

## Alignment Delays in the $N = Z$ Nuclei $^{72}\text{Kr}$ , $^{76}\text{Sr}$ , and $^{80}\text{Zr}$

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The ground state rotational bands of the  $N = Z$  nuclei  $^{72}\text{Kr}$ ,  $^{76}\text{Sr}$ , and  $^{80}\text{Zr}$  have been extended into the angular momentum region where rotation alignment of particles is normally expected. By measuring the moments of inertia of these bands we have observed a consistent increase in the rotational frequency required to start pair breaking, when compared to neighboring nuclei.  $^{72}\text{Kr}$  shows the most marked effect. It has been widely suggested that these “delayed alignments” arise from  $np$ -pairing correlations. However, alignment frequencies are very sensitive to shape degrees of freedom and normal pairing, so the new experimental observations are still open to interpretation.

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Short range correlations of fermions to form bosonlike “Cooper pairs” are known to have a dramatic influence on physical observables in materials, causing effects such as superfluidity and superconductivity. The nature of these correlations is described by the Bardeen-Cooper-Schrieffer (BCS) pairing theory. Their strength has been extensively investigated through the destruction of the pair field by temperature or by magnetic fields. In nuclei, similar correlations play a crucial role in nuclear structure, especially of even-even nuclei where all the particles can be paired. The conditions for BCS-type pair fields are not always satisfied in nuclei, due to their small size leading to low level densities, and because the absolute number of particles in a nucleus is relatively small. However, it is well known that in most nuclei the observed properties can be described only if a pairing field is assumed. Experimentally, the most clear-cut way to investigate nuclear pairing is through transferring pairs of particles using light-ion transfer reactions such as  $(p, t)$  or  $(t, p)$  and measuring the probability of levels near the Fermi surface being occupied by scattered pairs [1]. Less directly, as pairing reduces the moment of inertia of deformed nuclei by about a factor of 2 compared to the rigid body value, the variation of the moment of inertia with angular momentum has been a useful tool for investigating the strength of pairing fields, in close analogy with the destruction of superconductivity by magnetic fields.

The effect of Coriolis forces on the pair field in well-deformed nuclei has been extensively investigated both experimentally and theoretically, and models with good predictive power have been developed [2–5] which cal-

culate the frequencies where pairs break. In heavy nuclei separate neutron and proton pair fields exist, each consisting of pairs of identical particles in time reversed orbits which are coupled to angular momentum  $J = 0\hbar$ , and isospin  $T = 1$ . In light nuclei, the neutron and proton Fermi surfaces can be equal ( $N = Z$  nuclei) and neutron-proton pairs should also be involved, either coupled to  $J, T = 0, 1$  (as in “normal” pairing) or with an isospin antisymmetric wave function with  $T = 0$  and  $J \neq 0$ , or both. The properties of  $np$  pairs have attracted interest over the years from Elliott [6], Goodman [7], Pittel [8], and others. Until recently, a serious impediment to progress has been the inaccessibility of intermediate-mass  $N = Z$  nuclei; they lie far from stability, and can be produced only with low cross-sections when stable beams and targets are involved.

Advances in experimental technique have opened up the  $N = Z$  line between  $^{56}\text{Ni}$  and  $^{100}\text{Sn}$  to observation. Considerable interest has turned to the issue of  $np$  pairing. An extensive review of recent calculations is presented in Ref. [7]. One particular line of investigation [7,9–12] involved consideration of the robustness of the various pair fields against rotation, and the realization that  $T = 0$  pairs are less easily destroyed by Coriolis forces, so it may be more important at high angular momentum when other fields are quenched. As these pairs are not easily broken, irregularities in the moment of inertia (“alignments” or “backbends”) are predicted to be delayed to higher rotational frequencies [10,11] or may disappear altogether [12]. At present, many calculations are schematic and reach widely differing conclusions on the role and relative

importance of  $T = 0$  and  $T = 1$   $np$  pairs. In this Letter we report on new experiments aimed at studying  $\gamma$  rays from rotational bands of  $N = Z$  nuclei in the middle of this region where deformations are large ( $\beta_2 \sim 0.4$ ) and there should be sufficient valence particles to support pairing fields. At the outset of this study, no data on the angular momentum region of interest existed. The goal was to identify levels above the region of spin where pair breaking is normally found, i.e., in the  $J = 8$  to  $14\hbar$  regime where  $g_{9/2}$  particles in this mass region normally align. Further, we wanted to study several nuclei systematically, in order to look for consistently delayed alignments which may be expected if a new collective pair field was in action. This research extends the work of deAngelis *et al.* [13], who suggested an  $np$ -pairing driven delayed alignment in  $^{72}\text{Kr}$ .

