The REX-ISOLDE project

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The Radioactive Beam Experiment REX-ISOLDE [1–3] is a pilot experiment at ISOLDE (CERN) testing the new concept of post acceleration of radioactive ion beams by using charge breeding of the ions in a high charge state ion source and the efficient acceleration of the highly charged ions in a short LINAC using modern ion accelerator structures. In order to prepare the ions for the experiments singly charged radioactive ions from the on-line mass separator ISOLDE will be cooled and bunched in a Penning trap, charge bred in an electron beam ion source (EBIS) and finally accelerated in the LINAC. The LINAC consists of a radiofrequency quadrupole (RFQ) accelerator, which accelerates the ions up to 0.3 MeV/u, an interdigital H-type (IH) structure with a final energy between 1.1 and 1.2 MeV/u and three seven gap resonators, which allow the variation of the final energy. With an energy of the radioactive beams between 0.8 MeV/u and 2.2 MeV/u a wide range of experiments in the field of nuclear spectroscopy, astrophysics and solid state physics will be addressed by REX-ISOLDE.

Keywords: radioactive beams, RIB-facilities, charge breeding, accelerators, ion sources

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1. Introduction

The physics with energetic radioactive beams represents one of the frontiers in nuclear physics, as advocated in a report on “European radioactive beam facilities” by the “Nuclear Physics European Collaboration Committee” [4] and discussed at many conferences [5–7]. In the last years several radioactive beam (RIB) facilities have been under construction or have been already completed which represent a first generation of RIB-facilities. These projects are RIB-facilities to explore the possibilities of production and post-acceleration with nuclei far from stability. In contrast to second generation facilities, where maximum yields of accelerated radioactive ion beams are envisaged, the beam intensities of first generation facilities are lower, but sufficient for specific physics questions. The efforts in Europe culminate now in EU-networks, where several institutes from all over Europe explore the specific questions to be solved for a future second generation RIB-facility EURISOL [8].

In contrast to other projects, REX-ISOLDE is an experiment with energetic radioactive beams at the already existing RIB-facility ISOLDE at CERN [9]. It makes fully use of the vast experience and availability of many low energetic radioactive 1^+ ion beams from the on-line mass separator ISOLDE. The starting point of REX-ISOLDE was a new concept to convert a low energetic radioactive beam from ISOLDE in an efficient way to a high energy beam. Figure 1 shows the general layout of the experiment and the concept of post acceleration.

REX-ISOLDE is the first RIB experiment using a device with buffer gas cooling for accumulation and bunching of ions and a high performance ion source like an EBIS for charge multiplication of the ions to simplify the accelerator as much as possible. This concept of charge breeding of the radioactive ions [10] in comparison to stripping will be explored in future in more detail in an EU-network for charge breeding [11]. Though REX-ISOLDE focuses on specific experiments with final beam energies up to 2.2 MeV/u, options for extensions to higher and lower beam energies are on hand, which open up a broad field of future experiments in nuclear spectroscopy, nuclear astrophysics and solid state physics. In contrast to the structure of stable nuclei, which are thoroughly investigated experimentally and theoretically, the structure of nuclei close to the neutron dripline is not well established yet. REX-ISOLDE provides a test of the shell model over a wide isospin range. Different predictions from the nuclear

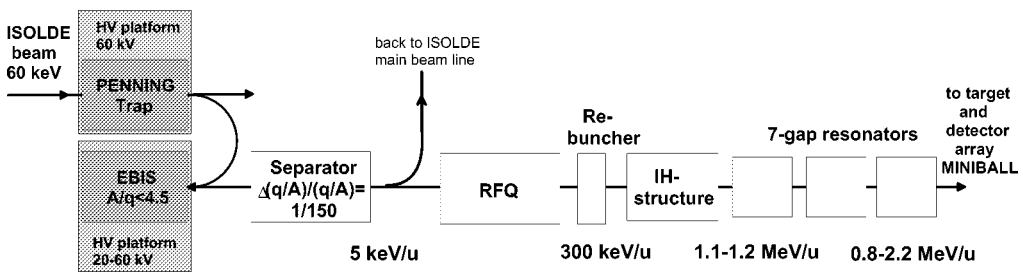

Figure 1. Schematic of the concept to produce energetic radioactive beams with REX-ISOLDE.

