Recoil distance lifetimes of rotational states in ^{236}U†

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Half-lives for members of the ^{236}U ground-state rotational band have been measured by the recoil-distance method following Coulomb excitation with $^{40}Ar^{8+}$ projectiles. The $B(E2, I\rightarrow I-2)$ values in units of e^2b^2 determined from the half-lives of the 4^+, 6^+, 8^+, 10^+, and 12^+ states are 3.03 ± 0.20, 3.28 ± 0.19, 3.42 ± 0.28, 3.11 ± 0.30, and $3.34^{+2.23}_{-0.95}$, respectively. Transition quadrupole moments $Q_{20}(I_i\rightarrow I_f)$ deduced from the lifetimes are constant within experimental error and thus support the characterization of ^{236}U as a good rotor to spin 12^+.

NUCLEAR REACTIONS ^{236}U(^{40}Ar, ^{40}Ar$'$,γ), E=153, 155 MeV; measured lifetimes 4^+, 6^+, 8^+, 10^+, 12^+ members g.s. band ^{236}U; deduced $B(E2)$ and $Q_{20}(I_i\rightarrow I_f)$ values, compared with theory.

I. INTRODUCTION

Because the rotational model has been successful in correlating experimental data for many deformed nuclei, it is desirable to investigate the limits of its applicability. One test of the model consists of checking the predicted $I(I+1)$ spacing of lower-spin levels in rotational bands. By this method one can roughly define the regions of applicability in the Periodic Table for the model. Of more interest are deviations from $I(I+1)$ spacing for high-spin members of bands whose lower members exhibit rotational behavior, the most striking instance being the phenomenon of backbending.[1,2] The less violent excursions from rotational behavior have been described reasonably well by band mixing,[3,4] centrifugal stretching,[5,6] Coriolis antipairing,[7] and fourth-order cranking[8] or variable moments of inertia models.[9] The more radical departure from rotational energy spacing exemplified by backbending has been ascribed to the action on neutron pairs of the Coriolis force—either the decoupling of a single neutron pair,[10] or the collapse of pairing for all neutrons[1,2,7,11] above a critical angular velocity.

A second sensitive test of the rotational model may be effected by measuring the transition probabilities between states in a rotational band. For a pure rotor, the reduced electric multipole transition probabilities $B(E\lambda)$ are related by squares of appropriate Clebsch-Gordan coefficients, and deviations from this behavior signal some degree of breakdown for the simple rotational model. For a transition proceeding by a single γ-ray multipolarity, the $B(E\lambda)$ may be related to the lifetime of the initial state if the total internal conversion coefficient is known. For actinide rotational states presently accessible by Coulomb excitation (I_{MAX} ~20), the lifetimes are expected to lie roughly in the range 10^{-9} to 10^{-12}s. The recoil-distance technique[12-14] is generally agreed to be the most reliable method for measuring lifetimes of that magnitude and therefore provides a powerful tool to test rotational behavior in actinide nuclei.

In addition to well-defined rotational spectra, a second interesting feature of actinide nuclei is the significant $E4$ deformation of the nuclear charge found for many of them using α-particle Coulomb excitation.[15,16] The $E4$ moment has a quadratic dependence on the α-particle Coulomb excitation cross section, however, and two quite different solutions are consistent for the $E4$ moments derived by this method.[15,16] Theoretical considerations[17-20] support the positive-root solutions adopted,[15,16] but experimental confirmation of the proper solution is available using multiple Coulomb excitation.[21,22] This method requires a knowledge of the $E2$ and $E4$ matrix elements connecting members of the ground-state band, however, and we have used the rotational model in previous experiments[21] to deduce them from the $B(E2, 0\rightarrow2)$ and $B(E4, 0\rightarrow4)$ of Bemis *et al.*[16] Therefore, lifetimes measured in this experiment also serve as a valuable check on the $E2$ matrix elements used to determine the sign of the ^{236}U hexadecapole moment by multiple Coulomb excitation.[22]