$^{72}\text{Kr}$  was produced in the  $^{40}\text{Ca}(^{40}\text{Ca}, 2\alpha)$  reaction at 160 MeV. Gamma rays were detected using the Gammastere detector, consisting of 101 Compton-suppressed high-purity germanium detectors. Channel selection was achieved using the Microball CsI light-charged particle detector. The efficiency for  $2\alpha$  detection was measured to be  $\sim 16\%$ . The cross section for  $^{72}\text{Kr}$  production was estimated to be  $120 \mu\text{b}$ .  $^{76}\text{Sr}$  and  $^{80}\text{Zr}$  were produced by the inverse  $^{24}\text{Mg}(^{54}\text{Fe}, 2n)$  and  $^{24}\text{Mg}(^{58}\text{Ni}, 2n)$  reactions at 180 and 200 MeV respectively. In these cases, channel selection was achieved using the Argonne fragment mass analyzer (FMA) with an ion chamber at the focal plane to allow the atomic numbers to be inferred from energy loss measurements. The FMA efficiency was about 12%, and the production cross sections were consistent with a previous measurement [14] of approximately  $10 \mu\text{b}$ .

Spectra of  $\gamma$  rays from the ground state bands of  $^{72}\text{Kr}$ ,  $^{76}\text{Sr}$ , and  $^{80}\text{Zr}$  are shown in Fig. 1. A tabulation of the relevant  $\gamma$ -ray energies and intensities can be found in Table I. In the upper panel, Fig. 1a, the  $2\alpha$ - $\gamma\gamma$  gated spectrum clearly shows the  $^{72}\text{Kr}$  ground state sequence extending above spin  $J = 26$ . The assignments of deAngelis *et al.* [13] were confirmed to spin  $J = 14$ , but the highest transition they reported, a 1368 keV  $\gamma$  ray, was not found to be a member of the yrast cascade. Instead, the band continues to spin 18 where an irregularity is clear, before smoothly continuing to the highest spin we observe, at  $J = 26$ . In addition, above spin  $J = 12$ , we find a fork in the ground state rotational band, with a more irregular second sequence apparently becoming yrast. This sequence appears to be a more spherical irregular “terminating” configuration, and does not enter into the following discussion of rotational alignment. In Fig. 1b the ground state sequence of  $^{76}\text{Sr}$  is shown. The best data on the ground state band come from applying mass, energy loss, and single  $\gamma$  gates. The dramatically lower cross section for strontium production is clearly evident. However, the band can be extended above spin  $J = 16$ , a considerable advance over the original study [14] which was limited to  $J = 4$ .  $^{76}\text{Sr}$  gated  $\gamma\gamma\gamma$  data indicate a tentative  $18 \rightarrow 16$  transition of 1666 keV. Figure 1c shows a  $^{80}\text{Zr}$  gated  $\gamma$  singles spectrum with contributions from

