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REDUCED TRANSITION PROBABILITIES FOR HIGH SPIN STATES IN $^{232}\text{Th}^*$

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Abstract

The lifetimes and reduced transition probabilities for spins $6^+ - 18^+$ in the ground-state rotational band of ^{232}Th have been measured by recoil-distance, Doppler-broadened lineshape, and multiple Coulomb excitation methods using ^{84}Kr and ^{136}Xe projectiles. Within the limits of experimental uncertainty, transition probabilities from all of the methods are consistent with those of a good rotor for spins $6^+ - 18^+$. The discrepancy with the prediction of simple β -band mixing and centrifugal stretching models is discussed.

NUCLEAR REACTIONS: $^{232}\text{Th}(^{84}\text{Kr}, ^{84}\text{Kr}', \gamma)$, $E_{\text{LAB}} = 385 \text{ MeV}$; $^{232}\text{Th}(^{136}\text{Xe}, ^{136}\text{Xe}', \gamma)$ $E_{\text{LAB}} = 595, 623 \text{ MeV}$; measured lifetimes for $6^+ - 18^+$ members g. s. band by recoil-distance and Doppler-broadened lineshape methods; yields for Coulomb excitation measured; $B(E2)$ values derived from lifetimes and yields, compared to theory.

1. Introduction

The measurement of lifetimes, or equivalently, reduced transition probabilities for high-spin states is of considerable interest because these measurements provide a stringent test of nuclear models. These lifetimes normally lie outside the range of conventional electronic methods, but are often amenable to determination by three complementary techniques: 1) the Doppler-shift recoil-distance method (RD),¹⁾ 2) the Doppler-broadened lineshape method (DBLS),²⁾ and 3) multiple Coulomb excitation methods. (COULEX).³⁾ Broadly speaking, the RD method may be applied to states with mean lives in the range 10^{-9} - 10^{-12} s, while DBLS techniques can be used to measure lifetimes in the range 10^{-11} - 10^{-14} s. In principle COULEX methods may be used for states with lifetimes of any value, but unresolved ambiguities in the exact calculation of multiple Coulomb excitation probabilities for high-spin states complicate the interpretation of experimental data.

The recent availability of very heavy-ion beams (eg. Kr and Xe) has made it possible to Coulomb excite rotational nuclei into high angular momentum states ($I^\pi \approx 20^+$), and presents the possibility of measuring the transition probabilities from these levels by one of the methods mentioned above. The spectra thus obtained are cleaner than those obtained by populating these states in a nuclear reaction, especially if the γ -rays de-exciting the states of interest may be detected in γ - γ or γ -particle coincidence. Furthermore, if the levels are excited by Coulomb excitation one does not have the problem of delayed ground-band feeding which may occur in heavy-ion xn reactions. For the present study one also encounters the difficulty of producing actinide nuclei

by heavy-ion xn reactions due to the high probability for fission of the compound system relative to evaporation processes.

We have undertaken a study of transition probabilities in ^{232}Th by recoil distance, DBLS, and multiple Coulomb excitation methods using ^{84}Kr and ^{136}Xe beams. These methods have yielded lifetimes in the ground state rotational band for spins $6^+ - 18^+$. The lifetimes for these states in ^{232}Th are ideal to provide a comparative test of the three methods as they generally lie in the overlap region of the optimum lifetimes for RD and DBLS methods. Therefore this study serves not only to elucidate the structure of ^{232}Th in high angular momentum states, but also provides a critical evaluation of the consistency and limitations of the general experimental procedures applicable to the measurement of short nuclear lifetimes.

In section 2 we discuss the lifetimes evaluated by RD for excited states produced by Coulomb excitation with ^{84}Kr particles detected in backscatter coincidence, while section 3 is devoted to an analysis of RD lifetimes from the singles γ -ray spectra in the same experiment. Lifetimes from a DBLS analysis for ^{136}Xe projectiles in singles and backscatter particle coincidence are discussed in 4, and in section 5 the yields from the ^{136}Xe experiment are evaluated in terms of multiple Coulomb excitation theory. Section 6 is devoted to a summary of averaged transition probabilities, a critical comparison of methods, and a comparison of the results to theoretical predictions. Finally, the primary conclusions of this work are summarized in section 7.

2. Lifetimes from Recoil-Distance Coincidence Spectra

Target foils were 1.5 mg/cm^2 thick, tightly stretched in the recoil-distance plunger device which is described elsewhere.⁴⁾ Excitation was produced by a 385-MeV ^{84}Kr beam from the Lawrence Berkeley Laboratory SuperHILAC. De-excitation γ -rays were detected at 0° with the 45 c.c. coaxial Ge(Li) detector operated in coincidence with an annular particle detector spanning a backscatter range of $160^\circ - 170^\circ$ with an average angle of 166° . The geometry favors the excitation of high-spin states by multiple-excitation processes and confines the recoiling Th ions to an average forward cone of $\sim 5^\circ$ relative to the beam axis. The efficiency of the Ge(Li) detector was calibrated with ^{152}Eu and ^{177}Lu sources. The nominal zero point was determined by electrical contact between the target and stopper of the plunger device. The relation of this nominal zero to the true zero is discussed below.

The data for each position setting of the recoil-distance apparatus were sorted with appropriate windows on the backscattered particle and time parameters to yield coincidence γ -ray spectra. The contribution of random events was judged negligible and these spectra were used to determine peak areas by two independent methods: a) a simultaneous 2-peak, variable width, least-squares Gaussian fit to the unshifted-shifted doublet; and b) simple integration of peak areas over background, with the background described by a cubic polynomial.

The peak areas obtained must be corrected for the tailing on the high-energy side of the unshifted peak due to the finite slowing time of the recoiling ion in the stopper. This correction was accomplished by using the DBLS computer code described in section 4 to generate a correction factor f_{DBLS} which was applied to the 'Gaussian' area of the unshifted peak to yield a total area corresponding to decay of the recoils after encountering the stopper. Since the correction factors f_{DBLS} generated by the DBLS program are lifetime dependent they must be determined in an iterative manner. For the 6^+ , 8^+ , 10^+ , 12^+ , and 14^+ states the final values of f_{DBLS} were 1.0, 1.01, 1.03, 1.12, and 1.30 respectively, indicating the sensitivity of the shorter lifetimes measured to the finite slowing time in the stopper.

As a first approximation, the ratio R of the unshifted to total intensity of a doublet is related to the mean life τ of the state by

$$R \equiv \frac{I_u}{I_u + I_s} = e^{-T/\tau} = \exp\left(-\frac{D}{\tau \cdot v \cdot \cos\theta}\right) \quad (1)$$

where T is the target-stopper flight time, D is the target-stopper distance, and $v \cos\theta$ is the average velocity component of the recoil on the beam axis. In actual practice this simple relationship is perturbed by 1) differing efficiencies for the unshifted and shifted peaks, 2) positional and velocity-dependent effects on the effective solid angles, 3) attenuation of the nuclear alignment by hyperfine interaction, and 4) cascade feeding from higher levels. These effects are accounted for

in a computer program based on a formalism described separately.⁵⁾ In general this program generates by self-consistent iteration a correction factor F , which is applied to the experimental ratios R_{exp} to compensate for the above-mentioned effects: $R_{\text{corr}} = F \cdot R_{\text{exp}}$. This corrected ratio R_{corr} may be identified with the 'unperturbed' R of eq. 1 and the lifetime follows from a least-squares linear fit to $\ln R_{\text{corr}} = \ln(F \cdot R_{\text{exp}})$ as a function of target-stopper distance.

