ANNEX 1

PHYSICS CASE

1 Introduction

A major aim of nuclear structure research is to achieve a better understanding of the effective nuclear interaction by measuring the properties of quantal systems having combinations of Z and N which are far from that of stable systems. The emphasis of this proposal will be to study nuclei having neutron/proton ratios very different to those of stable nuclei, not only those at the edges of stability, but nuclei at the end of the line of stability, isotopes with a mass and charge much larger than the heaviest naturally occurring nuclei. These nuclei will be produced in nuclear reactions induced by intense beams of stable nuclei. For compound nucleus reactions, the residual products will be isolated using recoil separators and ultra-sensitive instrumentation is required in order to measure both prompt and radioactive decay properties. Other instrumentation is required in order to observe products of deep-inelastic or fission reactions. The physics goals of various experiments, described in more detail below, will be the aims of a research programme carried out by UK physicists as part of a Finnish-German-UK collaboration based mostly at two accelerator laboratories, namely the University of Jyväskylä and GSI, Darmstadt.

2 Structure of the Heaviest Nuclei

If nuclei behaved simply as amorphous, charged liquid drops then even the most stable systems containing more than about 100 protons would have vanishingly small fission barriers as a consequence of the large Coulomb energy. A superheavy nucleus is one whose stability against fission arises from the additional shell-correction energy which has its origin in the properties of the quantum many-body system [1]. For superheavy spherical systems, the additional binding is largest at the shell closures for both protons and neutrons beyond Z=82 and N=126. The most recently published nuclear theories disagree on the nucleon numbers which correspond to this gap; the macroscopic-microscopic method has consistently predicted Z=114 and N=184 to be the next spherical magic numbers [2], but more recent self-consistent models suggest Z=126 and N=184 [3]. Both approaches agree, however, that extra binding is largest for deformed systems with Z=104-110 and N=162, with large positive quadrupole deformation and relatively large negative values of the hexadecupole deformation parameter, β_4 [4].

Experimentally, it is now known that heavy nuclei with Z up to 114 have isotopes which are relatively stable against fission; these have been identified in a series of experiments carried out at GSI, Darmstadt on the basis of their α-decay properties [5]. These experiments confirm that these superheavy nuclei have enhanced stability. This is thought to arise from the presence of deformed shell gaps in these nuclei. Although the stability and radioactive-decay properties of the ground states of these nuclei have been established, very few excited states in these heavy systems have been observed. As such, there is virtually no experimental information on the details of the single-particle levels and pairing strengths in this mass region, data which are vital to constrain the model interaction parameters extrapolated from lighter masses. Determination of the mid-shell electromagnetic properties would also clarify the position of the next spherical shell closure.

Limited spectroscopy has been shown to be possible in special cases in this region, albeit at the very limit of the sensitivity of existing experimental equipment. For example, the isotope, $^{254}_{102}$No, can be produced in the fusion of doubly magic nuclei, ^{48}Ca and ^{208}Pb, leading to a production cross section of the order of a few μbarns. Direct evidence that nuclei in this mass region are deformed comes from a study of the γ emission from this rotational nucleus in a series of recent experiments carried at Jyväskylä [6] and Argonne National Laboratory [7]. The ground-state rotational band observed is illustrated in Figure 1. Reactions producing other nuclei in this region do not have the advantages of the so-called cold fusion of doubly-magic systems, and the production cross sections fall too low for spectroscopy to be easily performed without improvement to current experimental devices, such as that offered by the GREAT spectrometer.

The nuclear properties that can be measured are not restricted to the ground state, or low-lying states. The nuclear reactions are capable of transferring considerable angular momentum to the heavy residue. This begs immediately a number of questions. How do the rotational forces affect the fission barrier when this arises from shell effects? Can the effect of very high-spin intruder orbitals from the next shell be observed in phenomena such as backbending? Does the nucleus have a propensity to form superdeformed shapes at modest spin? What is the effect of higher-order multipole deformations $(\beta_3, \beta_4, ...)$ on the nuclear stability and single-particle ordering. While remaining a challenge theoretically, many of these questions can potentially be addressed in the proposed experimental programme.

The key to the understanding of single-particle structure lies in the study of odd-A and odd-odd nuclei in this mass region. The cross sections for producing these nuclei are in the range 100nb - 1 μb [8] and the necessary measurements would employ both in-beam and α-decay techniques. In-beam γ-ray or electron spectroscopy of medium spin states in odd-mass and even-even nuclei will additionally probe strongly aligning intruder orbitals (such as proton $j_{15/2}$ and neutron $k_{17/2}$) as well as measure pairing properties. High K isomers are also expected in nuclei in this mass region (see section 6.3).

The study of α decay to daughter excited states provides a method by which low energy transitions, such as those between the lowest-lying states, can be determined; small transition energies and high atomic numbers mean that low-lying levels in transfermium nuclei decay mainly by conversion electron emission, rather than γ decay. Decay studies give direct information on the single-particle properties of the bandheads which will provide severe limitations on mean field calculations. Detailed γ-ray studies at the target will also allow the behaviour of the angular momentum dependence of the fission barrier to be measured. This will test the pervasiveness of shell effects into the high-spin region in giving stability to the metastable liquid drop system.

Inverse reactions will provide the recoils with sufficient momentum to allow secondary Coulomb excitation at the focal plane, which would enable $B(E2; 0^+ \rightarrow 2^+)$ values to be determined. This quantity provides a direct measurement of the nuclear collectivity. Of greater significance is the insight such measurements will provide on hexadecupole deformation and the position of the next proton shell gap, which can be extrapolated using N_pN_n systematics [9].