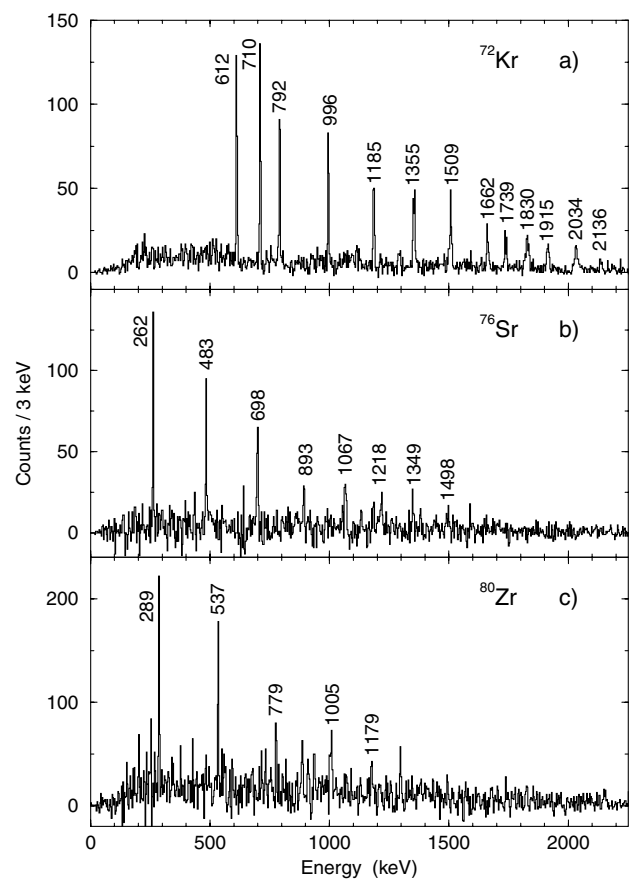


FIG. 1. Gamma-ray spectra of the ground state cascades in  $N = Z$  nuclei: (a)  $^{72}\text{Kr}$  ( $2\alpha$ -gated  $\gamma\gamma\gamma$  data, sum of  $\gamma\gamma$  gates with one transition below and one transition above  $J = 14$ , production cross section  $\sim 120 \mu\text{b}$ ); (b)  $^{76}\text{Sr}$  ( $A/Q = 76/24$  and  $dE/dx$  gated  $\gamma\gamma$  data, sum of  $\gamma$  gates for transitions below  $J = 10$ ,  $\sim 20 \mu\text{b}$ ); (c)  $^{80}\text{Zr}$  ( $A/Q = 80/25$  and  $dE/dx$  gated  $\gamma$  singles,  $\sim 10 \mu\text{b}$ ).

yttrium and strontium isobars subtracted. The data set on  $^{80}\text{Zr}$  is smaller than that for  $^{76}\text{Sr}$ , as the experiment was a trial run for this kind of study, the acquisition time shorter, and the cross section slightly lower. The  $^{80}\text{Zr}$   $\gamma\gamma$  coincidence data were very sparse, and could not be completely separated from  $^{80}\text{Y}$ , which is produced 400 times more intensely and has transitions of similar energies to  $^{80}\text{Zr}$ . However, the data were sufficient to verify the cascade coincidence relationship of the five transitions in Fig. 1c and Table I. Transitions of 1300 and 890 keV, visible in Fig. 1c, appear to be associated with  $^{80}\text{Zr}$  but do not form part of this sequence, perhaps belonging to the  $\gamma$  band. Clearly, a further study of  $^{80}\text{Zr}$  to obtain more data is both feasible and desirable.

The method of converting the sequence of  $\gamma$  rays into moments of inertia is well established [2]. Two moments are frequently considered: the kinematic moment,  $J^{(1)}$ , which is the slope of an energy vs (spin)<sup>2</sup> plot and is numerically equal to the recipe used in older “backbending” analyses; and its derivative, the dynamic moment of inertia  $J^{(2)}$ . In the heavy deformed nuclei of the rare earth and actinide regions, the deformation is

TABLE I. Ground state cascades for the nuclei  $^{72}\text{Kr}$ ,  $^{76}\text{Sr}$ , and  $^{80}\text{Zr}$ . Data were  $2\alpha$ -gated  $\gamma\gamma\gamma$  triples for krypton, mass and charge gated  $\gamma\gamma$  doubles for strontium, and mass and charge gated  $\gamma$  singles for zirconium. The intensities for  $^{72}\text{Kr}$  were from  $\gamma$  triples data and thus have been normalized to the  $8 \rightarrow 6$  transition, which is estimated to be half the  $2 \rightarrow 0$  flux. Transitions identified by an asterisk (\*) have measured  $\gamma$ -ray angular distributions consistent with quadrupole radiation.

