initial states than for the final states. See, e.g., J. V. Noble, Phys. Rev. C 17, 2151 (1978).
[12]R. D. Viollier and J. D. Walecka, Acta Phys. Pol. B 8, 25 (1977).
[13]Y. Horikawa, F. Lenz, and N. C. Mukhopadhyay, to be published.
[14]J. W. van Orden, Ph.D. thesis, Stanford University, 1978 (unpublished).

Anomalous Behavior of High-Spin States in ^{248}Cm

R. B. Piercey
Physics Department, Vanderbilt University, Nashville, Tennessee 37235, and Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany

and

J. H. Hamilton and A. V. Ramayya
Physics Department, Vanderbilt University, Nashville, Tennessee 37235, and Institut für Theoretische Physik, Universität Frankfurt, D-6000 Frankfurt, Germany

and

H. Emling, P. Fuchs, E. Grosse, D. Schwalm, and H. J. Wollersheim
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany

and

N. Trautmann
Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Germany

and

Amand Faessler
Institut für Theoretische Physik, Universität Tübingen, D-7400 Tübingen, Germany

and

M. Ploszajczak
Institut für Theoretische Physik, Universität Tübingen, D-7400 Tübingen, Germany, and Institute of Nuclear Physics, PL-31-342 Cracow, Poland
(Received 24 November 1980)

The ground-state band of ^{248}Cm has been studied up to spin 28^+ and tentatively to 30^+ by observing γ rays following multiple Coulomb excitation with use of ^{208}Pb ions at 5.3 MeV/u. A smooth, gradual increase in the effective moment of inertia is seen at lower spin with an anomalous forward bend above spin 22^+. Calculations are presented which indicate that this behavior including the forward bend can be understood in terms of the alignment of single-particle angular momenta along the rotation axis.

PACS numbers: 25.70.Kk, 21.10.Re, 27.90.+b

Anomalies in the energy level spacings of yrast states in well-deformed rare-earth and transition-metal nuclei have generated much theoretical and experimental activity.[1-3] The anomalous yrast spectra of rare-earth nuclei at spins around 12–16 are understood in terms of a superband built on two-quasiparticle rotation-aligned states which crosses the ground rotational band. Now additional crossings of rotation-aligned bands have been discovered at even higher spin.[4] The question of what happens to the collective-rotation and single-particle configurations as the nuclear angular velocity increases further is of much current interest.[1-3] Important to the extension of our understanding is to observe the behavior of more purely rotationallike states to higher angular momenta and of rotation-aligned configurations in very-high-J orbitals like $\nu j_{15/2}$ and $\pi i_{13/2}$ as can occur in actinide nuclei.

With one of the lowest first excited 2^+ energies and largest collectivity, ^{248}Cm should offer one of the best opportunities to study a rotational band to high spin by multiple Coulomb excitation. Traditional techniques based on (H.I., *xn*) reactions are of little use for such studies since the main cross section for decay of the compound system is for fission rather than particle evaporation. We report here the first Coulomb excitation to high spin of a transuranic element. We observed states in ^{248}Cm to 28^+ and most probably to 30^+ via Coulomb excitation with ^{208}Pb ions. Anomalous behavior in the effective moment of inertia is observed above about spin 22^+. Theoretical calculations show that this observed deviation can be understood in terms of the alignment of single-particle angular momenta along the rotation axis.

A 250-μg/cm^2 target of isotopically enriched ^{248}Cm was bombarded with 5.3-MeV/u ^{208}Pb ions from the Darnstadt UNILAC. The target was produced by molecular plating from an isopropyl alcoholic solution onto a Ti backing of 1 mg/cm^2. With this method, up to 95% of the Cm can be deposited on the backing. The projectile energy used is thought to be sufficiently below the Coulomb barrier so that no Coulomb nuclear interference takes place. Thus, the ^{248}Cm nuclei are excited via multiple Coulomb excitation to very high spin. The resulting γ rays were then detected in high-resolution Ge(Li) detectors. The γ rays emitted from the recoiling curium nuclei were corrected for the strong Doppler broadening ($v_{\text{recoil}}/c \approx 0.1$) by detecting both the scattered Pb and the recoiling Cm particles in two large-area parallel-plate proportional chambers. A fast Doppler correction (available on line during data taking) was achieved by utilizing specially shaped, microstrip delay lines as the cathodes of the gas detectors.[5] The delay lines in the forward detector were designed such that the time delay between the anode and cathode signal was proportional to the Doppler shifts of the γ rays which were emitted in flight by the scattered ^{248}Cm registered in this detector. By also measuring the time-of-flight difference of the kinematically coincident particles and their kinematic angular correlation it was possible to distinguish Pb from Cm ions. A more detailed discussion of the experimental setup, which has been used so far in Coulomb excitation experiments performed at the UNILAC on a series of lighter target nuclei, will be published elsewhere.[5,6] A corrected γ-ray spectrum is shown in Fig. 1. The $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions are too highly internally converted to be seen. The spin assignments are based on systematics and the impact-parameter dependence of the γ-ray yields. From its enhancement in the low-impact-parameter data, the $30^+ \to 28^+$

