Studies of exotic nuclei using accelerated radioactive beams at REX-ISOLDE and HIE-ISOLDE in CERN

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The REX-ISOLDE facility at CERN provides accelerated ISOL beams at energies up to 3 MeV/u. REX-ISOLDE is notable for the wide diversity of available beam species, and beams which have been succesfully delivered for experiments since its commissioning in 2001. An overview of the Physics programme at REX-ISOLDE, particular Coulomb excitation and single-particle transfer reactions will be given. The future perspective will be presented for the HIE-ISOLDE facility, a phased upgrade of REX-ISOLDE to 5.5 MeV/u and latterly to 10 MeV/u.

1. Introduction

Increasingly, the focus of experimental nuclear physics is turning from experiments with intense stable beams to secondary radioactive beams. Such beams expand the possibilities for studying nuclear properties, often unobtainable in any other way, but bring with them challengees associated with radioactive backgrounds and low intensities. The ISOLDE facility at CERN [1] has a long history of producing radioactive beams using the ISOL technique. Develoment of different techniques such as cooled transfer lines, laser ionsiation and molecular sidebands has allowed beams of over 700 isotopes of 70 different chemical elements to be extracted with varying intensity and isobaric purity. The REX-ISOLDE facility (see figure 1), commisioned in 2001, allows the re-acceleration of these low energy radioactive beams to 3 MeV/u. The beams which have been accelerated span the full range from light nuclei (A$\sim$10) to the very heavy nuclei (A$\sim$220). In particular, REX-ISOLDE can generate accelerated beams of proton-rich species using spallation reactions on heavy primary targets like UC_x. Selective laser ionisation can also be used to provide isomeric beams, which is also a unique feature worldwide. The key technology behind the REX-ISOLDE concept, is the coupling of a Penning trap (REX-TRAP) to an electron beam ion source (REX-EBIS). REX-TRAP traps and purifies the low energy beam from ISOLDE. It then injects into the REX-EBIS where the ions are rapidly bred up to a high-charge state for injection into the LINAC. The LINAC comprises an RFQ, an IH structure and a series of normal-conducting 7- and 9-gap resonators (see figure 1).

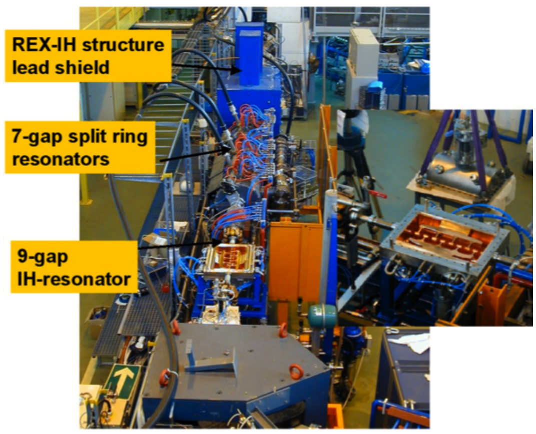

FIG. 1: The REX-ISOLDE post-accelerator.

2. Coulomb excitation

The principal experimental tool used at REX-ISOLDE is Coulomb excitation. Historically speaking, this is a key technique for studying the evolution of nuclear collectivity. When used in the context of radioactive beams, it becomes very challenging, and given the beam energy available at REX-ISOLDE,

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essentially only single-step excitation occurs as multi-step excitation is very limited. Nevertheless, a wide range of interesting experimental studies have been carried out at REX-ISOLDE since 2001, tackling many issues concerning collectivity in different regions of the nuclear chart. Coulomb excitation is a particularly sensitive probe of nuclear shape coexistence. This phenomenon, where different shape minima lie very close together and near the ground state appears ubiquitous through the nuclear landscape, from the island of inversion in the neutron-rich magnesium isotopes, through the N=Z line around A= 70 [6] to the proton-rich lead region (see e.g. figure 2).

