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High-spin properties of octupole bands in ^{240}Pu and ^{248}Cm

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High-spin states in $^{240}_{94}$Pu and $^{248}_{96}$Cm have been populated with Coulomb excitation at beam energies slightly above the Coulomb barrier. In each nucleus a new side band has been identified in γ-γ coincidence measurements and has been interpreted as the lowest-lying octupole excitation. The alignments and Routhians of these bands, as well as the branching ratios of $E1$ decays to the ground-state bands, are in good agreement with results from cranked RPA calculations. [S0556-2813(98)51203-4]

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The interest in the properties of rotational bands built on octupole-phonon excitations in actinide nuclei has recently been renewed by two experimental results. The first is the work of Ref. [1] which has demonstrated the power of inelastic scattering at beam energies slightly above the Coulomb barrier on thick targets as a means of studying in detail collective excitations in these rotational nuclei. These reactions are still dominated by Coulomb excitation, and by using this technique with a relatively modest array of γ-ray detectors, Ward *et al.* observed the yrast band and a previously-known low-lying ($K^\pi = 0^-$) band in ^{238}U to high spins ($\sim 30\hbar$). More importantly, six new rotational structures were identified, including bands coupled to the $K^\pi = 1^-, 2^-$ components of the octupole phonon. The second is the growing body of experimental data (spins, parities, excitation energies, and $E1$ inter-band transition rates) [2,3] favoring an interpretation of the excited superdeformed (SD) bands in even-even nuclei of the $A \sim 190$ region of superdeformation as bands built on octupole vibrational band-heads rather than on quasiparticle excitations. Octupole correlations are strongest when pairs of orbitals with $\Delta j = \Delta l = 3\hbar$ are near the Fermi surface [4], and it is noteworthy that the same sets of pairs, e.g., $j_{15/2} \otimes g_{9/2}$ neutrons and $i_{13/2} \otimes f_{7/2}$ protons, are at the Fermi surface in both the Hg-Pb SD nuclei and in the heavy U-Pu-Cm actinides. Nakatsukasa *et al.* [5] have demonstrated that the dynamic properties (e.g., aligned spins i_x and Routhians e' as a function of rotational frequency $\hbar\omega$) of the SD bands in the $A \sim 190$ region are well reproduced in a cranked random-phase approximation (RPA) model. In fact, this work proposes that most, if not all, excited SD bands in the even-even nuclei of this region are associated with octupole vibrations. This suggestion is not without debate.

In this communication, we report on the high-spin properties of the lowest-lying octupole bands in $^{240}_{94}$Pu and $^{248}_{96}$Cm. These bands provide an opportunity to test further the RPA calculations of Ref. [5] at normal deformation. These results represent part of a systematic study of high-spin states in the ^{240,242,244}Pu and ^{246,248}Cm actinide nuclei, and further details will be reported in a subsequent paper [6].

The highest spin states in stable nuclei are best populated with multiple Coulomb excitation (Coulex) with heavy, high-Z projectiles. Traditionally, Coulex experiments have been performed at energies well below the Coulomb barrier in order to ensure that the excitation is purely electromagnetic. The projectile, the target, or both are usually detected in position-sensitive counters, in coincidence with the γ-rays of interest. A Doppler shift correction of the γ-ray energies can be applied on an event-by-event basis from the velocity vectors of the outgoing particles. This technique provides reliable measurements of electromagnetic transition matrix elements [7]. It has been used quite successfully in studies of yrast bands in actinide nuclei (see Ref. [8]). This approach has, however, some limitations. Thin layers of target material must be used to minimize the perturbation of the velocity vectors by multiple scattering or energy loss in the target material: this limits the overall yield. Also, regardless of how accurately the recoil velocity vector is determined, the γ-ray energy resolution is limited by the opening angle of the γ-ray detector.