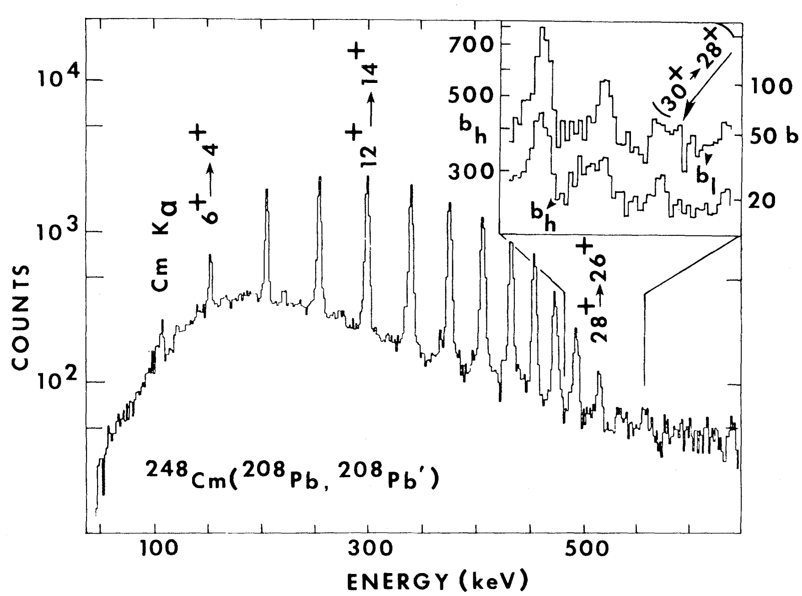

FIG. 1. A Doppler-shift–corrected spectrum showing the γ rays observed for low impact parameters in ^{248}Cm. The inset compares data which include higher impact parameters, $30° \leq \theta_{\text{Pb}} \leq 147°$, to an enlarged region of the main spectrum which has only low–impact-parameter data, $105° \leq \theta_{\text{Pb}} \leq 147°$. The scattering angles of the Pb projectiles, θ_{Pb}, are given in center-of-mass coordinates. The enhancement of the proposed $30^+ \to 28^+$ transition can be seen in the low–impact-parameter data.

transition at 541.8 keV is most probably the upper member of the doublet in Fig. 1.

The transition energies were obtained by averaging the γ-ray energies observed in two detectors 180° apart for ten different projectile scattering angles. These angles ranged over large and small (where the γ-ray emitted perpendicular to the recoiling ejectile has zero first-order Doppler shift) Doppler shifts. The consistency of the corrected γ-ray energies as a function of projectile scattering angle (and Doppler shift) was used as a measure of the error involved in correcting the energies. Only a fraction of the available data (sum of three large center-of-mass angles) is shown in Fig. 1. The γ-ray energies (in kiloelectronvolts) for the $6^+ \to 4^+$ to $30^+ \to 28^+$ transitions are 154.6(5), 206.9(4), 255.8(3), 300.8(2), 341.5(2), 377.3(2), 408.2(2), 433.9(3), 455.7(3), 475.4(3), 495.0(4), 516.3(4), and 541.8(8), respectively.