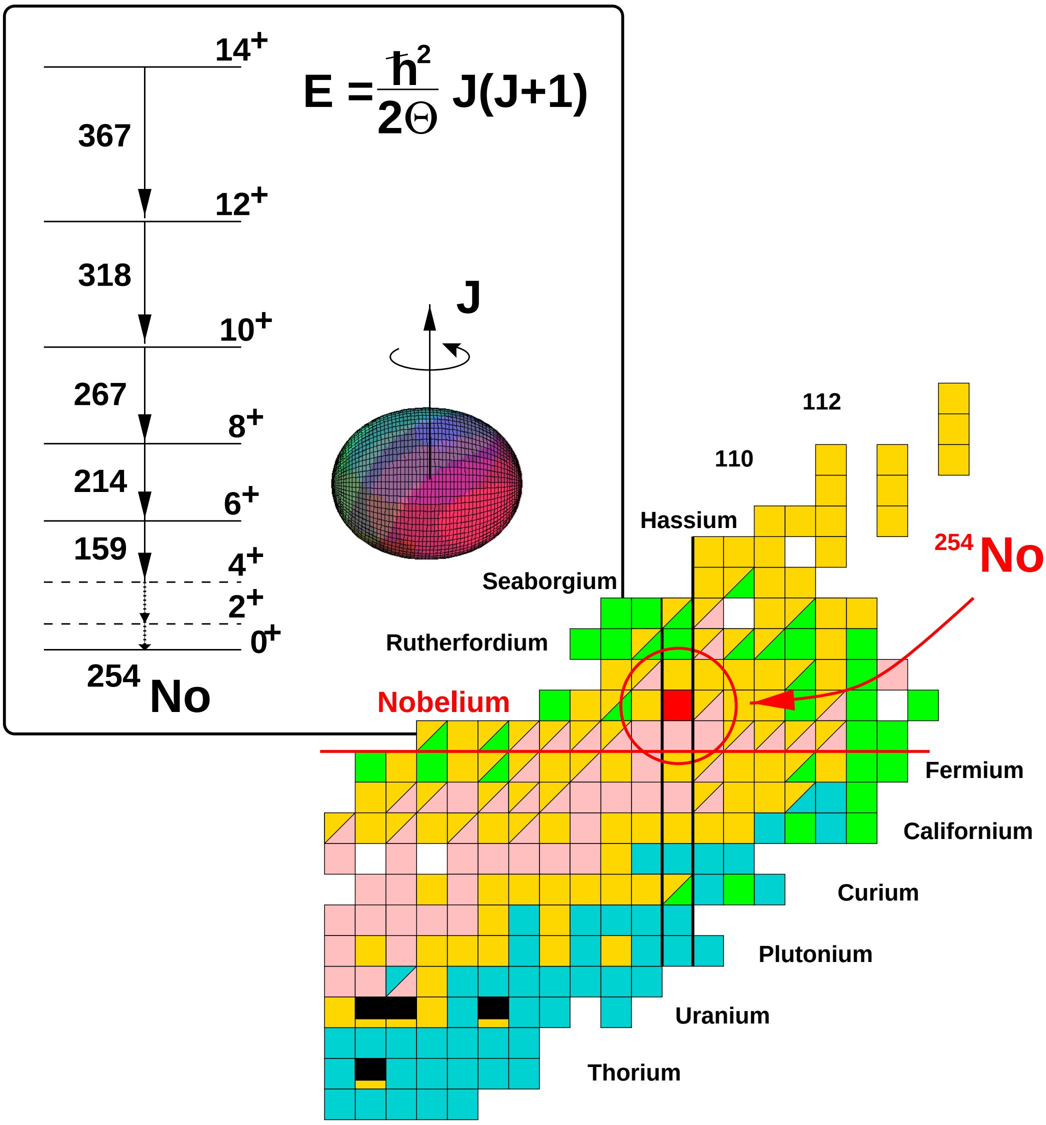

Figure 1: The ground-state band in ^{254}No and its position on the chart of the nuclides. The dotted low-lying transitions were not observed in the experiments [6,7] since they decay predominately by electron conversion. Detection of conversion electrons and the measurement of such 'non-radiative' decay will be routine with the GREAT spectrometer. ^{254}No lies at the centre of a region of nuclei which can be accessed to high spin by the GREAT spectrometer.

3 Shape Coexistence Phenomena in Heavy Nuclei Around the Z=82 Shell Closure

The occurrence of two different nuclear configurations at similar excitation energies, each with very different deformations, is referred to as shape coexistence. Such effects are expected in transitional regions, where the nuclear ground state is evolving from sphericity towards a permanent deformed shape [10]. There are some examples in light nuclei, such as ^{16}O and ^{40}Ca, where deformed multiparticle-multihole excitations across a shell gap occur at low energy with respect to the spherical ground states. Analogous proton excitations, across the Z=82 gap, are thought to give rise to similar intruder configurations in the neutron-deficient lead region. Prolate intruder states coexist with mildly oblate ground states in mercury nuclei, whilst in platinum isotopes such intruders fall so low in energy in the neutron mid-shell (N=104) region that they assume the ground-state position. In lead nuclei, there is some evidence for the coexistence of both oblate and prolate states close to the spherical ground state. Above Z=82, direct evidence becomes more scant, but energy level systematics do suggest the presence of similar structures in polonium and radon nuclei. Experimental investigations of the development of shape coexistence through and beyond the mid-shell, the onset of permanent ground-state shapes, and the mixing between coexisting configurations put constraints on the general theoretical problem of modelling the structure of heavy nuclei. Mean-field calculations cannot easily predict proton excitations as the effect of proton diffuseness is not well understood. Such problems are similar to those faced in predicting the next proton shell gap as discussed in section 2. The highly neutron-deficient nature of these species invariably means making measurements of nuclei in the face of extreme competition from reaction channels resulting in fission, leading to production cross sections at the limits of experimental techniques. Efficient and effective tagging using radioactive decay correlations, usually with α decay in this region, is essential.

3.1 Oblate Shapes, Superdeformation and Shape Competition Above the Z=82 Gap

With the addition of valence protons and neutrons outside of the doubly-magic ^{208}Pb core, polarising effects are evident with the onset of permanently deformed ground-state shapes in actinide isotopes with N>126 and Z>82. In contrast, the structural consequences associated with the addition of valence particles, in combination with valence holes, are not well established experimentally. In the region with N<126 and Z>82, many theoretical calculations have been made (for example references [11-13]) which predict an extended region of oblate deformed nuclei far from stability. Of note are extremely deformed ground-state configurations, where the ground-state deformation approaches superdeformed magnitudes, which are predicted in the very neutron-deficient thorium isotopes. To date, there is no direct experimental evidence for any permanent ground-state deformation in this region. In contrast to the theoretical predictions, recent experimental work on the in-beam spectroscopy of the radon isotopes, $^{198-202}$Rn [14-16] (see Figure 2), indicates that the onset of ground-state deformation has not yet been observed, and therefore must occur in isotopes lighter than those predicted. In order to establish the onset of ground-state deformation, the low-lying structure of more neutron-deficient radon, and in addition, radium and thorium isotopes can be studied.

Predictions of proton np-2h excitations across the Z=82 shell closure leading to intruder states in polonium and radon isotopes can be made by analogy with the well-known 2p-nh intruder bands in neutron-deficient mercury and platinum isotopes. So far evidence for these states in Z>82 isotopes is rudimentary and based purely on energy level systematics and relative measurements. Both in polonium [17-21] and radon isotopes [14-16], low-lying excited states in nuclear chains extending to mass 192 and 198 respectively show a parabolic fall, characteristic of intruder structures. However, such systematics have also been interpreted in terms of particle-vibration coupling models [17] without the need to introduce deformation at all. The existing experimental evidence, based on energy and branching ratio systematics, fails to discriminate between these two alternative explanations, leaving the question of the presence of intruder states above the Z=82 shell closure open. Extension of energy systematics across the mid-shell region and lifetime measurements, which would yield absolute transition strengths between the low-lying states, would greatly constrain the theoretical descriptions being used.

In addition to possible normal-deformed intruder configurations, radon isotopes are of par-

