Physics Case for the Stopped Beam RISING Campaign

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(A) Structure Around ^{100}Sn

Doubly-magic nuclei are essential bench marks within the nuclear chart. They and their near neighbours serve as sources and act as constraints for the shell-model parameter sets by providing key ingredients to any nuclear mean-field model such as single-particle energies and residual interactions. The region around N=Z=50 is of particular interest, since ^{100}Sn is the heaviest particle-bound self-conjugate doubly-magic system and as such, may be susceptible for continuum and isospin effects. In addition, the structure of the region has astrophysical consequences since it is predicted that the region 'southwest' of ^{100}Sn lies on the rapid proton capture path, which ends shortly beyond the N=Z=50 shell closure due to fast alpha decays [1].

RISING will open new perspectives in the spectroscopy of nuclei in the vicinity of ^{100}Sn.

1. Beta-decay information of the exotic nuclei in the region remains scarce [2-5]. In spite of the recent progress at ISOL mass separators in Z identification by exploiting chemical and laser ionisation selectivity in many cases even fundamental quantities such as masses or ground state half-lives are not well known. The combination of a powerful germanium-detector array such as RISING coupled with an efficient and comprehensive β-decay set-up at the final focus of the Fragment Separator will provide a significant improvement in the experimental sensitivity in this region.

2. The study of quantities which are difficult to access by means of other well established reaction mechanisms such as fusion-evaporation reactions will become available using β-delayed spectroscopy. These newly-developed experimental techniques will allow access to information such as the identification of specific non-yrast single-particle states resulting from the population of low-spin orbits (e.g. $s_{1/2}$, $d_{3/2}$ etc.)

The very neutron deficient nature of ^{100}Sn also implies low production rates. However, this is not necessarily an experimental disadvantage, since too high rates potentially destroy correlations between implanted ions and subsequent beta decays. In that sense, the region around ^{100}Sn appears to be ideal for β-delayed studies during the proposed stopped RISING campaign. Three specific physics cases are presented in some detail.

1. Neutron Single-Particle States

In the past, the main portion of nuclear structure information in the ^{100}Sn region has arisen from fusion-evaporation reactions. Recently, the splitting of the neutron $d_{5/2}$ and $g_{7/2}$ single-particle states has been deduced from excited states in ^{103}Sn [6]. However, the single-particle levels of the low-spin neutron $s_{1/2}$ and $d_{3/2}$ orbits are effectively unknown, indeed it is only in ^{107}Sn, seven neutrons away from the doubly-magic core, where excited states with tentatively assigned spin and parity $I=3/2^+$ are known. We suggest measuring the Gamow-Teller (GT) β-decay of ^{105}Sb, which has a half-life of about one second. The GT decay of the proton $d_{5/2}$ ground state should mainly populate the spin-orbit partner neutron $d_{3/2}$ state in the ^{105}Sn daughter. Depending on its location, a gamma-ray branch into the neutron $s_{1/2}$ level may be observed as well from GT feeding of higher lying $3/2^+$ states, though this is expected to be suppressed due to the reduced phase space. Both states are likely to subsequently gamma-decay into the known $7/2^+$ and $5/2^+$ states in ^{105}Sn. An additional attractive aspect of such studies using fragmentation beams and RISING is that Sb isotopes are difficult to process with ISOL techniques. In the absence of any information on spectroscopic factors for the single-particle states, the GT M1 and E2 selection rules, along with large-scale shell-model calculations, provide an indirect measure of the spectroscopic strength. The evolution of the single-particle energies from ^{100}Sn to ^{132}Sn and to ^{90}Zr is decisive for the change in shell structure from ^{132}Sn towards neutron rich N=82 isotones along the astrophysical r-process path.

2. Fermi-Decays and Isospin Mixing

From previous campaigns at GSI (using the Cluster Cube and TAS at the GSI Online Mass Separator) it was established that a measurement of the full Gamow-Teller strength of the decay of proton-rich nuclei is difficult to achieve solely using high-resolution gamma-ray spectroscopy. Therefore, we suggest instead a focus on Fermi decays of odd-odd N=Z nuclei below ^{100}Sn. Due to their much shorter half-lives the Fermi decays can be discriminated from beta-decaying high-spin states, which are also populated in these isotopes [3-5]. In particular we would like to search for weak branches parallel to the main superallowed Fermi decays. A measurement of the number of gamma rays in the daughter nuclei with respect to the number of incoming ions shall allow for an estimate of the isospin mixing in medium heavy N=Z nuclei. The identification of isomeric states with lifetimes in the microsecond range in the heavy odd-odd N=Z nuclei ^{82}Nb and ^{86}Tc [7] is also of relevance here in determining the energy difference and possibly the degree of isospin mixing by identifying the decay branches and lifetimes between the T=0 excited configurations and the T=1 ground states. The RISING setup will allow unprecedented sensitivity for isomeric decays from fragmentation products along the N=Z line (using a ^{112}Sn or ^{124}Xe beam) and should even allow g-g coincidence information to be measured for these decays allowing the unambiguous construction of the nuclear decay schemes for these highly exotic nuclei.

