Secondary maximum in octupole correlations in the actinides near ^{238,240}Pu

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(Received 16 December 1999; published 29 March 2000)

The systematics of the lowered energies of the 1^- states and the lowered hindrance factors in α decay populating these 1^- states suggest an increased octupole correlation for Pu and U nuclei with 144 and 146 neutrons.

PACS number(s): 21.10.Re, 23.60.+e, 27.80.+w, 27.90.+b

Just beyond the double spherical closed shells in ^{208}Pb, the $g_{9/2}$ and $j_{15/2}$ neutron orbitals and the $f_{7/2}$ and $i_{13/2}$ proton orbitals are energetically very close together and close to the Fermi surface. The combination of these low lying orbitals gives rise to low-energy $K^\pi = 3^-$ two quasiparticle configurations which form the microscopic basis for stable octupole deformation. The energetic position of these orbitals reaches an especially favorable position for $^{224}_{88}$Ra$_{136}$. Indeed, the $1^-, 3^-, 5^-, \ldots,$ rotational band corresponding to the octupole degree of freedom is observed beginning at 215.9 keV in this nucleus, the lowest observed of any even-even nucleus (see Fig. 1). Other negative-parity bands are observed almost as low in neighboring even-even nuclei. As a result, the early suggestion of stable octupole deformation [1] was given much greater credence for a range of nuclei with $A \sim 220$–230. This resulted from a large number of experiments which established some of the criteria for octupole deformation (see Ref. [2]). These included (a) the observation of parity doublets (rotational bands with nearly degenerate states of the same spin but opposite parity) for odd-A nuclei, and ground state rotational bands approaching but not achieving the spin sequence $0^+, 1^-, 2^+, 3^-, 4^+, 5^-, \ldots,$ in even-even nuclei; (b) decoupling parameters for $K^\pi = 1/2^+$ bands in odd-A nuclei which approach the same absolute value but have opposite signs; (c) magnetic moments for parity doublets in odd-A nuclei which have the same value, although very different values are predicted in the standard independent-particle models with reflection-symmetric potentials; (d) relatively strong $E1$ transition rates of order 10^{-2}–10^{-3} s.p.u. between members of reflection asymmetric bands in both odd-A and even-even nuclei [typical $B(E1)$ values are less than 10^{-5} s.p.u. [2]]; and (e) very low hindrance factors (HFs) in α decay observed between nuclear ground states and the states of the same spin but opposite parity in the parity doublet of the daughter in odd-A nuclei and between the 0^+ ground states and the very low lying 1^- states in daughter even-even nuclei (see Fig. 1). In addition, a series of calculations [2] have given a minimum in the nuclear potential energy for nonzero octupole deformation.

The lowering of the ground state energy due to the octupole deformation improves the agreement between calculated and experimental masses around ^{224}Ra, and many spectroscopic features can be explained by octupole deformation. Similar effects, but somewhat less pronounced, are observed in the Ba-Sm region of nuclei [2]. A number of other possible regions of large octupole correlation effects have also been suggested.

Very recently, Wiedenhover *et al.* [3] have suggested large octupole correlation effects in ^{238}Pu and ^{240}Pu leading to possible stable octupole deformation at the highest spins. They have also pointed out very reasonable low-lying deformed configurations, which arise from the $g_{9/2}$ and $j_{15/2}$

