Lifetime measurements of normally deformed and superdeformed states in $^{82}$Sr

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Lifetimes of a superdeformed band in $^{82}$Sr were measured with the centroid shift method. The measured average quadrupole moment of this band corresponds to a quadrupole deformation of $\beta_2^* = 0.49$, which is slightly smaller than both the theoretical prediction, and the measured deformation of the SD band in the neighboring isotope $^{84}$Zr. Lifetimes of high spin states of three normally deformed rotational bands in $^{82}$Sr were also measured with the Doppler shift attenuation method technique. The quadrupole moments of these normally deformed bands show a decrease at the highest spins, supporting the predicted band terminations.

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I. INTRODUCTION

The recent discovery of superdeformed (SD) bands in nuclei with mass $A \sim 80$ [1–4] showed exciting new aspects in the study of superdeformed phenomena. As a result of their large rotational frequencies, the SD bands in mass 80 region present experimental difficulties due to the increased Doppler broadening of $\gamma$-ray peaks and the decreased detection efficiency at large $\gamma$-ray transition energies. The high efficiency of large detector arrays such as Gammasphere [5] makes it possible to identify weak transitions in a complicated $\gamma$-ray spectrum, and the use of an auxiliary detector array such as the Microball [6] provides not only a powerful tool for reaction channel selection, but also an effective way to correct the Doppler-broadened $\gamma$-ray peaks. Therefore, it is now possible not only to identify superdeformed bands in mass $A \sim 80$ region, but also to measure the lifetimes of these states.

Superdeformed bands in $^{82}$Sr were established [2] from a previous Eurogam [7] experiment. Two SD bands were identified by Smith et al., using the $^{58}$Ni($^{30}$Si,$a2p$) reaction. In this paper we report the measurement of lifetimes for the SD band 1 in $^{82}$Sr. The experimental information of this measurement is presented in Sec. II A, and a comparison of these results with theoretical calculations and other SD bands in this mass region are discussed in Sec. III A.

The normally deformed rotational structures in $^{82}$Sr are also very interesting. An earlier study [8] of high spin states in $^{82}$Sr suggested shape coexistence among normally deformed rotational band structures. Another study [9] measured lifetimes of four rotational bands in $^{82}$Sr up to spin...
II. EXPERIMENT AND RESULTS

High spin states in $^{82}$Sr were populated using the $^{58}\text{Ni}(^{28}\text{Si},4p)$ reaction. The 130-MeV $^{28}\text{Si}$ beam was provided by the 88 Inch Cyclotron at the Lawrence Berkeley National Laboratory. The $\gamma$ rays were detected by the 57 large-volume Ge detectors of the Gammasphere phase I array, and the charged particles were detected by the 95 CsI detectors of the Microball. Both thin target and backed target were used in the experiment. The thin target was an isotopically enriched self-supporting $^{58}\text{Ni}$ foil with a thickness of approximately 400 $\mu$g/cm$^2$. The backed target consisted of a 420 $\mu$g/cm$^2$ $^{58}\text{Ni}$ foil evaporated onto a $^{181}\text{Ta}$ backing which is sufficiently thick to stop the recoils completely.

A total of $1.53 \times 10^8$ and $300 \times 10^6$ threefold or higher $\gamma$-ray coincidence events were collected from the thin- and backed-target experiments, respectively. By imposing a four-proton gate, the statistics of the thin- and backed-target data were reduced to $97 \times 10^6$ and $17 \times 10^6$ events, respectively. The selection of the reaction channel by imposing the four-proton gate proved to be very useful and efficient. The cross section of the 4$p$ channel is less than 10% of the total cross section, which contained more than 20 reaction channels. The 4$p$-gated events, however, are very clean and have less than 15% contaminants from other reaction channels. In the thin target experiment, the $\gamma$-ray energies were corrected for Doppler shifts according to the energy and angle of the recoil ion determined by tracking the angles and energies of the four correlated protons detected by Microball. Such an event-by-event, Microball-aided Doppler correction reduced the width of the $\gamma$-ray peaks by approximately 30%. As a result, the overall peak-to-total of the $\gamma$-ray spectra was significantly improved. The analysis and results of these events are presented in the following two subsections.

A. Analysis and results of the thin-target data

The 97 million 4$p$-gated, Doppler corrected events from the thin-target experiment were sorted into a three-dimensional cube. Using a three-dimensional rotational band search program of Ref. [12], the superdeformed band 1 of $^{82}\text{Sr}$ was immediately picked out. Figure 1 shows the sum of spectra obtained by double gating on all possible combinations of the known [2] transitions in this band. This spectrum confirmed the SD band 1 reported by Smith et al. [2]. The relative intensity of this band is shown in Fig. 2. This intensity pattern is slightly different from that reported in Ref. [2]. Compared with the result of Smith et al., our data show that the intensity drops at lower spins at the top of the band, i.e., the feeding of the SD band 1 occurs at a lower spin than that observed by Smith et al. This may be associated with the difference of $(a2p)$ and $(4p)$ reaction channels employed by the two studies. The other possible cause for this difference is the effect of imposing the 4$p$ gating with the Microball. It was found in our analysis that by imposing charged-particle gating, the intensities of the highest-spin states are slightly reduced. This may be responsible for the sharper decrease of the SD band 1 intensities at high spin.