3. Spin-Gap Isomeric or Beta-Decaying States

Near doubly-magic nuclei spin-gap isomers may arise from specific couplings of a few valence nucleons or holes (e.g., $19/2^-$ states in the A=53 mirror nuclei ^{53}Co and ^{53}Fe), which will de-excite by gamma- and/or beta-decay. By studying their properties valuable information on the neutron-proton part of the nucleon-nucleon interaction and the influence of the core excitations can be obtained [8-10]. Until recently only the $^{21}/_{2}{}^{+}$ spin-gap beta-decaying isomer in ^{95}Pd has been observed. The information has been greatly expanded by the identification of the predicted $23/2^+$ and the unexpected $37/2^+$ isomers in ^{95}Ag [9] and the record spin 21^+ state in ^{94}Ag [8], which was also ‘unpredicted’. The latter isomers become isomeric only by regarding excitations of the ^{100}Sn core [8,9]. A core excited 12^+ isomer has recently been reported in ^{98}Cd, which implies a analogous spin/parity 14^+ beta-decaying spin trap and an 6^+ isomer in ^{100}Sn [10]. An E2 isomer is predicted to exist in ^{96}Ag$_{49}$, and the beta-delayed proton decay observed in ^{97}Cd$_{49}$ is thought to originate from a $25/2^+$ high-spin state. Similarly, the N=Z isotope ^{96}Cd is expected to reveal a highly energetically favoured, beta-decaying 16^+ state. The latter isotope has been identified in projectile fragmentation reactions (see, e.g., Ref.~[3]), however to date, no spectroscopic information has been observed.

Clearly, delayed high-efficiency gamma-ray detection will help to (I) discover isomers in the 'southwest' of ^{100}Sn, and (II) establish a comprehensive decay scheme of, for example, ^{97}Cd. The halflives for the $½^-$, $23/2^+$ isomers in ^{95}Ag will provide the first quantitative information on the E3 and E4 effective operators close to ^{100}Sn (see Table.1)

The predicted 8^+ proton $(g_{9/2})^{-2}$ seniority isomer predicted in ^{130}Cd is of major interest in that it should have an identical valence structure to the observed 8^+ isomer decay in ^{98}Cd (due to both cases having closed neutron shells). Such studies are now viable using projectile fission reactions coupled to the RISING spectrometer placed with a passive stopped at the focal plane of the FRS. In particular measurements of the B(E2:8^+->6^+) strength will shed new light on the effective charges for shell model calculations across an unprecedented range of neutron numbers. There are also a number of related isomer decay studies which are predicted by state of the art shell model calculations around the doubly-magic ^{78}Ni and ^{132}Sn cores which would also be likely to be studied in the stopped beam phase of RISING. For compleness, these are also listed in Table 1.

Table 1. Isomer list for the stopped-RISING Campaign

Nucleus	**State (decay mode)**	**Beam**	**Measurment**
^{100}Sn region			
^{95}Ag	**37/2$^+$ (E4), 23/2$^+$(E3), 1/2$^-$ (E3)**	**^{106}Cd**	**T1/2**
^{96}Ag	**15$^+$(E2)**	**^{106}Cd**	**Gamma-gamma, T1/2**
^{96}Cd	**16$^+$(E6,beta)**	**^{124}Xe**	**Beta,gamma, T1/2**
^{97}Cd	**25/2$^+$(E6,beta)**	**^{124}Xe**	**Beta,gamma, T1/2**
^{98}Cd	**14$^+$(E6,beta)**	**^{124}Xe**	**Beta,gamma, T1/2**
^{100}Sn	**6$^+$ (E2)**	**^{124}Xe**	**Gamma-gamm, T1/2**
^{78}Ni region			
^{72}Fe	**12$^+$(E2)**	**^{238}U**	**Gamma-gamma, T1/2**
^{74}Fe	**14$^+$(E4/E6, beta)**	**^{238}U**	**Beta,gamma,T1/2**
^{76}Ni	**8$^+$(E2),12$^+$(E4)**	**^{238}U**	**Gamma,T1/2**
^{132}Sn region			
^{125,127}Cd	**7$^-$ (E2)**	**^{238}U**	**Gamma-gamma,T1/2**
^{126,128}Cd	**18$^+$(E4/E6, beta)**	**^{238}U**	**Beta, gamma, T1/2**
^{130}Cd	**8$^+$(E2)**	**^{238}U**	**Gamma-gamma, t1/2**
$^{125-129}$In	**23/2$^-$(E2)**	**^{238}U**	**Gamma-gamma, T1/2**
^{136}Sn	**6$^+$(E2)**	**^{238}U**	**Gamma-gamma, T1/2**

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(B) g-factor measurements on isomer beams.

Nuclear magnetic moments are very sensitive probes of the intrinsic structure and especially of the underlying single-particle nature of nuclear states. Measurements of nuclear g-factors can also serve as stringent tests of spin and parity assignments [1], especially in far-from-stability regions where such assignments are often based on systematics and theoretical predictions. Numerous new isomers in various regions have been recently discovered in heavy-ion fragmentation reactions [2-7].

RISING will provide the unique possibility to perform measurements of electromagnetic moments of isomeric states that are not accessible by any other means. The spin alignment of fully stripped projectiles from the high-energy fragmentation reactions at the FRS-facility at GSI is a crucial ingredient of these measurements.

The g-factor campaign, which needs its own specific experimental set-up (figure 1) including at least 8 (and likely 14 or more) of the RISING cluster detectors positioned in a ring (or a two-ring) structure around a vertically oriented magnetic field, is aiming for two major goals:

1. establishing the presence and the amount of spin-orientation in high-energy projectile fission reactions.
2. Investigating the g-factor of some 'key' isomeric states (e.g. close to a magic number, isomers related to special nuclear structure phenomena, etc…) in order to deduce relevant new nuclear structure information, not accessible via other methods or production schemes.