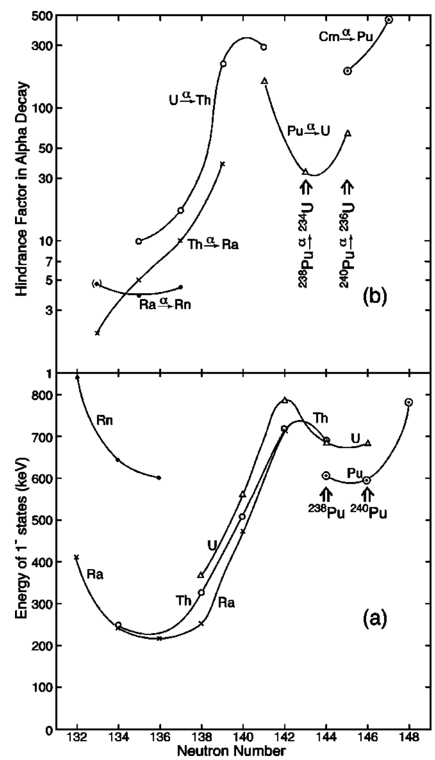

FIG. 1. (a) Energies of the lowest 1^- states plotted against neutron numbers 132–148 for even-even Rn, Ra, Th, U, and Pu isotopes. (b) Log of the hindrance factors (HFs) for α decay between even-even nuclei with neutron numbers between 133 and 147 plotted against neutron numbers. Note the neutron numbers against which the HFs are plotted are intermediate between the neutron numbers of the parent and daughter in the α decay. Energies and HFs are taken from the *Table of Isotopes* [4].

neutron shell model orbitals and the $f_{7/2}$ and $i_{13/2}$ proton shell model orbitals, which could lead to these octupole effects. This very interesting suggestion [3] of a secondary maximum in the octupole correlation just beyond the major region of octupole deformation has prompted the present systematic investigation of low energy octupole effects in even-even nuclei from $A=218$ to $A=242$. The results are shown in Fig. 1 and utilize the criteria (a) and (e) mentioned above for experimentally recognizing octupole correlation in even-even nuclei.

Figure 1(a) is a plot of the energies of the lowest lying $J^{\pi}=1^{-}$, $K^{\pi}=0^{-}$ states in keV relative to the 0^{+} ground state versus neutron number. The energies of isotopes are connected by smooth lines labeled with the appropriate elemental symbol. We see quite clearly the deep depression in the 1^{-} energies for the Ra and Th isotopes particularly with neutron numbers from 132 through 140. However, there is a smaller depression in the 1^{-} states of Pu [3] and to a lesser extent U for neutron numbers 144 and 146. As pointed out in Ref. [3], ^{240}Pu is the lowest point in the secondary minimum.

Figure 1(b) is a plot of the log of the HFs of α decay versus neutron number. Since α decay involves both parent and daughter nuclei, the HFs are plotted on the odd neutron number intermediate between that of the parent and daughter. Again there is a secondary minimum with ^{238}Pu and ^{240}Pu lying near the bottom of the minimum. If the $K^{\pi}=0^{+}$, and $K^{\pi}=0^{-}$ states of even-even nuclei are just different projections from the same configuration of broken reflection symmetry, then α transitions to both parities should be allowed. The considerable decrease in the HF in the secondary minimum thus implies large octupole correlations. The secondary minimum in the HFs clearly mirrors that of the energies of the 1^{-} states even more so if we had plotted against the neutron numbers of the parent alpha decays. The relative size of the two minima allows one to judge the relative strengths of the octupole correlations at low spin. It should be noted that the first hint of the effect of this secondary minimum was observed already in 1961 [5] by one of us. At that time it was ascribed to the refilling of the 13/2[606] $i_{13/2}$ orbital and a core reorientation resulting in deformation changes in the the $N\sim144$ Pu isotopes. However, a huge body of experimental knowledge has been obtained for actinide nuclei since that time, and considerable experience gained with regard to experimental signatures associated with octupole correlations. This knowledge when taken together with the new observations of Wiedenhover *et al.* [3] have convinced us that the secondary minima in the HFs and 1^{-} energies near $N=144$ and 146 are better interpreted as evidence consistent with significant octupole correlations being present in these nuclei.

In summary then, both the systematics of the energies of the 1^{-} states and the α decay HFs populating those states suggest a secondary maximum within the landscape of large octupole correlations in actinide nuclei, which is centered near neutron numbers 144 and 146 for Pu (and to a lesser extent U) isotopes. These results support similar conclusions from recent high spin work on the Pu isotopes.

Useful discussions with Robert Janssens are gratefully acknowledged. This research was supported by the State of Florida and the National Science Foundation.

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