Excited Superdeformed K$^\pi$ =0$^+$ Rotational Bands in β-Vibrational Fission Resonances of ^{240}Pu ◇

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The detailed spectroscopic information obtained in conversion electron [1] and γ spectroscopy [2] for the lowest phonons in the second minimum of ^{240}Pu has been extended to the third and fourth β-vibrational phonon by transmission resonance spectroscopy [3] (for the proton spectrum and details on the experiment and analysis see [4]). Two vibrational resonance groups centered at E^*=4.6 MeV and 5.1 MeV, and attributed to the excitation of three and four β-phonons, were resolved into individual substates, which could be assigned to the low-spin members of $K^\pi = 0^+$ superdeformed rotational bands.

Individual dynamical moments of inertia could be extracted for the first time in the high excitation energy region of the 4.6 MeV resonance group for the three well separated K=0$^+$ bands with band head energies of E^*=4434, 4526 and 4625 keV. For the other rotational bands of this resonance group, as for the energy region above E* $\sim$5 MeV only an average moment of inertia could be determined, respectively. The resulting moments of inertia are shown in Fig. 1 together with those for the SD ground state rotational band [10] and the low-lying collective excitations in the second minimum that were observed in recent γ-ray spectroscopy [2] and conversion electron experiments [1], respectively.

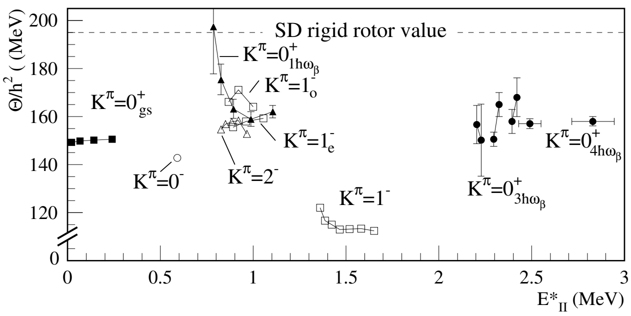

Fig. 1: Moments of inertia of rotational bands in the second minimum of ^{240}Pu as a function of the excitation energy E$_{II}$ in the second minimum. Subscripts 'e' and 'o' denote moments of inertia that have been extracted for the even- and odd-spin members of the respective rotational band.

The moments of inertia of the SD ground state band and the higher phonon bands show a surprising agreement, while larger variations arise for the low-lying excited SD bands. One might have expected that the moments of inertia for the bands built on the third and fourth β-vibrational phonon might be closer to the rigid body moment of inertia because of the reduced pairing at higher excitation energies. However, this is not observed experimentally. While in the first minimum $K^\pi = 0^+$ vibrations show strong admixtures of pairing vibrations we expect much less admixtures in the second minimum as a significantly larger collectivity of β-vibrations in the second minimum was observed [1]. Therefore pairing vibrations and blocking could be reduced, which might explain the observed preservation of the moment of inertia of the SD ground state band.

In Fig. 2 all presently known vibrational band heads in the second minimum of ^{240}Pu are shown.

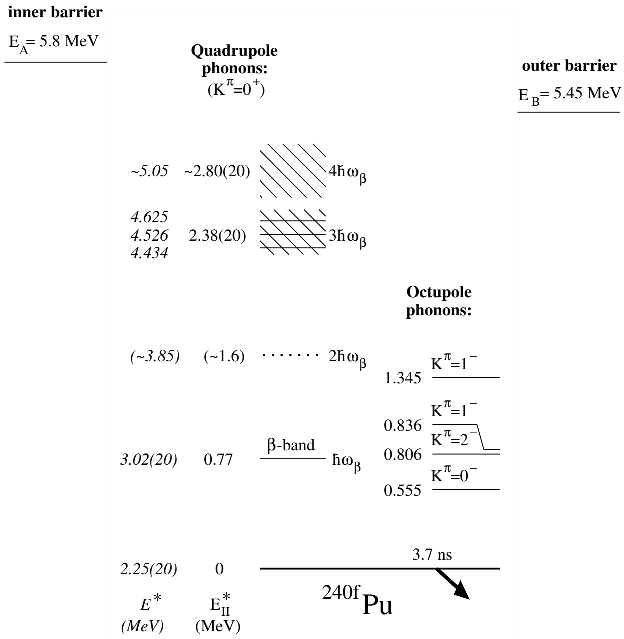

Fig. 2: Vibrational excitations in the second minimum of ^{240}Pu. The low-lying collective band heads have been observed in Ref. [2] and [1].

