PHYSICAL REVIEW C, VOLUME 65, 067305

Lifetime and $B(E2)$ values for the 3_1^+ level in ^{152}Sm

N. V. Zamfir,[1,2,3] H. G. Börner,[4] N. Pietralla,[1,5] R. F. Casten,[1] Z. Berant,[1,2,6] C. J. Barton,[1] C. W. Beausang,[1] D. S. Brenner,[2] M. A. Caprio,[1] J. R. Cooper,[1] A. A. Hecht,[1] M. Krtička,[7] R. Krücken,[1] P. Mutti,[4] J. R. Novak,[1] and A. Wolf[1,2,6]
[1] *WNSL, Yale University, New Haven, Connecticut 06520*
[2] *Clark University, Worcester, Massachusetts 01610*
[3] *National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[4]*Institut Laue-Langevin, F-38042 Grenoble, France*
[5]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[6]*Nuclear Research Center Negev, Beer-Sheva, Israel*
[7]*Charles University, Prague, Czech Republic*

(Received 15 April 2002; published 17 June 2002)

Existing data for the 3_1^+ state of ^{152}Sm present serious uncertainties for any collective interpretation of this nucleus. In this work the lifetime of the 3_1^+ state in ^{152}Sm was remeasured, using the gamma ray induced Doppler technique in the (n,γ) capture reaction, and the $E2/M1$ mixing ratio of the $3_1^+ \rightarrow 2_3^+$ transition was obtained from linear polarization measurements of γ rays following the ϵ decay of ^{152}Eu. The results remove the previous potential discrepancies and are in agreement with the interpretation of ^{152}Sm as exhibiting phase coexistence near the critical point of a spherical-deformed phase transition.

DOI: 10.1103/PhysRevC.65.067305 PACS number(s): 21.10.Tg, 23.20.Gq, 27.70.+q

Recent measurements [1–3] of $B(E2)$ values and branching ratios in ^{152}Sm have led to significant alterations in the existing level scheme. With these new data ^{152}Sm has been interpreted [2–5] in terms of a mixing of coexisting spherical and deformed phases. In this view, ^{152}Sm is considered as a nucleus very near the critical point of a first-order spherical-deformed phase transition in the variables β and γ [6].

Most of the attention so far has focused on the yrast levels and the yrare states built on the 0_2^+ state. There is also, however, a level sequence built on the 2_3^+ level, and this sequence, in particular the decay of the 3_1^+ level at 1234 keV could present serious problems with *any* interpretation of ^{152}Sm. The situation is illustrated in Fig. 1. All model interpretations of ^{152}Sm, whether in a coexistence picture [2] or earlier models, would predict a $B(E2{:}3_1^+ \rightarrow 2_3^+)$ value $\sim$150–250 Weisskopf unit (W.u.). Yet the existing literature gives a lifetime for the 3_1^+ level of $\tau < 9$ ps [7,8] which corresponds to a $B(E2)$ value >56 W.u. [assuming a pure $E2$ transition, or even less if (as we measured — see below) there is an $M1$ component]. Of course, the lower limit on the $B(E2)$ value, in principle, allows any value, but, clearly, until this potential problem with the $B(E2{:}3_1^+ \rightarrow 2_3^+)$ value is resolved, any further interpretation of the 2_3^+ sequence of levels is precluded.

Therefore, the purpose of this Brief Report is to present the results of measurements of the lifetime of the 3_1^+ level. The lifetime was measured using the GRID (gamma ray induced Doppler) technique in the (n,γ) reaction at the ILL in Grenoble. To help establish if the $3_1^+ \rightarrow 2_3^+$ transition has a significant $E2$ component we also measured its mixing ratio with a linear polarization measurement of γ rays, following ϵ decay of ^{152}Eu, with clover Ge detectors as Compton polarimeters at Yale.

