MULTIPLE REFLECTION ASYMMETRIC TYPE BAND STRUCTURES IN ^{220}Th AND DINUCLEAR MODEL*

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(Received February 9, 2011)

The lowest negative parity bands in ^{220}Th are analysed within the dinuclear system model. The model is based on the assumption that the cluster type shapes are produced by the collective motion in the mass-asymmetry coordinate. The observed excitation spectrum, angular momentum dependence of the parity splitting and the staggering behaviour of the $B(E1)/B(E2)$ ratios are described.

DOI:10.5506/APhysPolB.42.481
PACS numbers: 21.60.Ev, 21.60.Gx

The main idea of the cluster model developed in [1] is that a dynamics of a reflection asymmetric collective motion can be treated as a collective motion of nucleons between two clusters or as a motion in a mass-asymmetry coordinate. Such collective motion simultaneously creates deformations with even and odd-multipolarities [1]. As shown in our calculations, the α-cluster system $^{A}Z \rightarrow ^{(A-4)}(Z-2) + ^{4}$He gives a significant contribution to the formation of low-lying nuclear states. Within this approach, the existing experimental data on the angular momentum dependence of the parity splitting in the excitation spectra and the multipole transition moments of the low-lying alternating parity states in many odd and even actinides are well described. The predictive power of our model was demonstrated to be rather high [1]. To describe the properties of low-lying collective states related to the reflection asymmetric collective mode and characterized by non-zero values

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", August 30–September 5, 2010, Zakopane, Poland.

of K in the framework of the cluster approach, we should take into account intrinsic excitations of the clusters forming a state under consideration. In this case a simultaneous creation of an α-particle on the surface of the heavy fragment and a quadrupole wave can create a configurations without axial symmetry. The aim of the present paper is the formulation of simple model which gives a quantitative description of the low-lying positive and negative parity bands in the spectra of nuclei like ^{220}Th.

The degrees of freedom chosen to characterize a system with nearly spherical heavy cluster are related to the description of the rotation of the DNS as a whole, the quadrupole oscillations of heavy fragment, and the transfer of nucleons between the fragments. The Hamiltonian of the model is presented in the form $\hat{H} = \hat{H}_0 + \hat{V}_{\rm int}$, where

$$\begin{aligned} \hat{H}_0 &= \hbar\omega(\xi)\hat{n} + \frac{\hbar^2}{2\mu(\xi)R_m^2}\hat{L}^2 - \frac{\hbar^2}{2B_\xi}\frac{1}{\xi}\frac{\partial}{\partial\xi}\xi\frac{\partial}{\partial\xi} + U_0(\xi)\,, \\ \hat{V}_{\rm int} &= V_0\xi\sum_\mu \alpha^*_{2\mu}Y_{2\mu}(\theta,\phi)\,. \end{aligned} \tag{1}$$

As assumed here the heavy cluster performs harmonic quadrupole oscillations around the spherically symmetric shape with frequency $\hbar\omega$, while the light cluster stays in its ground state. The transfer of nucleons between clusters is described by means of mass-asymmetry variable $\xi = 2A_2/A$, where A_2 is the mass of the light cluster. The value of internuclear distance $R = R_m(\xi,\alpha_{2\mu})$ is set to be equal to the minimum of the potential in R for a given values of ξ (touching configuration of the clusters [2]), $\mu(\xi) \approx m_0A\xi/2$ is the reduced mass of the DNS, m_0 is the nucleon mass, $\hat{n}$ is the operator of the number of the quadrupole phonons of heavy cluster, $\alpha_{2\mu}$ describes quadrupole oscillations of the surface of the heavy fragment and $\hat{L}^2$ is the operator of the square of angular momentum of the relative rotations of two fragments. The procedure of calculation of mass tensor B_ξ is given in [3]. We take $B_\xi = 10\times10^5\ m_0\ {\rm fm}^2$. In order to define $U(\xi)$ and $\hat{V}_{\rm int}$ we calculate the potential energy of the dinuclear system as

$$U(R_m,\xi,\alpha_{2\mu}) = B_1 + B_2 - B_{12} + V(R_m,\xi,\alpha_{2\mu}) + \frac{\hbar\omega_R(\xi)}{2}\,, \tag{2}$$

