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Coulomb Excitation of High-Spin States in ^{238}U†

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Coulomb excitation with Kr and Xe ions has excited the ground-state band of ^{238}U up to the 22^+ (tentatively 24^+) state and the lowest octupole vibrational band up to 19^-. No backbending is observed. The behavior of the octupole band at high spins suggests a Coriolis-induced alignment of the rotational and vibrational angular momenta.

The strong electromagnetic interaction produced in the encounter of a deformed target nucleus by a heavy projectile excites high-spin states in the ground-state rotational band and in rotational bands built on collective states coupled to the ground-state band. Such multiple Coulomb excitation is a powerful tool for investigating collective nuclear properties at high rotational frequencies. Of special interest are the rotational bands of the strongly deformed actinide nuclei, which cannot be studied by (HI, $xn\gamma$) reactions because of the strong fission competition. In the present Letter we report levels in the ground-state and octupole-vibrational bands of ^{238}U excited by Kr and Xe ions up to $I \sim 20\hbar$. From such studies one obtains the level energies and their branching ratios for γ decay. One can then, in principle, obtain transition probabilities from the Coulomb-excitation cross sections for exciting these states. Such quantities are of considerable interest, as is a careful study of these cross sections for new effects possibly occurring in these very strong electromagnetic interactions. However, accurate cross-section analyses cannot be made at present, mainly because of the lack of fully quantum-mechanical-calculated cross sections. The quantum-mechanical code that exists[1] becomes prohibitively expensive to run above $\sim 10\hbar$, and no reliable methods for extrapolation to higher-spin values are known. Thus a meaningful discussion of the Coulomb-excitation yields must be postponed, and the present Letter will deal with the level energies and decay properties observed in the ground and octupole bands of ^{238}U.

Thick metallic targets, enriched in ^{238}U, were bombarded at the Lawrence Berkely Laboratory SuperHILAC with beams of ^{84}Kr (385 ± 5 MeV), ^{86}Kr (394 ± 6 MeV), ^{132}Xe (605 ± 20 MeV), and ^{136}Xe (640 ± 40 MeV). The decay γ rays were observed by two (~ 40 cm^3) coaxial Ge(Li) detectors at $\theta_\gamma = 0°$ and $\theta_\gamma = 90°$ with respect to the beam direction and 4–5 cm from the target. Singles, γ–backscattered-projectile, and γ-γ coincidences were simultaneously stored. The low-energy portion of the singles γ-ray spectrum and the γ-γ coincidence spectrum is shown in Fig. 1 for the ^{136}Xe bombardment. Almost all the lines shown here belong to the ground-state and lowest-energy octupole bands of ^{238}U. We do not see many lines of the higher vibrational bands, and are at

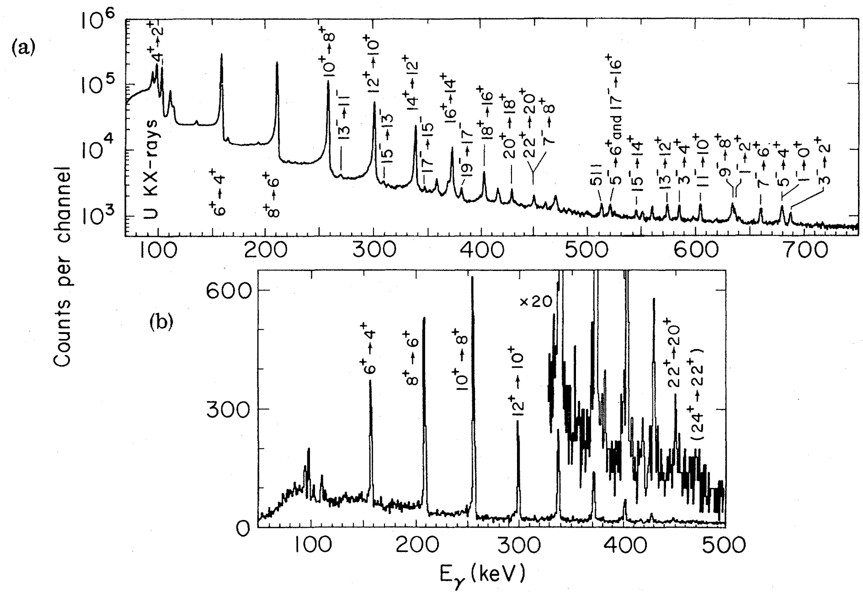

FIG. 1. Portions of the (a) γ-ray singles spectrum and (b) γ-γ coincidence spectrum from a thick ^{238}U target Coulomb excited with 640-MeV ^{136}Xe ions. The γ-γ coincidence spectrum is the sum of spectra gated by the 6-4, 8-6, 10-8, 12-10, and 14-12 transitions.

present developing techniques to determine whether this represents a weak population of these states or simply a difficulty in identification because of Doppler broadening. The combined data from all projectiles lead to the level scheme for the ground and octupole bands shown in Fig. 2. The $I = 24^+$ state is considered tentative, but the other levels in Fig. 2 seem rather certain. Some of the branching ratios from the octupole state were also determined; within the experimental uncertainties, they are consistent with those for a pure $K = 0$ band. In addition, the $E1$-$E2$ branching ratios are consistent with a constant Q_0 value for the octupole band.

