High spin states in ^{78}Sr

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^{78}Sr was produced in the reaction ^{58}Ni(^{24}Mg, $2p2n$) with a relative cross section of less than 2.5% of the total fusion cross section at 110 MeV, but high spin states up to $16\hbar$ were firmly identified. Fifteen neutron detectors and fifteen Compton suppressed Ge detectors were used in a large solid angle arrangement. $2n\gamma\gamma$ and $n\gamma\gamma$ coincidences were recorded. A small irregularity in the dynamic moment of inertia $J^{(2)}/\hbar^2$ is evidence for a strongly mixed band crossing at $\hbar\omega \approx 0.55$ MeV in agreement with what is observed in ^{80,82}Sr.

INTRODUCTION

The neutron deficient nuclei with $A \approx 80$ have been found to exhibit many interesting spectroscopic phenomena. Even-even Se isotopes have been found[1–4] to display shape coexistence effects at low spins and yet have good rotational behavior at higher spins. Shape coexistence effects are reduced in the even-even Kr isotopes[5–7] and apparently few or none are observed in the Sr (Refs. 8 and 9) and Zr (Ref. 10) isotopes. The shape coexistence effects in Se and Kr isotopes are reduced and larger deformations result when an odd proton or neutron is added to an even-even core.[11–16] The odd nucleon polarizes the core, driving it to a more stable deformation.

As we move further from the valley of stability toward the $N = Z$ line, the cross sections for production of these nuclei become small, and thus detector systems must grow in complexity. Only recently[17] has the $N = Z$ ^{76}Sr nucleus been observed. The Sr isotopes have been predicted[18–20] to have large deformations because of the gap in the single particle energy levels at $Z = 38$. Deformations of $\beta \approx 0.38$ have been determined for Sr isotopes using lifetime measurements[8,9,16,21] and more recently, isotope shifts.[22–24] Despite a band crossing, ^{80}Sr has been shown[9] to display very gradual alignment and the $B(E2)$ values indicate a constant deformation throughout the reported spin range.

Previous work[8] on ^{78}Sr has shown rotational behavior up to $10\hbar$ with the lowest two transitions having large $E2$ transition strengths (> 100 Weisskopf units). Recent results[9] for ^{80}Sr indicate a band crossing involving $g_{9/2}$ proton alignment at a frequency a little higher than the extent of the previous data for ^{78}Sr. Accordingly, the present work was initiated to extend the rotational band of ^{78}Sr above this band crossing frequency and increase our knowledge of the properties of nuclei close to the $N = Z$ line.

EXPERIMENTAL PROCEDURE

Populating the light Sr nuclei near the $N = Z$ line is extremely difficult. The compound nucleus must be very far from stability, where charged particle evaporations are heavily favored over neutron emission. As one approaches the $N = Z$ line, the detection of events involving multiple neutron emission becomes very important. Therefore the use of large neutron detector arrays is one way in which the low yield, multiple neutron evaporation channels can be selected.

High spin states in ^{78}Sr were populated in the reaction ^{58}Ni(^{24}Mg,$2p2n$) at 110 MeV using the Science and Engineering Research Council (SERC) Nuclear Structure Facility at Daresbury Laboratory. Because of the small relative cross section of less than 2.5% of the total[25] fusion cross section (approximately 1 b) for this reaction, the POLYTESSA framework was used with 15 neutron detectors at forward angles and 15 bismuth germanate (BGO) Compton suppressed Ge detectors at back angles. The experimental setup is shown in Fig. 1. The neutron detectors were specially designed so that they are the same shape as a BGO anti-Compton shield. The neutron detectors used the pulse shape discrimination properties of an NE-213 liquid scintillator for separating the neutrons from the intense γ-ray flux. A disk of 3-mm-thick brass followed by several disks of Pb the same thickness were placed on the front face of each detector to prevent this γ-ray flux from entering the counters. Despite these absorbers, some discriminators operated at rates approaching 100 kHz.

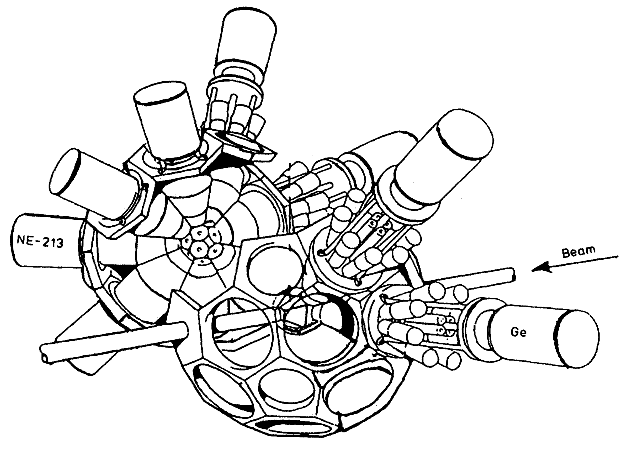

FIG. 1. The experimental setup showing the POLYTESSA frame containing 15 neutron detectors in the forward hemisphere and 15 Compton suppressed Ge detectors in the back hemisphere.

