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Lifetime of the 3_1^- state and octupole collectivity in ^{96}Zr

D. J. Horen, R. L. Auble, G. R. Satchler, J. R. Beene, and I. Y. Lee*
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

C. Y. Wu, D. Cline, M. Devlin, R. Ibbotson, and M. W. Simon
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
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The half-life of the 1897.2-keV, 3_1^- state in ^{96}Zr has been measured as (67.8 ± 4.3) ps using the recoil-distance technique following inelastic excitation by 105-MeV ^{32}S ions. This is equivalent to a lifetime which is about 40% longer than those reported from two recent centroid-shift measurements. Our lifetime implies $B(E3)\uparrow=(0.180\pm0.018)\ e^2b^3$, i.e., (47.1 ± 4.7) W.u., which is the most enhanced one-phonon g.s.$\rightarrow 3_1^-$ transition strength observed in nuclei. A recent quasiparticle random-phase approximation (QRPA) calculation reproduces our result. Serious doubts are raised about an earlier conclusion that the reduced octupole transition probabilities of "mirror" nuclei correspond to the harmonic low for small amplitude vibrations. The enhanced $B(E1{:}3_1^-\rightarrow 2_1^+)=(1.71\pm0.11)\ 10^{-5}\ e^2b$ deduced from the present work is consistent with appreciable octupole deformation. The measured $B(E3)\uparrow$ resolves problems in the interpretation of the isospin character of the $E3$ transition derived from inelastic scattering data.

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I. INTRODUCTION

Strong octupole correlations are expected to occur in ^{96}Zr because of the coherent superposition of proton $2p_{3/2}\rightarrow 1g_{9/2}$ and neutron $2d_{5/2}\rightarrow 1h_{11/2}$ particle-hole excitations. Two recent centroid-shift measurements of the half-life of the 1897.2-keV 3_1^- state in ^{96} Zr report values of (46 ± 15) ps [1] and (50 ± 7) ps [2] which imply $B(E3)\uparrow$ values that are (69^{+34}_{-17}) and (65 ± 10) W.u., respectively. This unusually strong octupole enhancement has been suggested as inconsistent with simple harmonic vibrations and implying the possible existence of octupole shape instability and the breakdown of the RPA formalism for ^{96}Zr [2].

The unusually enhanced $B(E3)\uparrow$ strength implied by these centroid-shift measurements has important implications for the interpretation of the isospin character of this $E3$ transition as derived from inelastic hadron scattering [3–5]. It was found that to fit inelastic ^{6}Li data for the 3_1^- state using the deformed optical model potential (DOMP) with this reported $B(E3)\uparrow$ [1,2] would require [5] $M_n/M_p<0.5$, where M_n and M_p are the neutron and proton multipole transition matrix elements, respectively. Such a small value of M_n/M_p would imply that this octupole transition has a very strong isovector component, contrary to generally accepted views. On the other hand, it might imply that the interpretation of the parameters (deformation lengths) deduced from a DOMP analysis of the inelastic data is incorrect [5]. It has been noted in Ref. [5] that there was an inconsistency between DOMP and folding model calculations of the inelastic cross sections for 3^- excitations in the $^{90-96}$Zr isotopes.

A precise knowledge of the $B(E3)\uparrow$ value could help to clarify a number of questions pertaining to the 3_1^- state in ^{96}Zr. The recoil-distance technique [6] is an accurate and reliable method for measuring lifetimes in the time range appropriate for the 3_1^- state in ^{96}Zr, and we report here the results of such a measurement.