Our effort of trying to confirm the SD band 2 reported by Smith et al. was not successful. Smith et al. reported that an excited superdeformed band was observed in $^{82}\text{Sr}$ consisting of eight transitions with an intensity of about 1/3 of that of the SD band 1. When double gating on these transitions in our 4$p$-gated cube, we observed no obvious band structures. When summing up spectra double gated on all possible combinations of transitions in the reported SD band 2, we ob-
tained a weakly correlated sequence of $\gamma$ rays which included strong transitions from the normally deformed $(-\frac{1}{2},\frac{1}{2})$ band of $^{82}\text{Sr}$ as well as the reported SD band 2, see Fig. 3(a). The presence of these transitions from the normally deformed $(-\frac{1}{2},\frac{1}{2})$ band [marked with stars in Fig. 3(a)] is mainly due to the 1537- and 1695-keV transitions in the reported SD band 2 [marked with down triangles in Fig. 3(a)], which are also present in the normally deformed $(-\frac{1}{2},\frac{1}{2})$ band, see also Fig. 5. When summing up spectra double gated on all possible combinations of transitions in the reported SD band 2 except the 1537-keV transition, we obtained a spectrum showing a correlated sequence of five transitions which belong to the reported SD band 2, see the peaks marked with down triangles in Fig. 3(b). However, this sequence is also strongly in coincidence with the normally deformed yrast band of $^{79}\text{Rb}$ [via the $\alpha 3\gamma$ channel], indicated by closed circles in Fig. 3(b). Meanwhile, the normally deformed transitions of $^{82}\text{Sr}$ shown in Fig. 3(a) have disappeared from Fig. 3(b). Figure 3(b) seems to connect the reported SD band 2 to $^{79}\text{Rb}$ instead of $^{82}\text{Sr}$. Further investigation shows that three of the transitions in the reported SD band 2 [transitions marked with open circles in Fig. 3(b)] have very similar or identical energies as transitions in $^{79}\text{Rb}$. This can be clearly seen when comparing Fig. 3(b) to Fig. 3(c). The latter was obtained by double gating on the 1141-, 1316-, and 1500-keV transitions of the yrast band in $^{79}\text{Rb}$. Among those strong transitions of $^{79}\text{Rb}$ (marked with closed circles), the 1687-, 1859-, and 2005-keV transitions have similar or identical energies as transitions in the reported SD band 2, see also the peaks marked with open circles in Fig. 3(b). These observations strongly indicate that the reported SD band 2 does not convincingly exist in our data. The sequence marked with down triangles in Fig. 3(b) most likely results from the correlation of the yrast band of $^{79}\text{Rb}$ instead of any true SD band correlation.

The thin-target data allowed us to extract lifetimes of fast transitions in SD 1 with the centroid shift method. Transitions in the superdeformed band are ultra fast compared with those in the normally deformed bands. For the latter, $\gamma$ decay occurs in general after the recoil ions have exited the thin target and when they are traveling in vacuum at a constant speed. For the former, however, $\gamma$ decay occurs mostly when the recoil ions are still inside the target while their speed is being slowed down by the target material. The slowing-down time can then be used as a "clock" to measure the lifetime of each superdeformed state with the Doppler shift attenuation method (DSAM). Due to their very large transition quadrupole moments, and correspondingly very short lifetimes, the $\gamma$-ray peaks associated with these transitions are always completely shifted. In addition, these transitions are also very weak, and therefore, it is difficult to determine the lifetimes of superdeformed states individually. An average lifetime of the decay sequence, however, can be determined using the centroid shift method.

In the analysis process, the data are first gain matched and corrected for Doppler shifts associated with the average recoil velocity $v_R$ of the recoiling ion while traveling in the vacuum. This velocity was determined experimentally to be $v_R = 0.0306c$ for the four-proton evaporation channel. The Doppler-corrected data are then sorted into two matrices, one requiring the coincidence between a forward-angle detector and any other detector, and the other requiring the coincidence between a backward-angle detector and any other detector. The forward-angle detectors consist of five Ge’s at $31.7^\circ$, five Ge’s at $37.4^\circ$, and the backward detectors consist of five Ge’s at $162.7^\circ$, four Ge’s at $148.3^\circ$, and five Ge’s at $142.6^\circ$ with respect to the beam direction. When gating on clean transitions of SD band 1, the forward- and backward-
angle spectra show that the $\gamma$-ray peaks are shifted to slightly larger energies in the forward-angle spectrum, and to slightly lower energies in the backward-angle spectrum. Such ‘residual shifts’ exist because the SD transitions are emitted when the recoiling ions are traveling at a velocity higher than the out-of-the-target velocity ($v_R=0.306c$) that is used for the Doppler correction. Therefore, the Doppler shifts of peaks associated with the SD bands are undercorrected, resulting in the so called ‘residual shifts.’