Alternatively, Coulex measurements may be performed with thick targets at beam energies above the Coulomb barrier where cross sections for feeding the highest spin states are enhanced. As shown in Ref. [1], the deexcitation from these states can be selectively studied with detection systems comprising a number of Compton-suppressed Ge spectrometers surrounding a high-efficiency sum-energy/multiplicity inner array. By selecting events with a high γ-ray multiplicity, the longest rotational cascades (which involve the highest spin levels) can be selected. Under such conditions, most of the γ-rays are emitted after the excited nucleus has come to rest, and most of the transitions in a collective cascade are

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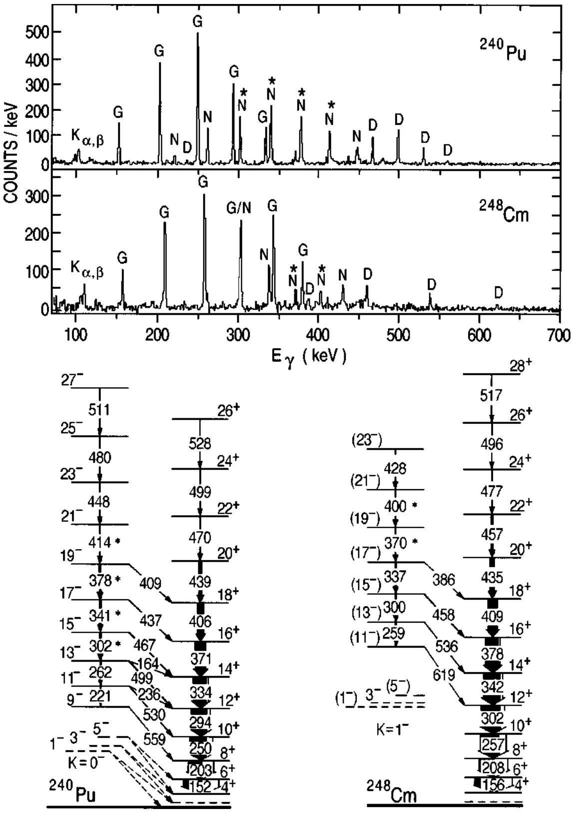

FIG. 1. Representative coincidence spectra of the γ decay of the octupole bands in ^{240}Pu (top panel) and ^{248}Cm (bottom panel) together with the deduced level schemes. In the spectra, the letters N, D and G identify transitions associated respectively with the new octupole bands, the decay between the octupole and the yrast bands, and the yrast sequence. The dashed levels and the dashed transitions in the level schemes were not observed in the present data, but were taken from other references, see text for details. The asterisks mark transitions used as coincidence gates for generating the spectra.

measured with the intrinsic resolution of the Ge detectors. In this way, weak cascades which were not seen in traditional particle-γ experiments can be resolved in γ-γ coincidence measurements. The technique imposes no limit on the thickness of target material, and in special cases (e.g., ^{238}U [1], ^{232}Th [9]), a thick foil of the material can be used both as target and stopper. One deficiency of this alternative technique is that it is not possible to reliably measure absolute transition matrix elements directly from the γ yields. In the present work this drawback is not critical as only level schemes and branching ratios are discussed.

In the experiments, beams of ^{208}Pb ions at an energy of 1300 MeV from the ATLAS accelerator bombarded targets consisting of <0.5 mg/cm^2 layers of ^{240}Pu (98% enriched) or ^{248}Cm (97% enriched) electroplated onto ~ 50 mg/cm^2 backing foils of Au or $^{\mathrm{nat}}$Pb. The thickness of the targets was obtained from the measured α activity. Gamma rays were detected with the Argonne-Notre Dame BGO gamma-ray facility, which comprised 12 Compton-suppressed Ge (CSG) spectrometers and a sum-energy/multiplicity array of 46 BGO scintillators. Events were written to tape when $\geqslant 2$ BGO elements and $\geqslant 2$ CSG's fired in prompt coincidence. Several γ-γ coincidence matrices with different requirements on the multiplicity measured in the array were generated [6], and the subsequent analysis of these was performed with ESCL8R [10].

The level schemes deduced from the analysis and sample coincidence spectra are presented in Fig. 1. The ^{240}Pu yrast structure, previously known up to $14\hbar$ [11], has been extended to the 26^+ state, and a side band consisting of nine intra-band transitions was identified as well. The absolute intensity of the new band is $\sim 6\%$ relative to the strongest observed transition in the ground-state band. Gamma rays linking the two sequences have been observed (see Fig. 1), and for two levels in the new band, decay branches to two yrast states are seen. The deduced energy levels form a natural extension of a $K^\pi = 0^-$ level sequence ($1^-, 3^-, 5^-$) previously observed in ^{240}Pu [12]. Therefore, the new levels are assigned as the high-spin part of this $K^\pi = 0^-$ octupole band for which all but the 7^- state are now known.

