GRANT REPORT ON
STUDIES OF NUCLEI FAR FROM STABILITY BY TAGGING TECHNIQUES
Submitted October 2004

Background and Context

Leading laboratories across the world are actively pursuing research programmes investigating the properties of nuclei far from stability. As part of this endeavour, the UK has invested, through a multi-institutional grant award, in a specialised spectrometer to detect and characterise the radioactive decays of the products of nuclear reactions. This is a report on the status of the GREAT project and the associated physics that has been completed during the grant. The GREAT focal plane spectrometer with its novel total data readout (TDR) data acquisition system, the SACRED electron spectrometer and the JUROGAM γ-ray detector array combined with the RITU recoil separator at JYFL now form the most powerful instruments in the world for tagging studies of exotic neutron-deficient and super-heavy nuclei. The following institutions, with associated grant numbers, have produced this report: CCLRC Daresbury Laboratory and the Universities of Liverpool, Manchester, Surrey and York. The grant report from Keele University has already been favourably reviewed.

A major aim of nuclear structure research is to provide a proper description of the effective interaction between the nucleons in the many-body nuclear system, from which the properties of the nucleus can be deduced. The route to achieving a better understanding of the effective nuclear interaction lies in testing the predictions and limits of applicability of nuclear models by probing nuclei under extreme conditions. One approach, which has been followed by many research groups worldwide and has been advanced to a new level in this grant, is to examine the quantal behaviour of nuclei having either extremes in overall mass (heavy and superheavy nuclei) or extreme values of the ratio of neutrons to protons (exotic nuclei). Superheavy and exotic nuclei provide a severe test of candidate theoretical models and demand a rigorous derivation of the nuclear Hamiltonian if the theories are to be applied globally. The methodology for studying these nuclei in this project requires high incident beam intensities and extremely sensitive instrumentation in order to isolate the channel of interest. Studies of the rarest nuclear species will require the separation from a large background of other products, their identification, and the detection of their decay processes. This can be achieved using tagging techniques where prompt radiation emitted at the target position is correlated with the subsequent decays of recoiling nuclei at the focal plane of a recoil separator. The combination of the GREAT spectrometer, constructed in this grant, with the separator, RITU, and the JUROGAM and SACRED spectrometers is a unique one and undoubtedly world leading in its field.

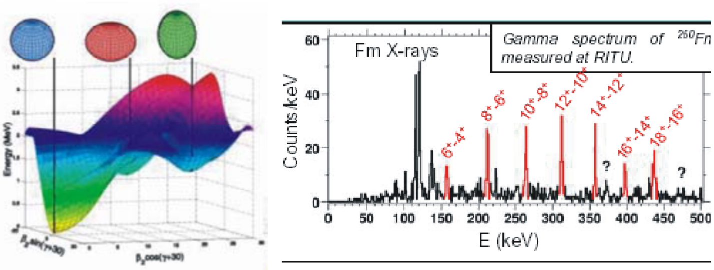
A highly effective method for producing the elusive nuclei of interest in this project is through fusion evaporation reactions. Product nuclei recoil into the RITU separator, which separates reaction products from unreacted primary beam and transports them within ~1 μs to its focal plane with ~30% efficiency. In addition to dedicated studies of nuclear decays at the focal plane, the characteristic radioactive decay properties can also be used as a unique tag for identifying prompt radiation at the target position. This powerful 'Recoil Decay Tagging' (RDT) technique has been the key to unlocking the secrets of a wide range of exotic nuclei produced with extremely low cross sections. We have exploited this technique at Jyväskylä and other laboratories to study the structure of heavy exotic nuclei and superheavy nuclei.

In order to deliver the ambitious science aims of this grant, we proposed the concept of a spectrometer capable of measuring efficiently all possible radioactive decay processes. This demanded a spectrometer holistically designed for the detection of protons, α particles, β particles, γ rays, X rays and conversion electrons emitted by reaction products transported to the focal plane of RITU. We have successfully realised this concept by constructing GREAT, which comprises a combination of gas, silicon and germanium detectors optimised for the study of nuclei produced with very low cross sections. GREAT has heralded a new generation of tagging spectrometers and the concept has since been copied at several leading international facilities, including GANIL and Oak Ridge. GREAT represents a major investment by the UK in a large-scale international facility and the programme of research launched by the six institutions in this joint grant has the common theme of the studies of exotic nuclei far from stability by tagging techniques.

Key advances and supporting methodology

Spectroscopy of the superheavy elements

In the study of superheavy nuclei GREAT and TDR play several interlocking roles. In in-beam studies they allow an excellent recoil detection and identification at high total rates, while not losing any of the rare decay events. In decay studies, GREAT provides complete spectroscopy of all emitted radiations. Experiments were successfully performed in both modes.