shell model are obtained when going from the valley of stability to the neutron rich region. One prediction is the change of the nuclear potential from a box shaped Woods–Saxon potential to a parabolic potential [12]. This modification leads to changes of the magic numbers and hence to new predictions of regions of nuclear deformations.

REX-ISOLDE itself is placed in the experimental hall where no heavy shielding is required and the low radioactivity allows easy access. The scheme of REX-ISOLDE is pursued in several steps fulfilling separated functions. The 1^+ beam is first bunched in a Penning trap and its phase space is reduced by cooling. In the electron beam ion source (EBIS) the 1^+ ions are then converted to highly charged ions by bombarding them with an intense electron beam. In the next step a separator selects the wanted charge-to-mass ratio. This bunched low-energetic beam of highly charged ions is first accelerated in a 4-rod RFQ-LINAC to 0.3 MeV/u. In the following IH-structure and the three 7-gap resonators the ions are further accelerated to a tunable final energy between 0.8 MeV/u and 2.2 MeV/u. After a momentum analysis in a dipole magnet, which can switch the beam to different ports, the ions are transported to a target, which is surrounded by a highly efficient detector system.

An additional beam line will be used for experiments which do not require the MINIBALL γ-detection array [13]. The detailed overview of the experiment is shown in figure 2. In addition to the high energy experiments, ions from the trap or from the mass separator can be guided back to the ISOLDE main beam line for low energy experiments of, e.g., solid state physics [14].

2. Preparation of the ions

As the simplicity, efficiency and costs of the accelerator is directly related to the charge state of the low energy ions, it is of great importance to produce multiply charged ions before injecting them into the accelerator. One of the established sources for highly charged ions is the EBIS [15], where an intense electron beam ionizes trapped ions stepwise by electron impact ionization. Following the different components of the experiment the singly charged ions coming from ISOLDE with 60 keV energy are retarded by the Penning trap platform potential of nearly 60 kV and injected continuously into the trap, where they are accumulated and cooled. After some milliseconds determined by the required charge breeding time inside the EBIS, the 10 μs long bunches extracted from the trap are re-accelerated to 60 keV and transferred to the EBIS. After charge breeding (5–20 ms) to a charge-to-mass ratio >0.22 the ions are injected into the RFQ accelerator via an achromatic mass separator [16,17]. Due to the required low injection energy (5 keV/u) of the RFQ the EBIS platform potential has to be lowered while charge breeding takes place from the 60 kV retarding potential down to 20 kV.

The time structure of the experiment is shown in figure 3. The 1 GeV proton pulses from the PS booster have a repetition time of 1.2 s. The bunching of the pulses from the EBIS is done by the RFQ where the pulses at the exit will have a length of 0.8 ns and a distance of 10 ns.