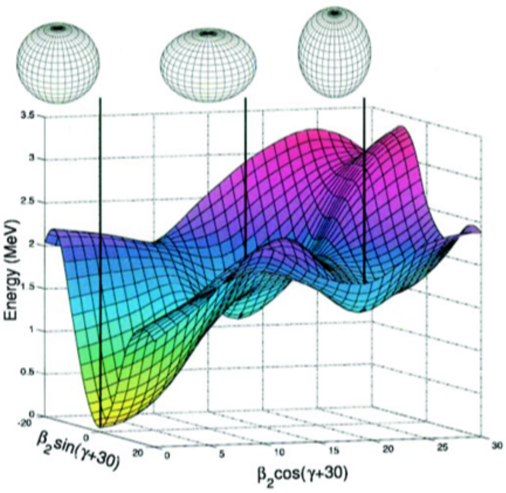

FIG. 2: Predictions for the coexistence of three different low-lying mean-field shapes in ^{186}Pb: spherical, oblate and prolate (taken from ref [2].)

The main apparatus used for Coulomb excitation studies is the MINIBALL array (figure 3) of eight germanium cluster detectors coupled to a QQQ silicon CD detector (see figure 4). The incoming accelerated beam undergoes Coulomb excitation on a secondary target situated at the centre-point of the MINIBALL array, typically a metal foil of around 2 mg/cm^2 thickness. Scattered beam and target recoils are detected in the silicon CD detector which spans an angular range from around 15 to 50 degrees in the lab.

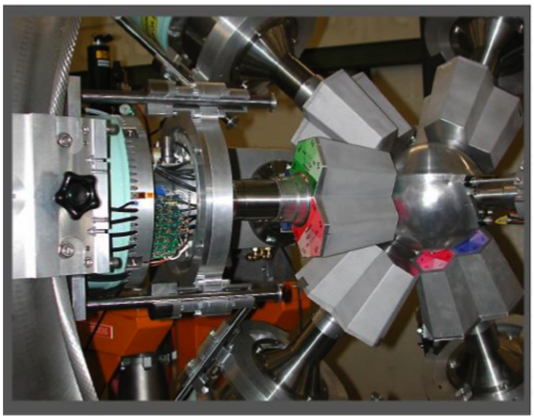

FIG. 3: The MINIBALL array comprising eight hyper-pure germanium cluster detectors.

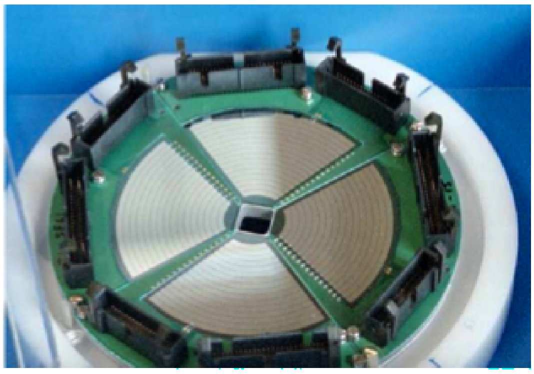

FIG. 4: QQQ-pattern silicon CD detector from Micron Semiconductor

A. Island of inversion

The early focus of the programme at REX-ISOLDE was on the so-called island of inversion in the neutron-rich neon and magnesium isotopes, suggested by Warburton [4]. This is a region where neutron intruder configurations come down due to a melting of the N=20 shell closure, leading to strong nuclear collectivity. This overturns the naive expectations of the sd shell model. Although the language is different here, this falls clearly within the general context of shape coexistence in nuclei. One of the early successes with REX-ISOLDE was a Coulomb excitation study of ^{30}Mg [5] where it was possible to obtain a B(E2) measurement for one of the nuclei very close to the island of inversion.

