Prospects for studies of exotic nuclei at the new K=130 MeV cyclotron at JYFL*

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1. Introduction

The study of nuclei far from stability has greatly increased our knowledge of nuclear properties in the past years. Experiments have been pushed to the very limits of nuclear stability among light neutron-rich and proton-rich nuclei. Astrophysical relevance of nuclear physics experiments has consequently become of high importance. This has been possible only by the development of the experimental techniques and accelerators. One of these developments has taken place at the Department of Physics of the University of Jyväskylä (JYFL), where new on-line mass separator and He-jet techniques were developed.

At the new JYFL K=130 MeV cyclotron the future research program concerning nuclei far from stability will be based on the new, improved IGISOL facility and the gas-filled recoil separator RITU. Additionally a general purpose 1.5 m scattering chamber and a He-jet transport system will become available. Research program in the near future will concentrate on (i) studies of production techniques and reaction mechanisms to produce exotic nuclei and radioactive beams, (ii) studies of weak interaction processes in nuclei via the Fermi and/or Gamow-Teller decays, (iii) studies of very proton-rich and light neutron-rich nuclei, nucleon halos and exotic decay modes, (iv) systematic studies of nuclear structure and decay with the isospin degree of freedom of very n-rich nuclei produced in fission and neutron-deficient heavy nuclei produced in (HI,xn) reactions and (v) spectroscopy of the heaviest elements with $Z \approx 100$. In this lecture we shall concentrate on the research program around the two main instruments IGISOL and RITU under construction in the laboratory. The first experiments at these facilities are expected to be carried out during the spring 1993.

2. New Cyclotron Facility

Construction of the new K=130 MeV cyclotron and the associated ECR ion source in the new science campus area of the University of Jyväskylä was completed in 1991. The building for the actual research laboratory [1], that will consist of eight separate experimental areas, was completed in June 1992 and the installations of the first experiments were started. These include two major facilities for studies of exotic nuclei far from the valley of beta stability, the on-line mass separator IGISOL and the gas-filled recoil separator RITU. The plan of the laboratory is shown in Figure 1. The other main research interests in nuclear physics will be nuclear shapes and high spin states, heavy ion reactions and specialized measurements on electron spectroscopy. The nuclear physics

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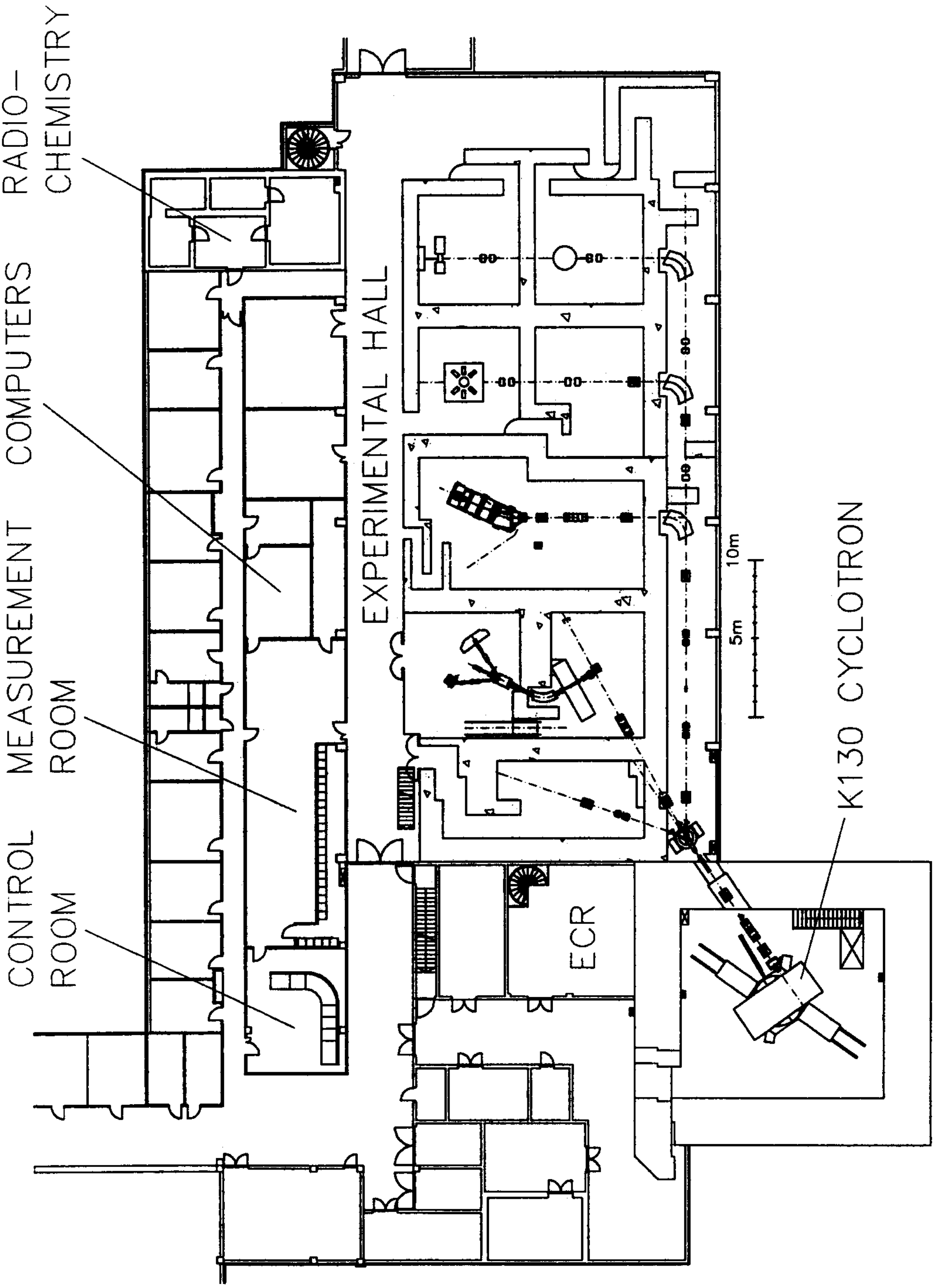

Figure 1. The lay-out of the new accelerator laboratory of the University of Jyväskylä.

program will use 80 % of the beam time during the first years of operation. Other fields of interest in the laboratory are solid state physics, medical radioisotope production and small scale applications in environmental and space sciences.