In the GRID technique [9], the lifetime is obtained by measuring the Doppler broadening of a deexcitation γ ray from a nucleus that is recoiling due to the prior emission of another γ ray following neutron capture. Since such recoil energies are very small, the observation of Doppler broadening demands extraordinarily high resolution. This requires the use of the ultrahigh resolution GAMS4 flat crystal spectrometer at the ILL in Grenoble [10]. This spectrometer can provide resolution of a few eV for 1 MeV transitions, which is suitable for GRID measurements for nuclei in the mass 150 region. For details of this device and the GRID technique, see Refs. [9,10]. In the present experiment, levels in ^{152}Sm were populated following double neutron capture on a ^{150}Sm target situated in the core of the high-flux reactor at the ILL.

The major uncertainty in extracting level lifetimes with the GRID technique is actually not due directly to the mea-

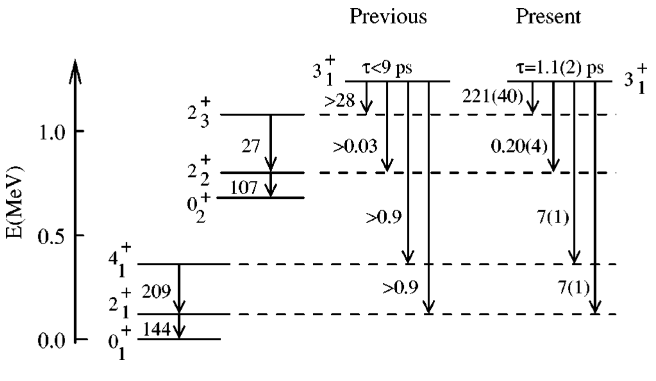

FIG. 1. Partial level scheme for ^{152}Sm exhibiting the decay of the 3_1^+ state at 1234 keV. The existing lifetime limit for the 3_1^+ level is shown along with our new results. The present work shows that the actual lifetime of the 3_1^+ level is an order of magnitude less than the previous limit. The numbers on the transition arrows are the $B(E2)$ values in W.u. from Refs. [2,8]. On the far right the $B(E2)$ values from the present study are shown. For the $B(E2;3_1^+ \rightarrow 2_3^+)$ both previous and current values are calculated with the $\delta = 1$ value from the present polarization measurements.

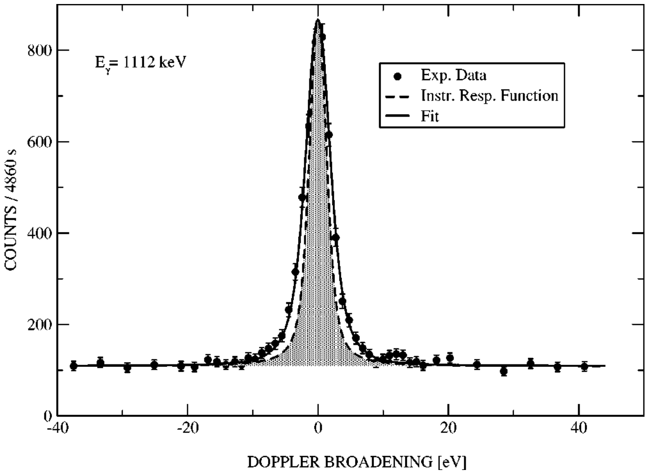

FIG. 2. The Doppler broadened line shape for the 1112 keV, $3_1^+ \rightarrow 2_1^+$ transition from 34 scans over this transition with the GAMS spectrometer. The dotted line shows the instrumental line width. The solid line is a fit to the data that incorporates Doppler broadening due to the finite lifetime.