The large component of the correction factor F due to cascade feeding depends on the lifetimes and relative populations of those states feeding the state of interest. The populations determined experimentally through spin 14^+ are consistent with the predictions of the Winther-deBoer code⁶⁾ using rotational $M(E2)$ and $M(E4)$ matrix elements. Therefore, experimental populations have been used for spins $6^+ - 14^+$, while those for the 16^+ and 18^+ states were estimated by (iteratively) scaling Winther-deBoer predictions in terms of the trends noted in the recoil-distance results for the 12^+ and 14^+ $B(E2)$ values. The feeding lifetimes for the $8^+ - 14^+$ states were determined experimentally from the recoil-distance data, and those for the 16^+ and 18^+ states (iteratively) inferred by extrapolation. To check the criticality of this prescription, a calculation was also run using rotational lifetimes for the 16^+ and 18^+ states with all population parameters taken from calculations with rotational matrix elements. This increases the 14^+ lifetime by 10% with the lifetime of all other states changed by less than 1%.

Very little is known about the nature of the alignment attenuation for this nucleus. We have adopted the Abragam-Pound formalism,⁷⁾ with spin-independent relaxation constants $\tau_2 = 25\text{ps}$, $\tau_4 = 3/10 \tau_2$, to correct for this effect. To test the maximum error associated with the uncertainties in τ_2 and τ_4 (we assume for now the essential correctness of an exponential alignment decay) we have run several calculations for τ_2 in the range 0.5 to 100 ps. These indicate that the maximum effect on any one state for τ_2 in this range is $\lesssim 3\%$ relative to the adopted case of $\tau_2 = 25\text{ ps}$.

In first order the lifetime depends only on the slope of $\ln R$, not the intercept. This is not true when large time-dependent corrections (e.g. feeding) are necessary. The true zero of $\ln R$ vs. D was allowed to vary independently for all the transitions. Since the properly corrected curves must satisfy $\ln R(D=0)=0$, the common zero-point was shifted until the corrected $\ln R$ curves for all states passed through the origin, within experimental error. This iterative adjustment corresponded to a difference of $15\text{ }\mu\text{m}$ between nominal and true zero.

Recoil velocities were determined in the standard manner from the separation of the peaks in the spectrum,⁸⁾ and were also calculated from the kinematics of the excitation process as described in section 4. Remembering that the detector is somewhat transparent at the edges to γ -rays, and thus presents a smaller effective solid angle than that expected from the nominal detector geometry, the recoil velocity determined experimentally is consistent with the calculated value of 0.0492 C .

The above-mentioned corrections and the ones for differing efficiencies and solid angles were applied simultaneously to the data by the program ORACLE.^{5,9} The linear fits to the corrected values of $\ln R_{\text{corr}} = \ln (F \cdot R_{\text{exp}})$ are shown in fig. 1. The lifetimes deduced from these fits are displayed in column 4 of table 1. The $B(E2)$ in units of $e^2 b^2$ is related to the experimental mean life τ in ps by

$$B(E2, I \rightarrow I-2) \cong \frac{0.0812}{(1+\alpha_T) \cdot E^5 \cdot \tau} \quad (2)$$

where α_T is the total conversion coefficient, and E is the transition energy in MeV. Typically, the tables of Hager and Seltzer¹²⁾ with the higher shell corrections of Dragoun, et al.¹³⁾ are used for the conversion coefficients. However, in a systematic survey of measured lifetimes and $B(E2)$ values for $2^+ \rightarrow 0^+$ transitions in actinide nuclei, Stelson and Raman¹⁴⁾ have found evidence that the conversion coefficients are $\sim 6\%$ lower than those from ref. 12 and 13. Therefore, we have used the theoretical values,^{12,13)} scaled down by 6%, in eq. 2. Because the conversion coefficients are small for the states considered, the maximum effect in the lifetime generated by this scaling is 2% or less. In Fig. 9 we show a comparison of the experimental values of the $B(E2)$ to those calculated using the experimental value of the matrix element $M(E2, 0 \rightarrow 2)$ ^{10,11)} and the rotational model prediction

$$\begin{aligned}
 B(E\lambda, I_i \rightarrow I_f) &= \frac{1}{2I_i + 1} |\langle I_i || M(E\lambda) || I_f \rangle|^2 \\
 &= (2I_f + 1) \begin{Bmatrix} I_i & \lambda & I_f \\ 0 & 0 & 0 \end{Bmatrix} |\langle 0^+ || M(E\lambda) || \lambda^+ \rangle|^2
 \end{aligned} \tag{3}$$

where I_i and I_f are the initial and final spins, λ is the multipole order of the transition, and the quantity in brackets is a 3-j symbol.

The errors in the lifetimes of table 1 reflect a folding of uncertainties in the slopes determined from the fits, uncertainties in recoil velocity; and uncertainties in the parameters for the corrections due to the efficiencies, solid angle, and feeding. In addition an uncertainty of $\pm 3\%$ has been added linearly to account for the unknown nature of the alignment attenuation correction. The errors in the experimentally determined values of the $B(E2)$ include, besides the uncertainty in the lifetime, uncertainties in the transition energy and in the total conversion coefficient.

In addition to the data analysis procedure discussed in this section, the independent method described in the RD singles section (sect.3) was also applied to the coincidence RD data. The agreement between the two techniques was very good, with the small ($< 5\%$) deviations lying in the range explicable by differing levels of approximation in the two approaches.

3. Lifetimes from Recoil-Distance Singles Spectra

The singles γ -ray spectra were also collected at the various

plunger distances for the experiment described in section 2. Figure 2 shows the line shapes from the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transitions for the singles spectra at plunger distances comparable to their mean distance of decay. The broadness of the shifted peak, which is caused by the angular distribution of the recoiling Th ions, makes resolution of the unshifted and shifted components difficult for the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $10^+ \rightarrow 8^+$ transitions. For these transitions, the energy centroid of the total (unshifted and shifted) peak, E , was measured rather than the component areas I_u and I_s . The centroids of the spectral lines from the tantalum collimator were used to calibrate the spectrum. The ratio $R' =$

$(E_\infty - E)/(E_\infty - E_0)$, where E_0 and E_∞ are the centroids corresponding to zero and infinite plunger distances, has a functional form similar to that of the ratio of areas $R = \left(\frac{I_u}{I_u + I_s} \right)$ in eq. 1:

$$R' = \left[\int_0^{\pi/2} \omega v \cdot \cos\theta \exp(-D/\tau v \cdot \cos\theta) d\theta \right] / \left[\int_0^{\pi/2} \omega v \cdot \cos\theta d\theta \right] \quad (4)$$

