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Phys. Rev. C 85, 041303 — Published 19 April 2012

DOI: 10.1103/PhysRevC.85.041303
Observation of mutually enhanced collectivity in self-conjugate $^{76}$Sr$_{38}$

A. Lemasson,$^1$ H. Iwasaki,$^{1,2}$ C. Morse,$^{1,2}$ D. Bazin,$^1$ T. Baugher,$^{1,2}$ J.S. Berryman,$^1$
A. Dewald,$^3$ C. Fransen,$^3$ A. Gade,$^{1,2}$ S. McDaniel,$^{1,2}$ A. Nichols,$^4$ A. Ratkiewicz,$^{1,2}$
S. Stroberg,$^{1,2}$ P. Voss,$^{1,2,5}$ R. Wadsworth,$^4$ D. Weisshaar,$^1$ K. Wimmer,$^1$ and R. Winkler$^1$

$^1$National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
$^2$Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
$^3$Institut für Kernphysik der Universität zu Köln, D-50937 Köln, Germany
$^4$Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
$^5$Simon Fraser University, Burnaby, British Columbia, V5A 1S6 Canada

(Dated: April 10, 2012)

The lifetimes of the first $2^+$ states in the neutron-deficient $^{76,78}$Sr isotopes were measured using a unique combination of the $\gamma$-ray line-shape method and two-step nucleon exchange reactions at intermediate energies. The transition rates for the $2^+$ states were determined to be $B(E2;2^+\rightarrow0^+) = 2220(270)\;e^2fm^4$ for $^{76}$Sr and $1800(250)\;e^2fm^4$ for $^{78}$Sr, corresponding to large deformation of $\beta_2 = 0.45(3)$ for $^{76}$Sr and $0.40(3)$ for $^{78}$Sr. The present data provide experimental evidence for mutually enhanced collectivity that occurs at $N = Z = 38$. The systematic behavior of the excitation energies and $B(E2)$ values indicates a signature of shape coexistence in $^{76}$Sr, characterizing $^{76}$Sr as one of most deformed nuclei with an unusually reduced $E(4^+)/E(2^+)$ ratio.

PACS numbers: 21.10.Tg, 23.20.-g, 25.70.+e

Deformation of finite quantum systems is a manifestation of spontaneous symmetry breaking. In analogy to the Jahn-Teller effect in molecular physics [1], the coupling between collective vibrations and degenerate excitations of individual nucleons plays an important role in inducing nuclear ground-state deformation [2]. In nuclei, pairing correlations can also compete with the deformation driving particle-vibration coupling, further highlighting rich aspects of this many-body quantum system.

Self-conjugate nuclei have provided challenges to our understanding of the role of deformation driving mechanisms including neutron-proton correlations [3, 4]. In $N = Z$ nuclei, proton and neutron shell effects can act coherently, promoting an extreme sensitivity of nuclear properties to small changes of nucleon numbers. A well known region is the middle of the $pfg$ shell, where the nuclear shape evolves drastically from triaxial ($^{64}$Ge [5]), to transitional ($^{68}$Se [6]), to oblate ($^{72}$Kr [7]) shapes with a gradual increase of collectivity accompanied by the intrusion of the deformation driving $\delta_{3/2}$ orbital [8–10]. This region at $N = Z$ represents a unique location in the nuclear chart, where a strong enhancement of collectivity is expected from sizable numbers of valence protons and neutrons occupying the same orbitals. However, questions remain to be answered regarding the magnitude and location of – and evolution towards – the maximum collectivity.

In this Rapid Communication, we report on the first measurement of the lifetime of the first $2^+$ state in the self-conjugate nucleus $^{76}$Sr at $N = Z = 38$. We deduce the reduced transition probability $B(E2;2^+\rightarrow0^+)$ (noted $B(E2\downarrow)$ hereafter). This quantity provides a direct measure of quadrupole collectivity and often serves as a good indicator of the ground-state deformation, particularly for well-deformed nuclei. A lifetime measurement was also performed for $^{78}$Sr as a reference. Of particular interest are the very low excitation energies $E(2^+)$ of the first $2^+$ states measured for $^{76}$Sr [3] and neighboring $^{78}$Sr [3] and $^{80}$Zr [3], which suggest the occurrence of large deformation at $A \sim 80$ in agreement with theoretical predictions [8–16]. For $^{76}$Sr, the Gamow-Teller strength distribution measured in the $\beta$-decay study strongly favors a prolate deformation [17]. Rotational properties of the yrast band are well established in medium and high-spin states up to $22^+$ in $^{76}$Sr [18]. However, the measured energy ratio $R_{4/2} = E(4^+)/E(2^+)$ of 2.85 could indicate a triaxial deformation [19] with a reduced collectivity, hampering the establishment of a consistent picture for $^{76}$Sr. Here, based on new $B(E2\downarrow)$ data, we provide a new perspective on the evolution of collectivity at $N = Z$ and an insight into the character of the ground-state deformation of $^{76}$Sr.