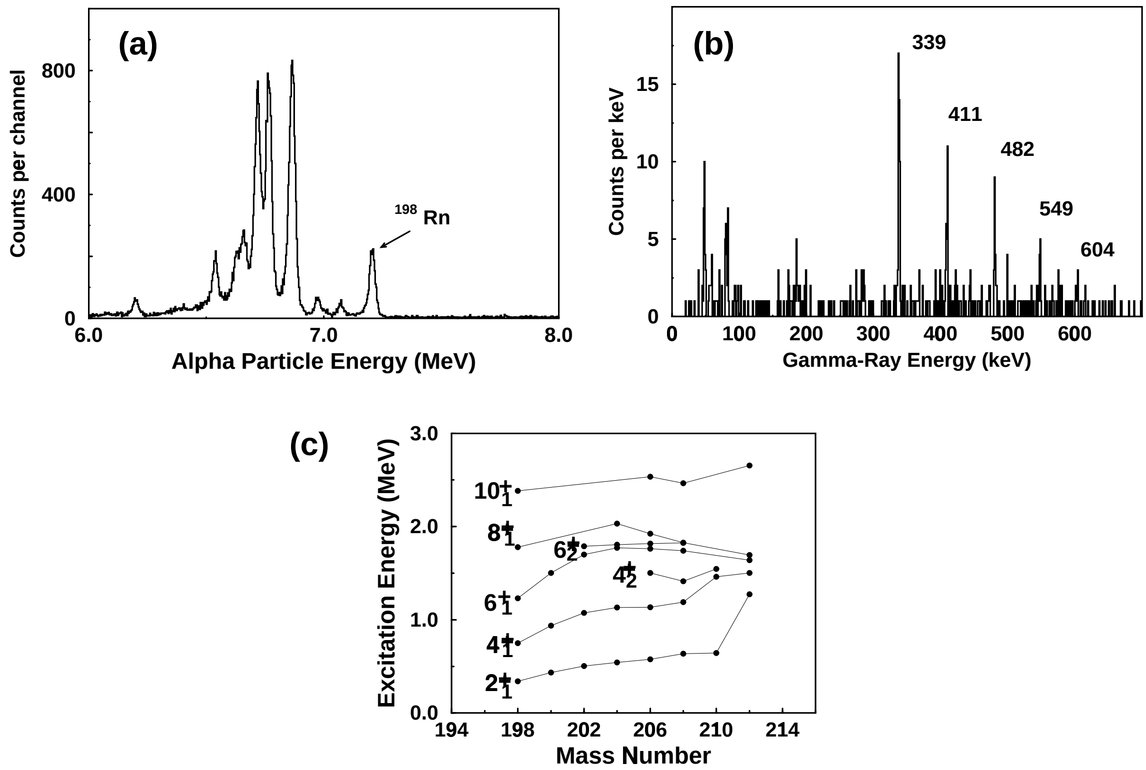

Figure 2: Results of a study of light radon isotopes showing in (a) the energy spectra of radioactive α particles at the focal plane of a recoil separator. (b) shows the prompt γ-decay correlated with the implantation of recoils which subsequently decay with the characteristics of ^{198}Rn. The excitation energy systematics for low-lying levels in radon isotopes are illustrated in (c). The fall in low spin levels in isotopes lighter than A=202 is suggestive of the presence of deformed intruder configurations, but the 2_1^+ energy never falls low enough to be consistent with the predicted ground-state deformation. The reaction used in this experiment has one of the lowest cross sections for which in-beam γ-ray spectroscopy has been performed, at a level of around 180 nb.

ticular interest due to the predictions of superdeformed minima at low spin and excitation energy. Following the discovery of actinide fission isomers in the late sixties, calculations [22] indicated the existence of another region of nuclei around Z=85 and N=118 with secondary minima at modest excitation energies. A careful study was undertaken [23] to search for cases of fission isomerism in this region. No cases of delayed fission were observed for products in the range Z=84-87, N=116-122, with half-lives between 2×10^{-9} and 2×10^{3} seconds and production cross sections down to 70 nb. This did not preclude the existence of shape isomers in this region as theoretically predicted, but does suggest that, if they do exist, the dominant decay mode is γ emission. Predictions of shape isomers in this region have persisted in modern calculations [24-26], indicating a large region of superdeformed nuclei with deep minima at low excitation energy. The predicted properties of such superdeformed minima are very sensitive to the energetic location of high-j single-particle orbitals from the next major shell above. As such, experimental information on superdeformed configurations will give information which will be useful in predicting the position of the next spherical superheavy shell gap, discussed in section 2.

Recent experimental activity has vindicated these predictions in the A$\sim$190 region, however, there is only one candidate for a superdeformed band in a nucleus with Z> 83, in ^{198}Po. In order to produce data sets for viable superdeformed searches in this region, high rate experiments are necessary. Since the low-lying levels of the best candidates, centred around ^{202,204}Rn, are known detailed identification techniques, such as correlation with radioactive decay, are not required. However, a fission veto is required to isolate the 1 mbarn production cross sections from background. In these cases it is therefore advantageous to replace the Si detectors at the focal plane with a higher rate focal plane detector such as a multi-wire proportional counter.

3.2 Coexisting Shapes in Lead Isotopes and Below Z=82

In lead isotopes, there are predictions of several different shapes which all coexist at low excitation energies, although different theoretical approaches yield quite different results, indicating a need for experimental input for neutron-deficient isotopes. Recent calculations, using a relativistic mean field approach in the Hartree approximation [27,28], suggest that light lead isotopes should have prolate deformed ground states, but the validity of these calculations has been the focus of much attention [29,30]. Nilsson-Strutinsky calculations predict that a spherical to deformed shape transition should occur at very low spin (I$\sim$ $2\hbar$). In particular, ^{184,186}Pb should exhibit a spherical to prolate transition, whilst in ^{188}Pb the oblate-prolate energy difference is predicted to be essentially zero and for ^{190,192}Pb the transition was expected to be spherical to oblate at low spin. Results of more sophisticated Nilsson-Strutinsky calculations using the shell correction approach with the axial/reflection-asymmetric Woods-Saxon model are shown in Figure 3. These predict spherical ground states for all neutron-deficient Pb isotopes, however,an interesting feature is the prediction of low-lying ($E_x \sim 2.5$ MeV) deformed oblate ($\beta_2 \sim -0.35$) states for N $\leq$104. Such structures are not predicted to exist in the light mercury nuclei [31], indeed, oblate deformations of this size are not known at all in heavy nuclei.

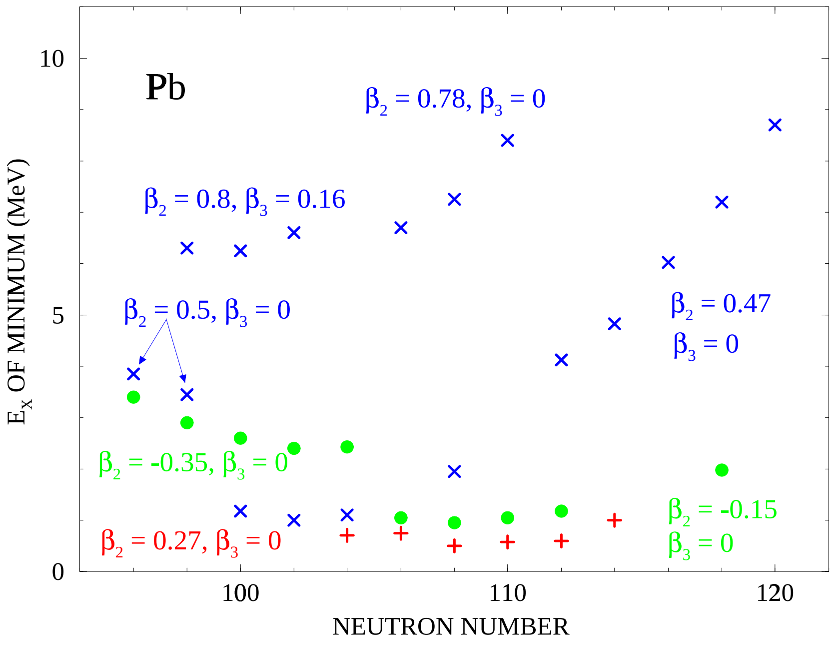

Figure 3: Predicted excitation energies of various coexisting configurations in the even-even lead isotopes with 96$\leq$N$\leq$118. The prolate (oblate) states are indicated by segments (dots). The crosses show the experimental energies of deformed 0^+ states.

Coexistence between oblate and prolate shapes is also expected in light thallium nuclei (Z=81), where the $h_{9/2}$ and $i_{13/2}$ proton orbitals have small projections of angular momentum on the symmetry axis and are down sloping as a function of increasing prolate deformation. Prolate bands built on the proton $h_{9/2}$ and $i_{13/2}$ orbitals have been observed in ^{185,187}Tl [32,33]. Whereas the energy of the prolate minimum in mercury nuclei becomes lowest at N=104 (relative to the lower oblate state), the prolate bands in Tl are predicted [33] to proceed to even lower energies for the lighter isotopes as a consequence of the shape-driving nature of these single-particle states. The particle-hole excitations, which form the prolate bands in lead nuclei, involve one or both of these high-j intruder states, and so the comparison of the prolate bands in lead, thallium and mercury nuclei will provide important information about the configurations of the structures residing in this minimum.

