Nuclear-Structure Effects in Proton Evaporation Spectra

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Energy spectra and angular distributions of evaporated protons from the reaction ^{52}Cr(^{34}S,$2p2n$)^{82}Sr at 130 MeV were measured in coincidence with discrete γ transitions. Large shifts and changes in the shape of the proton spectra were observed when high-spin states in different rotational bands are populated. They are interpreted as due to near-yrast stretched proton emission, which preferentially populates the yrast band by sub-barrier protons.

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The study of rotational motion of highly deformed nuclei is perhaps one of the best ways of studying collective motion in small quantal many-body systems. A striking example is the recent observation of superdeformed bands corresponding to a spheroidal shape with axis ratio 2:1.[1] Theoretical calculations that explain these shapes predict structures with even larger deformations ("hyperdeformed" nuclei with axis ratio ~3:1) for rare-earth nuclei at high spins that are near the stability limit against fission.[2] Since superdeformed nuclei are produced in very small yields in heavy-ion fusion reactions, it is important to understand the mechanisms for populating these local minima, if ways of producing hyperdeformed nuclei are to be found. The mechanism for their population may be determined by the influence of the potential-energy minima on the particle-emission probabilities via enhanced level densities and penetrabilities. These influences will be more pronounced for charged-particle emission, because evaporation below the emission barrier is expected to be enhanced by deformation or structural effects.[3,4] Therefore, charged-particle emission may play an important role in the population of hyperdeformed nuclei. In particular, proton emission may be more important than α emission, since protons do not remove much angular momentum and can probe deformation with minimal perturbation of the emitting system.

Here we address experimentally the issue of structural influences on the shapes of the proton spectra. We have observed for the first time a strong dependence of the probability for sub-barrier proton emission on the nature of the rotational bands populated in the final nucleus.

It has been known for some time that α-particle emission from excited nuclei, particularly below the evaporation Coulomb barrier, is sensitive to nuclear shapes.[3-7] Previous work has demonstrated that a decrease in the evaporation barrier for α particles due to deformation is capable of explaining α-γ angular-distribution data[5,7] and α-particle energy spectra.[8] In earlier heavy-ion fusion work, such data were obtained with small detection efficiency, and either without or with limited exit-channel selection by gating on γ-ray multiplicity. We have taken a major step forward by combining exit-channel selection with 4π detection of charged particles and γ rays. This allowed us to obtain proton spectra with high statistics in coincidence with specific transitions in rotational bands in the final nucleus, and to study their shapes as a function of the spin of the entry states in the same final nucleus.

We have chosen to study ^{82}Sr as the final nucleus because it was predicted to have a superdeformed band structure at high spins.[9] The experiment was performed at the Oak Ridge heavy-ion facility (HHIRF). The reaction used was ^{52}Cr(^{34}S,$2p2n$)^{82}Sr at 130 MeV. The ^{86}Zr* compound nucleus had an excitation of 71.2 MeV. The target was a stack of two 270-μg/cm^2 self-supporting Cr foils, enriched to 98% in mass 52. Discrete γ rays were detected with eighteen Compton suppressed Ge detectors inserted in the Spin Spectrometer[10] at a distance of 22 cm from the target. The γ-ray multiplicity was recorded event by event with the Spin Spectrometer, a 4π array of 72 NaI(Tl) detectors. The light charged particles (protons, deuterons, ^{3}He, and α particles) were detected with the Dwarf Ball,[11] a 4π array of 72 CsI(Tl) detectors. Coincidences between two or more Ge detectors and one or more CsI(Tl) detectors provided the event trigger. Particle identification was accomplished by pulse-shape discrimination with the CsI(Tl) pulses. The energy calibration of the Dwarf Ball detectors was based on elastic and inelastic scattering of protons from the reaction ^{12}C(p,p') at 9.0 and 20.0 MeV. The particle energies were converted event by event to the center-of-mass system, assuming compound-nucleus formation and decay by one proton. This allowed total spectra and angular distributions in the center-of-mass system to be obtained by appropriate summing of spectra