The K=130 MeV cyclotron [2] has a magnet pole diameter of 2.4 m and consists of three 58° spiral sectors with maximum and minimum pole gaps of 0.33 m and 0.174 m, respectively. The main magnet is trimmed by 15 circular correction coils and 4 sets of harmonic coils. The bending limit of the magnet is 130 MeV and the focusing limit is 90 MeV for protons. The acceleration system consists of 2 active 78° "dee" electrodes with a maximum voltage of 50 kV. The RF frequency is 10-21 MHz and the 1st, 2nd and 3rd harmonic modes of operation will be available first. The cyclotron vacuum is produced by two 5000 l/s cryopumps, reaching the operation pressure of 10^{-7} mbar, essential for handling slow, highly charged heavy ions in the center region. The available maximum energy for protons will be about 90 MeV and for other ions the energy is obtained from the formula (0.2 - 1.0) 130 q^2/A MeV. Ions are produced in an external ECR-type ion source, which is similar to the RT-ECRIS at MSU with some modifications and improvements. The first beam, 6 MeV/u $^4He^{1+}$, was extracted from the cyclotron in January 1992. Since then also a 6 MeV/u $^{40}Ar^{10+}$ beam has been accelerated. In all these tests the h=2 mode of operation was used. Presently also a h=1 mode of operation has become available and in June 1992 a 70 MeV proton beam was accelerated to the full radius. Figure 2. shows the expected beams and their energies for two different lower limits of intensity. The values are based on the measured performance at the MSU RT-ECR source and 5 % transmission from the ECR source through the cyclotron to the target.

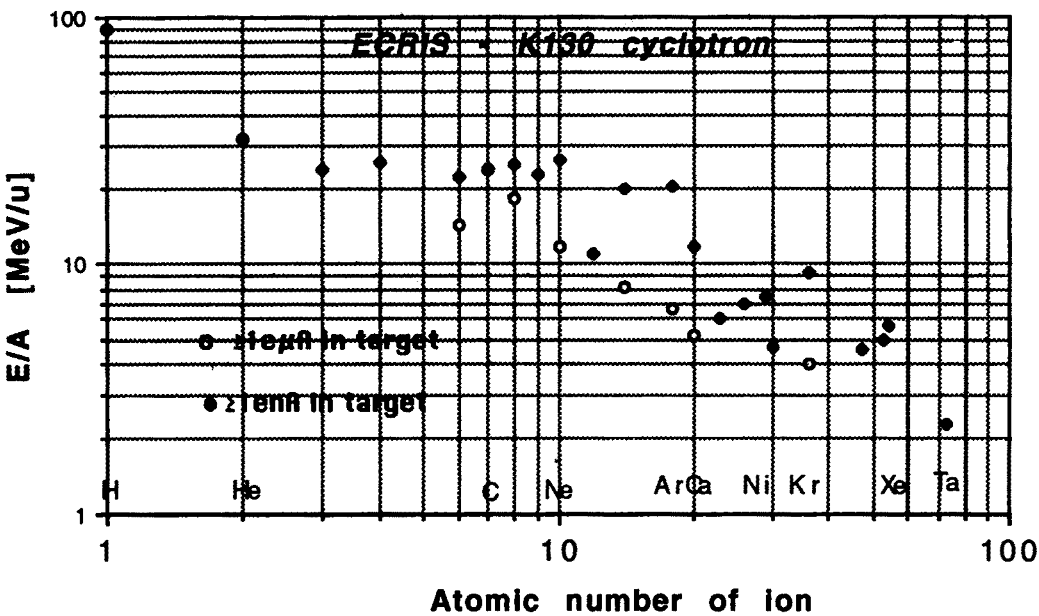

Figure 2. The maximum energies from the new K=130 MeV cyclotron at JYFL. Two sets of points correspond to the minimum intensities of 1 eμA and 1 enA.

3. Ion Guide Isotope Separator On-Line at the K130 Cyclotron

3.1. Ion guide technique and its applications

The ion guide method, first developed in Jyväskylä in the early eighties, allows fast injection of singly charged primary reaction products, thermalized in helium, into the mass separator without a significant efficiency dependence on the elemental properties [3,4]. The method, generally termed as IGISOL (Ion Guide Isotope Separator On-Line), has been successfully applied in spectroscopic studies of exotic nuclei produced in light ion induced fusion and fission reactions.The application of the technique to heavy ion fusion recations has been limited due to the side effects of the intense plasma generated by the primary beam in helium. In the ion guide method the initially highly charged recoils lose their charge while slowing down in target and helium buffer gas. Due to the high first ionization potential of helium the thermalized recoils remain as singly or doubly charged, unless they undergo charge transfer with impurities in helium or three-body e^--recombination with thermal electrons present in helium. Ions may also be lost to the walls of the buffer gas chamber by diffusion. The life of a recoil ion in the ion guide is not fully and quantitatively understood, but it has been observed that a very large fraction of ions remain singly charged over a period of several ms in commercial grade (a few ppm) helium gas at a pressure of the order of 10 kPa. This means that ions have to be transported away by fast gas flow using volume flow rates typically over 500 cm^3/s. This results in average delay times of only a few ms, which is one to three orders of magnitude shorter than in conventional on-line mass separators. This requires a fairly efficient differential pumping system, because the final vacuum inside the mass separator is typically 10^{-6} mbar. An integral part of the differential pumping system is the electrode system, skimmer or squeezer, which is used to focus the ions through a helium-skimming aperture into vacuum for further acceleration and separation by mass.