The ‘residual’ energy-shift, $\Delta E_\gamma = E_\gamma(\text{forward}) - E_\gamma(\text{backward})$, of the $\gamma$-ray peaks in spectra are extracted for all transitions in SD band 1, and then converted to the total energy shift (without any Doppler correction) $\delta E$. The total energy shifts are then used to calculate the instantaneous recoil velocity, $\beta(t) = v/c$, according to the following equation:

$$\beta(t) = \frac{\delta E}{E_0(\cos \theta_f - \cos \theta_b)}.$$  
(1)

where $\cos \theta_f$ is the average of the cosines of the angles of the forward-angle detectors, and $\cos \theta_b$ is that of the backward-angle detectors. The ratio $F(\tau)$ of the instantaneous recoil velocity $v(t)$ and the maximum recoil velocity $v_m$ is then obtained:

$$F(\tau) = v/v_m = \beta(t)\beta_m,$$  
(2)

where the maximum recoil velocity $v_m=0.0325c$ is calculated according to the kinematics of the reaction.

The experimental $F(\tau)$’s for transitions in the superdeformed band 1 are plotted in Fig. 4 as a function of $\gamma$-ray energy. These data are compared with the calculated $F(\tau)$’s with different average quadrupole moments, shown in solid curves. The calculations were carried out using the program LINESHAPE [14] modified for centroid shift analysis. The program determines the lifetime of a state by comparing the $\gamma$ decay with the time-dependent velocity distribution of the recoiling ions while they are slowed down in the target. The slowing down process is the result of interactions between the recoiling ions and the electrons in the target (electronic stopping power), and that of the nucleus-nucleus collisions (nuclear stopping power). In the calculation, the electronic stopping power is taken from the tabulated values of Ref. [15], and corrected for atomic shell effect according to measured [16] stopping powers for He ions in the target material.

The nuclear scattering contribution is less important for ions traveling at high speeds. Since the decay of SD states occurs in the thin target when the recoil ion is traveling at a relatively high speed, nuclear stopping power is practically negligible in this analysis. For example, a Monte Carlo simulation shows that for the current reaction each recoiling ion on average only has a 2% probability of having one nucleus-nucleus collision while traveling through the thin target. As a result, the calculated velocity distributions are primarily based on the electronic stopping powers. The program then uses these velocity distributions to calculate theoretical $F(\tau)$’s by assuming that all states in the SD band have the same $Q_I$. For side feeding, the program assumes a rotational sequence of five levels feeding into each state of interest. The quadrupole moment $Q_t$ and moment of inertia of these side feeding sequences are assumed to be the same as those of the SD band. The uncertainty associated with such assumptions is not included in the final results, but is expected to be small. The time structure of the unobserved transitions at the top of the band was simulated by including a rotational top-feeding sequence on top of the SD band. The quadrupole moment of this top-feeding sequence is assumed to be the same as the SD band. When varying the number of levels in this top-feeding sequence, it was found that the two-level top-feeding sequence gives the best fit. Therefore, the final results were obtained using the two-level top-feeding sequence.

From the comparison of experimental data with calculated $F(\tau)$’s, it was found that the theoretical curve of an average $Q_t=4.5e$ b fits the data with the smallest $\chi^2$. Thus the quadrupole moment of the SD band 1 in $^{82}$Sr is estimated to be $Q_t = 4.5 \pm 0.9e$ b (see Fig. 4).

In order to illustrate the difference of deformation between the superdeformed and normally deformed bands, the experimental $F(\tau)$’s have also been extracted for the highest spin transitions of one of the normally deformed bands, the yrast band. These data points are shown in Fig. 4 as closed squares. Indeed, the figure shows that for transition energies up to 2.2 MeV, the $F(\tau)$’s for the normally deformed band are substantially smaller than those for the superdeformed band. More accurate results of lifetime measurements for the normally deformed bands were extracted from the backed-target experiment and are described in the following subsection.

B. Analysis and results of backed-target data

The 17 million backed-target events (gated on $4p$ channel) were sorted into forward- and backward-angle matrices defined in the same way described in the previous subsection. These matrices are used to extract lifetimes of high-spin states in normally deformed bands in $^{82}$Sr. A partial level
scheme of normally deformed rotational bands of \(^{82}\)Sr is shown in Fig. 5 [10]. The cleanest gates on transitions of the lower-spin part of three normally deformed bands [the yrast band, the \((-1,1)\) band, and the \((-1,0)\) band] were selected and the sum of these spectra were used for line shape analysis. An example of backward-angle versus forward-angle spectra is shown in Fig. 6. The line shapes of the \(\gamma\)-ray peaks were least-square fitted to extract lifetimes.

