Linear polarization measurements and negative-parity states in ^{80}Sr

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High-spin states in ^{80}Sr were studied using the ^{54}Fe(^{28}Si, $2p$) reaction at 90 MeV and the ^{58}Ni(^{28}Si, $\alpha 2p$) reaction at 110 MeV. Prompt γ-γ coincidences were measured from the ^{54}Fe(^{28}Si, $2p$) reaction using an array of 10 Compton-suppressed Ge detectors. γ-ray linear polarizations were measured in both reactions using three clover detectors as Compton polarimeters. Negative parity has been conclusively assigned to one band and is favored for two others based on the polarization measurements and the observation of six new linking transitions between the bands near their band heads. This evidence supports a picture of strong mixing between low-lying states with negative parity, similar to what has been observed in ^{82}Sr. Directional correlation of oriented nuclei ratios support the spin assignments made in the most recent in-beam study.

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Despite extensive experimental and theoretical study, uncertainties still remain in the spins and parities of several low-lying nonyrast states in ^{80}Sr. Although the situation has recently been improved by thorough spectroscopy both in-beam [1] and following the β decay of ^{80}Y [2], the most recent level scheme of ^{80}Sr still shows uncertain spin and/or parity assignments for even the lowest states in five of seven observed band structures [1]. Included in these are states in a band (labeled SB3 in Ref. [1]), which has been observed to high spin in several previous studies [1,3,4], in which there are only tentative spin assignments and a completely open parity assignment. Adding to the uncertainty are conflicting results from angular distribution measurements [1,3,4] for transitions near the bottom of this band and others. Although the very clean channel selection provided by the most recent in-beam study [1] has helped to clarify the disagreements among some of the existing angular distribution measurements, this experiment was not designed to measure parity directly.

One experimental method that has yet to be brought to bear on the spin-parity puzzle in ^{80}Sr is a measurement of the linear polarization of the γ-ray transitions. Because there are several known [1–4] linking transitions between states belonging to excited configurations and states in the ground-state band (GSB), which clearly has positive parity, such a measurement could in principle determine the multipolarity of these transitions when used in conjunction with angular distribution results and thus determine the parity of the parent state in the transition. Therefore, the goal of the present work was to measure the linear polarizations of as many transitions in ^{80}Sr as possible, with a particular emphasis on the important interband linking transitions. In addition, very weak γ-ray coincidences (with peak intensities on the order of 1% or less of the $2^+ \rightarrow 0^+$ GSB transition) were investigated to search for more interband linking transitions between known excited states in an attempt to infer spins and parities from selection-rule and transition probability arguments. Directional correlation of oriented nuclei (DCO) ratios were also remeasured for some transitions in order to provide additional evidence for the current spin assignments.

High-spin states in ^{80}Sr were produced following the ^{54}Fe(^{28}Si, $2p$) reaction at 90 MeV and the ^{58}Ni(^{28}Si, $\alpha 2p$) reaction at 110 MeV using the John D. Fox superconducting accelerator at Florida State University (FSU). The ^{54}Fe(^{58}Ni) target was $14 \text{mg/cm}^2 (40 \text{mg/cm}^2)$ thick, and both targets were isotopically enriched to 99%. Prompt γ-γ coincidences were measured from the ^{54}Fe(^{28}Si, $2p$) reaction using the FSU array of 10 Compton-suppressed germanium (Ge) detectors, which included three clover detectors positioned at 90° relative to the beam direction.

The linear polarization measurements used the three clover detectors as Compton polarimeters [5] placed at an average distance of about 24.5 cm from the target. In the ^{54}Fe(^{28}Si, $2p$) coincidence experiment, the data acquisition system recorded signals from each of the four Ge crystals in each clover detector whenever at least two fired in coincidence with at least one other detector in the array. The energies measured by each crystal pair were added and sorted into one of two square coincidence matrices depending on whether they represented a perpendicular or parallel scattering event relative to the beam direction. Spectra representing either

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TABLE I. Theoretical angular distribution coefficients a_2 and a_4, mixing ratios δ, experimental (P_{exp}) and theoretical (P_{thy}) linear polarizations, and DCO ratios R_{DCO} for selected transitions in ^{80}Sr. The sign of δ follows the convention of Ref. [12].