$J_i$	$^{72}\text{Kr}$		$^{76}\text{Sr}$		$^{80}\text{Zr}$	
	$E_\gamma$ (keV)	$I$ (arb.)	$E_\gamma$ (keV)	$I$ (arb.)	$E_\gamma$ (keV)	$I$ (arb.)
2	710.1(2)*	(~200)	261.5(3)*	100	288.9(2)*	100
4	611.8(2)*	...	483.2(3)*	76(6)	536.9(3)*	80(10)
6	791.5(2)*	...	697.9(5)*	67(11)	779.2(5)	60(10)
8	995.6(2)*	100	893.3(5)*	33(6)	1005(1)	43(8)
10	1185.0(3)*	76(12)	1067(1)*	33(8)	1179(1)	25(5)
12	1354.9(3)*	61(11)	1218(1)	21(6)		
14	1508.9(3)*	65(12)	1349(1)	21(8)		
16	1662.0(6)*	39(10)	1498(2)	15(8)		
18	1738.6(6)*	26(9)	(1666)	<10		
20	1829.7(1)	36(12)				
22	1915(1)	25(9)				
24	2034(1)	19(6)				
26	2136(2)	9(4)				

quite constant and stable, and so changes of the moment of inertia directly give information on the pair field. Further, for rigid shapes, a core moment of inertia can be fitted (a reference) and the total angular momentum then decomposed into “core” and “aligned particle” components. In the mass  $A = 80$  region, it has long been known that these premises are less valid [3] as the alignment of particles can have a significant polarizing effect on the core [15,16]. Consequently, the extraction of the crossing frequency, alignment, and interaction strengths need to be treated with caution. Despite these concerns, the reduction of the data to kinematic and dynamic moments of inertia serves as a useful basis for interpretation and comparison with neighboring nuclei. Such a comparison is shown in Fig. 2 where we present  $J^{(1)}$  (top panels) and  $J^{(2)}$  (bottom

panels) for each of the nuclei of interest, compared to its nearest neighbors with  $N = Z + 2$  [17] and  $N = Z + 4$  [18–20].

Sharp upbends are found in  $^{74,76}\text{Kr}$  at  $\hbar\omega = 0.65$  MeV associated with simultaneous proton and neutron alignment. An important recent study of  $^{74}\text{Kr}$  shows that the nucleus shrinks 30% in quadrupole deformation during this process and at higher frequencies, shifting the neutron crossing down in frequency to overlap the proton alignment [15]. In  $^{72}\text{Kr}$ , no sudden discontinuities of this type are found at low frequency, just a more gradual interaction at  $\hbar\omega = 0.85$  MeV. It is unclear why an analogous alignment to  $^{74,76}\text{Kr}$  is not seen in  $^{72}\text{Kr}$ , perhaps suggesting that new correlations are in play. We performed a traditional rigid-cranking analysis, with

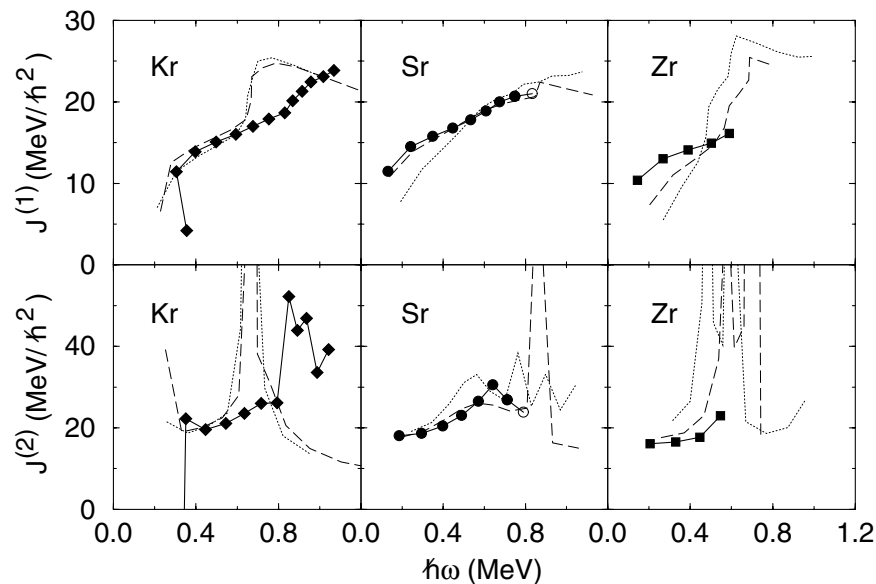


FIG. 2. The kinematic moments of inertia  $J^{(1)}$  (top panels) and dynamic moments of inertia  $J^{(2)}$  (bottom panels) of the ground state bands of  $^{72}\text{Kr}$ ,  $^{76}\text{Sr}$ , and  $^{80}\text{Zr}$  calculated according to Ref. [2]. Tentative data points are marked with open symbols. The dashed curves are the moments of inertia for isotopes with  $N = Z + 2$ , and the dotted curves for isotopes with  $N = Z + 4$ .