B. Shape coexistence around the N=Z line

A notable region of shape coexistence is predicted in proton-rich nuclei between A=60 and 80. Strong deformations appear driven by increasing occupation of the $g_{9/2}$ intruder orbital. These effects are reinforced for the N=Z nuclei where both protons and neutrons are occupying the same shape-driving orbitals. An evolution is predicted from spherical at ^{56}Ni through gamma-soft nuclei (^{64}Ge) to very strongly prolate deformed nuclei at ^{76}Sr and ^{80}Zr. In the centre of this region, ^{68}Se and ^{72}Kr are predicted to have oblate ground states but with a very close-lying prolate configuration. Typically, such shape evolution has been mapped out experimentally through determining the layout of experimental levels but this leads to a much weaker understanding of this complex phenomenon than can be gained through extraction of electromagnetic matrix elements. Coulomb excitation can allow the extraction not only of transition matrix elements but also diagonal matrix elements which can be used to determine the sign of the spectroscopic quadrupole moment of excited states and hence the sign of the nuclear deformation. Reaching the N=Z line is very challenging experimentally but Coulomb excitation has been used as a tool for investigating nuclei close to this limit in this mass region. Notably, studies by Clement *et al.* of Coulomb excitation of ^{74}Kr and ^{76}Kr at GANIL have become the textbook example of what can be achieved using low-energy Coulomb excitatio with radioactive beams. At REX-ISOLDE, it is also possible to investigate the proton-rich selenium nuclei. An accelerated beam of ^{70}Se was produced at REX-ISOLDE. Importantly, this beam could be produced in an isobarically pure form by obtaining $SeCO^+$ molecules from ISOLDE and subsequently breaking them up in the EBIS. This two-stage mass separation effectively removed all contaminants and is a good example of what can be achieved at REX-ISOLDE in terms of isobaric selectivity. Initially, analysis of a Coulomb excitation study of ^{70}Se performed at REX-ISOLDE pointed to a prolate shape for this nucleus [6] but this relied upon data from an earlier lifetime measurement. A repeat of a plunger RDM lifetime measurement for ^{70}Se showed that the earlier data was in error and a fresh comparison with the Coulomb excitation data clearly pointed to an oblate shape for ^{70}Se in keeping with theoretical predictions [7]. This shows the value in combining different data sets and in repeating historic plunger measurements which often were singles measurements and suffered from underestimated uncertainties in feeding lifetimes.

C. Shape coexistence in proton-rich heavy nuclei

A further dramatic region for nuclear shape coexistence is in the proton-rich nuclei around the Z=82 shell closure. Here, strong oblate and prolate shapes compete with low-lying spherical configurations (the ground state in the light lead nuclei). REX-ISOLDE is unique worldwide in being able to directly address this Physics question through Coulomb excitation as accelerated beams of proton-rich mercury, lead, polonium and radon are available. The mercury isotopes can be obtained in an isobarically pure form from a molten lead primary target, while a thorium carbide target and cooled transfer line can be used to obtain pure beams of light radon isotopes. Figure 5 shows an example of the quality of the data obtained from a Coulomb excitation study of the light radon isotopes, ^{202}Rn and ^{204}Rn. Data on the light radon and mercury nuclei is presently under analysis. As part of a broad approach to the shape coexistence phenomenon in this mass region, the Coulomb excitation measurements have been complemented with plunger RDM lifetime measurements, and also coincident γ ray - conversion electron measurements carried out using the unique SAGE apparatus at the University of Jyvaskyla in Finland. Conversion electron measurements are particularly valuable in this mass region, not only due to the high conversion coefficients for many transitions but also the important role played by E0 transitions especially in interband J→J transitions. The B(E0) transition strengths are of high interest as the transition rate has a dependence of the different in the mean squared charge radius of the different configurations which it connects. It is therefore a very sensitive diagnostic of shape coexistence. Combining these various and rich data-sets is ongoing at the time of writing.

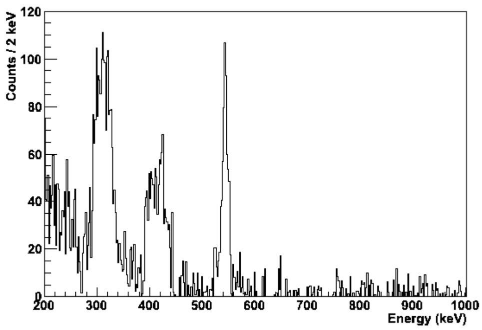

FIG. 5: Gamma ray spectrum associated with Coulomb excitation of ^{204}Rn on a silver target at 2.9 MeV/u. The spectrum has been Doppler-corrected for the scattered Rn nuclei and clearly shows the $2^+ \rightarrow 0^+$ transition in ^{204}Rn with an energy of 543-keV.