Shape coexistence in ^{186}Pb **Spectroscopy of the heavy elements**
Physics from UK-lead tagging experiments supported by this grant, taken from the NuPECC long-range plan

In-beam experiments to study $^{252,\,254}$No, ^{250}Fm and ^{251}Md with SACRED and JUROGAM were performed. In all cases the high granularity and excellent performance of the focal-plane instrumentation allowed the clean identification and correlation of the recoils to their characteristic α decays. Only this correlation allows the unambiguous assignment of prompt radiation to a specific nucleus. With GREAT it has been possible to correlate a record 36-hour decay half-life of the ^{250}Fm → ^{246}Cf→ ^{242}Cm decay chain. The accumulated statistics were much higher than previous experiments and allowed a coincidence analysis for the first time. Several transitions from excited bands have been observed in No and Fm and will allow more stringent tests of the mean-field calculations describing the order of the single-particle Nilsson orbitals in these nuclei. The experiments on ^{251}Md using both γ rays and conversion electrons were also highly successful. The ground-state rotational band of ^{251}Md was identified and the transitions assigned an E2 character. This allows a determination of the single-proton structure in this Z=101 nucleus and is by far the most sensitive test of the nuclear model calculations, helping theorists to narrow their diverging predictions for the next superheavy spherical proton shell gap. In-beam conversion electron measurements in ^{254}No carried out using SACRED revealed the presence of high-multiplicity M1 cascades that arise from the population of many high-K rotational bands present in this nucleus

Dedicated decay studies were performed on ^{255}Lr, ^{251}Fm and ^{254}No. The α decay of at least two different states in ^{255}Lr into excited states of ^{251}Md was observed, governed entirely by the single-proton orbitals close to the Fermi surface. This provides extremely sensitive tests of the predictive power of the order and relative spacing of the deformed single-proton Nilsson orbitals. The α decay of the ground state of ^{255}No into excited states of ^{251}Fm was used to establish the low-lying level scheme of ^{251}Fm. Here several levels were populated and the α-decay hindrance factors allow the determination of the odd-neutron single-particle structure. Finally in the decay study of ^{254}No, a first indication of the de-excitation of the predicted 8^- isomer into the ground-state band has been seen. While the rotational properties of even-even nuclei in this region are reasonably well reproduced by a variety of model calculations, predictions of the structure, lifetime and excitation energy of this isomer vary greatly. The final results are eagerly awaited by theoreticians working in the area.

Shape coexistence in nuclei with Z≤82

The UK leads a major research programme into shape coexistence in heavy neutron-deficient nuclei below the Z=82 shell gap, in many cases establishing comprehensive level schemes for the first time. Shape coexistence refers to the phenomenon where collective bands at similar excitation energies are built on differently deformed nuclear configurations. This phenomenon occurs in nuclei near closed shells, where particle-hole type excitations across the shell gaps form the microscopic basis for deformed intruder structures at low excitation energies. Nuclei in the vicinity of the Z=82 shell gap are ideal for investigating this phenomenon.

The light lead nuclei are predicted to possess excited states based upon prolate, oblate and spherical shapes. Studies of even-even Pb nuclei have been carried out using the RDT technique at Jyväskylä. Prior to the installation of the GREAT spectrometer, we identified the first excited states in ^{182}Pb, which was populated with a cross section of ~300 nb, using a 16 strip Si detector located at the focal plane of RITU. These data revealed that the prolate minimum had risen significantly in energy compared to the prolate states known in ^{184}Pb, and provided firm evidence for the minimisation of this configuration with respect to the spherical ground state at neutron number N=103. More recently, we have carried out experiments using the GREAT spectrometer in conjunction with the JUROGAM γ-ray array to search for the predicted oblate states in ^{184,186}Pb. The spectroscopy of ^{186}Pb is very interesting since our α-decay experiments have shown that the first three excited states in this nucleus are 0^+ states, each of which can be associated with a different (spherical, oblate, prolate) shape. A preliminary analysis and interpretation of the data on ^{186}Pb suggests that some of the new states observed result from a β vibration based on a prolate shape. If correct, this would indicate that the triple shape coexistence picture is somewhat more complex than originally conceived. Triple shape coexistence has also been identified in the light mercury isotopes with three characteristic shapes being identified in ^{177,179}Hg.