where, B_1, B_2 and B_{12} are the binding energies of the fragments and the compound nucleus, respectively, and $\hbar\omega_R(\xi)/2$ is the energy of the zero-order vibrations in R around equilibrium value R_m. The nucleus–nucleus potential in (2) is the sum of the Coulomb and the nuclear interaction potential. The nuclear interaction potential is obtained within the double-folding procedure using density dependent nucleon–nucleon interaction [2]. To simplify the calculations, the potential energy $U(R_m,\xi,\alpha_{2\mu})$ is expanded in degrees of $\alpha_{2\mu}$ up to the linear order. The mass-asymmetry ξ is treated as a continuous variable and a smooth parametrization of the potential $U(R_m, \xi, \alpha_{2\mu})$ is used

$$U(\xi) + \frac{\hbar\omega_R(\xi)}{2} = U_0(\xi) + V_0\xi \sum_{\mu} \alpha^*_{2\mu} Y_{2\mu}(\theta, \phi) ,$$
$$U_0(\xi) = U(\xi = 0) + \sum_{k=1}^{k=3} a_{2k}\xi^{2l} , \qquad (3)$$

where parameters a_{2k} are determined by the experimental ground-state energy, the values of $U(\xi) + \hbar\omega_R(\xi)/2$ for $\xi = \xi_\alpha$ and $\xi = \xi_{Li}$, and by the requirement of potential minimum for alpha-particle DNS in the case of $U(\xi_\alpha) + \hbar\omega_R(\xi_\alpha)/2 < 0$. For the potential energy of the α-particle DNS $U_{\xi_\alpha} = -2.1$ MeV. The value of $\hbar\omega_R(\xi_\alpha) = 6$ MeV is determined for the potential V in R. The potential energy at $\xi = 0$ and the characteristics of the quadrupole vibrations of the heavy fragment ($\hbar\omega_0$ and β_0) cannot be determined in the model and considered as parameters. They are fixed as to reproduce the experimental energies of the lowest 0^+ and 2^+ states and the experimental value of reduced transition probability between these states $B(E2, 2^+ \rightarrow 0^+)$. Note, that there are no free parameters related to the reflection-asymmetric deformation of the nucleus as well as for to the dynamical moment of inertia.

The results of calculations of the energy spectra of the ground state band and the two lowest negative parity bands in ^{220}Th are presented in Fig. 1 together with the available experimental data [4]. One can see the agreement between the calculated and experimental spectra. In the experiment, the lowest negative parity band is seen starting from the state $I = 5^-$. The states with $I = 1^-$ and $I = 3^-$ are not seen. This leaves an open question about the band head of negative parity band. If one assumes that the first negative parity band has an octupole one-phonon origin then the band should start with $I = 3^-$. In this case the lowest $I = 1^-$ is expected to be two-phonon state with energy approximately given as a sum $E_{1^-} \approx E_{3^-} + E_{2^+}$, *i.e.* $I = 1^-$ is expected above $I = 3^-$ state. If $I = 3^-$ is an octupole state there should be significant $E3$ transitions from this state to the ground state and from $I = 5^-$ to $I = 2^+$ state which are not observed experimentally. Contrary, in our model a dynamical octupole deformation of the whole nucleus is generated by an appearance of the mass asymmetric configurations which has simultaneously a quadrupole deformation. For this reason the model predicts an appearance of the 1^- state below $I = 3^-$. If the model is correct this suggests that the lowest states of the band $I = 1^-$ and $I = 3^-$ are experimentally missed.

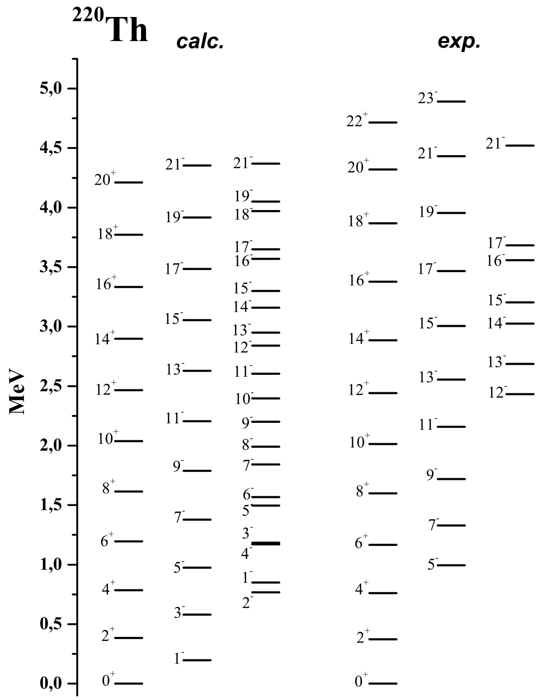

Fig. 1. Calculated and experimental level scheme of ^{220}Th. Experimental energies, spin and parity assignments are taken from [4].