E_γ (keV)	I_i^π	I_f^π	a_2[a]	a_4[a]	δ[b]	P_{exp}	P_{thy}[c]	R_{DCO}	σL[d]
725	5^+	3^+	0.289	−0.062	0	0.44(23)	0.48	1.43(7)	$E2$
799	9^-	7^-	0.358	−0.108	0	0.69(44)	0.60	0.90(13)	$E2$
970	11^-	9^-	0.364	−0.115	0	0.85(74)	0.61		$E2$
1185	3^+	2^+	0.162	0.006	−0.45(8)[e]	−0.18(39)	−0.30	1.01(5)	$M1/E2$
1817	7^-	6^+	−0.238	0.000	0	0.54(30)	0.32	0.53(9)	$E1$
1839	7^-	6^+	−0.238	0.000	0	0.52(40)	0.32	0.59(8)	$E1$
1917	5^-	4^+	−0.203	0.000	0	0.49(46)	0.28	0.68(9)	$E1$

[a]Theoretical result at the value of δ given in the same row.
[b]Assumed to be 0 for $E1$ transitions.
[c]Calculated using the a_2, a_4, and δ values given in the same row.
[d]Multipolarity of the transition.
[e]From Ref. [4].

perpendicular or parallel scattering were then obtained from background-subtracted gates projected from these square matrices. The ^{58}Ni(^{28}Si, $\alpha 2p$) "singles" experiment recorded only the Compton-scattered events between the individual crystals of each clover detector whenever at least two fired, without the coincidence requirement with another detector signal (and thus the perpendicular and parallel scattering events were sorted directly into separate one-dimensional histograms). In both experiments, the sorting software was used to process only those events that involved a nondiagonal pair of clover crystals.

The experimental linear polarizations P_{exp} were calculated from the perpendicular ($N_\perp$) and parallel ($N_\parallel$) scattering intensities according to Eq. (1) in Ref. [6]. An energy-independent relative normalization of $a(E_\gamma) = 1.001(16)$ was determined from a measurement of $N_\perp$ and $N_\parallel$ for the isotropic ($P_{exp} = 0$) lines of a ^{152}Eu source, consistent with a previous measurement [6] using one of the three clover detectors used in this study. The functional form of the polarization sensitivity $Q(E_\gamma)$ was reproduced from the results of Ref. [5], which determined $Q(E_\gamma)$ for a similar clover detector. The quoted values of P_{exp} for the 1817-, 1839-, and 1917-keV transitions (see Table I) represent the weighted average (based on the measurement uncertainty) of the results from both experiments. All other P_{exp} values were obtained from the coincidence experiment only, as the associated lines in the singles spectra were either too weak or were contaminated by other decays. As a test of the method, the linear polarizations of known $E1$, $E2$, and mixed $M1/E2$ transitions in ^{79}Sr [7] and ^{80}Y [8] were measured [9] and found to be in good agreement with the theoretical expectation. Theoretical polarizations were calculated as a function of the multipole mixing ratio δ according to the formalism given in Refs. [10,11]. Because there is considerable variation in the measured a_2 and a_4 coefficients found in the literature [1,3,4], the theoretical polarizations were calculated using purely theoretical a_2 and a_4 values as a function of δ using the formalism and sign conventions of Rose and Brink [12] and the spin changes given in Ref. [1]. A similar technique was used to interpret the polarization measurements in ^{86}Nb [6]. This differs from another commonly used approach in which the measured a_2 and a_4 coefficients are used to calculate the theoretical polarization. However, the two methods converge to predict the same polarization at the value of δ that reproduces the experimental a_2 and a_4 values.

