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In-beam spectroscopy at the RITU gas-filled recoil separator

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Abstract. In recent years (1996-2001) the recoil-decay tagging technique has been employed with great success at the Department of Physics of the University of Jyväskylä. Various arrays of germanium detectors have been coupled to the RITU gas-filled separator in order to study nuclei far from stability. An overview of the physics studied with these arrays, along with discussion of technical development of the RITU separator, is presented. Even with a comparatively modest array of germanium detectors it has been possible to study nuclei produced with cross-sections as low as 200 nb.

PACS. 23.20.-g Electromagnetic transitions – 23.60.+e α decay – 25.70.-z Low and intermediate energy heavy-ion reactions

1 Introduction

Over the past five years, much of the in-beam spectroscopic work carried out at the Physics Department of the Jyväskylä University (JYFL) has been centred around the RITU gas-filled recoil separator [1]. The recoil-decay tagging (RDT) technique, first used at GSI [2] and further developed at Daresbury Laboratory [3], has been employed with several γ-arrays at the target position of the RITU separator. The basic principle of the technique is that the characteristic decay properties of nuclei implanted into a detector at the focal plane of the separator are used to select prompt radiation detected at the target position. The RDT technique allows very weak reaction channels to be resolved from the large background due to fission and other competing processes. Recoil-decay tagging studies began rather humbly in JYFL when in 1995 one TESSA-type Ge detector was placed outside the RITU target chamber and used to measure transmission efficiencies for the ^{159}Tb(^{22}Ne,4n)^{177}Re and ^{141}Pr(^{40}Ar,4n)^{177}Ir reactions. This was followed in 1996 by the DORIS array of nine Compton-suppressed TESSA-type Ge detectors, which was used in studies of ^{192,194}Po [4,5] and a preliminary study of ^{226}U. Following these initial successes, in 1997 the JUROSPHERE array was built, consisting of 15 EUROGAM Phase I-type and 10 TESSA-type CSGe. The Phase-I detectors were provided by the UK-France Loan Pool, and the array had a photopeak efficiency of around 1.5% at 1.3 MeV. A total of nineteen experiments were performed in the first JUROSPHERE campaign, highlights of which were the first observation of excited states in ^{226}U [6], ^{168,170}Pt [7], ^{184}Pb [8] and ^{198}Rn [9]. In 1998, an array of four unsuppressed clover detectors was constructed, known as SARI. The array was used in the first in-beam heavy element study to be performed at JYFL, the γ-ray spectroscopy of ^{254}No [10]. This experiment followed an earlier study carried out at Argonne National

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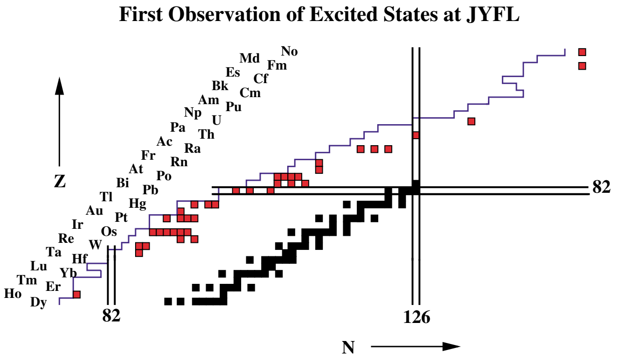

Fig. 1. A section of the chart of the nuclides, showing those nuclei for which excited states were observed for the first time at JYFL. The solid line to the left marks the last known nucleus in the isotopic chain.

Laboratory, confirming and extending the results obtained there [11]. The period from 1999 to 2001 saw three campaigns of JUROSPHERE experiments concentrating on studies of shape coexistence effects in the region of the $Z = 82$ shell gap, and on the structure of heavy elements in the region of ^{254}No. Five NORDBALL-type detectors were used in place of 5 TESSA detectors, increasing the photopeak efficiency to around 1.7%. To give an impression of the range and number of nuclei studied in the various campaigns, fig. 1 shows those nuclei in which excited states were observed for the first time at JYFL. The solid line to the left marks the last known nucleus in the isotopic chain. It can be seen that the excited-state structure has been observed for the first time in almost 40 nuclei, ranging from Ho to No.