Exploring deformation of heavy $N = Z$ nuclei represents an experimental challenge. In this work, the $\gamma$-ray line-shape method [20, 21] was applied to measure the lifetimes of the $2^+$ states of $^{76,78}$Sr, which were produced in two-step nucleon exchange reactions at intermediate energies [22]. A dedicated configuration for the present lifetime measurements was employed for the first time using the Segmented Germanium Array (SeGA) [23] at the National Superconducting Cyclotron Laboratory (NSCL). Also, the present reaction scheme allows access to nuclei that are neutron-deficient but with higher $Z$ than available primary beams, providing an attractive alternative to the use of fusion evaporation or fragmentation reactions in lifetime measurements. This approach facilitates a clear identification of reaction products and a sizable population of excited states simultaneously.
The experiment was performed at the Coupled Cyclotron Facility of NSCL at Michigan State University. Secondary beams of $^{76}\text{Sr}$ and $^{78}\text{Sr}$ were produced by reactions of a primary beam of $^{76}\text{Kr}$ at 140 MeV/nucleon with a $^{9}\text{Be}$ target and separated by the A1900 fragment separator [24] using an Al degrader. The momentum acceptance of the A1900 was set to 0.5%. The resultant beams were $\approx 30\%$ $^{76}\text{Rb}$ at 104.5 MeV/nucleon and $\approx 70\%$ $^{78}\text{Rb}$ at 101.6 MeV/nucleon for each setting. The available intensity was typically around $4\times 10^4$ pps for $^{76}\text{Rb}$, while for $^{78}\text{Rb}$ the beam was used at a rate of $1\times 10^5$ pps. The $^{76}\text{Sr}$ and $^{78}\text{Sr}$ isotopes were produced and studied using the secondary nucleon exchange reactions $^9\text{Be}(^{76}\text{Rb},^{76}\text{Sr})X$ and $^9\text{Be}(^{78}\text{Rb},^{78}\text{Sr})X$, respectively, on a 376-mg/cm$^2$-thick $^9\text{Be}$ reaction target. The outgoing particles were identified (Fig. 1(a)) based on the time-of-flight and energy-loss measurements using the focal-plane detection system of the S800 spectrometer [25].

De-excitation $\gamma$ rays were detected by 15 Ge detectors from SeGA [23]. Each Ge crystal has a diameter of 7 cm and is divided into eight 1-cm wide segments along the crystal length. The detectors were arranged around the target in a barrel configuration with the long side of the crystal parallel to the beam axis. Two rings of 7 and 8 detectors were used to cover the forward angles of 50–80$^\circ$ and the backward angles of 95–125$^\circ$, respectively. The full-energy peak efficiency was measured to be 17.5(3) % at 244 keV by a standard $^{152}\text{Eu}$ source. The present setup was chosen to maximize $\gamma$-ray detection efficiencies as well as the sensitivity to lifetime effects on the $\gamma$-ray line-shape as explained later. Figure 1(b) shows an energy spectrum of $\gamma$ rays measured in coincidence with $^{76}\text{Sr}$, where the Doppler-shift correction was made by assuming that all $\gamma$ decays occur in the middle of the target with an average velocity of $\beta_{\text{mid}}=v/c=0.396$. The $\gamma$-ray peaks are evident for the yrast band from the $2^+$ to the $8^+$ states, demonstrating the ability of the present reaction to populate medium-spin states. Inclusive populations, which are the sum of direct and indirect populations, are estimated to be 51(12)% and 36(8)%, respectively, for the $2^+$ and $4^+$ states, showing that about 70% of the $2^+$ state population was made by feeding from the $4^+$ state.

In this work, the lifetimes of the $2^+$ states of $^{76,78}\text{Sr}$ were determined by the $\gamma$-ray line-shape method [20, 21], which is based on the emission-point distribution of $\gamma$ rays emitted from reaction residues in flight. At the current beam velocities of $v/c \approx 0.4$, if an excited-state lifetime is on the order of 100 ps, the $\gamma$ decay occurs, on average, about 1 cm behind the target. Since we assume the $\gamma$-ray decay occurs at the target position to define
the γ-ray emission angles for Doppler-shift corrections, the lifetime effect results in a low-energy tail for a γ-ray peak as well as a slightly lower final peak position. To maximize the sensitivity of the γ-ray line-shape to the lifetime, we produced Doppler-shift corrected spectra of $^{76,78}$Sr by using velocities of outgoing Sr ions measured event-by-event in the S800 (the averaged velocities were $\beta_{sr} = 0.335$ for $^{78}$Sr and 0.330 for $^{76}$Sr). As shown in Fig. 2, asymmetric shapes of γ-ray peaks are clearly seen for the $2^+ \rightarrow 0^+$ transition both in $^{76}$Sr (Figs. 2 (a) and (b)) and $^{78}$Sr (Fig. 2(c)). However, the $4^+$ peaks are not aligned between the forward and backward data which indicates that the $4^+$ state decays mostly inside the target with higher recoil velocities. This suggests that the lifetime of the $4^+$ state is much shorter than the flight time ($\approx 20$ ps) of the ejectiles passing through the target.