The program LINESHAPE [14] was used to calculate velocity distributions and fit the line shapes. The calculation of velocity distribution of the recoil ions takes into account both the electronic stopping power and the nuclear stopping power. For electronic stopping, the calculation uses tabulated [15] values as described in the previous subsection. Since the thick target and backing completely stop the recoil ions, the nuclear stopping power is non-negligible, especially at lower recoil velocities. The calculation uses a multiple Coulomb scattering formalism [17] to simulate the nuclear scattering contribution to the stopping power. The Monte Carlo simulation treats the electronic stopping as a continuous process, assuming that discrete nuclear collisions occur at a rate given by the Lindhart [17] cross section. The final velocity distribution seen by the forward- and backward-angle detectors as a function of time is obtained from 10,000 histories.

Since the spectra used for the line shape analysis were the sum of clean spectra gated below the states of interest, contributions of time delay from side feedings must be taken into account. The side feeding intensities were obtained from experimentally determined relative intensities. The time structure of side feeding was modeled by assuming a two-level rotational side feeding sequence for each state. Each side feeding sequence has a constant dynamic moment of inertia and quadrupole moment. The side feeding quadrupole moments can be fitted simultaneously with the in-band transition quadrupole moments, whereas the \(J^{(2)}\) moments of inertia of the side feeding sequences are fixed during the fitting. In the analysis, the moment of inertia was chosen to be 25 \(h^2/\text{MeV}\). A 20% variation of this value proved to have little influence on the values of the fitted in-band quadrupole moments.

Examples of fitted spectra for the three normally deformed bands are shown in Fig. 7. From the analysis, lifetimes of six states in the yrast band, seven states in the \((-1,1)\) band, and six states in the \((-1,0)\) band were extracted and tabulated in Table I. These lifetimes are converted into transition quadrupole moments using the following equation:

\[
Q_t^2 = \frac{16\pi}{5} \times \frac{1}{\tau} \times \frac{1}{1+\alpha} \times [12.3E_y^{5}(I|K20|I-2K)^2]^{-1}
\]

where \(Q_t\), \(E_y\), and lifetime \(\tau\) are in units of e b, MeV, and ps, respectively. \(\alpha\) is the total internal conversion coefficient.
The resulting transition quadrupole moments are plotted in $K$ bands. These although one should note that the experimental uncertainty is slightly smaller than the predicted quadrupole deformation, $\sim 5.2$ e b [4] and $Q_t = 4.5$ e b for $^{84}$Zr and $^{82}$Sr, respectively. The measured quadrupole moment for the SD band in $^{84}$Zr is about 16% larger than that in $^{82}$Sr and $^{83}$Y. According to a theoretical analysis [18] of $^{84}$Zr, the yrast superdeformed band in $^{84}$Zr also has the $\nu^2 \pi^3$ configuration. Therefore, in terms of intruder-orbital excitations, $^{84}$Zr and $^{82}$Sr are the same. Thus the larger deformation measured in $^{84}$Zr seems to be unrelated to the excitation of the shape-driving, $h_{11/2}$ intruder orbitals. It is possible, however, that this small shape difference is caused by the occupation of the proton $[431]1/2^+$ orbital in $^{84}$Zr as opposed to $^{82}$Sr. The proton $[431]1/2^+$ orbital has marginal shape-driving force, although not as drastic as the $N = 5$ intruder orbitals, and thus the occupation of this orbital in $^{84}$Zr could result in a larger deformation.

A recent systematic analysis [20] based on preliminary results of measured quadrupole moments of superdeformed bands in $^{80,81,82}$Sr shows that the quadrupole moment of the SD band in $^{82}$Sr is the largest among these Sr isotopes. This may be an indication of the important role played by the $N = 44$ superdeformed shell gap. For $^{80,81}$Sr, the neutron Fermi levels are moving away from the $N = 44$ gap, thus the contribution of the neutron shell gap is lessened, resulting in a smaller deformation.

B. Lifetimes of the normally deformed bands

Lifetimes of 19 levels in three rotational bands were measured for $^{82}$Sr. Figure 8 shows the measured transition quadrupole moments $Q_t$ as a function of spin for the positive-parity, yrast band (closed circles), the negative-parity, $\alpha = 0$ band (triangles), and the negative-parity, $\alpha = 1$ band (diamonds) in $^{82}$Sr.