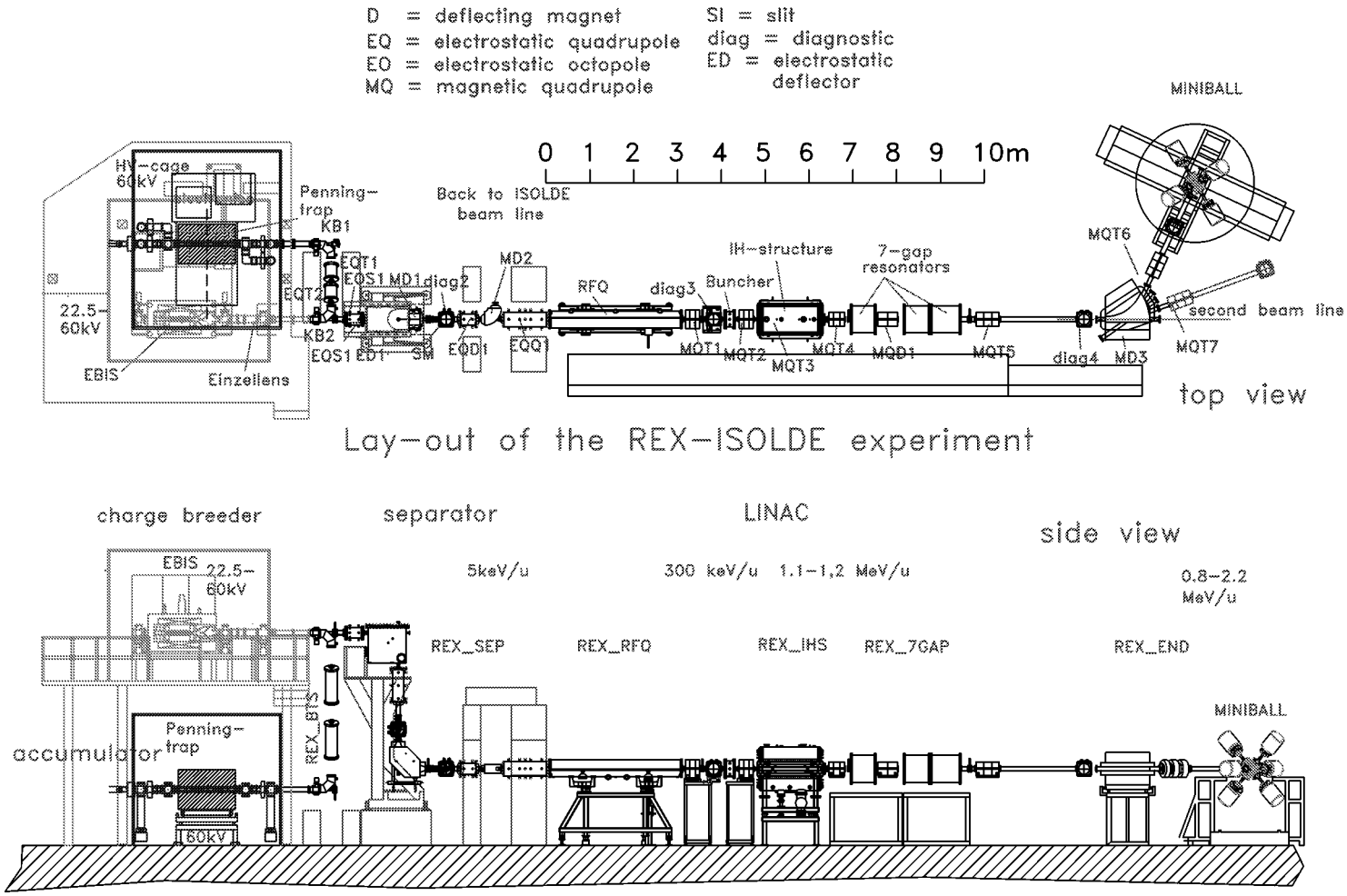

Figure 2. Detailed lay-out of REX-ISOLDE.

