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Neutron alignment at the first crossing in ^{78}Kr

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The inverted ^{12}C(^{68}Zn,2n) reaction was used to populate states in ^{78}Kr in the region of the first alignment of the yrast band at $\hbar\omega=0.56$ MeV. The precessions of these states in the transient magnetic field of an ^{54}Fe foil were measured to determine the nature of the alignment. The relatively small precession angle of the 8^+ state indicates that the aligning nucleons at the first crossing are neutrons. This is contrary to expectations based on the systematics in this region, and it suggests this shape-coexistent nucleus has an oblate shape throughout the ground state band.

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The recent extensions of high-spin energy levels in the isotopes ^{74}Kr [1,2] and ^{76,78}Kr [3,4] have revealed striking similarities in structures. For example, the yrast bands display a strong upbend at rotational frequencies $\hbar\omega\approx 0.6$ MeV, and the negative parity bands are classic examples of rigid notation with $\mathcal{J}^{(1)}=\mathcal{J}^{(2)}$—the large deformation and rigid nature of these states suggests they are formed with a broken proton pair lying just below the large deformed shell gap at particle number 38. Lifetime measurements have indicated moderate to large quadrupole deformations which are supported by numerous theoretical calculations. One irregularity in the comparison of these isotopes is that, while the yrast band alignment of ^{74}Kr and ^{76}Kr is so large that it can only be explained by simultaneous alignment of $g_{9/2}$ protons and neutrons, in ^{78}Kr the first modest alignment occurs 70 keV earlier than in ^{76}Kr and a second much-delayed crossing is seen at $\hbar\omega=0.85$ MeV. These differences—particularly the delay in the second alignment—have been very hard to explain theoretically. It can be misleading to infer the character of the alignments by extrapolations from neighboring isotopes and isotones since the shape and structure of these nuclei change rapidly with neutron and proton number. The best way is through g factor measurements. For proton alignment there is a significant increase in the g factors above the crossing region when compared with the lower spin states, while for neutron alignment the g factors are reduced and may even be negative. In the experiment reported here, we observed the precession of the 8^+ yrast state in ^{78}Kr in the transient field of an ^{54}Fe foil. The precession is related to the g factors of the 8^+ state and the short-lived 10^+ and 12^+ states which feed it. In a similar experiment, Ward *et al.* [5] used the rotations of the 2^+, 4^+, and 6^+ states in ^{78}Kr as probes to compare average g factors of states (predominantly non-yrast) above the alignment region with those below, but they detected no difference. They suggested that the strong effects of neutron or proton alignment were averaged out in the low-spin probe states. It thus seemed very desirable to repeat the measurement with high statistics for ^{78}Kr and to focus particularly on the yrast $8^+,10^+,12^+$ sequence.

The apparatus, experimental method, and analysis pro-

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cedure have been described in some detail in Ref. [6]. The states of interest were populated by the inverted ^{12}C (^{68}Zn,2n)^{78}Kr reaction. The beam was provided by the VICKSI Cyclotron at the Hahn Meitner Institute, Berlin. The low beam energy of 195 MeV was chosen to minimize the feeding delay from the continuum to the yrast states. The carbon target was deposited by an aquadag spray to a thickness for 0.4 mg/cm^2 on a 6.8 μm rolled and annealed ^{54}Fe foil, backed with 5 mg/cm^2 of copper. The foil was polarized in a periodically reversing field of 0.15 T provided by a small electromagnet. The excited nuclei recoiled through the iron with an initial velocity of 0.063c, where the transient field precessions were accumulated, and stopped in the copper where the cascade to the ground state was completed. The nuclear precessions were determined for these stopped nuclei by measuring the small rotations (about 3°) of the γ-ray distribution patterns about the applied magnetic field. The γ rays were detected by four large-volume Ge detectors positioned at ±56° and ±124°. Neutrons were detected at forward angles by a seven-element array described in Ref. [7] incorporating both time-of-flight and pulse shape discrimination. Singles and neutron-gated γ-ray spectra were collected. The rotations were deduced from the double ratio, ρ, of counting rates for the two field directions:

$$\rho_\theta = \frac{N_{+\theta}(\uparrow)}{N_{+\theta}(\downarrow)} \frac{N_{-\theta}(\downarrow)}{N_{-\theta}(\uparrow)}, \quad \rho = \sqrt{\rho_{56°}\rho_{124°}}$$

and then the precession angles were obtained from

$$\Delta\phi = \frac{(\sqrt{\rho}-1)}{(\sqrt{\rho}+1)} \frac{1}{S(\theta)} .$$

The logarithmic slopes $S(\theta)=(1/W)(dW/d\theta)$ were measured during the experiment by monitoring the change in counting rates when the forward detectors were rotated by ±4° from their mean position.

The observed γ-ray cascade is shown in Fig. 1 and an example of the neutron-gated spectra is given in Fig. 2. An accurate measurement of the slopes $S(\theta)$ for these transitions is difficult because the line shapes of the shorter-lived states are substantially Doppler broadened, and also the forward focusing of neutrons in this highly inverted heavy ion reaction causes a reduction in the Ge detector photopeak efficiency at the more forward angles [5] which weakens the apparent anisotropy of stretched $E2$ transitions. In producing the best set of values for the cascade we have also considered the angular distribution results of Hellmeister et al [8]. Following the procedure described in Ref. [6] we have fitted the experimental values to a model of the cascade which, apart from six mixing ratios, has a single free parameter which is the attenuation coefficient [9] of the entry spin alignment. Model results for the yrast cascade are shown in Table I. The anisotropies are weaker than expected when compared with results of the similar ^{12}C(^{72,74}Ge,2n)^{82,84}Sr reactions [6] but since we fit the whole cascade with a single attenuation coefficient the relative slopes—and hence the deduced relative transient field precessions—should be reliable.

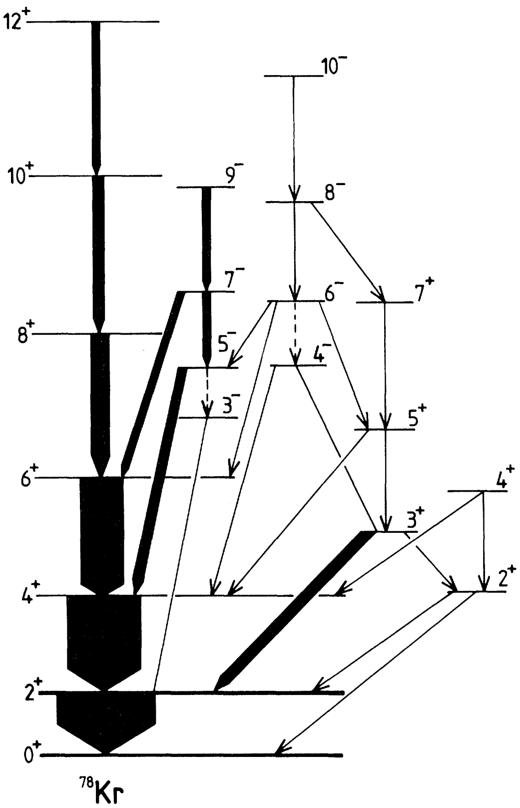

FIG. 1. The γ-ray cascade observed in the present work. The widths of the arrows represent the γ-ray intensities.

A good statistical accuracy for the double ratios was obtained from the neutron-gated spectra for most of the states of interest. Despite the increased background in the singles spectra the agreement between the singles and coincidence data sets was good except for a tendency of the coincidence data to show a larger precession effect. In Table I we show the deduced rotations for the yrast band from the coincidence data, using the model $S(\theta)$ values. In order to separate out the yrast cascade alone we have corrected the observed rotations for every feeding rotation shown in Fig. 1 other than the in-band feeding and the extent to which this affects the data can be seen by comparing the "Raw" and "Corrected" rotations $\Delta\phi_{\rm coinc}$ from the neutron-coincidence spectra. The corrected "singles" results are shown for comparison. Since the experiment is so similar (in recoil velocity, iron foil thickness) to that of Ward et al. [5], we have also included the results in the last column for their ^{16}O(^{65}Cu,2np) reaction. Our rotations are perhaps larger, partly because of our slightly thicker iron foil. There are also small differences in $S(\theta)$ values [Ward et al. use $S(2^+,4^+,6^+$ at 60°$)=-0.33,-0.41,-0.41$].