Lifetimes were obtained by comparing the measured spectra to simulated ones as shown in Fig. 1. Lifetimes of the $4^+$ states were determined in a different fit. The spectral shapes of $\gamma$ rays depopulating the $4^+$, $6^+$, and $8^+$ states were included in the fit, where the amplitudes were determined in a different fit. The lifetimes of the $4^+$ states of $^{76,78}$Sr were both fixed to be equal to that for $^{78}$Sr (half-life $T_{1/2} = 5.1$ ps) [3]. Based on the reduced $\chi^2$ distributions as shown in the insets of Fig. 2, $T_{1/2}$ of the $2^+$ state in $^{76}$Sr was found to be $207^{+16}_{-14}$ ps and $203^{+18}_{-16}$ ps for the forward and backward data, respectively. For $^{78}$Sr, $T_{1/2} = 188^{+17}_{-15}$ ps (forward) and $194^{+26}_{-15}$ ps (backward) were obtained. Systematic errors were mainly due to ambiguities in the geometry of the setup (3%), the feeding from the $4^+$ state (1%), γ-ray anisotropy effects (1.5%), and the assumption of the background (3%). The overall systematic error in the present measurement was taken to be 4.6% by adding these uncertainties in quadrature.

By combining the forward and backward data, the present results were determined to be $T_{1/2} = 205(25)$ ps for $^{76}$Sr and $T_{1/2} = 191(27)$ ps for $^{78}$Sr, where both the statistical and systematic errors are included. The present result for $^{78}$Sr is slightly larger, but consistent with the previous data of 155(19) ps [3]. By adopting $E(2^+) = 262.3$ keV for $^{76}$Sr [18] and 277.6 keV for $^{78}$Sr [27], the $B(E2_{\downarrow})$ values are determined to be $2220(270)$ e$^2$fm$^4$ for $^{76}$Sr and $1800(250)$ e$^2$fm$^4$ for $^{78}$Sr. Note that main sources of the systematic errors are common for $^{76,78}$Sr, and thus the present results indicate that the collectivity of $^{76}$Sr is larger than that of $^{78}$Sr by about $2\sigma$. Following the prescription from Ref. [28] for a rigid rotor, deformation parameters are obtained as $\beta_2 = 0.45(3)$ for $^{78}$Sr and 0.40(3) for $^{78}$Sr.

The systematic behavior of the $E(2^+) \text{ and } B(E2_{\downarrow})$ values in the vicinity of $^{76}$Sr are plotted in Fig. 3. Along the $N = Z$ line, the $B(E2_{\downarrow})$ data depict a rapid increase of collectivity from $^{72}$Kr to $^{76}$Sr, accompanied by a sudden decrease in $E(2^+)$ (Fig. 3(a)). This is consistent with the occurrence of the deformed shell gap at the nucleon number 38 in the Nilsson diagram [8]. However this scheme does not easily account for possible mutual effects of proton and neutron deformation driving contributions at $N = Z$. Such effects are studied in Figs. 3 (b) and (c), where the $B(E2_{\downarrow})$ data are plotted as a function of $Z$ (N) for the isotonic (isotopic) chain around $^{76}$Sr. In Fig. 3(b), the collectivity increases toward $Z = 38$ for all the isotonic chains, while the enhancement is largest in the $N = 38$ chain. For the isotopic chains (Fig. 3(c)), the collectivity is enhanced at $N = 38$ only when $Z = 38$. This observation indicates that the deformed shell gap at the single nucleon number 38 is not strong enough to induce a large ground-state deformation and a mutual support from proton and neutron contributions is essential.
for the enhanced collectivity observed for $^{76}\text{Sr}$.