Where τ is the mean life of the state, D is the plunger distance, and the weights ω are the relative probabilities that the Coulomb-excited state of interest emits a photon in the direction of the detector when the Th nucleus is recoiling at velocity v in a direction θ relative to the beam axis. The weights are written as a product of two terms:

$$\omega = \left(\frac{d\sigma}{d\theta} \right) \times (1 + a_2 + a_4) \quad (5)$$

Both the differential cross section $\left(\frac{d\sigma}{d\theta} \right)$ for excitation of the state and the Legendere coefficients a_k were calculated using the Winther-deBoer multiple Coulomb excitation computer program.⁶⁾ The recoil velocities

v , after correction for slowing down in the target, are approximately given in terms of v_0 , the recoil velocity in the forward direction at the front edge of the target, by the relationship (see appendix):

$$v \approx v_0 \left[\cos\theta \left(1 - \frac{s}{4} \left\{ \frac{dE/dx}{E} \right\}_P \right) - \frac{s}{4\cos\theta_n} \left\{ \frac{dE/dx}{E} \right\}_T \right] \quad (6)$$

where $\left\{ \frac{dE/dx}{E} \right\}_P$ and $\left\{ \frac{dE/dx}{E} \right\}_T$ are the stopping powers per unit energy at the front edge of the Th target for Kr and Th ions respectively traveling in the beam direction, and s is the target thickness in the beam direction. The stopping powers used were extrapolated from the work of Chu and Ziegler¹⁵⁾ as described in section 4.

The peak areas and centroids were extracted from the γ -ray spectra using the technique described in section 4. The areas for the $8^+ \rightarrow 6^+$ transition were corrected for contamination from the Ta 220-keV line. The degree of contamination (of the order of 10%) was estimated from a 5.2 mm run, where the Ta line and the $8^+ \rightarrow 6^+$ peak are well separated. The uncertainty due to variation in contamination from the Ta collimators during the course of the experiment should not have significant effect on the lifetimes. The corrected areas for the other runs were obtained by comparing the relative intensities of the Ta 160- and 302-keV lines with the lines from the other Th transitions. The shifted areas for all the transitions were corrected for effects due to the energy dependence of the γ -ray detector and dependence of the detector solid angle on the recoil ion's velocity when emitting the γ -ray. These corrections tended to cancel each other for the $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transitions, but were of the order of 10% and 4% for the $6^+ \rightarrow 4^+$ and $8^+ \rightarrow 6^+$ transitions respectively. The ratios R [eq. 1] and R' [eq. 4] were subsequently corrected to take into account the finite slowing

time of the recoil ions in the Pb stopper. This has the effect of changing the ratios for a particular transition by a constant factor, which, in the absence of feeding, merely shifts the origin of the ratio-distance curve. The magnitude of the correction was estimated using the DBLS line-shape program described in section 4. The maximum effect on the lifetime was 11% for the $12^+ - 10^+$ transitions. The ratios were also corrected for the distance dependence of the detector solid angle, but this effect was small ($< 1\%$), even for the largest distances.

Expressions (1) and (4) were modified to include feeding from higher spin states. The correction for feeding requires knowledge of the weights ω for each level, and these were calculated using the Winther-deBoer program.⁶⁾ The normalization of these weights was also estimated by measuring the total intensity of each transition using the area of the γ -ray peak in a zero-distance bombardment with a lead-backed target. For the transitions where these measurements were possible ($6^+ \rightarrow 4^+$ through $12^+ \rightarrow 10^+$) the experimental values agreed within error with the calculations. In the computer fit a cascade of four states was used to describe the data. The data for the two lowest states were least-squares fitted, with their lifetimes and common origin of the plunger distance scale as free parameters. The origin determined here agreed within experimental error with that in the coincidence RD section, as it should. The data for the $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transitions were first fitted together in this fashion, the lifetimes of the two feeding states (14^+ and 16^+) being fixed at rotational values. The value of the lifetime of the 12^+ state found from this analysis was then used when fitting together the $8^+ \rightarrow 6^+$ and $10^+ \rightarrow 8^+$ transitions, and so on. The adopted values of lifetimes for the lower spin states were taken from the

particular fit where that state was lowest in the cascade. This minimizes the error due to truncation of the cascade. The fitted curves and experimental ratios corrected for solid-angle effects are shown in fig. 4.

The effect of alignment attenuation for the recoiling ions was also investigated. The same considerations were applied as to the coincidence data described in section 2, and the errors quoted include the uncertainty ($\pm 3\%$) due to this effect.

The lifetimes are subject ultimately to the confidence which can be placed in the velocity weights ω . It is therefore useful to compute some quantity which depends on these weights and which can be directly compared to experimental measurement. Such a quantity is the full-energy shift $\Delta E = E_{\infty} - E_0$ of the lineshapes. This is given by (see appendix):

$$\Delta E = E_0 \sum_j \int_0^{\pi/2} \omega(j) \left\{ \frac{1}{2} \frac{v_0}{c} (1 + \cos\phi) \left[\cos^2\theta \left(1 - \frac{s}{4} \left\{ \frac{dE}{dx} \right\}_{Kr} \right) - \frac{s}{4} \left\{ \frac{dE}{dx} \right\}_{Th} \right] \right. \\ \left. + \frac{1}{6} \left(\frac{v_0}{c} \right)^2 \cos^2\theta \left[\cos\phi (1 + \cos\phi) (3\cos^2\theta - 1) - 1 \right] \right\} d\theta / \sum_j \int_0^{\pi/2} \omega(j) d\theta \quad (7)$$

where higher order terms like $\left(\frac{v_0}{c}\right)^3$ and $\left(\frac{v_0}{c}\right)^2 \cdot \left\{ \frac{dE}{dx} \right\}$ have been ignored.

The index j denotes the levels of the cascade (ΔE is calculated for the

lowest level), c is the velocity of light, and ϕ is the detector half-angle. The calculations were made with and without deorientation, using a relaxation time τ_2 of 25 ps. The results for the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$ and $10^+ \rightarrow 8^+$ transitions are presented in table 2. There is a consistency between the calculated and the experimental full-energy shifts, which suggests that the effect of the uncertainty in the knowledge of the weights $\omega^{(j)}$ on the lifetimes is at least smaller than the statistical error.

The lifetimes determined from the singles RD data are shown in Column 5 of table 1. A comparison of the $B(E2)$ to that predicted by the rotational model is displayed in fig. 9. Although the 10^+ and 12^+ ratios lie somewhat below unity, all the $B(E2)$ values lie within experimental uncertainty of the rotational value.