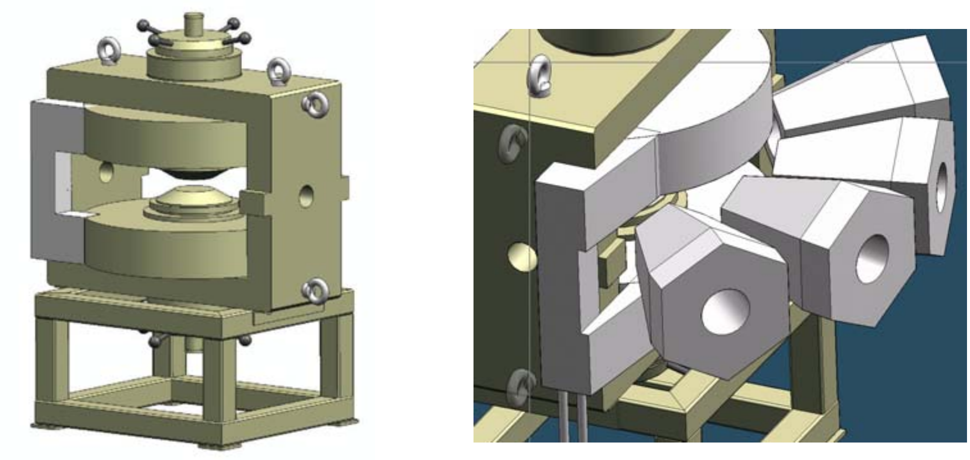

Figure: (left) Schematic drawing of the magnet for g-factor measurements with RISING. The pole gap is variable, including the pole tips. The diameter of the poles is 25 cm, diameter of the coils is 72 cm. (right) In the most closed-packed geometry, 8 cluster detectors can be positioned in a ring around the vertically oriented field. A more open configuration could hold more than 14 clusters, in two rings symmetric with respect to the horizontal plane. The optimal detection set-up is being investigated at the moment.

A proposal on item (1) was presented on the 'Stopped Beams workshop' at Surrey [8]. It is our aim to study the Time Differential Perturbed Angular Distribution pattern of isomeric states produced via projectile fission [5,9]. From the amplitude of the TDPAD pattern, we can deduce the amount of spin-alignment created and maintained after the selection of high-energy (150-200 MeV/u) fission fragments. This amount of alignment [10] could be significantly larger than that produced in the projectile fragmentation reaction [11-14]. If we can establish the presence of a large alignment, then this will open a wide range of possible exotic isomeric g-factor measurements to be performed with the upgraded future GSI facility, in neutron rich nuclei around the mass A~130 (^{132}Sn) and the mass A~80 (^{78}Ni) regions. In particular the heavier mass region is inaccessible for short-lived (100 ns – 100 μs) isomeric g-factor studies by any other means.

Several proposals in item (2), nuclear structure studies through g-factor measurements, can be considered. The g-factor of the isomeric projectile or fission fragments is directly deduced from the frequency of the observed TDPAD pattern, which shows an oscillatory behaviour as a function of time (cosine). g-factor studies in regions that are difficult to access by other production and/or orientation methods will be favoured, in combination with their nuclear structure interest.
Examples of proposals that are considered are:

- studying the single particle structure and deformation of isomers near the N=50 shell closure in proton mid-shell (Z~34-44) mass A~80 nuclei. Study of nuclear structure effects related to the N=50 shell closure, and the Z=40 sub-shell closure are the aim of this proposal. Numerous new isomers have been discovered in this region in heavy ion fragmentation reactions [2]. These were produced following the fragmentation of a ^{112}Sn beam at GANIL with primary beam energies of 58 A.MeV and 63 A.MeV on a natural nickel. For maintaining the spin-alignment during the in-flight selection process, the higher primary beam energies of GSI are favoured (pick-up of electrons is avoided if the secondary beam remains at an energy above 100 MeV/u for the A~80 region). Also, a projectile with a mass closer to the nuclei of interest is favoured, due to the larger amount of spin-alignment that is expected [15]. Therefore we suggest using ^{98}Mo as primary beam, at an energy of about 150-200 MeV/u. The dependence of the spin-alignment on the target is not so clear at this moment. Until now, significant amounts of alignment have been observed by fragmentation on light (^{9}Be) targets.

- the region along the Z=82 proton shell closure. Many measurements of nuclear moments have been performed already in this mass region, revealing very interesting nuclear structure information [1]. For example, the perpendicular coupling of the neutron- and proton components of the ‘shears’ band heads could be established by a measurement of their g-factor [15], while the deformed nature of the intruder π(2p-2h) isomeric states observed in the neutron deficient Pb-chain could be established by measuring their quadrupole moments [16]. With the fragmentation of the ^{238}U beam, several isomers east and south-east of ^{208}Pb have now become accessible for the first time for nuclear structure studies. It is obvious that g-factor measurements can be of importance for assigning spins and parities to the isomeric states and to pin down the single particle configuration. The difficulty in these experiments will be to obtain a fully stripped fragment beam, and to maintain the fragment beam fully stripped up to its implantation in the crystal between the poles of the electromagnet. The presence of singly or multiply charged ions in the implanted isomeric beam, will result in a significant loss of amplitude in the observed R(t) function [17].
- The region around the Z=50/N=82 shell closure (combined with the alignment study from fission fragments).