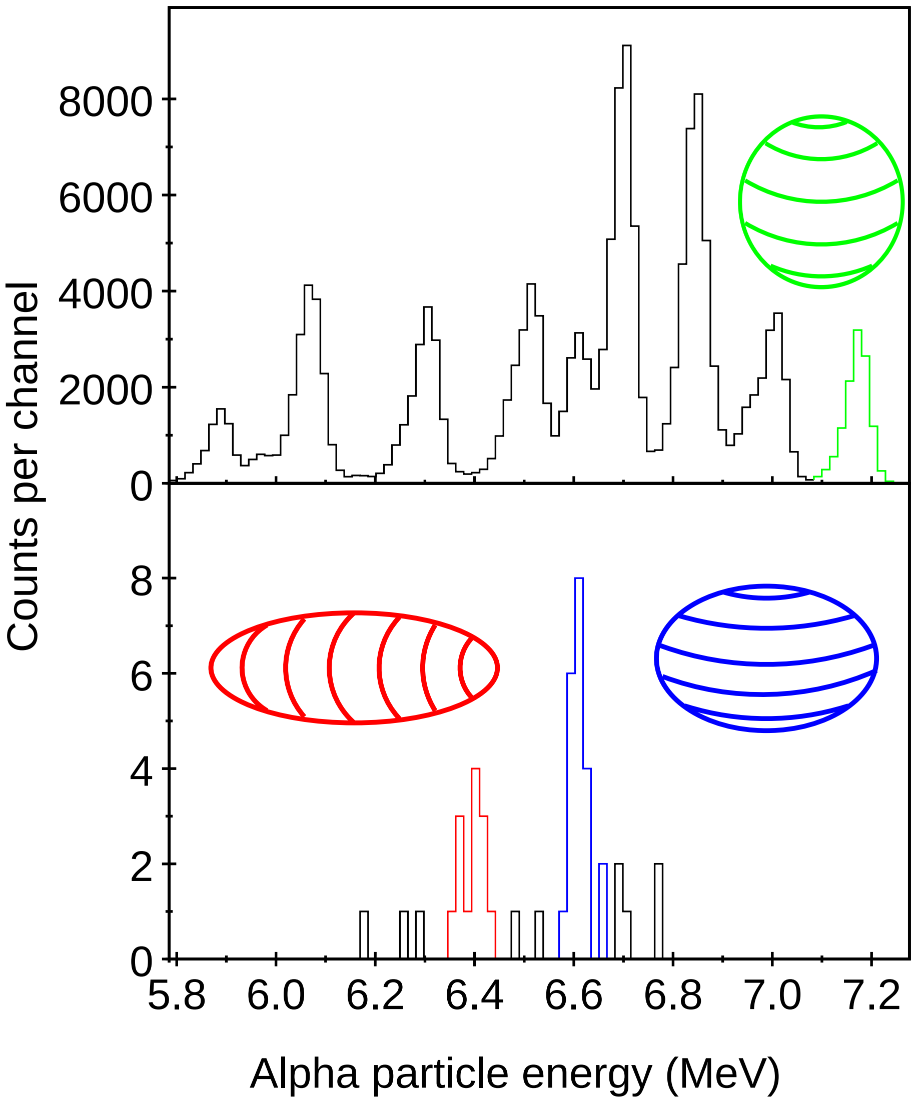

Figure 4: Alpha-particle energy spectra following the decay of ^{192}Po to differently deformed configurations in ^{188}Pb. The upper spectrum is an α spectrum correlated with recoils, whilst the lower figure indicates those α particles which are in coincidence with a conversion electron, i.e. those which feed excited states in the daughter nucleus. All the groups in colour have decay times consistent with decays from the ground state of ^{192}Po. These alpha decays are to states with very different types of shape: spherical ground state (green), and prolate (red) and oblate (blue) excited structures [37].

Experimental evidence for low-lying deformed states in neutron-deficient lead isotopes has been known for some time (for example, reference [10]). The deformed 0_2^+ states have been interpreted as resulting from 2p-2h proton excitations $(s_{1/2}^{-2}h_{9/2}^2)$ across the Z=82 shell gap and such states, which are weakly oblate, have been found in several lead isotopes with N≥106 [10,34]. Tentative evidence for low-lying collective prolate structures has been reported in the N≤106 nuclei ^{186,188}Pb [35,36]. The lightest isotope known to contain an oblate minimum associated with 2p-2h excitations across the Z=82 shell gap is ^{188}Pb, where the 0^+ state has been identified at an excitation energy of 570 keV. In addition, a further, probably prolate, 0^+ state was observed at 770 keV, as in Figure 4. In this example [37], α decay of ^{192}Po has been used to populate the highly non-yrast 0^+ states. These would not have been observed in γ-decay following fusion-evaporation. α-decay measurements of this sort also allow the extraction of information concerning the mixing of the different intruder configurations. Careful selection of α-decay events in coincidence with conversion electrons from the decay of the 0^+ states is necessary; the GREAT spectrometer is ideally suited to such studies. For even lighter isotopes, it is predicted that the prolate configuration becomes more important, whilst the oblate structure ceases to be so energetically competitive.

In mercury, platinum and osmium isotopes, there is evidence from energy-level systematics, lifetime measurements and rotational band structures for the influence of deformed intruder configurations. The information available on how these configurations develop once the midshell region is passed is very limited and is a necessary element in order to test descriptions of the onset of collectivity. Yrast states have been studied for the first time at Jyväskylä, using the Jurosphere array in ^{168,170,171,172}Pt [38,39], ^{176}Hg [40] and ^{184,187}Pb [41,42]. These experiments have yielded the first rudimentary information on the structure of isotopes past the midshell region and have been important in refining the theoretical treatments of shape coexistence. However, further advances in understanding will require the measurement of non-yrast levels using γ-γ coincidence techniques in conjunction with radioactive-decay correlations. Such measurements are out of the scope of current experimental equipment, but become possible with the improved sensitivity available with the spectrometers proposed here.

4 Octupole Correlations

Strong octupole correlations arise from the high degree of mixing of opposite parity orbitals in very heavy nuclei, itself a consequence of the spin-orbit force in the nuclear mean field. It is well established experimentally and theoretically that actinide nuclei with $N \approx 132$ have the largest octupole correlations in their ground state [43]. Of all the nuclei so far experimentally investigated only six examples exhibit alignment properties consistent with clear static octupole deformation at low rotational frequencies, namely ^{222,224,226}Ra, ^{224,226}Th [44], and ^{226}U [45]. In the $N = 132$ nuclei, $^{220}_{88}$Ra and $^{222}_{90}$Th, strong alignment effects reduce the octupole coupling of proton and neutron pairs of $\Delta\ell = 3$ orbitals leading to, in the case of ^{222}Th, a termination of the octupole band at spin 24. In contrast the radon isotopes with neutron numbers $N = 132 - 136$ and the heavier radium and thorium isotopes can be described as octupole nuclei in which the octupole phonon aligns with the rotation axis.