II. RECOIL-DISTANCE METHOD

The recoil-distance or "plunger" technique[12-14] entails the excitation of nuclei in a thin target foil with a beam of sufficient energy to cause the excited nuclei to recoil from the target until halted by a movable metallic stopper. Deexcitation γ

rays emitted by this ensemble of recoiling nuclei are partitioned into two subsets by the action of the stopper: (1) those γ rays emitted after the nuclei strike the stopper, having the characteristic energy E of the transition, and (2) those γ rays emitted from nuclei that are still in flight, which are shifted to an energy $(E+\Delta E)$ as a consequence of the relative motion in the detector direction (Doppler effect). Customarily, one defines a quantity R as the ratio of unshifted to total intensity for the doublet. For a target-stopper flight time of T, it is easily shown that R is related exponentially to the mean life τ of the state

$$R \equiv \frac{I_u}{I_u+I_s} = e^{-T/\tau}\,,$$
$$\ln R = -D/v\tau\,, \tag{1}$$

where v is the average recoil velocity component on the beam axis, and D is the target-stopper separation. The mean life is then taken from the slope of $\ln R$ as a function of D provided one knows the recoil velocity, which is available from the experimental Doppler shift in the energy spectrum or from kinematic calculations.

In practice these simple considerations are altered by several effects: (1) The efficiencies for detection of the unshifted and shifted γ rays differ because their energies are not equivalent. (2) Different average solid angles are presented to unshifted and shifted γ rays for two reasons: (a) The unshifted and shifted γ rays are emitted at different average distances from the detector. (b) The shifted photons are emitted from a reference frame in motion relative to that of the detector, necessitating a velocity-dependent transformation of angles between the two frames. (3) The nuclear alignment of the recoiling ion may be perturbed by fields encountered during flight. Shifted γ rays are emitted from nuclei after a shorter average flight time than for unshifted ones; therefore, the average alignments may differ for the shifted and unshifted subsets. (4) Cascade feeding of a level alters in a time-dependent manner both its population and its alignment. (5) If determined experimentally from the Doppler shift, the nominal recoil velocity component must be corrected for the finite size of the detector. This correction is slightly state-dependent since the probability of γ-ray absorption in different regions of the detector is an energy-dependent phenomenon. (6) The effect of velocity spreads, target irregularities, and nonparallelism of the target and stopper must be evaluated. (7) For very fast transition ($\tau \sim 1$ ps) the unshifted "peak" may possess significant tailing due to a finite slowing time in the stopper.

A forthcoming publication[23] describes our comprehensive method of correcting the experimental data for these effects with the computer code ORACLE, which was used to determine all lifetimes reported in this work. These corrections are discussed further in Sec. IV, where the method of data reduction is considered in more detail.

III. EXPERIMENTAL METHOD

A 153-MeV $^{40}Ar^{8+}$ beam was used to produce Coulomb excitation of ^{236}U nuclei in a thin (2 mg/cm^2), tightly stretched, rolled metallic foil. The nuclei recoiled from the target with a velocity $v/c \sim 0.022$, and were stopped by the movable ^{208}Pb-covered stopper of the plunger apparatus which is described elsewhere.[24] The γ rays emitted from the excited nuclei were detected in an 18% Ge(Li) detector placed at 0° to the beam axis and positioned 5 cm from the target foil. Backscattered heavy ions were detected by an annular silicon detector subtending an average angle of 166°, thereby limiting the forward-scattered recoils to an average cone of ~6°. Linear signals from the germanium and silicon detectors, and the time relation between them from a time-to-amplitude converter, were digitized by a fast analog-to-digital converter and placed into temporary buffer storage as three-parameter data words in an SEL-840A computer. This information was transferred to disc storage, and finally written on magnetic tape. The tapes were scanned with appropriate windows on the heavy-ion and time parameters to yield prompt γ-ray spectra for each position setting of the plunger apparatus. These were corrected for the contribution of random events to yield the final spectra, from which lifetimes for the 6^+, 8^+, 10^+, and 12^+ states were deduced.

In a second experiment we found it necessary to use a 6 mm diameter, planar Ge(Li) x-ray detector of 500 eV resolution at 122 keV to cleanly separate the $4^+ \rightarrow 2^+$ unshifted-shifted doublet from a surrounding envelope of $K\alpha$ and $K\beta$ x-rays. Excitation was produced by a 155-MeV $^{40}Ar^{8+}$ beam on a 2.5 mg/cm^2 target, and the target-detector separation was 2.0 cm. Other aspects of the experimental procedure were similar to those described above.