In order to carry out these experiments at the FRS using the RISING cluster detectors, a dedicated magnet system allowing magnetic fields up to about 1.5 T (with a gap of 5 cm between the poles) up to 1.1 T (with a gap of 10 cm) is under construction. It will be available for experiments from the spring of 2005 on.

The feasibility of TDPAD experiments for the GSI energy regime has been demonstrated by Schmidt-Ott et al. [11] and the present collaboration has performed two successful experiments at GANIL to measure the g-factors of single particle isomers around Z~28 and N~40 [12-14]. It has been demonstrated in the second experiment, that a pulsed secondary beam (allowing e.g. 1 short production pulse every 500 ns) greatly enhances the observed anisotropy in the TDPAD pattern.

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(C) Proton Dripline physics around A~130

Decays from deformed isomeric single and multi-quasi-particle states are of particular interest for the stopped beam program using RISING. Specificially, those which lie in the vicinity of the proton drip-line for the N=74 isotones. The analogous Z=72-76 (Hf-Os) region of deformed nuclei is particularly rich in energetically favoured high-K states which often lead to the existence of isomeric levels [1,2]. More recently, a programme of work to study analogous states in the N=74 series of nuclei has produced some intriguing results about the 'robustness' of the K quantum number across this range of isotones [2,3]. The observed isomers have $K=8^-$ and are interpreted as being based on the two quasi-neutron $7/2^+[404] \times 9/2^-[514]$, Nilsson structure which couples to produce a $K=8^-$ state. The quadrupole deformation of the N=74 isotones is predicted to increase with increasing mass (see e.g. [3]) as implied by the lowering of the first 2^+ excitation energies, and the nominally 'K-forbidden' decay to the (K=0) ground-state band should thus become *more* hindered as the K quantum number becomes better defined with increasing deformation. In fact the opposite is observed and two theories have been proposed [3] to explain this anomaly. Currently the heaviest N=74 isotone whose spectroscopy has been studied is ^{140}Dy which was recently identified using fusion evaporation reactions [4]. Note, that in an earlier experiment the N=74 isomers in ^{138}Gd was clearly observed within a few hours of beam time using the fragmentation of a ^{208}Pb primary beam [5] and thus we feel that a dedicated experiment aimed at the production of ^{142}Er$_{74}$ and (possibly) heavier N=74 isotones could best be done using a fragmentation reaction. The initial aim of such an experiment would be to identify the gamma-decay of the isomeric state in ^{142}Er (which is expected to have a half-life of about 5 miroseconds). This would automatically give information about the low-lying states in the ground-state band, allowing an estimate of the deformation to be obtained using the Grodzin's formula. The information also provides indirect confirmation of deformation parameters extracted following proton radioactivity of neighboring odd-A parents (e.g., ^{141}Tb decaying to ^{140}Dy) [6].

Following an initial isomer/gamma-ray study, it would be of interest to consider the possibility of observing proton decay from the isomeric state. Although the probability for such a decay depends on the decay lifetime of the isomeric state, such an exotic decay mode should not be too readily dismissed since it was the search for two-proton decay from an isomeric state which led to the first example of one-proton radioactivity being serendipitously discovered [7].

Another intriguing possibility in this mass region is the nuclei at the proton dripline in the cerium (Z=58) region, which are predicted to possess large ground-state quadrupole deformations. As a consequence, the high-Ω $[404]9/2^+$ proton orbital approaches the Fermi surface and it may be possible to form two-quasi proton high-K isomeric states similar to the two-quasineutron isomers seen in the N=74 isotones [2]. In addition, doubly odd nuclei of this neutron-deficient region would be expected to form low-lying high-j isomeric states.

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(D) Fission fragment studies: Opportunities with RISING

One of the advantages of GSI is the availability of isotopically separated secondary beams of neutron-rich reaction fragments produced by in-flight fragmentation or fission of heavy projectiles. In particular, the use of relativistic fission opens up many interesting possibilities to study the evolution of nuclear structure in medium-mass nuclei far from stability as a function of the increasing neutron-to-proton ratio. The in-flight fission process has been studied in detail at GSI, and cross sections have been measured [1-3]. The kinematics of the process is well understood, allowing accurate predictions of both production yields and the transmission throughout the fragment separator.

A number of state of the art, mean-field calculations predict that when the nuclear system become more weakly bound on the neutron rich side of the valley of stability, their spatial extent increases as neutron skins develop and the surface becomes more diffuse [4,5]. The resultant decoupling of proton and neutron motion, as well as the influence of levels in the particle continuum, is predicted to strongly affect the spin-orbit interaction, causing a 'rearrangement' of the standard shell model single particle orbitals. The result could be the disappearance or quenching of the standard magic shell gaps and possibly, the reappearance of harmonic-oscillator magic numbers. Indeed, recent work on the excitation energies of single particle orbitals approaching ^{132}Sn suggests empirical evidence for the weakening of the l.s term in the standard mean-field potential associated with this effect [6].

