Eur. Phys. J. A **16**, 11–15 (2003)
DOI 10.1140/epja/i2002-10104-y

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

First observation of the $\nu\,9/2[404]$ orbital in the A $\sim$ 100 mass region

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Received: 11 September 2002 /
Published online: 17 January 2003 –
Communicated by D. Schwalm

Abstract. A new band, populated by the spontaneous fission of ^{248}Cm and studied by means of prompt γ-ray spectroscopy using the EUROGAM2 array, was observed in ^{99}Zr. The 1038.8 keV band head with a half-life $T_{1/2} = 54(10)$ ns is interpreted as a K-isomer, corresponding to the 9/2[404] neutron-hole excitation. It is the first observation of this orbital in the mass $A \sim 100$ region. The quadrupole moment, $Q_0 = 3.9(3)$ eb deduced for the new band indicates a large deformation of $\beta_2 = 0.41$, which is produced by a specific shape-coexistence mechanism, known in other regions and now found in the $A \sim 100$ nuclei.

PACS. 23.20.Lv Gamma transitions and level energies – 21.60.Cs Shell model – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

For three decades the onset of deformation in the neutron-rich nuclei of the mass $A \sim 100$ region has remained one of the most interesting subjects in nuclear spectroscopy. The key question here concerns the structure of the deformed configurations observed in these nuclei. Numerous experimental observations indicate that the $h_{11/2}$ neutron orbital plays a crucial role. There are, however, calculation-based arguments, which indicate that the 9/2[404] neutron orbital is very close to the Fermi level, at a deformation $\beta \sim 0.3$ in Sr and Zr isotopes. An interesting question is how this strongly upsloping orbital affects the deformation. There are reports of two- and three-quasiparticle deformed configurations involving the $\nu\,9/2[404]$ orbital [1,2]. On the other hand, calculations of the 9/2[404] orbital position in ^{99}Sr and ^{101}Zr nuclei fail, predicting it to be well below the observed ground states. Therefore, a direct observation of the $\nu\,9/2[404]$ orbital in odd-N nuclei from the $A \sim 100$ region is of great importance. To our best knowledge, the 9/2[404] orbital has not been observed in this region.

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In this note we report the first observation of the 9/2[404] neutron orbital in the $A \sim 100$, neutron-rich nuclei and explain its influence on deformation. The orbital was discovered in the ^{99}Zr nucleus, from studies of coincidences of prompt γ-rays following the spontaneous fission of ^{248}Cm, measured using the EUROGAM2 array of anti-Compton spectrometers at Strasbourg. Since our previous study of this nucleus, using the same set of data [3], we have improved significantly our analysis methods [4], enabling observation of weaker effects.

Figure 1a shows a γ-ray spectrum double-gated on the 121.7 keV and 536.0 keV lines in ^{99}Zr, obtained from triple-gamma coincidences. Apart from the known lines of ^{99}Zr, and complementary barium isotopes, one can see a line at 381.1 keV. A spectrum double-gated on 536.0 keV and 381.1 keV lines, shown in fig. 1b, indicates that this line belongs to ^{99}Zr. There are also other new lines at 218.0, 251.1 and 283.3 keV clearly seen in this spectrum. Further gating revealed a new band in ^{99}Zr built on the 1038.8 keV level, as shown in fig. 2. The 1038.8 keV band head level has four decay branches of 188.5, 360.1, 381.1 and 786.8 keV and appears to be an isomer. This is seen in