4. Lifetimes from Doppler-Broadened Lineshape Analysis

The experiments were performed with the ^{136}Xe beam from the LBL SuperHILAC at laboratory energies of 595 and 623 MeV. The self-supporting thorium target was of sufficient thickness to stop completely the beam particles and the recoiling nuclei. The γ -ray spectrum was taken in the singles, γ - γ coincidence, and particle- γ coincidence modes. Because of the scattering kinematics with a massive projectile like Xe, the traditional annular detector geometry is not practical for the γ -particle coincidence. Instead, we used a specially designed axially symmetric gas scintillation counter for particle detection. This method, which will be discussed in a separate publication¹⁶⁾, allowed detection of scattered Xe ions in the laboratory angular range $105^\circ - 150^\circ$. The de-excitation γ -rays following Coulomb excitation were detected at 0° and 90° with respect

to the beam direction by two 45cc coaxial Ge(Li) detectors and at -90° by a 7.5 cm $\times$ 7.5 cm NaI detector. Low energy x-rays were absorbed by 1mm thick sheets of copper, silver and lead attached to the front of the detectors. The γ -ray energy signals from the Ge(Li) detectors were analyzed and accumulated in two 4096 channel spectra. The γ - γ coincidences between the 0° detector and either of the 90° detectors were determined using fast-slow coincidence techniques and the energies were recorded event by event on a magnetic tape.

The singles γ -ray spectrum recorded at 0° for ^{136}Xe (623 MeV) on a thick foil of thorium is shown in fig. 4. The lineshapes for transitions above the $8^+ \rightarrow 6^+$ showed considerable broadening on the high-energy side. This was because a significant number of decays occurred before the recoiling nuclei were brought to rest, and the corresponding γ -rays in the 0° spectrum were shifted upwards in energy by the Doppler effect. Analysis of the γ -ray lineshape provides a measure of the nuclear lifetimes if the stopping power of the medium for the recoiling ions is known. This method has recently been used by several groups studying Coulomb excitation with heavy ions. Lineshape analysis following Coulomb excitation with γ -rays detected in coincidence with backscattered ions has been described in refs. 17 and 18. In the case of a singles experiment the analysis is more complex. Since one does not select any particular particle trajectory in a singles measurement, it is necessary to integrate over all particle orbits. This kind of analysis has been described by Kearns et al.¹⁹⁾ and Inamura et al.²⁰⁾ The present analysis takes into account the same effects using similar principles.

The first step in the analysis is subtraction of background under the photopeaks. The procedure for doing this is very important since the measurement depends on the intensity of the shifted component, which lies very close to background level for the slower transitions. Our procedure is illustrated in figs. 5 and 6. Flat background regions were selected on either side of the photopeak. Under the peak, the calculated background in any given channel differs from background level 1 in proportion to the integral of the net counts in the peak up to that channel number. The constant of proportionality was varied iteratively such that this background meets background level 2 at the highest channel of the peak. This procedure treats systematically the characteristic "steps" in the background levels which occur in Ge(Li) spectra. The Doppler-broadened tail on the $10^+ \rightarrow 8^+$ compared to the $6^+ \rightarrow 4^+$ transition is clearly evident in figs. 5 and 6.

Electronic stopping powers of thorium for ^{232}Th ions were obtained by modifying values given in the compilation of Northcliffe and Schilling²¹⁾ in the following way. We compared the stopping power of thorium for ^4He ions given in Northcliffe and Schilling to those given by Chu and Zeigler¹⁵⁾ at the same values of energy per nucleon. A "correction factor" to the Northcliffe and Schilling data was then generated. This factor was very dependent on the energy, being 1.00 at ~ 4 MeV/A and rising systematically to 2.00 at ~ 0.1 MeV/A. The Northcliffe-Schilling values for ^{232}Th ions in thorium were then scaled by the correction factor appropriate to the energy per nucleon. This procedure combines the extensive knowledge of the medium dependence of stopping powers contained in the Chu-Zeigler tables (for ^4He ions only) with the experimentally determined effective charges for heavy ions used in the Northcliffe-Schilling tables. It should be noted that the procedure accurately accounts for the empirical renormal-

izations of Northcliffe and Schilling values used in refs. 18 and 19. Nuclear stopping powers were obtained from a parameterization of the numerical results of Lindhard et al.²²⁾ The stopping powers used in the analysis are shown in fig. 7. The effects of large-angle scattering were taken into account using the Blaugrund prescription.²³⁾ With these stopping powers, the most energetic ^{232}Th recoils are brought to rest in about 3 ps.

The Coulomb excitation of ^{232}Th with ^{136}Xe results in appreciable population of the ground-state rotational band up to spin $\sim 20^+$. The analysis of lower-spin members is therefore strongly affected by delayed feedings from the higher-spin states. Furthermore, the distribution of the direct population among the various rotational levels depends on the scattering angle. Therefore in a singles experiment, the lineshape calculation, with feeding correction, has to be performed for each scattering angle. The relative populations of the rotational levels as a function of recoil angle were derived from the Winther-deBoer program. To make the calculated feedings as realistic as possible, these relative weights were scaled so that the calculated total Coulomb excitation cross section was in agreement with that observed. Since the observed yields were found to be in close agreement with the Winther-deBoer calculations, these scaling factors were near unity in all cases. For the $8^+ \rightarrow 6^+$ and the $10^+ \rightarrow 8^+$ transitions, it was necessary to include six higher levels to take delayed feeding into account with sufficient accuracy. The program calculates all lineshapes with a grid of scattering angles from 5° to 175° in the center-of-mass system, and a grid of five incident energies to account for the energy loss in the thick target.

The primary calculation gives results applicable to a γ -ray detector with infinitely good resolution. To compare this with the experimental spectrum we fold in the response function of the detector. The $6^+ \rightarrow 4^+$ transition is sufficiently slow that we may consider it to represent the response function (cf. fig. 5). Essentially our procedure is to convolute the observed $6^+ \rightarrow 4^+$ lineshape with the ideal calculation, and generate a lineshape which may be directly compared with the experiment. To introduce the effect of increasing full width at half maximum (FWHM) with increasing γ -ray energy, we have first broadened the $6^+ \rightarrow 4^+$ shape by a simple convoluting procedure. The broadening was adjusted to match the changes in FWHM that were observed with the same Ge(Li) detector for a ^{152}Eu source.

The computer code calculated the expected lineshape for a given choice of input parameters. For each choice of the state lifetime, the area of the calculated and observed peaks were normalized before calculating the χ^2 for the fit. In many cases there were contaminant peaks in the region of the lineshape of interest. These peaks were excluded from the area normalization and from the χ^2 for the fit. The results are shown in fig. 8, where open points correspond to excluded regions. The analysis began with the $18^+ \rightarrow 16^+$ transition, for which the feeding corrections were least significant. In this case the feeding intensities and lifetimes were taken from a Winther-deBoer calculation with rotational matrix elements. The result for the $18^+ \rightarrow 16^+$ lifetime was then used for the $16^+ \rightarrow 14^+$ calculation and so on down the band.