An alternative scenario is provided by the monopole driven shell evolution due to the monopole part of the residual interaction, which was recently shown to be responsible for new shell structure in light nuclei changing shell closures N=8 -> 6, 20 -> 16 (14), and which predicts a change N=40 -> 34(32) [7,8]. This mechanism with different experimental signature could act in neutron rich N=50 and N=82 isotones, too [8]. Although the heavy neutron drip-line will not be directly accessible with RISING, studies of nuclei at the edge of what is currently known will help locate the onset of such effects. (Work from ISOLDE [9] indicate that nuclei close to ^{132}Sn could already be influenced)

The connection to nuclear astrophysics is also strong: the rapid n-capture process paths are thought to proceed through nuclei "below" ^{78}Ni and ^{132}Sn. The importance of the properties of these exotic systems is illustrated by the strong dependence of nucleosynthesis abundance calculations on the choice of mass surface – mass models including the above mentioned shell quenching lead to a superior reproducibility of observed solar system abundances compared to those that preserve near-to-stability magic numbers. [10]. Recent calculations on the lifetimes of neutron-rich nuclei along the r-process path have been shown to be very important in understanding the rate of this nucleosynthesis mechanism [11]. Many of the nuclei of interest will be populated via projectile fission and their ground state (and in some cases isomeric state) β-decay lifetimes will be measured for the first time. The lifetimes and spectroscopy of the neutron-rich nuclei around ^{132}Sn also will also light on the ongoing question of possible 'shell quenching' for N=82 at large neutron excess [12].

Systematic studies of fission fragment angular momentum will also give important insights on the neck formation and scission of the fissioning system, as well as "temperature" information (because of the correlation between average fragment spin and excitation energy). Up to now, data on angular momentum aspects of fission are relatively scarce, and mostly originate in studies of low-energy processes, such as spontaneous fission [13]. The measurement of isomeric ratios of especially high-spin (I>10 hbar) isomeric states would be extremely useful

With the arrival of RISING, it will be possible both to continue the isomer spectroscopy studies, not only of nuclei close to the doubly-magic fix-points ^{78}Ni and ^{132}Sn, studying a T=1 and T=0 interaction via seniority and spin-gap isomers but also in new areas, including the potential region of new (doubly) "K-magic" nuclei [14]. This possibility should offer a unique probe into the development of deformation as the number of valence particles increases in the mass ~120 region.

In addition, efficient β-decay studies of also very rare fission product isotopes become possible. Here the nuclei of interest would be implanted in an active catcher and the subsequent gamma-radiation in coincidence with beta-particles recorded – the betas in the catcher system and the gammas in the surrounding germanium detectors (as demonstrated in the Munich ^{100}Sn-experiment at GSI [15]). This technique can be applied to any region of the nuclidic chart accessible with fission. Both of these measurement types can be combined with "fast timing" [16], using ancillary BaF_2-

arrays, and this possibility should not be forgotten. Using either the isomeric [17] or the beta transition as trigger, the much shorter (down to picosecond) lifetimes of lower-lying states populated in the (isomer) decay can be measured, adding useful nuclear structure information (transitions, multipolarities etc.).

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(E) The Neutron-rich Hf-Pt region

The region of the neutron-rich Hf-Pt nuclei is an established testing ground for a number of nuclear structure phenomena, including K-isomerism, configuration dependent pairing effects, gamma softness, hexadecapole deformation, dynamical nuclear symmetries and subshell closures. However, our current knowledge of the neutron-rich isotopes of these elements is severely limited due to the difficulty in synthesising these species in an environment which allows detailed spectroscopy. Recent experiments have shown that the structure of neutron-rich nuclei can be studied using the novel technique of fragmentation reactions. Technically the most straightforward is to obtain structural information from the delayed radiation originating from isomeric states (with no Doppler broadening, and almost no background).

The structure of nuclei in the Yb-Hf-W-Os (Z=70-76) region of deformed nuclei is characterised by the presence of K-isomeric states [1]. These are multi-quasiparticle states formed by orbitals with large angular-momentum projections (Ω) on the symmetry axis ($K=\Sigma_i\Omega$). The isomers present in the chain of the heavy Pt (Z=78) isotopes are of different nature, in that they are classical, ‘spin-traps’ which de-excite via hindered, low energy transitions. The wide-ranging presence of such isomeric configurations in the Hf-Pt region [2] almost guarantees a plethora of new spectroscopic information using the projectile fragmentation-isomer spectroscopy method. Not only are K isomers of interest in themselves in that they point to the robustness of the quadrupole deformation in both the isomeric state and the level(s) to which it decays, but they also serve as an excellent spectroscopic tool, providing access to excited states in these very neutron-rich nuclei where novel subshell structures may be manifest (e.g. [3]).

A significant amount of information on the global behaviour of nuclei can be obtained from the energy spacing of the lowest lying states. In even-even systems the excitation energy of the first 2^+ state can be used to infer the extent of quadrupole deformation. Similarly, the ratio of the excitation energies of the first 4^+ and 2^+ states can be used to distinguish between an axially symmetric deformed rotor, a spherical, vibrational nucleus and a triaxial rotor. In general, for nuclei, where the spectroscopic information is available, the systematics follow smooth trends, providing sub-shell closures are taken into account.

As shown in Figure 1, the experimental data obtained on the neutron-rich ^{190}W isotope (following the highly successful experiment at GSI in April 1999 investigating isomeric decays following the fragmentation of a 1GeV.A ^{208}Pb beam) suggests a new subshell effect for heavy neutron-rich systems [3]. The energy ratio of the first two excited states, for this nucleus shows a striking deviation from the pattern for the lighter isotonic chains, a feature which is not currently understood. The deviation at ^{190}W is reminiscent of the systematics representing the breakdown of the Z=64 subshell gap for neutron numbers between N<78 and N>88. More data on the ground state bands of neutron rich even-even nuclei in this region are needed, and we propose to study nuclei such as ^{186,188}Hf and ^{192}W to address this question. The high efficiency of RISING will also significantly improve statistics, allowing detailed gamma-gamma coincidence information to be obtained. This is crucial in the case of the odd-odd and odd-A nuclei, from which the proton-neutron interaction and single-particle energies can be extracted.

