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Precise Coulomb Excitation $B(E2)$ Values for First 2^+ States of the Actinide Nuclei*

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Precise transition probabilities have been measured for the first 2^+ states of ^{230,232}Th, ^{234,236,238}U, ^{238,240,242,244}Pu, ^{244,246,248}Cm, and ^{252}Cf by Coulomb excitation with 17- and 18-MeV α particles. Comparison is made with theoretical values. An excitation energy of 44.0 ± 0.5 keV was measured for the first excited level of ^{252}Cf.

Theoretical predictions of the existence of superheavy nuclei are based on the calculated properties of heavy nuclei, as functions of the deformation, and the location of single-particle orbitals within deformed potentials.[1-4] The transuranic nuclei furnish a testing ground for these theories where calculated transition rates and moments may be compared with experiment. Precise measurements of the $E2$ transition probabilities for the first 2^+ states in actinide nuclei are presented here for comparison with theoretical values.

Measurement of $B(E2)$ values in this mass region is difficult because of the large internal conversion coefficients and the hazardous nature of the target material. However, extremely accurate measurements are made possible by observation of the inelastically scattered particles, which requires only a small amount of material and no knowledge of the conversion coefficients. Many of the present $B(E2)$ values had not been previously determined or were known only indirectly from lifetime measurements.

α particles were accelerated to 17 and 18 MeV in the Oak Ridge National Laboratory tandem Van de Graaff. The inelastically scattered α particles were detected at the focal plane of an Enge split-pole spectrograph[5] by a 20-cm-long position-sensitive proportional counter. This is a single-wire detector,[6,7] of the type designed by Borkowski and Kopp, in which the central anode is an 8000-Ω/mm quartz fiber with pyrolytic carbon coating. Details of the construction of the present detector and its application with this spectrograph have been presented.[8]

Isotopically pure targets were prepared using a 150-cm-radius isotope separator.[9] The material was implanted into thin Ni backings at an incident ion energy of 4 keV to yield a target spot 0.06 cm wide and 1 cm high. Such targets were typically 20 μg/cm^2 thick containing a total of about 1 μg of material, and had a width ideally suited to optimize the resolution of the spectrograph.

Figure 1 shows the spectra for 17-MeV α particles scattered from ^{246}Cm at a laboratory angle of 150°. The ground state and excited 2^+ and 4^+ states at 43 and 142 keV, respectively, are seen. The energy resolution is about 14 keV. Determining the total number of counts in each peak yields the 0^+ to 2^+ transition probability as $B(E2) = (15.03 \pm 0.45)e^2$ b^2. The major sources of error are the estimation of the elastic tail under the peak for the 2^+ state, despite the good peak-to-valley ratio, and the uncertainty in the incident beam energy which is estimated to be 50 keV.

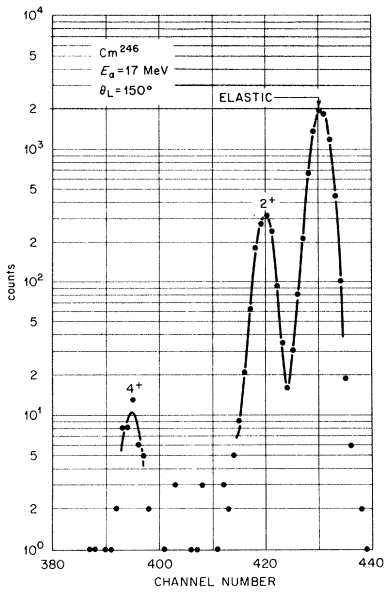

FIG. 1. Spectra for 17-MeV α particles scattered from ^{246}Cm at a laboratory angle of 150°.

One must consider whether or not direct nuclear reactions are contributing to the excitation process. The Coulomb barrier for α particles incident on ^{238}U is approximately 24 MeV, and experience with lighter targets at this laboratory indicates that the ratio of the incident energies used in the present experiment to the Coulomb barrier should ensure that nuclear reactions be unimportant. Furthermore, measurements by Barnett and Phillips[10] of the very small cross sections for Coulomb excitation of the 3^- state in ^{208}Pb show that even in this case Coulomb excitation is the dominant process at α-particle energies of 17.5 and 18 MeV, although direct reactions are evident at 19 MeV. Nevertheless, the $B(E2)$ for ^{238}U was measured at 17 MeV and 150°, as well as at 18 MeV and 90° and 150°, resulting in values of $(11.64 \pm 0.25, 12.15 \pm 0.35$, and $11.58 \pm 0.16)e^2$ b^2, respectively. Averaging these three values yields $(11.70 \pm 0.15)e^2$ b^2 after weighting each measurement by its error. The above results are consistent with pure Coulomb excitation of the first excited state at the energies used.

The quantities measured in the present experiment are presented in Table I. The first columns give the nucleus involved and the excitation energy of the first 2^+ state. The energies quoted to five figures are those of Schmorak *et al.*,[11] while the others with the exception of ^{252}Cf are the values adopted in the compilations

TABLE I. The measured $B(E2)$ values for 2^+ states of even-even actinides and derived quadrupole moments. The excitation energies are those of Refs. 11–13, and earlier $B(E2)$ values are shown taken from Refs. 14–15.