The positive-parity, yrast band. Lifetimes of the low-spin portion ($I = 4–10\hbar$) of the positive-parity, yrast band in $^{82}$Sr have been measured previously [21] with the recoil distance method (RDM), which gives an average $Q_t$ of about 2.5 e b. Another previous study [9] extended the lifetime measurement of this band to spin 18 with the DSAM method. Our new measurement covers the spin range of $I = 12–22$, see Fig. 8. From spin 12 to 18, our measurements overlap with those of Ref. [9] within the experimental uncertainties. A previous theoretical analysis [8] suggests that for spins $I > 14\hbar$, the positive-parity, yrast band has a four quasiparticle nature with a pair of $g_{9/2}$ protons and a pair of $g_{9/2}$ neutrons excited, and has an oblate shape with deformation $\beta_2 = 0.22$, $\gamma = -50^\circ$. Using the equation

$$Q_t = \frac{6ZeA^{2/3}}{(15\pi)^{1/2}F^*(0)\beta_2(1 + 0.36\beta_2)\cos(30^\circ + \gamma)},$$

these deformation parameters correspond to a quadrupole moment of $Q_t \approx 2.6$ e b. This agrees well with the average value of measured $Q_t$'s for states with $I = 12–18\hbar$, see Fig. 8.

III. DISCUSSION

A. Lifetimes of the superdeformed band

The yrast superdeformed band in $^{82}$Sr has been interpreted [2] as having the $\nu^2 \pi^3$ configuration, i.e., the excitation of two $N = 5$, $h_{11/2}$ intruder neutrons, which corresponds to the $N = 44$ shell gap with a large deformation, and a single proton excitation of the $N = 5$, $h_{11/2}$ intruder orbital. The predicted $[2]$ deformation for this band is $\beta_2 = 0.55$, $\gamma = 0^\circ$. Our measured average quadrupole moment for the yrast superdeformed band of $^{82}$Sr is $Q_t = 4.5 \pm 0.9$ e b, which corresponds to $\beta_2 \approx 0.49$ when $\gamma = 0^\circ$ is assumed. This is slightly smaller than the predicted quadrupole deformation, although one should note that the experimental uncertainty is rather large.

A more interesting feature is observed when comparing the measured deformation of the yrast superdeformed band in $^{82}$Sr with that of its isotones $^{84}$Zr and $^{83}$Y. Figure 9 shows a comparison of the experimental $F(\tau)$'s of the SD band in $^{82}$Sr with that of the SD band in $^{84}$Zr [4] and in $^{83}$Y [19]. Although all three measurements have large uncertainties, the $F(\tau)$'s for $^{84}$Zr are systematically larger than those for $^{82}$Sr and $^{83}$Y. The two solid curves shown in Fig. 9 are calculated $F(\tau)$'s which fit the $^{84}$Zr and $^{82}$Sr data sets with the smallest $\chi^2$, corresponding to $Q_t = 5.2$ e b [4] and $Q_t = 4.5$ e b for $^{84}$Zr and $^{82}$Sr, respectively. The histograms are experimental data and smooth curves are least-square fitted line shapes.

FIG. 7. Examples of fitted line shapes for the normally deformed bands: The 1004 keV transition in the $(-0)$ band shown in (a) and (b); the 1116 keV transition in the yrast band shown in (c) and (d); and the 1178 keV transition in the $(-1)$ band shown in (e) and (f). The histograms are experimental data and smooth curves are least-square fitted line shapes.
TABLE I. Measured lifetimes $\tau$, transition quadrupole moments $Q_t$, and side feeding quadrupole moments $Q_s$, for three normally deformed bands in $^{82}\text{Sr}$.