The standard version of the IGISOL has already been used in several spectroscopic studies of light and heavy nuclei. These include the measurements of the Gamow-Teller strength and its quenching among the fp-shell mirror nuclei [5], the studies of the isomerism [6] and the delayed particle emission [7] as well as the study of the reflection asymmetry in the actinide region [8]. Our recent work using an ion guide specially designed for fission products has concentrated on the studies of new nuclei produced in symmetric fission. The IGISOL technique has been adopted by several laboratories up to now and for more information the reader is referred to the session devoted to the ion guides in the proceedings of the last two conferences on electromagnetic isotope separators and their applications, which were held in Los Alamos, USA and in Sendai, Japan [9,10].

3.2. Symmetric fission and neutron-rich nuclei

We review here our recent studies on beta decay of rare neutron-rich nuclei produced by charged particle induced fission at the IGISOL on-line mass separator facility. Fission fragments from four natural uranium targets, bombarded with 20 MeV protons from the old JYFL MC20 cyclotron, were thermalized in helium and transported by the ion guide into the isotope separator [4]. Chemical nonselectivity and short delay time ($\approx$ 1 ms) allow separation of very neutron-rich nuclei of all elements with nearly constant efficiency. Typical intensities of the order of 10^3 ions/s per isobar were obtained for highly refractory elements such as Zr through Pd. About 20 new neutron-rich isotopes of these elements have been discovered. The most rare nuclides [11] are the very n-rich isotopes ^{105}Zr, ^{107}Nb, $^{109,110}Mo$, ^{113}Tc, ^{115}Ru, ^{117}Rh and $^{119,120}Pd$.

Our investigations have resulted in experimental information about the evolution of the neutron and proton shell structures between nearly spherical Z=47 (Ag) and highly deformed Z=40 (Zr) neutron-rich nuclei. We have identified a new region of rather strongly deformed nuclei among the most n-rich Ru isotopes with a breaking of the axial symmetry [12]. We have also established a shape coexistence and studied the evolution of deformation in the A≈100 Zr-region [13]. Candidates for the new shape isomers are suggested through the observation of isomers, such as ^{114}Ag ($T_{1/2}$=1.5 ms), ^{113}Pd ($T_{1/2}$=400 ms) and ^{117}Pd ($T_{1/2}$=19 ms), which are populated directly in fission [14]. Simultaneously, the large body of our experimental data is used to study the strength and its distribution for the Gamow-Teller beta decay as a function of deformation [15]. The acquired half-life and decay energy data for new n-rich nuclei are also very valuable in testing the validity of theoretical models for half-lives and binding energies used, for example, in the analysis of nuclear synthesis of elements in the r-process.

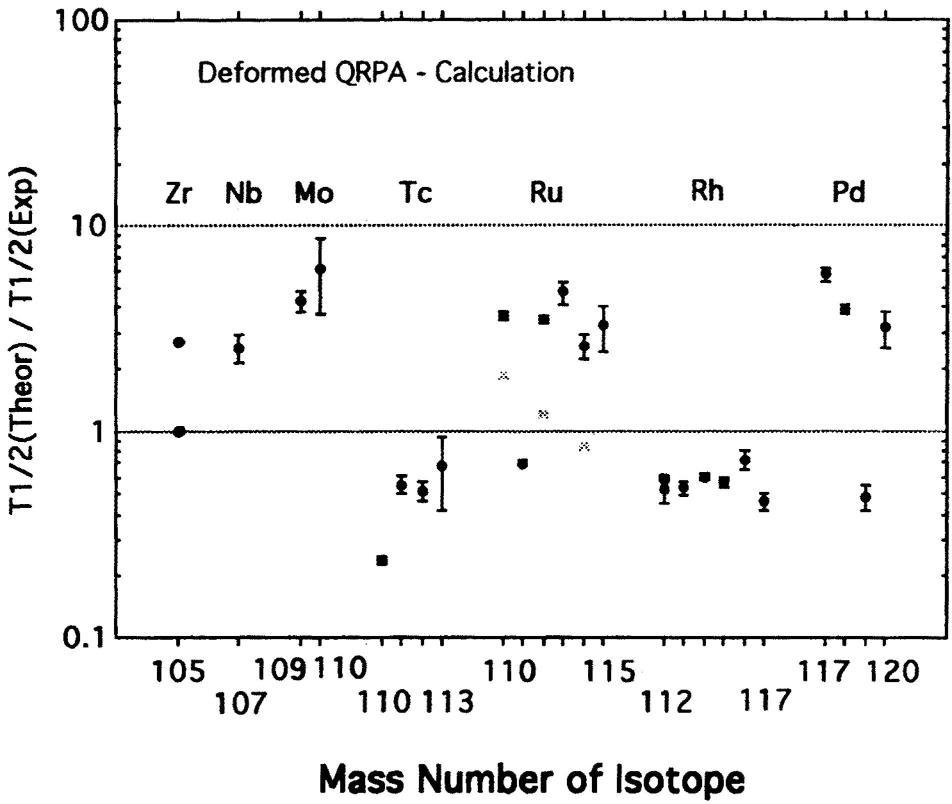

Figure 3. The ratio of the theoretical and the experimental half-lives for all new isotopes observed at IGISOL. The lower values for even Ru isotopes are obtained using the experimental values for Q_{β}.