The energy levels of ^{248}Cm determined in this way show an anomalous tendency at the highest observed spins to be too low as compared to the rotational model and also as compared to an extrapolation from the low-spin members of the ground band using the variable-moment-of-inertia prescription (which is equivalent to an expansion in the second and the fourth power of the rotational frequency ω). This trend corresponds to a forward bending in the effective moment of inertia above spin 22 (Fig. 3). The deviation is illustrated in a more dramatic way in Fig. 2 as a smooth, but strong, rise in the plot of the difference in two successive γ-ray energies, versus I,[7] above spin 22^+. A similar, although less pronounced, irregularity in the effective moment of inertia of the ground band has been observed in the ^{232}Th and ^{238}U isotopes.[6,8]

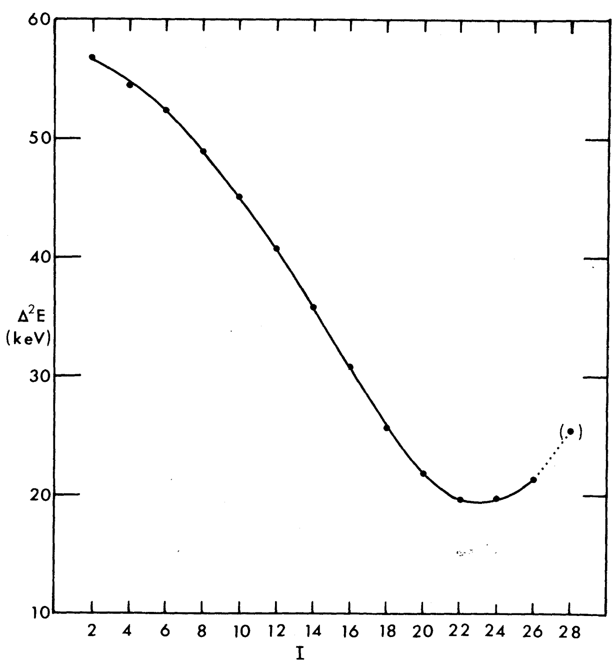

FIG. 2. Δ^2E plot for the γ rays belonging to ^{248}Cm showing the anomalous behavior at high spin, where $\Delta^2E(I) = E_\gamma(I+2 \to I) - E_\gamma(I \to I-2)$.

To understand the physics behind this increase of moment of inertia at high spin we applied the cranked Hartree-Fock-Bogolyubov (HFB) approach to ^{248}Cm. Subsequently, we learned that a similar but more phenomenological approach has been applied to ^{238}U.[9] We proceed in two steps[10]: (1) In the first step, one constructs a HFB trial wave function

$$\psi_{\rm trial} = |\beta_2, \lambda, \beta_4, \Delta_p, \Delta_N, \langle I \rangle\rangle_{\rm HFB}$$

with the help of a model Hamiltonian:

$$H_{\rm trial} = \sum_{i=1}^{A} [h_{Nil}(i, \{\beta_j\}) - \omega j_x(i)] + H_{\rm pair}(\Delta_p, \Delta_n). \quad (1)$$

The average angular momentum in the wave function $\psi_{\rm trial}$ is determined by the cranking condition. (2) In the second step, one performs the minimization of the particle-number-projected energy expectation value:

$$E_J(\{\beta_j\}, \Delta_p, \Delta_n) = \langle\psi_{\rm trial}|\hat{H}\hat{Q}_p\hat{Q}_n|\psi_{\rm trial}\rangle / \langle\psi_{\rm trial}|\hat{Q}_p\hat{Q}_n|\psi_{\rm trial}\rangle \quad (2)$$

with respect to all the collective parameters except β_j (as discussed below) of $\psi_{\rm trial}$ for each total angular momentum J:

$$\langle\psi_{\rm trial}|\hat{J}_x\hat{Q}_p\hat{Q}_n|\psi_{\rm trial}\rangle / \langle\psi_{\rm trial}|\hat{Q}_p\hat{Q}_n|\psi_{\rm trial}\rangle = [J(J+1)]^{1/2}. \quad (3)$$

For more details and a detailed definition of all the quantities used here, see Ref. 10 and references quoted therein. $\hat{H}$ in Eq. (2) denotes the pairing plus quadrupole force Hamiltonian[11] which is consistent with $H_{\rm trial}$.[10] In Refs. 10 and 11, $\hat{H}$ is defined by use of the spherical single-particle (s.p.) energies in shells $N=4$ and 5 ($N=5$ and 6) for protons (neutrons). This s.p. space is not sufficient to calculate actinides. Therefore, we have included[12] the s.p. orbitals $\pi i_{13/2}$ ($N=6$) and $\nu j_{15/2}$ ($N=7$) from higher shells, neglecting states $\pi g_{9/2}$ ($N=4$) and $\nu h_{11/2}$ ($N=5$). Matrix elements of the quadrupole force involving high-j intruder states were multiplied by a factor $\chi = (N+\frac{3}{2})/(N+\frac{7}{2})$ to correct for deficiencies of the quadrupole force.[11] N is the number of oscillator quanta for the lower shell of a given parity.