In the measurement with the ^{248}Cm target, two cascades have been identified in addition to the well-known yrast sequence [8]. The first one of these sequences is given in Fig. 1. It consists of six in-band γ-rays which are in clear coincidence with ^{248}Cm yrast transitions. This band has an absolute intensity of $\sim 4\%$ relative to the strongest yrast band transition. As in the case of ^{240}Pu, inter-band transitions are observed, but only one from each level. Angular correlations rule out that these γ-rays correspond to $J \rightarrow J \pm 2$ inter-band transitions. They are assigned as $J \rightarrow J+1$ transitions for reasons similar to those discussed above for ^{240}Pu, namely, extrapolating the band to low spin yields excitation energies within ~ 20 keV of the previously known, low spin, negative-parity states assigned as $K^\pi = 1^-$ [13].[1] Another new band with transition energies of 153, 205, 253, 298, 338, 374, 405, and 434 keV was observed at an intensity of $\sim 3\%$ of the strongest ^{248}Cm yrast band transition. Its lowest two transitions have the same energies to within 0.5 keV as the $8^+ \rightarrow 6^+ \rightarrow 4^+$ cascade in ^{246}Cm [14]. As the γ-rays do not exhibit coincidence relationships with lines in ^{248}Cm, this second band is assigned as the extension of the ^{246}Cm yrast sequence. The enriched ^{248}Cm stock included a $\sim 3\%$ ^{246}Cm isotopic impurity, which accounts fully for the yield in the ^{246}Cm yrast band. No other cascades were identified, therefore, in this experiment there is no evidence for the even-spin states of the ^{248}Cm $K^\pi = 1^-$ band. However, unlike fusion-evaporation reactions, one would not expect equal population of both signatures of a $K \neq 0$ band by Coulex. As in the present data, Ward *et al.* observed only one signature of the $K^\pi = 1^-$ and $K^\pi = 2^-$ bands in ^{238}U [1].

Theoretical treatments of octupole correlations employ the cranked RPA approach to make the problem of coherent particle-hole excitations tractable [5,15,16]. As indicated above, the RPA model of Ref. [5] has been applied to the $A \sim 190$ superdeformed bands and also to ^{238}U [1]. The

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[1] The coincidence and angular distribution data alone cannot rule out the possibility that these are instead $J \rightarrow J-1$ or $E2$ $J \rightarrow J$ transitions; however, with those assignments, the extrapolated low-spin excitation energies would be >100 keV *lower* than those of known low-lying excitations, and they would give rise to large aligned spins which cannot be explained by the collective modes excited in Coulex experiments.