A long-standing prediction based on Strutinsky-type potential energy calculations employing a Woods-Saxon potential, is that the neutron deficient uranium nuclei should have the deepest octupole minimum in the region and should exhibit evidence of low-lying structure expected for stable octupole deformed shapes [46]. For example, it is expected that ^{224}U

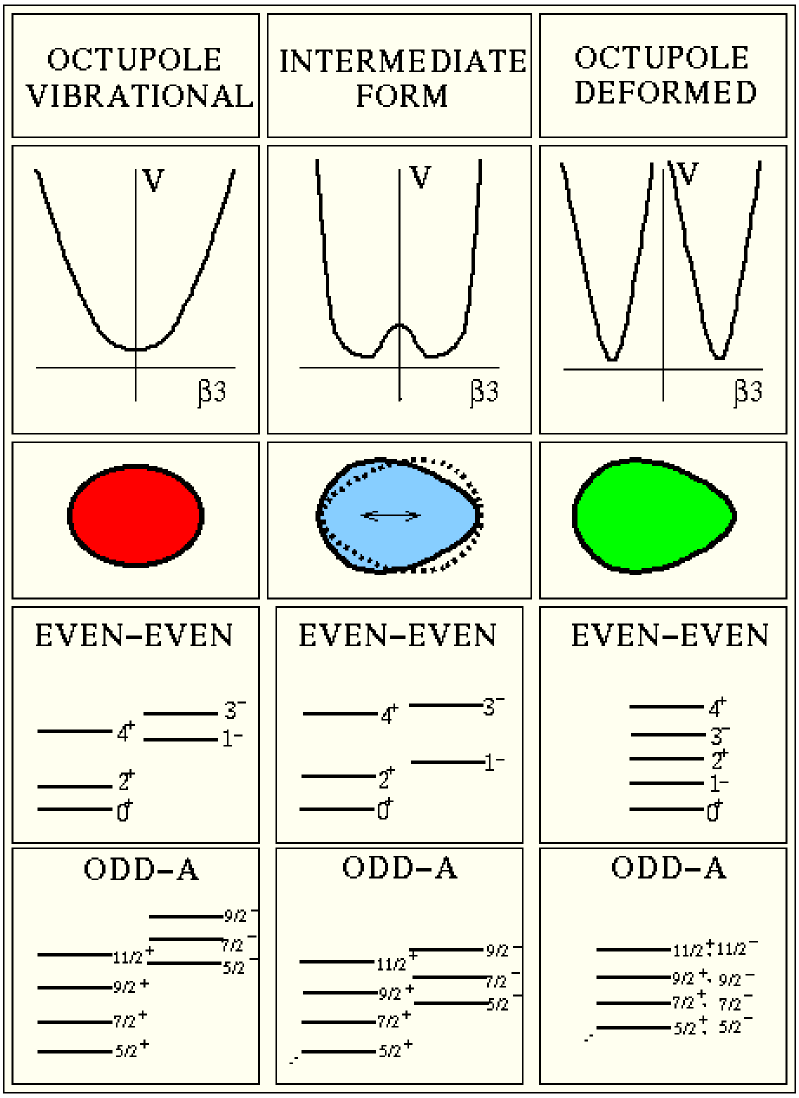

Figure 5: Different forms of octupole correlations in atomic nuclei. Notice the relative position of the first 2^+ and 1^- states is an indicator of octupole effects in even-even nuclei.

will exhibit similar behaviour to the six octupole deformed nuclei measured previously, but at lower rotational frequencies. Of additional interest is the prediction that this U isotope should have the largest low-lying transition $E1$ moment of any heavy mass nucleus. Of more fundamental importance is the understanding of how pairing forces compete with the octupole-octupole coupling strength. The relative position of the low-lying 1- and 2+ states in even-even nuclei (see figure 5) is sensitive to the interplay between these interactions. In this mass region, these two states are predicted to have comparable excitation energies indicating a high degree of octupole correlation. The high sensitivity and resolving power of GREAT will be necessary in order to observe the low-lying states, such as the 2^+ and 1^- levels, populated by the α decay of the parent nuclei.

Recent mean-field calculations using the Skyrme Hartree-Fock plus BCS approach [47] have predicted that nuclei in the mass region A $\approx$ 60-80 with Z=N (see section 6) can have very exotic asymmetric shapes because of strong octupole mixing between Δ j =3 orbitals which are identical for both protons and neutrons. For example, ^{68}Se and ^{80}Zr are predicted to have respectively triangular and tetrahedral deformations respectively, shapes which violate both reflection and axial symmetries (in contrast to the trans-actinide nuclei which only violate the former symmetry). Such structure could be observed experimentally using β-tagging techniques to enhance the channel of interest or by observation of the delayed E3 emission from low-lying 3- states.

5 Highly Deformed Shapes at the Drip Line Near Z=64

How the ordering of the single-particle level structure is affected by extreme proton/neutron ratios is a fundamental question in nuclear structure. For example, in drip-line nuclei, weak binding of nucleons can give rise to much more diffuse central potentials compared with nuclei close to stability. The very neutron-deficient rare-earth region around mass 130 has long been recognised as a transitional region where the deformation of the nuclei appears to increase as the neutron-deficient nature of the nuclei is increased [48]. The occupation of specific single-particle levels at both the neutron and proton Fermi surfaces can be exposed by investigating the alignment properties in the near-yrast rotational structures in these nuclei. In this way, a systematic study of the effect of different single-particle population in the deformation of various configurations can be obtained. The centre of this deformed region is predicted to lie in the most neutron-deficient systems at, or even beyond, the proton drip line [13].

The recent observation of direct proton decay from deformed states in the very neutron-deficient rare earth systems ${}^{141}_{67}$Ho and ${}^{131}_{63}$Eu [49] provides an ideal experimental tag with which to observe excited states in these proton-unbound nuclei near Z=64. The observation of backbending phenomena can be used to determine if the ordering of the single-particle structure is altered in these systems, where the protons are quasi-bound. However, these are only two isolated nuclei and more general tagging techniques are required to explore the evolution of these effects with deformation as the proton drip line is approached. Fortunately, the many nuclei in this region that are not direct proton emitters possess large electron capture/β-decay Q-values. Consequently, excited states in the daughter species are populated strongly and decay by emitting either γ-rays or protons, both of which processes can be exploited for tagging in-beam γ-rays. Good candidates for the use and development of the new technique of tagging with β-delayed protons include ${}^{127}_{60}$Nd and ${}^{131}_{62}$Sm.

6 Self-Conjugate and Mirror Systems

6.1 Mirror Pairs in the Shape Coexistence Region around N=Z=36

Coulomb energy difference between pairs of mirror nuclei is very sensitive to the difference in the structure associated with the two types of nucleon. Such mirror pairs should have very similar structures due to charge symmetry, and deviations arise purely from Coulomb effects associated with the proton charge distribution. Recently Coulomb energy differences have been studied as a function of spin in fp-shell nuclei and are found to reflect changes in the structure of states along the yrast line, from collective rotation, through rotational alignments to fully aligned terminating states [50,51]. The Coulomb energy difference between the symmetric states in these mirror pairs can be used to infer the type of nucleon which is responsible for alignments at medium to high spins. For heavier deformed mirror pairs in the A=70 region, the Coulomb effects are greater relative to the fp-shell cases and thus any perturbations associated with proton-neutron differences should be more significant. It is possible that the large Coulomb energy is sufficient to perturb proton single-particle structures sufficiently to leave the mirror pairs with different ground-state spins [52]. Such perturbation may also result in very different deformation for the two mirror pairs; the region around $N \sim Z \sim 36$ is well known for the presence of well deformed competing prolate and oblate minima [53]. As an example, the recent measurement of ${}^{71}_{36}\mathrm{Kr}_{35}$ [54] suggests that this nucleus decays fast enough to be tagged by β^{+}-decay using the GREAT spectrometer, allowing a comparison with its mirror, ${}^{71}_{35}\mathrm{Br}_{36}$. The GREAT spectrometer will therefore provide information on mirror symmetry and the persistence of charge independence of the nuclear force in heavier systems than currently available in the mass 50 region.