Spin changes were measured based on DCO ratios, defined according to Eq. (1) in Ref. [13]. One or more stretched $E2$ transitions were used as gates. In such cases, the DCO ratios for stretched $E2$ transitions as well as for pure dipole $\Delta I = 0$ transitions are expected to be approximately unity, whereas $\Delta I = 1$ transitions yield ratios of about 0.5 if the mixing ratio is small [14]. The measured polarizations and DCO ratios of selected transitions in ^{80}Sr are given in Table I. These measurements, along with the investigation of weak γ-ray coincidence relationships, were used to confirm and enhance the existing "in-beam" level scheme of ^{80}Sr [1]. A level scheme of low-lying states in ^{80}Sr, as deduced from the present work, is shown in Fig. 1.

The lowest nonyrast band (SB2 in Fig. 1) has been interpreted [1,2] as a γ vibrational band based on its strong similarity to other γ bands in several neighboring even-even nuclei [13,15,16]. Although there is some disagreement in the literature concerning the spin of the 1570-keV state [3], the spin assignments shown in Fig. 1 are supported by the results of three independent angular distribution measurements [1,4,17] and on the observed feeding and depopulation pattern resulting from the β decay of ^{80}Y [2]. The current study shows that the measured polarization of the 1185-keV decay from the 1570-keV state to the 386-keV state in the GSB is consistent with the theoretical expectation for a strongly mixed $M1/E2$ transition (no parity change) [4], as is the measured DCO ratio that is in excellent agreement with the previous measurement [4] (see Table I).

The band labeled SB1 in Fig. 1 was initially suggested to have positive parity [3,4], but negative parity was favored, although not proven, in the most recent high-spin work due to the observed angular distributions of the 1817- and 1839-keV transitions to the GSB, as well as from systematic and theoretical considerations. The very large mixing ratio of 4.7 (2.8) measured [4] for the 1817-keV (1839-keV) transition argued for highly mixed $M1/E2$ radiation, but as shown in Fig. 2 this

