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Rotational and neutron-hole states in ^{43}S via the neutron knockout and fragmentation reactions

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The recent assertion that shape coexistence occurs in the neutron-rich isotope ^{43}S implies that a state observed at 940 keV in a previous study is a rotational excitation of the deformed ground state. Here we use results from two intermediate-energy reactions to demonstrate that this state—assigned an energy of 971 keV in the present work—is indeed a rotational state. This result strengthens the case for shape coexistence in ^{43}S.

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The neutron-rich nuclei in the vicinity of ^{44}S presently provide a critical testing ground for the idea that neutron shell structure is significantly different close to the neutron dripline than it is in the valley of stability. Gaudefroy *et al.* [1] recently published the results of a g-factor measurement of an isomer in ^{43}S at 320 keV and argued on the basis of their result that spherical and deformed shapes coexist in that nucleus.

Gaudefroy *et al.* interpret the 320 keV isomer as a spherical $f_{7/2}$ single-neutron hole state (with $J^\pi = 7/2^-$), and assign the ground state $J^\pi = 3/2^-$ on the basis of the $E2$ transition deexciting the isomer. They further argue that the ground state must be deformed to have this J^π value. Finally, they suggest that a state observed by Ibbotson *et al.* [2] and assigned an energy of 940 keV is a $J^\pi = 7/2^-$ rotational excitation of the ground state. In the present work, we report on a test of this interpretation of the state observed by Ibbotson *et al.* using both the direct single-neutron knockout reaction ^{9}Be(^{44}S,^{43}S)X and the reaction ^{9}Be(^{45}Cl,^{43}S)X. The latter involves both direct and nondirect removal of a neutron and proton, and is referred to here as a fragmentation reaction. The relatively small cross sections for population of this state observed in these reactions supports its interpretation as a rotational excitation built on the ground state and strengthens the case for shape coexistence in ^{43}S.

The experiment was performed at the Coupled-Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University. A cocktail beam comprising 84% ^{44}S and 14% ^{45}Cl was produced by fragmentation of a 140 MeV/nucleon ^{48}Ca primary beam incident on a 705 mg/cm^2 ^{9}Be fragmentation target. Components of the secondary beam were separated in the A1900 fragment separator [3] and delivered to a 376 mg/cm^2 thick ^{9}Be reaction target mounted at the target position of the S800 magnetic spectrograph [4]. In the one-neutron knockout measurement, 1.5×10^8 ^{44}S beam particles were incident on the reaction target. The midtarget beam energy was 92 MeV/nucleon. The fragmentation measurement was performed with a total of 1.6×10^8 ^{45}Cl beam particles and a midtarget beam energy of 98 MeV/nucleon. Incoming beam particles were identified from their time-of-flight difference measured between scintillators mounted at the extended focal plane of the A1900 and at the object of the S800 analysis line. Projectile-like reaction products were identified by the time of flight to the focal plane of the S800 and energy loss in the S800 ionization chamber.

An inclusive single-neutron knockout cross section of $\sigma_{\text{inc}} = 79(7)$ mb to bound final states of ^{43}S was determined from the number of outgoing ^{43}S particles relative to the number of incoming ^{44}S beam particles and the particle density of the reaction target. The uncertainty in the inclusive cross section includes the stability of the incoming beam (8%), the correction for the momentum acceptance of the S800 (3%), and the software gates used to select the reaction of interest (1%). The dominant contribution to the uncertainty, the stability of the incoming beam for normalization, was quantified by comparison of several measurements of the unreacted beam, which were used to deduce the number of incoming beam particles in knockout measurements.