<table>
<thead>
<tr>
<th>$I^+_i$</th>
<th>$E_y$ (keV)</th>
<th>$\tau$ (ps)</th>
<th>$Q_t$ (e b)</th>
<th>$Q_s$ (e b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Yrast band</td>
<td></td>
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<tr>
<td>4$^+$</td>
<td>820.3</td>
<td>1.90$^{+0.50}_{-0.27}$</td>
<td>2.43$^{+0.40}_{-0.27}$</td>
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<tr>
<td>6$^+$</td>
<td>840.2</td>
<td>0.90$^{+0.50}_{-0.27}$</td>
<td>2.61$^{+1.30}_{-0.52}$</td>
<td></td>
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<tr>
<td>8$^+$</td>
<td>786.2</td>
<td>1.00$^{+0.50}_{-0.27}$</td>
<td>2.63$^{+1.10}_{-0.48}$</td>
<td></td>
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<tr>
<td>10$^+$</td>
<td>801.0</td>
<td>1.30$^{+0.30}_{-0.23}$</td>
<td>2.32$^{+0.32}_{-0.23}$</td>
<td></td>
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<tr>
<td>12$^+$</td>
<td>1003.1</td>
<td>0.58$^{+0.14}_{-0.10}$</td>
<td>2.07$^{+0.21}_{-0.21}$</td>
<td></td>
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<tr>
<td>14$^+$</td>
<td>1116.5</td>
<td>0.36$^{+0.09}_{-0.08}$</td>
<td>1.99$^{+0.26}_{-0.21}$</td>
<td></td>
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<tr>
<td>16$^+$</td>
<td>1268.4</td>
<td>0.26$^{+0.08}_{-0.07}$</td>
<td>1.68$^{+0.28}_{-0.20}$</td>
<td></td>
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<tr>
<td>18$^+$</td>
<td>1425.7</td>
<td>0.13$^{+0.06}_{-0.04}$</td>
<td>1.75$^{+0.31}_{-0.31}$</td>
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<tr>
<td>20$^+$</td>
<td>1634.6</td>
<td>0.10$^{+0.04}_{-0.03}$</td>
<td>1.48$^{+0.28}_{-0.23}$</td>
<td></td>
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<tr>
<td>22$^+$</td>
<td>1886.0</td>
<td>0.15$^{+0.18}_{-0.07}$</td>
<td>0.81$^{+0.28}_{-0.26}$</td>
<td></td>
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<tr>
<td>The ($-1,1$) band</td>
<td></td>
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<tr>
<td>5$^-$</td>
<td>415.6</td>
<td>4.40$^{+0.80}_{-1.14}$</td>
<td>1.79$^{+0.19}_{-0.14}$</td>
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</tr>
<tr>
<td>11$^-$</td>
<td>941.3</td>
<td>0.43$^{+0.15}_{-0.10}$</td>
<td>3.00$^{+0.42}_{-0.42}$</td>
<td></td>
</tr>
<tr>
<td>13$^-$</td>
<td>1059.0</td>
<td>0.27$^{+0.09}_{-0.07}$</td>
<td>2.72$^{+0.41}_{-0.35}$</td>
<td></td>
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<tr>
<td>15$^-$</td>
<td>1178.0</td>
<td>0.23$^{+0.06}_{-0.05}$</td>
<td>2.21$^{+0.30}_{-0.24}$</td>
<td></td>
</tr>
<tr>
<td>17$^-$</td>
<td>1297.6</td>
<td>0.15$^{+0.04}_{-0.04}$</td>
<td>2.13$^{+0.31}_{-0.28}$</td>
<td></td>
</tr>
<tr>
<td>19$^-$</td>
<td>1416.0</td>
<td>0.11$^{+0.03}_{-0.03}$</td>
<td>1.97$^{+0.28}_{-0.22}$</td>
<td></td>
</tr>
<tr>
<td>21$^-$</td>
<td>1540.0</td>
<td>0.08$^{+0.03}_{-0.02}$</td>
<td>1.91$^{+0.31}_{-0.30}$</td>
<td></td>
</tr>
<tr>
<td>23$^-$</td>
<td>1696.0</td>
<td>0.04$^{+0.03}_{-0.01}$</td>
<td>2.06$^{+0.30}_{-0.22}$</td>
<td></td>
</tr>
<tr>
<td>25$^-$</td>
<td>1921.0</td>
<td>0.04$^{+0.01}_{-0.01}$</td>
<td>1.50$^{+0.23}_{-0.21}$</td>
<td></td>
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<tr>
<td>The ($-0,0$) band</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>8$^-$</td>
<td>693.9</td>
<td>3.80$^{+0.60}_{-0.16}$</td>
<td>2.32$^{+0.21}_{-0.16}$</td>
<td></td>
</tr>
<tr>
<td>10$^-$</td>
<td>875.9</td>
<td>1.02$^{+0.26}_{-0.28}$</td>
<td>2.62$^{+0.32}_{-0.28}$</td>
<td></td>
</tr>
<tr>
<td>12$^-$</td>
<td>1004.2</td>
<td>0.57$^{+0.15}_{-0.12}$</td>
<td>2.31$^{+0.30}_{-0.26}$</td>
<td></td>
</tr>
<tr>
<td>14$^-$</td>
<td>1152.2</td>
<td>0.21$^{+0.04}_{-0.05}$</td>
<td>2.47$^{+0.25}_{-0.25}$</td>
<td></td>
</tr>
<tr>
<td>16$^-$</td>
<td>1310.5</td>
<td>0.19$^{+0.04}_{-0.04}$</td>
<td>1.85$^{+0.22}_{-0.18}$</td>
<td></td>
</tr>
<tr>
<td>18$^-$</td>
<td>1464.0</td>
<td>0.16$^{+0.04}_{-0.07}$</td>
<td>1.51$^{+0.26}_{-0.24}$</td>
<td></td>
</tr>
<tr>
<td>20$^-$</td>
<td>1538.0</td>
<td>0.09$^{+0.04}_{-0.02}$</td>
<td>1.77$^{+0.29}_{-0.31}$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Recoil distance measurement from Ref. [21].
$^b$DSAM measurement from Ref. [9].

At higher spins, the $Q_t$'s decrease with increasing spin, indicating a decrease of collectivity. In fact, band termination has been suggested [10,11] for a number of bands in $^{82}\text{Sr}$. An alternative explanation is that the high spin states are strongly mixed and the decay strength is highly fragmented, resulting in a reduced $Q_t$'s. A more detailed description of such mixing and fragmentation of decay from a microscopic calculation is given in Sec. III C.