II. EXPERIMENTAL

The lifetime of the 3_1^- state in ^{96}Zr was measured using the recoil-distance technique and the MP tandem Van de Graaff accelerator at the Nuclear Structure Research Laboratory of the University of Rochester. We used an incident beam of 105-MeV ^{32}S ions to inelastically excite

*Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720.

the 3_1^- state. The target consisted of a $\sim$1-mg/cm^2 stretched, self-supporting foil of ^{96}Zr (enriched to 85.3%), and the recoiling Zr ions were stopped in a stretched 11.5-mg/cm^2 nickel stopper foil which also served as a beam stop. Deexcitation γ rays were detected at 0° by a Compton-suppressed (21.5% efficiency) Ge detector located at a distance of 11.1 cm from the target in coincidence with backscattered sulphur ions which were detected in an annular parallel-plate position-sensitive counter which covered an angular range $138° < \theta < 168°$. The target and stopper foils were carefully aligned by optical means with an accuracy of $< 0.2°$. The stopper foil was movable by a commercial "Inchworm" device that uses three piezoelectrical crystals to move in 6-nm steps over a range of 25 μm, and also includes an optical measurement transducer that measures the position to an accuracy of 2 μm [7]. Measurements were made at seven separation distances between the target and stopper foil varying from 100 to 2500 μm. The zero and short-distance calibration was determined by capacitance measurements. The detected backscattered ions correspond to target nuclei which recoil inside a forward cone from 4° to 14.6°. The average recoil velocity must be known accurately to transform the measured target-foil distance to time of flight needed to determine the lifetime. The average recoil velocity was determined as $v/c = 0.0364 \pm 0.0020$ from the measured Doppler shift of the moving γ-ray peak with respect to the stopped peak.

In an earlier study using the same reaction (i.e., 105-MeV ^{32}S ions on the same ^{96}Zr target) carried out at the Holifield Heavy Ion Research Facility (HHIRF) at ORNL, it was observed that there was negligible feeding of the 1897.2-keV, 3_1^- state from higher lying levels [8]. However, it was found that the cascade feeding of the 1750.5-keV 2_1^+ state is appreciable under these conditions. Hence, we concentrated upon using the 146.7-keV transition ($3_1^- \to 2_1^+$) for determining the half-life of the 3_1^- state. The intensity of the cross over transition to the ground state was too weak to be useful in determining the half-life.

Shown in Fig. 1 are γ-ray spectra obtained at target to stop foil distances of 500 and 2000 μm. The channel position of the unshifted and Doppler-shifted peaks corresponding to the 146.7-keV transition are indicated. In Fig. 2 are shown the ratios of the areas of the unshifted to unshifted+shifted peaks versus the distance between the target and the stop foil. The data points designated by ovals represent the raw data.

The data were corrected and fitted using a modified version [9] of the computer code ORACLE [10] which corrects for feeding (negligible in this case), relative γ-ray detection efficiency, relativistic solid angle effect, finite size of the Ge detector, angular distribution and deorientation effect. The data points after correction for these effects are indicated by the diamonds in Fig. 2, while the solid curve represents the best fit. Use of an average recoil velocity $v/c = 0.0364 \pm 0.0020$ results in a half-life for the 3_1^- state of $T_{1/2} = (67.8 \pm 4.3)$ ps. The measured lifetime is insensitive to correction effects; e.g., switching off the γ-ray angular distribution correction increases the half-life by 0.5 ps which is much smaller than the quoted uncertainty.

To deduce a $B(E3)\uparrow$ value from this half-life requires knowledge of the $E3$ branch. There have been four reasonably accurate measurements of the relative intensities of the $E1$ (146.7-keV) and $E3$ (1897.2) γ rays. Molnar *et al.* report $I_{\gamma_{147}}/I_{\gamma_{1897}}$ ratios of 8.06 ± 0.75 and 5.37 ± 0.38 from $(n,n'\gamma)$ measurements using reactor and 4-MeV neutrons, respectively [11]. From studies of the decay of ^{96}Y, Klein *et al.* [12] give 6.16 ± 0.75 and Sadler *et al.* [13] report 6.86 ± 1.05. We use an unweighted average $I_{\gamma_{147}}/I_{\gamma_{1897}} = 6.61 \pm 0.57$ which is essentially the same as used previously [1,2] and total conversion coefficients for the 146.7-keV transition of $\alpha_T = 0.0371$ [14] to obtain $B(E3)\uparrow = (0.180 \pm 0.018)\ e^2b^3$. This corresponds to (47.1 ± 4.7) W.u. Due to the weakness of the $E3$ decay branch, the branching ratio and its uncertainty have the largest effect on determining the $B(E3)\uparrow$ value and its