The means lives for the singles experiments at 595 and 623 MeV are shown in table 1. Also shown in table 1 are data from a particle- γ coincidence run at $E_{\text{LAB}} = 623$ MeV. For this case the data analysis was similar to that for the singles, but far simpler since classically the particle coincidence defines a small range of orbits for the projectile. Although the statistics were poor because of the coincidence experiment's brevity, it was possible to extract lifetimes for the $14^+ \rightarrow 12^+$ through the $18^+ \rightarrow 16^+$ transition in this case. In fig. 9 the ratios $B(E2)_{\text{Exp}}/B(E2)_{\text{Rot}}$ are plotted for the 595-MeV and 623-MeV singles and 623-MeV particle- γ coincidence DBLS experiments. Within experimental uncertainty, all DBLS measurements are consistent with the rotational model.

The uncertainties quoted for the DBLS results include estimated contributions from uncertainties in the stopping powers, feeding corrections, contaminating peaks in the lineshape, and detector efficiency and resolution, as well as the statistical uncertainty in the lineshape and the background subtraction. The large errors for the particle- γ coincidence data primarily reflect poor statistics because of a short data accumulation period. Given sufficient statistics, the particle- γ coincidence method is capable of greater intrinsic precision than the singles DBLS approach.

5. $B(E2)$ Values from Coulomb Excitation Yields

As has previously been described in section 4, γ -ray spectra at 0° and $\pm 90^\circ$ were accumulated both in the singles and γ - γ coincidence mode for the multiple-Coulomb excitation of ^{232}Th by 595-MeV and 623-MeV ^{136}Xe . These data have been analyzed using the theory of semi-classical multiple-Coulomb excitation.⁶⁾

Figure 4 shows a singles γ -ray spectrum at 0° for $E_{\text{LAB}} = 623$ MeV. The γ -ray transitions within the ground-state band can be identified from $4^+ \rightarrow 2^+$ to $20^+ \rightarrow 18^+$. The $2^+ \rightarrow 0^+$ transition is not seen because it is highly converted and because of the loss in the absorbers. The resolution of the peaks was about 2.4 keV at 1133 keV for the spectrum obtained from the Ge(Li) detectors.

The total counts in the peaks of the singles γ -ray spectrum were obtained by integrating the spectrum after the background was subtracted, as discussed in section 4. To compare the experimental results with the theoretical calculations, the yields in the unit of b/sr $\cdot$ mg/cm² were calculated according to the formula

$$Y_I = 0.266 \times 10^{-9} \frac{N_I}{\Delta\Omega \cdot \epsilon \cdot \ell} \frac{Z}{Q} A \quad (8)$$

where N_I is the number of counts in the peak I, $\Delta\Omega$ is the solid angle of the γ -ray detector in sr, ϵ is the absolute photopeak efficiency of the detector, ℓ is the percentage live time of the data acquisition system, Q is the accumulated beam charge in μC , Z is the charge state of the projectile, and A is the mass of the target in amu.

The efficiencies and the solid angles of the γ -ray detectors were determined experimentally using a ^{152}Eu γ -ray source in the target position. By comparing the counts in the γ -ray peaks with the known strength and the branching ratios of the source, the values of $\Delta\Omega \cdot \epsilon$ were determined for the energies of the ^{152}Eu gamma rays. The values of $\Delta\Omega \cdot \epsilon$ at other energies were then obtained by interpolating between these values. To determine the live time of the data acquisition system, pulses with a rate proportional to the instantaneous counting rate were fed into the preamplifiers during the course of the

experiment. The ratio of the number of pulse counts appearing in the spectrum to the number of pulses fed in gives the fractional live time of the system. The beam current was collected in the electrically insulated scattering chamber to give the charge Q . The experimental yields obtained are listed in table 3.

The calculation of the Coulomb excitation cross section was performed using the Winther-deBoer computer program⁶⁾ expanded to give the angular distribution of the decay γ -rays. The calculation includes 13 levels in the ground state rotational band with spin up to 24. The possible effects of vibrational levels on the calculation will be discussed below. For levels with spin less than 20 the experimentally determined level energies were used. For levels with spin higher than 20 the extrapolated energies based on a constant moment-of-inertia were utilized. All the E2 and E4 matrix elements between these levels were included. The values of the matrix elements $\langle 0^+ \| M(E2) \| 2^+ \rangle = -3.03 \text{ eb}$, $\langle 0 \| M(E4) \| 4^+ \rangle = 1.36 \text{ eb}^2$ determined from α -particle Coulomb excitation experiments^{10,11)} were used, and the values of other matrix elements were derived using eq. 3.

The thick-target γ -ray yield is given by

$$Y_I(\theta_\gamma) = \frac{1}{1 + \alpha_T(E_\gamma)} \int_0^{E_{\text{lab}}} \int_{4\pi} \frac{d\sigma_I^2}{d\Omega_p d\Omega_\gamma}(E_p, \theta_p, \theta_\gamma) \frac{d\Omega_p dE_p}{dX(E_p)} \quad (9)$$

where $\alpha_T(E_\gamma)$ is the total internal conversion coefficient for the γ -ray transition with energy E_γ ; $\frac{d\sigma_I^2}{d\Omega_p d\Omega_\gamma}(E_p, \theta_p, \theta_\gamma)$ is the double differential Coulomb excitation cross section of state I for particle scattering angle θ_p and emitted γ -ray angle θ_γ at incident particle energy E_p , and $\frac{dE}{dX}(E_p)$

is the stopping power for the particle in the target material. All quantities are defined in the laboratory coordinate system. For the thick-target singles γ -ray yield the integrations are performed over the 4π particle solid angle Ω_p , and over the beam energy E_p from 0 to the incident beam energy, E_{lab} .

The value of the conversion coefficients α_T were obtained as described in section 2. The stopping powers were obtained by scaling the values of Northcliffe and Schilling²¹⁾ using the procedure discussed in section 4. The double integrations in Eq. 9 were carried out numerically. Table 3 gives the calculated yields.

Since all the levels considered here are reached by multiple-step excitation, the yield for a particular state depends upon a large number of matrix elements. This fact makes the direct comparison of yields quite complicated. A significant part of the complexity can be removed, however, by comparing the ratio of the yields of successive levels, $R_I = \frac{Y_I}{Y_{I-2}}$. In the limit of first-order perturbation theory³⁾

$$\frac{R_I^{exp}}{R_I^{calc}} = \frac{B(E2, I-2 \rightarrow I)_{exp}}{B(E2, I-2 \rightarrow I)_{calc}} \quad (10)$$

so this ratio is a measure of the ratio of the experimental $B(E2)$ value to the calculated $B(E2)$ value, correct to first order. Moreover, for the experimental ratio, the dependence on the detector solid angle, electronic live time and beam-charge collection are all cancelled. The dependence on the absolute detector efficiency is reduced to the relative efficiency, which can be determined more accurately.

Table 4 shows the values of R_I obtained from the experiment, those obtained from the calculation, and their ratios. If the theoretical matrix elements follow the rotational model relations, the deviation of the ratio from unity is an indication of the deviation of the $B(E2)$ value from that of a good rotor. The $B(E2)$ ratios thus determined are shown in fig. 9. These results are consistent with the rotational model for the 10^+ and 12^+ states, but the $B(E2, 14 \rightarrow 12)$, and $B(E2, 16 \rightarrow 14)$ lie some 15% below that expected from the rotational model. The relation of these results to those obtained by the RD and DBLS techniques will be discussed in section 6.