The measured cross section for populating a final state characterized by J^π can be compared with model predictions by combining the shell-model spectroscopic factor C^2S with the single-particle cross section $\sigma_{\text{sp}}(J,l,B_n)$ from reaction theory calculations via [5]

$$\sigma_{\text{th}}(J^\pi) = \left(\frac{A}{A-1}\right)^N C^2S\sigma_{\text{sp}}(J,l,B_n), \qquad (1)$$

where N is the oscillator quantum number of the removed nucleon, l is the angular momentum of its orbital, and $B_n = S_n + E_x$ is the energy required to remove the nucleon and populate the final state of the residue with excitation energy E_x. The inclusive theoretical cross section for knockout to bound states is given by

$$\sigma_{\text{th}}^{\text{inc}} = \sum_{nJ^\pi} \sigma_{\text{th}}(nJ^\pi), \qquad (2)$$

where the sum is over all shell-model states with E_x below the ^{43}S neutron threshold.

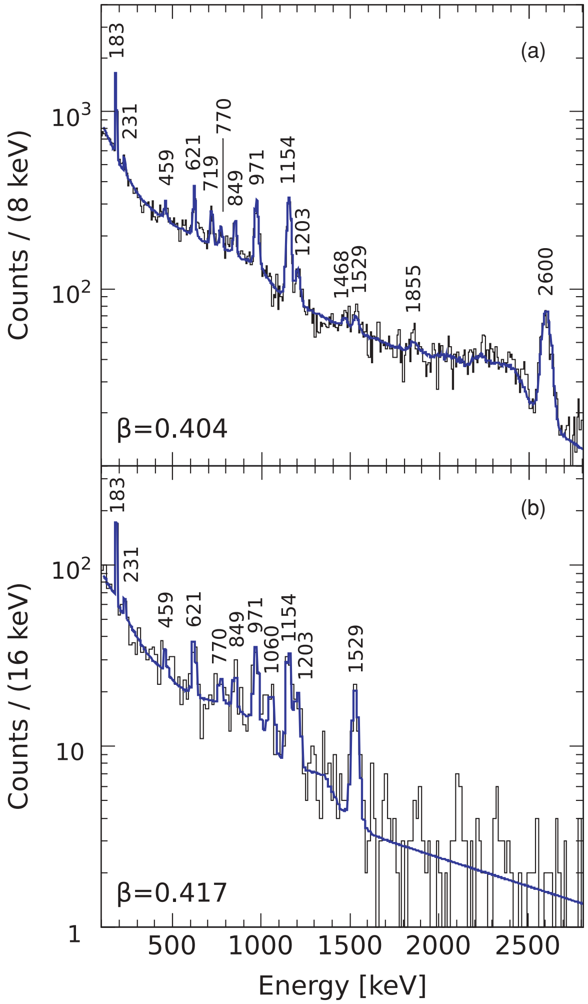

FIG. 1. (Color online) Gamma-ray spectra measured in coincidence with recoiling ^{43}S particles produced via one-neutron knockout (a) and fragmentation (b). The solid curves are GEANT4 fits described in the text.

In the present work, we used eikonal-model calculations using the method described in Ref. [6]. Shell-model calculations were carried out in the $\pi sd - \nu pf$ basis with the SDPF-U Hamiltonian [7] using the code NUSHELLX [8]. We find a theoretical cross section for knockout to bound states in ^{43}S of $\sigma_{\text{th}}^{\text{inc}} = 84.4$ mb.

It is now well established that cross sections measured in $(e,e'p)$ and single-nucleon knockout reactions are systematically lower than theoretical predictions based on model calculations [9]. This quenching is attributed to correlation effects not taken into account by the shell model and is typically quantified by a reduction factor $R_s = \sigma_{\text{exp}}^{\text{inc}}/\sigma_{\text{th}}^{\text{inc}}$. Combining the measured inclusive cross section with the theoretical prediction, we obtain a reduction factor $R_s = 0.94(8)$. Based on the systematic dependence of reduction factors on the difference in proton- and neutron-separation energies established in Ref. [9], a reduction factor $R_s = 0.83(4)$ is expected for one neutron removal from ^{44}S, consistent with the value extracted here.

