Such states may deexcite by emitting a neutron rather than a γ ray, thus making it difficult to locate the neutron levels in this nucleus through γ-ray measurements.

In a recent work [11], the delayed-neutron β^--decay of ^{134}In was employed to populate excited states in ^{133}Sn. Three excited states proposed at 854 keV, 1561 keV and 2005 keV were interpreted as the $p_{3/2}$, $h_{9/2}$ and $f_{5/2}$ neutron levels, respectively. The assignments were based on indirect arguments derived from systematic trends and calculations. It is important to verify the conclusions of [11] by independent measurements. Support for interpreting the 1561 keV level in ^{133}Sn as the $\nu h_{9/2}$ single-particle state has already come from a study of the ^{134}Sb nucleus, where the 1071 keV level has been assigned [34] the two-particle configuration $(\pi g_{7/2}\nu h_{9/2})_{8+}$.

The present study of ^{134}Sn provides further support for the $\nu h_{9/2}$ single-particle state proposed in [11]. Detailed discussion and calculations concerning the $\nu(f_{7/2}h_{9/2})_{8+}$ excitation in ^{134}Sn were presented in Sect. 2.1. Due to the good agreement between the predicted and observed excitation energies of the $(\nu f_{7/2}h_{9/2})_{8+}$ configuration in ^{134}Sn, the new 2509 keV level identified in ^{134}Sn provides strong support for the position of the $h_{9/2}$ neutron excitation at 1561 keV in ^{133}Sn [11]. The population of ^{134}Sn in our measurement was too low to observe higher-lying levels, involving the $i_{13/2}$ neutron level.

3.4 The $(\nu f_{7/2}{}^2)(\pi g_{7/2}{}^2)_{12+}$ configuration in ^{136}Te

While the experimentally observed excitation energies of the 10^+ and 12^+ levels in ^{136}Te agree well with the systematic trends for such levels in the N=84 isotones (see Fig. 10), OXBASH calculations show a distinct deviation from the experiment for the 12^+ level in ^{136}Te, as displayed to the left-hand side of Fig. 6. According to the calculations there should be a long-lived isomer in the yrast cascade of ^{136}Te. Our experimental data suggest that there is no such isomer in this nucleus.

The spin and parity assignments for the 10^+ and 12^+ levels in ^{136}Te are based on a firm angular correlation and linear polarisation data (see Fig. 5). With these assignments, the excitation energies of the 10^+ and 12^+ levels in ^{136}Te fit well the systematics of the 10^+ and 12^+ yrast excitations in the N=84 isotones, as illustrated in Fig. 10. If the 3187 keV level was a non-yrast 12^+_2 excitation, it should decay to the yrast 12^+_1 level through a fast transition of energy E_γ $\sim$400 keV. Such a transition should be clearly seen in a spectrum double-gated on transitions placed above the 3187.0, 12^+ level. Figure 4 shows a spectrum double-gated on the 533.4 keV and 1074.0 keV lines. All the transtions of interest are clearly observed in the spectrum, but there is no candidate for the hypothetical $12^+_2 \rightarrow 12^+_1$ decay. This indicates that the 3187.0 keV, 12^+ level in ^{136}Te has yrast character. Also the 14^+, 3720.4 keV level should decay to the lower-lying, 12^+_1 level rather than to the non-yrast 12^+_2 one. We do not see such a decay and conclude, that the observed levels in ^{136}Te are yrast in character and there is no isomeric 12^+ state.

The discrepancy between measured and calculated excitation energies of the 12^+ level may be due to admixtures of collective states in ^{136}Te. As discussed in Sect. 3.1, collective effects are present in ^{138}Xe and the heavier N=84 isotones. In a recent theoretical investigation [35] of nuclear properties in the vicinity of ^{132}Sn, transition energies in the yrast cascade of ^{136}Te were calculated using the projected shell model [36]. The deformation parameters of the potential adopted for ^{136}Te were ϵ_2=0.06 and ϵ_4=-0.004. The predicted $12^+_1 \rightarrow 10^+_1$ transition energy of about 410 keV (cf. Fig. 3 in [35]) agrees well with the experimental value of 394.8 keV. It remains an open question whether the position of the 12^+ level can be explained within the spherical shell model, using experimental interactions, which are at present not known sufficiently.