Aiming at a deduction and interpretation of the spin-dependent fission probabilities, we discuss in the following relevant properties, which are compiled in Table 1, analog to Ref. [5]. The relative fission cross sections $\alpha_f(J^\pi)$ were obtained from the fit of the proton energy spectra. In the maximum of the 5.1 MeV resonance we obtain (taking an average of the values from our measurement and that of Ref. [5]) a dominance of the 2$^+$ states with $\alpha_f = 0.66 \pm 0.05$, which nicely agrees with the value of 0.67 ± 0.06 obtained by Britt et al. [6].

The relative (d,p)- compound cross sections $\alpha_c(J^\pi)$ at E$_d$ = 12.5 MeV were obtained in DWBA-calculations for deformed nuclei, where the final Nilsson orbitals were distributed over the compound nuclear levels by strength functions [5]. They agree quite well for the 5.1 MeV resonance with values of $\alpha_c(J^\pi)$ calculated in Ref. [7] for E$_d$ = 13.0 MeV. The excitation energy dependence of $\alpha_c(J^\pi)$ for states in the 4.6 MeV resonance was taken from Ref. [7].

For the energy- and spin-averaged fission probabilities at the maxima of the two resonances values of $\langle P_f(5.1\text{ MeV})\rangle_{\max} = 0.10$ and $\langle P_f(4.6\text{ MeV})\rangle_{\max} = 2.0 \cdot 10^{-3}$ could be deduced in Ref. [8]. While the upper resonance could be well reproduced in a theoretical description assuming K$^\pi$=0$^+$, for the lower resonance also a

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contribution from a 0^- resonance was discussed. However, a satisfactory description of this resonance could also be achieved with pure $K^\pi = 0^+$ characteristics, assuming a fragmentation of the third β phonon over states with energies of 4.2 MeV (30%), 4.5 MeV (45%) and 4.7 MeV (25%). Using $\langle P_f \rangle$, the average spin dependent fission probability $\langle P_f(J^\pi)\rangle$ can be calculated by $\langle P_f(J^\pi)\rangle = \langle P_f\rangle \cdot \alpha_f(J^\pi)/\alpha_c(J^\pi)$. The level spacings D_I given in the fifth column of Tab. 1 are calculated with the back-shifted Fermi gas formula [9]. However, for the level spacing in the second minimum, D_{II}, the restriction to $K^\pi = 0^+$ bands, in contrast to earlier publications [5,10], causes 0^+, 2^+ and 4^+ levels to have the same level density. The numbers given in Table 1 are experimentally determined by the fit procedure described in [4,3]. For the FWHM W_{cII} of the fission probability of class-II compound levels the relation

$$W_{cII} = \frac{D_{II}}{\pi} \cdot arcos\left(1 - \frac{2\langle P_f(J^\pi)\rangle^2}{1-\langle P_f(J^\pi)\rangle^2}\right)$$

is deduced in Ref. [5] under the assumption that $\Gamma_{cII} \ll D_{II}$. As long as $\langle P_f(J^\pi)\rangle$ is smaller than $\sqrt{(1/2)}$ this width W_{cII} can be determined. For larger values of $\langle P_f(J^\pi)\rangle$ the class-II levels overlap too strongly. We used this relation to calculate the W_{cII} widths given in Table 1. We cannot calculate a W_{cII}-value for the 0^+ levels in the centre of the 5.1 MeV resonance, however, within the experimental error of $\langle P_f(J^\pi)\rangle$ a value of $\geq$15 keV is estimated. Therefore, a fit with $K^\pi = 0^+$ bands in the upper resonance still appears reasonable.