Gamma rays emitted by excited reaction products were detected by the Segmented Germanium Array (SeGA) [10] of 32-fold segmented high purity germanium detectors. In Fig. 1, the Doppler-reconstructed energy spectra of γ rays from outgoing ^{43}S particles produced in one-neutron knockout from ^{44}S (top panel) and fragmentation (bottom panel) are shown. Measured laboratory-frame γ-ray energies were Doppler corrected using velocities $\beta = 0.404(1)$ (knockout) and $\beta = 0.417(1)$ (fragmentation). GEANT4 [11] simulations of the response of SeGA to γ rays were used to extract total γ-ray yields from the measured spectra. Each measured spectrum was fitted with a linear combination of the simulated responses of the observed γ rays and two exponential functions included to account for the empirically-observed prompt component of the background. The resulting fits are shown as solid curves in Fig. 1.

Measured energies and relative intensities of the γ rays corresponding to transitions shown in the level scheme of Fig. 2, deduced level energies, and knockout branching ratios and cross sections are listed in Table I. The energies and intensities of the other γ rays seen in the spectra of Fig. 1 are also included.

The experimental statistics were not sufficient to allow the extraction of useful γ-γ coincidence gates. However, the intensities and energies of the γ rays observed in coincidence with ^{43}S particles—along with data on ^{43}S from previous experiments—allowed the construction of the level scheme shown in Fig. 2. We identify the 971 keV γ ray observed here with the 940 keV γ ray reported by the authors of Ref. [2] since the energies are consistent to within experimental uncertainty. The sum of the energies of the 971 keV γ ray and the 183 keV γ ray observed strongly in the present experiment add to the energy of the 1154 keV γ ray also seen with a large intensity here. Therefore, we propose the existence of an excited state at 1154 keV that deexcites via both 1154 and 183 keV γ rays, with the 183 keV γ ray populating the 971 keV state. We deduce a cross section of 5(1) mb for population of the 1154 keV state in the present neutron-knockout reaction. Furthermore, a strong 2600 keV γ ray is evident in Fig. 1(a). The energy of this γ ray is consistent with the sum of the 1154 keV and 1468 keV γ rays within uncertainty. The uncertainty-weighted mean of the 2600(16) keV γ-ray energy and the 1154(7) keV–1468(9) keV cascade is 2614(9) keV. We suggest that a state exists at 2614 keV that is deexcited by both the 2614 keV and 1460 keV transitions. This state has a relatively large knockout cross section of 13(1) mb.

While the 971 and 1154 keV γ-rays are observed in the spectra from both the knockout and fragmentation reactions, the 1468 and 2600 keV γ-rays are not seen in the fragmentation reaction. The large cross section for the population of the 2614 keV state in the knockout reaction supports the interpretation of the 2614 keV state as a single-neutron hole state. While it is possible that the 2614 keV state was populated by feeding from a state(s) at higher energy, this is unlikely, given that 2614 keV is at the upper limit of the error range of the measured one-neutron separation energy of ^{43}S [12]. Furthermore, the absence of the γ-rays deexciting the 2614 keV state in the fragmentation reaction spectrum can be explained simply. Fragmentation reactions have been observed to preferentially populate states that are yrast or near

