Lifetimes in Neutron-Rich Nd Isotopes Measured by a Doppler Profile Method

A. G. Smith, W. R. Phillips, J. L. Durell, W. Urban, B. J. Varley, C. J. Pearson, and J. A. Shannon
Department of Physics and Astronomy, University of Manchester, M13 9PL, United Kingdom

I. Ahmad, C. J. Lister, L. R. Morss, K. L. Nash, and C. W. Williams
Argonne National Laboratory, Argonne, Illinois 60439

M. Bentaleb, E. Lubkiewicz,* and N. Schulz
Institut National de Physique Nucléaire et de Physique des Particules—Centre de Recherches Nucléaires, IN2P3-CNRS, Université Louis Pasteur, 67037 Strasbourg, France
(Received 6 June 1994)

The Eurogam-1 array has been used to study γ rays emitted following the spontaneous fission of a ^{248}Cm source. Yrast level schemes for the neutron-rich nuclei ^{152,154,156}Nd have been constructed. The stopping of the Nd fragments in the source material leads to Doppler-broadened line shapes for those states that have lifetimes comparable to the stopping time. This paper describes the first measurements of lifetimes of medium-spin states in very neutron-rich nuclei obtained from the analysis of these line shapes. The transition quadrupole moments for the yrast states in the spin range $(10-16)\hbar$ have been deduced to be 5.88 ± 0.08 e b (^{152}Nd), 5.75 ± 0.10 e b (^{154}Nd), and 5.33 ± 0.16 e b (^{156}Nd).

PACS numbers: 21.10.Tg, 23.20.Lv, 27.70.+q

There is at present considerable interest in the extension of experimental data to cover new regions of the nuclear chart far from stability. Such data will determine whether existing approaches to nuclear structure at low excitation energy remain valid as isospin varies significantly from that of the stable species. The determination of level energies and spins is often insufficient to differentiate between competing models, and additional information on the lifetimes of the states provides a more stringent test of theoretical approaches.

Lifetime measurements of medium to high spin nuclear states (with spin quantum number $I \geq 10$) have, in the past, been confined to neutron-deficient nuclei produced in fusion evaporation reactions and to stable species excited by Coulomb excitation. In these neutron-deficient nuclei, states with lifetimes of less than 2 ps have been measured using the Doppler shift attenuation method (DSAM). This involves stopping the recoiling nuclei in a target backing, thereby attenuating the Doppler shift of the emitted radiation with time and producing asymmetric line shapes in the γ-ray energy spectra observed in a fixed detector. Knowledge of the stopping powers and initial recoil velocity enables lifetimes to be extracted by fitting the line shapes. DSAM is normally performed in cases where there is a well defined recoil cone and therefore a well defined angle between the initial recoil velocity and the detector-target axis. In this Letter we describe a modified DSAM that has enabled the measurement of lifetimes of states ($12 \leq I \leq 16$) in the fragments from spontaneous fission. These are the first measurements of the lifetimes of such states in very neutron-rich nuclei.

In this work the spontaneously fissioning isotope ^{248}Cm was used as a source of neutron-rich fragments whose electromagnetic decay properties were to be studied. The source consisted of about 5 mg of curium oxide (giving a fission rate of about 7×10^4 nuclei per second) embedded uniformly in a pellet of potassium chloride. The Eurogam phase 1 array [1] of Compton-suppressed germanium detectors was used to detect the emitted γ radiation. Events for which three or more detectors fired were used to construct a cubic data array whose axes represented the energies of the detected γ rays and the contents of each channel the number of events with that particular combination of γ-ray energies. This data structure enabled the fast creation of one-dimensional spectra of γ rays that occur in coincidence with any two supplied gating energies, thus providing the selectivity needed to separate the decays of the fragments of interest from those of the many other products of the fission process.