2 Technical development of RITU

In parallel with the improvements of the γ-arrays at the target position, much development has also taken place to improve the quality of the data obtained with the RITU separator itself. Much of this development work aims at reducing the level of unwanted events at the focal plane, which affect the "purity" of the correlations obtained between the implant and decay events. The first major development was the addition of a multiwire proportional avalanche counter (MWPAC) upstream of the Si-strip detector, details of which can be found in ref. [12]. This allowed the discrimination of scattered beam from fusion events, on the basis of $E - \Delta E$ determination. Operated in anti-coincidence mode, the gas detector could also be used to remove low-energy scattered beam events from the region in which the α-decays are observed, increasing the detection sensitivity for weak reaction channels. The system was later extended to two gas counters, allowing a determination of the time-of-flight (TOF) over a flight path of around 40 cm. This information, combined with the energy of the implantation in the Si detector, provided improved discrimination of scattered beam from fusion products with respect to that provided by the $E-\Delta E$ method. Another development was the modification of the RITU dipole chamber. In the dipole field, the primary-beam particles follow a trajectory with a much tighter radius than the fusion products, and are dumped in a "ski" on the inner wall of the chamber. The design of the original chamber was such that for symmetric reactions, where the difference in magnetic rigidities of the beam and fusion products is smaller, a high counting rate of scattered beam particles was observed at the focal plane. The new dipole chamber was extended in a direction approximately perpendicular to the beam line, reducing the possibility of scattering to the focal plane. The effect of the new chamber is shown in fig. 2, where a comparison is made of total Si-strip detector spectra. Both the spectra are from the bombardment of a ^{109}Ag target with a beam of ^{83}Kr at an energy of 357 MeV. In the upper panel, with the original dipole chamber, the fusion products constitute approximately 2% of the total number of events. In the lower panel, after modification of the chamber, the fusion products form around 50% of the total number of events.

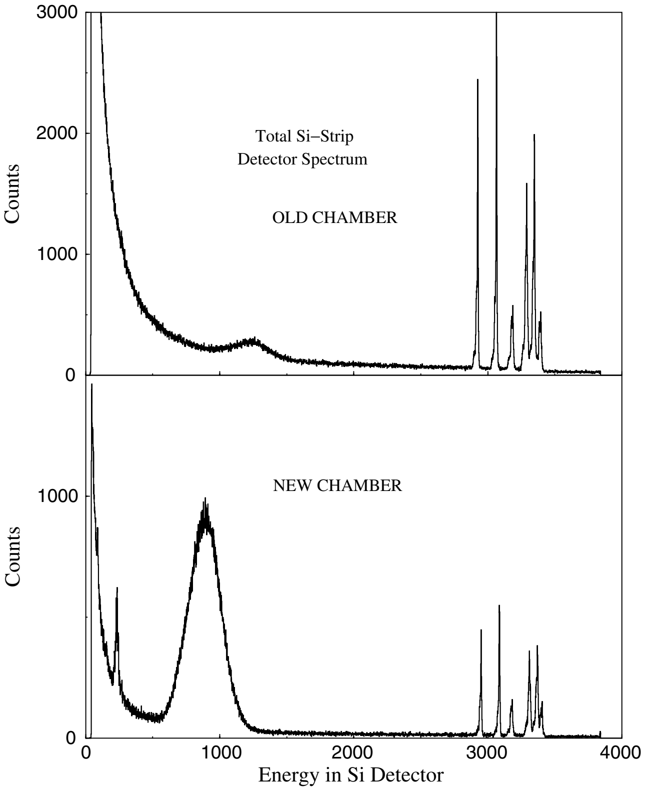

Fig. 2. Comparison of spectra obtained from the bombardment of ^{109}Ag with a ^{83}Kr beam at an energy of 357 MeV. The spectra show the energy of events observed in the Si-strip detector at the focal plane of the separator. The upper panel is with the original dipole chamber, the lower panel with the new modified chamber.

3 Studies around the Z = 82 shell gap

As mentioned in the introduction, many of the experiments performed have been dedicated to studies of shape coexistence phenomena in nuclei close to the $Z = 82$ shell closure. Extensive systematic studies have been performed for isotopes of Os [13,14], Pt, Hg [15], Pb, Bi [16,17], Po, and Rn [9,18]. For an extensive review of the properties of the light Hg, Pb and Po isotopes, see ref. [19]. The data to be presented here is from studies of the light Po ($^{190-195}$Po [20,5]) and Pb isotopes (^{182,184,188}Pb [21,8,22,23]).