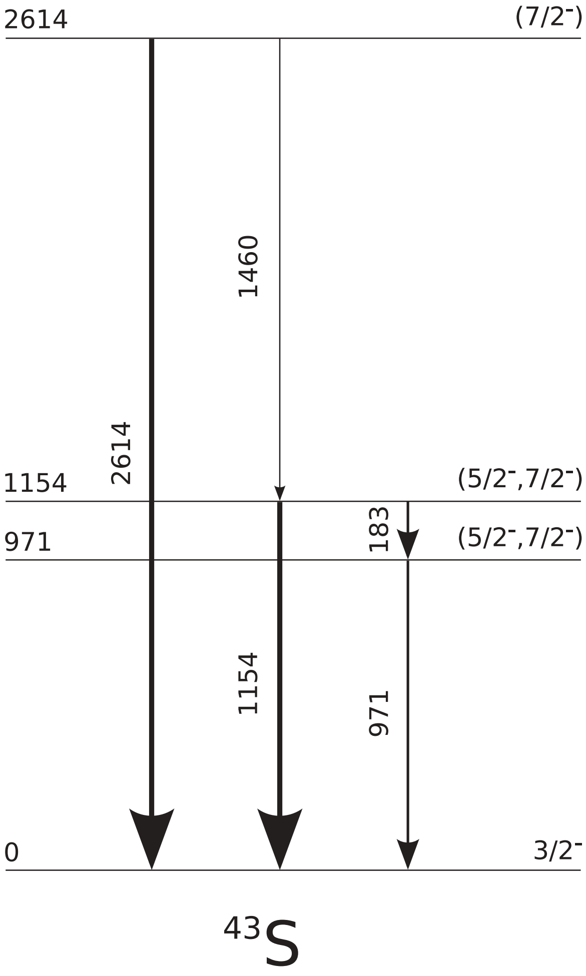

FIG. 2. The level scheme of ^{43}S deduced in the present work.

yrast [13]. However, the 2614 keV state must have $J \leqslant 7/2$ because it is a single-neutron hole state, so that it is far from the yrast line and would not be observed in a fragmentation reaction.

For the purposes of characterizing the 971 keV state, the most important information in Table I is that the intensities of the 183 keV and 971 keV γ rays are equal to within experimental uncertainty. This implies that the cross sections for populating the 971 keV state with the present neutron-knockout and fragmentation reactions are very small. It follows from the small knockout cross section that this state cannot be characterized as a single-neutron hole state. Instead, the small cross section suggests an interpretation of this state as a rotational excitation, as concluded in Ref. [1].

Figure 3 compares the experimentally observed states of ^{43}S, including the states seen in the present work and the 320 keV isomer, with the states calculated to occur under 3.0 MeV with the shell model. The figure includes the spectroscopic factors C^2S calculated in the shell model. Even though the present knockout data are not sufficient to determine spectroscopic factors that have quantitative significance, we can draw qualitative conclusions, as we did in the above discussion of the 971 keV state.

TABLE I. Deduced ^{43}S level energies E_{level}, measured energies of deexcitation γ rays E_γ, γ-ray intensities observed in one-neutron knockout I_γ^{knock} and fragmentation I_γ^{frag} relative to that of the 1154 keV transition, and knockout branching ratios BR and cross sections σ from the present work.

E_{level} [keV]	E_γ [keV]	I_γ^{knock} [%]	I_γ^{frag} [%]	BR [%]	σ [mb]
971(6)	971(6)	56(4)	62(17)	0.4(10)	0.3(8)
1154(7)	1154(7)	100	100	19(2)	15(1)
	183(1)	53(3)	58(12)		
2614(9)	2600(16)	98(7)	–	13(2)	10(1)
	1468(9)	5(3)	–		
	231(1)	6(1)	8(5)		
	459(3)	7(2)	10(7)		
	621(4)	31(3)	34(11)		
	719(4)	21(3)	–		
	770(5)	12(3)	15(10)		
	849(5)	24(3)	23(12)		
	1060(6)	–	40(15)		
	1203(7)	21(3)	51(15)		
	1529(9)	8(3)	93(22)		
	1855(11)	5(3)	–		