^{226}Ra and ^{182}Ta sources were used to calibrate the efficiency of the γ-ray detector, while ^{241}Am and ^{57}Co sources were used to calibrate the efficiency of the x-ray detector. In both experiments the nominal zero-separation point was defined by electrical contact between the target and stopper. The conversion of this value to a true zero point is discussed subsequently.

IV. ANALYSIS AND CORRECTION OF DATA

Some representative spectra obtained with the 18% Ge(Li) detector for different nominal target-stopper distance settings are shown in Fig. 1, while those obtained utilizing the x-ray detector are shown for several distances in Fig. 2. In both figures the variation of the relative unshifted and shifted intensities with target-stopper distance is readily apparent.

The interesting shifted-unshifted doublets in these spectra were analyzed by a fitting routine[25] using two overlapping Gaussian functions for *each* member of the doublet. Care was taken to preserve the width and area ratios between the overlapping functions for each member at various distance settings. Since the lifetimes measured here are long compared to the characteristic slowing time in the stopper, any structure on the unshifted peak due to a finite slowing time is assumed negligible. The areas obtained by this procedure were used as input data for the computer code ORACLE,[23] a computer program to correct for the previously mentioned effects which perturb the simple exponential behavior of Eq. (1).

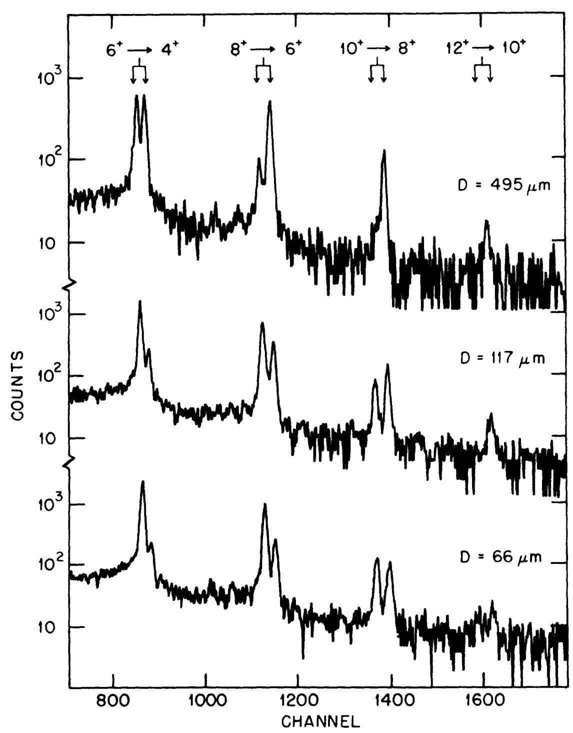

FIG. 1. γ-ray spectra for different target-stopper separations taken with a Ge(Li) γ-ray detector. Excitation was produced by a 153-MeV ^{40}Ar beam on the ^{236}U target.

A. Cascade feeding

The correction due to cascade feeding is dependent upon the parameters η_{ji} defined by

$$\eta_{ji} = P_j / P_i . \tag{2}$$

The quantities P_j and P_i are the relative probabilities for excitation of the states j and i, respectively, where the state j feeds the state i being analyzed either directly or through some intervening cascade sequence. For the case of Coulomb excitation these excitation probabilities may be obtained from two sources: (a) relative intensities in the γ-ray spectrum, or (b) theoretical calculations (e.g., from the Winther-de Boer code[26]). At present method (b) is subject to significant uncertainties for high-spin states; with these uncertainties being related to questions regarding quantal corrections to semiclassical calculations, the nature and magnitude of the matrix elements to be used in the calculations, etc. Therefore we have used the summed intensities of the unshifted and shifted peaks to determine the probability ratios from the relation

$$\eta_{ji} \cong \frac{\xi_i}{\xi_j}\left[\frac{(1+\alpha_j)N_j - \xi_j T_j}{(1+\alpha_i)N_i - \xi_i T_i}\right], \tag{3}$$

