Lifetime of the 6_1^+ state in ^{144}Nd

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Using a comparative delayed coincidence technique the lifetime of the 6_1^+ level in ^{144}Nd has been measured as $\tau = 30 \pm 3$ ps, leading to a $B(E2;6_1^+ \rightarrow 4_1^+)$ value of 25 ± 3 W.u. This value is almost a factor of 3 less than that expected for a purely collective three-phonon state, but is in agreement with particle-core coupling calculations that predict significant noncollective $L=4$ and $L=6$ components in the 4^+ and 6^+ yrast state wave functions.

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I. INTRODUCTION

In recent years the nucleus ^{144}Nd has become a laboratory for the examination of several different aspects of nuclear excitation. For example, aspects of the level scheme have been examined in the context of particle-core coupling [1–3], collective mixed symmetry states [4,5], quadrupole-octupole coupling [6,7], and two-phonon octupole structure [8,9]. Although particle-core coupling models strongly suggest that even the low-lying states contain significant components consisting of two-particle excitations of the two valence neutrons outside the $N=82$ core closed shell, attempts have also been made to explain the low-lying structure in terms of purely collective models, such as IBM-1 [10,11], IBM-2 [5,12], and the dynamic deformation model (DDM) [13]. However, evidence that the underlying structure of ^{144}Nd is probably not that of a simple harmonic vibrator is given by the measured properties of the low spin yrast states. First, the level-energy ratios of $E(4_1^+)/E(2_1^+) = 1.89$ and $E(6_1^+)/E(2_1^+) = 2.57$ are significantly lower than the harmonic values of 2.0 and 3.0 respectively. In addition, the measured $B(E2;4_1^+ \rightarrow 2_1^+)$ value of 20.8 ± 1.6 W.u. (average of values from Refs. [5,14,15]), is of the same magnitude as the $B(E2;2_1^+ \rightarrow 0_1^+)$ value of 22.0 ± 0.3 W.u. (average of values from Refs. [5,16–18]), whereas in the harmonic picture it should be double this value [19].

The particle core coupling models naturally account for these energy level ratios and the relative reduction in the $B(E2;4_1^+ \rightarrow 2_1^+)$ value by the increasing amplitude of the $\nu^2(L=4)$ and $\nu^2(L=6)$ configurations in the wave functions of the 4^+ and 6^+ yrast levels, with a corresponding decrease of contributions built from collective quadrupole $(L=2)$ configurations. However, all the collective models have trouble reproducing this behavior. In particular, while it is true that certain combinations of model parameters in both IBM-1 and IBM-2 can reproduce the low lying yrast level energies (up to $J^\pi = 6^+$), they cannot produce a $B(E2;4_1^+ \rightarrow 2_1^+)/B(E2;2_1^+ \rightarrow 0_1^+)$ ratio of close to unity. Therefore, the current evidence favors the interpretation that the 4^+ and 6^+ yrast states in ^{144}Nd contain significant two-particle components, which lie outside the model space of purely quadrupole collective models, such as the *sd*-IBM. To investigate this further we have measured the lifetime of the 6^+ yrast state, in order to extract a $B(E2;6_1^+ \rightarrow 4_1^+)$ value to compare with model predictions.

II. EXPERIMENT PROCEDURE

A. Selection of coincidence schemes

The 1791-keV 6_1^+ state in ^{144}Nd is strongly fed (42%) in the electron capture (EC) decay of ^{144}Pm, so this decay was selected to attempt to measure the lifetime of this state. A simplified level scheme for this decay is shown in Fig. 1, from which it can be seen that the only other significant decay branch (55%) feeds the 1315-keV 4_1^+ state. In principle a measure of the 1791-keV level lifetime could then be obtained by recording delayed coincidences between the *K* x rays, which accompany the EC decay, and 477-keV γ rays.