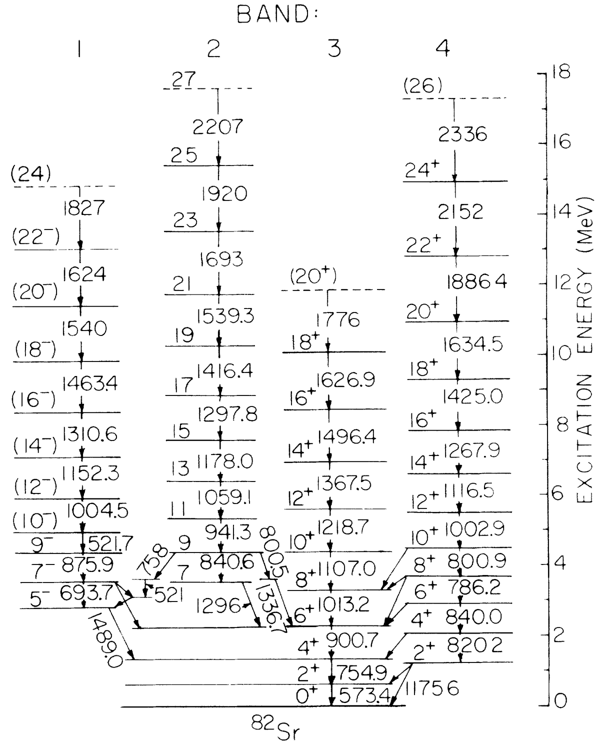

FIG. 1. Partial level scheme for ^{82}Sr showing four major rotational bands. Band 3 is the ground band, and band 4 is the yrast one. The odd-spin band 2 becomes yrast at spins higher than 23.

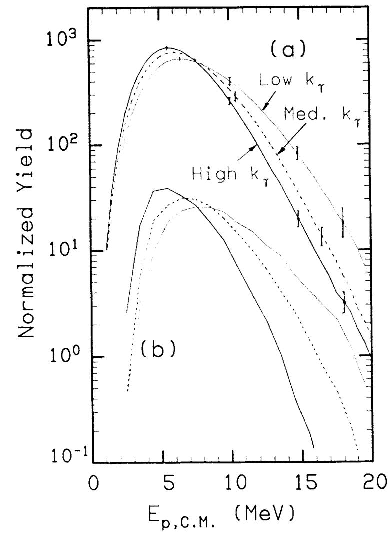

FIG. 2. (a) Proton spectra coincident with the $2^+ \rightarrow 0^+$ transition in the ground band (band 3 in Fig. 1) of ^{82}Sr for the three k_γ gates indicated. The spectra are normalized to the same area for comparison [(peak counts)/(0.5 MeV) are 8036 $\pm$135, 25025$\pm$213, and 15369$\pm$171, respectively]. Typical statistical error bars are shown for selected bins. (b) Normalized theoretical proton spectra calculated with the evaporation code PACE for the three γ-ray multiplicity gates corresponding approximately to the k_γ bins in (a).

from the Dwarf Ball detectors. For charged-particle channel selection, all the Dwarf Ball detectors were used, but for energy spectra the detectors at θ_{lab} of 24°, 42°, 50°, 63°, 68°, 78°, 87°, 93°, and 102° were employed. A total of 1.5×10^8 events were recorded and processed.

A new level scheme for ^{82}Sr (Fig. 1) was constructed[12] from a γ-γ matrix obtained from any two Ge detectors in coincidence with one proton and ten or more NaI(Tl) detectors ($k_\gamma \geq 10$). This matrix was dominated by ^{82}Sr γ rays. In the level scheme, band 4 is yrast for spins between $10\hbar$ and $22\hbar$, while the odd-spin band 2 becomes yrast for $I>23$.

Proton spectra associated with ^{82}Sr were sorted by requiring that any Ge recorded one of the characteristic γ rays placed in the decay scheme (contributions from underlying Compton events were subtracted by placing a nearby Ge gate), that two protons were identified by the Dwarf Ball, and that k_γ lay in one of the three gates 1–7 (low k_γ), 8–12 (medium k_γ), or 13–23 (high k_γ).

Proton spectra coincident with the $2^+ \rightarrow 0^+$ ground transition are shown in Fig. 2(a) for the three k_γ gates. For the higher-k_γ gates the proton spectra shift to lower energies and become narrower, but the high-energy slopes (above ~15 MeV) for all the k_γ gates are similar. This behavior is understood in terms of the decreasing thermal energy as k_γ or equivalently the spins of the entry region are increased [the three k_γ gates correspond to $I\sim(4\text{–}19)\hbar$, $(17\text{–}29)\hbar$, $(26\text{–}45)\hbar$, and to average yrast energies of 7, 14, and 23 MeV, respectively]. A statistical-model calculation for this system with the evaporation code PACE (Ref. 13) reproduces these features qualitatively. This is shown in Fig. 2(b).