The upper part of Fig. 3 shows the usual backbending plot for ^{248}Cm. For each angular momentum, the energy gaps Δ_p and Δ_n are minimized whereas the deformation parameters are kept fixed to $\beta_2 = 0.2$ and $\beta_4 = 0.05$ corresponding approximately to the ground-state deformation of nuclei in this mass region.[13] The calculated curve of the moment of inertia is further renormalized[10,12] by adding a constant core-correction term $2\mathcal{J}_{\rm core}/\hbar^2 = 30$ MeV^{-1}. The agreement between experimental and calculated values of the

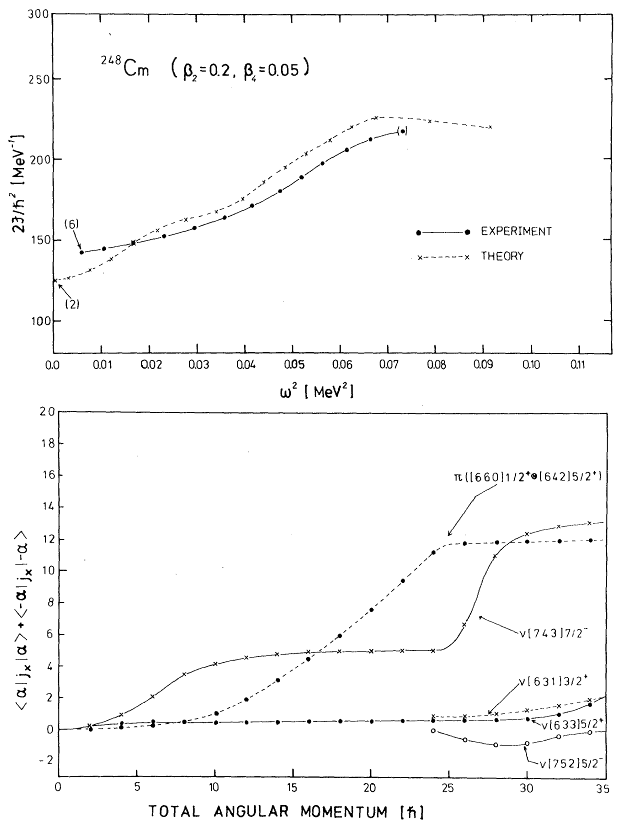

FIG. 3. The upper part of the figure shows the backbending plot for ^{248}Cm. The solid line gives the experiment and the dashed line the theory. The lower part of the figure shows the alignment of the s.p. angular momenta along the rotational axis for conjugate pairs $|\alpha\rangle$ and $|-\alpha\rangle$ as a function of the total angular momentum for ^{248}Cm. The levels with the largest contribution to the total angular momentum are included; we indicated the asymptotic quantum numbers of their main configuration at high spin. In the case of the proton $i_{13/2}$ level, there are two admixtures of approximately equal strength.

moment of inertia is remarkable in the region of the high-spin anomaly. For higher spins ($I = 32\hbar$, $34\hbar$) the calculated curve $2\mathcal{J}/\hbar^2$ shows downbending. The experimental data also are reproduced if one uses $\beta_2 = 0.3$.

The reason for the approximately monotonic increase of the moment of inertia at $I < 30\hbar$ can be seen in the lower part of Fig. 3 which shows the alignment of the s.p. angular momenta along the rotational axis for conjugate s.p. states $|\alpha\rangle$ and $|-\alpha\rangle$ as a function of the total angular momentum. The assigned asymptotic quantum numbers describe the main components at high spins.