3.1 Light Pb isotopes

The lead isotopes provide beautiful examples of nuclear shape coexistence effects. In the heavier isotopes (with $N \geq 106$) low-lying 0^+ states are observed, associated with weakly oblate deformed 2p-2h intruder structures. In the lighter isotopes, more strongly deformed prolate structures are also predicted to appear at low excitation energies. Indeed in ^{186,188}Pb, two low-lying 0^+ states have been observed, one associated with the oblate shape, and one with the prolate shape [24,25,22]. Rotational bands have been observed at low excitation energy in these nuclei, showing similarity to bands observed in their Hg isotones, ^{184,186}Hg. These bands are associated with the excitation of four protons across the $Z = 82$ shell gap. The extension of in-beam data to the lighter isotopes ^{182,184}Pb was achieved in two experiments carried out at JYFL, using the JUROSPHERE array. In the first, the ^{148}Sm(^{40}Ca,4n)^{184}Pb reaction was employed, with bombarding energies of 195 and 200 MeV. The data allowed the level scheme to be constructed up to the 8^+ state, and was the first in-beam spectroscopic study of the Pb isotopes beyond the $N = 103$ mid-shell [8]. The second experiment employed the ^{144}Sm(^{42}Ca,4n)^{182}Pb reaction at a beam energy of 209 MeV. The cross-section for population of ^{182}Pb was estimated to be around 300 nb. Shown in fig. 3 is the spectrum of prompt γ-rays correlated with the α-decay of ^{182}Pb. In total, approximately 3500 ^{182}Pb α-particles were observed. The 888 keV γ-ray is assigned to be the 2^+ to 0^+ transition, with the other five observed γ-rays assigned to be a rotational band of $E2$ transitions based upon the 2^+ state [21]. Inspection of the level systematics for the light Pb isotopes shows that in ^{182,184}Pb the prolate configuration rises in energy rapidly below $N = 103$, in accordance with expectations. The behaviour is very similar to that observed in the Hg isotopes.

3.2 Light Po isotopes

The level energy systematics for the even-even Po isotopes are shown in fig. 4. The data for ^{190,192}Po and partly for ^{194}Po were obtained from measurements at JYFL. It can be seen that the level energies have a rather smooth, flat behaviour until at ^{198}Po a drop in the level energies is observed, indicating the onset of collectivity. This onset of collectivity has been associated with the influence of the oblate 4p-2h intruder configuration. The level energies seem to flatten again at ^{192}Po, indicating that the oblate configuration has become the ground state. Simple two-level mixing calculations indicate that in ^{194}Po the ground state has approximately 45% deformed character, rising to 73% in ^{192}Po [5]. The 2_1^+ state in ^{194}Po has approximately 99% deformed character, whilst the corresponding state in ^{192}Po should be purer still. Excited states in ^{190}Po were observed for the first time at JYFL in an experiment using the ^{142}Nd(^{52}Cr,4n)^{190}Po reaction. The bombarding energy was 255 MeV, and the production cross-section was estimated to be around 200 nb. Four γ-ray transitions were

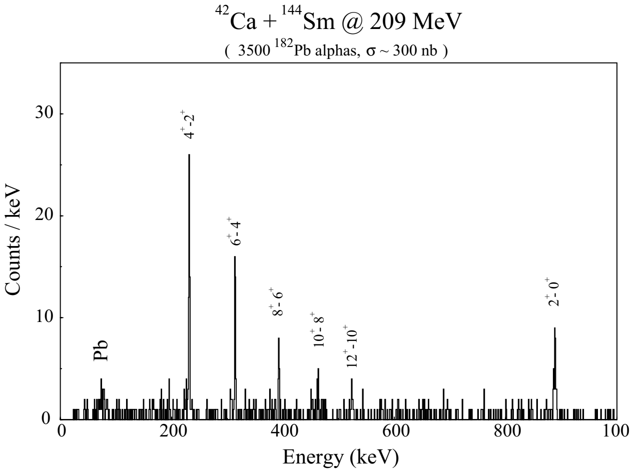

Fig. 3. Spectrum of prompt γ-rays correlated to the α-decay of ^{182}Pb. The cross-section for production of ^{182}Pb is estimated to be 300 nb.