Ward et al. deduced an average g factor of $+0.54(5)$ from their results corresponding to the mean rotation of the 2^+, 4^+, and 6^+ states. It is similar to the value expected for collective nuclear states where $g_{\rm collective} \approx Z/A \approx +0.5$. In the present experiment we have extended the measurement to the 8^+ state. From the neutron-coincidence data we find a rotation for the

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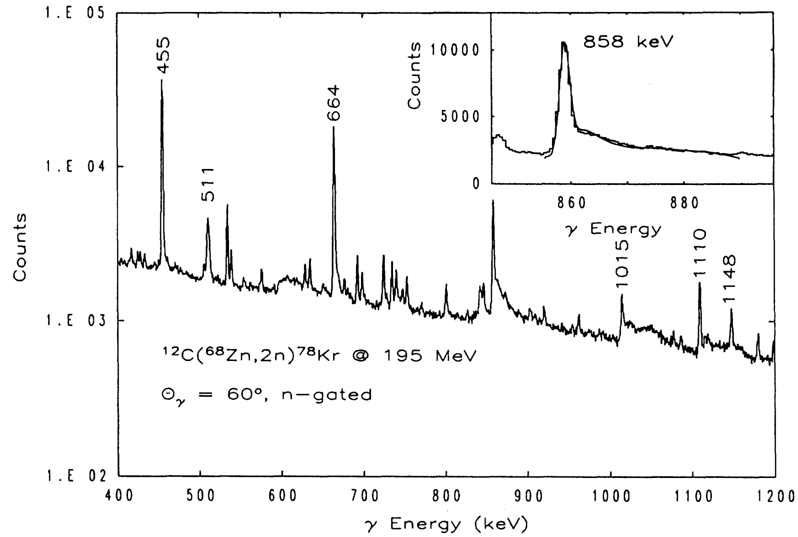

FIG. 2. The γ-ray spectrum at 60° in coincidence with neutrons. The inset shows the line shape fitted to the 858 keV ($6^+ \rightarrow 4^+$) transition.

8^+ that is only 38±13% of the mean rotation of the lower spin states (or 58±7% from the singles data). This clearly shows that some of the states above or including the 8^+ state must have *g* factors significantly smaller than the collective value. This is a strong indication of *neutron* alignment. In the case of proton alignment the 8^+ rotation would have been even higher than the mean rotation of the low spin states.

Although this conclusion appears to be based on a single data point, the reduced magnitude of the rotation is evident from the double ratios deduced from either the neutron-gated spectra or the singles spectra, for each of the two detector pairs. The same method of using the transient field technique following a heavy-ion reaction has been used previously [6] for 8^+ states in some Sr isotopes, where it correctly identified the known neutron character of the yrast 8^+ state in ^{84}Sr. In the same work, the *g* factors of the second 8^+ state in ^{84}Sr and the first and second 8^+ states in ^{82}Sr were measured, revealing the proton character of these states. The lifetimes of two of these states were about 1 ps and so the problems with the Doppler broadened line shapes were similar to those here. Thus we are confident that had the first alignment in ^{78}Kr been a proton alignment we would have seen the effect quite clearly in the present experiment.

The extent to which the 8^+ rotation reflects the *g* factors in the $8^+, 10^+, 12^+$ sequence depends on the feeding history during the time the transient field acts. In principle, this information is contained in the Doppler-broadened line shapes of the yrast γ-ray transitions. The line shapes of transitions from the 4^+, 6^+, 8^+, 10^+, and 12^+ yrast states, observed at 124° and 56°, were analyzed as described in Ref. [2]. Side feeding times were fitted as free parameters and determined to be less than 100 fs in

TABLE I. Precession angles (in mrad) measured in this experiment and compared with results of Ref. [5] for ^{78}Kr.

