γ-ray decays in ^{232}Th and the $K^{\pi}=4^{+}$ two-phonon γ vibration

A. Martin,[1,*] P. E. Garrett,[1,2] M. Kadi,[1,†] N. Warr,[1] M. T. McEllistrem,[1] and S. W. Yates[1]
[1]*University of Kentucky, Lexington, Kentucky 40506-0055*
[2]*Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551*
(Received 14 July 2000; published 8 November 2000)

A recent Coulomb excitation study has called into question the 4^{+} spin assignment of the 1414-keV level in ^{232}Th, which had earlier been interpreted as a two-phonon γ-vibrational excitation, and had suggested instead a 3^{-} assignment. Data obtained in the present neutron scattering study of ^{232}Th are inconsistent with the 3^{-} suggestion and support an $I^{\pi}=4^{+}$ assignment for the 1414-keV level, lending credence to the argument that it is a $K^{\pi}=4^{+}$ band head.

PACS number(s): 21.10.Hw, 23.20.En, 23.20.Lv, 25.40.Fq

The existence and persistence of two-phonon states in deformed nuclei has been a longstanding point of contention and controversy. The measurement [1] of an enhanced $B(E2)$ value from a 4^{+} state at 2055 keV in ^{168}Er, the first firm evidence of the $K^{\pi}=4^{+}$ two-phonon γ vibration, has done little to silence the controversy which now centers on how wide spread such excitations are, and the magnitude of the two-phonon component in their wave functions. A survey [2] of energy and $B(E2)$ ratios from 4^{+} states suggested many two-phonon candidates in the well-deformed rare earth region. However, it was pointed out [3] that consideration of all data such as that from single-nucleon transfer and β decay were in serious conflict with a two-phonon interpretation for many of these candidates.

One example of an assigned 4^{+} two-phonon γ-vibrational state, for which no other data were in conflict, was the 1414-keV level in ^{232}Th. This state was first observed in a Coulomb excitation experiment [4], and the 4^{+} assignment was made using angular correlations; the data indicated that the 628-keV γ ray feeding the 2^{+}_{γ} level was $E2$ in nature [4]. The branching ratio from the newly established level was also consistent with a $K^{\pi}=4^{+}$ assignment. A later measurement [5] of the lifetime of the level yielded a $B(E2;4^{+}\rightarrow 2^{+}_{\gamma})$ value of 14 W.u., consistent with a two-phonon interpretation. The energies and $B(E2)$ values extracted for the 4^{+} level were in excellent agreement with those expected for a harmonic oscillator, and thus made the 1414-keV level in ^{232}Th a prime example of a $K^{\pi}=4^{+}$ two-phonon γ vibration.

Very recently, however, in another Coulomb excitation experiment [6], a different conclusion was reached regarding the I^{π} value for the 1414-keV level. This measurement favored a 3^{-} assignment, which, if true, would clearly negate the two-phonon γ-vibration assignment. A Coulomb excitation experiment by Günther *et al.* [7] confirmed the 628- and 585-keV decays from the 1414-keV level, but their data could not distinguish between the two possible spin assignments. In an attempt to resolve the spin assignment conflict, $(n,n'\gamma)$ measurements were performed with the explicit purpose of examining the decays from the 1414-keV level, as shown in the partial level scheme in Fig. 1.

The experiments were performed at the University of Kentucky accelerator facility. The $(n,n'\gamma)$ reaction is particularly useful for determining the spins of low-lying, low-spin excited levels. If the neutron bombarding energy is limited to only a few hundred keV above a level's excitation threshold, cascade feeding from higher states is typically negligible and the level can be highly aligned [8]. Therefore, the angular distribution of the γ rays deexciting the 1414-

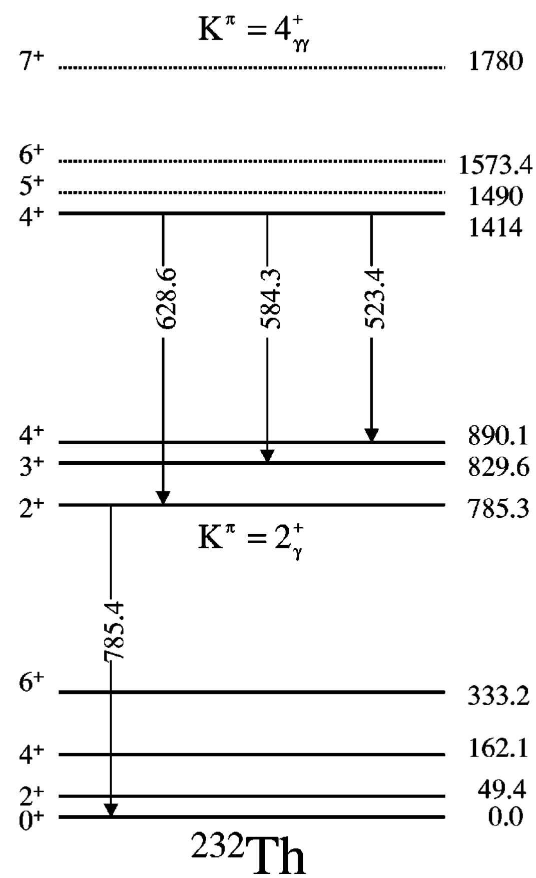

FIG. 1. Partial level scheme for ^{232}Th showing the γ-band excitations [4,5].