In order to help understand the microscopic structure of the prolate bands in the Hg and Pb isotopes, we have studied odd-mass nuclei such as ^{183}Tl and ^{179}Au. The first experiment on ^{183}Tl revealed the presence of a decoupled prolate band resulting from the odd proton occupying the $i_{13/2}$ orbital. Further experiments have identified new bands that are believed to result from the occupation of low-Ω, prolate $f_{7/2}$ and $h_{9/2}$ orbitals and high-Ω, oblate $h_{9/2}$ orbitals. Systematics suggest that the $f_{7/2}$ and $h_{9/2}$ prolate bands reach a minimum in excitation energy at N=104, which agrees well with the minimum excitation energy of the prolate intruder bands in the even mass Hg and Pb isotopes. These observations are consistent with the $f_{7/2}$ and $h_{9/2}$ configurations being important components of the prolate deformed states in the Hg and Pb nuclei. Calculations suggest these states are based on complex 4p-6h and 4p-4h configurations involving excitations into low-Ω orbitals from $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ shells.

We studied the α-conjugate nucleus ^{179}Au at the Argonne National Laboratory using GAMMASPHERE plus the Fragment Mass Analyzer (FMA) and utilising the RDT technique. This work firmly identified structures associated with the prolate $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ proton configurations. It also revealed that the deformation of the $i_{13/2}$ band is larger than that of the same configuration in the heavier Au nuclei, despite the nucleus being beyond the mid-shell. This result is in disagreement with theoretical calculations and is not currently understood. A further interesting feature is that the α-decay studies of ^{183}Tl reveal the presence of three new low spin states in ^{179}Au, none of which appears to be populated in the GAMMASPHERE experiment. The reasons for this are again not completely understood, but the answer may lie in the fact that the γ rays observed in the α-decay work are all low energy (<90 keV) and that GAMMASPHERE is known to be inefficient at detecting transitions in this region, particularly as they are likely to be strongly converted.

Shape coexistence takes on special relevance in the Os–Pt isotopes where the coexisting configurations are expected to mix strongly. The interaction between coexisting bands is often manifested as irregularities in the energy-level spacing of the ground-state bands. In experiments performed at Jyväskylä, we have identified the ground-state bands in ^{166}Os and ^{168}Os, which show little perturbation of their level energies. Band-mixing analyses indicate that the deformed intruder configurations in these isotopes lie at higher excitation energies relative to the ground state, compared with the heavier isotopes. This has been interpreted in terms of lower average deformations for the lighter isotopes where the Z=82 shell gap is wider and more excitation energy is required to promote proton pairs across the gap to form the deformed configuration. Consequently, the deformed intruder states have little influence on the yrast states in the N≤92 isotopes. Evidence of shape coexistence in the platinum isotopes has been more difficult to obtain since the ground-state bands in the light (A= 169-173) platinum isotopes are less well developed, if known at all. In a previous pre-GREAT experiment, γ-ray transitions were assigned to the nucleus ^{170}Pt, however a detailed level scheme could not be constructed due to the low statistics level of γ-γ coincidences. In a recent experiment using the superior γ-ray detection efficiency of the JUROGAM array in conjunction with the GREAT spectrometer, we have established the level scheme up to spin 10^+ via analyses of α-γ-γ coincidences. In addition, the ground-state band in ^{173}Pt has been identified for the first time up to a tentative $41/2^+$ state. The irregular level structure of this band might indicate of the presence of a deformed intruder band.

The addition or removal of a few nucleons near closed shells can lead to dramatic changes in the structure of nuclei, particularly in the transitional regions approaching the Z (N) = 82 shell closures. A major scientific aim of the grant has focused on the evolution of collectivity in neutron-deficient nuclei in the mass 160-180 region. These nuclei are among the most neutron-deficient nuclei that can be synthesised and in some cases are over 20 nucleons away from the nearest stable isotope. We have spearheaded a campaign of experiments that has established excited states in light platinum and osmium nuclei, in the case of osmium isotopes extending down to the lightest known isotope, ^{162}Os. We have established in the light even-even nuclei that the ground-state configuration becomes less deformed as the N=82 shell gap is approached by observing the systematic behaviour of 2^+ energies and the $4^+/2^+$ energy ratio. In addition to these even-even nuclei, we have established the level schemes of odd-N and odd-Z nuclei for the first time. These nuclei are vital in order to understand the nature of the odd particle coupled to the even-even core. For example, with decreasing neutron number, the level energies of the odd-N Os-Pt isotopes become almost degenerate with their even-N neighbours. This feature has been attributed to Coriolis effects on the low-Ω, $i_{13/2}$ neutron states, which tend to align the angular momentum of the odd neutron in a quasi-parallel direction to the collective angular momentum vector, effectively decoupling it from the core. In the odd-Z nucleus, ^{167}Re, several coupled band structures have been observed. The energy differences between the bands, signature splitting, as a function of spin was interpreted as a transition from a triaxial nuclear shape to prolate as the first pair of $i_{13/2}$ neutrons aligned their spins with the axis of rotation.