The uncertainties in the experimental ratio R consist of the uncertainties from the data reduction and the uncertainties of the relative efficiencies of the detectors. The uncertainties associated with the counting statistics and background subtraction are about 5% for the weakest peak. The relative efficiencies of the detectors are determined with an accuracy of about 3%.

The accuracy of the calculated yield R^{calc} depends on the accuracies of the various input parameters, the approximations made in the calculation, and the numerical accuracy of the integrations. The beam energy was measured before and after the experiment using time of flight methods. During the 595-MeV experiment the beam energy profile was monitored by periodical insertion of a gold foil into the beam, with scattered beam particles detected by a solid state detector. The variation in the value of the beam energy thus obtained for the course of the experiment was 0.5%. This will give an uncertainty range from 2 to 7% for the yield of the 10^+ to the 18^+ state. But for the ratio of the yield

between the successive states the uncertainties are reduced to 1-2%. The 1% accuracy of the theoretical $B(E2)$ values will cause a 1% uncertainty in the calculated ratio. A 0.2 keV uncertainty in the measured level energies will contribute 0.1% to the total uncertainty.

In the calculation the excitation of other levels outside the ground band is not considered. Although experience with ^{40}Ar projectiles suggests that inclusion of, e.g., gamma and octupole vibrational bands can have significant effects on the yields (10-15%),²⁴⁾ the effect on the yield ratios should be smaller. We include for the present case an uncertainty of 5% in the $B(E2)$ values arising from failure to include vibrational excitation channels in the calculation.

The absolute stopping power used in the calculation of the thick target yields is accurate to 10%, but the effect on the uncertainty for the yield ratios is less than that. The conversion coefficient has been assumed to have an accuracy of about 3% (but see the discussion in section 2).

From the above considerations the total uncertainties of the ratios range from 10 to 15%. But the quantum-mechanical correction for the semi-classical Coulomb excitation calculation is not included. This correction is important for multiple-step excitations because it alters the phases of the transition matrix elements.²⁵⁾ Exact quantum-mechanical calculations including many high-spin levels is very time-consuming, making the cost of these calculations prohibitive. However, a comparison of the ratio obtained from the γ -ray yields to those obtained from lifetime measurements gives estimated upper limits of ~5%, 10%, and 15% for the quantum-mechanical correction to the yield of the 12^+ , 14^+ , and 16^+ states.

6. Discussion

In fig. 9 the ratios $B(E2)_{\text{Exp}}/B(E2)_{\text{Rot}}$ determined by all techniques discussed in this paper are displayed. For completeness we have also plotted ratios from previously published recoil-distance measurements with ^{40}Ar projectiles.²⁶⁾ The mutual consistency of the results and their agreement with the rotational model is striking. In fig. 10 we plot the weighted average of all $B(E2)$ ratios determined by lifetime measurements in the present work. The values from Coulomb excitation yields have been omitted from the average because of the uncertainties in extracting the $B(E2)$ discussed in section 5. For all states that have been studied, the average $B(E2)$ values are those of a good rotor, within the limits of experimental uncertainty. Neither the inclusion in the average of the results from ref. 26), nor those from the Coulomb excitation yields in the present work would alter this conclusion.

Insofar as was practical, the various analyses described here were carried out independently. Therefore the results displayed in figs. 9 and 10 provide criteria for judging the mutual consistency of the methods employed. This agreement is seen to be quite good. Comparing figs. 9 and 10 we note that no single determination differs by more than 2 standard deviations from the weighted average.

In particular, we note that the DBLS and RD results agree well with each other, although there seems to be a small tendency for the RD lifetimes to be longer than those determined by the DBLS method. This agreement supports the assertion of section 4 that the stopping-power normalization is equivalent to a normalization of DBLS lifetimes against ones

obtained by the RD method on overlapping states. Thus there is strong evidence for the reliability of the DBLS method outlined here, especially since the stopping-power correction in this particular case is quite large.

The mutual consistency of the singles and coincidence RD results is also evident in fig. 9. This confirms the validity of the centroid-shift approach applied to the singles RD analysis and, in particular, is further evidence for the reliability of the velocity weights as shown in table 2.

The comparison of the COULEX results to those of other methods is also rather good. We take this as evidence that the theoretical uncertainties inherent in determining the $B(E2)$ values by multiple excitation are small. Specifically, the maximum quantum-mechanical corrections to the semiclassical yields that are consistent with these results are $\sim 5-15\%$ for $I^\pi \leq 16^+$. This is of the order expected from theoretical considerations,^{27,28)} but experimental uncertainty precludes drawing further conclusions from the present data.

In ref. 26) it was concluded from an RD analysis that ²³²Th was rotational for spins $4^+ - 10^+$. Although the $B(E2)$ ratios were essentially constant there as a function of spin, they lay $\sim 5 - 10\%$ below unity. In the present work the $B(E2)$ ratios are nearer unity, but are still compatible with the results of ref. 26).

Phenomenologically, the moment-of-inertia for deformed nuclei is known to be spin dependent.²⁹⁾ The variation of the moment-of-inertia with angular momentum manifests itself in the rotational energy-level

spacings. Thus the energy of the 16^+ state in ^{232}Th is ~15% below that of the rigid-rotor prediction using the energy of the 2^+ state.

The smooth deviations of the energy levels from those of a pure rotor have generally been described with a formalism employing some combination of 4th-order cranking,³⁰⁾ Coriolis anti-pairing,³¹⁾ centrifugal stretching,³²⁾ or band-mixing calculations.³³⁾ These suggest that the moment-of-inertia depends both on the pairing and the deformation, while we expect the transition probabilities, to first order, to be sensitive to the deformation only. Therefore non-rotational energy spacings need not be attended by non-rotational transition probabilities.

If one considers a 1st-order band-mixing model, the $B(E2)$ values for the ground band can be written as³⁴⁾

$$B(E2, I \rightarrow I-2) = B(E2, I \rightarrow I-2)_{\text{Rot}}$$

$$\left\{ \frac{1 + \frac{1}{2}\alpha [I(I+1) + (I-2)(I-1)]}{1 + 3\alpha} \right\}^2 \quad (11)$$

The parameter α may be specified if explicit assumptions are made about the nature of the bands being mixed into the ground band.³⁴⁾ Thus, if we assume the mixing of a pure β -vibration into the ground band, the parameter α is fixed by two $E2$ matrix elements connecting the ground and β -bands. Using $B(E2, 0_g \rightarrow 2_\beta)$ and $B(E2, 2_g \rightarrow 0_\beta)$ of McGowan, et al.³⁵⁾ we deduce $\alpha \approx 1.1 \times 10^{-3}$.

Similarly, if one attributes deviations of the ground-band moment-of-inertia to centrifugal stretching brought about by admixture of the axially symmetric β -vibration in the ground band, α may be approxi-

mated from the energy spacings in the ground band,³⁴⁾ and has a value in this case of $\alpha \approx 1.4 \times 10^{-3}$. In fig. 10 we plot the B(E2) ratios expected from 1st-order mixing of the ground and β -bands using values of α determined from the ground-to- β matrix elements and from the energy spacings. Clearly neither curve is consistent with the experimental data.