*Present address: College of Medicine, University of Kentucky, Lexington, KY 40506.

†Present address: King Abdul Aziz University, Faculty of Science, Jeddah, 21314, Saudi Arabia.

TABLE I. Data and Legendre polynomial fit coefficients for decays from the 1414-keV level. The a_i are the fit coefficients. Uncertainties are shown in parentheses immediately after the coefficients, and B denotes the branching ratio.

E_γ (keV)	a_2	a_4	B
523.43	−0.11(10)	−0.004(12)	0.27(4)
584.28	−0.05(23)	−0.02(26)	0.25(5)
628.57	0.30(9)	−0.19(13)	0.48(5)

keV level should provide an unambiguous choice between the suggested 3^- and 4^+ spin possibilities.

For this experiment, neutrons of 2.0 MeV energy were produced using a pulsed proton beam and the ^{3}H$(p,n)^3$He reaction. The thorium scattering sample was an 8.6-g metal cylinder, 0.66 cm in diameter, and 2.4 cm in height, and was mounted 4.5 cm from the end of a cell containing tritium gas. The tritium was contained in a 1 cm diameter, 3.1 cm long cell at $\frac{3}{4}-1$ atmosphere pressure which was sealed from the beam line vacuum with a 7.6 μm Mo foil. With 2.0 MeV incident neutron energy, levels of ^{232}Th with excitation energies less than 1.8 MeV were appreciably populated. γ rays were detected in a bismuth germanate (BGO) Compton-suppressed, n-type HPGe detector. The efficiency of the detector was 57%, and the resolution was 2.0 keV at 1.33 MeV.

Conditions set on the time of events with respect to the proton beam pulse were used to separate prompt γ rays from the Th sample from those resulting from neutrons scattered in the detector or nearby materials. These gating conditions also discriminated against about 90% of time-uncorrelated room background. The γ-ray spectra were obtained at eight laboratory angles between 50° and 145°.

The distribution of intensities of all observed γ rays were plotted as a function of angle, and fitted using a Legendre polynomial expression

$$W(\theta)=1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta). \quad (1)$$

The coefficients obtained from least squares fits are listed in Table I. These experimental angular distribution data were compared to calculations from the code CINDY [9]. This code was developed particularly to provide angular distributions of reaction products and subsequent γ rays based on the statistical model [10]. Several studies [8,11] have shown that these distributions are characteristic of the angular momenta participating in the decays and nearly independent of nuclear reaction models. The angular distributions are determined by the spins and parities of initial and final levels and the multipole order of the transitions connecting the two states. For cases allowing mixed multipoles, the distributions reflect also the mixing ratio δ and thus the contributions from the two multipoles.

Figure 2 illustrates the region of interest of the spectrum obtained with 2.0 MeV neutrons and conditions on the time of events to accept only those coincident with the proton beam pulse. Nearly all ^{232}Th transitions are members of doublets or higher multiplets, largely because the fission threshold is just above 1 MeV and prompt fission γ rays contaminate the spectrum. Table I provides a list of the γ rays that are emitted from the 1414-keV level, as well as the Legendre fit coefficients, and their branching ratios. As noted above, these decays are also presented in the abbreviated level scheme in Fig. 1.

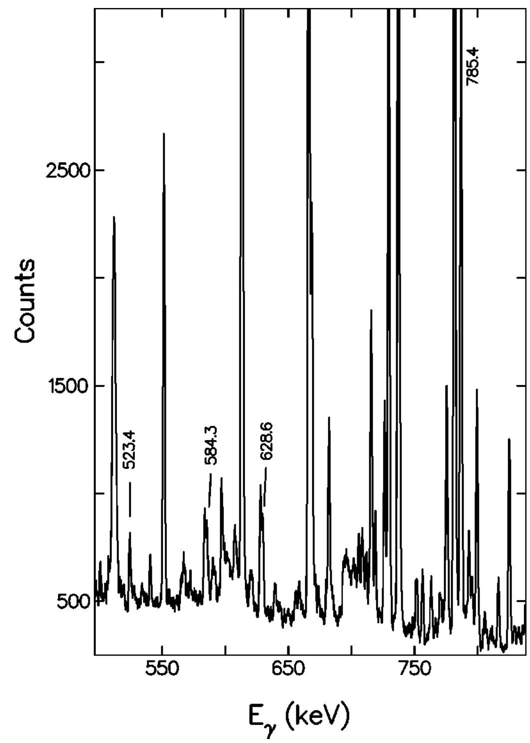

FIG. 2. Portion of a γ-ray spectrum containing the 628-keV γ ray obtained with a neutron bombarding energy of 2.0 MeV. Conditions on the time of the events were such that only those coincident with the proton beam pulse were accepted.