Development of collectivity in the neutron-deficient nuclei above Z=82

In several regions of the periodic table, the onset of deformation has been associated with the presence of deformed particle-hole intruder configurations that coexist with spherical ground-state shapes. While much information has been gained in the Z<82 regions, information on nuclei above the Z=82 shell closure is sparse due to the rapid increase in the fissility of nuclei with larger atomic numbers. We have used the improved sensitivity of the system at Jyväskylä to study in detail the development of collectivity in the Z≥82 region. A set of experiments, all of which used fusion reactions between beams of various Ar isotopes with Er targets to populate 4n reaction channels, looked at prompt radiation from ^{200,202,204}Rn and isomeric decays in ^{200}Rn. Techniques of RDT, recoil-γ and recoil-γ-γ tagging were used to extend significantly the level schemes for these nuclei, make spin-parity assignments and add to the understanding of the development of nuclear structure along the radon isotopic chain. The energy systematics deduced in these experiments suggest the presence of intruder states which fall in energy with increasing neutron deficiency in a similar fashion to nuclei of lower Z, indicating a common mechanism for the onset of deformation. Candidates have been found in ^{202}Rn for the non-yrast intruder states. The higher-spin levels in the lighter radon isotopes reflect the increasing importance of neutron-hole excitations. New long-lived isomers were established in ^{200,202}Rn, which appear to be produced by a similar mechanism to the 11^- isomers observed in the light polonium isotopes.

We have performed studies of heavier radon nuclei using isomer tagging with the SASSYER gas-filled separator at Yale University. These experiments have shed new light on the applicability of the seniority scheme to describe the structures in ^{210}Ra and a range of other heavy nuclei in the Z>82, N~126 region. The study of isomeric 8^+ seniority-changing isomeric decays has revealed new insights into the mechanism for angular momentum generation in such valence systems and evolution from single-particle to collective excitations with increasing proton-neutron valence product.

Nuclear structure at the proton drip line

The proton drip line represents one of the fundamental limits of nuclear existence. The exploitation of selective tagging techniques with GREAT spectrometer used in conjunction with a large gamma-ray detector array has allowed detailed investigations of nuclei for the first time at several points along the proton drip line above A=100. The recent upgrade of the RITU gas-filled separator has allowed near-symmetric reactions to be used for the first time in tagging experiments at Jyväskylä and has been central to the success of studying A~100 nuclei at the proton drip line.

Just above ^{100}Sn there is a region of nuclei that undergo radioactive α and proton decay. These are ideal candidates for study by tagging techniques. Nuclei close to ^{100}Sn are of significant interest because they can provide information on the single-particle energies and residual interactions with respect to the doubly-magic core. This information is crucial for developing theoretical tools such as the shell model. Furthermore, studies of heavy N~Z nuclei can reveal information on neutron-proton correlations and possibly n-p pairing, since the protons and neutrons occupy the same orbitals – which in the case of ^{107}Te are from the $d_{5/2}$ and $g_{7/2}$ subshells. The nucleus ^{107}Te primarily decays from its ground state via α decay to ^{103}Sn. This α decay has been used very recently in an RDT experiment to identify the excited states in ^{107}Te for the first time using the ^{58}Ni(^{52}Cr,3n) reaction and the GREAT and JUROGAM spectrometers. This work has led to the discovery of a first excited state at 90 keV (which is believed to be a $7/2^+$ state), a feature that could have important implications for the ^{107}Te(γ,α)^{103}Sn reaction rate studies. This reaction is of astrophysical interest since ^{107}Te is predicted to be the end point of the rp process. The lowering of the energy of the first excited state in ^{107}Te relative to the same state in ^{109,111}Te also reveals a trend, which is opposite to that found for the equivalent state in the odd-Sn isotopes. This indicates that np correlations are important in these N~Z nuclei. Further work is continuing on the implications and analysis of the data obtained from the experiment.

The understanding of proton decay from spherical nuclei is well advanced, but the anomalous half-lives of some proton emitters, such as ^{113}Cs, have often been attributed to the effects of deformation despite the lack of supporting evidence. A recent experiment has been performed using GREAT, harnessing RDT using protons to isolate prompt radiation from ^{113}Cs produced in the symmetric fusion reaction, ^{58}Ni(^{58}Ni,2pn), in order to address the issue of deformation, in addition to gaining more information on nuclear structure at the proton drip line. The experiment ran very smoothly and data are currently under analysis. It is already clear that sufficient data have been taken to perform a successful study of the low-lying levels in ^{113}Cs. A search is also being undertaken for the α-emitting nucleus, ^{110}Xe, produced via α2n evaporation and possibly ^{112}Cs, another proton emitting isotope corresponding to the p3n channel.