sured linewidth itself, but rather to estimating the initial recoil velocity distribution of ^{152}Sm nuclei at the time of population of the levels of interest. This velocity distribution depends on the energy distribution of the γ-rays feeding levels from the capture state and the lifetimes of the intermediate levels. Such feeding usually proceeds by many routes and is best treated as a statistical decay process. However, it is possible to deduce upper and lower lifetime limits by using extreme assumptions about the population routes and intensities. The highest recoil velocities will be given by assuming that all unobserved feeding is via a two-step cascade from the neutron capture state with intermediate level lifetime $\tau = 0$. (It is known that single-step population by primary transitions is very weak.) Then, a given Doppler broadening for a depopulating γ ray will correspond to the longest slowing down time before γ-ray emission and therefore to the longest lifetime. The lower limit on the lifetime comes from assuming that all the feeding of each level comes from a state of effectively infinite lifetime (hence the nucleus emitting the feeding γ ray has no initial recoil velocity) at the lowest possible energy consistent with the known level scheme.

Figure 2 shows the Doppler broadened line shape of the 1112 keV $3_1^+ \rightarrow 2_1^+$ transition. From an analysis of the instrumental and observed line shapes in Fig. 2, the extreme feeding assumptions give a lifetime for the 3_1^+ state of 0.44 ps $< \tau < 1.08$ ps. The large range of τ values for the 3_1^+ level allowed by the extreme feeding assumptions (extreme initial recoil velocity upper and lower limits) can be considerably narrowed by using the fact that the cascade feeding does not vary much from level to level in a small excitation energy and spin range, so comparison of GAMS4 data for nearby levels of known lifetimes can pin down the actual feeding scenario relevant to a particular nucleus. There are two such levels that can be used, at 1086 and 1372 keV. In both cases, as shown in Table I, the known mean lifetimes are very close to the upper limit from the extreme feeding assumptions. This preference for the upper lifetime limit is consistent with experience from previous GAMS4 measurements [11]. For the 1234 keV level, this gives $\tau = 1.1(2)$ ps. For comparison, Ref. [7] gives $\tau < 9$ ps. The present result therefore gives $B(E2)$ values, and, in particular, the $B(E2;3_1^+ \rightarrow 2_3^+)$ value, about an order of magnitude larger than the limits in Ref. [8], as shown on the far right in Fig. 1. In particular, the $B(E2;3_1^+ \rightarrow 2_3^+)$ value is now clearly collective. As Fig. 1 shows, using the value $\delta = 1.0$ (see below), gives $B(E2;3_1^+ \rightarrow 2_3^+) = 221(40)$ W.u., which is indeed considerably larger than the previous limit (with $\delta = 1$) of > 28 W.u.

TABLE I. Comparison of the lifetimes deduced in this work using the extreme feeding assumptions (see text) with the previously reported data.

J^π_{level}	E_{level} (keV)	E_γ (keV)	τ_{lit} (ps)	τ extreme limits (ps)
2_3^+	1086	964	1.57(20) [a]	0.46–1.55
3_1^+	1234	1112	<9 [b]	0.44–1.08
4_3^+	1372	1005	2.0(7) [b]	0.54–1.78

[a] Reference [3].
[b] Reference [8].

Since the multipole character of this $\Delta J = 1$ transition is not experimentally known we also studied its mixing ratio at Yale using the linear polarization of the emitted γ rays, in order to verify that it has substantial $E2$ character. For this purpose, four pairs of detectors (seven segmented Clover and one 70% Ge detector), with an angular separation of 98° between the two detectors in each pair, were used as a Compton polarimeter [12,13] in the Yale γ spectrometer SPEEDY [14]. The total full γ-energy detection efficiency was $\sim 2\%$ at 1.33 MeV. A standard ^{152}Eu source of 7 μCi activity populating excited states in ^{152}Sm was mounted at the center of the spectrometer and $\gamma\gamma$ and higher-fold coincidence events were recorded for ~ 10 days.