D. Isomeric beams

A unique feature of the REX-ISOLDE facility is the potential to selectively ionise isomeric beams using laser spectroscopy. This has been put to good effect in a study of Coulomb excitation of the odd-odd isotope, ^{68}Cu where the two isomers (6^- and 1^+) were separated by laser spectroscopy [8]. Future programmes envisage selective excitation of isomers in heavy nuclei, and potentially K-isomers in the Hf region.

3. Single-particle transfer reactions

Studies of single-particle transfer reactions in inverse kinematics have also taken place at REX-ISOLDE. These studies are presently severely limited by the available maximum beam energy of around 3 MeV/u. Neverthless, it has been possible to investigate, for example, (d,p) and (t,p) reactions in inverse

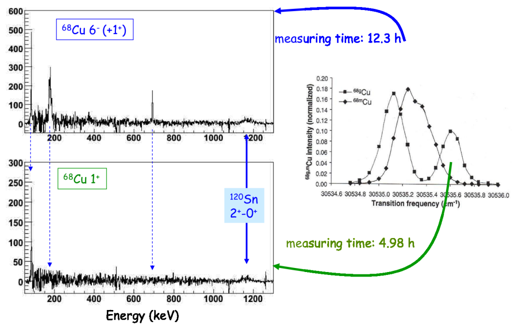

FIG. 6: Coulomb excitation of selectively laser-ionised isomeric beams of ^{68}Cu: 6^- isomer (top) and 1^+ isomer (bottom) taken from ref [8].

kinematics for nuclei around the island of inversion; the latter using a tritium-loaded foil. In order to detect the light ions from transfer reactions, a silicon barrel, called T-REX, has been built. This fits inside the MINIBALL germanium detector array. The advantage of carrying out particle-γ coincidence measurements is that it allows better identification of the states populated and can compensate for the poorer resolution of the silicon array. A number of different reactions have been studied so far including ^{66}Ni(d,p): some online data from this study is shown in figure 7.

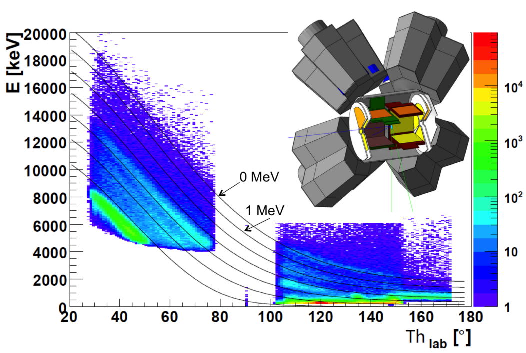

FIG. 7: Proton energies as a function of lab angle recorded for the ^{66}Ni(d,p) in inverse kinematics at 3 MeV/u

4. Nuclear astrophysics

In addition to transfer reactions, there has been some limited activity at REX-ISOLDE related to nuclear astrophysics. The topics encompassed here are explosive stellar scenarios such as novae and X-ray bursts. It is difficult to obtain very high intensity radioactive beams at REX-ISOLDE for carrying out direct reaction studies of e.g. (p,γ) reactions in inverse kinematics due to the EBIS technology used in generating the radioactive beams. There is considerable, scope, however, for indirect reaction studies. For example, the ^{14}O(α,p) reaction is extremely important in determining the break-out from the hot-CNO cycle. It is extremely challenging to measure this reaction rate directly but there have been some attempts to measure the inverse reaction ^{17}F(p,α). Of interest is the inelastic branch of the resonances as this is an important correction when going from the reverse to the forward reaction rate. An isobarically pure beam of ^{17}F was obtained at REX-ISOLDE by selecting a fully-stripped 9^+ beam in order to remove the ^{17}O stable contaminant. This led to a somewhat low radioactive beam intensity but this was sufficient to carry out a proof-of-principle ^{17}F(p,p'γ) experiment, where the inelastic scattering branch was selected by gating on the γ ray using the MINIBALL array [9].