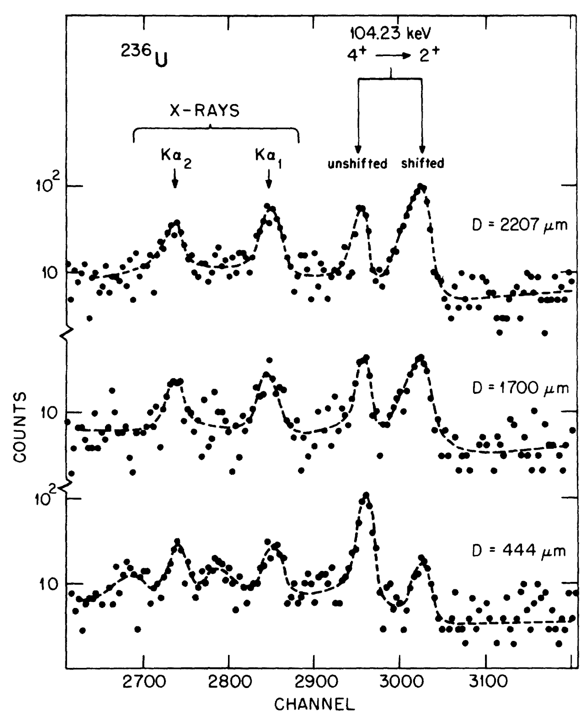

FIG. 2. Spectra for different target-stopper separations taken with an x-ray detector. Excitation was produced by a 155-MeV ^{40}Ar beam on the ^{236}U target.

where the total conversion coefficient and total (shifted and unshifted) peak area for the nth transition are denoted by α_n and N_n, respectively, and T_n represents the intensity due to cascade feeding. The quantity ξ_n measures the relative probability that an emitted γ ray is detected and is approximated by

$$\xi_n \approx \bar{\epsilon}_n \bar{\Omega}_n \bar{W}_n(\theta) ,$$

where $\bar{\epsilon}_n$, $\bar{\Omega}_n$, and $\bar{W}_n(\theta)$ represent efficiency, solid angle, and angular distribution functions suitably averaged over contributions from the unshifted and shifted component. The uncertainties inherent in extracting the feeding intensities from the experimental spectrum (typically 5–10% in η_{ji}) have been included in the lifetime uncertainties.

To correct properly for cascade feeding, the contribution of any 14^+ excitation to the feeding process must be considered. We have assigned to the 14^+ excitation probability a value equal to 10% of that for the 12^+ state and a half-life of 4.1 ps for correction purposes. These values are consistent with trends in excitation probabilities and lifetimes noted for lower-spin members of the band. Feeding from vibrational levels has been ignored in the present analysis.

B. Alignment attenuation

If the observed alignment for a nuclear state decays in a time-dependent manner, the angular distribution function may be written in the form

$$W(\theta,t) = 1 + \sum_{k=2,4} (2k+1) g_k \frac{F_k(I_m,I_n)}{F_0(I_m,I_n)} \frac{\alpha_{k0}}{\alpha_{00}} P_k(\cos\theta) G_k(t) , \tag{4}$$

where g_k represents the correction for finite detector solid angle,[27] $F_k(I_m,I_n)$ are defined by Winther and de Boer,[26] α_{k0} is the zero component of the kth order statistical tensor, $P_k(\cos\theta)$ is a Legendre polynomial, and $G_k(t)$ is a function describing the time dependence of the kth-order alignment. In the absence of experimental data for the perturbation of the nuclear alignment, we must make certain assumptions regarding the form and magnitude of $G_k(t)$. Though there have been other approaches,[28-32] it has been customary to correct for this effect using the Abragam-Pound[33] formalism for statistical perturbations, which predicts an exponential form for the function $G_k(t)$

$$G_k(t) = e^{-t/\tau_k} , \tag{5}$$

where τ_k is a relaxation constant of order k, determined by the magnitude and form of the perturbation.

Nordhagen *et al.*[34] have investigated the vacuum deorientation of high-spin states in ^{156,158,160}Er nuclei produced in (^{40}Ar, $4n$) reactions. They found less alignment loss for high-spin states than predicted and interpreted these results in terms of a simple model predicting less perturbation of the nuclear spin I when it is large in comparison to the electronic spin J. However, Ward *et al.*[35] have suggested a reinterpretation of these data since the light erbium nuclei have been shown to exhibit backbending in their ground-state bands.[1,2] There are calculations[36,37] based on the proposed "pairing collapse" explanation of backbending which predict that, in the phase-transition region and above, the nuclear g factors will be sharply reduced. If true, this would provide an alternate interpretation of the Nordhagen *et al.*[34] data, since their conclusions rest on the explicit assumption of constant g factors in the ground-state band. Then generalization of the erbium results to the case of nonbackbending nuclei may not be possible, and in support of the contention Ward *et al.*[35] report relaxation constants which are essentially spin independent for spins 2^+ and 4^+ in ^{150}Sm and 6^+ and 8^+ in ^{156}Gd.

