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Oblate Shapes and Alignment Delays in N=Z Nuclei from Se to Zr

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It has been 12 years since we had a conference dedicated to the zirconium region [1]. It is surprising that there are still things of interest to discuss after so much work on these nuclei. However, due to a re-evaluation of the workings of the astrophysical r-p process, due to steady improvements in theory, and due to considerably improved experimental technique, these nuclei are more in the mainstream of nuclear structure than ever before. It is appropriate to have the meeting here in Lund, as a great deal of the theoretical work which made these nuclei ”credible” was initiated here. This paper covers two topics: shape co-existence and the issue of ”alignment delays”. Both topics were visited at the Bad Honnef meeting. However, it is only during the last two years that we seem to have made rapid progress. Experimentally, most of the advances have come from the large arrays (Gammasphere, GASP and Euroball) reaching maturity, especially in their triggering, but also due to the ever-growing contribution from experiments involving fast-fragmentation beams.

Oblate-Prolate Shape Co-Existence

The topic of nuclear shape polarization and the stabilization of nuclear shapes has always been interesting but has received a great deal of attention during the last three decades. Once the influence of high-j deformed single particle states in fighting surface tension had been seen as the underlying mechanism [2], and a formalism developed to incorporate these effects [3] it was realized that most nuclei have non-spherical shapes. However, the abundance of prolate shapes, and the almost total absence of well deformed oblate nuclei remained puzzling [4]. At lowest order, the energy of a deformed liquid drop is symmetrical to deformation.

A naive inspection of any deformed shell-model level scheme reveals that strongly down sloping orbits, and large shell gaps are about as common on the oblate side as on the prolate. Simple calculations involving a single N-shell, or a single j-shell also indicate oblate-prolate symmetry as the shells fill: prolate polarization at the beginning of shell, followed by oblate polarization at the end. However, several subtle effects are in play, all of which favor prolate shapes. The liquid drop energy, when expanded to higher order [5,6], has terms in odd powers of beta, making prolate shapes both more bound and have larger deformation. Further, the shells are not isolated, and mixing between shells is much more important between K=1/2 states on the prolate side than high-K states on the oblate. Finally, residual interactions between particles favor prolate deformation [7]. Thus, finding the conditions which do favor substantial oblate deformation, and quantifying it, presents an unusually stringent test of our understanding of shape-polarization in nuclei.

The mass A$\sim$80 region is interesting in the context of oblate-prolate shapes competition. The N=Z nuclei are always special in the issue of shape polarization, as neutron and proton Fermi-levels are equal, so the particles at the Fermi-surface experience common shape-polarizing forces. Experimentally, light selenium isotopes [8], with light mercury isotopes, were some of the first ever cases where evidence for shape co-existence appeared. Pioneering calculations [9] indicated that oblate shapes should be very common in the neutron deficient mass A$\sim$80 nuclei. However, as the calculations became more refined [10,11,12] it became clear that a small region of nuclei near N=Z=34,36 should contain favorable cases for having well-bound oblate deformed ground states. This polarization comes from gaps in the oblate single-particle level scheme. In contrast, most of the heavier nuclei were predicted to be influenced by the prolate N=Z=38,40 gaps and have large prolate deformations.

Ideally, the shapes of nuclei are inferred directly from the static moments of their charge distributions, particularly their quadrupole moments. For the nuclei of greatest interest, N=Z=34, ^{68}Se, and N=Z=36, ^{72}Kr, the production cross sections are about 100 μb, which is below the level which can be reached in experiments sensitive to the sign of the deformation (positive for prolate shapes, negative for oblate). The magnitude of the deformation is straightforward, and can be precisely attacked through atomic physics measurements (rms radii) or nuclear measurements (electromagnetic transition rates). For the sign of the deformation, indirect studies of the moments of inertia, and the properties of odd-A neighbors must be invoked. For example, for a rigid body, oblate shapes have a moment of inertia smaller than an equivalent-mass sphere, while prolate shapes have a larger moment. With rotation, particle alignments (backbending) are more favored in prolate bands. Finally, if a nucleus has distinct prolate and oblate bands, then the band mixing is normally small. All these signatures we studied in N=Z=34 selenium.