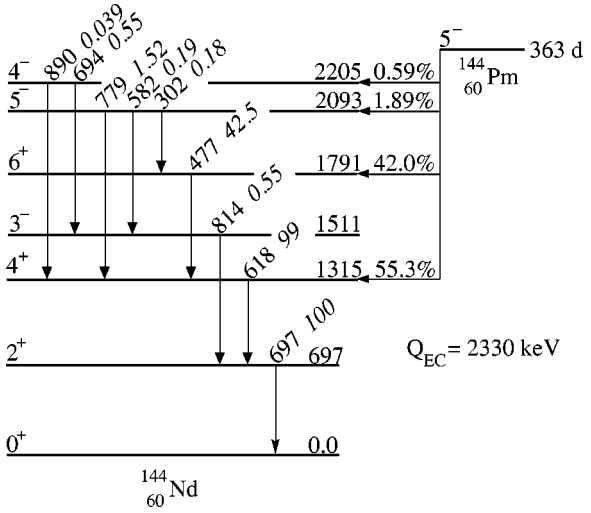

FIG. 1. A simplified level scheme of ^{144}Nd populated in the electron-capture decay of ^{144}Pm, showing only those decay branches relevant to the current measurement. Transition and level energies are given in keV.

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However, such a measurement would also require the determination of a ''prompt'' time reference for the same detected energies, which is difficult to obtain. To eliminate the need to determine this prompt reference we have used a comparative triple-coincidence technique in which the lifetime of the 1791-keV level is extracted from the difference between two separate delayed coincidence spectra.

Consider coincidences between the K x rays and the 618-keV γ transition from the 4_1^+ level. In the absence of any other conditions, a time spectrum from such coincidences would have two major components, corresponding to the two ways that the 4_1^+ level is fed, namely, directly from an EC decay or via an EC decay to the 6_1^+ level and then the emission of a 477-keV γ. Other, much smaller, components will come from EC decay branches to the 2205-keV (4^-) and 2093-keV (5^-) levels. Weighting all these contributions accordingly, the statistical centroid T of such a time distribution, relative to a hypothetical prompt position, will be given by

$$T = \tau_{4^+} + 0.429\tau_{6^+} + 0.0171\tau_{5^-} + 0.00039\tau_{4^-}. \quad (1)$$

If now an additional coincidence condition is added, that the 477-keV γ is observed simultaneously in a third detector, then the events selected will correspond only to the EC decay branches to the 6^+ and 5^-levels. In this case the centroid, T', of the associated K x ray–618-keV γ coincidence time distribution will be given by

$$T' = \tau_{4^+} + \tau_{6^+} + 0.0042\tau_{5^-}. \quad (2)$$

The difference between these two centroids will then be given by

$$T' - T = 0.571\tau_{6^+} - 0.0129\tau_{5^-} - 0.00039\tau_{4^-}. \quad (3)$$

Exactly the same centroid difference can also be generated using K x ray–696-keV γ coincidences and the same 477-keV coincidence condition.

At this point it should be noted that the lifetimes of both the 5^- and 4^- levels are known to be around 1 ps [7], and so, according to Eq. (3), any significant observed centroid difference, at the picosecond level or longer, can be entirely attributed to the lifetime of the 6^+ level. It should also be noted that, since the same energies (K x rays and either 618-keV or 696-keV γ rays) are used to generate both time distributions, no energy dependent corrections are necessary.

B. The triple coincidence system

The triple coincidence system used for this measurement consisted of two small BaF_2 scintillators, mounted on Hamamatsu H5321 photomultiplier assemblies, and a 20% efficient HPGe detector. The fast signals from the anode output of the photomultipliers were fed to ORTEC 9307 picoTiming discriminators, the outputs from which were used to start and stop an ORTEC 567 time to amplitude converter (TAC) set to 50 ns full scale. The triple coincidence condition was set using separate outputs from the two timing discriminators, together with logic information derived from the HPGe detector signal. The condition that all three of these signals should be present within a 50 ns window was used to generate an event signal, which triggered the recording of data in an ORTEC AD413A Quad 8K ADC. For each event four pieces of information were recorded, namely, the energy signals from the three detectors (after appropriate amplification) and the TAC output, representing the time difference between signals detected in the two BaF_2 scintillators. The timing resolution of the BaF_2-BaF_2 coincidence system was 180 ps at ^{60}Co energies, and approximately 550 ps for K x ray–618-keV coincidences.