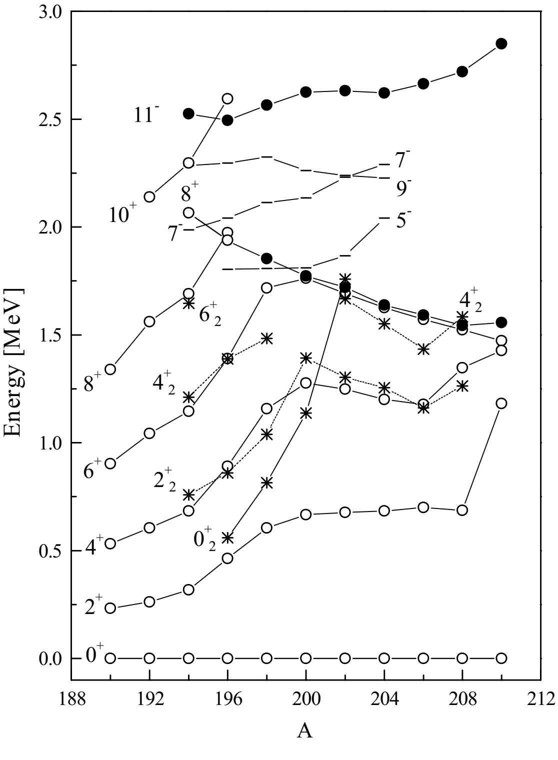

Fig. 4. Level energy systematics for the even-even Po isotopes.

clearly observed, and based on systematics and intensity arguments, assigned to form a cascade of $E2$ transitions. As can be seen in the level systematics, the 6^+ and 8^+ states drop rapidly compared to the levels in ^{192}Po. This is interpreted as being due to the crossing of the prolate intruder structure. Further support for this interpretation comes from the analysis of the kinematic moments of inertia. Above the 4^+ state the moment of inertia for ^{190}Po is very similar to that of the known prolate bands in ^{188}Pb and ^{186}Hg. This represents the first observation of the prolate structure in the Po isotopes. Further details can be found in ref. [20].

4 Heavy-element studies

Another programme of experiments at JYFL is dedicated to the study of heavy elements in the region of ^{254}No. Nuclei in this region are predicted to be deformed, with quadrupole deformation parameters of around $\beta_2 = 0.25$–0.28 (see, for example, ref. [26]). These nuclei are accessible for in-beam spectroscopy due to the rather high cross-section for reactions of doubly magic ^{48}Ca with stable targets close to ^{208}Pb. As mentioned earlier, the first in-beam heavy-element experiment to be performed at JYFL was a study of ^{254}No. The cross-section for the ^{208}Pb(^{48}Ca,2n)^{254}No reaction is approximately 3 μb, and the reaction has the advantage that the fusion-evaporation channels are totally dominated by the 2n exit channel. This means that recoil-gating techniques alone are sufficient to isolate the γ-rays belonging to ^{254}No. After the success of the ^{254}No experiment, the programme continued with a study of ^{252}No, produced by bombarding a ^{206}Pb target with ^{48}Ca, for which the production cross-section is on the order of 200 nb [27]. The resulting recoil-gated γ-ray spectrum is shown in fig. 5. A clear rotational sequence can be seen, assumed to form a band of $E2$ transitions. Note that the 4^+ to 2^+ and 2^+ to 0^+ transitions are not observed, due to the high internal conversion of these transitions. A fit of the rotational band allows the excitation energy of the 2^+ state to be determined, from which an estimate of the quadrupole deformation parameter β_2 can be obtained. The data for ^{252,254}No confirm that both these nuclei are deformed, with extracted deformation parameters of $\beta_2 = 0.28 \pm 0.02$ and $\beta_2 = 0.29 \pm 0.02$, respectively [27].

Shown in fig. 6 is a plot of the dynamical moments of inertia, $\mathcal{J}^{(2)}$, for ^{252,254}No and ^{250}Fm. The data for ^{250}Fm was also obtained in an experiment carried out at JYFL, through bombardment of a HgS compound target, isotopically enriched in ^{204}Hg. As can be seen in the figure, the moments of inertia for all three nuclei are similar at low frequencies, with ^{250}Fm and ^{252}No having slightly higher values than ^{254}No. In ^{252}No, a clear upbend is seen at a rotational frequency of around 200 keV, whereas ^{254}No shows a much smoother behaviour. With the current data, it is not clear whether ^{250}Fm follows the behaviour of ^{254}No or that of ^{252}No. Extension of the level scheme to higher energies would be desirable to investigate this further. The behaviour of ^{252,254}No has been very nicely reproduced theoretically, see ref. [29]. Attempts have also been made to extend the programme to studies of odd-mass nuclei, important for the determination of the position of single-particle states in this mass region. At JYFL, an attempt was made to study ^{255}Lr, through bombardment of a ^{209}Bi target. Whilst the yield of ^{255}Lr nuclei was

