Yrast decays in ^{43}K

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High-spin states in ^{43}K were studied using the ^{9}Be(^{36}S,$pn\gamma$)^{43}K reaction. Threefold ($p\gamma_1\gamma_2$) coincidence data and γ-ray intensity ratios were used to establish a decay scheme and identify negative- and positive-parity yrast decay chains. The $15/2^-$ yrast state is relatively poorly aligned prior to decay. Energies of positive-parity levels predicted by Johnstone are in good agreement with experiment.

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I. INTRODUCTION

Experimental information on excited states of the neutron-rich nucleus ^{43}K ($T_z=5/2$) has been summarized recently by Endt [1]. The γ-ray decay of high-spin states in ^{43}K was last studied over a decade ago by Behbehani *et al.* [2], who employed the ^{40}Ar($\alpha,p\gamma$)^{43}K reaction. The most recent charged particle spectroscopy work was performed by Mordechai, Fortune, and Clement [3] via the ^{41}K(t,p)^{43}K reaction. These authors identified multiplets of states based on the weak coupling of a $d_{3/2}$ proton hole to low-lying 0^+, 2^+, and 4^+ states in ^{44}Ca and compared their results with those from the shell-model calculations of Johnstone [4]. Levels excited through the β decay of ^{43}Ar have been studied most recently by Huck *et al.* [5]. The present work, which is the first heavy-ion-induced in-beam γ-ray study of ^{43}K, was undertaken to obtain a better picture of the high-spin structure of this nucleus.

II. EXPERIMENTAL METHOD

The Argonne–Notre Dame BGO γ-ray facility at the Argonne Tandem-Linac Accelerator System (ATLAS) was used to observe coincident events among charged particles and γ rays emitted from fusion-evaporation reactions of ^{36}S projectiles with ^{9}Be target nuclei. The beam energy was 100 MeV. The ^{43}K residues from pn evaporations were identified by using proton-gated γ-ray spectra together with known transitions in ^{43}K and other K isotopes. The experimental arrangement consisted of eight Compton-suppressed Ge detectors (CSGs) positioned above and below the horizontal reaction plane and two Si surface-barrier detector telescopes positioned at forward angles. The target consisted of a 2.34-mg/cm^2-thick rolled ^{9}Be foil with 10 mg/cm^2 of Pb evaporated onto the downstream side to stop most of the heavy reaction products. An additional Pb foil of 7.5 mg/cm^2 thickness served to stop the ^{36}S beam. The Si detector telescopes were placed at $\pm30°$ relative to the beam direction to detect light particles ($Z\leq3$) which had enough energy to traverse the beam stopper foil and the 54-μm-thick ΔE detectors. Four of the CSGs were positioned at polar angle $\theta=90°$ with respect to the beam axis with azimuthal angles (ϕ's) of 15°, 165°, 195°, and 345°, respectively. The other four were positioned at $\theta=147°$ with ϕ coordinates 28°, 152°, 208°, and 332°. Data were collected using the ATLAS acquisition code DAPHNE [6]. Energy and timing information from all CSGs and the telescopes were recorded for all twofold or higher-order coincidences among the CSGs and telescopes.

III. RESULTS AND DISCUSSION

A. Analysis

Event mode data were sorted initially to generate γp and $\gamma_1\gamma_2$ twofold coincidence spectra. A proton-gated γ-ray spectrum is shown in Fig. 1. A threefold $p\gamma_1\gamma_2$ coincidence sort was necessary to solve the decay scheme puzzle, owing to the fact that there are three transitions having energies in the 476–478 keV range. Our proposed decay scheme is shown in Fig. 2. Experimental information on the transitions is summarized in Tables I and II. Our results are generally in good agreement with previous measurements where they exist [1].