The moments of inertia of the ground and octupole bands are shown as a function of the square of the rotational frequency in Fig. 3(a). This type of plot corresponds to that generally made to display backbending behavior of nuclei in the rare-earth region. The ground band of ^{238}U does not backbend up to spin 22 (tentatively 24) even though the moment of inertia increases by ~ 50%. One should note, however, that as a result of lower rotational energies (frequencies), a backbend in the ground band (analogous to those observed in the rare-earth nuclei around $I = 16$) would not be expected until $I \gtrsim 24$ based on either an alignment or pairing-collapse model. Thus one or two more levels in the ground band of ^{238}U are needed to be sure about its backbending behavior. It is obvious that the octupole band has a larger apparent moment of inertia than the ground band, and behaves in a somewhat unusual manner with increasing rotational frequency. The nature of this band has been of interest for some time. The

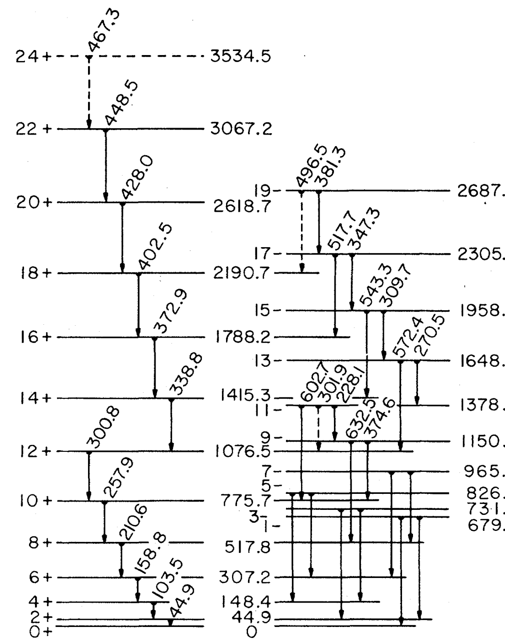

FIG. 2. Level scheme for the ground and lowest-energy octupole bands of ^{238}U.

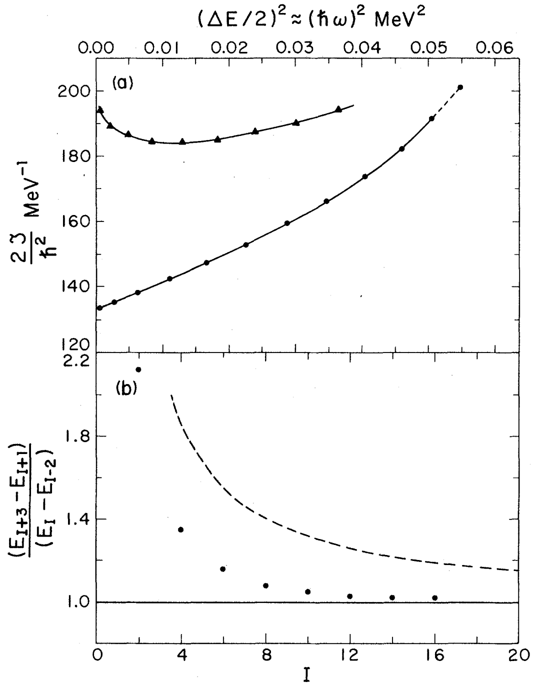

FIG. 3. (a) Plot of $2\mathcal{J}/\hbar^2 = (4I-2)/(E_I - E_{I-2})$ versus $(\hbar\omega)^2 = \frac{1}{4}(E_I - E_{I-2})^2$ for the ground (circles) and octupole (triangles) bands of ^{238}U. (b) Comparison of the data for the octupole band (circles) with the aligned-vibrator prediction (solid line) and the single-band prediction (dashed line).

very general occurrence of collective octupole vibrational states, having a frequency $\omega \sim 15/A^{1/3}$ MeV, is well known, and the sharp drop in energy of components of this state at the beginning of the rare-earth and especially the actinide deformed regions is understood and has been qualitatively reproduced in recent calculations.[2,3] Four low-lying octupole bands are expected in ^{238}U having K values of 0, 1, 2, and 3, and three collective negative-parity bands are known[4] below 1200 keV which may correspond to the $K=0$, 1, and 2 bands. The lowest observed band is the one shown in Fig. 2, which has (initially) a predominant K value of zero. There are at least three plausible types of behavior for these octupole bands at higher rotational frequencies. If the other rotation-vibration interactions are weak, then the Coriolis force will align the vibrational angular momentum along the rotation axis, producing a lowest band with energy spacings identical to those of the ground band, but having spins $3\hbar$ higher. Or, the octupole deformation might be stabilized by the rotation, resulting in the even- and odd-spin states merging into one band having the usual $I(I+1)$ energy spacings. A third possibility is that the collective octupole character of the band might be destroyed, for example by independent alignment of its particle (and/or hole) components, leading to irregular level spacings.