The conical detectors, their layout distributed over 2π, and time random subtraction reduced the problem of $1n$ events entering the $2n$ gated spectra due to the scattering of one neutron into two or more detectors. Even so, the $1n$ contamination resulted in 79% of the total counts accumulated by the $2n$ gating. Although this is a large fraction of the total number of counts, the total $1n$ cross section (approximately 392 mb for the ^{78}Rb$+3pn$, ^{77}Kr$+4pn$, and ^{75}Kr$+\alpha 2pn$ channels) is more than ten times greater than the $2n$ cross section (approximately 38 mb for the ^{78}Sr$+2p2n$ and ^{77}Rb$+3p2n$ channels) as estimated by PACE calculations.[25] A clean $2n$ gated spectrum can be obtained by subtracting a small portion (2%) of the $1n$ gated spectrum in order to eliminate this contamination. This clean $2n$ gated spectrum together with the uncorrected $1n$ and $2n$ gated $\gamma\gamma$ coincidence projections are shown in Fig. 2. The coincidence arrays used for projecting individual γ-ray gates were not subtracted in this manner. However, $1n$ events did not interfere with the identification of lines in ^{78}Sr except when the transition energies are similar. The efficiency of the detector arrangement for $2n$ events, i.e., the probability of detecting a second neutron after detecting the first, was approximately 6%.

The target for the $\gamma\gamma$ coincidences consisted of two enriched ^{58}Ni self-supporting, rolled foils of approximately 500 μg/cm^2 each. This allowed the nucleus recoiling at a velocity $v/c=0.0258(5)$ to decay in flight and be stopped in the beam catcher, away from the experimental apparatus. Therefore only fully Doppler shifted, prompt γ rays were recorded. The spectra were calibrated using the known[7] energies from ^{78}Kr transitions, which were populated strongly via the $4p$ reaction channel. By use of the calibration sources ^{133}Ba and ^{152}Eu (where the highest line is $E_\gamma=1408$ keV) the energy calibration required only a linear term with a small offset. This, coupled with previous experience with the ADC modules, allowed the calibration based on the ^{78}Kr lines ($E_\gamma \leq 1262.7$ keV) to be extended over the entire energy range. A global efficiency was calculated using the normalized yields of transitions in ^{133}Ba and ^{152}Eu added together from all 15 Ge detectors.

LEVEL SCHEME

Previously, transitions in ^{78}Sr had been observed[8] up to spin $10\hbar$. Despite deviations in the level spacings for a rigid rotor, transition quadrupole moments for the first