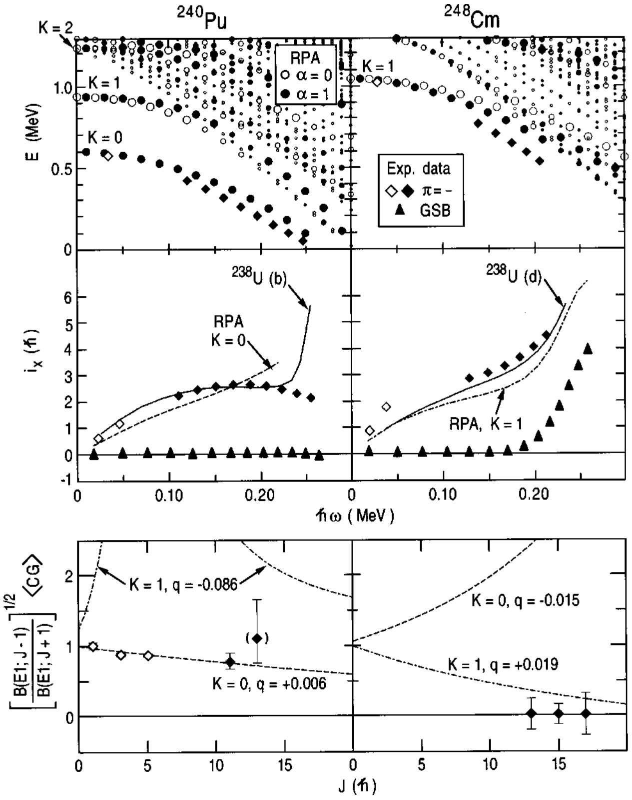

FIG. 2. Measured and RPA-calculated properties of the ^{240}Pu (left) and ^{248}Cm (right) octupole bands. Top panels: Diamonds, Routhians e' from the current experiment (filled) and existing low-spin data (open, see text for details). Circles, negative-parity RPA solutions calculated in 0.02 MeV intervals of $\hbar\omega$ for signature-exponent values $\alpha=0$ (filled) and $\alpha=1$ (open). Middle panels: aligned spins i_x from experimental data (diamonds, as above) and from the RPA calculations (dashed or dashed-dotted curves). Also plotted as solid curves are the aligned spins for the ^{238}U bands with the same K^π quantum number, i.e., 0^- (band b) and 1^- (band d) in the left and right panels, respectively. Bottom panels: Ratios of $E1$ matrix elements times Clebsch-Gordan coefficients corresponding to Eq. (1) in the text. Symbols are points derived from experimental branching ratios, while the curves correspond to expectations from the first-order generalized intensity relationship with the Coriolis mixing factors $q(E1)$ calculated in the cranked RPA approach. For ^{240}Pu, the highest-spin data point is tentative because of the presence of a contaminant γ-ray at the energy of interest. For ^{248}Cm, the uncertainties are derived from the upper limits on the intensity of the (unobserved) $J\rightarrow J-1$ transitions.

present data provide an opportunity to further test this RPA model. Experimental data and theoretical arguments suggest that as the $\Delta l=\Delta j=3\hbar$ subshells are filled, the lowest-lying component of the octupole phonon evolves from $K=0$ to $K=1$ or 2 [4]. However, only detailed calculations can predict the precise ordering of the different K components in a given nucleus. The top panels of Fig. 2 present the negative-parity RPA Routhians in the model of Ref. [5] for ^{240}Pu and ^{248}Cm, and compare the calculations with the data. The model predicts that the lowest octupole excitation in ^{240}Pu corresponds to $K=0$, while the $K=1$ excitation is the lowest in ^{248}Cm. This feature does not depend on the exact value of the octupole coupling strength. For comparison, the lowest-lying octupole states calculated for ^{240}Pu in Ref. [4] also correspond to the $K=0$ component, while for ^{248}Cm, the $K=2$ band is calculated to be lowest, in disagreement with the data. This discrepancy may be due to the smaller model space used in Ref. [4]. In order to compute the high spin behavior in the negative-parity bands, as in Ref. [1], the model space was truncated and the octupole strength was subsequently chosen to match the octupole band-head energies (i.e., the $\hbar\omega=0$ Routhian). From Fig. 2 it is clear that, at high frequencies, the agreement with the experimental data is satisfactory.

The ability to reproduce the measured aligned spins i_x of the octupole bands relative to their respective ground-state bands represents a more stringent test of the cranked RPA model. The measured alignment i_x is found to reach a plateau at $\sim 3\hbar$ (Fig. 2) in the case of ^{240}Pu, whereas a smooth rise with frequency is measured in ^{248}Cm. The cranked RPA calculations for the lowest-lying, $K=1$ excitation in ^{248}Cm reproduce the data quite well (Fig. 2). In contrast, the calculated alignment in ^{240}Pu does not exhibit the observed plateau. This observation is at present not understood, but may be related to the properties of the yrast band itself. The ^{240}Pu yrast band is the only one in nuclei of this region to show no evidence for a band crossing. It is possible that the interaction responsible for the band crossing is weaker in ^{240}Pu than in the neighbors and that, as a result, Coulomb excitation continues to follow the ground-state band rather than the crossing (aligned) band. An alternate interpretation relates the observation to the strength of octupole correlations. The octupole band is lowest in excitation energy in ^{240}Pu. It is possible that octupole degrees of freedom impact the single particle orbitals and modify the characteristics of band crossings and alignments along the yrast line.[2] Finally, Fig. 2 also demonstrates that the alignments of the two new octupole bands are very close to those of the negative-parity bands with the same K quantum number in ^{238}U. For ^{240}Pu, the comparison with the $K^\pi=0^-$ band in ^{238}U is especially striking and only breaks down at high frequencies (>0.2 MeV) where the behaviors of the ^{238}U and ^{240}Pu yrast bands diverge (see discussion above). This similarity of alignments between the ^{240}Pu, ^{248}Cm octupole bands and their K counterparts in ^{238}U may be accidental. It may, however, also suggest that the Coriolis alignment of the octupole phonon is *independent* of the location of the Fermi surface, a result which does not come out of the detailed numerical calculations.

