

Letter

First observation of medium-spin excitations in the ^{138}Cs nucleus

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Abstract. Medium-spin, yrast excitations in the ^{138}Cs nucleus, populated in the spontaneous fission of ^{248}Cm , were observed for the first time. ^{138}Cs was studied by means of prompt γ -ray spectroscopy using the EUROGAM2 array. The newly observed yrast cascade, built on the known 6^- isomer at 80 keV, was successfully described by shell model calculations. Analogously to the ^{136}I isotone, the 6^- isomer in ^{138}Cs has the $(\pi g_{7/2}^4 d_{5/2} \nu f_{7/2})_{6^-}$ dominating configuration and the 7^- excitation, located 175 keV above, corresponds to the $(\pi g_{7/2}^3 d_{5/2}^2 \nu f_{7/2})_{7^-}$ as dominating configuration. Similarly as in ^{136}I , changing the position of the $d_{5/2}$ proton orbital improves the reproduction of the data. However, in ^{138}Cs the energy of this orbital should be *increased* compared to its energy in ^{133}Sb , to get the best description, in contrast to ^{136}I and ^{135}Sb , where it had to be decreased. The best reproduction of excitation energies in ^{138}Cs is obtained assuming that the $\pi d_{5/2}$ orbital in ^{138}Cs is located about 100 keV higher than in ^{133}Sb . These observations suggest that the lowering of the $d_{5/2}$ s.p. energy in ^{135}Sb is not a physical effect due to the appearance of a neutron skin, as proposed by other authors, but rather an artifact due to some deficiency of the input data used in the shell model calculations in the region of the doubly magic ^{132}Sn core.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Tg Lifetimes – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

The ^{138}Cs nucleus has been studied before experimentally in a measurement of the IT decay of the 6^- isomer [1] and in beta decay of ^{138}Xe [2]. Very recently these low-spin excitations were investigated theoretically within the shell model [3]. This last study has shown that the SMPN set of two-body matrix elements (tbme's), proposed recently for the ^{132}Sn region [4], can reproduce rather well the 6^- isomer in ^{138}Cs . Interestingly, no other interaction, usually used in this mass region, can reproduce the isomeric nature of the 6^- state with a half-life of the order of minutes and even the 3^- ground state is not reproduced in some of these calculations (see refs. [3, 5] for details). Similarly good description was also obtained in our study of an analogous 6^- isomer in the isotone ^{136}I [6] where the single-particle energy of the proton $d_{5/2}$ orbital had to be lowered by 400 keV relative to its position in ^{133}Sb . This puzzling effect was first observed in ^{135}Sb and interpreted as due to the formation of neutron skin past the $N = 82$

shell [7, 8]. Using the SMPN set we confirmed the need to lower the $d_{5/2}$ orbital in ^{135}Sb but in ref. [6] we argued against the neutron skin hypothesis, noting that its formation should be a slow phenomenon like other changes in this region connected with the growing number of neutrons, whereas the need for a decrease of $d_{5/2}$ s.p. energy was rather abrupt. Instead, we suggested that the lowering of the $\pi d_{5/2}$ s.p. energy may be an artificial effect, which surprisingly well accounts for deficiencies of some of the tbme's, possibly proton-neutron interactions. To propose any improvement one would like to know how the effect varies with the proton and the neutron number. In fig. 1 we show the approximate shifts (in keV), which have to be applied to the $\pi d_{5/2}$ s.p. energy in various nuclei in the ^{132}Sn region in order to reproduce them properly.

Figure 1 suggests that the effect grows with the number of valence neutrons and/or the number of $\pi\nu$ pairs. It is thus of interest to find its magnitude in the ^{138}Cs nucleus. On one hand, fig. 1 suggests a non-zero value, on the other hand, the calculations of ref. [3] done

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Cs		?				
I		-400		-600		
Sb		0	-450			
¹³² Sn						
N =	83	84	85	86	87	

Fig. 1. Values of shifts (in keV) to $\pi d_{5/2}$ s.p. energy, which should be applied to reproduce properly the excitation energies in the indicated nuclei. The data are taken from refs. [3, 4, 6–9]. The value at ¹³⁵Sb is an average of values calculated in ref. [7] and using the SMPN set. See text for more explanations.

with SMPN interaction, which reproduced well low-spin levels in ¹³⁸Cs, were performed without any shift to the $\pi d_{5/2}$ orbital. We note that in ref. [3] although the isomeric nature of the 6^- state could be reproduced, its excitation energy was slightly under-predicted. The existing experimental data on ¹³⁸Cs, to be compared with the calculations, is rather limited. Therefore to get more precise answer one should first obtain more experimental information on the ¹³⁸Cs nucleus.