The rotational frequency ω corresponding to the alignment of $\pi i_{13/2}$ and $\nu j_{15/2}$ pairs is approximately the same $\omega_c(\pi i_{13/2}) \simeq 0.24$ MeV, $\omega_c(\nu j_{15/2}) \simeq 0.235$ MeV. At low I, a gradual alignment is seen for a $\nu j_{15/2}$ pair. At $I = 10\hbar$, a $\pi i_{13/2}$ pair begins to align along the rotational axis. The $\nu j_{15/2}$ pair remains partially aligned. This partial alignment is favored by pairing correlations. Above $I = 25\hbar$ the $\nu j_{15/2}$ starts to be fully aligned. Thus the alignment carried at intermediate angular momenta by the $\pi i_{13/2}$ pair is considerably smoothed out by the $\nu j_{15/2}$ pair.

In summary, we report the first studies to high spin in the transuranic region. A smooth, but definite deviation of the energies from the variable-moment-of-inertia extrapolation based on low-spin data is observed at high spin. Comparison with calculations in a cranked HFB approach indicate that our data can be understood in terms of the alignment along the rotation axis of angular momenta of single particles in the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals.

We wish to thank the Transplutonium Program Committee of the Basic Energy Sciences of the U. S. Department of Energy for the loan of the ^{248}Cm target material. Thanks are also due to J. G. Festag, H. Folger, R. Heimann, and the other members of their groups for helping with the preparation and handling of the radioactive targets. The friendly support from the operating staff of the UNILAC is gratefully acknowledged. This work was supported in part by the U. S. Department of Energy. Some of us (R.B.P., J.H.H., and A.V.R.) wish to thank Gesellschaft für Schwerionforschung, Darmstadt, for support and for kind hospitality. One of us (J.H.H.) gratefully acknowledges a Senior Alexander von Humboldt award and the hospitality and encouragement in this work of Professor Greiner at the University of Frankfurt. One of us (A.V.R.) received partial support from the University of Frankfurt, and one of us (R.B.P.) received partial support from Gesellschaft für Schwerionforschung, Darmstadt.

[1]A. Faessler, M. Ploszajczak, and K. R. Sandhya Devi, Nucl. Phys. A301, 529 (1978); A. Faessler, in Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980 (to be published).

[2]U. Mosel, in Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980 (to be published).

[3]R. Bengtsson and S. Frauendorf, Nucl. Phys. A327, 39 (1979), and A314, 27 (1979); R. Bengtsson, in Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980 (to be published).

[4]L. L. Riedinger, O. Anderson, S. Frauendorf, J. D. Garret, J. J. Gaardhøje, G. B. Hagemann, B. Herskind, Y. V. Markovetzky, J. C. Waddington, M. Guttormson, and P. O. Tjøm, Phys. Rev. Lett. 44, 568 (1980).

[5]P. Fuchs, H. Emling, E. Grosse, D. Schwalm, and H. J. Wollersheim, to be published.

[6]E. Grosse, H. Emling, P. Fuchs, R. Piercey, D. Schwalm, R. S. Simon, H. J. Wollersheim, D. Evers, and H. Ower, to be published.

[7]L. K. Peker and J. H. Hamilton, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, Japan, 1977*, edited by The Organizing Committee (International Academic Printing Co. Ltd., Tokyo, 1977), p. 110.

[8]H. Ower, Th. W. Elze, J. Idzko, K. Stelzer, H. Emling, P. Fuchs, E. Grosse, D. Schwalm, H. J. Wollersheim, N. Kaffrell, and N. Trautmann, in Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980 (to be published).

[9]S. Frauendorf, in Nobel Symposium: Nuclei at Very High Spins, Lund, Sweden, 9–13 June 1980 (to be published); R. S. Simon, F. Folkmann, Ch. Briancon, J. Libert, J. P. Thibaud, R. J. Walen, and S. Frauendorf, unpublished; S. Frauendorf and R. Bengtsson, private communication.

[10]A. Faessler, K. R. Sandhya Devi, F. Grummer, K. W. Schmid, and R. R. Hilton, Nucl. Phys. A256, 106 (1976); A. Faessler, M. Ploszajczak, and K. W. Schmid, to be published.

[11]M. Baranger and K. Kumar, Nucl. Phys. A110, 490–529 (1968).

[12]A. Faessler and M. Ploszajczak, to be published.

[13]H. C. Pauli, Phys. Rep. 7C, 35 (1973).