normal pairing fields, and found that it is possible to shift the alignments up to high frequency only by invoking an unrealistically large deformation ( $\beta_2 > +0.45$ ), or by invoking a highly deformed, collectively rotating oblate shape with ( $|\beta_2| > 0.3$ ). The latter seems unlikely as the band has almost the same moment of inertia as its neighbors which are known to be prolate at intermediate spin. Data on  $^{73}\text{Kr}$  [21] show that the odd- $A$  nucleus has an alignment pattern very similar to  $^{74}\text{Kr}$ , further highlighting the unique nature of the band crossing in  $^{72}\text{Kr}$ . In strontium isotopes the effect is more subtle as the interaction between ground-state and aligned bands is very large, so no abrupt irregularities are seen in either  $N = Z$  or  $N = Z + 2, 4$  isotopes. Only the dynamic moments of inertia reveal the crossing location and frequency.  $^{78,80}\text{Sr}$  have very similar proton crossings at  $\hbar\omega = 0.55$  MeV.  $^{76}\text{Sr}$  has an interaction of similar strength to its isotopes, but again shifted upwards, to  $\hbar\omega = 0.62$  MeV. Finally, in the zirconium isotopes, where sharp alignment irregularities are known in  $^{84}\text{Zr}$  and heavier nuclei, arising from proton pair breaking below  $\hbar\omega \sim 0.5$  MeV, we find that the  $^{80}\text{Zr}$  ground state band is smooth to the highest frequency we observe ( $\hbar\omega \sim 0.6$  MeV), again indicating an alignment delay. However, we note that  $^{82}\text{Zr}$  [17] shows similar behavior, so the situation is even less clear-cut. A recent experiment [22] has identified the ground state sequence in  $^{88}\text{Ru}$  which reveals another smoothly spaced sequence of transitions extending beyond the rotational frequency where alignment is expected. Thus, in cases from  $N = Z = 36$  to 44, there is consistent evidence that particle alignments are all shifted to higher frequency than is expected from systematic trends, and for  $N = Z = 36, 38$  the crossing frequency has been located.

There has been considerable theoretical speculation that such shifts may be an experimental manifestation of  $np$  pairing. To understand our observations a self-consistent analysis is needed, building on both the new  $N = Z$  measurements and the extensive data with  $N > Z$ . Careful studies of the  $N = Z + 2$  nuclei [15,17] which can be produced hundreds of times more prolifically, and are more extensively known, strongly constrain our interpretations. It is already clear that the situation is more complicated than originally perceived. In the nuclei under study, the band crossings are not a clean experimental probe of pairing, as the nuclei are easily polarized by changing the population of individual orbits, so "rigid-core" assumptions are not valid. Further, there is a close link between the equilibrium shapes and pairing. Modification of the strength and type of pair fields, especially introducing pairs not coupled to  $J = 0$ , will change the deformation, as  $J = 0$  coupling favors more spherical shapes to maximize degeneracy and overlap. Many theoretical groups are working on this interesting problem.

In conclusion, we have experimentally demonstrated a consistent shift to higher frequencies of the alignment of  $g_{9/2}$  particles in the ground state bands of  $N = Z$  nuclei

from krypton to zirconium. A similar observation has very recently been made for  $N = Z$  ruthenium [22]. The effect is most striking for  $^{72}\text{Kr}$ , more modest in  $^{76}\text{Sr}$ , and a limit in  $^{80}\text{Zr}$  and  $^{88}\text{Ru}$ . Considerable progress is still needed to reach an unambiguous understanding of these results. In experiment, progress can be made on even-even nuclei through measuring the transitional collectivity of the new bands and extending the data on the heavier systems, while studying the odd-odd  $N = Z$  nuclei can improve our understanding of  $np$  coupling. In theory, fully self-consistent analyses of shapes and pair fields across the entire region are badly needed.

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