^{68}Se was produced in the inverse ^{12}C(^{58}Ni,2n) reaction at 180 and 220 MeV using a 400 μg/cm^2 target. Identification of the residues was by the "Daresbury Method" [13], using the Argonne Fragment Mass Analyzer (FMA) for mass identification, and a standard ion chamber for Z-identification. For this reaction, and in the experimental geometry with the FMA subtending only 2 msr, the recoil detection was still quite efficient, about 10%. Ions of a single mass, A=68, and charge state, Q=25 were selected by focal plane slits, although some ions with A=65 and Q=24, and some scattered beam particles entered the ion chamber. For the ions under study, with energy of about 2 MeV/u, excellent Z-separation was achieved, with ΔE/E resolution of 2.5%. Gamma rays were detected in Gammasphere [14], consisting of 101 Compton suppressed high-purity germanium detectors. This allowed the creation of almost clean ^{68}Se spectra for analysis, despite the production cross-section being only 1/2000 of the evaporation residues. ^{68}Se has two distinct bands, and careful analysis of γ-γ coincidences, and angular distributions were needed to construct the decay scheme. A synopsis of our measurements is given in Table I. The low energy two-neutron evaporation reaction was especially useful in this case where observation of both yrast and non-yrast structures was essential. The 180 MeV run only populated the lowest states, which helped confirm their placement.

All the features expected for an oblate configuration are exhibited in the ^{68}Se ground state band. It has an unusually low moment of inertia, does not show and sudden alignments and does not interact strongly with the excited band [15]. In contrast, the excited band has characteristics of a prolate shape, with a larger moment of inertia, and an alignment. Because the two bands appear so distinct, we carefully looked for evidence for the excited prolate J=0 shape isomer. No evidence was found, though the nature of this experiment, which involved the residues flying away from the detector, was not very sensitive. No evidence of delayed γ-rays was found in fragmentation experiments either [16], though it is quite possible that the shape isomer lies close to (or below) the first J=2 state, so would decay purely by E0 conversion. A dedicated set of experiments looking for such isomers in selenium and krypton isotopes would be very interesting.

Our observations on ^{68}Se fits together with similar recent work on a shape isomer in ^{74}Kr [17,18]. The isomer was found following krypton production in a fragmentation reaction [17]. Here, the case is completely reversed with respect to ^{68}Se, with the ground state band having prolate deformation, and the isomer being a well-deformed oblate configuration, inferred from its decay rate [17,18]. For "in-beam" spectroscopy, this is a more difficult case, and the oblate band is hard to follow, starting non-yrast and rising steeply above yrast line due to its smaller moment of inertia [18]. The connection between these cases is very interesting, and a low-spin study of ^{72}Kr offers a "missing link". ^{72}Kr may have oblate and prolate configurations which are close-lying, but so far only the ground state band has been identified [19,20]. A low spin study would be very informative.

Alignment Delays in N=Z Nuclei

In practice, ^{72}Kr along with its N=Z partners ^{76}Sr, ^{80}Zr, ^{84}Mo and ^{88}Ru have been attracting considerable interest in connection with their high spin behavior. In particular, the issue of "delayed alignment" has been focussed on as a possible signature of np- pairing correlations. One argument goes that the nn- and pp- pairs which make up the normal T=1 J=0 pair-field can, on rotation can be broken down by the Coriolis force, with high-j, high-k states experiencing the greatest torque. The T=0 np-pairs are not coupled to spin zero and are less sensitive to this rotational breakdown, as their spin vectors are not opposite. Thus, "normal" backbending or alignment has been predicted to be delayed [20] or altogether absent [23]. Another argument [21,22] says a delay should exist but is caused by the T=1 part of the residual interaction between the unpaired particles. Of course, the experimenter is faced with the issue of "what is normal?" It is well known that alignments are very sensitive to shape, and to the normal T=1 pair-field. Consequently, whatever alignments are observed, it will be possible to find a shape and pair-field to reproduce them. The work on the less exotic nuclei, with N=Z+2 and N=Z+4 becomes important [11,24]. Amongst the elements of interest, there is a large body of data on alignments and shapes, and self consistent TRS calculations offer reliable predictive power of what is normal for the N=Z nuclei assuming T=1 pairing alone. An important new result on the collectivity of high spin states in ^{74}Kr [25] has shown how alignment and shape changes are inter-related, in this case having alignment which leads to a reduction of quadrupole deformation. Experiment and TRS calculations agree rather well. Thus, deviations from the standard predictions of shape and alignment will indicate new correlations of some sort are present. Consistent, systematic deviations of the same type in several nuclei would be expected from a new collective mode, such as np-pairing. A search for this type of effect has been made.