The use of recoil-isomer tagging was pioneered at Jyväskylä in studies of ^{138}Gd just before the start of the grant. This technique allows sensitive selection of prompt γ-ray transitions feeding an isomeric state by tagging on γ decay from the isomer. During the grant period, this technique has been fully exploited in studies of other neutron-deficient rare-earth nuclei in order to substantiate speculations concerning their structure made on the basis of proton-decay observations in the region. Reactions of ^{54}Fe beams on ^{92}Mo targets at several energies were used to populate states in ^{142}Tb and ^{144}Ho via 3pn and pn exit channels. New states were observed built on a known 15-ms isomer in ^{142}Tb. The feeding and decay of a 500-ns isomer were established in ^{144}Ho, the first observation of excited states in this nucleus. Similar experiments have also been performed which observed excited states in ^{140}Eu for the first time, along with a new isomer. The behaviour of states above the isomers suggests that they are built on low-deformation configurations with significant triaxiality. This is in contrast to the lighter-mass proton emitters that were previously interpreted as being well deformed, prolate and axially symmetric.

Pushing out to these lighter mass proton-emitting nuclei is very difficult due to rapidly reducing cross sections and increasing numbers of competing reaction channels. Critical information about ^{140}Dy, the daughter of the proton decay of ^{141}Ho, concerning deformation and Coriolis effects was missing and was needed to understand properly the proton radioactivity. Excited states were established in this nucleus following the decay a new 7-ms isomer in an experiment performed at Argonne. ^{140}Dy nuclei were populated in the α2n channel in ^{54}Fe on ^{92}Mo reactions mass analysed and transported to the focal plane of the FMA, where the isomeric decay was observed. The isomer decays into the yrast line at spin 8, revealing a rotational band based on an axially symmetric shape with a deduced deformation parameter, β_2, of 0.24. This supports previous single-particle assignments given to the two proton-emitting states in ^{141}Ho. Calculations using information concerning the ground-state band yield a proton branching ratio to the 2^+ state which is consistent with previously measured limits. The reduced hindrance factor for the isomer is consistent with the trend observed in the N=74 isotones and shows no deviations which could be attributed to the proton drip line. Very recently an experiment using GREAT was performed using recoil-isomer tagging in order to investigate states above this new 7 ms isomer and the data are currently being analysed. They have already yielded new information on neighbouring nuclei ^{143,144}Dy.

Heavy nuclei at the proton drip line have also been investigated. In the light ($N \leq 86$) tungsten and osmium isotopes in the vicinity of the proton drip line, the low-spin yrast states are expected to be based on near-spherical configurations formed by coupling the spins of aligned valence nucleons. For example, the low-spin structure of the N=86 isotones ^{160}W and ^{162}Os up to 6^+ are formed by neutron $(f_{7/2})^2$ excitations while the 8^+ state may be formed by either the neutron $f_{7/2},h_{9/2}$ or $(h_{9/2})^2$ configurations. Changes in the position of the $h_{9/2}$ orbital are manifest in the yrast spectra as variations in the excitation energy of the 8^+ state. For the even-even $_{66}$Dy to $_{76}$Os isotones with $N\geq88$, the 8^+ state is found to exhibit lower excitation energies for lower-Z nuclei. Work performed on the W and Os isotopes has shown that for $N\leq86$, an inversion in this trend occurs with higher 8^+ energy for the lower-Z isotones. This inversion is interpreted as being caused by a lowering of the neutron $h_{9/2}$ state due to an increasingly attractive proton-neutron interaction between the proton $h_{11/2}$ and neutron $h_{9/2}$ states with the pairwise addition of $h_{11/2}$ protons. This effect is also observed for the $27/2^-$ state in the proton emitting isotone ^{161}Re formed by coupling the odd $h_{11/2}$ proton to the neutron $(f_{7/2},h_{9/2})$ 8^+ configuration. These studies highlight the improved sensitivity of the GREAT-JUROGAM coupling with ^{162}Os and ^{161}Re being investigated via tagged γ-γ coincidences at the 400nb and 6µb level, respectively.

Neutron-rich nuclei

The region bounded by N=28-40 and Z=20-28 is of particular interest in the development of the shell model in neutron-rich systems. The full $\pi f_{7/2}$ νfp model space is small enough for large-scale calculations to be performed. New effective interactions have been developed, which have had some success in descriptions of low-lying excited states in neutron-rich fp-shell nuclei near N=28. Knowledge of excited states has, so far, been unavailable towards the mid-shell region, and the effective interaction and the extent of the applicability of the model space have not been tested extensively. A new programme of work was initiated to study neutron-rich nuclei in this region by applying recoil-tagging techniques to fusion reactions with neutron-rich beams and targets. Experiments sensitive to the weaker evaporation residues produced by multiple charged-particle emission have not been performed previously. Such channels require careful selection from the prolific xn and pxn residues and the best way of providing this is using a recoil separator with an inverse reaction induced by a ^{48}Ca beam. Inversion of the reaction improves transmission and produces fast recoils, optimising Z identification performed by energy-loss measurements in an ion chamber.