From a theoretical point of view, various works [8–16] have attempted to describe the ground-state deformation of nuclei in this region. In Fig. 3(a), the experimental data of $E(2^+)$ and $B(E2)$ are compared to the predictions from the constrained-Hartree-Fock-Bogoliubov theory together with a mapping to the five-dimensional collective Hamiltonian (CHFB+5DCH) [16]. Recently, improvements to mean-field theories involving quadrupole correlations [30] and mixing of different deformations [16, 30] have been undertaken to account for the mutually enhanced magicity [31]. A good agreement between the present data and the CHFB+5DCH calculations (Fig. 3(a)) suggests similar improvements are also required to account for the evolution of collectivity around $^{76}\text{Sr}$. Particularly, the CHFB+5DCH theory takes into account the mixing of different shapes including a triaxial degree of freedom, reproducing remarkably well the trend and amplitude of the data in the $A \sim 70$ region [6, 32] with pronounced prolate-oblate shape coexistence. While predictions for spectroscopic information are not available, large deformation for ($^{76}\text{Sr}$, $^{78}\text{Sr}$) are also predicted by other frameworks as (0.37, 0.37) [8], (0.45, 0.45) (RMF with NL-SH interaction [13]), (0.42, 0.42) (FRDM [33]), and (0.44, 0.43) (ETF-SI [34]).

The microscopic origin of the occurrence of the enhanced collectivity in $A \sim 80$ nuclei is ascribed to the occupation of nucleons in the $g_{9/2}$ orbital [8–10]. The effect due to the $g_{9/2}$ intrusion can be clearly seen in the sudden increase of collectivity from $^{27}_36\text{Kr}_{36}$ to $^{76}_38\text{Sr}_{38}$, where the occupation numbers for the protons and neutrons in the $g_{9/2}$ orbital are both predicted to increase from about 2 to 3 [9]. Interestingly, the $g_{9/2}$ occupation of neutrons is predicted to further increase from $N = 38$ to 40 in the Sr isotopes [9], while the present results show that the maximum collectivity occurs in $^{76}\text{Sr}$ with $N = Z = 38$. This suggests that the deformation driving effects are saturated at the nucleon number of 38 and hence one would expect there to be no additional increase of collectivity in $^{80}\text{Zr}$.

To better characterize the collective nature of $^{76}\text{Sr}$, a possible signature of shape coexistence phenomena can be investigated based on the systematic behavior for the $B(E2)$ with respect to the energy ratio $R_{4/2}$. If two different configurations coexist, the mixing among them can lead to a reduced $R_{4/2}$ of the yrast band, as the mixing lowers the ground $0^+$ state significantly more than other states [35]. In Fig. 4, we plot the correlation between $R_{4/2}$ and $B(E2)/A$ for the present results of $^{76,78}\text{Sr}$. For a systematic comparison, data are also plotted for neighboring Kr ($Z = 36$), Sr ($Z = 38$), and Zr ($Z = 40$) isotopes as well as heavier mid-shell nuclei with $Z = 62–70$. As discussed in Ref. [35], the $B(E2)$ values, when divided by $A$, have a clear correlation with $R_{4/2}$, starting from vibrational nuclei with $R_{4/2}$ of 2.0 and evolving to rotational nuclei with $R_{4/2}$ of 3.3. In fact, the correlation is evident in Fig. 4 for many of the Kr, Sr, and Zr isotopes, shown by the closed symbols, and most of the heavier nuclei. However, the present result for $^{76}\text{Sr}$, as well as the $A = 70 \sim 80$ nuclei highlighted by the open symbols in Fig. 4, significantly deviates from the global behavior, suggesting the signature of shape coexistence. A unique feature for $^{76}\text{Sr}$ is that the mixing amplitude obtained with a typical mixing strength of 0.2 MeV [36] and a predicted second $0^+$ state around 1 MeV [10, 16] is very small ($\sim 5\%$), preserving the large ground-state deformation. However, the mixing effect can be amplified in the excitation energy information due to the small $E(2^+)$, masking the deformed character of $^{76}\text{Sr}$ in $R_{4/2}$. This emphasizes the importance of the present $B(E2)\downarrow$ data as a direct indicator of the enhanced collectivity of $^{76}\text{Sr}$.

In summary, the present work demonstrated the usefulness of the $\gamma$-ray line-shape method combined with two-step nucleon exchange reactions in excited-state lifetime measurements, extending the $B(E2)$ systematics among self-conjugate nuclei up to $N = Z = 38$. The results indicate a large ground-state deformation of $^{76}\text{Sr}$ with $\beta_2 = 0.45(3)$ despite the unusually low $R_{4/2}$ ratio and illustrate the mutual enhancement of collectivity that uniquely occurs at $N = Z = 38$. The comparison with theoretical predictions as well as the systematic behaviour of the $R_{4/2}$ and $B(E2)$ values highlights the importance of the mixing of coexisting shapes for a rigorous description of well-deformed nuclei in the $A \sim 80$ $N = Z$ region.

This work is supported by the National Science Foundation under PHY-0606007 and PHY-1102511 and by the UK STFC.
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