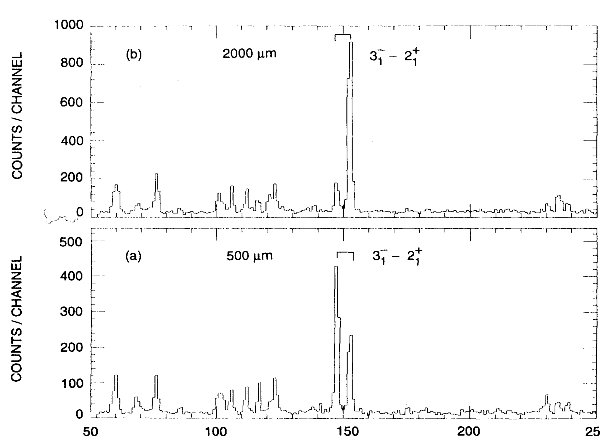

FIG. 1. Gamma-ray spectra showing the unshifted and shifted peaks for the 146.7-keV transition for target to stop foil distances of (a) 500 μm and (b) 2000 μm.

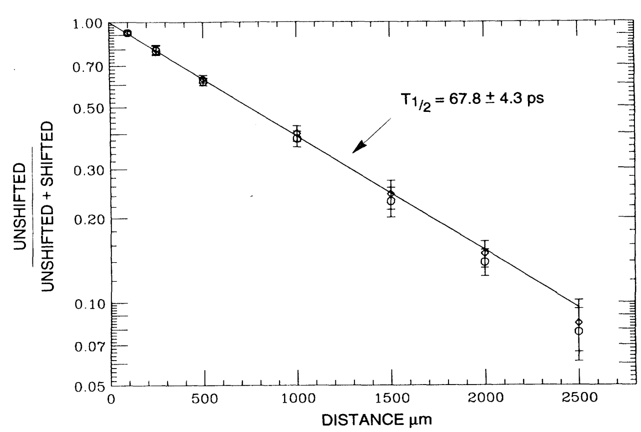

FIG. 2. Plot of the intensity of the unshifted to the sum of the unshifted plus shifted peaks for the 146.7-keV gamma-ray versus the target to stop foil distance. The ovals represent the raw ratios, while the diamonds correspond to the corrected data (see text). The solid curve represents the best fit to the corrected data.

uncertainty from the measured half-life. Thus, it would be desirable to have additional measurements of this branching ratio in view of the considerable disparity among the reported values. The present work implies a $B(E1:3_1^- \rightarrow 2_1^+) = (1.71 \pm 0.11) \times 10^{-3}\ e^2\mathrm{b}$ or $(1.27 \pm 0.08) \times 10^{-3}$ W.u. for the strong $E1$ decay branch. This result is not so sensitive to the precision of the branching ratio.

III. DISCUSSION

The deduced $B(E3)\uparrow = (47.1 \pm 4.7)$ W.u. is one of the most enhanced $E3$ transitions to a 3_1^- state [15]. The deduced $B(E1:3_1^- \rightarrow 2_1^+) = (1.27 \pm 0.08) \times 10^{-3}$ W.u. has a strength similar to that observed in the Ba-Nd and Ra region where octupole collectivity also is strong. Thus, the measured $B(E1)$ also supports the implication that octupole correlations are unusually strong in ^{96}Zr.

Ohm *et al.* [1] raised the question of whether the 3_1^- transition in ^{96}Zr satisfied the conditions expected for a harmonic vibrator. To do so, they compared the relationship between the $B(E3)\uparrow$ and the energy of excitation, E, predicted [16] by the hydrodynamical model with irrotational flow, i.e.,