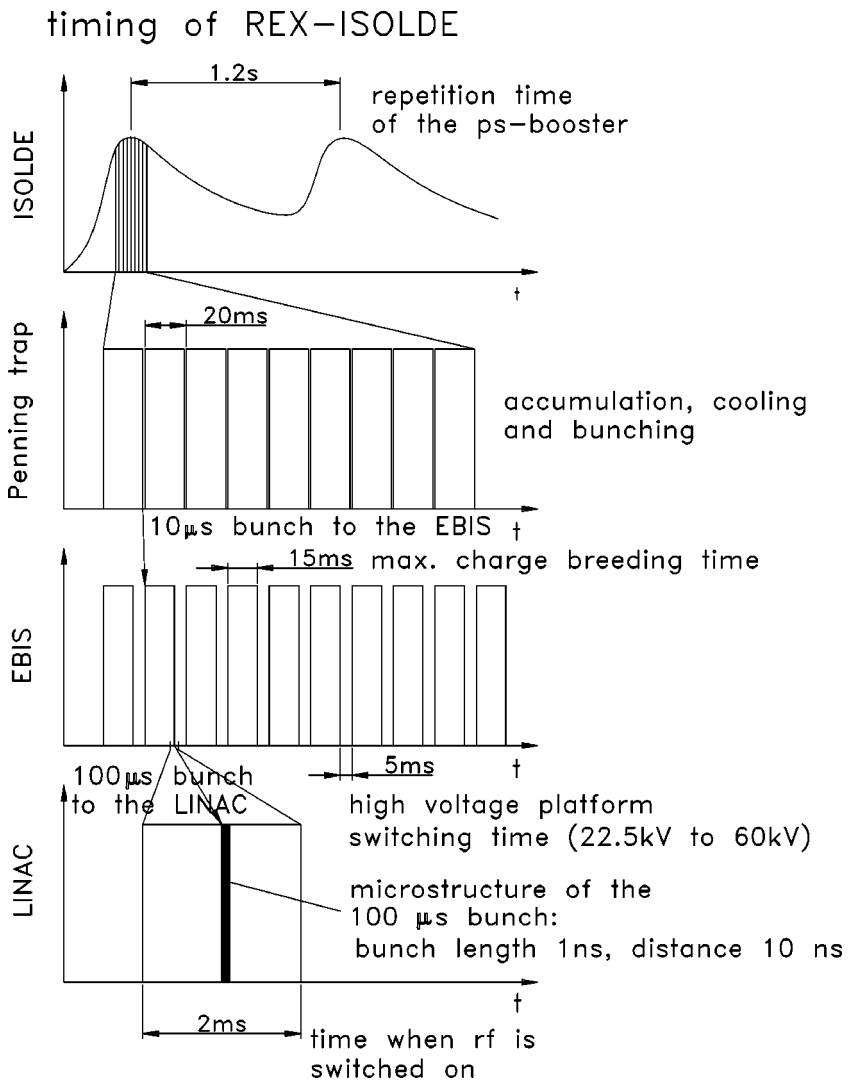

Figure 3. Time structure of REX-ISOLDE.

2.1. *Accumulation and bunching in the REXTRAP*

Bunching of the radioactive beam is required in the proposed acceleration scheme because charge-state breeding in the EBIS requires a typical time of about 20 ms and the LINAC operates with a duty factor of 10%. For the low-intensity radioactive beams it is furthermore advantageous to compress the ions in short pulses in order to increase the signal to background ratio in the measurements. The basic technique applied to accumulate and bunch the beam is to continuously inject the radioactive ions into a large Penning trap, where they are stopped by collisions with the atoms of a buffer gas, accumulated, purified and finally extracted as pulses. The functionality of such a

scheme has been demonstrated in the ISOLTRAP experiment [18,19], where a 20 cm long cylindrical Penning trap [20] in a 4.7 T magnetic field is used.

REXTRAP [21] is a 1 m long cylindrical trap structure filled with buffer gas in a 3 T magnetic field. It is mounted on a high voltage platform close to 60 kV in order to retard the ions from 60 keV to some eV suitable for injection into the trap. After the ions have passed the potential barrier at the entrance of the trap final deceleration is done by friction in the Ar buffer gas. The ions can be captured if their energy loss during a single oscillation in the trap is larger than the energy spread of the ISOLDE beam after deceleration. Then they can not overcome the entrance barrier again. From former experience with the cooler trap of the ISOLTRAP experiment [20] at ISOLDE a 100% capture efficiency is expected for the long trap and an Ar-pressure of about 10^{-3} mbar. Typical cooling times down to room temperature are a few ms. By this cooling the emittance of the extracted beam is considerably improved.