The applicability of the Abragam-Pound formalism to the recoil-distance situation must be questioned in principle since it is likely that an appreciable number of recoiling nuclei have reached stable electronic configurations shortly after leaving the target.[38] Such a situation would cast doubt on the proposed random perturbation due to electronic transitions during the recoil through vacuum, and thus undermine the validity of the first-order perturbation theory used in the Abragam-Pound formalism. Nevertheless, time-differential measurements for the $2^+ \to 0^+$ transition in ^{150}Sm are consistent with an exponential alignment decay.[39] Unfortunately, there has been no definitive time-differential measurement for higher-spin states to test the Abragam-Pound theory or to test the possible spin dependence of the relaxation constants τ_k.

Therefore, for correction purposes we assume that the Abragam-Pound formalism is at least a reasonable approximation. Furthermore, in very preliminary time-differential measurements[40] on ^{232}Th the alignment for the unshifted component appears to be highly attenuated after a flight time of 30 ps for the 4^+, 6^+, and 8^+ members of the ground-state rotational band. Assuming similar behavior for ^{236}U, we conclude that the use of Abragam-Pound theory[33] with short ($\tau_2 < 30$ ps) spin-independent relaxation constants should be sufficient for correcting the data even if that procedure should prove to be formally incorrect. To correct for the vacuum deorientation in ^{236}U then,

TABLE I. The effect of different sets of spin-independent relaxation constants τ_k on the extracted lifetimes. All changes are expressed relative to the half-life of the adopted case $\tau_2 = 20$ ps, $\tau_4 = 6$ ps.

State	% change in half-life of adopted case $\tau_2=5$ ps $\tau_4=1.5$ ps	$\tau_2=10$ ps $\tau_4=3$ ps	$\tau_2=30$ ps $\tau_4=9$ ps	$\tau_2=50$ ps $\tau_4=15$ ps	$\tau_2=100$ ps $\tau_4=30$ ps	$\tau_2=+\infty$ $\tau_4=+\infty$
10^+	−3.4	−0.9	−1.8	−3.0	−4.7	−6.1
8^+	−4.6	−2.1	−0.4	−1.7	−4.0	−5.9
6^+	−3.9	−2.7	+1.4	+2.1	+0.4	−4.3
4^+	+1.7	−0.2	+0.6	+1.7	+6.3	+1.8

we have adopted the Abragam-Pound formalism[33] and the somewhat arbitrary spin-independent relaxation constants $\tau_2 = 20$ ps, $\tau_4 = 6$ ps for all states of the ground band.

To investigate the consequences of these assumptions, the effects on the corrected half-lives extracted from the data using several other sets of relaxation constants were calculated. They are displayed in Table I. The table can be used to estimate the effect of incorrect spin-independent relaxation constants, and also to qualitatively estimate the effect of allowing the relaxation constants to increase with spin as proposed by Nordhagen *et al.*[34] An uncertainty of 5% has been included in the quoted errors for the lifetimes, reflecting this uncertainty in the alignment correction.

C. True zero

In the zero-order treatment of Eq. (1) the lifetime is determined from the slope of $\ln R$ as a function of D. Therefore only an arbitrary zero on the distance scale need be defined in order to extract lifetimes. In the real experimental situation, where cascade feeding, alignment attenuation, and positional dependence of the detector solid angle are important, the magnitude of the correction for these effects is a function of flight time for the recoiling ion, and hence of the absolute target-stopper separation. To correct the data properly, this true separation must be determined. We note that if the data were corrected properly the plot of $\ln R$ vs D should pass through $\ln R = 0$ for $D = 0$ for all transitions. Therefore, an iterative adjustment to the experimental distance scale (where arbitrary zero is defined by electrical contact) has been adopted: the distance scale is shifted linearly until the corrected curves satisfy the condition $\ln R\ (D=0) = 0$. This constraint on the corrected 6^+, 8^+, and 10^+ curves led to a linear shift of the distance scale by $-10\ \mu$m relative to that determined by electrical contact. In the x-ray detector experiment the same requirements on the 4^+ curve dictated a shift of 51 μm. The 12^+ lifetime was determined from a fit constrained to pass through the corrected zero point determined from the 6^+, 8^+, and 10^+ curves. The quoted uncertainty for the 12^+ lifetime reflects the possibility of an error of 13 μm in D_0.