6.2 Neutron-Proton Pairing

Nuclear superfluidity in self-conjugate systems is expected to be profoundly different from that found in other nuclei. The proximity of the proton and neutron Fermi surfaces allows pairs of unlike nucleons to compete energetically with normal like-nucleon pairing. Such neutron-proton pairs can be coupled to either isospin, T=0, or T=1 with intrinsic spin, S=1 or S=0, respectively. The T=1 pairs mimic regular pairing, but the the opportunity to observe the T=0 mode is unique to self-conjugate systems. It is not yet clear whether T=0 pairing is strong enough to produce a coherent superfluid state, but the best candidates are heavy N=Z systems where large numbers of valence nucleons and a relatively high level density related to nuclear deformation favour scattering of nucleon pairs between available levels. The most obvious results of such coherent scattering is the appearance of a pairing gap in odd-odd N=Z systems [55]. Other signatures which have recently been suggested include enhanced Gamow-Teller β-decay [56] and rotational alignment effects at high spin [57]. Thus spectroscopic studies which are capable of populating N=Z nuclei via both fusion evaporation and β-decay will be necessary to probe the existence and characteristics of the new class of pairing condensate, and the GREAT spectrometer is ideally suited to this task.

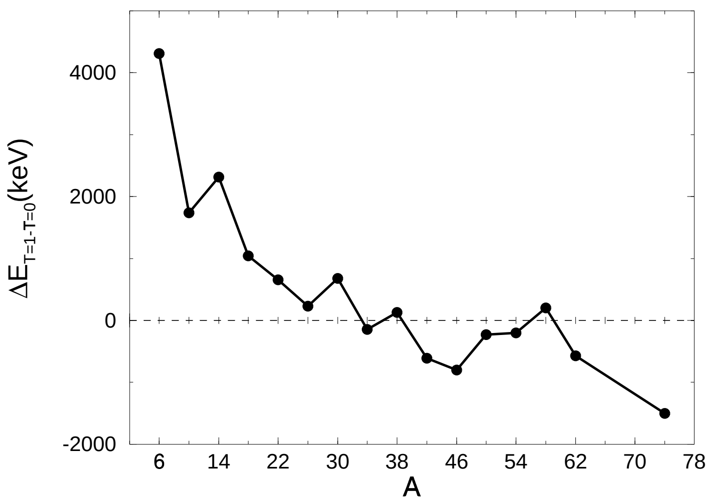

Figure 6: Relative energy between the lowest observed T=1 and T=0 states in odd-odd N=Z systems.

Of related interest is the relative excitation energy of the T=0 and T=1 states in N=Z nuclei. For odd-odd nuclei lighter than ^{40}Ca, with the exception of ^{34}Cl, the ground states have the 'textbook' $T_{gs}=T_z$ assignment. However, the T=1 states become progressively lower in excitation energy with increasing mass. As indicated in Figure 6, after ^{40}Ca, the T=1 states assume the ground-state position, with the sole exception of ^{58}Cu. Beyond this the T=0 states continue to rise in energy (see Figure 6). The origin of this behaviour is not yet fully understood, but has been shown to be linked to the relative energies of the T=0 and 1 pairs [58]. In order to pursue this problem further, it is essential to determine the separation of T=0 and T=1 states in systems heavier than that currently known in ^{74}Rb [59]. Recent fragmentation experiments have indicated that the heavy odd-odd N=Z systems, $^{78}_{39}$Y, ^{82}Nb and ^{86}Tc [60], decay by fast, Fermi superallowed transitions. The production cross sections of such isotopes in fusion-evaporation with stable ion beams are extremely small fractions of the total yield. However, the very short ($\sim$ 50 ms) β^+-decaying lifetimes, measured in the GREAT spectrometer, can be used as a trigger with which to discriminate them from other, longer-lived reaction products.

6.3 Nuclei Approaching ^{100}Sn

Nuclei close to doubly-magic nuclei have been a traditional source of empirical information on single-particle energies and the matrix elements of residual interactions between them. The self-conjugate nucleus ^{100}Sn has been shown to exist and is expected to stay bound up to around 4 MeV in excitation energy. It should exhibit the rather simple low-lying structure of a doubly magic system. The actual binding energies in such a weakly bound system are likely to be strongly influenced by the residual interactions and correlations. The study of nuclei around ^{100}Sn, at low excitation energy, will yield shell-model information of importance for the structure of all medium-mass nuclei. The higher-lying levels will enable studies of the breaking of the ^{100}Sn core and the generation of higher angular momentum and collectivity. Tests of the persistence of isospin symmetry can also be made; estimates of isospin mixing in the ground state of ^{100}Sn suggest a 5% admixture of T=1 components [61]. Such experiments are difficult due to the small production cross sections of the nuclei of interest in comparison with the more prolific exit channels. As such, very sensitive selection triggers are required. The use of isomer tagging is a powerful tool with the existence of several possible γ-decaying isomeric states in nuclei in this region [62]. The observation of prompt decays at the target position lying above an isomer is particularly useful for studies of core breaking.

7 K Isomers

In contrast to spherical seniority isomers, which are typical in the vicinity of closed-shell nuclei, K isomers correspond to states in axially deformed nuclei which have anomalously long decay half lives due to a rearrangement of the direction of the angular momentum vector from along the deformation axis to along the rotation axis. K isomers occur in deformed nuclei where there are many single-particle orbitals close to the Fermi surface with large angular momentum projections, Ω, onto the symmetry axis, as illustrated in Figure 7. The investigation of the decay of these states provides information on the underlying single-particle structure in exotic systems, the effect of seniority on pairing strength [63], the applicability and consistency of the K quantum number as a useful label for defining nuclear configurations and the usefulness of the concept of 'tilted' cranking in describing certain types of nuclear rotational states [64]. One long-standing question is what phenomenon causes the demise of the K selection rule. A number of different explanations have been proposed including tunnelling through triaxial shapes, a density of states effect and a move away from axial symmetry.

7.1 The Persistence of the N=74 Isomeric Chain Across the Z=50 and Z=66 Shell Gaps

A chain of $K^{\pi} = 8^{-}$ states for the N=74 isotonic chain has been established for even-Z nuclei from $^{138}_{64}$Gd to $^{128}_{54}$Xe [65]. The M1/E2 branching ratios of the rotational states above the isomers in ^{136}Sm [66] and ^{138}Gd [67] indicate that these isomers come from a favoured two quasi-neutron $7/2^{+}[404] \otimes 9/2^{-}[514]$, nominally prolate configuration. However, there are uncertainties regarding the nuclear shape change as the proton number reduces, with the question being raised as to whether the predicted oblate ground state in $^{130}_{56}$Ba affects the shape of the isomeric configuration [66,68]. To date, no clear evidence of oblate K isomers has been unambiguously demonstrated anywhere in the nuclear chart. It is therefore very important to obtain information on the branching ratios of the states built on top of all of the isomers giving clues to the shapes of the isomeric configurations in this wide N=74 chain. The N=74 chain affords the opportunity to probe the effect of deformation and triaxiality on the continuing validity of the K quantum number [68].