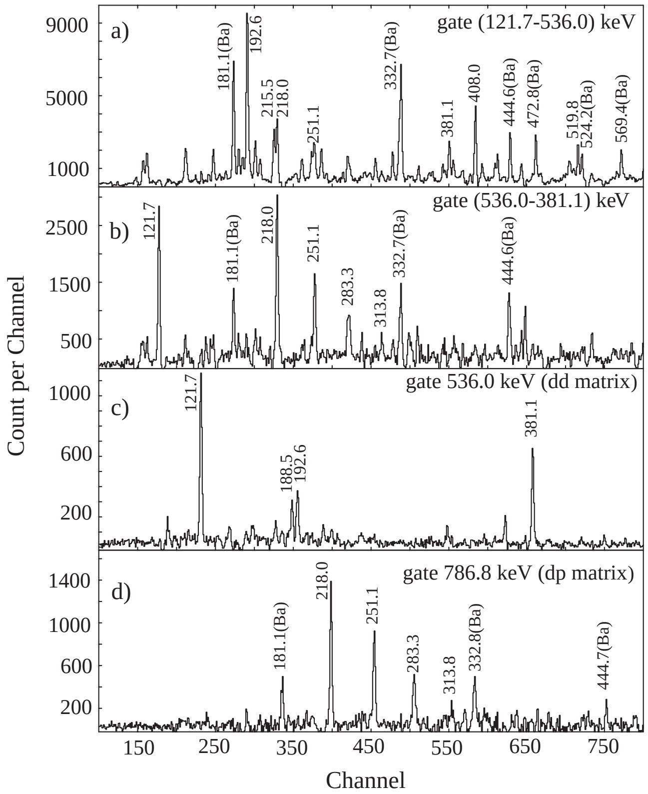

Fig. 1. Coincidence spectra of γ radiation following the fission of ^{248}Cm, gated on lines in ^{99}Zr.

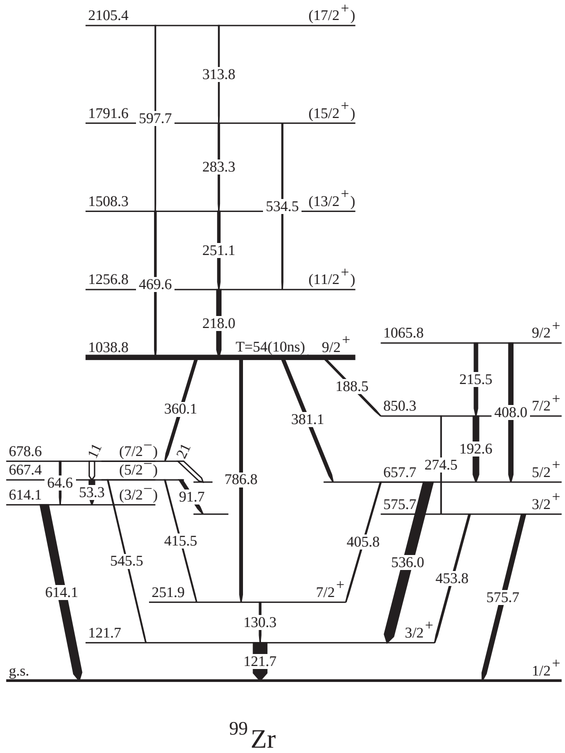

Fig. 2. Partial level scheme of ^{99}Zr, showing the new band based on the 1038.8 keV level, as obtained in the present work and several known levels in ^{99}Zr [3], which help the discussion.