$$B(E3)\uparrow Z^{-2} A^{-1/3} = CE^n$$

for a "selected" set of transitions. The classical harmonic oscillator model predicts that the exponent $n = -1$ [16]. They restricted their "selected" set to such transitions in "mirror," magic, and "mirror"-magic nuclei (see Fig. 3). They identified ^{96}Zr as a member of the latter group. In Fig. 2 of Ref. [1], the authors show a "fit" which corresponds to $n = -1.07 \pm 0.13$, and conclude that the selected subset of $E_{3_1^-}$ transitions represent harmonic vibrations characterizing small amplitude shape oscillations of the nuclear surface as discussed by Bohr and Mottelson [16]. We have attempted to fit the same "selected" set using the $B(E3)\uparrow$ of Ohm *et al.* [1], but have not been able to reproduce their quoted value of n. However, we find that with inclusion of their $B(E3)\uparrow$ for ^{96}Zr, and excluding the ^{146}Gd, ^{90}Zr, and ^{24}Mg data, $n = -1.39 \pm 0.17$ with $C = 8.66 \pm 1.07$. Using this same set but excluding their $B(E3)\uparrow$ for ^{96}Zr, we find $n = -0.72 \pm 0.13$ with $C = 3.39 \pm 0.62$. Refitting the latter set with our $B(E3)\uparrow$ for ^{96}Zr gives essentially the same values of n and C. Inclusion of the full "select" set of Ref. [1] with our $B(E3)\uparrow$ gives $n = -0.68 \pm 0.14$ and $C = 3.17 \pm 0.48$, as is shown in Fig. 3.

Contrary to the conclusion of Ohm *et al.* [1], we find that the "select" set appear to represent anharmonic vibrations (i.e., $n \neq -1.0$) with an energy dependence similar to that reported in a global study of octupole transitions [17]. In that work, the authors found $n = -0.72 \pm 0.13$ and $C = 1.8 \pm 0.3$ for a set defined as "vibrational" transitions, i.e., those cases for which the ratio of the energy of the first 4^+ state to the energy of the first 2^+ state was ≤ 2.7 [13]. Included in this "vibrational" set were most of the "select" set of Ohm *et al.* [1].

It was noted in Ref. [5] that a $B(E3)\uparrow = 0.18\ e^2\mathrm{b}^3$

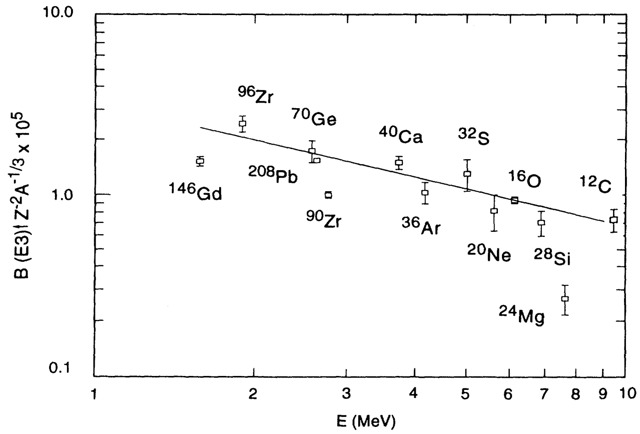

FIG. 3. Plot of $B(E3)\uparrow Z^{-2} A^{-1/3}$ versus excitation energy E for selected 3_1^- excitations. The solid curve represents a least-squares fit to the data.

(rather than the value 0.12 $e^2\mathrm{b}^3$ used therein) would lead to a ratio of neutron to proton multipole transition matrix elements of $M_n/M_p < 0.9$ if the ^{6}Li scattering data were analyzed using the DOMP. We have reanalyzed those data using the DOMP and our new value of $B(E3)\uparrow$ and find $M_n/M_p = 0.51$ which is considerably smaller than the value 1.22 obtained from QRPA calculations [5]. A small adjustment in the octupole-octupole strength used in the QRPA calculation can result in $B(E3)\uparrow = 0.18\ e^2\mathrm{b}^3$ with M_n/M_p remaining about the same, i.e., 1.25, and $E_x \sim 1.8$ MeV [18]. We have performed two folding model calculations of the inelastic cross section for exciting the 3_1^- state with 70-MeV ^{6}Li ions using the effective nucleon-nucleon interaction given in Ref. [5]. In one calculation, we scaled the RPA transition densities [5] in accordance with our deduced $B(E3)\uparrow$. As expected, the calculated cross sections were in much better agreement with the data than was found to be the case in Ref. [5]. This would then suggest that the reason for the apparent discrepancy between the DOMP and folding model analyses of the 3_1^- ^{6}Li data [5] resides in the interpretation of the nuclear deformation length deduced from the DOMP analysis. It has been noted that the DOMP cannot be justified by folding model calculations in which one assumes that the transition density is proportional to the derivative of the ground-state density [19], which is usually assumed to be the case for highly collective vibrational transitions. In fact, these studies indicate that the potential deformation length deduced for an $E3$ transition using a DOMP analysis of inelastic data would be smaller than the corresponding mass deformation length, and, hence, would lead one to infer too small a value of M_n/M_p.