We have made measurements on ^{72}Kr, ^{76}Sr and ^{80}Zr using Gammasphere [26], and a recent report has appeared on ^{88}Ru from GASP [27]. I will briefly summarize our observations on the ground state bands of the nuclei we studied and comment on them. Table II consists of a list of gamma rays in the yrast sequences and their intensities.

^{72}Kr was suggested to be a good candidate for seeking delayed alignment by DeAngelis *et al.* [20], who found that the sharp up-bends of ^{74,76}Kr were absent. Using the ^{40}Ca(^{40}Ca,2α) reaction, selected by Microball, and Gammasphere, we have made considerable progress and have advanced the ground state sequence to J=26. The cross-section for this reaction seems to be large, in excess of 100 μb, and the triggering efficient, about 16% for 2α gating. The data were of sufficient quality that triple γ-γ-γ correlations could be used. In the yrast-sequence, the backbend suggested by DeAngelis could not be found. Instead the sequence continues smoothly with a distinct alignment at hω=0.87 MeV. The ground state band is found to fork, with a more irregular sequence appearing above spin J=14. However, this does not seem to be a rotational sequence, so probably is not critical to the alignment issue. Thus, amongst the rotational states, we find a clear and substantial alignment delay in ^{72}Kr. When it happens, the interaction between ground state and aligned band is stronger (an upbend not a backbend) and the gain in aligned angular momentum is less. All these features can be qualitatively reproduced with a standard axial cranking calculation with normal T=1 pairing having a strength extracted from odd-even mass differences, but only if a deformation in excess of β_2=0.43 is assumed, which seems unrealistically large.

^{76}Sr appears to be the ideal nucleus for this study, as it lies at mid-shell and has a large and stable prolate deformation [28]. However, it is known that the interaction between the ground state and rotationally aligned bands is very large [11], so alignment effects are rather subtle and washed-out. Only by calculating the derivative of the moment of inertia can an interaction be observed and extracted. We studied ^{76}Sr using the inverse ^{24}Mg(^{54}Fe,2n) reaction, in conditions similar to our ^{68}Se experiment. One technical change, which reduced computer dead time by 30% and allowed "singles" acquisition, was to trigger adc conversion only when a recoil-gamma coincidence had been detected in hardware. Table II lists the transitions in the ground state band, which we could measure to spin J=12. Although the alignment could not be fully mapped, it seems to be delayed relative to ^{78,80}Sr. We are working hard to try to extend the decay scheme far enough to quantify the alignment frequency.

^{80}Zr was the first of this series of Gammasphere experiments and had several technical problems. Consequently, least progress was made. However, it was possible to advance the yrast sequence to J=10, above the point where alignment is found in ^{82,84}Zr. The band seems rather smooth, with no evidence of sudden alignment found in neighboring isotopes. Again, the new transitions are listed in Table II. A similar "non-observation" of an alignment near J=8 has also been very recently reported for ^{88}Ru [27].

In conclusion then, all along the N=Z line, the even-even nuclei appear to have a consistently delayed alignment when compared to neighbors, or to theoretical trends. This experimental fact is now firm. What is now needed is careful theoretical investigation to see how these delays can be understood. Free manipulation of deformation and/or normal pairing almost certainly will allow the delays to be reproduced. What is absolutely clear is that the issues of shape and pairing are intimately linked. At present, it appears that the deformations needed to reproduce the alignment effects are so large it is difficult to reconcile them with their neighbors. Consequently, the possibility of new pair correlations seems to be a plausible, even likely explanation of the data. However, a series of self-consistent calculations with and without np pairs needs to be made to clarify this issue. Such calculations are in progress [29].

The experiments described in this paper involved several groups working at Gammasphere over the last two years. Learning to use Gammasphere for this kind of physics is a still-developing art. Already, some studies have been done on nuclei produced at the 50 nb level, two orders of magnitude below the original Daresbury experiments. Using Microball and neutron detectors, or using the Fragment Mass Analyzer, even more sensitive experiments appear possible. We would like to thank all the ANL staff for making the Gammasphere project run so smoothly, and Demitrios Sarantites from Washington University for his help with Microball. In addition groups from LLNL, Penn, Rutgers and Manchester University all made important contributions to this project. This work was supported by numerous NSF and DOE grants, especially the grant which supported the fruitful running of Gammasphere at ATLAS, U.S. Department of Energy contract W-31-109-Eng-38.