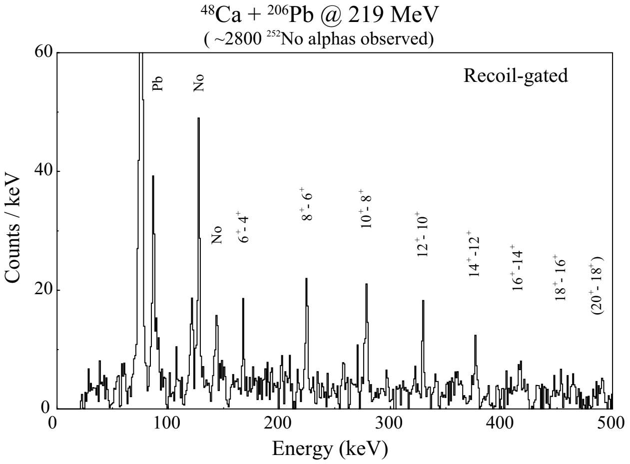

Fig. 5. Spectrum of recoil-gated γ-rays from the bombardment of ^{206}Pb with ^{48}Ca at an energy of 216 MeV. Since the 2n channel dominates the fusion-evaporation cross-section, all the observed γ-rays are assigned to ^{252}No.

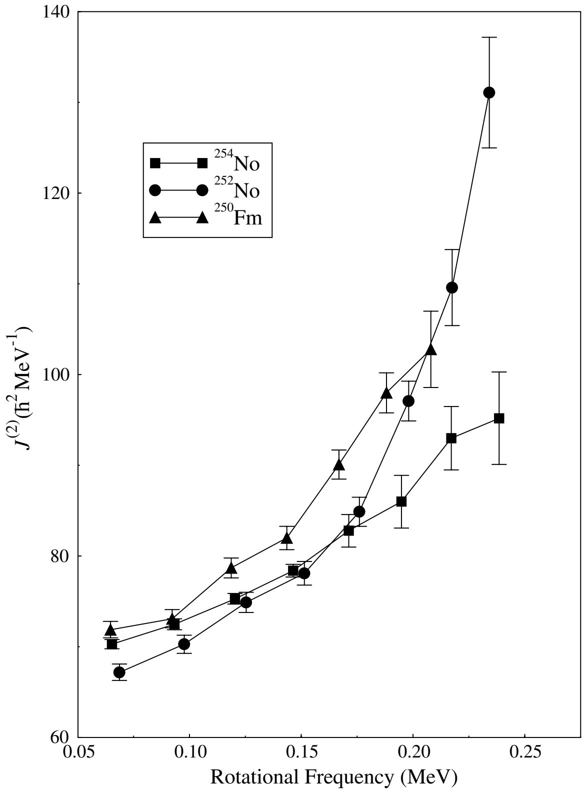

Fig. 6. Plot of the dynamical moments of inertia, $\mathcal{J}^{(2)}$, for ^{252,254}No and ^{250}Fm. The data are extracted from the experimental level schemes deduced in refs. [27,10,28].

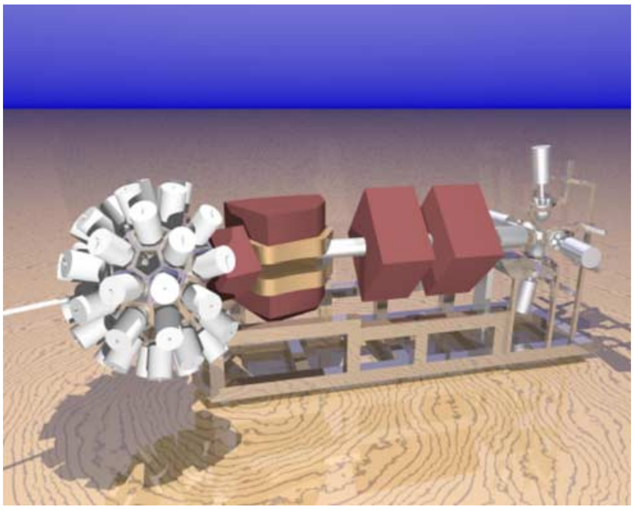

Fig. 7. An impression of the JUROGAM array of 45 EUROGAM Phase-I Ge detectors situated at the target position of RITU.