Figure 3 shows a comparison between our experimental half-lives and those calculated by the deformed QRPA-model of Möller and Randrup [16] for 24 β^{-}-decays from Zr to

Pd. The deformation and the Q_β-values are obtained from the mass model of Möller and Nix [17]. The average value for the ratio of the theoretical $T_{1/2}$ to the experimental one is 2.1 for these 24 cases. This indicates the superiority of the Möller-Nix masses over the other models applied [11], which result in too low Q_β -values leading to higher values for theoretical half-lives. The only cases in Fig. 3, where experimental Q_β-values are known, are $^{110,112,114}Ru$. The values are about 1 MeV higher than those predicted by Möller and Nix. Taking this into account reduces the $T_{1/2}$ ratios by a factor of about two and leads to considerably better agreement between theory and experiment. Thus, it would be very important to continue to measure decay energies (Q_β) and deduce more accurate neutron binding energies (B_n) and deformations furher and further from stability to remove uncertainties in half-life predictions. The role of these measurements is important to explain, for example, the severe underproduction of A ≈ 110 - 120 elements in the recent steady-flow r-process calculations of Thielemann et al. [18].

3.3. New IGISOL-facility

The IGISOL mass separator facility that is being modified for use in the new laboratory is shown in Figure 4. It will, hopefully, become possible to utilize it in connection with both fission and fusion reactions. With the improved beam intensity and new projectile possibilities we estimate that the production rates of fission products will be increased by a factor of over 100. This means that a large number of new nuclei should become accessible for the experimental studies using only fission.

The new large vacuum chamber at the high voltage part of the separator will house either the target-thermalization chamber for fission products or a special arrangement for fusion reaction products. The pumping capacity of the new pump station for helium will be about 8400 m^3/h, which is nearly 3 times higher than at the old set-up.The radioactive ions extracted by the ion guide are accelerated to 40 keV energy and transported through a concrete shielding using two einzel lenses into the 55^o dipole magnet for mass analysis. The mass resolving power of the instrument is mainly set by the energy spread of the ion beam and is typically 400 when using the single skimmer ion guide and over 1000 when using the so called squeezer ion guide [19].

The separated radioactive ion beams can be directed by the electrostatic switchyard into three different beam lines positioned after the IGISOL dipole magnet. These lines will include spectroscopy stations consisting of the conventional β- and γ- ray detector set-ups and special semiconductor, gas and scintillation counter set-ups for exotic particle radioactivity studies.

In addition to standard spectroscopic methods, we have developed a novel lens-type conversion electron spectrometer, ELLI, which can be used in the focal position of the IGISOL-system to measure directly implanted sources with high efficiency and low background [20]. Figure 7 shows the layout of the ELLI spectrometer. The radioactive ion beam from the IGISOL enters the spectrometer at 45^o angle with respect to the symmetry axis. The ions are implanted on a movable tape. A broad range of conversion electrons (up to 2.5 MeV) spirals down in the magnetic field, generated by the pair of coils, towards a cooled Si(Li) detector operated as an energy-dispersive unit. A ring-shaped cold trap is placed in the vicinity of the cooled Si(Li) detector. The inset shows a removable mini Faraday cup, which is used to tune the separator with a stable ion beam, and a surface barrier detector that can be placed only 7 mm away from the implantation spot. Simultaneously a gamma- or an X-ray detector can be placed outside the vacuum chamber in a close geometry with respect to the source. The total efficiency of the spectrometer employing a 300 mm^2 Si(Li) detector has been measured to be about 20 % at 100 keV and 10 % at 500 keV electron energy.