In order to explore any dependence of the proton emission probability on the structure of the final nucleus, we have compared the shapes of the proton spectra coincident with γ rays from levels of increasing spin in each rotational band and of the same spin in different rotational bands. The 2^+, 4^+, and 6^+ levels in the ground band (band 3 in Fig. 1) are populated strongly from all the bands in ^{82}Sr. Therefore, the proton spectra generated by gating on γ rays from these levels should be very similar to each other. This is indeed seen to be the case in Fig. 3(a). For spins higher than $8\hbar$ the observed γ decay stays within a given rotational band (Fig. 1). Therefore any dependence of the shape of the proton spectrum on structure should become apparent only for spins 10 or higher.

Next, we examine the proton spectra associated with high-spin levels in the same rotational band. Figure 3(b) shows the proton spectra associated with levels of spin 11, 13, and (19+23) in the odd-spin band 2 of ^{82}Sr. Again the spectra are essentially identical in shape.

In contrast, when we compare proton spectra associated with high-spin levels ($\geq 10\hbar$) at comparable excita-

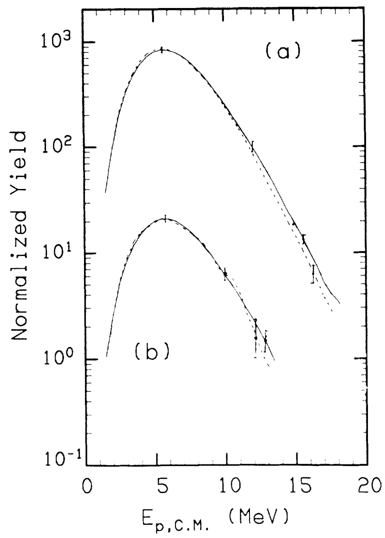

FIG. 3. (a) Proton spectra coincident with transitions from the 2^+, 4^+, and 6^+ levels of the ground band in ^{82}Sr for the high-k_γ gate [thin, thick, and dashed lines, with (peak counts)/(0.5 MeV) of 15369 ± 171, 9620 ± 130, and 6401 ± 109, respectively]. (b) Proton spectra associated with levels of spin 11, 13, and (19+23) in the odd-spin band (band 2) in ^{82}Sr for the high-k_γ gate [thin, thick, and dashed lines, with (peak counts)/(0.5 MeV) of 2003 ± 83, 1874 ± 85, and 838 ± 81, respectively]. The spectra in (a) and (b) were normalized to the same area.

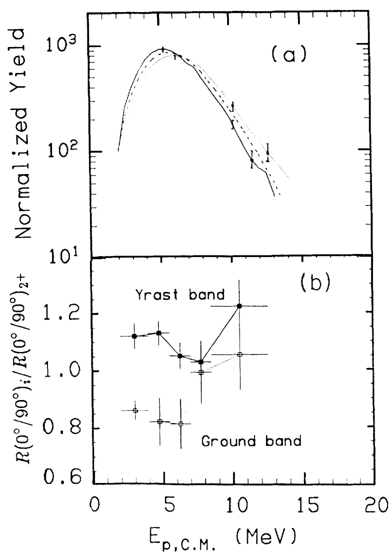

FIG. 4. (a) Proton spectra coincident with the discrete transitions from the $(10^+ + 14^+)$ levels of the ground band 3 (thin line), the spin-13 level of the odd-spin band 2 (dashed line), and the $(14^+ + 16^+)$ levels of yrast band 4 (thick line) for the high-k_γ gate. The normalized spectra had 1874 ± 85, 1999 ± 97, and 3140 ± 111 counts/(0.5 MeV) at the peak, respectively. (b) Ratio of the anisotropies of the protons for the high-spin levels of the ground band 2 (open squares and thin line) and of the yrast band 4 (solid squares and thick line) relative to the $2^+ \rightarrow 0^+$ ground-state transition for the high-k_γ gate. Vertical bars give statistical errors and horizontal ones the energy bins used for the angular distributions.

tion energies in various bands, large differences are found for all three k_γ gates. This is clearly seen in Fig. 4(a), where proton spectra associated with the sum of the 10^+ and 14^+ levels in the ground band 3 (thin line), the $I=13$ level of band 2 (dashed line), and the sum of the 14^+ and 16^+ levels of the yrast band 4 (thick line) are shown from the high-k_γ gate. The striking feature in these spectra is that for the same k_γ gate, the peak of the proton spectrum shifts down by 1 MeV in going from the band 3 to band 2 and then to the yrast band 4. This is comparable in magnitude to the shifts seen in Fig. 2(a) for the $2^+ \rightarrow 0^+$ transition from the low- to the high-k_γ gate.