Transition	E_γ (keV)	Relative intensity	$S(56°)$ (model)	$-\Delta\phi_{\rm coinc}$ Raw data	$-\Delta\phi_{\rm coinc}$ Corrected	$-\Delta\phi_{\rm singles}$ Corrected	$-\Delta\phi$ [5] Raw data
Ground state band							
$2^+ \rightarrow 0^+$	455	64.3[a]	−0.369	40.7(7)	39.5(18)	33.4(15)	31(4)
$4^+ \rightarrow 2^+$	664	54.6[a]	−0.387	44.9(10)	43.0(15)	39.6(9)	32(4)
$6^+ \rightarrow 4^+$	858	38.0[a]	−0.397	52.3(16)	50.7(19)	43.9(11)	47(14)
$8^+ \rightarrow 6^+$	1015	18.1	−0.399	16.8(55)	16.8(55)	23.3(28)	
Negative parity states							
$5^- \rightarrow 4^+$	1630	6.7	+0.253	55(9)			
$7^- \rightarrow 6^+$	1310	5.1	+0.253	51(11)			
$7^- \rightarrow 5^-$	539	4.1	−0.399	71(7)			
$9^- \rightarrow 7^-$	740	5.6	−0.399	75(7)			
$6^- \rightarrow 6^+$	1242	1.4	−0.403	64(19)			
$6^- \rightarrow 5^+$	920	1.8	+0.253	64(22)			
$8^- \rightarrow 6^-$	698	3.8	−0.399	65(8)			
Positive parity states							
$2_2^+ \rightarrow 0^+$	1148	3.9	−0.399	20(8)			
$4_2^+ \rightarrow 2_2^+$	725	7.4	−0.399	22(4)			
$5^+ \rightarrow 3^+$	735	5.2	−0.399	43(5)			

[a]Relative intensity after all observed discrete feeding contributions have been subtracted. The relative intensity before this correction was 100 for the 2^+ state.

all cases. The line shape of the 858 keV transition is given in the inset of Fig. 2. The results of the lifetime analysis are given in Table II and are in agreement with previous work [8,10]. Unfortunately, the decays from the 12^+ and 10^+ states have the same energy (1112 keV) and it was not possible to unfold the two line shapes. However, there was no indication of any abnormal delay in the decay of these states and the side-feeding times deduced from the 8^+ and 6^+ line shapes are $\tau_f=0.04(3)$ ps and 0.07(3) ps, respectively. We define the effective g factor of a state J^π as $-\Delta\phi(J^\pi)\hbar/(\mu_N \int B_{\rm TF} dt)$ where the transient field strength $B_{\rm TF}$ is integrated over the transit time of the nuclei in the iron foil. We can calculate the individual state contributions to the effective g factor of the 8^+ state using the feeding pattern of Fig. 1 and the life times published by Hellmeister [8]:

$$g_{\rm eff}(8^+)=41\% g(8^+)+42\% g(10^+)+17\% g(12^+) \quad (\tau_f=0.0 \text{ ps}) \qquad (1)$$

or, taking 0.2 ps as a reasonable upper limit for the side-feeding times,

$$g_{\rm eff}(8^+)=26\% g(8^+)+25\% g(10^+) +12\% g(12^+)+36\% g_c \quad (\tau_f=0.2 \text{ ps}),$$

where g_c is the continuum g factor. It is clear that the value of the effective g factor is dominated by the values of the states through the first alignment. For example if we consider a simple model where the 2^+, 4^+, 6^+, and 8^+ states all have g factors of $+0.5$ and the 10^+ and 12^+ states have g factors of $+0.18$ and $+0.23$ respectively (calculated [11] assuming $4\hbar$ of neutron alignment) then we find using Eq. (1) $g_{\rm eff}(8^+)=63\% g_{\rm eff}(2^+)$ compared with 43(14)% (coincidence data) and 70(9)% (singles data) from the present work. Note this comparison is independent of the transient field calibration.