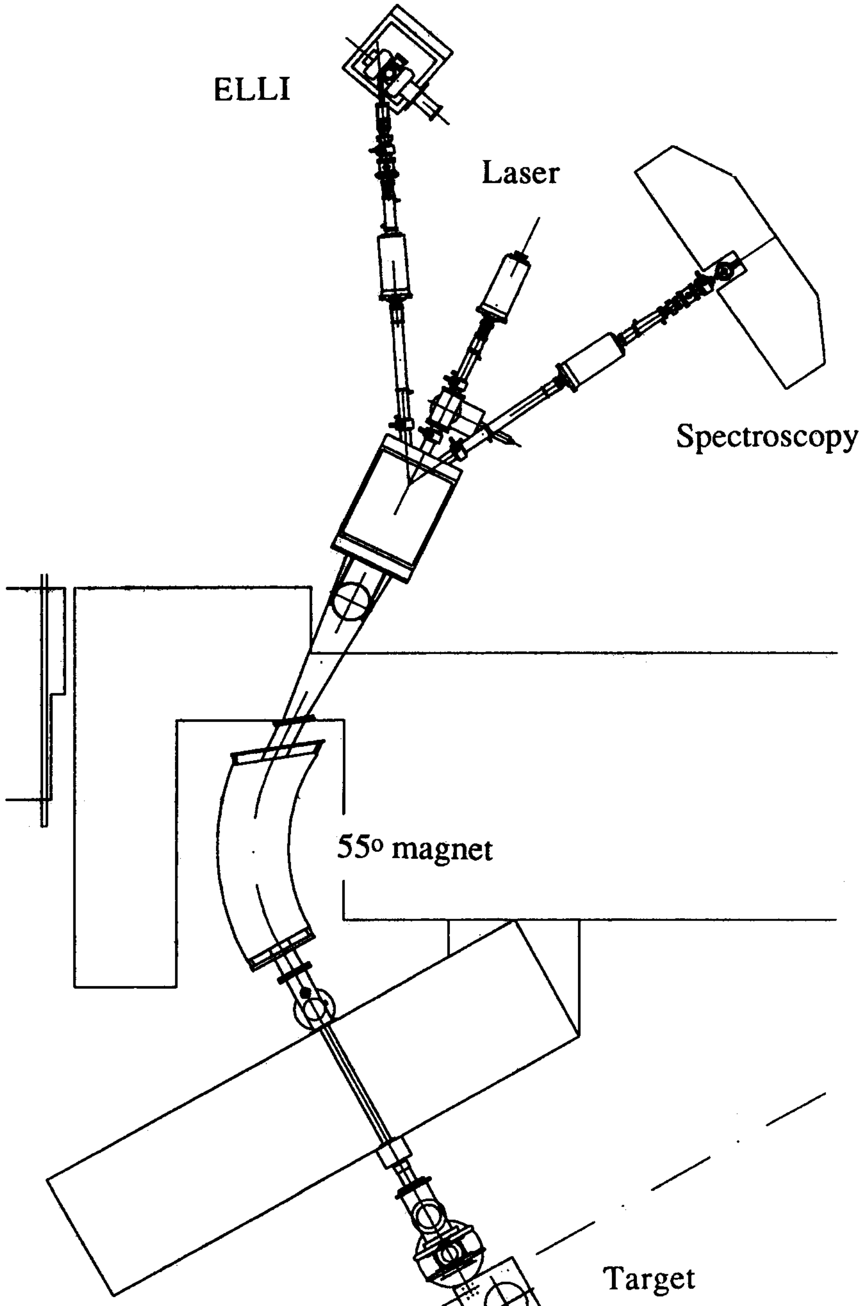

Figure 4. The new IGISOL system at the K130 cyclotron at JYFL.

The spectrometer can be used in various coincidence measurements with β-, γ- and X-rays. Especially, the X-ray coincident electron measurements should allow identifications and detailed quantitative measurements of single isomeric transitions populated directly in fission or fusion evaporation reactions.

The central beam line in Figure 4 is presently reserved for collinear laser spectroscopy. This will utilize a new technique for laser spectroscopy of fast ionic or atomic beams [21,22]. It involves measuring coincidences between resonantly scattered photons and ions in the fast beam. The technique has been developed at the Daresbury on-line separator DOLIS and measurements of Sr and Ba ions have shown that Doppler-free spectroscopy can be performed with less than 100 ions/s. It is clear that the combination of this technique and the fast ion guide technique will open up interesting possibilities for "a new era of collinear laser studies".

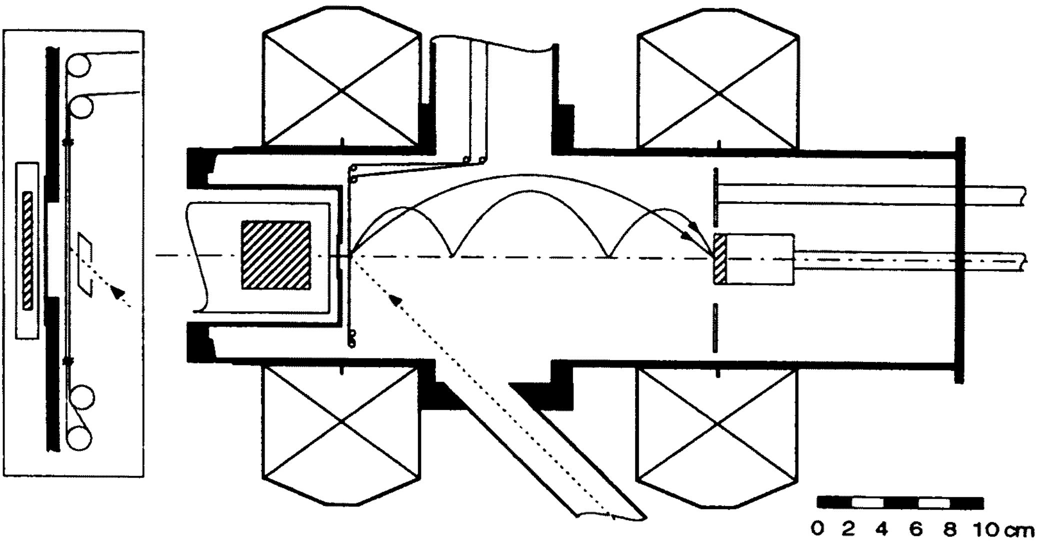

Figure 5. Lay-out of the electron spectrometer ELLI. See text for details.

Reactions and production rates

Spontaneous or induced fission of a heavy nucleus leads to the production of a few hundred different neutron rich nuclei and provides the most efficient way to produce n-rich medium-heavy nuclei. A series of spectroscopic experiments using the IGISOL technique on product nuclei from proton-, deuteron- and alpha-induced fission have allowed the determination of cumulative and independent yields of nearly 100 nuclei. These data have allowed us to deduce cumulative isotopic yield distributions as well as in some cases the charge dispersion corresponding to a certain mass number [23]. By using these data and the statistical model for fission [24] we can predict the yields for the new IGISOL-facility. Figure 6 shows an example of such predictions made for the independent yields of Zr, Tc and Pd isotopes produced in 30 - 40 MeV proton-induced fission on ^{238}U. In this prediction we have assumed that the pressure in the thermalizing chamber is 40 kPa, the proton beam intensity is 10 μA and the efficiency is constant and independent of the beam intensity. For example, the short-lived exotic Pd isomers can be produced with yields above 10^4 s^{-1}, which should allow direct laser spectroscopic studies of these puzzling states. For comparison we show also the yield for Tc isotopes from 20 MeV proton induced fission of ^{238}U at the old IGISOL-facility, where 10 kPa He pressure and 0.5 μA beam intensity were used.