5. Prospects with HIE-ISOLDE

There is a plan to upgrade the beam energy and intensity of the current REX-ISOLDE facility. This project called HIE-ISOLDE is approved by CERN and will take place in two stages; first to 5.5 MeV/u by 2014 and ultimately to 10 MeV/u. The first phase is funded and design and construction of the required superconducting cavities has already begun. The principal advantage connected with the beam energy of 5.5 MeV/u will be the potential to carry out multi-step Coulomb excitation of any of the suite of radioactive beams available at ISOLDE, using a secondary lead target. This is the most favourable situation for carrying out Coulomb excitation and has been used to great effect in studies of ^{74}Kr and ^{76}Kr at the SPIRAL facility in GANIL [3] (see figure 8).

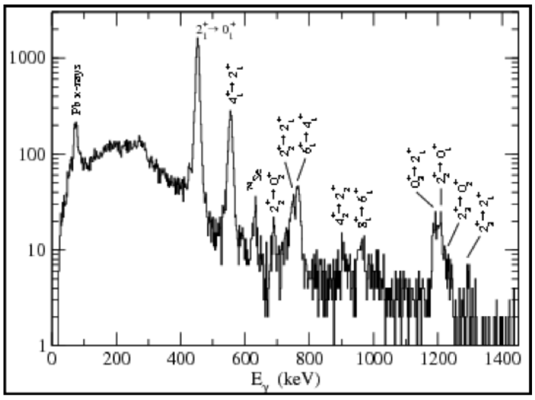

FIG. 8: Gamma-ray spectrum obtained for Coulomb excitation of ^{74}Kr on a lead target at 5.5 MeV/u (taken from ref [3].)

In the second phase of HIE-ISOLDE, the beam energy will be increased to 10 MeV/u. This is arguably the optimal energy for (d,p) reactions in inverse kinematics since at this energy the cross-sections are large and the angular distributions are very pronounced (see figure 9). The diversity of beams available at HIE-ISOLDE will open up many possible avenues for single-particle transfer studies such as looking at the breakdown of the known shell structure in very neutron-rich nuclei.

The future prospects for the HIE-ISOLDE facility are therefore very bright and the project will form an excellent complement to much larger projects such as SPIRAL2 and FAIR. HIE-ISOLDE will deliver a diverse suite of ISOL beams, many of which are unique to the facility, allowing a broad range of Physics topics to be addressed. New apparatus is envisaged from a helical-orbit spectrometer similar to the HELIOS project in Argonne National Laboratory [10], to major infrastructure like a storage ring for in-ring reactions.

Acknowledgments

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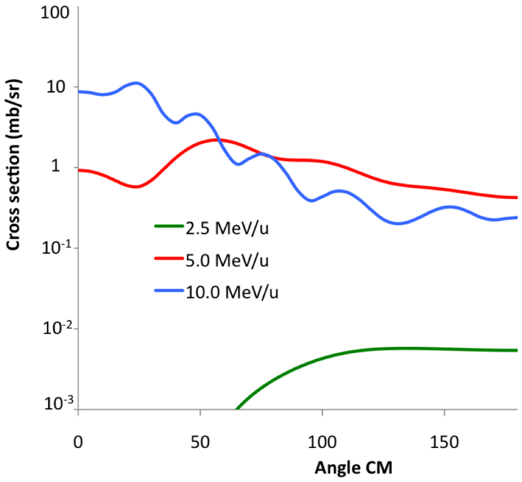

FIG. 9: DWBA calculations for the ^{146}Gd(d,p) reaction in inverse kinematics at a range of bombarding energies.

institutions principally from Belgium, Germany and the UK. HIE-ISOLDE is a major CERN project with contributions from many institutions across Europe. The author would like to acknowledge the many individual contributions to the work reported here.

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