We have carried out experiments at Argonne using the FMA to analyse recoils in terms of m/q; charge-state ambiguities have been resolved using an energy/time-of-flight method. Prompt electromagnetic radiation was detected in the GAMMASPHERE array. Two-proton evaporation from neutron-rich fp-shell compound nuclei has been observed for the first time in the fusion of ^{48}Ca beams with ^{13}C targets with production cross sections of a few µb. The low-lying levels in ^{59}Cr have been established and new data on ^{59}Mn, produced via the pn channel, have set limits on the ground state spin of ^{59}Cr and enabled some spin-parity assignments to be made. The structure of ^{59}Cr is clearly inconsistent with shell-model calculations within the full fp space. In fact, the presence of a low-lying $9/2^+$ state shows the influence of the neutron $g_{9/2}$ orbital at low excitation energies, suggesting a weak N=40 shell gap. The observed sequence of states appears to be consistent with a moderate oblate ground-state shape. Several other evaporation channels have yielded new data: transitions in ^{59}Mn have been established for the first time and existing information on ^{58,59}Fe has been extended to spins that appear to exhaust the available valence configurations.

Following the success of this experiment, even more neutron-rich compound nuclei have been produced in an experiment using a radioactive ^{14}C target. Various technical improvements have resulted in higher quality channel selection. It is already clear from the on-going analysis that new information will be extracted from the two- and three-particle evaporation channels, in particular extending the current rudimentary knowledge of excited states in ^{60}Fe and establishing transitions in ^{60}Mn and ^{57}Cr for the first time. A search of the data has very recently resulted in the observation of transitions in ^{60}Cr, from which it appears that the structure is not a simple oblate ground-state rotor as has previously been speculated.

Studies of Heavy, Neutron-rich using Multinucleon Transfer and Projectile Fragmentation Reactions

Initial studies of high-spin phenomena in a range of neutron-rich heavy nuclei have been made following production via multi-nucleon transfer reactions. This work concentrated on the identification of isomeric states with lifetimes in the ns–ms regime for future use as channel selectors. Experiments were performed at the Lawrence Berkeley National Laboratory using GAMMASPHERE and the CHICO gas detector array with variety of thin-target multi-nucleon transfer reactions to provide new insights in a range of neutron-rich nuclei. These experiments used isomer tagging with particle identification to elucidate a range of nuclear structure questions, including: (i) the role of the intruder $h_{11/2}$ neutron orbital in the vibrational-to-rotational phase changes in spin associated with N~58 isotones in the A~100 region, (ii) the study of spherical, neutron $(h_{11/2})^{-2}$ seniority isomers and related single-particle structure approaching the ^{132}Sn doubly magic nucleus, and (iii) the evolution of K-isomerism in heavy, rare-earth and transitional nuclei from the N=104 mid-shell towards the N=126 shell closure. This work is intimately linked to the parallel study made to identify new isomeric states in neutron-rich heavy nuclei following projectile fragmentation reactions using the FRS at GSI. This study investigated the angular momentum population in such relativistic reactions through the measurement of isomer decays at the focal plane of the FRS and the calculation of the associated isomeric ratios as a function of both angular momentum and number of abraded and abladed nucleons from the initial beam.

In related radioactive beam work, a new, β-decaying high-spin K-isomer was identified in ^{177}Lu following studies using the on-line mass separator at GSI. This is one of the first examples identified of a K-driven five-quasiparticle isomer.

B-delayed γ tagging

It was originally envisaged that β-γ tagging experiments on N~Z nuclei would be carried out. However, an initial test revealed that scattered beam in the RITU spectrometer was a problem for near symmetric reactions, which are essential for the production of such nuclei. The required modifications to the RITU spectrometer have been completed and very recent in-beam tests, using the ^{36}Ar+^{46}Ti reaction, have shown that it is now possible to study light N~Z nuclei with A~70-80 provided that they are produced around Coulomb barrier energies. The tests revealed that it is possible to separate the beam and reaction fragments and, most importantly, to ensure that the beam-like fragments do not enter the DSSSD detectors. This development means that it should now be possible to investigate the structure of weakly populated nuclei via the β-γ tagging technique, covered in a future grant application.