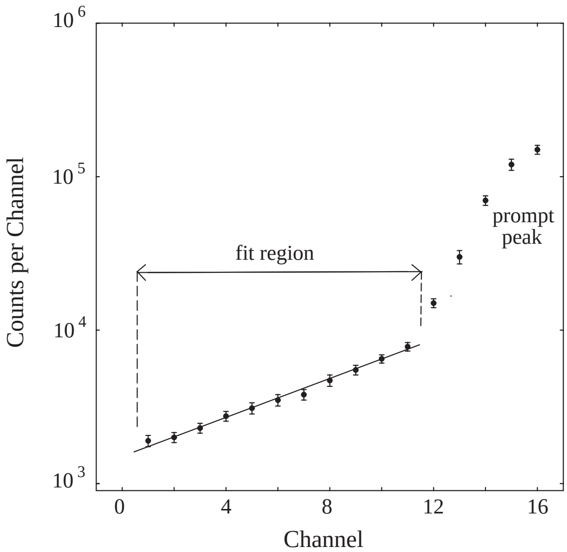

Fig. 3. Time spectrum gated on the 786.8 keV line of ^{99}Zr

fig. 1c, which displays a spectrum gated on the 536.0 keV transition in the "delay-delay" matrix (*i.e.* a matrix with a "delay" time window, $t > 100$ ns, imposed on all energies sorted into it). The spectrum shows 121.7, 188.5, 192.6 and 381.1 keV transitions in coincidence with the gate and the absence of other (prompt) transitions, observed otherwise in the 536.0 keV gate. Finally, fig. 1d shows a prompt spectrum gated on the 786.8 keV line in a "delay-prompt" matrix. One sees here lines above the isomer and prompt transitions from the complementary barium isotopes.

A time spectrum, gated on the 786.8 keV decay branch of the 1038.8 keV isomer is shown in fig. 3. The spectrum shows a slope corresponding to the half-life of the 1038.8 keV level. The prompt component is due to prompt contaminants of the 786 keV line from other fission products, mainly the 785 keV line of ^{106}Mo. There is, however, no delayed contaminant to the 786 keV line, as we checked (see also fig. 1d). The half-life of the 1038.8 keV level, deduced from the time spectrum shown in fig. 3 is $T_{1/2} = 54(10)$ ns. To obtain this value, we used the analysis methods and calibrations that are described in ref. [3]).

Table 1 shows branching ratios from the levels of the newly discovered band in ^{99}Zr. A partial half-life of 173(32) ns, deduced for the 381.1 keV decay branch of the 1038.8 keV isomer puts the upper limit of $I = 9/2$ for the spin of this level. Spin values lower than $I = 7/2$ were also rejected due to both the non-observation of decays to levels with spins lower than $I = 5/2$ and the rather strong population in fission of the new band, which indicates its near-yrast character.

To find the spin of the isomer we have measured angular correlations, using the techniques described in ref. [5]. The results, displayed in fig. 4, indicate a stretched quadrupole character of the 381.1 keV transition, considering the rather pure stretched-dipole character of the 536.0 keV transition evident from correlations with known

Table 1. Branching ratios for levels of the newly found band in ^{99}Zr.

Excited state (keV)	Transition energy (keV)	Transition intensity (rel. units)
1038.8	188.5	0.45(3)
	360.1	0.82(4)
	381.1	1.00(5)
	786.8	0.93(5)
1508.3	251.1	1.00(5)
	469.6	0.36(4)
1791.6	283.3	1.00(6)
	534.5	0.70(7)
2105.4	313.8	1.00(14)
	597.7	0.16(12)

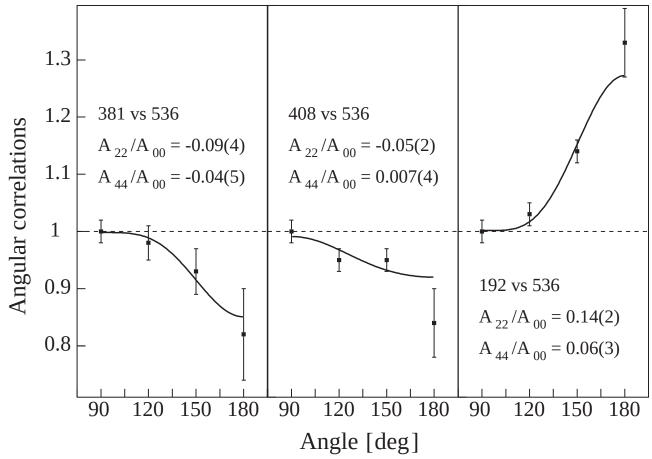

Fig. 4. Angular correlations for transitions of ^{99}Zr, as obtained in this work.

$\Delta I = 2$, 408.0 keV and $\Delta I = 1$, 192.6 keV transitions. Angular correlations indicate therefore a spin of $I = 9/2$ for the 1038.8 keV isomeric level. We could not measure angular correlations for the other levels of the new band due to the high complexity of the 218, 251 and 283 keV lines. The regular character of the band, with cross-over transitions suggests, however, the spins and parities as drawn in fig. 2.