The experimental level energies of the lowest odd-parity band in ^{238}U are compared with these possibilities in Fig. 3(b). The plot is constructed such that the rotation-aligned-vibrator prediction is unity; whereas, the dashed line is the stable-octupole-shaped-rotor (one-band) prediction. The data are very regular and converge rather convincingly to the rotation-aligned limit. This result is in excellent accord with explanations that have been given for the compression (large moment of inertia) of the lowest few states of this octupole band. These explanations have involved Coriolis mixing of the $K=0$, 1, 2, and 3 octupole components,[2] and this mixing is just the mechanism producing the alignment of the vibrational angular momentum with the rotation axis at higher spins. The mixing has been found to be rather heavy even for the lowest members of this band. This might appear to contradict the reasonable agreement with the $K=0$, $E1$ branching ratios; however, it has generally been found that the $E1$ matrix elements from the ground to the $K=0^-$ bands are much larger than those to the $K=1^-$ bands. Thus, even though the mixing may be large, the $E1$ transitions appear to come from a $K=0$ band. It is also interesting to consider the effect on the $E3$ transitions. At sufficiently high-spin values, each rotation-aligned state has a nearly unique value of core angular momentum, R. The $E3$ transitions cannot change R, so that the $I_{\rm gnd} \to (I+3)_{\rm oct}$ transitions to the aligned (lowest) band pick up all the $E3$ strength, and the other transitions between these two bands become small. The previous Coriolis calculations[2,3] have shown this tendency in the $0^+ \to 3^-$ transitions, in agreement with the experimental data.

The present Coulomb-excitation experiments provide by far the highest spin values known in actinide-region nuclei. The data show that ^{238}U does not backbend up to spin $22\hbar$ (probably not to $24\hbar$), though it is not yet clear that it will not backbend at still higher spin values. The evidence suggests that at the higher spin values observed, the octupole band aligns its angular momentum ($3\hbar$) with that of the rotating core. The energies fit this model so well that exceptionally weak rotation-vibration interactions of other types seem to be implied. This behavior is different from that observed in octupole bands of rare-earth nuclei,[5,6] where the octupole collectivity is weaker and appears to be destroyed at rather low spin values. The concept of the Coriolis force aligning an angular momentum vector along the rotation axis has previously been applied to one-particle states in weakly deformed nuclei,[7] and to two-particle states in strongly deformed even-even nuclei.[8] One sees from the ^{238}U case that this idea may apply to any angular momentum vector in a rotating system, including, in some circumstances, collective angular momenta.

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Observation of Magnetic Octupole and Scalar Spin-Spin Interactions in I_2 Using Laser Spectroscopy*

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Magnetic octupole and scalar spin-spin interactions have been observed in $^{127}I_2$ by precisely measuring (line centers located to 1 part in 10^{11}) the hyperfine spectrum on the $P(13)$, 43-0 line using laser–molecular-beam techniques. The values of the coupling strengths obtained from fitting the spectrum are, for the electric quadrupole, $eQq' = -554\,094 \pm 13$ kHz and $eQq'' = -2\,448\,025 \pm 10$ kHz; for the spin-rotation, $C' - C'' = 186.71 \pm 0.10$ kHz; for the tensor spin-spin, $D_t' - D_t'' = -100.5 \pm 1.0$ kHz; for the scalar spin-spin, $D_s' - D_s'' = -2.72 \pm 1.0$ kHz; and for the magnetic octupole, $\Omega m' - \Omega m'' = -2.17 \pm 0.70$ kHz.

We report the observation of magnetic octupole and scalar spin-spin interactions in the optical spectrum of I_2 at 5145 Å. The line spacings were measured with an accuracy of 5 kHz (1 part in 10^{11}) using a heterodyne technique employing two argon-ion lasers individually stabilized to I_2 hyperfine lines excited in molecular beams.

After the first observation of I_2 hyperfine structure[1,2] Kroll explained the results in terms of nuclear electric quadrupole and magnetic spin-rotation interactions.[3] Subsequently, Hanes *et al.*,[4] Hänsch, Levenson, and Schawlow,[6] and Ruben *et al.*[7] studied the hyperfine structure associated with a number of I_2 transitions. With further improvements in the measured data, Bunker and Hanes[8] introduced a tensor nuclear spin-spin coupling term to fit seven components of the $R(127)$ line to within a standard deviation of approximately 60 kHz.

In this Letter we report precision measurements of hyperfine transitions on the $P(13)$ 43-0, $B\,^3\Pi$-$X\,^1\Sigma$ line in $^{127}I_2$. Figure 1 shows the spec-