These results are surprising since the entry states are expected to lie at considerably higher excitation energies than the gating transitions and any correlation between the proton spectrum and the nature of the band being populated ought to be washed out by the statistical γ emission. In fact, somewhat higher thermal energy is available for the yrast band 4 and this should shift its associated proton spectrum in the opposite direction. A possible explanation might be that, although we have the same k_γ gate, the yrast band is populated from entry regions of higher spins compared to the ground or the other bands. This could cause a shift analogous to that in Fig. 2(a).

We can offer a strong argument against the latter simple explanation in terms of phase-space effects. We note that the energy shifts are comparable to those for the $2^+ \rightarrow 0^+$ transition in Fig. 2(a), where the spins and excitation energies for the three k_γ gates are greatly different. Consequently, a comparably large difference in the entry regions of the gating transitions should be easily observed experimentally by projecting the actual k_γ distributions coincident with the same discrete high-spin transitions. We found that the k_γ distributions associated with the high-spin discrete γ gates in the four bands are identical (the average k_γ values for the ground, odd-spin, and yrast bands were found to be 15.5 ± 0.2, 15.5 ± 0.2, and 15.4 ± 0.2, respectively). In addition, a statistical-model calculation in which the high-multiplicity gate was moved up by one unit produced a considerably smaller shift in the proton spectrum than observed in Fig. 4(a).

Another unlikely possibility would be that through fractionation the ground band samples the high-total-γ-energy part of the entry region and the yrast band the lower one. This would give the yrast and ground bands less and more thermal energy, respectively. According to a statistical-model calculation this does not affect the peak and sub-barrier portions of the proton spectra, but shifts the high-energy part in the opposite direction than observed.

A reasonable explanation for the observed large shifts in the proton spectra is suggested by the steep experimental yrast line and, consequently, the entry line in ^{82}Sr and the energy balance in this reaction which places the entry line only a few MeV above the yrast line. This is also confirmed by statistical-model calculations. These observations and the data suggest that a significant fraction of the population of the rotational bands in ^{82}Sr, and in particular the yrast band, occurs by proton emission from near-yrast to near-yrast states with the second proton playing that role. This mechanism could explain many features of the data and would in addition require that the last proton emission be stretched in character, particularly at and below the emission barrier, where it should exhibit a stronger anisotropy $R(0°/90°) \equiv W(0°)/W(90°)$ with respect to the beam direction. This is indeed what we observe in Fig. 4(b) where the anisotropy ratios for the high-spin gates of Fig. 4(a) of the ground and the yrast bands are plotted relative to the anisotropy of the $2^+ \rightarrow 0^+$ ground transition as a function of the proton center-of-mass energy for the high-k_γ gate. This further supports this explanation, since the direct population of the ground band has a higher Coulomb barrier compared to that for the population of the yrast band. This interpretation is reminiscent of the predicted type-II emission of sub-barrier α particles by Grover and Gilat[14] and further discussed by Fleury *et al.*[15] in the context of α traps.

Proton emission from the near-yrast states may also be associated with a predicted mechanism based on instability toward nucleon emission at large spins, connected with the population of $h_{11/2}$ resonance states in nuclei in this region.[16] These predicted yrast proton transitions were expected to have enhanced anisotropies as observed in our work.

In summary, we have observed a strong dependence of the proton energy spectra on the nature of the final high-spin states belonging to different rotational bands in ^{82}Sr, which cannot be explained by simple statistical-model calculations that exclude specific nuclear-structure effects. The large shifts toward lower energies and the stronger anisotropies when sub-barrier protons lead to high-spin states in the yrast band compared to the ground band are interpreted as due to near-yrast emission of high-l protons. These results suggest that spectra and angular distributions of sub-barrier protons may provide a sensitive probe of the structure of excited, highly spinning nuclei.

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