Let us note that assuming a spin and parity $I^\pi = 7/2^+$ and $K = 7/2$ for the 1038.8 keV level allows $E2$ transitions to the $K = 3/2$ band. The $M1$ component of the 188.5 keV line has, in this case an $n = 1$ degree of K forbiddenness, and is neglected. The ratio of probabilities for 381.1 keV and 188.5 keV $E2$ transitions can be calculated from Alaga rules, giving $B^{\mathrm{cal}}(E2, 381.1\,\mathrm{keV})/B^{\mathrm{cal}}(E2, 188.5\,\mathrm{keV}) = 2.5$. This value differs significantly from the experimental ratio of $B^{\mathrm{exp}}(E2, 381.1\,\mathrm{keV})/B^{\mathrm{exp}}(E2, 188.5\,\mathrm{keV}) = 0.07(1)$ and allows, therefore, rejection of the $K = 7/2$ hypothesis. Note that the $I^\pi = 7/2^-$ spin-parity assignment to the 1038.8 keV isomer is unlikely due to the non-observation of any decay to the 667.4 keV level, contrary to the prediction of the Alaga rules.

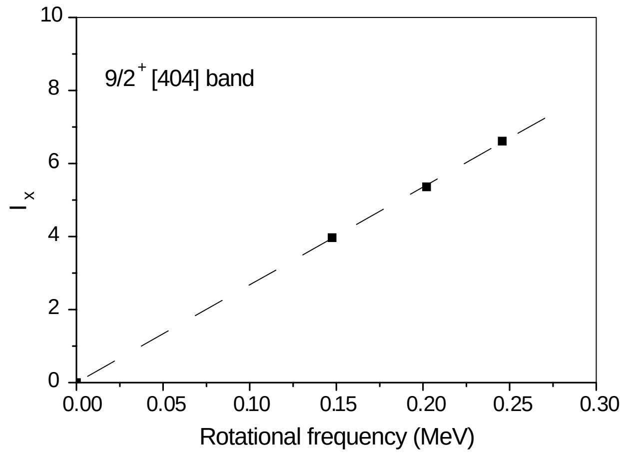

Fig. 5. Aligned angular momentum for the new $K = 9/2$ band based on the $9/2^+$, 1038.8 keV isomer in ^{99}Zr.

From the evidence presented above we conclude that the new band in ^{99}Zr is based on a level with spin and parity $I^\pi = 9/2^+$ and $K = 9/2$. The only neutron orbital in this region characterised by such quantum numbers is the $\nu\, 9/2[404]$ and we propose that this is the configuration of the 1038.8 keV isomer.

There is an additional argument supporting our proposition. It is expected that the 9/2[404] orbital will show very small alignment, because its spin is directed along the symmetry axis of the nucleus. In fig. 5 we have plotted the total aligned angular momentum, $I_x = \sqrt{(I + 1/2)^2 - K^2}$ for the new band and fitted a straight line to the experimental points, shown as the dashed line in fig. 5. The experimental points lie nearly exactly on the line, which is characteristic of rigid rotation. The moment of inertia of a nucleus, usually parametrized as $J = J_0 + J_1\omega^2$, has in such a case a negligible $J_1\omega^2$ component. Let us note that I_x can also be represented as $I_x = J\omega + i$, where the $J\omega$ term corresponds to the collective rotation and i is the aligned angular momentum of the valence particle. For the new band in ^{99}Zr, however the $J_1\omega^2$ can be neglected and $I_x = J_0\omega + i$ is represented by the straight line in fig. 5. Since this line goes very close to the (0,0) point, it is evident that the value of alignment i is close to zero, as expected for the 9/2[404] neutron orbital.