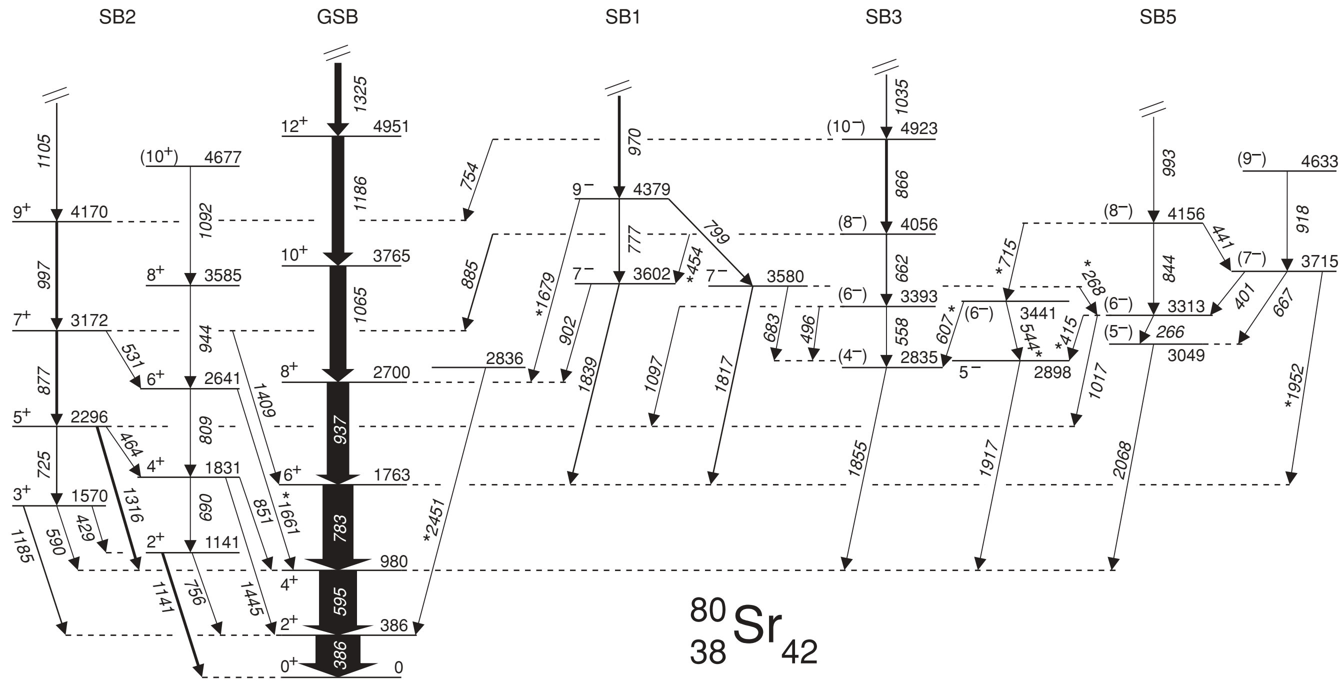

FIG. 1. The level scheme of ^{80}Sr below 5 MeV excitation energy as deduced from the present work. Transitions introduced in this work are indicated with asterisks. The energies of all other transitions as well as the labeling scheme of the decay sequences were taken from Ref. [1].

conclusion is inconsistent with the polarization measurement of the 1817-keV decay. The theoretical polarization curve for $M1/E2$ radiation (solid curve) is inconsistent with the measurement at all values of δ. However, $E1/M2$ radiation is consistent with the measurement over a wide range of δ, including very small values that would be most likely considering the approximate lifetime of the 3580-keV parent state [4]. This new measurement thus favors a 7^- assignment for the 3580-keV state. The polarization measurement of the 1839-keV decay does not, by itself, exclude the possibility of $M1/E2$ decay with a large positive mixing ratio because of a somewhat larger experimental uncertainty (see Table I).

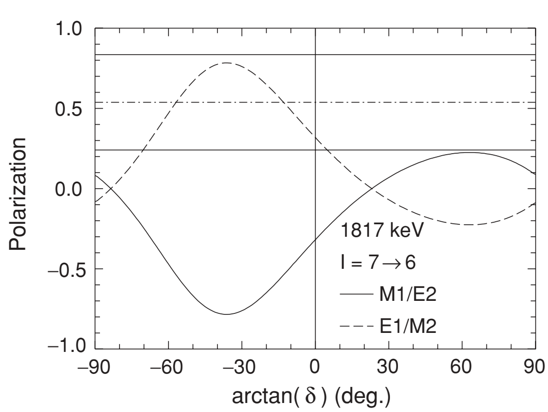

FIG. 2. The measured (dot-dashed line) and theoretically expected (solid and dashed curves) polarizations as a function of the multipole mixing ratio δ for the 1817-keV transition. The solid horizontal lines indicate the experimental uncertainty limits.

However, the $\Delta I = 2$ nature of the 799-keV transition assigns a spin-parity of 9^- to the 4379-keV state and, likewise, the $\Delta I = 2$ character of the 777-keV transition provides a 7^- assignment for the 3602-keV state. Together these results establish negative parity for SB1. The polarizations of the 799- and 970-keV transitions are consistent with $E2$, rather than $M2$, decay as expected (see Table I).

A similar decay pattern occurs near the bottom of the band labeled SB3 in Fig. 1, where two low-lying states decay to the 4^+ state in the GSB through the 1855- and 1917-keV transitions, although their intensities are weaker than the 1817- and 1839-keV decays and their mixing ratios have not been measured. The measured polarization of the 1917-keV decay is similar to that of the 1817- and 1839-keV transitions (see Table I), but the larger experimental uncertainty combined with the lack of a measured mixing ratio does not unambiguously distinguish $E1/M2$ from $M1/E2$ radiation for this decay. However, the observed [1] 683-keV $\Delta I = 2$ transition between the 7^- state at 3580 keV and the parent state of the 1917-keV decay at 2898 keV, confirmed in the present work, almost certainly requires negative parity for the 2898-keV state. The measured angular distribution [1] and DCO ratio (see Table I) of the 1917-keV decay strongly favor a $\Delta I = 1$ transition, and thus the 2898-keV state has been firmly assigned a spin-parity of 5^-.