A further unanswered question is whether these K-isomeric states persist as the N=74 isotonic chain approaches and crosses the Z=50 shell gap, where the nuclei become spherical in their ground states. Neutron-rich states in the N=74 isotones $^{124}_{50}$Sn and $^{126}_{52}$Te can be populated by deep-inelastic reactions and searches for decays from states with the $K^{\pi} = 8^{-}$ character sought using the proposed combinations of a large germanium array with either HIPS, in order to identify ejectile ions, or RITU and GREAT, in order to perform isomer tagging.

One further intriguing question regarding the N=74 K-isomeric chain is the absence of the expected analogous isomeric decays in the odd-Z, N=74 isotones. At present no evidence for such states has been observed, despite various searches. The extra sensitivity afforded with the GREAT spectrometer will allow searches at a much improved level of sensitivity.

7.2 K isomers and Configuration-Dependent Pairing Reduction

The classic region of K isomerism is centred about $Z \sim 74$ and $N \sim 104$. In this unique region, both the proton and neutron Fermi surfaces reside in the vicinity of many high-Ω orbitals and thus multiple couplings, corresponding to high spins can be achieved. For example, in $^{178}_{74}$W, an eight quasiparticle isomer with $K^{\pi} = 25^{+}$ has been observed [69]. The investigation of the transitions built on top of these multi-quasiparticle isomers allow an unprecedented opportunity to observe the effect of pairing on rotational motion in nuclei [63]. By blocking different numbers of orbitals in the vicinity of the Fermi surface by excitation of several quasiparticle states, a reduction of the pairing can lead to alterations of the observed moments of inertia.

A number of neutron-rich, K-isomer systems around A$\sim$ 180 have recently been discovered following deep-inelastic reactions on heavy, rare-earth targets [70]. The measurement of delayed γ rays and conversion electrons using the GREAT array will allow a determination of the spin/parity of the isomers to be made. It will also generate an experimental trigger with which to gate cleanly on in-beam transitions above the isomer. In this way, the recent

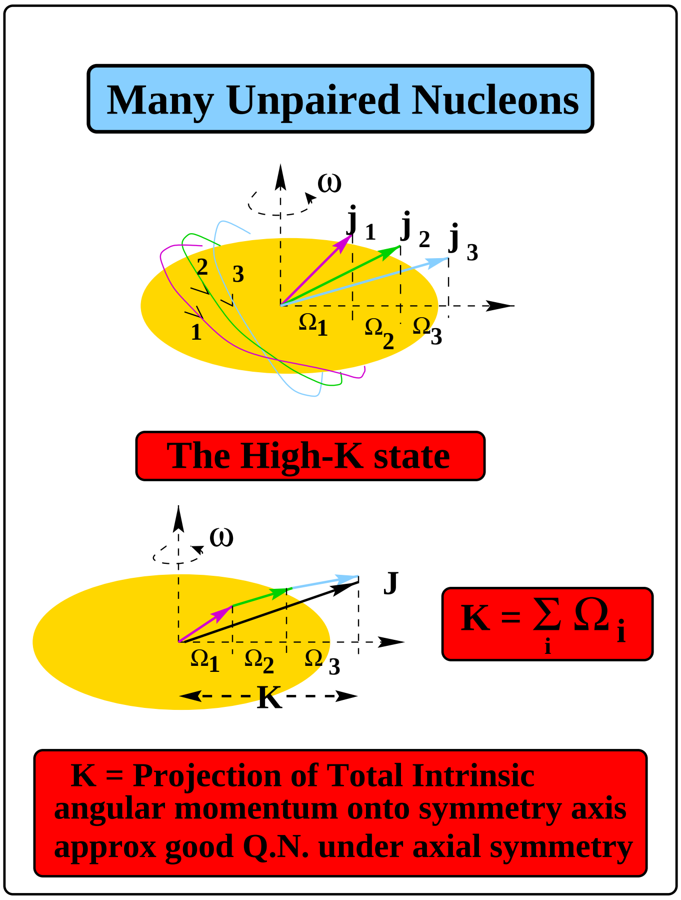

Figure 7: Pictorial representation of a high-K multi-quasiparticle isomer.

potential energy surface calculations [68,71] which suggest different shapes for different high-K configurations can be probed in detail.

7.3 K Isomers in Heavy Nuclei around Z∼102

The recent experimental identification of excited states in $^{254}_{102}$No using the technique of RDT (section 2) has opened up another region for the study of K isomers. The moment of inertia of the yrast band associated with ^{254}No suggests a substantial quadrupole deformation in the region on $\beta_2 \sim 0.3$ [6,7]. The proton number (Z=102) and large prolate deformation means that the single-proton Nilsson orbitals close to the Fermi surface should be similar to the neutron orbitals responsible for the generation of high-K states in the A∼180 region. In ^{254}No one would expect favoured coupling of proton $i_{13/2}$ and $h_{9/2}$ orbitals, from the $9/2^{+}[624] \otimes 7/2^{-}[514]$ configuration, to give rise to a K= 8^{-} state. Additionally, a high-K neutron configuration is expected for ^{254}No via the $j_{15/2}$ and $i_{13/2}$ coupling, $9/2^{-}[734] \otimes 7/2^{+}[624] \rightarrow \mathrm{K}^{\pi} = 8^{-}$. Indeed, for more than 20 years, there has been tentative indirect evidence for an isomeric high-K configuration in this nucleus [72], although hard evidence in the form of observation decays from this proposed $\mathrm{K}^{\pi} = 8^{-}$ state to states in the ground-state band of ^{254}No has been impossible to establish so far.

Coupling the favoured proton and neutron configurations together should in principle generate a highly favoured $K^\pi = 16^+$ state, in some ways analogous to the famous $K^\pi = 16^+$ isomeric configuration in $^{178}_{72}$Hf, which has a half life of 31 years. This raises the intriguing question of whether such a high-spin state would survive fission, and what effect the different orientations of the angular momentum (rotational and single-particle) have on the stability of heavy systems competing against fission breakup.

8 Neutron-Rich Systems and Deep Inelastic Reactions

There is considerable physics interest in the properties of neutron-rich nuclei which lie close to the proton and neutron magic numbers that have been established along and near to the line of stability. Theoretical calculations, supported by limited experimental data, suggest that changes in the shape of the central potential and the spin-orbit interaction may lead to the quenching of magicity when there is a large excess of neutrons.

Fission and deep-inelastic reactions have been shown to be viable mechanisms for the production and in-beam study of neutron-rich nuclei at medium spins. In particular, deep-inelastic reactions provide a mechanism for the in-beam study of neutron-rich nuclei in the A=50-60 region, which lie below the range of masses formed with significant yields in spontaneous or fusion-fission. This mass region, which lies to the 'north-east' of the doubly-magic nucleus, ^{48}Ca, is of particular interest as it is delineated by the shell closures at Z = 20,28 and N = 28,40. The isotopes, $^{48}_{20}$Ca and $^{68}_{20}$Ni, are established as good closed-shell nuclei, but, because of their inaccessibility, little is known about the neutron-rich nuclei lying within the boundaries of this region, and it is still an open question as to whether the N=40 sub-shell closure is maintained when the proton number is not itself magic. This area of the nuclear chart would be ideal for the application of a full shell-model calculation, since the protons are filling the $1f_{7/2}$ single-particle level only, and the neutrons are filling the $1p_{3/2}$, $1f_{5/2}$ and $1p_{1/2}$ levels. However, the testing of such calculations is severely handicapped by our lack of knowledge of the states of the nuclei involved.