All transitions reported by Behbehani *et al.* [2] and

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TABLE I. Energies and relative intensities of γ rays attributed to ^{43}K.[a]

E_γ (keV)	Transition	Relative intensity
303.09(5)	1510→1207	4.6(2)
413.97(5)	975→561	0.58(7)
451.83(6)	3592→3140[b]	7.7(2)
459.95(5)	2509→2049	20.7(6)
476.3(3)	1987→1510	4.5(5)
476.4(3)	3592→3116[b]	1.2(5)
478.1(2)	2987→2509[b]	2.4(1)
548.65(5)	1110→561	6.8(3)
561.11(5)	561→0	7.1(3)
630.86(12)	3140→2509[b]	1.5(2)
738.26(5)	738→0	> 18[c]
975.06(5)	975→0	9.3(3)
998.69(6)	2509→1510	15.5(5)
1083.03(10)	3592→2509[b]	9.4(3)
1109.99(10)	1110→0	13.4(5)
1112.09(10)	1850→738	100(3)
1206.94(11)	1207→0	14.3(5)
1265.16(15)	3116→1850	34.6(11)
1289.70(5)	3140→1850	10.4(4)
1310.57(7)	2049→738	24.8(8)
1510.35(7)	1510→0	38.4(12)

[a]Obtained from proton-gated γ-ray spectra, summed over all detectors.
[b]New via the present work.
[c]Long-lived state; most events were outside of coincidence window.

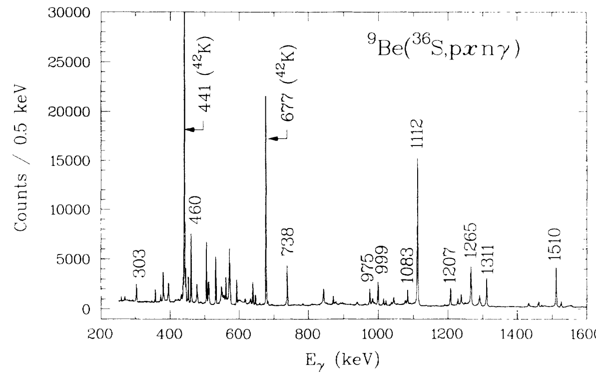

FIG. 1. Portion of a proton-gated γ-ray spectrum from reactions of 100-MeV ^{36}S with ^{9}Be. Unless otherwise indicated, labeled peaks correspond to transitions in ^{43}K.

some of those reported in the β-decay work of Huck *et al.* [5] were observed. In addition, five previously unreported transitions were identified, three of which have been assigned as decay branches of a new level at 3592 keV (see Tables I and II). We also confirm the existence of the 1987→1510 transition tentatively suggested in Ref. [2].

Fusion-evaporation reactions most strongly populate yrast states, which usually decay via "stretched" cascades of nearly pure multipoles of order L, where $L = J_f - J_i$. In order to exploit this property of the reaction mechanism, the data were sorted into two two-dimensional coincidence energy spectra. One of these was $\gamma_2(90°)$ vs $\gamma_1(147°)$, where the angles are polar angles with respect to the beam direction (θ's). The other array was $\gamma_2(90°)$ vs $\gamma_1(90°)$. Relative γ_1 intensities at $\theta=90°$ and 147° were compared with those expected for stretched dipole and quadrupole transitions when γ_2 was emitted at $\theta=90°$. The $I(90°)/I(147°)$ ratios (sometimes referred to

TABLE II. ^{43}K energy levels observed via the ^{9}Be(^{36}S,$pn\gamma$)^{43}K reaction.

		Decay branches (%)[b]										Side feeding[c]
E_x (keV)	$2J^{\pi}$[a]	g.s.	561	738	1207	1510	1850	2049	2509	3116	3140	(relative)
561.11(5)	1^+	100										−0.3(4)
738.26(5)	7^-	100										d
975.07(5)	3^-	94(2)	6(2)									9.9(3)
1109.87(12)	3^+	66(2)	34(2)									20.2(6)
1206.94(5)	$(5,7)^+$	100										9.7(5)
1510.19(16)	7^+	89(1)			11(1)							23.0(14)
1850.35(11)	11^-	100										55.0(32)
1986.53(16)	[9]					100						4.5(5)
2048.83(9)	[9]			100								4.1(10)
2508.84(16)	[11^+]					43(1)		57(1)				22.9(9)
2986.93(16)[e]	[13^-]								100			2.4(1)
3115.51(19)	15^-						100					33.4(12)
3139.79(24)	[13^+]						87(2)		13(2)			4.2(5)
3591.75(33)[e]	[15^+]								57(3)	6(2)	37(3)	18.3(6)

[a]Quantities in square brackets are suggestions (not assignments) based on the present work. Assignments are from Ref. [1].
[b]Levels for which only one decay branch was observed have been tentatively assigned a branching percentage of 100% for that branch.
[c]Obtained from relative intensities listed in Table I (same units).
[d]Long-lived state; most events were outside of coincidence window.
[e]New via the present work.