The degree of linear polarization of a γ-γ coincidence cascade observed at relative emission angle θ depends on the multipolarities of the two γ transitions (and on the spins and parities of the levels involved) [15]. It is defined as

$$P_\gamma(\theta) = \frac{W(\theta,\phi=0) - W(\theta,\phi=90)}{W(\theta,\phi=0) + W(\theta,\phi=90)}, \tag{1}$$

where $W(\theta,\phi=0), W(\theta,\phi=90)$ are the intensities of the components of the gamma radiation polarized parallel and perpendicular to the plane of the γ-γ correlation. For any given set of parameters $P_\gamma(\theta)$ has its maximum at $\theta = 90°$.

The experimentally measured quantity was the asymmetry ratio A_γ defined as

$$A_\gamma(\theta) = \frac{aN_\perp(\theta) - N_\parallel(\theta)}{aN_\perp(\theta) + N_\parallel(\theta)}, \tag{2}$$

where $N_\perp, N_\parallel$ are the number of Compton addback events within a given Clover detector perpendicular and parallel to the correlation plane in coincidence with an event in a detector at a relative angle θ. The parameter a takes into account the instrumental asymmetry of the polarimeter and has to be determined experimentally as a function of γ energy. In an

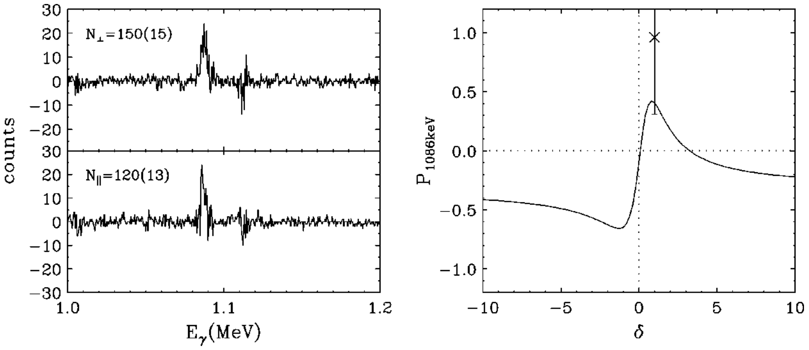

FIG. 3. Left: Polarization-sensitive add-back spectra of the $2_3^+ \rightarrow 0_1^+$, 1086 keV pure $E2$ transition in coincidence with the $3_1^+ \rightarrow 2_3^+$, 148 keV transition. Right: Comparison of the measured polarization for the $2_3^+ \rightarrow 0_1^+$ transition with the theoretical expectation as a function of the $E2/M1$ multipole mixing ratio δ of the $3_1^+ \rightarrow 2_3^+$ transition.

ideal apparatus a should be equal to 1 for all gamma-ray energies. The instrumental asymmetry a was measured from γ-γ coincidences taken at a relative angle $\theta = 180°$. At this correlation polar angle all γ rays are unpolarized, implying $A_\gamma(180°) \equiv 0$. This relation is used in order to extract an experimental value $a = 1.00 \pm 0.03$ at 1.1 MeV.

The relation between A_γ and P_γ is given by the equation:

$$A_\gamma(\theta) = Q(E_\gamma) P_\gamma(\theta), \tag{3}$$

where $Q(E_\gamma)$ is the (positive) polarization sensitivity of the system and was determined in our case using the known polarization for a pair of gamma rays (1112 keV, 121 keV) very close in energy with those involving the 3_1^+ state (1086 keV, 148 keV). The measured value, $Q(1.1\ \mathrm{MeV}) = 0.115(12)$, agrees very well with the results of a Monte Carlo calculation [16].