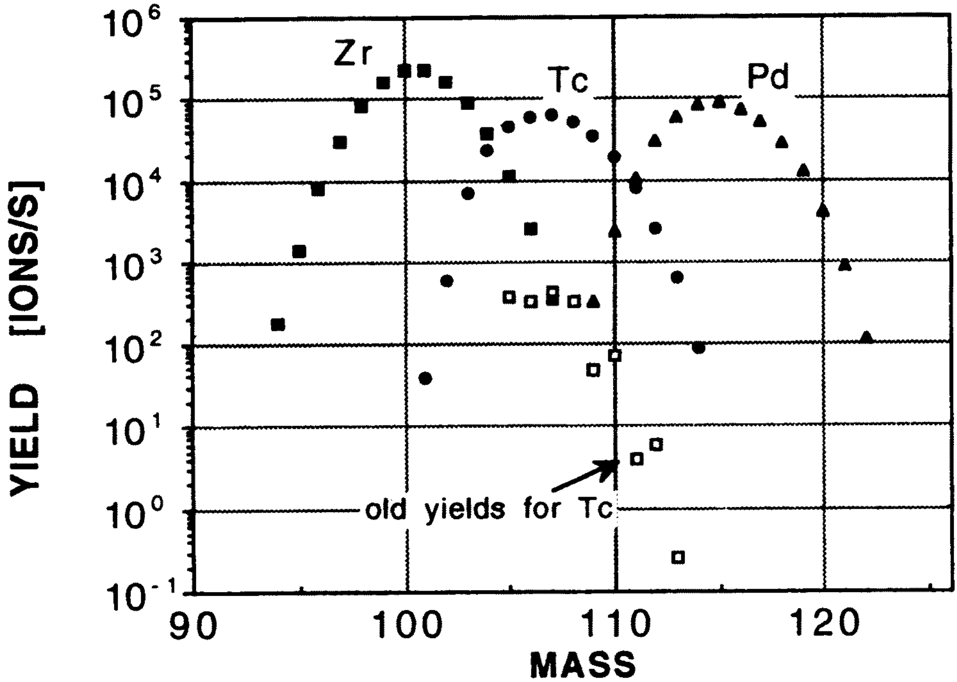

Figure 6. Estimated independent yields for Zr, Tc and Pd isotopes from p-induced fission of uranium at the new IGISOL-facility. See text for details.

Alpha- and heavy-ion-induced fusion-fission as well as direct reactions and multinucleon transfer leading to fission could also be used as production reactions. However, a comparison of the available experimental heavy ion data with our light ion results suggests that light ion induced fission remains an efficient way to produce extremely n-rich nuclides. Heavy ions, nevertheless, may offer interesting possibilities to reach some "remote" areas in the nuclear chart, such as the expected doubly magic region around ^{78}Ni.

Light neutron-rich nuclei could, in principle, be produced in transfer reactions of light n-rich projectiles or in ternary fission. Proton-rich nuclei in the sd-shell are best produced in p- and ^3He-induced fusion reactions and those of heavier elements in heavy ion induced reactions. The latter will require a modification in the present ion guide system, which due to the so called plasma effect cannot be used for HI-induced reactions. This modification is being designed and it will consist of a small gas-filled magnet, which separates the primary beam from the fusion products before they are thermalized in helium.

IGISOL research plans

At the beginning the studies of exotic nuclei will concentrate on proton-rich light nuclei and neutron-rich medium mass nuclei. The former studies involve detailed, high precision measurements of the fundamental properties of the Fermi- and Gamow-Teller decays, investigation of nuclear stability and exotic decay modes; especially the search for the di-proton radioactivity in ^{39}Ti decay. With the expected intense light heavy ion beams we anticipate to extend these studies through the fp-shell to Z≈N isotopes in the A≈90 region, which are becoming of interest not only for a rich variety of phenomena in their structure but also for astrophysical reasons, such as the rapid-proton capture reactions induced by hydrogen burning in stars.

Due to the expected rise in the yields of the fission products, several new studies involving weak interaction, nuclear structure as well as astrophysical aspects will be possible at the new facility. They will include items such as the search for new more n-rich nuclei and measurements of their beta-decay properties as well as decay energies. Extension of our previous studies concerning the shape coexistence and axially broken deformation further from stability will naturally be of great interest. In this connection the planned collaboration between our group and the British laser-group to measure nuclear moments, charge radii and spins will be very important.

In more distant future we are also planning to look for possibilities to produce and study the decays of very light neutron-rich nuclei via heavy ion transfer or ternary fission reactions. Similarly, in connection with our planned heavy element program, spectroscopic measurements employing electron spectroscopy as well as collinear laser studies are being planned for up to Z≈100 nuclei.

4. RITU, the JYFL recoil separator system

One of the main research facilities at JYFL will be the gas-filled separator RITU (Recoil Ion Transport Unit). Gas-filled recoil separators have earlier been used in studies of fission products [25]. During the last ten years or so, devices constructed in heavy ion accelerator laboratories have mainly been used in studies of heavy elements [26-30]. One notable exception is the use of an Enge split-pole magnetic spectrograph in connection with AMS spectroscopy in Argonne [31].