In this letter we report on the observation of a medium-spin cascade in ¹³⁸Cs decaying to the 6^- isomer at 80 keV. The new data were obtained from the measurement of prompt gamma radiation following spontaneous fission of ²⁴⁸Cm, performed using the EUROGAM 2 array [10], equipped additionally with four Low Energy Photon (LEP) detectors. We measured high-fold coincidences between gamma rays from fission fragments. The data were sorted into 3D histograms, which were used to produce doubly gated gamma spectra (see refs. [11, 12] for more details).

A useful technique to find new gamma cascades in fission fragments is based on the observation that in fission act a nucleus breaks into two fragments, which evaporate a few neutrons but not protons. Thus, in the spontaneous fission of ²⁴⁸Cm, Cs nuclei are produced in pairs with Nb nuclei. In addition 3.5 neutrons are evaporated from fission products, on average. All this happens in less than a femtosecond. Subsequently, the so-called prompt gamma rays are emitted from both fragments at the same time. Therefore by gating on gamma lines of Nb isotopes one can observe gamma rays from the complementary Cs isotopes in the gated spectra.

It is expected that the most abundant complementary fission fragment to ¹³⁸Cs in the spontaneous fission of ²⁴⁸Cm is the ¹⁰⁶Nb nucleus. Unfortunately, no prompt gamma cascades are known in ¹⁰⁶Nb. The heaviest Nb isotopes where such cascades are known is ¹⁰⁵Nb. This nucleus is produced together with ¹³⁸Cs when 5 neutrons are evaporated, which makes this process less likely, but still possible to observe. To search for prompt gamma rays in ¹³⁸Cs we thus gated on known lines from ¹⁰⁵Nb. A gamma spectrum, doubly gated on the 128 keV and 162 keV lines

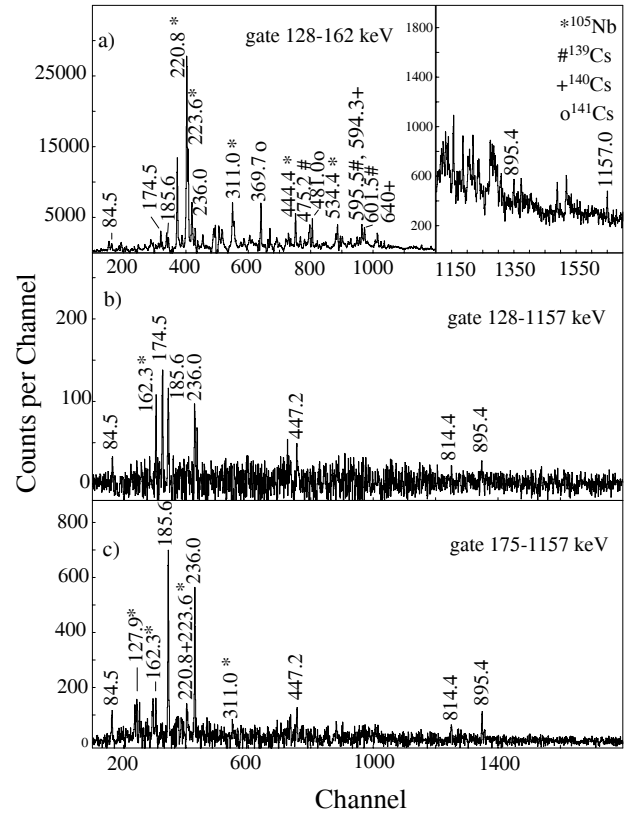


Fig. 2. Coincidence spectra of γ -rays following the fission of ²⁴⁸Cm, gated on lines in ¹⁰⁵Nb and ¹³⁸Cs. The lines are labeled with their energies in keV. See text for more explanations.

from ¹⁰⁵Nb [13] is shown in fig. 2a. Apart from the known lines in ¹⁰⁵Nb and ¹³⁹Cs, ¹⁴⁰Cs and ¹⁴¹Cs [14–16], one observes here a new gamma line at 1157 keV. A spectrum doubly gated on this new line and the 128 keV line, shown in fig. 2b, reveals new lines at 84, 175, 185 and 236 keV. A double gate on the 1157 keV and 175 keV lines is shown in fig. 2c, where one can see coincident lines at 84, 185, 236, 447, 814, 895 and 904 keV. Further gating allowed the construction of the decay scheme shown in fig. 3. Spins of the excited levels were proposed tentatively, based on the observed branching and the assumption that spins are growing with increasing excitation energy, as commonly observed in prompt gamma measurements from fission.