In the $3_1^+ \rightarrow 2_3^+ \rightarrow 0_1^+$ (148 keV, 1086 keV) coincidence cascade, the polarization of the $2_3^+ \rightarrow 0_1^+$ pure $E2$ transition depends on the $E2/M1$ mixing ratio δ of the $3_1^+ \rightarrow 2_3^+$ transition detected in coincidence in a detector at the relative angle θ. Figure 3 (left) shows the γ spectra showing the 1086 keV add-back line in the coincidence plane and perpendicular to it in coincidence with the 148 keV line in the other detector at a relative angle of 98°. The add-back spectra represent the background subtracted number of coincidence events between two leaves of the same Clover detector oriented perpendicular to the $\gamma\gamma$-correlation plane ($N_\perp$) and parallel to this plane ($N_\parallel$) as a function of the sum energy deposited in these two leaves. The measured asymmetry is $A_{1086\ \mathrm{keV}} = 0.11(7)$ and the corresponding polarization is $P = 0.96(65)$. Figure 3 (right) shows the calculated polarization $P_{1086\ \mathrm{keV}}(98°)$ as a function of the mixing ratio δ for the 148 keV $3_1^+ \rightarrow 2_3^+$ transition, along with the experimental value for this polarization. From this figure, we determine that $\delta(E2/M1) = 1.0 \pm 0.6$ with the sign convention of Krane and Steffen [17]. We note that the uncertainties correspond to the overlap interval of the expected polarization as a function of δ and the measured value within one standard deviation. The present results indicate a substantial $E2$ content of the $3_1^+ \rightarrow 2_3^+$ transition. This is in agreement with the total electron conversion coefficient for the 148 keV, $3_1^+ \rightarrow 2_3^+$ transition, $\alpha = 0.577(11)$ [8].

The predominant $E2$ character is also suggested by theoretical studies in the framework of the interacting boson model. In general, there are only small $B(M1)$ strengths between low lying states of collective nuclei resulting from small components with $F < F_{max}$ [18,19].

Thus, the $3_1^+ \rightarrow 2_3^+$ transition very probably has $E2$ character and, with the greatly shortened new value for the 3_1^+ level lifetime, this transition is collective. As noted above, the results of the present work for the decay of the 3_1^+ state are summarized on the far right in Fig. 1. In a phonon picture, based on the 0_2^+ level [2,4] the $3_1^+ \rightarrow 2_3^+$ transition would be an allowed three-phonon to two-phonon transition and is expected to have a $B(E2)$ value ~2.14 times that of the $2_2^+ \rightarrow 0_2^+$ transition. Experimentally, the ratio ~2.1, obtained using $\delta = 1$ for the $3_1^+ \rightarrow 2_3^+$ transition, is consistent with this interpretation. The $B(E2;3_1^+ \rightarrow 2_3^+)$ value of 221(40) W.u. is, in fact, reproduced by the IBA calculations of Ref. [2], which give 157 W.u. The collective character of the transition removes a potential problem that *any* model of ^{152}Sm would have faced with the longer lifetime value allowed by the previous measurement.

The shorter lifetime for the 3_1^+ state, of course, also leads to increased values for other transitions from the 3_1^+ level and it is important to verify that, while the new lifetime removes a difficulty for the $3_1^+ \rightarrow 2_3^+$ transition, it does not introduce new ones for the other transitions — to the 2_1^+, 4_1^+, and 2_2^+ levels — all of which should essentially be forbidden in any plausible interpretation of ^{152}Sm. The lower limit $B(E2)$ values from the 3_1^+ level to these states with the previous 3_1^+ lifetime of <9 ps were all below 1 W.u. With the new lifetime, the actual values, rather than limits, are now obtainable (see Fig. 1, right). They remain weak, ranging from ~7 W.u. for the $3_1^+ \rightarrow 2_1^+$ and $3_1^+ \rightarrow 4_1^+$ transitions to $\leqslant 1$ W.u. for the $3_1^+ \rightarrow 2_2^+$ transition. Relative to typical allowed collective $E2$ transitions in this nucleus of ~150 W.u., these new values remain comfortably small, and within the range of predictions of collective models. For example, in the coexistence interpretation [2,4] the 3_1^+ level is a three-phonon state built on the 0_2^+ state, so the $3_1^+ \rightarrow 2_2^+$ transition is forbidden. The small $B(E2)$ value supports this interpretation.