The technique previously described [2,3] for identifying new neutron-rich isotopes from γ-ray coincidence data was used to identify transitions in ^{156}Nd. These transitions were then used as gates to generate the partial level scheme shown in Fig. 1. Previously the ground-state band of ^{152}Nd was known up to spin $I = 8$ [4,5] and that of ^{154}Nd also to spin $I = 8$ [6]. The previous level schemes for both these nuclei have been confirmed and extended and these are also shown in Fig. 1. The average quadrupole moment of the low-spin 2_1^+, 4_1^+, and 6_1^+ levels in ^{152}Nd (populated in the β^- decay of ^{152}Pm) has been inferred from electronic-timing measurements of state lifetimes [7] to be 6.09(11) e b.

At spins above $I = 10$ symmetrically broadened γ-ray line shapes were observed. This broadening is due to the variable Doppler shifts of the radiation emitted from the randomly directed fission fragments as they stop in the source pellet and is associated with γ rays emitted from states with lifetimes in the range 1–2 ps, i.e., comparable to the stopping time of the fission fragments in the pellet. Such lifetimes are amenable to modified DSAM

 0031-9007/94/73(19)/2540(3)$06.00

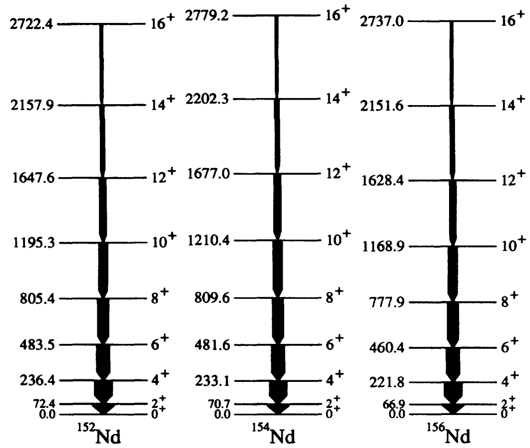

FIG. 1. Partial decay schemes for ^{152,154,156}Nd.

measurements in which the initial energy distribution and random velocity direction of the fragments are taken into account (Doppler profile method).

To determine the state lifetimes from the Doppler-broadened line shapes the velocity history of the Nd fragments as they stop in the source pellet was simulated using electronic and nuclear stopping powers given by the computer code ZBL [8]. The initial fragment kinetic energy distribution was assumed to be Gaussian with its centroid (67 MeV) taken from Ref. [9] and width (σ = 5.6 MeV) taken to be the same as that measured [10] for the heavy fragments from ^{252}Cf spontaneous fission. The simulation produced a two-dimensional data matrix (fractional Doppler shift, or FDS matrix) whose contents gave the probability of observing a particular fractional Doppler shift ($\beta \cos \theta$, where β is the velocity of the fragment and θ is the angle between the fragment velocity and the γ-ray detection axis) in the emitted radiation at any given time. Anisotropic angular distributions of the γ radiation relative to the fragment velocity direction can, in principle, affect the form of the FDS matrix, but these effects are small in fission and have been neglected in the present analysis. The FDS matrix was used in conjunction with a simulation of the decay process to generate line shapes that were compared with the experimental data.

The line shapes of the three transitions between spin I = 10 and 16 in each of the nuclei ^{152,154,156}Nd were fitted separately with a simple decay model that assumed a rotational band with a constant intrinsic quadrupole moment (Q). Although Q may vary somewhat with spin, this procedure gives the most consistent treatment of the data by reducing the effect on the analysis of small contaminant peaks under the broadened Nd peaks. These unwanted peaks arise unavoidably from decays in complementary Kr fragments and to a lesser extent from contaminants in the gates used to provide the spectra. Adopting a constant Q also reduces the effect of uncertainties in the form of the background spectrum that is subtracted from the raw gate. The analysis thus gives an average quadrupole moment in each Nd nucleus over the spin quantum number range 10 to 16. The quadrupole moment was varied to obtain the best fit to the data. To account for the feeding of the I = 16 states, each band has had its rotational energy sequence extended with three fictitious transitions which were assigned the same quadrupole moment as the observed band. Sidefeeding of the I = 12 and 14 states was determined to be about 30% of the appropriate decay intensities from the integrated photopeak areas in the γ-ray spectra. In spontaneous fission where the fragments are formed at rather low spin and excitation energy, the sidefeeding of the yrast states is thought to be direct and fast compared to the lifetimes of the medium spin yrast states. This is in contrast to the slow feeding that often occurs following fusion evaporation reactions where the nucleus follows the yrast line in its decay from a high initial spin ($I \approx 40-50$). In the model the sidefeeding intensity was assumed to be a result of prompt, direct feeding (zero feeding time). The fictitious continuation of the band was also assumed to have 30% prompt sidefeeding to each level.