As discussed above the newly constructed decay scheme belongs to a cesium isotope. Its pattern is characteristic of excitations in a spherical nucleus. In our earlier studies we identified excitation schemes of ^{141,143,145}Cs [16]. The ¹⁴¹Cs and ¹⁴³Cs nuclei exhibit a collective behavior [17] with signs of octupole deformation. It is expected that heavier Cs isotopes also will be deformed. We also found an excitation scheme of ¹³⁹Cs [14], which, although spherical, shows signs of some collectivity. The new cascade is similar in character to the excitation scheme of ¹³⁷Cs [18]. We therefore propose that the new cascade belongs to its neighbour, ¹³⁸Cs. An analogous cascade was found in ¹³⁶I [19], the isotope of ¹³⁸Cs. As we have shown recently, the cascade in ¹³⁶I is based on the 6^- isomer, with the 7^- excitation of $\pi g_{7/2} \nu f_{7/2}$ dominating

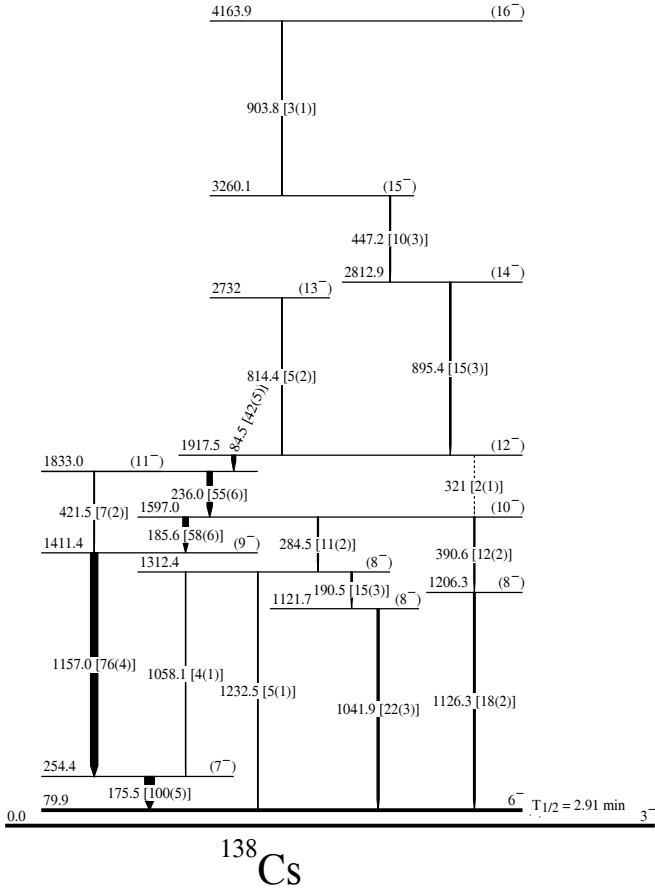


Fig. 3. Partial scheme of medium-spin excitations in ^{138}Cs , as obtained in the present work. Transition and excitation energies are given in keV. In square brackets relative prompt gamma intensities are shown, as observed in the spontaneous fission of ^{248}Cm .

configuration, located 42 keV above the isomer. In ^{138}Cs one may expect a similar excitation pattern. The new cascade is thus built on the known $T_{1/2} = 2.9$ min isomer with spin $I^\pi = 6^-$ and excitation energy of 79.9 keV [1] and the 7^- is located 175.5 keV above it.

To verify this hypothesis we performed unrestricted shell model calculations, where five protons were allowed to occupy the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ orbitals and the odd neutron was allowed on the $f_{7/2}$, $h_{9/2}$, $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $i_{13/2}$ orbitals. We used the SMPN set of two-body matrix elements [4] and the OXBASH computer code [20]. The results of the calculations are compared in fig. 4 with the experimental excitation energies, normalized to each other at the 3^- ground state.