D. Velocities

The recoil velocity v was determined from the expression of Quebert *et al.*[41] and from the less rigorous formula[42]

$$\frac{\Delta E}{E} = \frac{v}{2c}(1 + \cos\theta_c)\,, \tag{6}$$

where $\Delta E/E$ is the relative Doppler shift determined from the spectrum, c is the velocity of light, and θ_c is the maximum half-angle subtended by the detector face. For this work the difference between the two formulas is negligible. Velocities were determined from several peak separations in each experiment and averaged to yield recoil velocities of $v/c = 0.022\,37 \pm 0.000\,07$ for the γ-ray detector experiment. Adverse effects due to velocity spreads, target irregularities, and nonparallelism of the target and stopper were estimated and found to be negligible.

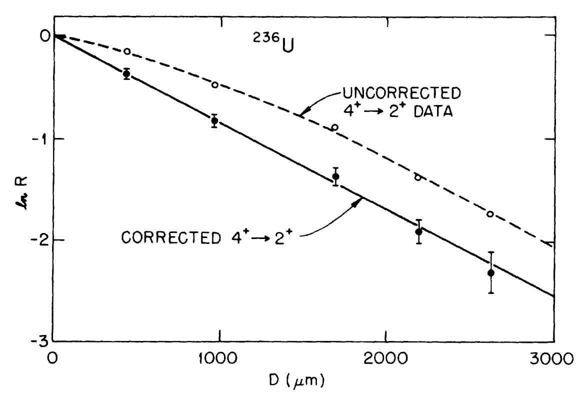

FIG. 3. $\ln R$ vs D for the $4^+ \to 2^+$ transition in the ^{236}U ground band. The open circles represent experimental data, while closed points represent the corrected data from which the lifetime is extracted.

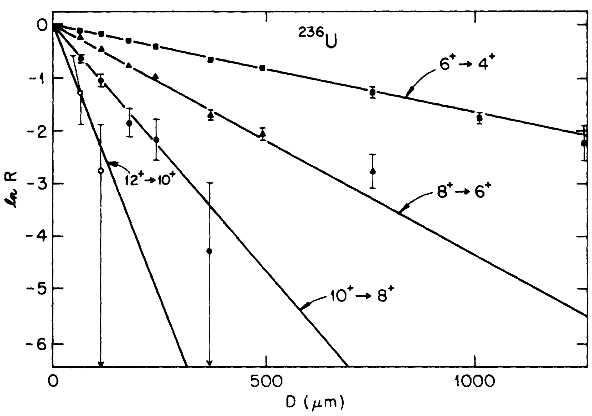

FIG. 4. LnR vs D for the $6^+\to4^+$, $8^+\to6^+$, $10^+\to8^+$, and $12^+\to10^+$ transitions in the ^{236}U ground-state band. All points have been fully corrected by the computer program ORACLE for feeding, alignment attenuation, efficiency difference, and solid-angle velocity and time dependence.

V. RESULTS

The corrections discussed above and the ones for solid-angle and efficiency differences were applied simultaneously to the data by the program ORACLE.[23] In Fig. 3 the ln R vs D curve for the $4^+\to2$ transition is displayed. The solid points represent the experimental data following correction and the solid line is the weighted linear least-squares fit to these points, from which the lifetime is extracted. For purposes of illustration, the uncorrected data points are also plotted as open circles with a dotted line through the points to emphasize their severe nonlinear deviation from the corrected points. The large corrections necessary in this particular case are primarily due to the intense cascade feeding of the 4^+ state by higher-lying members of the band. Total corrections for the higher-spin states are successively smaller until for the 10^+ state the various corrections largely cancel each other. Figure 4 displays ln R vs D plots for the higher-energy transitions in the ground band, where now only the corrected data are shown.