Figure 2 shows the line shapes in ^{152,154,156}Nd with the resulting fits superimposed upon the data. In the fitting procedure the data and simulated spectra were compared over regions that included the line shapes but excluded the large regions of background between them. The quadrupole moments along with their statistical uncertainties are 5.88 ± 0.08 e b (^{152}Nd), 5.75 ± 0.10 e b

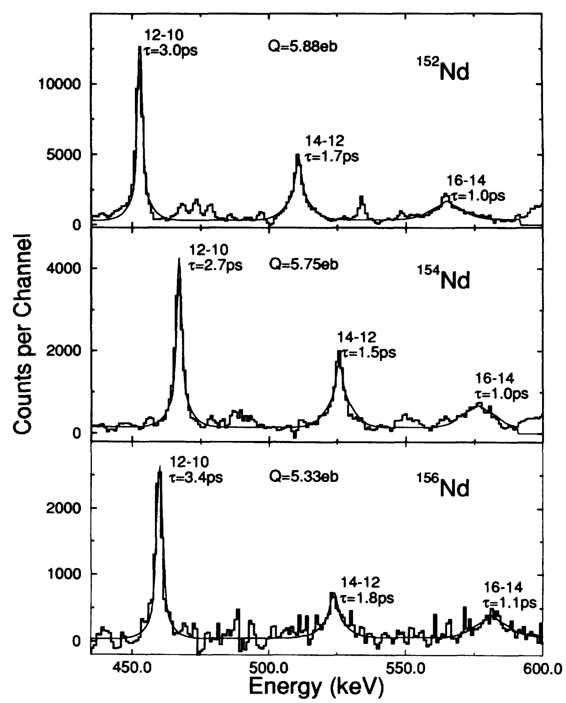

FIG. 2. Line shapes in the γ-ray energy spectra of ^{152,154,156}Nd. The fits (smooth lines) are superimposed on the data (histograms). Each photopeak is marked with the spin quantum numbers of the initial and final levels of the decay as well as with the mean lifetime (τ) of the initial level. The resulting transition electric quadrupole moments (Q) are also given.

(^{154}Nd), and 5.33 ± 0.16 e b (^{156}Nd). The respective values for the reduced χ^2 for the fits were 5.5, 4.1, and 0.9. The somewhat high values for ^{152}Nd and ^{154}Nd arise from the contamination of the broadened peaks and the difficulties of accurate background subtraction. These results are also subject to systematic errors due to uncertainties in the stopping powers (contributing an uncertainty of about 10% to the transition quadrupole moments) and in the way that the feeding is modeled (the introduction of a long 200 fs delay in the sidefeeding increases the solution quadrupole moments by about 3%). Because of these systematic errors it can only be noted that, for ^{152}Nd, $Q(I = 10 - 16)$ is consistent with $Q(I = 2 - 6)$. However, as the same model and stopping powers are used for each of the three isotopes, it is expected that these results are a reliable measurement of their *relative* average quadrupole moments in the spin range $I =$ 10–16.

As seen in Fig. 1, the energies of the $J^{\pi} = 2^+$ levels decrease as neutrons are added. This is a sign of increasing deformation. It may seem surprising therefore that the deduced Q of ^{156}Nd is smaller than those of ^{154}Nd and ^{152}Nd. Figure 3 shows the variation of the dynamic moment of inertia ($\mathcal{J}^{(2)}$) of the Nd yrast bands with rotational frequency ($\hbar\omega$). It can be seen that in the spin region where Q has been determined (I = 10–16), $\mathcal{J}^{(2)}$ for ^{156}Nd is lower than those of the other isotopes. The gradual increase in $\mathcal{J}^{(2)}$ with $\hbar\omega$ for all three isotopes suggests a strong interaction between crossing g and s bands [the ground-state band (g) represents rotational states built on the completely paired ground-state configuration, whereas the s band is built on an intrinsic state consisting of two aligned quasineutrons], with the yrast states slowly attaining the the structure of the s band. The interaction strength between the g and s bands may vary as the neutron number increases. If this strength is weaker in ^{156}Nd than in the lighter isotopes, as suggested by Fig. 3, the transition strength in the band-crossing region in ^{156}Nd would be reduced, thus resulting in a lower average Q as deduced from the lifetime measurements. An alternative explanation for the results may be that the s band in ^{156}Nd has a lower deformation than those of ^{154}Nd and ^{152}Nd.