4.1. Gas-filled recoil separators for heavy ion reaction products

Gas-filled separators are most naturally suited for separating evaporation residues produced in heavy ion fusion reactions from the primary accelerator beam. In a gas-filled recoil (mass) separator, reaction products recoiling out of a thin target are separated from the accelerator beam in a dipole magnet field region filled with dilute gas. Target thickness is usually on the order of 100-500 µg/cm^2. The magnetic rigidity $B\rho$ of a given nuclear species is determined by the momentum mv and the average charge state q_{ave} of the corresponding ions in the filling gas.

$$B\rho = mv/q_{ave}$$

For complete fusion, in particular, the ratio of the radius of curvature of the primary ions and the evaporation residues is given by the inverse of the corresponding q_{ave}-ratio. The physical separation of the full energy primary beam from the fusion products is excellent for a wide range of the mass ratio of bombarding ions and target nuclei - only for reverse kinematic reactions does the separation become inadequate [30].

The filling gas is typically helium under a pressure of about 100 Pa. With different choices for the filling gas and pressure, instead of a rough mass separator, the device will for example acquire properties similar to those of an isotone separator [32]. In the normal (beam dump) mode to be discussed here, full energy primary beam suppression is typically 10^{-12} - 10^{-15}

The inherent charge focusing of the separator leads to high transmission of nuclear reaction products. This is enhanced by the fact that, in first order, the average charge state q_{ave} of ions in gas is directly proportional to the velocity of the ions [27]. This leads to velocity focusing and so the total efficiency for detecting fusion products from a heavy ion reaction may in favorable cases exceed 50 %. In case of very asymmetric reactions such as O + U or Ne + Cm, efficiencies on the order of 1-10 % are typical [30,33]. Gas-filled separators have commonly a fairly high acceptance, 10 msr in case of RITU. This is especially advantageous in case of very asymmetric reactions where multiple scattering and neutron evaporation from the compound nucleus cause a large angular divergence of the products. In such cases, the transmission of a gas-filled separator may exceed the transmission of other recoil separators significantly.

Detection limits for rare nuclei are usually determined by the suppression of scattered low-energy primary beam particles and of heavy, target-like nuclei. Target-like knock-outs are typically only suppressed by a factor of 10^{-3} - 10^{-5} [27]. Products with cross sections on the order of 100 pb should still be observable. The lowest observable half-life is determined by the time-of-flight of the products through the separator which is on the order of 1 µs in most cases.

4.2. Description of the facility

The design of RITU (Fig. 7) is based on experience gained from earlier gas-filled separators [26-28,30]. The basic DQQ design has been modified by adding a vertically focusing quadrupole magnet in front of the C-type dipole magnet. This leads to better matching to the acceptance of the dipole and to an increase in the total efficiency. The target position is 400 mm upstream from the first quadrupole. The target chamber will be equipped with a rotating target wheel. Two detectors will be used for monitoring the targets as well as the beam intensity through Rutherford scattering of primary beam particles. RITU has been designed also for operation under vacuum and in this mode the first Q will improve the mass resolution - which is still only moderate being on the order of 1 % in a typical case. For the vacuum mode, a sextupole element has been added downstream from the dipole magnet.

The separator is mounted on air cushions and can be rotated through an angular range of +15° to -70° around the target position and used also for studies of transfer and deep inelastic reaction products as well as studies of the reaction process itself.

Since RITU has only moderate mass resolution - on the order of 10 % - in the gas-filled mode, the identification of activities produced must rely on versatile detector systems. One challenging goal will be construction of a time of flight detector system for the gas-filled mode. The main focal plane detector will be based on one or more position sensitive PIPS PAD-detectors each one consisting of 16 5 mm wide by 35 mm high strips. In case of alpha activities where a chain of decays leads to known nuclides, the identification will depend on the well-known time and position correlation technique [34]. Otherwise, more laborious excitation function and cross bombardment methods may become necessary.

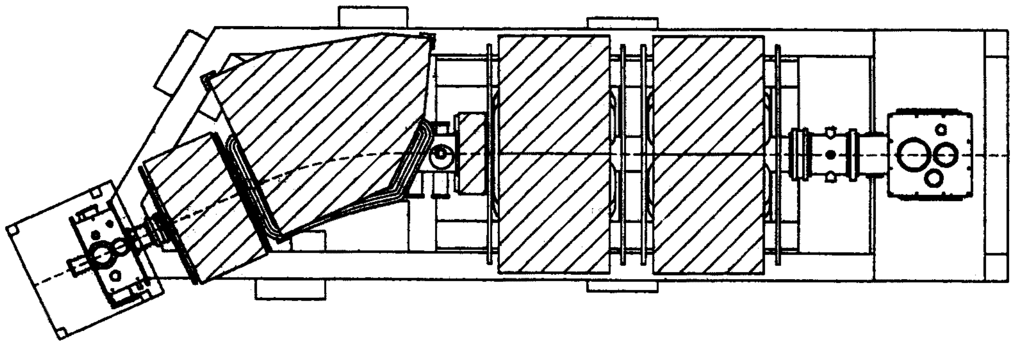

Figure 7. Schematic view of the gas-filled recoil separator RITU. The magnets are enhanced in the figure.