The isomerism of the 1038.8 keV level is caused by a difference in the K quantum number between the new band and bands to which it decays. In table 2. partial half-lives for the decay branches of the isomer are compared with their single-particle, Weisskopf estimates for $I^\pi = K^\pi = 9/2^+$. For all four transitions a considerable hindrance (H) is observed. Following the procedure of ref. [1] we calculated a hindrance per degree of forbiddenness, $(\log H)/n \approx 2$ for the 381.1 keV, $E2$ and 188.5 keV $M1$ decay branches to the band based on the $3/2^+$, 575.7 keV level with $K = 3/2$. The value obtained agrees well with the $(\log H)/n$ values observed for $M1$ and $E2$ transitions in this region [1,2].

One can estimate the quadrupole moment of the new band, because of the properties of the $\nu\, 9/2[404]$ "in-

Table 2. Properties of the transitions de-exciting the 1038.8 keV isomer in ^{99}Zr. $(\log H)/n$ values are not calculated for the 360.1 keV and 786.8 keV transitions due to the unknown K numbers of the final states (the 251.9 keV level corresponds to a spherical configuration whilst the negative-parity band in ^{99}Zr is highly aligned).

E_γ (keV)	Mult.	$T_{1/2}^{\text{part.}}$ (ns)	T_W (s)	H	$\frac{\log H}{n}$
188.5	$M1$	384(73)	3.3 10^{-12}	1.1 10^5	2.5
360.1	$E1$	211(40)	6.7 10^{-15}	3.1 10^7	
381.1	$E2$	173(32)	2.6 10^{-9}	6.8 10^1	1.8
786.8	$M1$	186(35)	4.6 10^{-14}	4.0 10^6	

truder" orbital, which is distinctly different from other neutron levels in this region and can hence produce rather clean configurations. For this orbital one gets a reliable estimate of g_K values, used in calculating gyromagnetic ratios $(g_K - g_R)/Q_0$. The g_K value is obtained from the formula

$$g_K = g_l + \frac{(g_s - g_l)}{2K} GMS(K \to K),$$

where $g_s = 0.6 g_s(\text{free}) = -2.296$ [6] and $GMS(K \to K)$ is a quantity, dependent on deformation, tabulated in ref. [6]. An important simplification is that for the $\nu\, 9/2[404]$ orbital $GMS(K \to K) = 1$, independent of deformation [6]. Therefore, for the 9/2[404] neutron orbital, where $g_l = 0$, one can calculate g_K simply as $g_K = \frac{g_s}{2K}$, where $K = 9/2$, yielding $g_K = -0.255$, a value obtained with good confidence, thanks to the simplified input. Experimental gyromagnetic ratios, $|g_K - g_R|/Q_0$ were derived for levels in the new $K = 9/2$ band in ^{99}Zr taking branchings from table 1 and following the calculation procedure described in ref. [7]. The values obtained in this way are 0.11(1), 0.12(1) and 0.30(12) for the $13/2^+$, $15/2^+$ and $17/2^+$ band members, respectively. For the new $K = 9/2$ band we take the average experimental value, denoted here as $\langle g^{\text{exp}} \rangle$, of 0.116(7). This value is used to estimate the quadrupole moment from the relation $Q_0 = |g_K - g_R|/\langle g^{\text{exp}} \rangle$. Assuming $g_R = 0.2\ \mu_N$, in accordance with ref. [7] and taking $g_K = -0.255\ \mu_N$, we obtain a value of $Q_0 = 3.9(3)$ eb.

From the quadrupole moment one can estimate the deformation parameter, β_2, using the standard formula $\beta_2 = (91.7 Q_0)/(Z A^{2/3})$ [8]. For the new band in ^{99}Zr we obtain $\beta_2 = 0.41(3)$. Interestingly, the deformation of the new band, based on the *upsloping* $\nu\, 9/2[404]$ orbital is significantly larger than in the other two deformed bands, previously found in ^{99}Zr [3]. For the $3/2^-$ band based on the 614.1 keV level in ^{99}Zr [3] we found $\beta_2 = 0.28(1)$. Also the $3/2^+$ band in ^{99}Zr, based on the 575.7 keV level, has smaller deformation. This is indicated by the kinematic moment of inertia, $J = J_0 + J_1\omega^2$, where we obtain $J_0 = 16\ \hbar^2\text{MeV}^{-1}$ and $J_1 = 100\ \hbar^4\text{MeV}^{-3}$, while for the $9/2^+$ band in ^{99}Zr the coefficents are $J_0 = 27\ \hbar^2\text{MeV}^{-1}$ and $J_1 = 0\ \hbar^4\text{MeV}^{-3}$.