In order to investigate the nuclear structure of the neutron-rich nuclei in the A=50-60 region, it will be necessary to use the N:Z equilibration characteristics of deep-inelastic reactions whereby a heavy target (which is naturally rich in neutrons) acts as a source of neutrons which can be transferred to a lighter beam species. One example of a reaction that can be used is that between ^{50}Ti and ^{208}Pb or ^{238}U. Many of the nuclei that will be produced in such a reaction have, as yet, no known excited states. Therefore, it will be required to identify the precise nucleus with which any observed γ rays are associated. This can be achieved by combining a heavy-ion spectrometer, which has the ability to identify detected ions, with an array of Ge detectors. Such a spectrometer (HIPS) has been installed and commissioned in Jyväskylä.

A further and important aspect of deep-inelastic measurements to form neutron-rich systems can be investigated by the fact that the HIPS heavy-ion detection system not only identifies the reaction products, but it also measures their energy and angular distribution. This implies that information can be obtained on the deep inelastic reaction mechanism itself. In such reactions there is considerable transfer of angular momentum from relative motion to intrinsic rotation of the reaction products. This intrinsic angular momentum is manifested by the cascade of γ rays that is subsequently emitted by the excited nuclei produced in the exit channel. Thus, the γ spectroscopic studies will also provide an insight into the angular momentum sharing in deep inelastic reactions.

References

[1] P. Moller *et al.*, Z. Phys. A359 (1997) 251
[2] P. Möller and J.R. Nix, J. Phys. G20 (1994) 639
[3] R. Smolanczuk *et al.*, Phys. Rev. C52 (1995) 1871
[4] Z. Patyk and A. Sobieczevski, Nucl. Phys. A533 (1991) 132
[5] S. Hoffman, Rep. Prog. Phys. 61 (1998) 639 and references therein
[6] R.-D. Herzberg, Spring Meeting of the German Physical Society, 1999
[7] P. Reiter *et al.*, Phys. Rev. Lett. 82 (1999) 509
[8] H.W. Gäggler *et al.*, Nucl. Phys. A502 (1989) 561
[9] N.V. Zamfir *et al.*, Phys. Lett. B357 (1995) 515
[10] J.L. Wood *et al.*, Phys. Reps. 215 (1992) 101
[11] P. Möller and J.R. Nix, At. Nucl. Data Tables 26 (1981) 165
[12] R. Bengtsson, P. Möller, J.R. Nix and J. Zhang, Phys. Scr. 29 (1984) 402
[13] P. Möller and J.R. Nix and W.J. Swiatecki, At. Nucl. Data Tables 59 (1995) 185
[14] S.J. Freeman *et al.*, Phys. Rev. C50 (1994) 1754
[15] R.B.E. Taylor *et al.*, Phys. Rev. C54 (1996) 2926
[16] R.B.E. Taylor *et al.*, Phys. Rev. C59 (1999) 673
[17] W. Younes and J.A. Cizewski, Phys. Rev. C55 (1997) 1218
[18] W. Younes *et al.*, Phys. Rev. C52 (1995) 1723
[19] K. Helariutta *et al.*, Phys. Rev. C54 (1996) 2799
[20] N. Fotiades *et al*, Phys. Rev. C55 (1997) 1724
[21] L.A. Bernstein *et al*, Phys. Rev. C52 (1995) 621
[22] C.F. Tsang and S.G. Nilsson, Nucl. Phys. A140 (1970) 275
[23] S. Bjørnholm, J. Borggreen and E. Hyde, Nucl. Phys. A156 (1970) 561
[24] S.J. Krieger *et al.*, Nucl. Phys. A542 (1992) 43
[25] W. Satula *et al.*, Nucl. Phys. A529 (1991) 289
[26] R.R. Chasman, Phys. Lett. 219B (1989) 227
[27] S. Yoshida *et al.*, Phys. Rev. C50 (1994) 1398
[28] S.K. Patra *et al.*, Phys. Rev. C50 (1994) 1994
[29] K. Heyde *et al.*, Phys. Rev. C53 (1996) 1135
[30] N. Takigawa *et al.*, Phys. Rev. C53 (1996) 1138
[31] W. Nazarewicz, Phys. Lett. B305 (1993) 195
[32] W. Reviol *et al.*, Phys. Rev. C49 (1994) 587
[33] G.J. Lane *et al.*, Nucl. Phys. A586 (1995) 316
[34] N. Bijnens *et al.*, Z. Phys. A356 (1996) 3
[35] J. Heese *et al.*, Phys. Lett. B302 (1993) 390
[36] A.M. Baxter *et al.*, Phys. Rev. C48 (1993) 2140
[37] R. Allatt *et al.*, Phys. Lett. B437 (1998) 29
[38] S.L. King *et al.*, Phys. Lett. B443 (1998) 82
[39] B. Cederwall *et al.*, Phys. Lett. B443 (1998) 69
[40] M.Muikku *et al.*, Phys. Rev. C58 (1998) 3033
[41] J.F.C. Cocks *et al.*, Euro. J. Phys. A3 (1998) 17
[42] A.M. Baxter *et al.*, Phys. Rev. C58 (1998) 2671
[43] P.A. Butler and W. Nazarewicz Rev. Mod. Phys. 68 (1996) 349
[44] J.F.C. Cocks *et al.*, Phys. Rev. Lett. 78 (1997) 2920
[45] P.T. Greenlees *et al.*, J. Phys. G24 (1998) 63
[46] W. Nazarewicz *et al.*, Nucl. Phys. A533 (1984) 249
[47] S. Takami *et al.*, Phys. Lett. B431 (1998) 242
[48] C.J. Lister *et al.*, Phys. Rev. Lett. 55 (1985) 810
[49] C.N. Davids *et al.*, Phys. Rev. Lett. 80 (1998) 1849

[50] M.A. Bentley *et al.*, Phys. Lett. B437 (1998) 243
[51] C.D. O'Leary *et al.*, Phys. Rev. Lett. 79 (1997) 4349
[52] R. Urkedal and I. Hamamoto, Phys. Rev. C58 (1998) 1889
[53] C. Chandler *et al.*, Phys. Rev. C56 (1997) 2924
[54] M. Oinonen *et al.*, Phys. Rev. C56 (1997) 745
[55] D.D. Warner, *Perspectives for the Interacting Boson Model*
edited by R.F. Casten *et al.*, *World Scientific, Singapore* (1988) 373
[56] P. Van Isacker, O. Juillet and F Nowacki (to be published)
[57] J. Terasaki, R Wyss and P. H. Heenen, Phys. Lett. B 437 (1998) 1.
[58] P. Van Isacker and D.D. Warner, Phys. Rev. Lett. 78 (1997) 3266
[59] D. Rudolph *et al.*, Phys. Rev. Lett. 76 (1996) 376
[60] C. Longour *et al.*, Phys. Rev. Lett. 81 (1998) 3337
[61] J. Dobaczewski and I. Hamamoto, Phys. Lett. B345 (1995) 181
[62] R. Grzywacz *et al.*, Phys. Rev. C55 (1997) 1126
[63] G.D. Dracoulis *et al.*, Phys. Lett. B419 (1998) 7
[64] C.J. Pearson *et al.*, Phys. Rev. Lett. 79 (1997) 605
[65] A.M. Bruce *et al.*, Phys. Rev. C55 (1997) 620
[66] P.H. Regan *et al.*, Phys. Rev. C51 (1995) 1745
[67] D.M. Cullen *et al.*, Phys. Rev. C58 (1998) 846
[68] F.R. Xu *et al.*, Phys. Rev. C59 (1999) 731
[69] C.S. Purry *et al.*, Nucl. Phys. A632 (1998) 229
[70] C. Wheldon *et al.*, Phys. Lett. B425 (1998) 239
[71] F. Xu *et al.*, Phys. Lett. B435 (1998) 257
[72] A. Ghiorso *et al.*, Phys. Rev. C7 (1973) 2032