The negative-parity bands. Lifetimes of the negative-parity bands in $^{82}\text{Sr}$ were measured by Tabor et al. [9], from spin 11 to 19 for the ($-1,1$) band and from spin 10 to 16 for the ($-0,0$) band. Our new measurement covers the spin range of $I=13$ to $25\hbar$ for the ($-1,1$) band and from $I=10$ to $20\hbar$ for the ($-0,0$) band. For the states which our measurements overlap with those of Ref. [9], the two results agree with each other within experimental uncertainties. The negative-parity bands in $^{82}\text{Sr}$ have been suggested [8] to have a two-quasiproton configuration at low spin with a pair of $g_{9/2}$ protons excited. The deformation of such a configuration is predicted to be triaxial with $\beta_2 = 0.28$ and $-30^\circ < \gamma < -20^\circ$, which corresponds to a quadrupole moment of about $3\varepsilon$ b. This qualitatively agrees with the average $Q_t$ value of $-2.8\varepsilon$ b from our measurement and that of Ref. [9] for the $10^-$ and $11^-$ states of the negative-parity bands. For the spin range of $I=15$ to $23\hbar$, the average $Q_t$ for the two negative-parity bands is about $2\varepsilon$ b. This reduction of $Q_t$ may be an indication of a shape change as a result of the neutron $g_{9/2}$ alignment discussed in Ref. [8]. The aligned $g_{9/2}$ neutrons are expected to drive the nucleus toward a nearly oblate shape. At the highest spins, both negative-parity bands start to show a decrease in $Q_t$. This occurs at the frequency where the next proton alignment is suggested [8] to take place. It is not clear, however, whether the decrease of $Q_t$ is the result of this alignment or an indication of band termination.

C. A microscopic calculation for the positive-parity bands

In order to understand the measured quadrupole moments from a microscopic point of view, we carried out theoretical
calculations by using the complex version of the excited Vampir model [22]. In this calculation, general symmetry-projected Hartree-Fock-Bogoliubov (HFB) quasiparticle determinants are used as trial configurations. The mean fields and the configuration mixing are determined by chains of variational calculations with symmetry projection before variation. The effective Hamiltonian and the model space used for the present investigation are the most adequate ones adjusted for the $A \approx 70$ mass region employing complex HFB transformations. This Hamiltonian results in a consistent microscopic picture for a few $N=Z$ nuclei from Kr to Mo [23,24]. For the effective two-body interaction the renormalized $G$ matrix from Ref. [23] is taken.

The positive-parity states up to spin $26^+$ in $^{82}$Sr were investigated. The yrast state of a given spin and parity was constructed by using intrinsically prolate and oblate deformed trial configurations and then selecting the most bound ones, and the optimal representation of the yrast states were obtained from single symmetry projected HFB quasiparticle determinants. For all investigated states from spin $0^+$ to $16^+$ the first minimum is oblate deformed. The excited Vampir approach was used to construct each additional excited state. Finally the residual interaction between the various solutions with the same symmetry was diagonalized. In cases where many states occurred in a small excitation energy interval, suggesting the possible mixing of configurations, the dimension of the model basis was increased up to 10. For the lowest spin states up to $6^+$ four states have been built for each spin.

Our calculated wave functions show that the yrast states below $I<16h$ have prolate shapes with small (less than 10%) admixture of oblate configurations. For higher spin states, especially for states with $I>18h$, the mixing becomes stronger, and the level density becomes larger. (For example, the main determinants for the $16^+$ states belonging to the oblate sequences labeled as $o_2$, $o_3$, and $o_4$ in Fig. 10 represent 60 to 80% of the total wave function.) The high level density and the strong mixing of states result in a very complicated decay pattern as seen in Fig. 10. Here the states are organized in bands according to the $B(E2)$ values connecting these states. Table II summarizes the $B(E2)$ values of decaying branches with significant strength. To illustrate the collectivity of these states, the $B(E2)$’s of branches which are not shown in Fig. 10 are shown in brackets in Table II.

For comparison, experimental $B(E2)$’s converted from ex-
TABLE II. $B(E2,I\rightarrow I-2)$ values (in $e^2\text{fm}^4$) for the low-lying positive-parity states of various configurations ($p_1-p_4$, $o_1-o_4$) in $^{82}\text{Sr}$, calculated with the excited Vampir approximation. Effective charges of $e_p=1.5$ and $e_n=0.5$ have been used. The strengths for the secondary branches are given in parentheses and the spin indicates the initial state of the transition. For transitions not shown in Fig. 10, the $B(E2)$ strengths are given in brackets. For comparison, experimental $B(E2)$ values (converted from experimental $Q_t$'s, see also Table I) for the yrast band are given in the last column.