Figure 3 presents a comparison of measured and calculated angular distributions for the 628-keV γ ray, one of the three which are emitted from the 1414-keV level. The experimental results, with their uncertainties, are given along with the model calculations—one for a 4^+ spin and parity assignment for the 1414-keV level and the other for a pre-

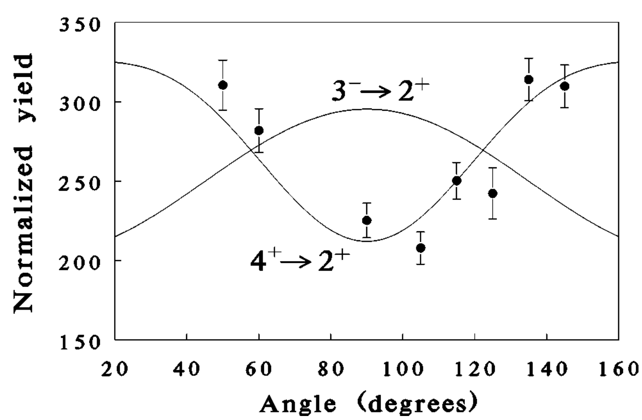

FIG. 3. Angular distribution of the 628.6-keV γ ray of ^{232}Th. The curves show statistical model calculations for 4^+ and 3^- assignments.

sumed 3^- assignment. Clearly, the data can only be represented as a decay from a 4^+ level; the 628-keV transition is a typical stretched $E2$ decay from a 4^+ to a 2^+ level. The calculated distribution for a 4^+ assignment provides a result equivalent to the Legendre polynomial fit. It should be noted that there are no parameters to adjust in the calculated distribution; it is a parameter-free result.

The least squares fit coefficients for two additional γ rays from the 1414-keV level—524 and 585 keV—were also compared to theoretical coefficients generated using the code CINDY [9]. Both of these γ rays, however, are members of triplets of transitions. Reliable, good statistics angular distributions were difficult to extract for the separate lines. The data for the 524 keV transition were consistent with either 3^- or 4^+ spin and parity assignments. The angular distribution for the 585-keV transition, however, was consistent only with 4^+. Consistency was defined in terms of theoretical coefficients within a 2σ range of the experimental Legendre coefficients.

In summary, data from $(n,n'\gamma)$ measurements are consistent with a 4^+ spin and parity assignment for the 1414-keV state of ^{232}Th. The recently reported [6] assignment of 3^- is excluded by the angular distributions of two of the decays from that level. This experimental evidence confirms previous work of Korten *et al.* [4,5], and supports the identification of the 1414-keV level as the band head of a two-phonon γ-vibrational excitation.

We wish to thank W. Korten for useful exchanges of information. This work was supported by the U.S. National Science Foundation under Grant No. PHY-9803784, and was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[1] H. G. Börner *et al.*, Phys. Rev. Lett. **66**, 691 (1991).
[2] X. Wu, A. Aprahamian, S. W. Fischer, W. Reviol, G. Liu, and J. X. Saladin, Phys. Rev. C **49**, 1837 (1994).
[3] D. G. Burke, Phys. Rev. Lett. **73**, 1899 (1994).
[4] W. Korten, T. Härtlein, J. Gerl, D. Habs, and D. Schwalm, Phys. Lett. B **317**, 19 (1993).
[5] W. Korten *et al.*, Z. Phys. A **351**, 143 (1995).
[6] J. Gerl *et al.*, Prog. Part. Nucl. Phys. **38**, 79 (1997).
[7] C. Günther, R. Krücken, C. J. Barton, C. W. Beausang, R. F. Casten, Gh. Cata-Danil, J. R. Cooper, J. Gröger, J. Navak, and N. V. Zamfir, Phys. Rev. C **61**, 064602 (2000).
[8] E. Sheldon and D. M. Van Patter, Rev. Mod. Phys. **38**, 143 (1966).
[9] E. Sheldon and V. C. Rogers, Comput. Phys. Commun. **6**, 99 (1973).
[10] J. W. Tepel, H. M. Hofmann, and H. A. Weidenmuller, Phys. Lett. **49B**, 1 (1974); J. W. Tepel, H. M. Hoffman, and M. Herman, *Proceedings of the International Conference on Nuclear Cross Sections for Technology,* Knoxville, 1979, Natl. Bur. Stand. Special Pub. No. 594 (U.S. GPO, Washington, D.C., 1980).
[11] M. T. McEllistrem, in *Nuclear Research with Low Energy Accelerators*, edited by J. B. Marion and D. M. Van Patter (Academic, New York, 1967).