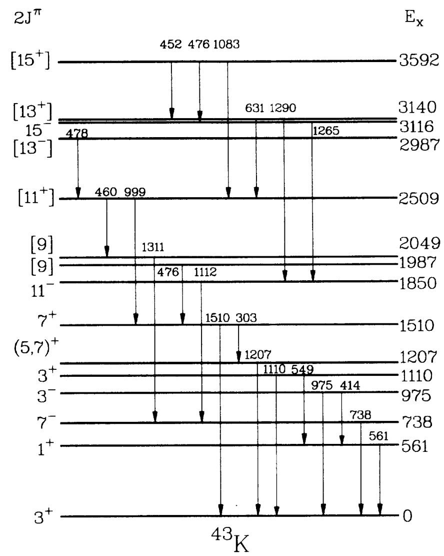

FIG. 2. Decay scheme for ^{43}K. Energies are in keV. Preferred spins (not to be viewed as assignments) are shown in square brackets. See Tables I and II for further details.

as ratios of directional correlations from oriented states, or DCO ratios [7]) should be about 1.2–1.4 for stretched dipoles and 0.8–0.9 for stretched quadrupoles, depending on the degree of alignment of the nucleus and, to a lesser extent, on the properties of the gating transition.

Experimental ratios, determined in each case by using an adjacent lower transition as a gate, ranged from 0.64(7) to 1.50(10). This wider-than-normal range indicates a relatively high degree of nuclear alignment. In order to fully exploit this situation, i.e., to learn as much as possible about transitions having intermediate values, DCO ratios were calculated using standard angular correlation theory and compared with the experimental ratios in a self-consistent manner. In general, the calculated $I(90°)/I(147°)$ ratios ranged from a minimum of 0.7 for a stretched quadrupole cascade with no mixing of higher-order multipoles and only one substate to about 1.4 for a stretched dipole cascade with no mixing and only one substate. The experimental and calculated ratios are summarized in Table III.

B. Decay scheme, spins, and parities

In most cases, it was possible to obtain good agreement with the data (for a reasonable choice of spins) by assuming an initial uniform population of only a few magnetic substates along the $\theta=90°$ direction and little or no mixing [8]. One illustration of this feature is the 1850→738→0 cascade, the first entry in Table III, which is known to be an $11/2^- \rightarrow 7/2^- \rightarrow 3/2^+$ cascade with an $E3/M2$ mixing ratio of 0.13(2) for the 738→0 transition [1,2]. Other transitions are discussed below in the same order as their listing in Table III.

The intensities of the transitions between levels (Table I) and the side-feeding of energy levels (Table II) clearly indicate two relatively strong decay sequences: 3116→1850→738 and 3592→2509→1510→0. The first of these (Table III, row 2) has been unambiguously established by Behbehani *et al.* [2] as a negative parity, 15/2→11/2→7/2 sequence. Behbehani *et al.* have also

TABLE III. $I(90°)/I(147°)$ for transitions in ^{43}K.

Row no.	γ_1	90° gate (γ_2)	Decay sequence	$2J$'s	Assumed $\lvert m\rvert$'s	$I(90°)/I(147°)$ Calc.	Expt.[a]	Footnote
1	1112	738	1850→738→0	11→7→3	1/2, 3/2, 5/2	0.76	0.77(3)	b
2	1265	1112	3116→1850→738	15→11→7	1/2→11/2	0.93	0.93(4)	c
3	999	1510	2509→1510→0	11→7→3	1/2, 3/2	0.74	0.72(5)	c
				9→7→3	1/2 only	1.30		c
4	1083	999	3592→2509→1510	15→11→7	1/2 only	0.73	0.64(7)	c
5	476	1265	3592→3116→1850	15→15→11	1/2 only	0.86	0.77(10)	c
6	1290	1112	3140→1850→738	13→11→7	1/2 only	1.27	1.50(10)	c
				11→11→7	1/2 only	0.82		c
7	631	999	3140→2509→1510	13→11→7	1/2 only	1.27	1.42(22)	c
8	452	1290	3592→3140→1850	15→13→11	1/2 only	0.89	0.89(5)	d
9	452	631	3592→3140→2509	15→13→11	1/2 only	0.89	1.06(12)	d
10	476	1510	1987→1510→0	9→7→3	1/2 only	1.30	1.31(9)	c
11	1311	738	2049→738→0	9→7→3	1/2, 3/2, 5/2	1.21	1.22(10)	b
12	460	1311	2509→2049→738	11→9→7	1/2, 3/2	0.91	0.92(3)	d
13	631	460	3140→2509→2049	13→11→9	1/2 only	1.37	1.32(14)	e
14	478	999	2987→2509→1510				1.04(11)	
15	478	460	2987→2509→2049				0.90(7)	