The transverse emittance of the extracted beam can be improved as well by using a special sideband cooling technique in the trap [19,22]. This can also be used to purify the stored ion cloud from unwanted species. In this mode all ions are first

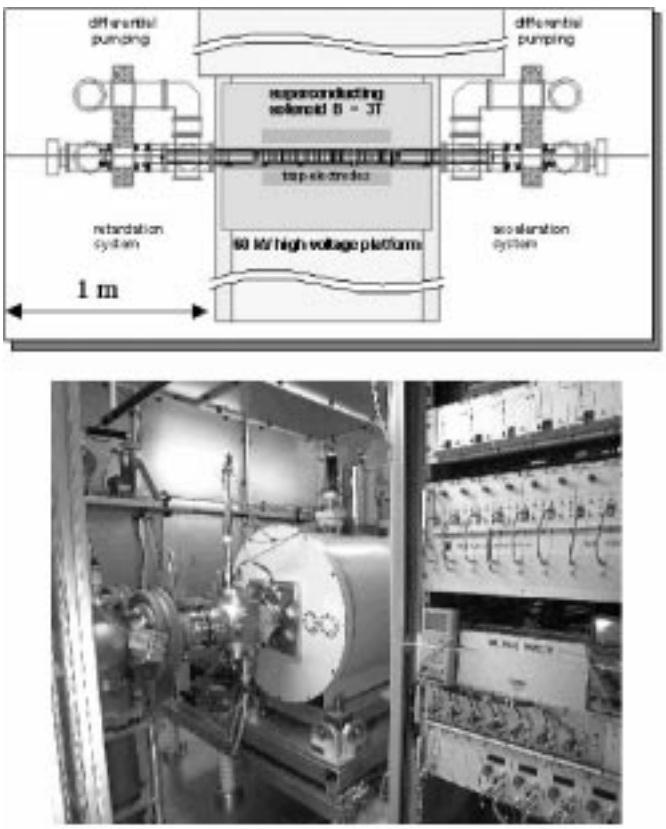

Figure 4. Photograph of the REXTRAP.

driven within a few ms to magnetron orbits larger than the diameter of the extraction hole of the trap and then only the desired species are recentered by excitation at the cyclotron frequency. In this way only ions with a special q/A-ratio are centered on the axis of the Penning trap and can be extracted through the narrow exit hole. This technique is particularly interesting for the removal of undesired higher-charged ions contaminating the ion beam from ISOLDE. These ions will most probably be converted into singly-charged ions in the buffer gas and can be removed easily by the sideband cooling technique. With increasing gas pressure in the trap the damping and cooling times become shorter, but at the same time the mass resolution is decreased. At high ion densities ($\approx 10^6$ ions in the trap) a deterioration of the mass selectivity should occur due to collective screening of the ion cloud. This will not be a limitation for REX-ISOLDE as the production yield for the radioactive ions of interest will be much below this number, but it will be interesting to explore the limits of mass selective buffer gas cooling in the REXTRAP. The REXTRAP and a schematic of the setup are shown in figure 4.