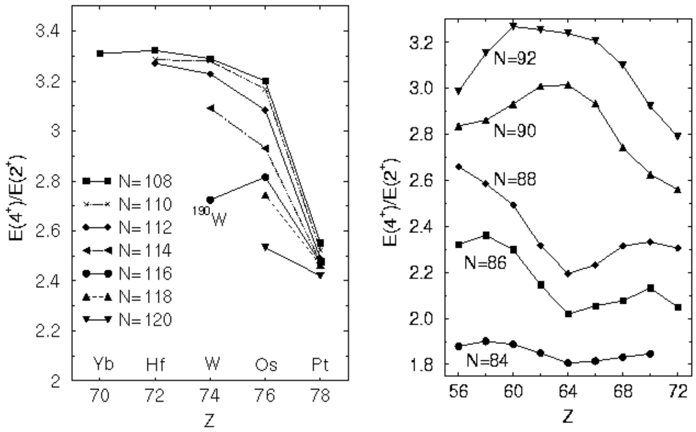

Figure 1: Excitation energy ratios for the even-even nuclei around Z=64 and N=90 (right) and Yb to Pt isotopes around N=116. Note the apparent signature for a sub-shell closure observed from the ^{190}W ratio as identified via isomer spectroscopy following ^{208}Pb projectile fragmentation.

Another major question to be addressed is the underlying reason for the shape transitions between axially deformed, triaxial and spherical nuclei. This can be investigated by studying nuclei close to the spherical ^{208}Pb nucleus via previously inaccessible neutron-rich nuclei. The first choice is the ^{204}Pt nucleus, where a 7$^-$ spherical isomer is expected. Recently a similar isomer in ^{202}Pt was identified [5], with a lifetime four orders-of-magnitude longer than those of similar states in the lighter platinum isotopes, caused by the lowering of the ($h^{-1}_{11/2}d_{3/2}$) 7$^-$ two-proton state below the (most likely 2 proton $h^{-1}_{11/2}s_{1/2}$) 5$^-$ level.

The most favoured conditions for the formation of K isomers are when the neutron and proton Fermi levels are high, but not too high, in their respective shells. Thus, Z=72 (about 70 percent through the Z=50-82 shell) is strongly favoured, and so are nuclei around N=116. These nucleon numbers could be described as "K magic". However, to combine simultaneously optimum proton and neutron numbers requires the study of neutron-rich nuclei that have to date been inaccessible, such as ^{188}Hf, ^{146}Hf, ^{118}Ru – nuclei that may be termed "doubly K magic". The ground state of the "doubly K magic" ^{188}Hf (Z=72) has recently been identified following relativistic projectile fragmentation performed at GSI [2]. We propose the study of its excited collective and multi-quasiparticle structures.

A deeper insight into the wavefunction of individual states can be obtained by measuring lifetimes. Lifetimes of the states down to the sub-nanosecond regime can be determined by electronic timing methods using fast-response BaF$_2$ detectors. This technique will be used to determine the lifetime of the first excited states (most importantly, the 2^+ states) in the nuclei connected to the proposed subshell effect around ^{190}W. Lifetimes of short-living isotopes will be measured as well. Previous experiments identified such isomers in the ^{200,201}Pt [2,4,5] isotopes with lifetimes below the time resolution of germanium detectors.

The nuclei of the neutron-rich Hf-Pt region will be populated using ^{208}Pb and ^{238}U primary beams. Generally speaking, the former will give higher cross sections, the latter will populate higher spins. Previous experiments showed that stopped isomeric beams can be successfully used to study the neutron-rich rare-earth nuclei. The increased sensitivity of the Ge detectors (RISING) gives the possibility to push further the limit of known nuclei and to investigate some of the above issues that we have only glimpsed at present.

This region also allows a unique insight into the angular momentum input for projectile fragmentation with the wide range of isomeric spins and excitation energies. The initial studies of isomeric ratios in this region have established population of I=35/2 ħ K-isomeric states [6] and this has been complemented by studies of isomeric ratios in neutron-deficient Pb region [7]. The recent study has identified decays from a spin 43/2 isomer in ^{213}Rn from ^{238}U fragmentation [8] suggesting a wide range of new high-spin isomers in neutron-rich systems are within experimental reach for the first time.

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(F) Isomer and Particle Decay Probes of Shape Coexistence Around Z=82

Neutron-deficient lead isotopes close to the neutron mid-shell near N=104 represent a particularly important example of the quantum mechanical mixing of nearly degenerate eigenstates characterised by different intrinsic shapes [1,2]. Calculations predict three different shape configurations at relatively low excitation energies, arising from the excitation of pairs of protons from the closed shell core: the spherical ground state, associated with the Z=82 shell closure (0p-0h configuration), along with an oblate 2p-2h and more strongly deformed 4p-4h or even 6p-6h prolate configurations [3,4]. Furthermore, new shapes, including a highly deformed oblate configuration at an excitation energy of ~2.5 MeV are also predicted for extremely light lead isotopes [3].