This, somewhat unexpected, appearance of a large deformation at $N = 59$ can be explained by recalling the shape-coexistence mechanism [9], which was observed in other regions but not in the $A \sim 100$ neutron-rich nuclei [10]. Out of the three deformed configurations in ^{99}Zr, the $3/2^+$ based on the 575.7 keV level is the lowest one, corresponding to the "ground structure" for the deformed bands in ^{99}Zr. It probably corresponds to the configuration where two neutrons are in the deformation driving 1/2[550] orbital originating from the $\nu h_{11/2}$ shell, two further neutrons are in the 9/2[404] upsloping orbital and the valence neutron occupies the 3/2[411] orbital of the $\nu g_{7/2}$ shell (possibly mixed with the 3/2[422] orbital). The next deformed configuration in ^{99}Zr can be obtained by promoting the odd neutron to the close-lying 3/2[541] orbital, without moving core particles. This configuration corresponds to the $3/2^-$ band based on the 614.1 keV level. Both $3/2^+$ and $3/2^-$ bands have comparable deformations, corresponding to the same core configuration. The $9/2^+$ band, however, placed about 0.4 MeV above the previous two has a different core structure. It can be obtained from the $3/2^-$ band configuration by promoting one of the pair of neutrons in the 9/2[404] subshell into the 3/2[541] subshell. In this way four neutrons are placed in the core, on two deformation-driving orbitals originating from the $h_{11/2}$ shell, and only one neutron in the upsloping 9/2[404] orbital. Both, the increase in the occupation of the deformation-driving $h_{11/2}$ shell and a decrease, by 50%, in the occupation of the upsloping 9/2[404] orbital contribute to the increased deformation of the $9/2^+$ band.

Finally, let us note that the $\nu\, 9/2[404]$ excitation is located about 1 MeV above the ground state of ^{99}Zr, far higher than predicted by calculations [2]. As has been pointed out in ref. [2], the position of the $\nu\, 9/2[404]$ orbital is a very sensitive function of the spin-orbit splitting. The newly discovered position of the $\nu\, 9/2[404]$ orbital in ^{99}Zr provides, therefore, a crucial test of such calculations.

In summary, we have found at 1038.8 keV in ^{99}Zr a $T_{1/2} = 54(10)$ ns, K-isomer to which a spin and parity of $I^\pi = 9/2^+$ and $K = 9/2$ have been assigned. This state corresponds to the 9/2[404] neutron excitation, observed in the $A \sim 100$ region for the first time. For the new band a quadrupole moment $Q_0 = 3.9(3)$ has been deduced, indicating a deformation of $\beta_2 = 0.41(3)$, larger than that observed for the other two deformed bands in ^{99}Zr. We suggest that the new, strongly deformed structure has four neutrons in the deformation-driving $h_{11/2}$ shell, while the other two have only two neutrons in this shell. Our finding extends the observation of the occurence of a shape-coexistence phenomenon, related to strongly upsloping orbitals to a new region of $A \sim 100$ neutron-rich nuclei.

The authors wish to thank Dr. Ragnar Bengtsson for helpful discussions. The work was supported by the French-Polish IN2P3-KBN collaboration No. 01-100, by the UK EPSRC under grant No. GRH71161 and by the US Department of Energy under contract No. W-31-109-ENG-38. The authors are also indebted, for the use of ^{248}Cm to the Office of Basic Energy Sciences, US Department of Energy, through the transplutonium element production facilities at the Oak Ridge National Laboratory.

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