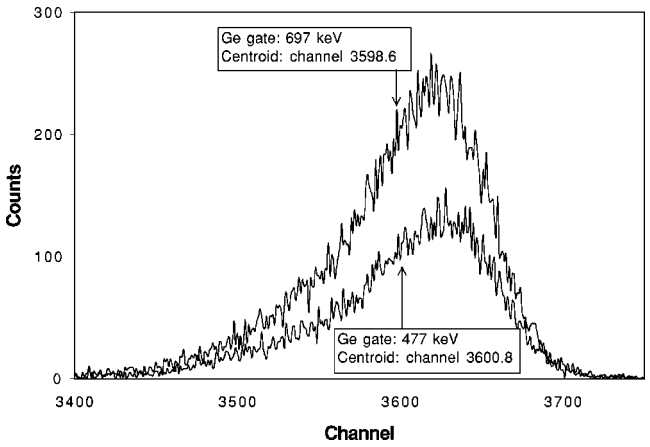

FIG. 2. Portions of the TAC spectra from K x ray–618-keV coincidences used to extract the lifetime of the 6_1^+ state in ^{144}Nd. The two spectra are those generated by gating the Ge detector on energies of 697 keV (upper) and 477 kev (lower). The statistical centroids of both spectra are indicated.

The ^{144}Pm source used for this measurement was that described in Ref. [20], which had a strength of approximately 4.3 μCi at the start of the experiment. Triple coincidence data were collected over a period of 68 days, during which time approximately 1.5×10^8 events were recorded.

C. Data analysis and results

The data were sorted offline to generate the desired TAC spectra. Although the generation of the TAC spectrum associated with Eq. (1) strictly requires only double (BaF_2-BaF_2) coincidences, it was actually generated by also requiring the

TABLE I. Relative centroid shifts (in picoseconds) for various time distributions extracted from the triple coincidence schemes indicated. The figures in parentheses give the uncertainty in the least significant digits.

Ge gates	BaF_2 gate (Start)	BaF_2 gate (Stop)	Centroid shift (ps)
697 keV/477 keV	x ray	618 keV	13.8(38)
	618 keV	x ray	−18.1(31)
618 keV/477 keV	x ray	697 keV	16.3(44)
	697 keV	x ray	−17.5(38)
697 keV/618 keV	x ray	476 keV	2.5(31)
	476 keV	x ray	1.3(25)

TABLE II. Comparison of experimentally determined values with various model predictions for the $B(E2;4_1^+\rightarrow 2_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ and $B(E2;6_1^+\rightarrow 4_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ ratios in ^{144}Nd.

Expt./model	$\frac{B(E2;4_1^+\rightarrow 2_1^+)}{B(E2;2_1^+\rightarrow 0_1^+)}$	$\frac{B(E2;6_1^+\rightarrow 4_1^+)}{B(E2;2_1^+\rightarrow 0_1^+)}$	Reference
Expt.	0.95 ± 0.07	1.14 ± 0.14	Current work
Liq. drop	2.0	3.0	[19]
DPPQ	1.90		[21]
DDM	1.49	1.49	[13]
PCM	0.86	0.74	[1,3]
CVM	1.15	1.01	[2,22]
IBM-1 (U5 limit $N=6$)	1.67	2.00	[23]
IBM-1 (U5 limit $N=5$)	1.60	1.80	[23]
IBM-1	1.5–1.6	1.7–1.8 [a]	[10,11]
IBM-2 (U5 limit $N_\pi=4N_\nu=1$)	1.60	1.80	[4,5]
IBM-2	1.3–1.4	1.4–1.5 [a]	[1,3,12]

[a]Values calculated using the model parameters given in the original references.

observation of 697-keV γ from the 2_1^+ state in the Ge detector. To generate the TAC spectrum associated with Eq. (2) a gate was set on the 477-keV transition in the Ge detector. Similarly the equivalent time distributions for x ray–697-keV coincidences were generated by setting Ge gates on the 618- and 477-keV transitions. A check of the system was performed by also examining the time distributions of x ray–477-keV coincidences gated on the 618- and 697-keV transitions in the Ge detector. Since identical decay branches are selected in both of these coincidence schemes, these time distributions should show no relative shifts.