As an example, unique cases of *triple* (prolate-oblate-spherical) shape coexistence have recently been observed in the very neutron-deficient isotopes ^{186,188,190}Pb [2,4,5]. Pb nuclei of interest have been produced in the complete fusion reactions with heavy ions and studied by means of in-beam gamma and conversion electron spectroscopy [4-7] or via α-decay of parent Po nuclei [2,8]. However, quite often these states are not (or only weakly) populated in the in-beam and/or α-decay experiments. An alternative approach to investigate these structures is the studies of high-K μs isomers, the decay of which may cascade through the states of interest. As discussed in [4], high-K states have the robust characteristics of a well-defined axially-symmetric deformation, both prolate and oblate. Such isomers are known in many even-mass lead nuclei, down to ^{188,190}Pb [4] and the intensity distributions of the recently observed yrast bands in the lighter even-mass lead isotopes [7] also suggest existence of similar isomers. Unfortunately, the production yields of these nuclei in traditional complete fusion reactions plummet with decreasing neutron number, see Figure 2, making these studies with conventional techniques very difficult or even impossible.

Using RISING, we propose to considerably extend these studies towards more neutron-deficient lead isotopes for which only scarce information on some of the yrast states is available [7]. In particular, we suggest the exploitation of the unique possibilities arising from the use of intense radioactive beams of Pb from the fragmentation of relativistic 1 GeV/A ^{238}U beam at the FRS. The figure shows the measured and expected yields for Pb isotopes from the reaction ^{238}U(1 GeV/A)+C. Note the rather good agreement between the measured and calculated yields for $^{188\text{-}190}$Pb, which gives us confidence in predicting yields for lighter isotopes. Figure 2 clearly shows the advantage of fragmentation reactions for this case, providing a luminosity of up to 10^{32} (based on 10^{9} ^{238}U ions/s and 5 g/cm^{2} C target), compared to a luminosity of 10^{29}-10^{30} for the typical complete fusion reactions used previously. We therefore expect an intensity increase of produced $^{182\text{-}186}$Pb isotopes by at least two orders of magnitude, compared to complete fusion reactions. A similar high intensity gain is also predicted for Tl, Bi and Po nuclei, which we plan to investigate in the complimentary studies in the future.

As a first approach we propose to study the γ-ray decay of μs isomers in the very neutron-deficient isotopes ^{182,184,186}Pb in order to search for the hitherto unobserved non-yrast transitions. Expected counting rates of up to a few thousand per second are high enough to perform a detailed spectroscopy of yrast and non-yrast states in these nuclei. The isomeric states will be identified by standard isomer tagging technique.

S*imultaneously* with the study of the isomeric states in ^{182,184,186}Pb nuclei we propose to perform a search for the fine-structure α-decays of these isotopes to unknown low-lying (~400-600 keV) excited 0^{+} prolate band heads in the daughter ^{178,180}Hg. The prolate rotational bands are known in these nuclei, but due to decay-out no 0^{+} band heads have been observed yet. As shown in [2,8], α-decay is especially suited for such studies. The experimental signature for identification of an excited 0^{+} state in the daughter nucleus is the observation of a fine structure ΔL=0 α-decay of the parent nucleus, feeding this excited level in the daughter isotope, which de-excites further by a prompt fully converted transition to the 0^{+} ground state.

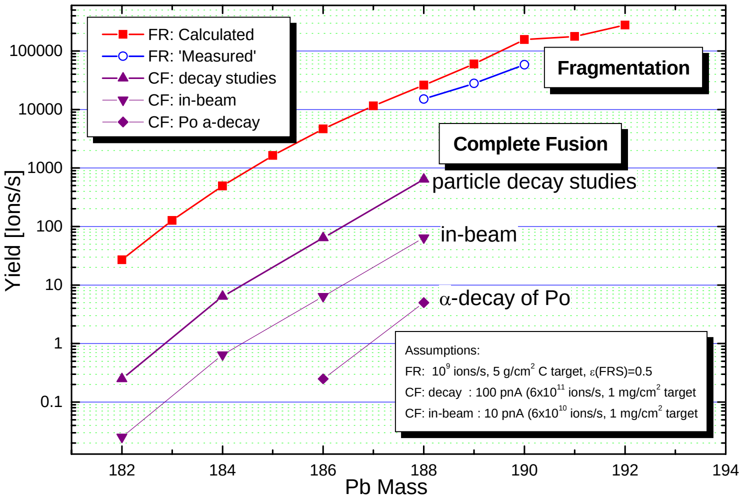

Figure 2. *Measured and calculated yields of Pb isotopes, produced in fragmentation reactions (FR) and in typical complete fusion reactions (CF). For complete fusion reactions 3 types of typical measured yields are shown: direct production of Pb isotopes with the high beam intensity (for particle decay studies); direct production with lower beam intensity (in-beam studies [4-7]); and production via the α-decay of parent Po nuclei [2,8]. The calculated and measured data for fragmentation reactions are taken from [9].*

To perform this study, ions of interest, after slowing down to an energy of ~10 AMeV will be stopped in an active stopper, composed of a set of position-sensitive Si-detectors, where their subsequent α-decays will be measured. To register conversion electrons the Si-detectors will be surrounded in a backward/forward hemisphere by a set of Si-detectors/PIN-diodes which will allow to achieve an efficiency of ~30-40% for α-e^- coincidences. The method is well established by now and was earlier used, for example, to identify such 0^+ states in ^{182,184}Hg [8] and recently – to identify 0^+ prolate and oblate states in ^{186,188}Pb [2].