Nucleus	Excitation Energy (keV)	B(E2)↑ (e^2b^2)	Q_{20}	Previous B(E2) Values
^{230}Th	53.222 ± 0.019	8.01 ± 0.11	8.975 ± 0.053	7.9 ± 0.8
^{232}Th	49.369 ± 0.009	9.40 ± 0.20	9.72 ± 0.10	9.7 ± 0.5
^{234}U	43.491 ± 0.009	10.33 ± 0.26	10.19 ± 0.13	10.10 ± 0.75
^{236}U	45.242 ± 0.006	11.62 ± 0.23	10.81 ± 0.11	10.80 ± 0.80
^{238}U	44.915 ± 0.013	11.70 ± 0.15	10.84 ± 0.07	12.6 ± 0.6
^{238}Pu	44.08 ± 0.05	12.58 ± 0.35	11.25 ± 0.16	12.25 ± 0.90
^{240}Pu	42.824 ± 0.008	12.57 ± 0.35	11.25 ± 0.16	12.7 ± 0.4
^{242}Pu	44.545 ± 0.009	13.26 ± 0.35	11.55 ± 0.15	13.9 ± 1.2
^{244}Pu	45	13.83 ± 0.37	11.79 ± 0.16	
^{244}Cm	42.9	14.86 ± 0.35	12.22 ± 0.15	18.1 ± 2.0
^{246}Cm	42.852 ± 0.005	15.03 ± 0.45	12.29 ± 0.18	
^{248}Cm	43.4	15.03 ± 0.55	12.29 ± 0.22	14.70 ± 1.55
^{252}Cf	44.0 ± 0.5	16.7 ± 1.1	12.9 ± 0.4	

of Ellis and Wapstra[12] and Ellis.[13] The excitation energy of the first excited state of ^{252}Cf was measured for the first time in the present experiment in which an energy of 44.0 ± 0.5 keV was obtained. The next column contains the measured $B(E2)$ values for excitation measured at an incident energy of 17 MeV and a laboratory angle of 150°, except for ^{238}U where the average value is shown. The errors given are absolute values. With the exception of the ^{252}Cf value, the errors of the present $B(E2)$ measurements are 3% or less. The high radioactivity of the ^{252}Cf target produced radiation damage and diffusion of the material within the nickel backing which effectively broadened the target, thus increasing the error in the $B(E2)$ measurement to 7%.

The intrinsic quadrupole moments can be derived from the $B(E2)$ values by the expression[16]

$$B(E2; 0 \rightarrow 2) = (5/16\pi)Q_{20}^2,$$

and are shown next. Extraction of deformation parameters β_2 from the data requires that the influence of hexadecapole as well as quadrupole moments be considered, and will be reported elsewhere. However, we comment here that the influence of a sizable β_4 deformation on the $B(E2; 0 \rightarrow 2)$ values given in this paper has been studied and it is found to be a small effect. A β_4 deformation of 0.1 increases the $B(E2; 0 \rightarrow 2)$ values by about 0.5 to 0.7%.

The last column contains the results of earlier $B(E2)$ determinations by electromagnetic tech-

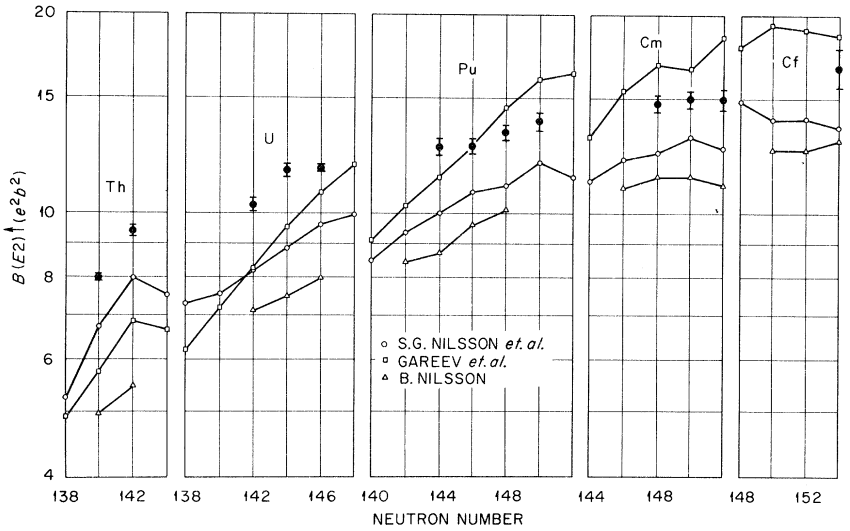

FIG. 2. The measured $B(E2)$ values as a function of neutron number. The curves show the theoretical values of Refs. 2–4.

niques. Those shown for ^{234,236}U, ^{238}Pu, and ^{248}Cm were recently reported by Ton *et al.*,[14] and the others are the adopted values of Stelson and Grodzins.[15]

In Fig. 2 the measured $B(E2)$ values are plotted as a function of the target neutron number. The transition rates generally increase with mass over the entire mass region studied. Also shown are curves calculated from the theoretical deformation parameters β_{20} and β_{40} of Nilsson *et al.*[3] by means of the following expression:

$$Q_{20} = \frac{3ZR_0^2\beta_{20}}{(5\pi)^{1/2}}\left(1+0.36\beta_{20}+0.967\beta_{40}+0.328\frac{\beta_{40}^2}{\beta_{20}}\right),$$

where R_0 is the average radius and Q_{20} is related to $B(E2)$ by the equation given earlier. The curves shown for Nilsson[2] and for Gareev, Ivanova, and Pashkevitch[4] were obtained from their values of Q_{20}. The calculations of Nilsson *et al.*[3] provide the closest agreement with the experimental results in their variation with neutron number. However, the experimental data are 15 to 25% larger than the calculations of Nilsson *et al.*[3] All of the theoretical $B(E2)$'s show an increase as one proceeds from neutron number 144 to 146. Yet the experimental values for both the uranium and plutonium isotopes remain constant for this change in neutron number. Thus, accurate experimental data in the transuranic mass region, such as presented here, should result in improved nuclear models, including the microscopic level structure, on which are based the predicted properties of superheavy nuclei and heavy-ion interactions.

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