Although the experimental approach used in the present work precludes measurements of transition matrix elements, it is possible to test the theory by investigating the competition between the $E1$ $J^-\rightarrow(J-1)^+$ and $J^-\rightarrow(J+1)^+$ transitions linking the octupole and yrast bands. As shown in Ref. [1], this competition depends strongly on Coriolis mixing which is expressed in the general intensity relationships [17] through the $q(E1)$ parameter:

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[2] We note that the same phenomenon might be happening in superdeformed nuclei near $A=190$, where the strongest octupole correlations in the second well appear to occur in ^{190}Hg, a nucleus where the $\mathcal{J}^{(2)}$ moment of inertia of the yrast SD band is also different from all others in the region [2].

$$\left[\frac{B(E1;J\rightarrow J-1)}{B(E1;J\rightarrow J+1)}\right]^{1/2}\left|\frac{\langle J,K;1,-K|J+1,0\rangle}{\langle J,K;1,-K|J-1,0\rangle}\right| = \left|\frac{1-2Jq(E1)}{1+2(J+1)q(E1)}\right|. \quad (1)$$

The left side of this equation is measured from the decay-out γ-ray intensities, while on the right side, $q(E1)$ can be calculated within the cranked RPA according to Ref. [18]. The value of $q(E1)$ is a measure of the rate at which the Coriolis interaction mixes the different components of the octupole phonon. This value varies from nucleus to nucleus, and within a given nucleus there is also a strong dependence on the K quantum number of the octupole excitation being considered. Following Ref. [1], the quantities in Eq. (1) are presented as a function of the spin J in the bottom part of Fig. 2. The data points at high spin are from the present measurements for both nuclei. In the case of ^{240}Pu, the low-spin data of Ref. [12] have been added to the figure. The curves correspond to the $q(E1)$ values calculated within the RPA. For the appropriate K value (i.e., 0 for ^{240}Pu, 1 for ^{248}Cm), the calculated $q(E1)$ values describe the observed trends in the $B(E1)$ ratios. The calculated $q(E1)$ is small ($0.006\hbar^{-1}$) in the case of the $K=0$ band in ^{240}Pu and reproduces the observations. In ^{248}Cm, the positive $q(E1)$ ($0.019\hbar^{-1}$) calculated by the RPA for the $K=1$ band predicts that, given the observed intensity of $J\rightarrow J+1$ transitions linking the octupole and yrast bands, the $J\rightarrow J-1$ competing branches are at the very limits of the detection sensitivity of the present data. For comparison, fits to the data with the generalized intensity relation give $q(E1)=0.001(6)\hbar^{-1}$ in ^{240}Pu and $q(E1)=0.030(6)\hbar^{-1}$ in ^{248}Cm. To illustrate that the $q(E1)$ parameter is a sensitive test of the K assignments, curves for the second lowest octupole bands calculated in the RPA ($K=1$ in ^{240}Pu, $K=0$ in ^{248}Cm) are also shown in Fig. 2. These curves do not agree with the data; bands with these values of the $q(E1)$ parameter would also have measurably different $J\rightarrow J\pm 1$ intensity ratios than seen here.

In conclusion, Coulomb excitation experiments on ^{240}Pu and ^{248}Cm targets with ^{208}Pb beams at energies slightly above the Coulomb barrier have provided new data on negative-parity bands associated with octupole excitations. The extracted Routhians, alignments and intensity ratios are reproduced satisfactorily in RPA calculations which associate the negative parity structure with the $K=0$ component of the octupole phonon in ^{240}Pu and with the $K=1$ component in ^{248}Cm. Remarkably, the alignments are strikingly similar to those observed for octupole bands with the same K quantum number in ^{238}U.

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