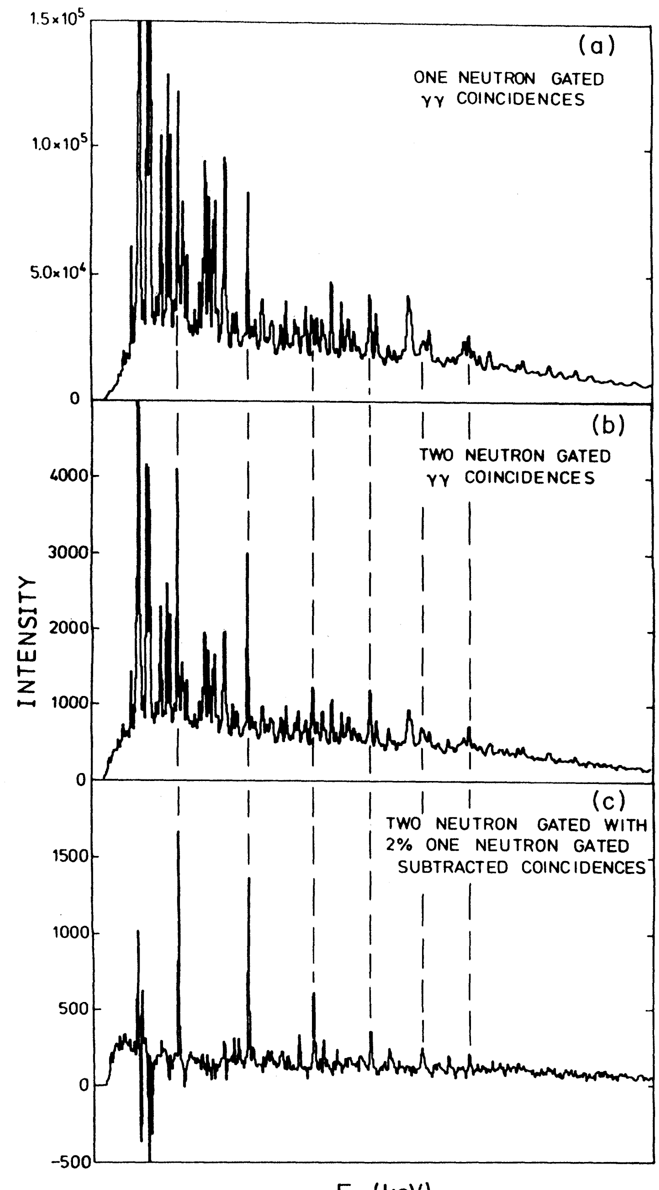

FIG. 2. The projections of the $1n$ and $2n$ gated arrays are shown in (a) and (b), respectively. The intensity scale has been expanded in order to highlight the smaller peak yields at the higher energies. As a result some low-energy peaks extend beyond what is shown. (c) is the corrected $2n$ gated spectrum with 2% of the $1n$ gated spectrum subtracted. The peaks seen in this spectrum are from ^{78}Sr and ^{77}Rb. The latter resulting from the $3p2n$ reaction channel. The dashed lines indicate the position of some transitions in ^{78}Sr.

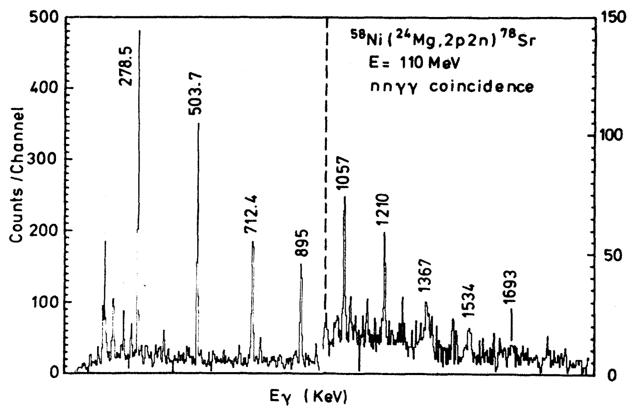

FIG. 3. The spectrum from the sum of the 278-, 504-, 712-, 895-, and 1057-keV gates showing the transitions in ^{78}Sr. The peaks that are unlabeled belong to transitions from the $3pn$ contaminant channel, ^{78}Rb: 278, 503 (Ref. 21) and 895 keV (present work).

two excited states indicate the nucleus to have rotational behavior with a deformation of $\beta_2 \approx 0.40$, if axial symmetry is assumed. These transitions and others observed in the present work can be seen in Fig. 3, which is a spectrum generated by gates set on the 278-, 504-, 712-, 895-, and 1057-keV transitions in the $2n\gamma\gamma$ data. Three new transitions are clearly visible and perhaps a fourth at 1693 keV. The indicated transitions have been placed in the level scheme shown in Fig. 4, the ordering of which is based on the γ-ray intensities observed in the spectra in

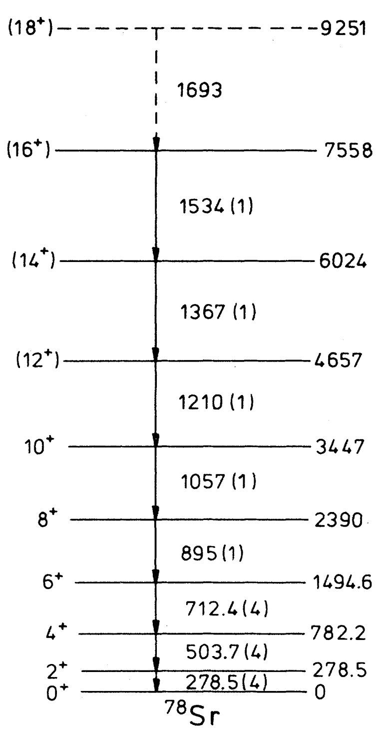

FIG. 4. The yrast states of ^{78}Sr. All states above the 10^+ are from the present work.

coincidence with various gates set in the $2n\gamma\gamma$ and $n\gamma\gamma$ data. In the case of the 1367- and 1534-keV transitions, the higher statistics of the $n\gamma\gamma$ data allowed the observation of all the other lines. The 1693-keV transition is tentatively placed in ^{78}Sr and is indicated by the dashed lines. It can only be observed in the summed coincidence spectrum shown in Fig. 3. A 1693-keV gate set in the $n\gamma\gamma$ data indicated the presence of transitions belonging to ^{78}Sr. Its placement in the level scheme is based on the regular energy spacing between the lower spin states. All spins are tentatively assigned as indicated by parentheses and are consistent with the expected stretched $E2$ transitions comprising the ground state rotational bands of even-even nuclei.