SACRED spectrometer

The UK has pioneered the development of the SACRED spectrometer for in-beam conversion electron measurements. In this grant period SACRED was adapted for use with RITU by devising a completely novel beam-collinear geometry. In this way RDT methods could be employed that enabled prompt conversion electron spectroscopy be carried out with unprecedented sensitivity.

Design and construction of GREAT

The GREAT spectrometer was completed on time and within budget. The UK led all aspects of the GREAT project from the detector design to the storage of data. The GREAT spectrometer comprises: a transmission multiwire proportional counter (MWPC); two double-sided Si strip detectors (DSSSD); an array of 28 Si PIN diodes; a planar double-sided Ge strip detector; and a segmented clover Ge detector surrounded by a BGO Compton suppression shield. UK physicists defined the specification of these detectors and the design team performed all the mechanical design work to ensure the optimal configuration of the detectors with provision for electrical and cooling-system connections. This included defining the 3D geometrical shapes using CAD and finite-element analysis of the complex structure, which was manufactured in the collaboration's workshops and by outside contractors. Trial assembly was performed in the UK before installation and commissioning at

Jyväskylä. The UK purchased all of the above detectors and their associated mechanical components and vacuum system. In addition, we provided the automatic liquid nitrogen filling system for the Ge detectors, including the hardware and remote control system. We also supplied the remote system for the high voltage supplies for all the detectors.

Performance of GREAT detectors

The individual detectors of the GREAT spectrometer all met their specifications and the entire spectrometer system has proved to be extremely reliable. This was amply demonstrated in the first year of operation with JUROGAM (from May 2003) when GREAT was used in experiments for over 3000 hours for experiments involving 26 institutions from 11 countries. GREAT has also been used for many dedicated decay spectroscopy experiments, as well as in conjunction with JUROGAM and SACRED. It has been the most heavily demanded and used instrument at the Jyväskylä cyclotron facility since its commissioning.

The nuclei of interest are implanted into a pair of adjacent DSSSDs after passing through the transmission MWPC. The DSSSDs are used to measure the energies of ions that are implanted and of the decay particles they subsequently emit with a resolution of ~20 keV FWHM. Energy-loss and timing measurements from the MWPC are combined with the energy measured in the DSSSDs to make a clean distinction between fusion reaction products and scattered beam particles. The 48cm^2 active area of the two DSSSDs results in a typical recoil collection efficiency of ~85 %. The strip pitch is 1mm in both directions, matching the position resolution of the MWPC and giving a total of 4800 pixels. After allowing for the non-uniform distribution of ions across the focal plane, this is at least an order of magnitude increase compared with the previously used detector and provides a significant improvement in correlation performance.

An array of 28 Si PIN diodes is mounted in a box arrangement around the perimeter of the DSSSDs to measure the energies of the conversion electrons emitted during the radioactive decay. The resolution of the PIN diodes is ~5-10 keV FWHM. The geometrical efficiency of the array is ~30 %, but the probability of electrons scattering between PIN diodes means that the efficiency for registering any signal is significantly higher at ~40 % for electron energies above ~200 keV.

A planar double-sided Ge strip detector has been designed for GREAT to measure the energies of X rays and low-energy γ rays. The Ge crystal has an active area of 120mm x 60mm and a thickness of 15mm. The strip pitch on both faces is 5mm, providing position information that can be correlated with other GREAT detectors. The detector is housed in its own cryostat and mounted directly behind the DSSSDs and can also be used to detect high-energy β particles (~2 MeV) that penetrate through the DSSSD. The energies of higher energy γ rays are measured using a Clover Ge detector mounted outside the vacuum chamber. The efficiency of the Ge detectors has been simulated using GEANT. A suppression shield with bismuth germanate crystals surrounds the detector to improve its peak-to-total ratio. The Clover support structure has been designed to accommodate additional detectors to give an even bigger improvement in the detection efficiency for high-energy γ rays. Typical values for the energy resolution are 1.7 keV at 122 keV for the planar detector and 2.4 keV at 1.33 MeV for the Clover.

GREAT and its coupling to JUROGAM, SACRED, VEGA and RITU

During the early phases of the grant period in which GREAT was being designed and constructed, campaigns of experiments were performed with the 15-detector JUROSPHERE array (efficiency ~ 1.5% at 1.33 MeV) and the SACRED conversion electron spectrometer, which was adapted for use in RDT experiments providing an entirely unique capability. VEGA detectors were used at the focal plane for decay experiments. Immediately following the successful commissioning of GREAT, a second campaign of SACRED experiments and two campaigns with the 43-detector JUROGAM array (efficiency ~ 4.2% at 1.33 MeV) were performed. In these campaigns, data were acquired using the novel Total Data Readout (TDR) system designed and commissioned as part of this project, as described below. We led the JUROSPHERE and JUROGAM array developments and were responsible for the designs of their mechanical support structures, and the design and construction of an automatic liquid nitrogen filling system for up to 48 detectors at the target position.