In summary, the identification of non-yrast 0^+ band head states of coexisting configurations is of particular importance since it provides a constraint on the unmixed band head energies and the mixing strengths between the structures in these nuclei. Furthermore, the development of the shape isomerism beyond the neutron mid-shell at N=104 along with identification of higher-spin, non-yrast states would provide a sensitive test of the shell-model and mean-field calculations.

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(G) Neutron-rich A~110 nuclei: Transitional Behavior and Shape-Coexistence

Recently, new kinds of symmetries, called critical-point symmetries have been proposed [1,2]. They provide analytic solutions within the framework of the collective model for atomic nuclei lying at the critical point of a shape-phase transition. Several atomic nuclei have been identified as possible examples of the X(5) symmetry [3,4,5], which describes the critical-point behaviour of a nucleus undergoing a shape transition from a spherical vibrator to an axially-deformed rotor. Candidates displaying E(5) symmetry properties, describing the critical-point behaviour of a spherical-vibrator to triaxially-soft rotor have also been suggested [6,7]. A strong correlation between the occurrence of critical-point nuclei with the associated P-factor, (P = NpNn/(Np+Nn) where, Nn and Np are the number of valence neutrons and protons, respectively) has been identified [8]. Notably, in medium-heavy nuclei X(5) nuclei occur when P takes the value of 5, e.g. the N=90 region. It would be of considerable interest to study whether such a relationship holds away from stability. Figure 3 illustrates the prediction and shows that most of the predicted nuclei are situated away from stability.

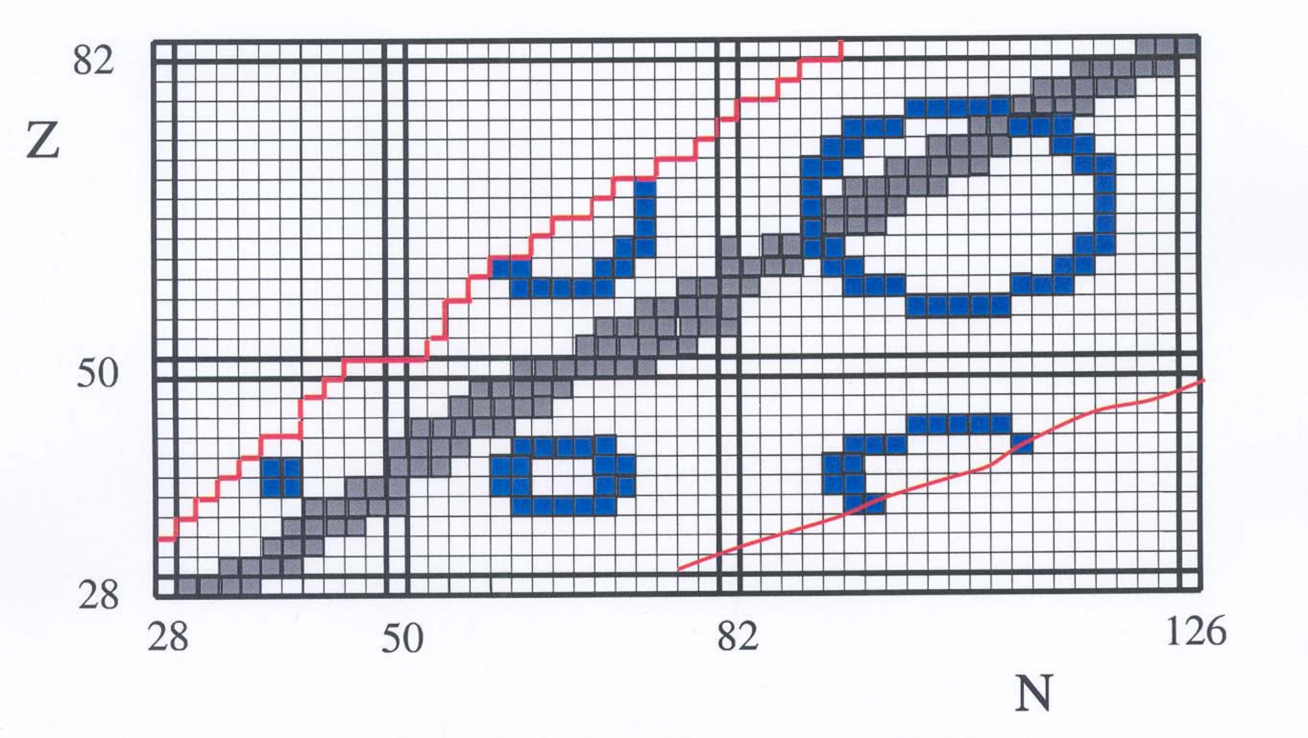

***Figure 3.** The lines presents nuclei with P= 5 for which the occurrence of a X(5) structure is predicted [9].*

We would like investigate candidates for X(5) behaviour which are situated in the very neutron-rich Mo and Zr region with A~110. This is also a region where there are predictions of stable oblate shapes, possibly occurring even as the nuclear ground-state [10,11]. Oblate shapes occur rarely in nuclei and are sensitive to details of the nuclear potential such as the strength of the spin-orbit force [12]. Since the isospin dependence of the spin-orbit force is not well established, the observation of a new region of neutron-rich nuclei with oblate shapes would provide an important testing ground of different mean-field models. The neutron-rich Mo-Zr region may be reached by projectile fission and the subsequent beta-decay and the gamma-decay of shape coexisting isomers may be searched for and studied.

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