[a]Uncertainties are statistical only.
[b]$\delta_1=0.0$, $\delta_2=0.13$ [1,2].
[c]$\delta_1=\delta_2=0.0$.
[d]$\delta_1=-0.2$, $\delta_2=0.0$.
[e]$\delta_1=0.0$, $\delta_2=-0.2$.

determined a spin and parity of $7/2^+$ for the 1510-keV level. As shown in Table III (row 3), the DCO ratio of only 0.72(5) for the 999-keV (2509→1510) transition, when gated by the 1510-keV transition, strongly indicates that the 2509→1510 is a stretched $E2$ transition. This would suggest a probable spin and parity of $11/2^+$ for the 2509-keV level. Similarly, the small ratio for the 1083-keV (3592→2509) transition, [0.64(7)] when gated by the 2509→1510 transition, would suggest that the 3592→2509 transition, too, is of stretched $E2$ character (Table III, row 4). Thus, the spin and parity of the 3592-keV level is probably $15/2^+$. The experimental DCO ratio of the 476-keV transition which connects this proposed $15/2^+$ state with the known [2] $15/2^-$ state at 3116 keV (row 5) is consistent with that expected for a 15/2→15/2 transition. Thus, it would appear we are observing two yrast decay chains, one of each parity, and both starting at $J=15/2$ (see Fig. 3).

The DCO ratio for the 3140→1850→738 decay sequence (Table III, row 6) strongly suggests a stretched dipole for the 3140→1850 transition, and thus a $J=13/2$ assignment for the 3140-keV level. This same spin preference for the 3140-keV level is reached if one assumes stretched transitions for the 3140→2509→1510 sequence (row 7), provided the 2509-keV level has $J=11/2$, as suggested above.

The intensity ratio for the 3592→3140→1850 sequence is 0.89(5) (Table III, row 8), while that for a stretched dipole would exceed unity. Thus, if this is a $15/2^+\rightarrow 13/2\rightarrow 11/2^-$ sequence (as the conjectures stated above would suggest), the 3592→3140 decay probably has an $E2$ admixture which, in turn, would require positive parity for the 3140-keV level. A mixing ratio of -0.2 gives good agreement with the experimental result (Table III). Using this same mixing ratio for the 3592→3140 decay, but gating with the 3140→2509 branch (row 9) gives only fair agreement with the experimental result if we again assume a 15/2→13/2→11/2 sequence. Perhaps the 3140→2509 decay is also mixed;

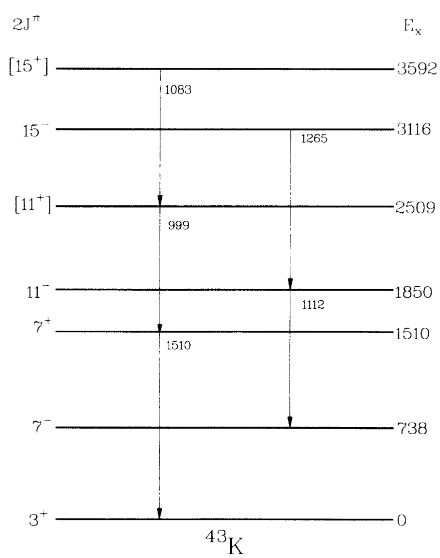

FIG. 3. Yrast decays in ^{43}K. See text for discussion.

the error on our experimental ratio for this transition (row 7) is too large to give a clear indication.

Since the experimental DCO ratios for both the 1987→1510→0 and 2049→738→0 cascades are both significantly greater than unity, it would appear that both of the initial decays are probably stretched dipole transitions, i.e., both are probably 9/2→7/2→3/2 cascades (Table III, rows 10 and 11). Any other reasonable combination of spins, polarization, and mixing results in worse agreement with experiment. From basic structure considerations and observed decay preferences, it seems likely that the 1987- and 2049-keV states have opposite parity. It is not clear, however, which is positive and which is negative.