3.5 Non-yrast excitations

The population of the non-yrast levels in ^{136}Te and ^{138}Xe in the present experiment was too low for determinations of spins and parities. The 3340.0 keV level in ^{136}Te, probably corresponds to a non-yrast 10^+ excitation, though the corresponding angular correlations are not conclusive. Some support is given by the OXBASH calculations, which predict the 12^+_2 and 10^+_2 levels at 3022 keV and 3118 keV, respectively. It is interesting to determine if the suggested 10^+ assignment is correct and to search for the 12^+_2 state in ^{136}Te. This could provide further confirmation of the yrast character of the 3187 keV level.

Based on the observed decay properties and the fact that fission tends to populate the yrast or near-yrast state, some conclusions can be drawn concerning the spins of the non-yrast levels in ^{138}Xe. Levels in the side band shown to the left in Fig. 8 probably have even spins and parities. They may correspond to gamma vibrations. ^{138}Xe lies on the border of transitional nuclei where such vibrations are expected.

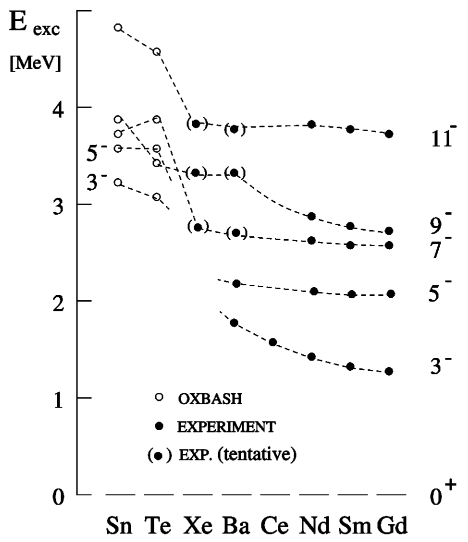

Fig. 11. The systematic behaviour of the negative-parity levels in the even-even, N=84 isotones. Data are from this work and [27–29]. Dashed lines are drawn to guide the eye

The other band in ^{138}Xe, shown to the right in Fig. 8., probably results from coupling octupole excitations to the yrast cascade. Such levels are observed in the heavier isotones, as illustrated in Fig. 11, which displays the systematic trends of octupole vibrations in the N=84, even-even isotones. Fig. 11 suggests spin-parity assignments of 7^-, 9^- and 11^- to the 2710.1, 3276.5 and 3876.6 keV levels, respectively. These are consistent with the decay properties of the levels. These assignments are neither complete nor unique. A candidate for the 3^- state is missing and there is no good candidate for the 5^- excitation. Spin-parity 9^- could also be assigned to the 3412.7 keV level.

Despite these uncertainities, one interesting fact occurs. In Fig. 11 OXBASH predictions are included for the negative-parity levels in ^{134}Sn and ^{136}Te. There seems to be a sharp rise in energy of the negative parity levels between the Xe and Te isotones. This suggests that in ^{138}Xe one may observe enhanced octupole effects characteristic of transitional, neutron-rich lanthanides [6], while in ^{136}Te octupole excitations are due to vibrations of the ^{132}Sn core. It is of a great interest to identify experimentally the 3^- and 5^- excitations in ^{138}Xe to examine this hypothesis.

4 Conclusions

In the ^{134}Sn nucleus we have identified experimentally the 8^+ level interpreted as the $\nu(f_{7/2}h_{9/2})_{8^+}$ configuration. This observation supports the interpretation of the previously proposed 1561 keV level in ^{133}Sn as the $\nu h_{9/2}$ single-particle excitation.

Analysis of an inconsistency between the calculated and observed excitation energies of the 12^+ level in ^{136}Te suggests that this state may have contributions from collective modes. This suggestion is supported by the observation of collective-type, quasivibrational bands in ^{138}Xe. Consequently, the shell-model description may be of limited use already in ^{136}Te, which has only two valence protons and two valence neutrons outside the ^{132}Sn core. On the other hand, more advanced shell-model calculations, may be able to reproduce the position of the 12^+ level.

The newly observed levels in ^{134}Sn, ^{136}Te and ^{138}Xe have significantly enriched the systematics of excited levels in the N=84 isotones. Further studies are however needed. New information on the nature of the 8^+, 10^+ and 12^+ levels in the N=84 isotones can be obtained from an experimental search for such levels in ^{142}Ce. There is also a need for further studies of the negative-parity levels in the N=84 isotones.

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