The energy and spin dependence of the averaged fission probability $\langle P_f(J^\pi)\rangle$ can be explained by: (i) a rather complete K-mixing in the first well, (ii) a K-conservation in the second well and (iii) the competition between γ-decay in the first well and fission through the double-humped barrier. The processes can be described by a width Γ or by a transmission coefficient T, which are connected by: $T = (2\pi/D)\cdot\Gamma$, where D is the level spacing of states of the appropriate spin and parity. The γ-"transmission coefficient" $T_{\gamma I}(J^\pi) = (2\pi/D_I(J^\pi))\cdot\Gamma_\gamma^{J^\pi}$ increases with spin and excitation energy, while the decay width $\Gamma_\gamma^{J^\pi}$ is $\approx$ 23 meV at 5 MeV [5] and changes little with excitation energy (10 meV/MeV [11]), spin J, spin projection K and parity [11]. The double-humped fission barrier predominantly selects $K^\pi = 0^+$ states for transmission resonances for a given J-value in the first well. For the lower 4.6 MeV resonance the K-components with $K \neq 0$ decay predominantly by γ-decay and the decrease of $\langle P_f(J^\pi)\rangle$ for $K^\pi = 0^+$ states with increasing spin J is approximately proportional to $1/(2J+1)$. For the upper 5.1 MeV resonance the decay by fission of $K^\pi = 0^+$ states is faster than the γ-decay (or comparable). Thus the spread of $\langle P_f(J^\pi)\rangle$ with spin is reduced at the upper resonance, explaining also the smooth increase of the I_{2+}/I_{0+} ratio with excitation energy. The fission probabilities $\langle P_f(J^\pi)\rangle$ are strongly spin dependent, but the effective transmission $\langle T_f(J^\pi)\rangle = \langle P_f(J^\pi)\rangle \cdot T_{\gamma I}(J^\pi)/(1-\langle P_f(J^\pi)\rangle)$ through the barriers turns out to be rather spin independent. This is expected, because the barrier heights vary little for different J members of a rotational band with $K^\pi = 0^+$. When multiplying the $\langle T_f\rangle$ values for the 4.6 MeV resonance with 300 the values for the different spins of the 5.1 MeV resonance are nicely reproduced. Though $\langle P_f(J^\pi)\rangle = \langle \Gamma_{fI}(J^\pi)/(\Gamma_{fI}(J^\pi)+\Gamma_{\gamma I}(J^\pi))\rangle \neq \langle\Gamma_{fI}\rangle/(\langle\Gamma_{fI}\rangle+\langle\Gamma_{\gamma I}\rangle)$, the relation can be recovered with a fluctuation factor F which may be smaller than 1 by up to 30% [11]:

$\langle P_f(J^\pi)\rangle = (F\cdot\langle\Gamma_{fI}\rangle)/(\langle\Gamma_{fI}\rangle+\langle\Gamma_{\gamma I}\rangle)$

For ^{240}Pu F is close to 1 and the effective barrier transmission coefficient is a useful, easy to interprete quantity.

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Resonance: 5.1 MeV	J^π	$\alpha_f(J^\pi)$	$\alpha_c(J^\pi)$	$\langle P_f(J^\pi)\rangle$	D_I (all K) (keV)	D_{II} ($K^\pi = 0^+$) (keV)	W_{cII} (keV)	$T_{\gamma I}(J^\pi)$	$\langle T_f(J^\pi)\rangle$
	0^+	0.19(3)	0.024	0.79(12)	0.175	21	≥15	$8.3\cdot10^{-4}$	$3.0\cdot10^{-3}$
	2^+	0.66(5)	0.14	0.47(3)	0.039	21	7.5	$3.7\cdot10^{-3}$	$3.3\cdot10^{-3}$
	4^+	0.15(5)	0.08	0.19(6)	0.027	21	2.6	$5.4\cdot10^{-3}$	$1.3\cdot10^{-3}$

Resonance: 4.6 MeV	J^π	$\alpha_f(J^\pi)$	$\alpha_c(J^\pi)$	$\langle P_f(J^\pi)\rangle$	D_I (all K) (keV)	D_{II} ($K^\pi = 0^+$) (keV)	W_{cII} (keV)	$T_{\gamma I}(J^\pi)$	$\langle T_f(J^\pi)\rangle$
	0^+	0.31(6)	0.015	0.042(5)	0.51	96	2.2	$2.3\cdot10^{-4}$	$1.0\cdot10^{-5}$
	2^+	0.59(6)	0.12	0.0098(9)	0.11	96	0.6	$1.1\cdot10^{-3}$	$1.1\cdot10^{-5}$
	4^+	0.10(5)	0.07	0.0029(13)	0.08	96	0.2	$1.5\cdot10^{-3}$	$0.4\cdot10^{-5}$

Table 1: Spin dependent properties of the two β-vibrational fission resonances in ^{240}Pu around E^* =4.6 MeV and 5.1 MeV. $\alpha_f(J^\pi)$ ($\alpha_c(J^\pi)$) is the normalized relative fission (compound) cross section. $\langle P_f(J^\pi)\rangle$ is the average spin dependent fission probability, while D_I is the (calculated) level spacing for all K-values in the first minimum and D_{II} the (experimentally determined) level spacing in the second minimum ($K^\pi = 0^+$). W_{cII} is the width (FWHM) of the fission probability of class-II compound levels. In addition the γ-transmission coefficient $T_{\gamma I}$ in the first well and the effective transmission coefficient $\langle T_f(J^\pi)\rangle$ are given.