In summary, the transitional nucleus ^{152}Sm was studied. The extraordinarily high-energy precision and resolution of the GAMS4 spectrometer at the ILL in Grenoble were used to obtain the lifetime of the 3_1^+ state at 1234 keV in ^{152}Sm, in the range $0.4 < \tau < 1.1$ ps with the GRID technique assuming extreme feeding assumptions. With feeding calibrated by comparison to known lifetimes of other levels a best value $\tau = 1.1(2)$ ps is obtained. This is nearly an order of magnitude faster decay than the earlier limit. Linear polarization measurements at Yale give a mixing ratio of $\delta = 1.0 \pm 0.6$ for the $3_1^+ \rightarrow 2_3^+$ state, indicating a substantial $E2$ content. The present results show that the $E2$ part of the $3_1^+ \rightarrow 2_3^+$ transition is indeed collective. For example, using $\delta = 1$, the lifetime measurement gives a $B(E2{:}3_1^+ \rightarrow 2_3^+)$ value of 221(40) W.u. Thus, the result that this transition is most probably collective, even comparable to those within the yrast and yrare sequences and considerably greater than the lower limit from Ref. [8], removes, to a large extent, a potentially serious difficulty with *any* plausible interpretation of ^{152}Sm and gives a $B(E2;3_1^+ \rightarrow 2_3^+)$ value compatible with our current understanding of this pivotal nucleus.

Work supported under U.S. DOE Grant Nos. DE-FG02-91ER-40609 and DE-FG02-88ER-40417 and by the DFG Grant No. Pi393/1.

---

[1] R.F. Casten *et al.*, Phys. Rev. C **57**, R1553 (1998).

[2] N.V. Zamfir *et al.*, Phys. Rev. C **60**, 054312 (1999).

[3] T. Klug, A. Dewald, V. Werner, P. von Brentano, and R.F. Casten, Phys. Lett. B **495**, 55 (2000).

[4] F. Iachello, N.V. Zamfir, and R.F. Casten, Phys. Rev. Lett. **81**, 1191 (1998).

[5] J.Y. Zhang, M.A. Caprio, and N.V. Zamfir, and R.F. Casten, Phys. Rev. C **60**, 061304(R) (1999).

[6] R.F. Casten and N.V. Zamfir, Phys. Rev. Lett. **87**, 052503 (2001).

[7] T. Seo, Nucl. Instrum. Methods Phys. Res. A **325**, 176 (1993).

[8] Agda Artna-Cohen, Nucl. Data Sheets **79**, 1 (1996).

[9] H.G. Börner and J. Jolie, J. Phys. G **19**, 217 (1993).

[10] E.G. Kessler *et al.*, J. Phys. G **14**, S167 (1988).

[11] H.G. Börner, M. Jentschel, N.V. Zamfir, R.F. Casten, M. Krticka, and W. Andrejtscheff, Phys. Rev. C **59**, 2432 (1999).

[12] P.M. Jones *et al.*, Nucl. Instrum. Methods Phys. Res. A **362**, 556 (1995).

[13] A. Wolf *et al.*, Phys. Rev. C (in press).

[14] R. Krücken, in *Proceedings of the International Conference on Applications of Accelerators in Research and Industry, Denton 2000*, edited by J.L. Duggan and I.L. Morgan, AIP Conf. Proc. No. 576 (AIP, New York, 2001), p. 310.

[15] L.W. Fagg and S.S. Hanna, Rev. Mod. Phys. **31**, 711 (1959).

[16] L.M. Garcia-Raffi *et al.*, Nucl. Instrum. Methods Phys. Res. A **391**, 461 (1997).

[17] K.S. Krane and R.M. Steffen, Phys. Rev. C **2**, 724 (1970).

[18] D.D. Warner, Phys. Rev. C **34**, 1131 (1986).

[19] H. Harter, P. von Brentano, A. Gelberg, and T. Otsuka, Phys. Lett. B **188**, 295 (1987).