In Fig. 4, we show the results of a folding model calculation in which it is assumed that the transition density is proportional to the derivative of the ground-state density. For the latter, we use the parameters for a two-parameter Fermi model with $c = 5.162$ fm and $a = 0.475$ fm [5,20]. We assume identical radial shapes for the neutron and proton transition densities, and choose the proton defor-

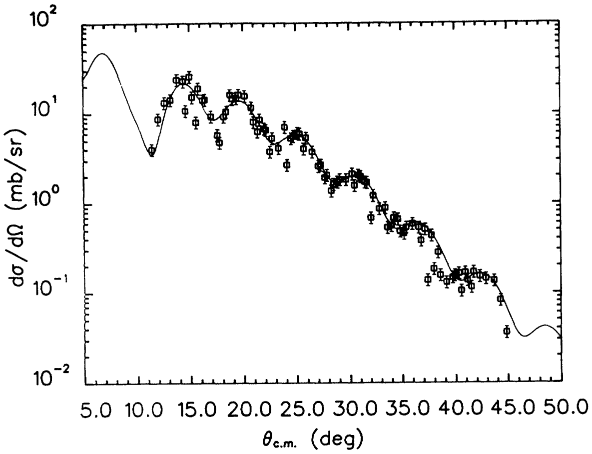

FIG. 4. Comparison of folding model predictions of the cross section for exciting the 3_1^- state of ^{96}Zr by 70-MeV ^{6}Li ions with the experimental data. (The data are from Ref. [5].)

mation length to reproduce our $B(E3)\uparrow$. This gives $\delta_3^p = 1.387$ fm. We then adjust the mass deformation length by matching the calculated cross sections to the measured ones. The solid curve in Fig. 4 is the result for $\delta_3^m = 1.329$ fm, which then corresponds to the ratio $M_n/M_p = 1.30$.

Another type of QRPA model calculation reports $B(E3)\uparrow = 0.208\ e^2b^3$ and an excitation energy $E = 1898$ keV [21], which also are in quite good agreement with the experimental results. This calculation gives $M_n/M_p = 1.30$. When transition densities become available from this calculation, it will be interesting to see how well their use in folding calculations will reproduce the inelastic cross section data.

IV. CONCLUSIONS

The half-life of the 1897.2-keV, 3_1^- state in ^{96}Zr has been measured as (67.8 ± 4.3) ps using the recoil-distance technique following inelastic excitation by 105-MeV ^{32}S ions. From this lifetime, we deduce $B(E3) \rightarrow (0.180 \pm 0.018)\ e^3b^3$ and $B(E1{:}3_1^- \rightarrow 2_1^+) = (1.71 \pm 0.11) \times 10^{-5}\ e^2b$. Our $B(E3)\uparrow$ is about 40% smaller than values deduced from centroid-shift measurements. We have used our $B(E3)\uparrow$ in folding model calculations to reanalyze inelastic ^{6}Li scattering data [5]. We find that these data are well reproduced with $M_n/M_p = 1.30$ which is in good agreement with the predictions of two QRPA calculations. This tends to support the arguments [19] that DOMP analysis of the inelastic data for 3^- transitions can lead to erroneous conclusions. Use of the folding model is likely to give more reliable results. This conclusion would resolve the discrepancy between the DOMP and folding model calculations noted in Ref. [5].

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