A sample TAC spectrum is shown in Fig. 2. The asymmetric shape is caused by the fact that very different energies (K x rays and 618 keV) are detected in the two BaF_2 scintillators. Because of this asymmetric shape, no fitting of the TAC spectra was performed and the statistical centroid and its uncertainty were derived from the data using the formulas

$$\bar{x}=\frac{\sum n_i x_i}{\sum n_i}, \tag{4}$$

$$\sigma_{\bar{x}}=\frac{\sqrt{\sum n_i(x_i-\bar{x})^2}}{\sum n_i}, \tag{5}$$

where n_i is the number of counts in channel x_i.

The results of the data analysis are shown in Table I, derived using a time calibration of 6.25 ± 0.19 ps per ADC channel. Note that the first two pairs of results show shifts in opposite directions, as would be expected when the roles of the start and stop detectors are reversed. The last pair of results are those which should show no shifts, as is indeed the case. The magnitudes of the first four results give an average shift of 17 ± 2 ps, which translates, using Eq. (3), to a lifetime for the 1791-keV 6^+ state of 30 ± 3 ps. This, in turn, leads to a $B(E2;6_1^+\rightarrow 4_1^+)$ value of 25 ± 3 W.u. and a $B(E2;6_1^+\rightarrow 4_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ ratio of 1.14 ± 0.14.

III. DISCUSSION

Table II shows a comparison of the measured relevant $B(E2)$ ratios with various model predictions. The current result indicates that the absolute $B(E2)$ values stay essentially constant up to the 6^+ yrast state.

As can be seen from Table II all purely collective model calculations overestimate the $B(E2;4_1^+\rightarrow 2_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ and $B(E2;6_1^+\rightarrow 4_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ ratios. Within the *sd*-IBM a significant reduction from the harmonic $B(E2)$-ratio values in the yrast sequence is possible as a natural consequence of the finite number of bosons employed in model calculations [23]. Such cutoff effects are especially noticeable in calculations for nuclei near closed

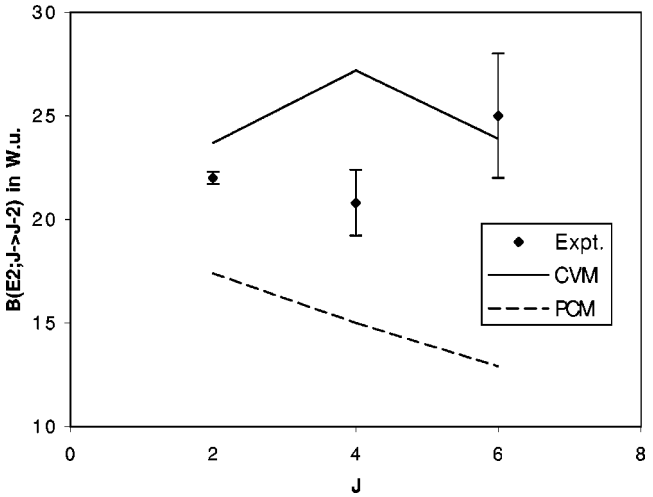

FIG. 3. Absolute $B[E2;J^+\rightarrow(J-2)^+]$ values (in W.u.) for transitions from yrast states in ^{144}Nd. Experimental values are plotted as individual points with error bars. The solid and dashed lines connect the CVM and PCM calculations, respectively.

TABLE III. Wave function components, expressed as percentages, of the $(2f_{7/2})^2_J$ two-neutron configuration in the low lying yrast states of ^{144}Nd.