The spin and parity of the 2835-keV state has been debated for some time and is important in assigning spin and parity values to other states in SB3. A (5^-) assignment was favored by one high-spin study [3] and the recent decay work [2], but a tentative spin of $I = (4)$, without a parity assignment, was suggested in the most recent in-beam study [1]. The angular distribution of the 1855-keV transition [1] favors a spin of

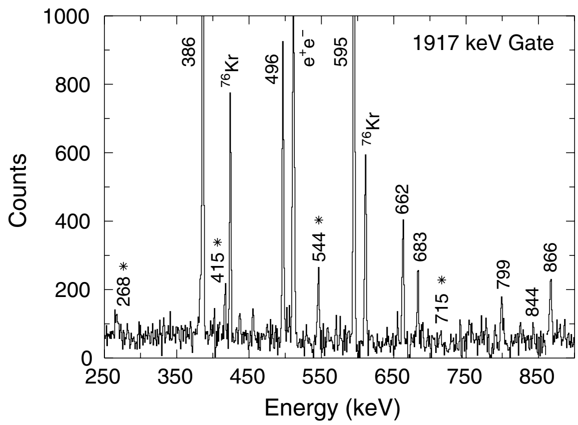

FIG. 3. A portion of the background-corrected γ-ray coincidence spectrum projected from a gate on 1917 keV, as measured by all detectors in the ^{54}Fe(^{28}Si, $2p$) reaction. New transitions placed in the ^{80}Sr level scheme are indicated with asterisks.

$I = 4$, and its DCO ratio of 1.16(25), measured for the first time in this work, is in agreement with this interpretation. However, a highly mixed $M1/E2$ transition cannot be ruled out because the 1855-keV decay was too weak to uniquely assign a multipolarity from the polarization measurement. Still, the available evidence favors a 4^- assignment for the 2835-keV state. The measured DCO ratio of 0.43(6) for the 496-keV transition between the 3393-keV state in SB3 and the 5^- state at 2898 keV strongly suggests $I = 6$ for the 3393-keV state, and thus an even-spin sequence for SB3, as suggested in Ref. [1]. Even-spin bands with similar decay patterns have been suggested [18] to have negative parity in several neighboring nuclei, and the observation of six new linking transitions between states near the bottom of bands SB1, SB3, and SB5 (see Figs. 1 and 3) potentially indicates strong mixing between states with like parity. The interband transitions between SB3 and positive-parity band SB2 that occur at higher spin (see Fig. 1), which could argue for positive parity for SB3, have also been observed between a similar even-spin negative-parity band and the positive-parity γ band in ^{82}Sr [16]. In addition, the negative a_2 coefficient measured [1] for one such transition, the 885-keV decay, is consistent with $E1$ decay. Thus SB3 is proposed to be an even-spin negative-parity band and under this interpretation is likely the even-spin signature partner to SB1. Note that the 386-keV GSB transition was observed to be in coincidence with a 2451-keV line, placing the parent state of the 2451-keV decay very close in energy to the 2835-keV state associated with SB3 (see Fig. 1). However, the 2451-keV decay was not observed to be in coincidence with any of the known transitions in SB3, and thus the parent state of the 2451-keV transition is very likely not the 2835-keV state in SB3.

Another high-spin sequence (labeled SB5 in Fig. 1) that has been suggested [1] to have negative parity is much more weakly populated than either SB1 or SB3, and thus the existing spin and parity assignments could not be verified from this study. However, the observation of the new 268- and 415-keV transitions that directly link states in this band to other states with a firm negative-parity assignment (see Fig. 1) is at least consistent with the suggestion of negative parity for SB5 and fits the picture of considerable mixing between states near the negative-parity band heads.

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