In the calculations we varied the single-particle energy of the proton $d_{5/2}$ orbital to check its role in the neutron-rich nuclei, as discussed at the beginning of this letter. The change to the $\pi d_{5/2}$ s.p. energy (in keV) is marked in fig. 4 as D . The calculation was performed at D values of -300 , 0 , 100 and 300 keV. The calculated excitation energies are marked as circles in fig. 4. The data corresponding to the same level are linked by dashed lines. The calculations for spins up to 7^- are shown on an expanded energy scale.

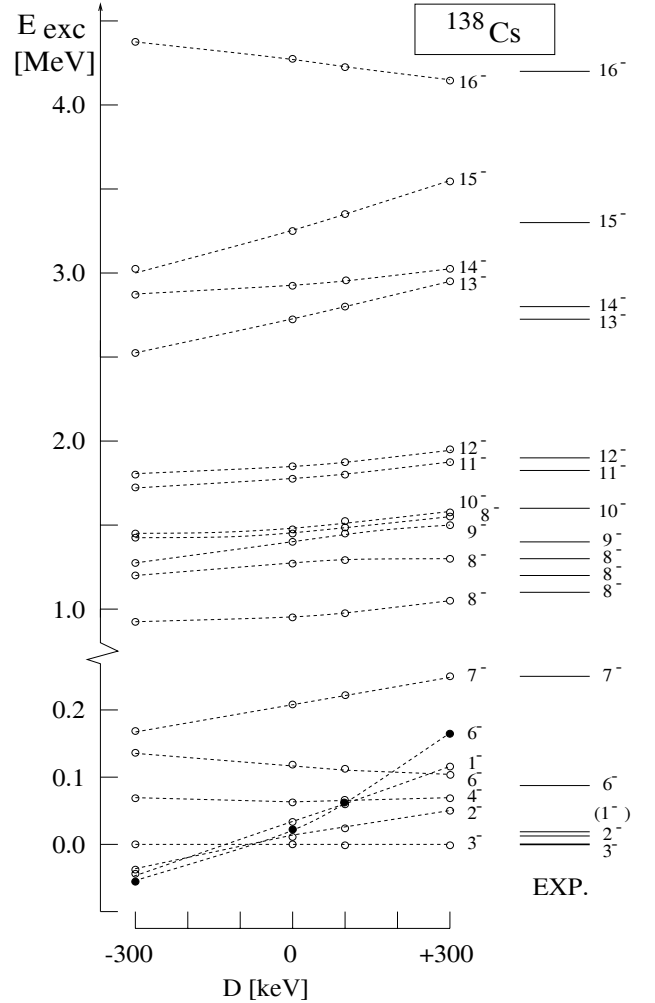


Fig. 4. Comparison of the calculated and the experimental excitation energies in ^{138}Cs . The calculation are performed as a function of the $d_{5/2}$ s.p. energy (see text for more explanations). The experimental data for the levels up to spin 6^- are taken from refs. [1, 2] and for higher-spin levels from this work.

The gross feature of the calculated scheme, rather independent of the D value, is a clear distinction between low-spin levels (up to spin 7^-), dominated by the $\pi g_{7/2}\nu f_{7/2}$ configuration (with essential $\pi d_{5/2}$ contribution) and higher-spin excitations. The calculated scheme corresponds very well to the experimental excitation pattern, where similar distinction is observed. We note that this pattern is similar to the one observed in the ^{136}I isotone.

Closer inspection shows that the description improves when the $\pi d_{5/2}$ s.p. energy increases and the optimum is reached at $D \approx 150$ keV. Again, as observed in the case of ^{136}I , one of the 6^- levels varies rapidly its energy as a function of D (it is marked by full circles in fig. 4). This 6^- state is dominated by the $\pi d_{5/2}\nu f_{7/2}$ configuration, which explains its behavior. The wave function of the 7^- state contains the odd proton in the $g_{7/2}$ orbital. We mention, though, that there is an upper limit to the $\pi d_{5/2}$ s.p. position, imposed by the observed half-life of the 6^- level. Above $D \approx 130$ keV the 4^- state comes below the 6^-