The 2509→2049→738 cascade (row 12) is consistent with the 11/2→9/2→7/2 spin sequence argued above, provided some mixing is assumed for the 460-keV (2509→2049) transition ($\delta_1=-0.2$). Using this transition with the same mixing ratio as a gate for the 3140→2509 transition (row 13) results in a ratio of 1.37 for the latter, in good agreement with experiment [1.32(14)], although the experimental uncertainty is relatively large.

We place the 478-keV γ ray as a transition from a level at 2987 keV to the 2509-keV level (Fig. 2). Experimental DCO ratios for the 2987→2509 transition (Table III, rows 14 and 15) were extracted for both decay branches from the 2509-keV level, and both are near unity. However, no calculated ratios are given, as there are many reasonable combinations of parameters which would reproduce the experimental ratios. A transition feeding the 2987-keV level from a state of known spin would be needed to establish a spin preference on the basis of DCO ratios, and no such transition is observed in the present work. However, the 2987-keV level appears to have only one decay branch of relatively low energy (478 keV) to a level which probably has $J^\pi=11/2^+$. Thus, the 2987-keV level is likely to have relatively high spin, and may be a candidate for the (missing) $13/2^-$ state formed in coupling an $f_{7/2}$ proton with the four $f_{7/2}$ neutrons in a 4^+ configuration. A level near this excitation energy was observed in the ^{44}Ca$(t,\alpha)^{43}$K (proton pickup) reaction by both Santo *et al.* [9] [at 2976(15) keV] and Ajzenberg-Selove and Igo [10] [at 2995(25) keV], but no spins or parities were assigned. It is possible that this level corresponds to the 2987-keV level discussed here. The probability of directly picking up a proton from a single-particle orbital having $j\geq 11/2$ in the ^{44}Ca ground state would be immeasurably small, but the state could be excited by a multistep process in the (t,α) reaction.

C. Alignment of the $15/2^-$ state

We return for a moment to the second entry in Table III, the 3116→1850→738, $15/2^-\rightarrow 11/2^-\rightarrow 7/2^-$ yrast cascade, which appears strongly in both the p-γ and γ_1-γ_2 coincidence data. We measured a DCO ratio of 0.93(4) for the 3116→1850 transition when gated by the 1850→738 transition. This ratio disagrees with the other measured DCO ratios for stretched $E2$ transitions by as much as 5σ. The calculated ratio for stretched $E2$'s could be brought into agreement with the measured value, but only if all the initial magnetic substates from $\pm 1/2$ through $\pm 11/2$ were included. Yet, there can be no doubt as to the spin and parity assignments for these states; the evidence presented in the work of Behbehani *et al.* [2], is very convincing. Thus, it would appear that the 3116-keV state is not nearly as well aligned as the other yrast states.

If this misalignment occurred after the nucleus stopped in the target, its decay must have been delayed by many picoseconds. The lifetimes of the 3116- and 1850-keV states have been measured to be 5.0 ± 1.5 and 6.7 ± 1.7 ps, respectively [2]. Nevertheless, the lower, 1850-keV state seems to be the better aligned of the two (Table III, row 1), probably because of the large (and apparently highly aligned) side-feeding into this state (Table II). It is possible that an unobserved, long-lived precursor could be feeding the 3116-keV level. This would require a very strong transition (e.g., a stretched $E2$ from the $19/2^-$ yrast state) having an energy of less than 100 keV (our experimental lower limit). As discussed by Behbehani *et al.* [2], the negative parity yrast structure of ^{43}K looks very much like that of ^{45}Sc, at least up to $J=15/2$; the $B(E2)$ values for corresponding transitions are essentially the same for the two nuclei. However, in ^{45}Sc, the proposed $19/2^-$ state lies more than 1.5 MeV above the $15/2^-$ state [11]. Another possibility for a long-lived precursor might be a $17/2^+$ or $19/2^+$ state which lies below the 3592-keV level (which we have tentatively assigned to be the $15/2^+$ yrast state). However, the systematics for positive-parity yrast states in this mass region would indicate that this, too, is extremely unlikely [1,11]. Thus, the possibility that the state is being fed by a strong transition from a long-lived precursor is difficult to explain, given the apparent structure involved.