Throughout this period, our collaborators at Jyväskylä undertook a continuous programme of beam development and introduced differential pumping at the entrance to RITU, which itself was upgraded to improve beam suppression. This unique combination of spectrometers has consistently attracted a broad range of scientists from the international community to the facility. We were highly successful in obtaining beam time for these campaigns in internationally competitive peer-reviewed processes. These campaigns highlighted the wide applicability of tagging techniques to investigate nuclear structure in heavy nuclei.

Electronics and data acquisition for GREAT

In-beam experiments with conventional data acquisition systems suffer the severe limitation of crippling dead-time losses. We therefore proposed and developed a novel triggerless data acquisition method, Total Data Readout (TDR) to circumvent this problem. The energy signals from the detectors are sent to the inputs of VXI cards, each having 32 independent 14-bit ADC channels. Each conversion is timestamped and passed on to the

Event Collator, which then assembles the fragmented information using spatial and temporal associations required by the experiment. A VME module, known as the Metronome, facilitates the timestamping, controlling the distribution and synchronization of a 100 MHz clock for all ADCs. UK electronic engineers designed, constructed, commissioned and supported the VXI ADC cards and the Metronome module. The software for the data acquisition and control system was written by the software engineers to provide a user-friendly interface. The TDR system performs to specification with no data losses and has sufficient data processing capacity to handle experiments with the highest data rates (typically 300,000 signals per second).

Project plan review and explanation of expenditure

The collaboration established the UK Tagging Management Group to oversee the design, construction and exploitation of the GREAT spectrometer. The Group was chaired by Prof P.A. Butler (and at a later stage Dr R.D. Page) and had representatives from all six institutions involved. The Group also ensured regular communication with Jyväskylä, with wider interaction with the international community being achieved through participation in the HENS and EXOTAG projects. The GREAT spectrometer and its associated TDR data acquisition system have been successfully delivered. GREAT has been exploited as a stand-alone instrument as well as in conjunction with the JUROGAM and SACRED spectrometers. All these devices are now operational and available to the international nuclear physics community. The status of the project was continually monitored and controlled by the Management Group.

Dissemination and future research

The principal mode of dissemination has been through publications in internationally recognised high-impact journals such as Physical Review Letters, Physical Review C and Physics Letters B. Across all six institutions, over 143 refereed publications have followed from the research supported through these grants, with selected key publications for each institution highlighted on the individual IGRs. A full list of publications can be found at http://www.dl.ac.uk/NPG/great.html Another key dissemination mode is through presentations at national and international conferences. Over the grant period, over 56 such presentations (including many invited talks) have been made discussing the research supported through the grants. In addition, wider dissemination and publicity has been achieved through articles in more general journals, such as Nature. The detailed research results from this work are of most immediate interest to the international nuclear physics community. Since we demonstrated the TDR method, it has been adopted by a number of international projects e.g. AGATA. In a broader context, the development of position-sensitive detectors has the potential to benefit greatly medical-imaging systems. In particular, the GREAT planar Ge detector is being evaluated for use in a Compton camera as part of a medical imaging research programme. There is important knowledge transfer, of wide benefit to society, through a significant fraction of the highly trained manpower going on to work in the nuclear, medical and environmental sectors. In the course of this grant, 12 PhD students have written and defended their theses from work supported by this grant. Furthermore, the research funded by this grant has been used to directly inform the teaching syllabi at some of the institutions involved leading to dissemination of results to undergraduate students.

The GREAT project represents a significant capital investment by the UK. Now that it has been commissioned and is operational a period of physics exploitation is in progress and will continue with physics themes related to those above. In the longer term, the UK-led SAGE spectrometer with a capability for coincident γ-ray and conversion electron detection is under discussion. In addition a charged-particle spectrometer, LISA, is planned for use at the RITU target position in association with GREAT for the study of extremely proton rich nuclei. The flexible modular design of GREAT affords possibilities for enhancements for specific experimental programmes. In particular, plans for a second MWPC for studies of isomeric states and the installation of thicker DSSSDs for β-delayed γ-ray tagging experiments in the A=70-80 region are being pursued in new grant applications. In addition, extra germanium detectors will be deployed at the focal plane to increase the total photopeak efficiency at the focal plane. Furthermore, an array of BaF_2 detectors for fast-timing measurements at the focal plane is also planned. In addition, the GREAT project has spurred further investigations at other international facilities. For example, the work on fp-shell nuclei is being followed up by measurements using PRISMA to perform spectroscopy of more neutron-rich nuclei with deep-inelastic reactions.