similar to that obtained for ^{252}No, no clear γ-ray transitions were observed. This leads to the conclusion that in ^{255}Lr it is likely that the decay proceeds mainly via highly converted $M1$ transitions. This observation, along with the non-observation of the low-lying states in other nuclei in this region, was part of the motivation to modify the SACRED electron spectrometer. The spectrometer can now be used in conjunction with RITU for RDT studies. Details of the SACRED spectrometer can be found in refs. [30–32].

5 Future developments

It has been agreed by the EUROBALL Coordination Committee that in 2003 thirty EUROGAM Phase-I detectors will be made available for a campaign of experiments at RITU. A further fifteen Phase-I detectors from the UK-France loan pool will be added to these thirty to construct a new array, known as JUROGAM. The array will be similar to EUROGAM I, with an efficiency of approximately 4% at 1.3 MeV. The efficiency for γ-γ coincidences will be around a factor of ten greater than for previous arrays at JYFL, aiding enormously the study of odd-mass nuclei. It is envisaged that fifteen to twenty experiments will be run in a nine-month period. An impression of the array situated at RITU is shown in fig. 7. Another large development is the addition of the UK Universities GREAT spectrometer at the focal plane of RITU. The spectrometer consists of two double-sided Si-strip detectors for detection of recoils and α-particles, 28 Si PIN diodes detectors for conversion electrons, a multiwire proportional counter for recoil detection, a segmented planar Ge for detection of low-energy γ-rays and β-particles, and a large-volume segmented Ge clover for detection of higher-energy γ-rays. The spectrometer will provide much higher granularity and efficiency for the detection of all types of decay products. A schematic of the spectrometer is shown in fig. 8. Construction and testing of the spectrometer is currently underway at JYFL. Also part of the GREAT project is the development of a new type of data acquisition system, known as total data readout, or TDR [33]. The system operates without a hardware trigger, and is designed to minimise dead time in the acquisition process. All detector electronic channels run independently and are associated in software, the data words all being time-stamped from a global 100 MHz clock. This system is also currently being tested in JYFL, and will be used as the acquisition system for experiments employing the GREAT, JUROGAM and SACRED devices in the coming year.

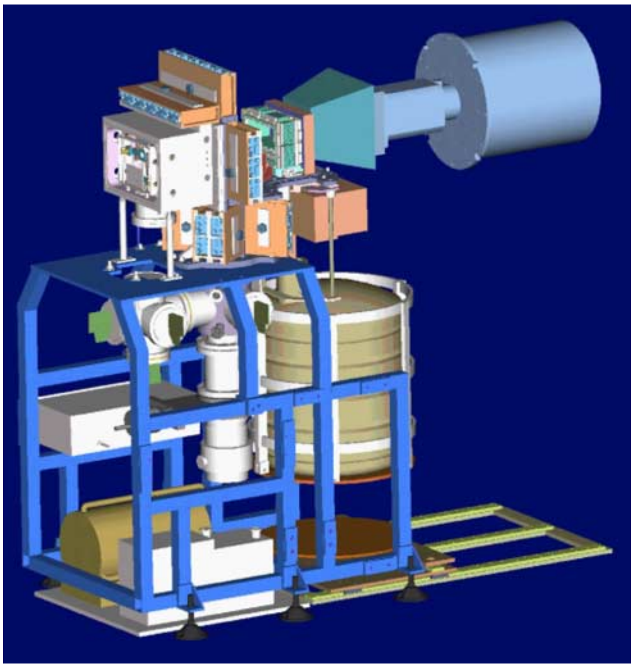

Fig. 8. A schematic of the UK Universities GREAT spectrometer.

It has been shown that the combination of an efficient recoil separator coupled to a large array of Ge detectors is an extremely powerful tool for the study of exotic nuclei. Installation at JYFL of the efficient new JUROGAM array, along with the GREAT spectrometer and innovative TDR data acquisition system, will extend our knowledge to nuclei still further from stability. It is hoped that the improved efficiency of the combined system will also shed light on high-spin phenomena, and yield data on non-yrast states in these exotic regions of the nuclear chart.

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