The failure of the curve determined from the centrifugal-stretching model to fit the lifetime data is not difficult to understand, since the moment-of-inertia is sensitive to other than centrifugal-stretching effects. For instance, alterations in the pairing interaction brought about by Coriolis anti-pairing effects will have significant effect on the moment-of-inertia, but should have little influence on the nuclear deformation and on the transition probabilities, which are determined primarily by the deformation. In addition one must consider the possible admixture of bands other than the β -band, such as higher-lying $K = 0$ bands and the $K = 2$ γ -band, into the ground band.

The α parameter derived from the matrix elements is less model-dependent than that derived from the energy spacings since it is related directly to transition probabilities between the ground and higher-lying band. In ref. 35) it is concluded that the lowest excited 0^+ level is of β -vibrational character. The matrix elements used to derive α only connect the lowest two members of the ground and β -bands. Therefore, our results are consistent with admixture of a pure β -band at low spins since the small deviations of the B(E2) from rotational values at low spins

lie within experimental uncertainty. At higher spins our results are incompatible with continued admixture of a single band with the same characteristics as that determined by the matrix elements of ref. 35).

We may use eq. (11) and the experimental $B(E2)$ values phenomenologically to set upper an upper limit of $|\alpha| \leq 2 \times 10^{-4}$ for the higher-spin region. Assuming the collective $B(E2)$ values to depend only on the nuclear shape we have³⁴⁾

$$\frac{\Delta\beta_2(I)}{\beta_2(0)} \approx \alpha I(I+1) \quad (12)$$

and on the basis of the present data we conclude that $\Delta\beta_2(16^+)/\beta_2(0) \leq |0.06|$. This lack of softness against further quadrupole deformation for well-deformed nuclei is expected according to recent deformed shell model calculations.³⁶

7. Conclusions

We have measured nuclear lifetimes and reduced transition probabilities for spins $6^+ - 18^+$ in the ground-state rotational band of ^{232}Th by recoil distance (RD), Doppler-broadened lineshape (DBLS), and multiple Coulomb excitation (COULEX) methods. The results are consistent with those of good rotor for all states investigated. There is mutual agreement among the various techniques. The agreement suggests that the DBLS method outlined here can be used with confidence to determine very short nuclear lifetimes for high-spin states, and that the quantum-mechanical corrections to semi-classical multiple-Coulomb excitation theory are not appreciably larger than theoretically predicted. The rotational nature of the $B(E2)$

values precludes a simple admixture at high spins of a pure β -vibration consistent with the known ground to β -band matrix elements at low spins.

The rotational $B(E2)$ values are also inconsistent with centrifugal stretching inferred from variation of the ground-band moment-of-inertia with angular momentum. This is reasonable because the transition probabilities depend primarily on the deformation, while the moment-of-inertia is sensitive to both the deformation and the pairing interaction. Thus variations in the pairing for high angular momentum states may affect appreciably the moment-of-inertia, while the transition probabilities remain unchanged unless the alteration in pairing is large enough to affect significantly the overlap between initial and final states in the transition matrix element.

Appendix

Recoil Velocities and Full-Energy Shifts

In this appendix we outline the derivation of eqns. (6) and (7) in the text. Assume the projectile enters a target of thickness s with velocity v_0 , travels a distance x , and scatters a target nucleus in a direction θ relative to the beam axis and a distance $y = (s-x)/\cos \theta$ through the target before emerging. Assuming constant energy loss through the thin target we have

$$E(z) = E_0 - \int_0^z \frac{dE}{dz} dz \approx E_0 \left\{ 1 - \frac{dE}{dz} \frac{z}{E_0} \right\} \quad (A-1)$$

where $E(z)$ is the particle (projectile or target) energy as a function of distance z , and $E_0 = \frac{1}{2} m v_0^2$ is the initial particle energy.

For inelastic scattering we can write

$$E_T(\theta, x) = E_T(\theta, 0) \left(1 - \left(\frac{dE}{dx} \right)_p \frac{x}{E_p(0)} \right) \quad (A-2)$$

where $E_T(\theta, x)$ is the kinetic energy of the target nucleus immediately after scattering into the angle θ by the projectile, the reaction occurring at x . The incident energy of the projectile is denoted by $E_p(0)$. It follows that the velocity of the target nucleus after traversing an additional distance y is given by

$$v(\theta, x, y) \approx v_0 \cos \theta \left(1 - \beta x - \frac{\alpha(s-x)}{\cos \theta} \right)^{1/2} \quad (A-3)$$

where we have defined

$$\alpha(\theta) = \left[\frac{dE}{dy} \right]_T / E_T \quad (A-4)$$

$$\beta = \left[\frac{dE}{dx} \right]_p / E_p \quad (A-5)$$

The average recoil velocity is given by

$$\bar{v} = \frac{1}{s} \int_0^s v(\theta, x, y) dx \quad (A-6)$$

Expansion of (A-2) in a binomial series and substitution into (A-6) gives

$$\bar{v} = v_0 \{ \cos\theta - \frac{1}{4} \beta s \cos\theta - \frac{1}{4} \alpha(\theta) s \} \quad (A-7)$$

The further approximation is made that, for velocities considered here

$$\left(\frac{dE}{dy} \right)_T \propto v \quad (A-8)$$

in which case

$$\alpha(\theta) = \frac{\alpha(0)}{\cos\theta} \quad (A-9)$$

Substitution of (A-4), (A-5) and (A-9) into (A-7) leads to eq. (6) of the text. Equation (7) results from substitution of (A-7) into eq. (4) of ref. 34), followed by logarithmic and binomial expansions, and neglect of higher-order terms.

FOOTNOTES AND REFERENCES

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Table 1. Lifetimes and B(E2) ratios determined from recoil-distance (RD) and Doppler-broadened lineshape analysis (DBLS) in the ground-state band of ^{232}Th

Transition	E_γ (keV)	α_T ^{a)}	τ_{MEAN} (ps)						$\tau_{\text{AVG.}}$ (ps) ^{b)}	$\left \frac{B(E2)_{\text{Exp}}}{B(E2)_{\text{Rot}}} \right _{\text{AVG}}$ ^{c)}
			RD	COINC.	RD SINGLES	DBLS SINGLES	595-MeV	623-MeV		
6→4	171.00	1.128	81.0±8.0	89.0±9.0	—	—	—	84.4±6.0	1.06±0.08	
8→6	223.84	0.416	35.2±2.0	34.3±1.7	33.7±5.2	31.0±4.0	—	34.3±1.8	0.98±0.05	
10→8	270.47	0.220	14.1±1.0	16.3±1.1	15.1±2.6	14.4±2.0	—	15.0±0.9	0.98±0.06	
12→10	210.7	0.143	9.3±1.0	8.2±0.6	7.0±1.9	7.1±0.8	—	8.0±0.6	0.97±0.07	
14→12	346.5	0.106	5.0±0.7	—	4.3±0.7	4.6±0.5	4.0±0.7	4.5±0.3	1.02±0.07	
16→14	376.1	0.086	—	—	3.7±0.8	3.0±0.3	3.1±0.6	3.1±0.3	0.99±0.10	
18→16	404.0	0.07	—	—	—	1.8±0.3	2.4±0.6	1.9±0.3	1.13±0.18	

^aTotal internal conversion coefficients are from refs. 12 and 13, scaled down by 6% according to the suggestion of ref.14 as discussed in the text.