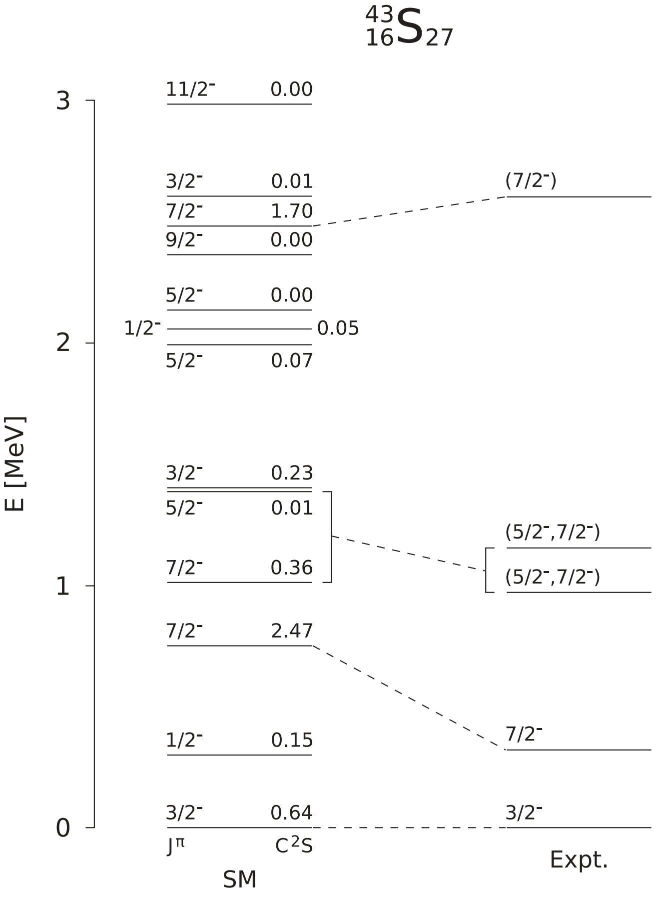

FIG. 3. Comparison of the experimental level scheme of ^{43}S with the results of the shell-model calculation described in the text.

The first excited state is calculated to be a $1/2^-$ member of the ground-state rotational band. Therefore, the calculation gives a small spectroscopic factor, which would make this state difficult to observe in our neutron-knockout experiment. It has not been reported in previous experiments, either. The shell-model calculation gives the $7/2^-$ isomer at 0.75 MeV, while the observed energy is somewhat lower. This state is calculated to have a strong single-neutron hole component, resulting in a large spectroscopic factor. Because of the long lifetime, we were unable to observe the deexciting γ-ray in the present experiment.

The shell-model calculation predicts that the $5/2^-$ and $7/2^-$ members of the ground-state rotational band occur at 1400 keV and 1010 keV, respectively, with strong $E2$ transitions connecting each of these states to the ground state. In the calculation, there is some mixing of the rotational $7/2^-$ state with the neutron-hole $7/2^-$ states, although this results in only a modest spectroscopic factor ($C^2S = 0.36$). This result is similar to that given by Gaudefroy *et al.* [14]. Of course, the rotational $5/2^-$ state does not have a significant spectroscopic factor because the $f_{5/2}$ neutron strength is at a much higher energy.

Our comparison of the present data with the shell-model calculation leads us to conclude that the states we observe at 971 and 1154 keV are the $5/2^-$ and $7/2^-$ members of the ground-state rotational band, although we are unable to determine which state is which. Therefore, the conclusion of Gaudefroy *et al.* [1] that $J^\pi = 7/2^-$ for the 971 keV state seems premature, although our results strongly support their most important argument that this state is a member of the ground-state rotational band.

Finally, Fig. 3 provides significant confidence that we can identify the experimental 2.61 MeV state with a $7/2^-$ state calculated to occur at 2.48 MeV, since this state is the only one in this energy range calculated to have a large spectroscopic factor.

The authors of Ref. [14] argued that the primary factor driving the deformed $3/2^-$ state to be the ^{43}S ground state, below the spherical $7/2^-$ state, is the correlation energy of the $3/2^-$ state. Using the shell model, these authors calculate that the correlation energy increases with decreasing proton number along the $N = 27$ isotone chain. Thus, the “inversion” that results in the deformed $3/2^-$ ground state in ^{43}S should be even stronger in ^{41}Si. In contrast, the ground state in ^{45}Ar appears to be dominated by the spherical $f_{7/2}$ neutron-hole configuration [14].

In summary, we have used the intermediate-energy single-neutron knockout reaction to characterize states in the $N = 27$ nucleus ^{43}S. We have determined that the cross section for populating the 971 keV state is small and have solidified the interpretation of this state as a member of a rotational band built on the $3/2^-$ ground state. This provides added support for the argument of Gaudefroy *et al.* [1] that shape coexistence occurs in ^{43}S, signaling the collapse of the $N = 28$ shell closure in neutron-rich isotopes.

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