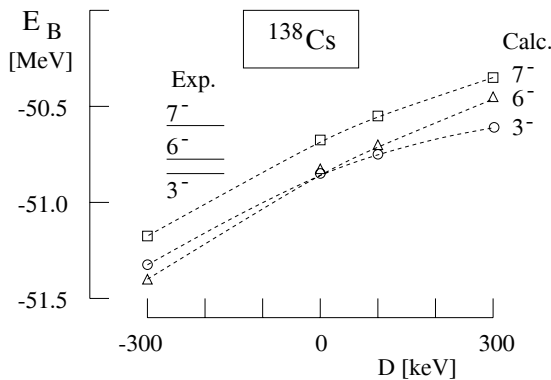


Fig. 5. Comparison of calculated and experimental binding energies in the ^{138}Cs nucleus. See the text for more explanations.

state leading to a half-life much shorter than the observed 2.9 min. For $D = 100$ keV the 6^- state will decay to the 3^- ground state by an $M3 + E4$ transition. After inclusion of the internal conversion effect, the half-life of the 6^- state comes to be about 1 hour (with standard values of g -factors and effective charges [4]), while that calculated with no shift of $\pi d_{5/2}$ yields a value of 13 min. So with $D = 100$ keV shift, although the energy of the 6^- level is reproduced better the wave function deteriorates.

What differs the ^{138}Cs case from other cases indicated in fig. 1 is that here the optimum reproduction requires the $\pi d_{5/2}$ s.p. energy to be *increased* relative to its position in ^{133}Sb . Figure 4 shows, again, that the $\pi d_{5/2}$ s.p. energy is a (surprisingly) convenient parameter to compensate for some unknown deficiencies of the shell model description in the ^{132}Sn region. However, the change to this energy, applied in the calculations, probably does not correspond to any real $\pi d_{5/2}$ s.p. energy change in nuclei. While one could consider the argument of refs. [7,8] about the neutron skin pushing the $\pi d_{5/2}$ down in energy, it would require some *anti* effect to push it up.

It was found that shell model calculations give too high binding energies (E_B) for the ground states in the ^{132}Sn region [4,21]. Decreasing the s.p. energy of the $\pi d_{5/2}$ orbital makes the situation even worse [6,9]. It is interesting to see that in ^{138}Cs , where the $\pi d_{5/2}$ orbital is not lowered, the calculated energies agree rather well with the experiment. This is illustrated in fig. 5 where we compare, on the “absolute” energy scale (binding energies, relative to the g.s. energy of ^{132}Sn), calculated and experimental energies for the three lowest levels in ^{138}Cs . While the distances between the levels in ^{138}Cs are best reproduced at $D \approx 150$ keV (see fig. 4), the absolute energies for the three discussed levels, calculated at $D = 150$ keV are slightly higher than experimental values. This result, combined with the observations for other nuclei [6,9], indicates that the overbinding grows with the increasing neutron number.

We have argued against the “neutron skin” hypothesis above. Nevertheless, this work supports the observation that there is a new, unexplained effect in the neutron-rich nuclei of the ^{132}Sn region. The “map” shown in fig. 1, en-

riched now by the $D \approx +100$ keV value at ^{138}Cs , suggests that the discussed effect concerning the $\pi d_{5/2}$ s.p. energy depends on the number of valence neutrons past the $N = 82$ line. At the beginning of this letter we also mentioned about a possible dependence on the number of $\pi\nu$ pairs. The new data on ^{138}Cs suggest, however, that such a dependence is less likely as can be deduced from the comparison of the $\pi d_{5/2}$ s.p. energy shifts in ^{138}Cs and ^{135}Sb . Consequently, the solution of the problem may require something else than correcting proton-neutron interactions in the region. The present work still does not provide the answer. New studies are required, preferably of the most neutron-rich rich nuclei, close to the $Z = 50$ closed shell, where, on one hand, the effect is expected to be clearly present and, on the other hand, the nuclei in question could be described in the framework of the shell model.

In summary, a medium-spin cascade was identified on top of the 6^- isomer in ^{138}Cs . The new cascade is well reproduced by shell model calculations using the SMPN set of two-body matrix elements proposed recently for the ^{132}Sn region. The best fit to the experimental data, including the ground state and the 80 keV isomer is obtained when the position of the $d_{5/2}$ orbital is increased by 100 keV, compared to its position in ^{133}Sb . This result again shows an important role of $\pi d_{5/2}$ s.p. energy in the region of ^{132}Sn , but the positive sign of the energy shift is an argument against the “neutron skin” hypothesis, proposed in other works, though we confirm that the effect depends on the number of valence neutrons.

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