^bAverage of mean lives determined by recoil-distance and Doppler-broadened lineshape methods. The mean lives were weighted by $1/\sigma^2$ in the average, and the uncertainties represent a folding of uncertainties from each individual determination.

^cThe $B(E2)_{\text{Rot}}$ is calculated from the value $B(E2, 2 \rightarrow 0) = 1.84$ given in refs.10 and 11.

Table 2. Calculated and measured full-energy shifts of the lineshapes for $^{84}\text{Kr} + ^{232}\text{Th}$ at 385 MeV.

	<u>Transition</u>		
	<u>6-4</u>	<u>8-6</u>	<u>10-8</u>
Calculated ($\tau_2 = 0$)	2.36	2.80	3.19
($\tau_2 = 25_{\text{ps}}$)	2.32	2.78	3.19
Experimental	2.32 ± 0.07	2.72 ± 0.08	3.06 ± 0.09

Table 3. Experimental and calculated thick target γ -ray yields in b/sr $\cdot$ mg/cm² following Coulomb excitation of ^{232}Th by 595-MeV and 623-MeV ^{136}Xe . a)

I_i	I_f	$\theta_\gamma = 0^\circ$		$\theta_\gamma = 90^\circ$	
		γ^{exp}	γ^{calc}	γ^{exp}	γ^{calc}
6	4	1.89	2.23	---	---
		---	---	---	---
8	6	1.26	1.46	1.12	1.11
		1.89	1.64	---	---
10	8	0.69	0.74	0.53	0.54
		0.92	0.92	---	---
12	10	0.33	0.36	0.24	0.25
		0.45	0.48	---	---
14	12	0.134	0.163	0.084	0.111
		0.205	0.231	---	---
16	14	0.045	0.066	0.028	0.044
		0.089	0.104	---	---
18	16	---	---	---	---
		0.048	0.042	---	---

^aThe first line for each transition is from the 595-MeV experiment, and the second line is from the 623-MeV experiment. The experimental yields from the 623-MeV data have been normalized to the average yield for all transitions. The final yield ratios (table 4) are independent of this normalization.

Table 4. Ratio of the yield of successive levels obtained from experiment and calculation for Coulomb excitation of ^{232}Th with 595-MeV and 623-MeV ^{136}Xe . a)

I_i	I_f	$\theta_\gamma = 0^\circ$		$\theta_\gamma = 90^\circ$		$(R^{\text{exp.}}/R^{\text{calc.}})_{\text{avg}}$
		R^{exp}	R^{calc}	R^{exp}	R^{calc}	
8	6	0.67	0.65	----	----	1.03
		----	----	----	----	----
10	8	0.55	0.51	0.47	0.48	1.03
		0.49	0.56	----	----	0.86
12	10	0.48	0.49	0.45	0.46	0.98
		0.49	0.52	----	----	0.96
14	12	0.41	0.45	0.35	0.44	0.85
		0.45	0.49	----	----	0.93
16	14	0.34	0.41	0.33	0.39	0.83
		0.44	0.45	----	----	0.97
18	16	----	----	----	----	----
		0.53	0.40	----	----	1.34

^aThe first line for each transition is for $E_{\text{LAB}} = 595$ MeV and the second line is for $E_{\text{LAB}} = 623$ MeV.

FIGURE CAPTIONS

Fig. 1. Plots of R vs. D for the $^{84}\text{Kr} + ^{232}\text{Th}$ coincidence data. The points have been corrected by the method described in section 2, and the lines depict the weighted, least-squares, linear fits to the corrected points.

Fig. 2. Line shapes for the shifted-unshifted doublet of the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $10^+ \rightarrow 8^+$ transitions in the $^{84}\text{Kr} + ^{232}\text{Th}$ singles data. The representative spectra shown were taken at recoil distances comparable to the mean distance of decay for the state. The broadness of the shifted peak is a consequence primarily of the angular distribution of recoiling Th ions from which γ -rays detected in the singles spectrum are emitted.

Fig. 3. The fits to R vs. D for the $^{84}\text{Kr} + ^{232}\text{Th}$ singles data. Note that these data were not analyzed in the same manner as those of fig. 1. See text for details.

Fig. 4. Singles γ -ray spectrum following multiple Coulomb excitation of ^{232}Th with 623-MeV ^{136}Xe . The spectrum was taken at 90° on a thick target, and the E2 transitions in the ground-state band can be identified from the $4^+ \rightarrow 2^+$ to the $20^+ \rightarrow 18^+$ transition.

Fig. 5. Analysis of the $6^+ \rightarrow 4^+$ photopeak observed with a Ge(Li) detector at zero degrees. The background under the peak is calculated so that in any given channel its difference from background 1 is proportional to the net area in the peak up to that channel. The process is iterated so that at the last channel of the peak, the background matches the level 2.

Fig. 6. Analysis of the $10^+ \rightarrow 8^+$ photopeak observed with a Ge(Li) detector at zero degrees. The background under the peak is calculated so that in any given channel its difference from background 1 is proportional to the net area in the peak up to that channel. The process is iterated so that at the last channel of the peak, the background matches the level 2.

Fig. 7. Stopping powers used in the present calculation. The values given by Northcliffe and Schilling have been modified to take into account pronounced dependencies on the medium not included in the Northcliffe and Schilling tables. This is done by comparing stopping powers for ^4He ions given by Northcliffe and Schilling, to those given by Chu and Ziegler (see text).

Fig. 8. Lineshape fits to transition in ^{232}Th following excitation by 623-MeV ^{136}Xe . The spectra were taken in singles mode.

Fig. 9. Values of the ratio $B(E2)_{\text{exp}}/B(E2)_{\text{rot}}$ for states in ^{232}Th determined in this experiment and in previous work. The assignment of the uncertainties represented by the error bars has been discussed in the text.

Fig. 10. Weighted average of the ratio $B(E2)_{\text{exp}}/B(E2)_{\text{rot}}$ determined from RD methods (^{84}Kr projectiles in backscatter coincidence and in singles), and from the DBLS experiment (^{136}Xe projectiles in singles and backscatter coincidence modes). The dashed lines represent the $B(E2)$ ratios expected from simple centrifugal stretching and β -band mixing models, as discussed in the text.

Fig. 1

XBL 756-3292

Fig. 2

XBL 756-3291

Fig. 3

XBL 762-2211

Fig. 4

Fig. 5

Fig. 6

XBL756-3174A

XBL756-3171

Fig. 7

Fig. 8

Fig. 9

Fig. 10

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