MOMENTS OF INERTIA OF ^{78}Sr

The dynamic $(J^{(2)}/\hbar^2)$ and kinematic $(J^{(1)}/\hbar^2)$ moments of inertia for the ground bands in ^{78,80,82}Sr (Refs. 9, 26, and 27) are shown in Fig. 5. At low spins, the curves

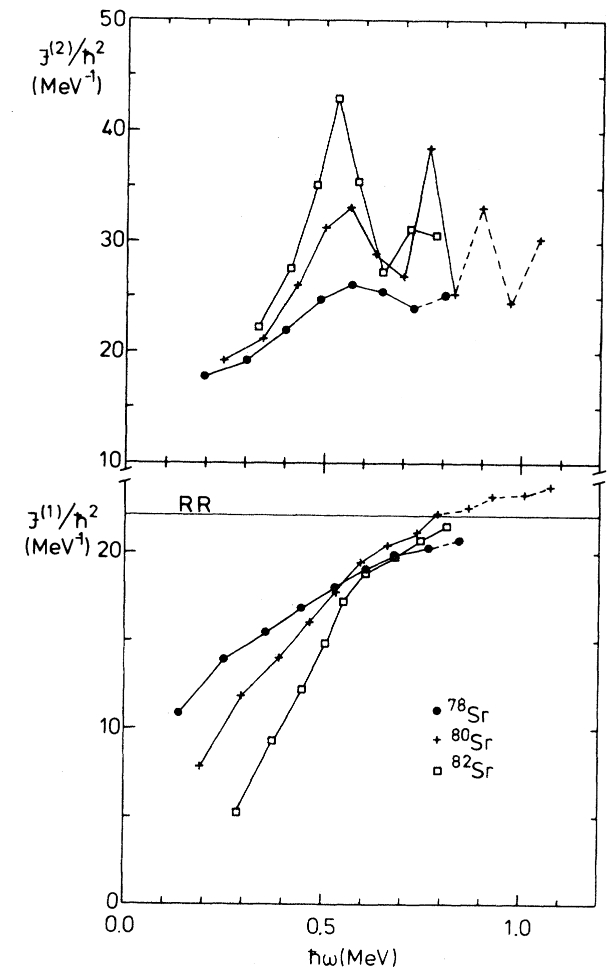

FIG. 5. The dynamic $(J^{(2)}/\hbar^2)$ and kinematic $(J^{(1)}/\hbar^2)$ moments of inertia for the ground bands in ^{78,80,82}Sr are plotted versus rotational frequency. A band crossing is evident at $\hbar\omega \approx 0.55$ MeV for all three nuclei and is discussed in the text. The horizontal line in $J^{(1)}$ represents the prolate rigid body values for ^{78}Sr, $\beta_2 = 0.40$.

gradually increase with ^{78}Sr having the largest $J^{(1)}$ values. In the frequency interval $0.5 \le \hbar\omega \le 0.6$ MeV these curves converge and at higher frequencies, ^{78}Sr has the smallest kinematic moment of inertia. No sudden changes occur in the ground bands to indicate band crossings throughout the reported frequency range although we do note that Refs. 9 and 26 have reported the lowest band crossings in ^{80,82}Sr at $\hbar\omega \approx 0.55$ MeV.

Since no dramatic effects can be seen in the $J^{(1)}$ curves for the Sr isotopes, it is beneficial to look at the $J^{(2)}$ moments which are more sensitive to small changes. Indeed, all three isotopes reveal a broad "bump" centered about $\hbar\omega \approx 0.55$ MeV. We interpret this peak as evidence for the occurrence of a $g_{9/2}$ proton band crossing in all three isotopes. A band crossing involving protons was predicted in Ref. 18 to occur at a slightly higher frequency. A neutron crossing was also predicted at $\hbar\omega \approx 0.75$ MeV. The peak in the $J^{(2)}$ curve for ^{78}Sr is low and broad as compared to ^{80,82}Sr. This is an indication that the interaction between the two bands is larger in ^{78}Sr than in the other nuclei, resulting in the near constant energy spacing of 160 keV between the transition energies observed in ^{78}Sr.

In conclusion, through the use of a large neutron and Ge detector array, γ-ray spectroscopy may be performed on low yield nuclei. The level scheme for ^{78}Sr has been extended to a state of probable spin $16\hbar$. The kinematic moment of inertia ($J^{(1)}$) indicates that ^{78}Sr has a more stable structure than ^{80,82}Sr as the spin evolves. At $\hbar\omega \approx 0.55$ MeV a band crossing due to two $\pi g_{9/2}$ quasiparticles can be observed in all three Sr isotopes. The two bands in ^{78}Sr seem to interact strongly and over a large range of frequencies. This may contribute to the stability of the nuclear shape despite the band crossing.

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