It seems possible that the ^{9}Be(^{36}S,pn)^{43}K reaction mechanism could be strongly influenced by nuclear structure effects. When light, cluster-structured nuclei interact, other reaction mechanisms may compete effectively with the fusion-evaporation process. However, this approach does not lend itself to a simple explanation for the misalignment either.

Experiments designed to search for the $19/2^- \rightarrow 15/2^-$ transition in ^{43}K could prove interesting. It might also be interesting (albeit difficult) to measure p-n-γ angular correlations associated with populating these states with the ^{9}Be(^{36}S,pn)^{43}K reaction.

IV. COMPARISON TO THEORY

The low-lying positive parity states in ^{43}K can, to first order, be described as a $1d_{3/2}$ proton hole weakly coupled to four $1f_{7/2}$ neutrons, although the extreme weak coupling model is inadequate to give complete, accurate descriptions of these states. Calculations for single-hole states in ^{43}K have been performed by Johnstone [4]. The model space included the $(1f_{7/2})^4(d_{3/2}s_{1/2})^{-1}$ and $f^3_{7/2}p_{3/2}d^{-1}_{3/2}$ configurations, and the parameters of the neutron and particle-hole interaction were determined by least-squares fit to energy levels of Ca and K isotopes. The energy levels predicted for positive-parity states in ^{43}K are compared to those seen in the present work (including tentative assignments) in Fig. 4. As discussed by Mordechai and co-workers [3], these calculations reproduce the energies of the $J=1/2$, 5/2, 7/2, and 11/2 positive-parity yrast states in ^{43}K quite well. The energies of the $13/2^+$ and $15/2^+$ yrast levels were calculated to be 3.14 and 3.5 MeV, respectively. Our strongest candidates for these states lie at 3140 and 3592 keV, respectively, in excellent agreement with Johnstone's predictions. In a weak coupling shell-model picture, the lowest negative-parity states of ^{43}K should be composed primarily of two $d_{3/2}$ proton holes coupled to $J^\pi=0^+$, and a $1f_{7/2}$ proton coupled to four $f_{7/2}$ neutrons. This gives rise to multiplets based on 0^+, 2^+, 4^+, etc., couplings of the four neutrons. As pointed out by Behbehani *et al.* [2], a similar configuration should dominate for negative parity states in ^{45}Sc, except that the two $d_{3/2}$ proton holes would be filled. As mentioned in the previous section, the $B(E2)$ values for corresponding transitions in the yrast cascade, $15/2^- \rightarrow 11/2^- \rightarrow 7/2^-$, are in excellent agreement for ^{45}Sc and ^{43}K [2]. We are aware of no theoretical calculations for negative parity states in ^{43}K.

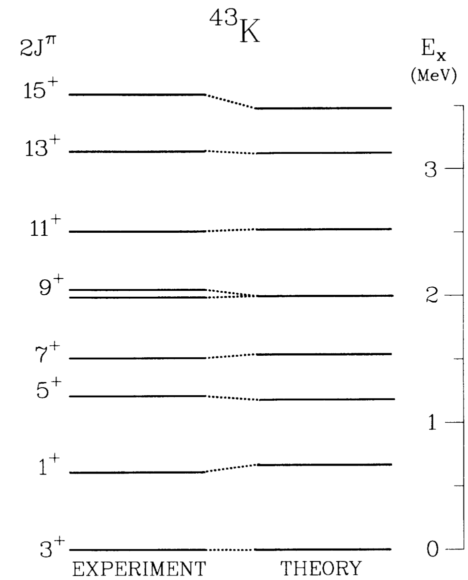

FIG. 4. Comparison of experimental energy levels (present work) with theoretical predictions of Johnstone [4]. Spins and parities shown are theoretical only, but correspond to established or tentative values deduced from experimental work.

V. SUMMARY AND CONCLUSIONS

The ^{9}Be(^{36}S,$pn\gamma$)^{43}K reaction was used to study high-spin states in ^{43}K. A new decay scheme has been established with five previously unreported transitions. We have identified two stretched-$E2$ yrast decay chains, one of each parity, and both apparently starting at $J=15/2$. The alleged $15/2^+$ state seems to be highly aligned in the experiment, whereas the $15/2^-$ state is much less aligned, an effect for which we have no explanation. Energies of positive-parity levels predicted in the shell-model calculations of Johnstone are in good agreement with experiment.

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