The fits to the corrected data and Eq. (1) were used to extract half-lives which are related to the reduced electric-quadrupole transition probability by

$$B(E2,I\to I-2)=\frac{0.056\,56}{(1+\alpha_T)(E)^5T_{1/2}}\,, \tag{7}$$

where α_T is the total conversion coefficient, E is the energy of the transition in MeV, $T_{1/2}$ is the half-life in ps, and the $B(E2)$ value is in units of e^2b^2. The transition quadrupole moment $Q_{20}(I_i\to I_f)$ is given by

$$Q_{\lambda0}{}^2(I_i\to I_f)=\frac{16\pi}{2\lambda+1}\,\frac{B(E\lambda,I_i\to I_f)}{|\langle I_i\lambda K0\,|I_fK\rangle|^2}\,. \tag{8}$$

Values for $T_{1/2}$, $B(E2,I_i\to I_f)$, $Q_{20}(I_i\to I_f)$, and relevant nuclear information for states studied in this work are displayed in Table II. Uncertainties quoted for the half-life reflect the standard deviation of the corrected fit, the standard deviation of the average recoil velocity, and estimated errors in the feeding intensity, alignment relaxation constants, efficiency ratios, and solid-angle ratios. Uncertainties quoted for the $B(E2,I_i\to I_f)$ and $Q_{20}(I_i\to I_f)$ include additional estimated errors in conversion coefficients and transition energies.

VI. DISCUSSION AND CONCLUSIONS

The transition quadrupole moment $Q_{20}(I_i\to I_f)$ is a measure of the nuclear deformation in the rotational model. The constancy of the $Q_{20}(I_i\to I_f)$ as a function of angular momentum is then a defining characteristic of the (unperturbed) rotational nucleus. Figure 5 displays graphically the quadrupole moment deduced from this experiment as a

TABLE II. Half-lives, reduced transition probabilities, and transition quadrupole moments determined by recoil-distance measurements on transitions in the ^{236}U ground-state rotational band.

Transition	Energy (keV)	α_T [b]	$T_{1/2}$ (ps)	$B(E2,I\to I-2)$ (e^2b^2)	$Q_{20}(I_i\to I_f)$ (e b)
$4\to2$	104.233 ± 0.005 [c]	10.2 ± 0.2	124.0 ± 7.3	3.03 ± 0.20	10.33 ± 0.34
$6\to4$	160.310 ± 0.008 [c]	1.78 ± 0.04	58.2 ± 3.3	3.28 ± 0.19	10.23 ± 0.29
$8\to6$	212.400 ± 0.100 [c]	0.59 ± 0.01	23.9 ± 1.9	3.42 ± 0.28	10.22 ± 0.43
$10\to8$	260.6 ± 0.5 [a]	0.29 ± 0.01	11.6 ± 1.1	3.11 ± 0.30	9.61 ± 0.48
$12\to10$	303.4 ± 0.5 [a]	0.18 ± 0.004	$5.5^{+1.8}_{-3.3}$	$3.34^{+2.23}_{-0.95}$	$9.87^{+2.88}_{-1.52}$

[a] Multiple Coulomb excitation data from Guidry *et al.* (Ref. 22).
[b] A 2% uncertainty is estimated, with the values taken from Hager and Seltzer (Ref. 44) and Drajoun, Plajner, and Schmutzler (Ref. 45).
[c] γ-ray measurements on the decay of ^{240}Pu from Schmorak *et al.* (Ref. 43).

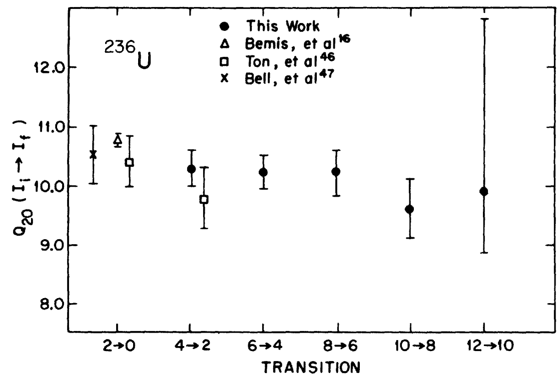

FIG. 5. Transition quadrupole moments $Q_{20}(I_i \to I_f)$ deduced from the values of $B(E2, I_i \to I_f)$ in this and other recent work.