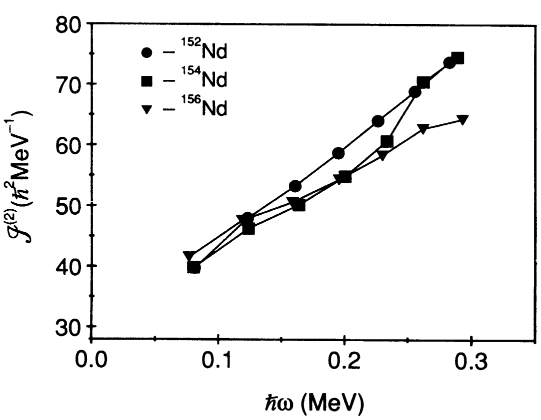

FIG. 3. Dynamic moment of inertia against rotational frequency for the yrast bands in ^{152,154,156}Nd.

This Letter has reported the first measurements of state lifetimes at medium spin in the fragments of spontaneous fission. The measurements have been made possible by the quality of the data from the Eurogam array, which has enabled, for the first time, the observation of Doppler-broadened line shapes of γ rays decaying from states with $I > 10$ in fission fragments. For the purpose of examining lifetimes over a sequence of isotopes this paper has described examples from the heavy side of the mass distribution ($A \approx 150$), and line shapes discussed here are fairly typical of those that are obtained from decays in other heavy fission fragments. The light fragments near $A = 100$ are emitted with much higher kinetic energies (typically about 100 MeV). This high initial kinetic energy, together with the high γ-ray energies of rotational bands in this mass region, leads to line shapes that can be several tens of keV broad. The line shapes in the light fragments may provide fertile territory for future investigations. Since many different products are formed in spontaneous fission, the Doppler profile method may be used to survey the quadrupole moments of rotational nuclei over a large range of the neutron-rich side of the nuclear chart and should thereby prove a useful tool in the exploration of low energy nuclear structure far from stability.

This work was supported by the Science and Engineering Research Council of the U.K. under Grant No. GRH71161, by the National Science Foundation Grant No. PHY88-02279, and by the U.S. Department of Energy under Contracts No. W-31-109-ENG-38 and No. DE-FG02-87ER40346. The authors are also indebted for the use of ^{248}Cm to the Office of Basic Energy Sciences, U.S. Department of Energy, through the transplutonium element production facilities at the Oak Ridge National Laboratory.

*Permanent address: Jagellonian University, Krakow, Poland.

[1] F. Beck, Prog. Part. Nucl. Phys. **28**, 443 (1992).
[2] M. A. C. Hotchkis *et al.*, Phys. Rev. Lett. **64**, 3123 (1990).
[3] M. A. C. Hotchkis *et al.*, Nucl. Phys. **A530**, 111 (1991).
[4] J. B. Wilhelmy, S. G. Thompson, R. C. Jared, and E. Cheifetz, Phys. Rev. Lett. **25**, 1122 (1970).
[5] R. Chapman, W. McLatchie, and J. E. Kitching, Nucl. Phys. **A186**, 603 (1972).
[6] E. Cheifetz, J. B. Wilhelmy, R. C. Jared, and S. G. Thompson, Phys. Rev. C **4**, 1913 (1971).
[7] M. Hellstrom, H. Mach, B. Fogelberg, D. Jerrestam, and L. Spanier, Phys. Rev. C **47**, 545 (1993).
[8] J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Heavy Ions in Solids* (Permagon Press, New York, 1985).
[9] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).
[10] S. L Whetstone, Jr., Phys. Rev. **131**, 1232 (1963).