The important feature of the spectra at low energy is an appearance of the second excited negative parity band which contains the states of the even and odd angular momenta. In the heavier deformed isotopes of Th and U the second negative parity bands are seen up to low angular momentum. Our calculations show [5] that these bands can be assigned to be second negative parity bands revealed in the calculations. This allows us to conclude that the same holds for the case of ^{220}Th considered. However, there are no straightforward proofs that second negative parity band obtained in the calculation can be related to the experimentally seen band started from 12^- in ^{220}Th. Dependence of the experimental and calculated values of a parity splitting in the ground state and the first negative parity bands, treated as a unified alternating parity band, on angular momentum is illustrated in Fig. 2. It is seen from the figure that for low angular momenta the parity splitting is positive and becomes negative with angular momentum increase. There is an experimental indication that the parity splitting starts to increase again around spin $I = 20$. In our model the increase of parity splitting at high angular momentum can be described by setting the frequency $\hbar\omega$ and the moment of inertia μR_m^2 slowly increasing with I (dashed line in Fig. 2).

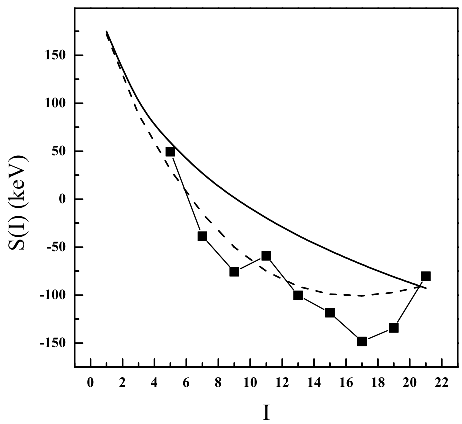

Fig. 2. Calculated (lines) and experimental [4] (solid squares connected by lines) values of parity splitting. Dashed line represents the calculation with angular momentum dependent moment of inertia $\mu R_m^2 \to \mu R_m^2(1 + 0.00023I(I+1))$, and frequency $\hbar\omega \to \hbar\omega(1 + 0.003I(I+1))$.

The $B(E1)/B(E2)$ ratio as a function of an initial angular momentum is presented in Fig. 3. Calculated ratios for the odd initial angular momentum (*i.e.* for transitions from the states of the negative parity) lie systematically lower than the ratios for the even initial angular momentum (transitions from the state of the ground state band) because the $B(E1)$ transitions from the state of negative parity to the state of positive parity are hindered. This is in agreement with the experimental data besides two data points at

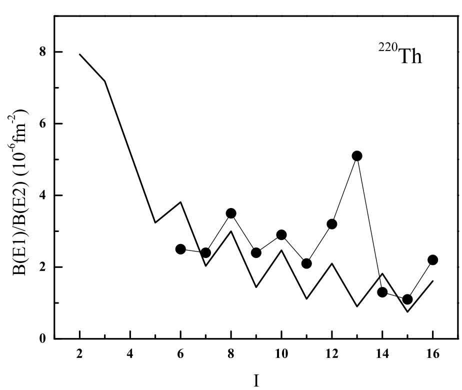

Fig. 3. $B(E1)/B(E2)$ ratio as a function of the initial angular momentum for transitions in the ground and the first negative parity bands. Experimental values (closed circles) are taken from [4].

13^- and 14^+. As mentioned in [4], the large value of $B(E1)/B(E2)$ ratio at 13^- can be attributed to the loss of $E2$ strength in the back bending. The rather small $B(E1)/B(E2)$ value for the 14^+ attributed to the spread of $E1$ strength due to the presence of two 13^- final states.

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