function of the initial spin I_i in the ground-state rotational band. In addition, values determined from other work on 2^+ and 4^+ states in ^{236}U have been included.[16,46,47]

The values of $Q_{20}(I_i \to I_f)$ determined by the recoil-distance technique agree to within 1% for the 4^+, 6^+, and 8^+ states. There is some suggestion of a slightly reduced quadrupole moment for $I > 8$, but there is no statistically significant deviation. Furthermore, the weighted average quadrupole moment of the 4^+, 6^+, and 8^+ states, $Q_{20} = 10.28 \pm 0.36$ eb, agrees within experimental error with the $Q_{20}(2 \to 0)$ in all previous determinations[16,46,47] and is also consistent with the $Q_{20}(4 \to 2)$ of Ton *et al.*[46] These results suggest that the ^{236}U nucleus is a good rotor through spin 10^+ in its ground band, with the small decrease in $Q_{20}(10 \to 8)$ approximately equal to the experimental uncertainty in its determination.

Although the average quadrupole moment extracted from our data is consistent within experimental error with the precise $Q_{20}(2 \to 0)$ of Bemis *et al.*,[16] the fact that our moments are systematically lower than the one extracted from Ref. 16 is of some concern. If ^{236}U is interpreted as a reasonably good rotor, the data presented here are most consistent with a $B(E2, 2 \to 0)$ some 5–10% below that found from α-particle Coulomb excitation. The possibility of an error of that magnitude in the $B(E2, 2 \to 0)$ is unlikely due to the precise nature of α-particle Coulomb excitation measurements.

There are at least two considerations that could account for a portion of this systematic discrepancy: (1) deviations from the calculated conversion coefficients used to relate the lifetimes measured to the transition probabilities, and (2) the unknown nature of the correction for alignment attenuation in the recoil-distance data.

Johnson *et al.*[48] have considered the effect of changes in conversion coefficients for highly stripped recoiling ions due to altered electron densities within the nuclear volume. They concluded, on the basis of estimates from recent work in atomic physics,[49-51] that such changes would have negligible effect on the lifetime results. The same considerations and conclusions are applicable here.

A second aspect of the situation concerning conversion coefficients is more significant. Stelson and Raman[52] have recently surveyed data on Coulomb excitation and direct lifetime measurements for 2^+ states in actinide nuclei. This survey suggests that theoretical $E2$ conversion coefficients[44] for actinide nuclei are too large by ~6%. If this adjustment is made in the conversion coefficients the transition quadrupole moments of Fig. 5 are raised by 3%, 2%, and 1% for the 4^+, 6^+, and 8^+ states, respectively. The data interpreted in this manner would be consistent with a quadrupole moment gradually decreasing with increasing spin. However, the decrease in $Q_{20}(I_i \to I_f)$ between the 2^+ and 10^+ states would not lie significantly beyond the limits of experimental error. Almost identical results have been obtained[48] in a related experiment on ^{232}Th, but there also the suggested decrease in $Q_{20}(I_i \to I_f)$ is only of the order of the experimental uncertainty.

As Table I indicates, the unknown nature of the alignment attenuation for this case can cause errors as large as 6% in the mean life (3% in $Q_{20}(I_i \to I_f)$) for a particular state. If the relaxation constants are not a function of spin this effect will, in general, only be significant for the one or two states whose mean life is comparable to the second-order relaxation constant τ_2. However, if the relaxation constants change with spin as proposed by Nordhagen *et al.*,[34] a more systematic effect on all the lifetimes as large as 3–6% [1.5–3% in $Q_{20}(I_i \to I_f)$] is conceivable.

Thus it seems that a significant part of the systematic deviation of $Q_{20}(I_i \to I_f)$ from that of Ref. 16 could be accounted for by the uncertainties in the $E2$ conversion coefficient and in the alignment relaxation constants τ_2 and τ_4. To remove these ambiguities in the interpretation of lifetime data it is of obvious importance to test the validity of the theoretical conversion coefficients and to elucidate the mechanism of alignment attenuation for ions recoiling into vacuum.

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