State	Model	
(J^+)	CVM [a]	PCM [b]
2^+	6%	30%
4^+	11%	35%
6^+	26%	45%

[a]Reference [2].
[b]Reference [3].

shells, which have only a few valence nucleons. This reduction can be further enhanced in ^{144}Nd by the introduction of a reduced effective proton boson number, due to the influence of the $Z=64$ subshell closure [24]. In the strict vibrational limits of both IBM-1 and IBM-2 (and using the boson numbers $N_\pi=4$, $N_\nu=1$), the ratio of these $B(E2)$ values is 1.6 [4,5]. More detailed calculations, in which states of different *d*-boson number and *F* spin are allowed to mix, can further reduce the value of this ratio to around 1.4 [3,12], but no further reduction is possible, and no combination of parameters can produce the essentially flat behavior of the $B(E2)$ values.

By contrast, the PCM calculations of Ref. [3] gave the result $B(E2;4_1^+\rightarrow 2_1^+)/B(E2;2_1^+\rightarrow 0_1^+)=0.86$, which is very close to the experimentally determined value of 0.95 ± 0.07. However, these calculations actually produce a consistently downward trend in the absolute $B(E2)$ values. This manifests itself in a significant underestimation of the $B(E2;6_1^+\rightarrow 4_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ ratio. In fact, since these calculations already produced an absolute $B(E2;2_1^+\rightarrow 0_1^+)$ value that was 25% smaller than the measured value, this results in a calculated $B(E2;6_1^+\rightarrow 4_1^+)$ value which is only one half of the value measured in the current work, as can be seen in Fig. 3.

Figure 3 shows that the model that comes closest to reproducing both the absolute $B(E2)$ values, and their ratios is the CVM calculations of Ref. [2], though it slightly overestimates the $B(E2;4_1^+\rightarrow 4_1^+)/B(E2;2_1^+\rightarrow 0_1^+)$ ratio. The CVM and PCM approaches are essentially the same, in that they both explicitly couple the two valence neutrons to a collective core, which represents the semi-closed shell $N=82$ nucleus, ^{142}Nd. It is therefore instructive to examine the $\nu^2(L=4)$ and $\nu^2(L=6)$ components in the yrast state wave functions produced by these two calculations. In particular, since the neutron single-particle level structure is dominated by the isolated $2f_{7/2}$ orbital a good indication of these components can be gained from the percentage of the $(2f_{7/2})^2_J$ two-neutron components in the calculated wave functions. Table III shows these components for the low lying yrast states from the two model calculations. From this comparison it is evident that the underestimation of absolute $B(E2)$ values, and their ratios, in the PCM calculations, is due to the overestimation of the amplitude of the two-neutron components in the wave functions. A comparison of the parameters used in both models suggests that this is, in turn, due to a combination of factors, such as an underestimated pairing strength and particle-core coupling strength, and an overestimated core quadrupole phonon energy. The parameters used in the CVM calculations produce a slightly more collective picture by spreading the two-neutron strength more evenly over the available single particle level combinations (so producing a slightly more collective neutron quadrupole excitation), and by increasing the influence of the vibrational core. This combination of CVM parameters reproduces the data for the 2^+ and 6^+ states quite well, but overestimates the collectivity of the 4^+ state. Evidently for this state, the true picture lies somewhere between the two models.

Between them, the PCM and CVM calculations, when compared with the experimental $B(E2)$ values and their ratios, serve to characterize the low lying yrast structure of ^{144}Nd rather well. While the 2^+ state can be described as a collective quadrupole excitation, the 4^+ and 6^+ states show clearly a mixing of collective multiphonon excitations and pure two-neutron $(L=4)$ and $(L=6)$ configurations. This latter influence is probably due to the unusual nature of the neutron single-particle level spectrum, which is dominated by the isolated $2f_{7/2}$ orbital. It would be interesting to extend this study to higher yrast states, for which other neutron couplings would become important, since two $2f_{7/2}$ neutrons cannot couple to higher angular momenta.

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