The focal plane detector chamber provides versatile possibilities for installing different ionization chambers as well as semiconductor photon detectors. We also plan to employ a relatively simple detector system surrounding the target position to be able to perform in-beam measurements. If we take as a practical limit for conventional gamma and x-ray spectroscopy a counting rate at the focal plane of RITU of 10 ions/s and assume a separation efficiency of 5 % and a beam intensity of 10^{12}/s, we arrive at a cross section level of 200 μb for a typical asymmetric heavy ion fusion reaction. Gamma rays can in some cases be observed even from nuclei produced with low cross sections. In a study of element 105, produced with a peak cross section of a few nb [35], gamma rays were observed in coincidence with alpha decays.

In Table 1 the parameters describing the separator system are given. The magnets of the separator and their power supplies, the separator stand as well as the air cushions, all provided by DANFYSIK A/S, have been delivered and the separator has been installed in the experimental cave. Construction of the detector systems is in progress. The target chamber, including the beam window and the rotating target wheel system, is under construction. The first experiments are scheduled for the beginning of 1993.

4.3. Planned RITU research projects

The nuclear physics research to be done with RITU in the first two years or so will depend on the accelerator beams available. Most of the experiments will deal with relatively heavy nuclides (A > 140) produced in fusion reactions. Since the development of methods to produce beams of metallic elements such as Fe and, in particular, Ni, is still at an early stage at JYFL, the first research projects will rely on C, O, Ne, and Ar beams.

One important field is research on nuclear reaction properties. Some examples of this kind of work will be mentioned in connection with more specific projects discussed in the following. The equilibrium charge state q_{ave} of an ion species in the filling gas [27] is an important experimental parameter. Extensive work in a wide energy and elemental range has been done already in this field [27,36,37]. This work will be continued also at JYFL.

Table 1: RITU parameter values

Magnetic configuration	$Q_1DQ_2Q_3$	Pole gap (D)	100 mm
Maximum beam rigidity	2.2 Tm	Q_1 maximum gradient	13.5 T/m
Bending radius	1.85 m	Q_1 effective length	350 mm
Acceptance	10 msr	Q_1 aperture diameter	105 mm
Dispersion	10 mm/% of $B\rho$	$Q_{2,3}$ maximum gradient	6.0 T/m
Mass resolving power (vacuum mode)	100	$Q_{2,3}$ effective length	600 mm
Dipole bending angle	25°	$Q_{2,3}$ aperture diameter	200 mm
Dipole entrance angle	0°	Total weight	17500 kg
Dipole exit angle	-25°	Total length	4.8 m

Very neutron-deficient nuclei with Z = 82 - 86

Extensive studies have been performed in this region using ions with A ≈ 20 and the helium-jet method for separating evaporation residues [38]. Later on, recoil separators have been used to continue studies of even more neutron-deficient nuclides [26,39]. At present, the properties of nuclides on the known borderline are very suitable for recoil separators; the half-lives are typically in the ms region so that correlation analysis works well, and the production cross sections are still reasonably high. At least for some elements, the proton drip line has already been crossed. Search for ground state proton emission thus becomes feasible. Determination of the alpha (or beta) decay branch through the alpha-alpha correlation method works well for some nuclei in this region. This makes possible the reliable determination of the reduced alpha width δ^2 which is an important observable. Another line of study in this region would be the continuation of the search for low-lying $I^\pi = 0^+$ states in even-even nuclei populated in alpha decay [40].

Heavy nuclei with Z ≈ 100

The region of heavy and very heavy elements has provided several important findings in the past years such as the unexpected stability of the heaviest elements with Z = 107-109 against spontaneous fission [41], cluster decays [42], and bimodal spontaneous fission of heavy No, Md, and Fm isotopes [43]. The discovery of elements Ns, Hs, and Mt (107-109) [41] has only been possible through the use of the cold fusion process based on Pb and Bi targets and Cr and Fe ions. Recently, however, the possibility of using the hot fusion reaction and somewhat lighter ions has gained new interest [44]. Research can be done on the decay properties of actinides also using Ne and Ar beams. In particular, very little is known about level schemes of many of these nuclei.

Study of basic decay properties such as total and partial half-lives of very neutron-deficient actinide isotopes is fruitful even when detailed spectroscopic studies are out of the question. To give just one example from earlier work, the cross section for producing ^{244}Fm in the reaction ^{208}Pb(^{40}Ar,4n) is 1.5 nb [45]. A crucial factor in this type of work is the decrease of the cross section for the production of evaporation residues as the number of evaporated neutrons increases. The emerging picture seems to be that fission is a relatively slow process and can successfully compete with neutron evaporation only after the excitation energy of the system is quite low. To get more information on this, we are planning to measure excitation functions for a variety of fusion products using different ions and spherical as well as deformed target nuclides such as ^{208}Pb and ^{238}U. The more enhanced cold fusion behaviour when using for example Ti and Cr ions may turn out to be of crucial importance [46].

Work at the extreme limit of high proton numbers [41] with production cross sections in the pb region requires a very clean separation and may never be possible with a gas-filled separator in stand-alone mode. However, interesting work can be done in the region $Z \approx 104$-106. For example, search for the alpha decay of the key isotope ^{260}104 [47] and confirmation of the discovery of ^{263}106 [48] would be challenging projects but in practice require access to transuranium targets.

In-beam γ-ray spectroscopy

An attractive possibility to reduce non-fusion related background activities in an in-beam experiment is to require a (delayed) coincidence between radiation observed at the target position and a recoil nucleus which has traversed the separator. Again, if the evaporation residue is alpha-active, this may lead to its identification. Even when identification through radioactive decay is impossible and a gas-filled separator with low mass resolution is used such work may be productive. Collaboration in this field with the NORDBALL-group will start in 1993.

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