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TABLES

TABLE I. Energies and Intensities of Gamma Rays and Levels in ^{68}Se

E_{level} (keV)	E_γ (keV)	J^π initial	J^π final	I_γ (arb)	Br (%)
853.4 (1)	853.4 (1)	2_1^+	0_1^+	88.6 (1.3)	100
1593.4 (3)	1593.8 (3)	2_2^+	0_1^+	12.7 (1.1)	63 (3)
	739.6 (2)	2_2^+	2_1^+	7.5 (6)	37 (3)
1941.2 (3)	1087.8 (1)	4_1^+	2_1^+	45.3 (1.2)	100
2433.1 (10)	2433.1 (10)	?	0_1^+	2.9 (7)	100
2544.3 (5)	1691.1 (3)	4_2^+	2_1^+	16.6 (1.1)	43 (4)
	951.1 (1)	4_2^+	2_2^+	22.4 (10)	57 (4)
	602 (1)*	4_2^+	4_1^+	<3	<2
3073.1 (10)	2219.8 (1.5)	?	0_1^+	2.7 (8)	36 (11)
	639.1 (1.4)	?	?	4.7 (8)	64 (11)
3302.9 (4)	1361.7 (3)	6_1^+	4_1^+	23.0 (10)	100
3570.3 (10)	1629.6 (8)	$5_1^{(-)}$	4_1^+	4.9 (10)	100
3708.2 (15)	1162.7 (2)**	6_2^+	4_2^+	~18	~85
	1767.8 (12)*	6_2^+	4_1^+	3.2 (10)	~15
4196.8 (15)	626.5 (8)	$7_1^{(-)}$	5_1^-	4.0 (6)	100
4753.0 (6)	1045.4 (2)	8_1^+	6_2^+	13.7 (8)	52 (2)
	1449.4 (3)	8_1^+	6_1^+	12.9 (10)	48 (2)
4870.2 (8)	1567.3 (6)	8_2^+	6_1^+	6.4 (10)	>90
	[1162]**	8_1^+	6_2^+	<0.8	<10
5959.5 (8)	1206.5 (3)	10_1^+	8_1^+	16 (15)	100
6603 (1)	1732.6 (9)	10_2^+	8_2^+	5.2 (11)	100
7332 (1)	1373.0 (9)	12_1^+	10_1^+	7.4 (9)	100
8825 (2)	1492 (15)	14_1^+	12_1^+	5 (1)	100

* Gamma ray transitions are clear in ^{68}Se-gated singles, but too weak for rigorous assignment with γ-γ coincidence data.

** This transition is a doublet with a possible $J=8_2^+$ to $J=6_2^+$ decay and other transitions. Coincidence data indicate the latter decays are <10% of the intensity at 220 MeV.

TABLE II. Preliminary energies and intensities of gamma rays in the ground state cascades for nuclei ^{72}Kr, ^{76}Sr and ^{80}Zr. Only in the high spin regime near J=20 in ^{72}Kr are alignment effects evident. The ^{72}Kr intensities are from triple coincidences and normalized to the decay from the spin J=8 state. Other experiments indicate this transition is about twice the intensity of the decay from the J=2 state.

Spin	^{72}Kr E_γ(keV)	I_γ	^{76}Sr E_γ(keV)	^{80}Zr E_γ(keV)	I_γ
2	710.1 (.2)	(100)	262	288.9 (.2)	100 (10)
4	611.8 (.2)	(100)	483	536.9 (.2)	90 (10)
6	791.5 (.2)	(100)	698	779.0 (.4)	80 (10)
8	995.6 (.2)	100	892	1005.1 (.5)	45 (15)
10	1185.0 (.3)	76(12)	1067	1179 (1)	35 (15)
12	1354.9 (.3)	61(11)	1218	(1350) (2)	(15)
14	1508.9 (.3)	65(12)	1347		
16	1662.0 (.5)	39(10)			
18	1738.6 (.6)	26(10)			
20	1829.7 (.6)	36(9)			
22	1915 (1)	25(12)			
24	2034 (1)	19(6)			
26	2136 (2)	9(4)			