| $I$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $o_1$ | $o_2$ | $o_3$ | $o_4$ | Expt.
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 4$^+$ | 1169 | [118]$o_3$ | 292 | [146]$p_1$ | | | | | $1678\pm391$
| | | 1885 | | [41]$p_3$ | | | | | $1622\pm578$
| 6$^+$ | 1682 | 1854 | 1151 | | | | | | $2132\pm1502$
| 8$^+$ | 1503 | | 2089 | | | | | | $2266\pm1341$
| (249)$p_3$ | | 1781 | | | | | | | $1811\pm353$
| 10$^+$ | 1557 | 971 | | | | | | | $1373\pm254$
| (340)$p_3$ | [138]$p_1$ | | | | | | | | $1468\pm301$
| 12$^+$ | 1603 | 1344 | 1924 | 728 | | | | | $1468\pm301$
| [94]$o_3$ | (189)$p_3$ | | | | | | | | $1080\pm270$
| | [76]$p_1$ | | [84]$p_2$ | | | | | | $777\pm208$
| 14$^+$ | 1492 | 1176 | 1980 | 1608 | | | | | $1373\pm254$
| [145]$p_2$ | [197]$p_1$ | | | | | | | | $988\pm233$
| 16$^+$ | 1428 | 1331 | 1888 | 448 | 1748 | | | | $988\pm233$
| (112)$o_3$ | | | | | | | | | $1070\pm166$
| 18$^+$ | 1174 | 1074 | 1812 | 739 | 1727 | [220]$p_2$ | | | $1080\pm270$
| [117]$o_3$ | | | [61]$p_3$ | | | | | | $777\pm208$
| | | | [137]$o_3$ | | | | | | $777\pm208$
| 20$^+$ | 697 | 1554 | 762 | 1142 | 979 | 959 | | | $234\pm114$
| | | | (669)$o_4$ | | | | | | $959\pm106$
| | | | [137]$o_3$ | | | | | | $234\pm114$
| 22$^+$ | 876 | [126]$p_3$ | 880 | 1458 | 959 | 959 | | | $234\pm114$
| | | | (236)$p_3$ | | | | | | $959\pm106$
| | | | [148]$o_3$ | | | | | | $234\pm114$
| 24$^+$ | 738 | 410 | 424 | 1513 | 1842 | | | | | $234\pm114$
| (191)$p_3$ | (397)$p_3$ | (316)$p_3$ | (278)$p_4$ | | | | | | $234\pm114$
| | [106]$p_2$ | | | | | | | | $234\pm114$
| 26$^+$ | 1135 | 521 | 1161 | | | | | | | $234\pm114$
| | | | (512)$o_4$ | | | | | | $234\pm114$
| | | | (246)$o_3$ | | | | | | $234\pm114$
| 28$^+$ | 918 | 863 | 1310 | | | | | | | $234\pm114$
| | | | [159]$o_3$ | | | | | | $234\pm114$
| | | | [233]$p_1$ | | | | | | $234\pm114$

Experimental $Q_t$'s (see Table I) are also given in Table II. The dotted lines in Fig. 10 indicate $M1,\Delta I=0$ transitions with $B(M1)$ values varying between 50 and 500 mWu, which make the decay pattern of the high spin states even more complex. Figure 10 and Table II show that the strong mixing of states which are intrinsically oblate deformed produces a strong fragmentation of the total $B(E2)$ strength for high spin states. Such a highly fragmented decay pattern could be a theoretical explanation for the experimentally measured decreasing $Q_t$ values as a function of spin. Finally, it is worth noting that our calculations do not indicate any sudden decrease in the pairing energy, either in the form of like-nucleon or proton-neutron pairs.

IV. CONCLUSION

High spin states in $^{82}\text{Sr}$ were populated using the $^{58}\text{Ni}(^{38}\text{Si},4p)$ reaction. The experiment was performed at the Lawrence Berkeley National Laboratory using the Phase I array of Gammasphere in conjunction with the Microball. The experiment failed to confirm the excited SD band identified by an earlier study [2], but confirmed the yrast SD band. Lifetimes of this yrast SD band were measured using the centroid shift method, and an average quadrupole moment of $Q_t=4.5\pm0.9$ e fm$^2$ was derived from the measurement. This value is slightly smaller than the predicted deformation and that of the SD band in $^{84}\text{Zr}$. The latter may be the result of the occupation of proton [431]1/2$^+$ orbital in $^{84}\text{Zr}$. Lifetimes of high spin states in three normally deformed bands in $^{82}\text{Sr}$ are also measured using the DSAM technique. At medium high spins, these measured results agree with the previous lifetime measurements, as well as the predicted deformation parameters, which correspond to multiquasiparticle excitations. At the highest spins, both the yrast band and the ($-1$) band show a decrease of $Q_t$ as a function of spin. This
may be a supporting evidence for band terminations which are predicted by theory and suggested by previous spectroscopy studies. An alternative explanation is given by a microscopic calculation based on the excited Vampir approximation. This calculation suggests that for the positive-parity band, the mixing of configurations at high spin results in large fragmentation of decay paths, which reduces the $B(E2)$ strengths and may explain the observed smaller $Q$, values at high spin.

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