We mention briefly the results for the rest of the ^{78}Kr cascade, which also are displayed in Table I. The negative parity states ($9^-,8^-,7^-,6^-$) all show similar rotations of 55–75 mrad which are significantly larger than the low-spin yrast rotations. This is strong evidence for the dominant proton structure of these bands. Similar observations have been made on the low-spin negative parity states in ^{82,84}Sr [6]. The lowest rotations are seen for the 4_2^+ and 2_2^+ states of the positive parity side band [22(4) mrad and 20(8) mrad respectively] which are smaller than the expected collective-band value. There were indications [6] that the 2_2^+ states in ^{82,84}Sr also had low g factors and this may be a general property of this quasi-gamma band.

A detailed discussion using systematics and Hartree-Fock-Bogolyubov cranking (HFBC) calculations with a Woods-Saxon potential was given by Gross *et al.* [3] and they concluded that the first yrast band crossing is most likely proton alignment based on systematics and the lack of a crossing in the negative parity bands for $\hbar\omega \leq 0.65$ MeV. They did note, however, that HFBC calculations supported both proton and neutron scenarios but for different nuclear shapes (prolate for proton alignment and oblate for neutron). Our result for the 8^+ rotation strongly favors the neutron alignment description, requiring an oblate shape for the ground state band of this nucleus. In figure 13 from Ref. [3] the predicted band crossing frequencies in the axial limit for proton and neutron quasiparticles are given as a function of β_2 for oblate and prolate shapes. The observed yrast band crossings ($\hbar\omega_1=0.56$ and $\hbar\omega_2=0.85$ MeV) are best described by a large oblate deformation ($\beta_2 \geq 0.30$) with $\hbar\omega_\nu=0.55$ and $\hbar\omega_\pi=0.80$ MeV. This is to be expected as the Coriolis force acts more strongly on the low-K orbitals and the neutron Fermi surface lies higher in the $g_{9/2}$ shell. We note that this deformation is much larger than that predicted by Gross *et al.* for the secondary potential energy minimum ($\beta_2=-0.25$). Quadrupole moments derived from lifetime measurements [10], however, are in good agreement with the larger value. The lack of an early (neutron) crossing in the negative parity (proton) bands can then be attributed to a difference in shape. The HFBC calculations predict a large prolate deformation whose magnitude ($\beta_2 \approx 0.4$) agrees well with that derived from lifetimes [10]. Galeriu *et al.* [12] have applied the Nilsson-Strutinsky model to the light Kr and Sr isotopes. They accurately predict the large prolate deformations in the Sr isotopes and the shape coexistence in the Kr isotopes. For ^{78}Kr they predict an oblate deformation of $\beta_2=-0.32$ in good agreement with experiment and our results. Their potential energy surface also indicates that the shape coexistent prolate minimum lies higher in energy and thus does not become yrast around spin 6^+ as is thought [3] to occur in the lighter Kr isotopes. We also note that the calculations of Möller and Nix [13] predicted an oblate ground state deformation of $\beta_2=-0.20$.

To conclude, we have measured the average g factors for bands in ^{78}Kr and have confirmed the previously suggested proton character of the negative parity bands. The first observed alignment in the yrast band is assigned to $g_{9/2}$ neutron alignment which is expected to occur at

TABLE II. Lifetime and feeding time results from the line-shape analysis.

Yrast state	Lifetime (ps) Ref. [8]	Ref. [10]	Present work	Sidefeeding time (ps) Present work
4^+	3.6(3)	3.7(5)	3.9(5)	≤ 0.1
6^+	0.90(15)	0.85(20)	1.2(2)	0.07(3)
8^+	0.45(6)	0.32(6)	0.53(7)	0.04(3)
10^+	≤ 0.5	0.30(6)	0.6(2) (effective)	
12^+		0.25(15)		

oblate shape. The lack of such a crossing in the negative parity bands suggest that their shapes (and hence their Fermi surfaces) are different. HFBC calculations [3] support these interpretations but do not predict the large oblate ground state deformation. The Nilsson approach of Galeriu *et al.* [12] does predict a large oblate ground state deformation. Our result brings into question the suggested alignment pattern in ^{74,76}Kr that aligned protons trigger a subsequent neutron alignment. This work illustrates the danger of using only systematics to argue the character of band crossings and highlights the importance of magnetic moment studies.

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