2.2. Charge breeding inside the REXEBIS

An EBIS makes use of a dense electron beam that is focused to a high current density by a strong magnetic field of a solenoid. The electron beam forms a radial potential well for the ions while the longitudinal confinement is performed by electric potentials applied to cylindrical electrodes surrounding the electron beam. Trapped low-charged ions undergo stepwise ionization via electron impact collisions until the ions are extracted by changing the longitudinal potential distribution. The centroid of the charge distribution is determined by the product of the confinement time and the electron beam current density. In the REXEBIS the 0.5 A electron current is compressed by the magnetic field into a current density larger than 200 $\mathrm{A/cm^2}$ [23]. The electron beam has an energy of 5 keV. A superconducting solenoid creates the magnetic field of 2 T, with a homogeneity of about 0.25% along the confinement length of 0.8 m. The isotopes used at the REX-ISOLDE experiments will require breeding times between 5 and 20 ms to reach a charge-to-mass ratio larger than $1/4.5$. In order to decrease the injection energy into the RFQ to 5 keV/u the platform voltage has to be switched from 60 kV (injection potential) down to 20 kV, and rapidly back again to accept the next bunch of ions. The REXEBIS platform capacitance is <1 nF. Figure 5 shows the REXEBIS on the high voltage platform, including the vacuum chambers of the electron gun and the ion extraction system.

To assure a high efficiency, the injection, breeding and extraction have been extensively simulated. The efficiency for injection of singly-charged ions into an EBIS has also been studied experimentally [24,25]. Total efficiencies of up to 59% were already observed. With a matched and optimized injection of the high-quality beam delivered from the Penning trap an efficiency of about 95% seems to be possible. Though, the internal efficiency is limited to around 30% due to the charge state distribution. The REXEBIS has an acceptance of 3π mm mrad for 1^+ ions injected at

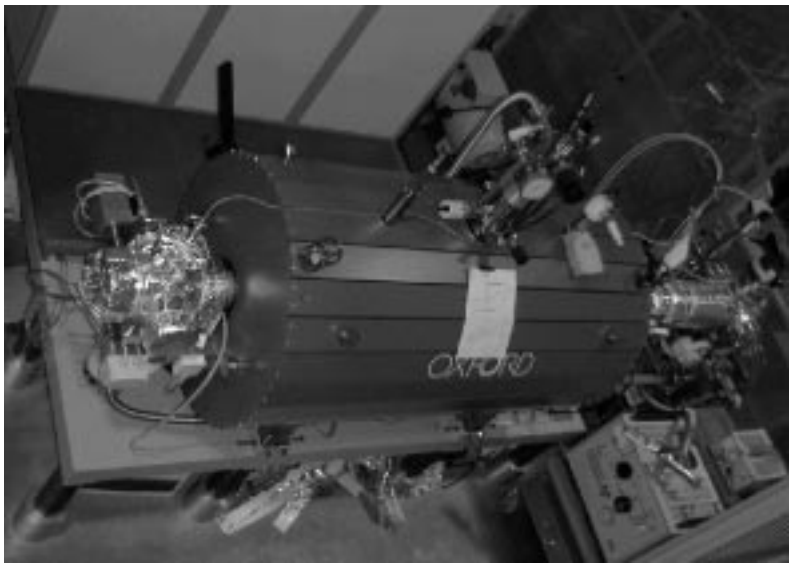

Figure 5. Photograph of the REXEBIS.

60 kV platform potential, and an emittance of about 10π mm mrad for ions extracted at 20 kV. The extracted pulse length is $<$100 μs, with a calculated energy spread of 15 eV/q (1 σ).

In contrast to the Penning trap a very good vacuum (better than 10^{-11} mbar) is aimed for inside the EBIS to reduce the contamination of the extracted charge state distribution by ionized residual gas atoms. This requires a multi-stage differential pumping between the Penning trap and the EBIS.

2.3. The separator behind the EBIS

The yield of Na, Mg, K and Ca-isotopes from ISOLDE can be up to 100 times lower than the amount of residual gas ions from C, N, O and Ar coming out of the EBIS. Due to the energy spread of the ions which are expelled from the EBIS ($\Delta E/E$ of $\approx 5 \cdot 10^{-3}$) a simple magnetic achromat with two 90° dipoles is insufficient, because the momentum spread $\Delta p/p$ results in a deterioration of the $\Delta(q/A)/(q/A)$ resolution. We will therefore employ a separator similar to a Nier-spectrometer [26]. From the known residual gas spectrum of the EBIS it is concluded that a mass separation with a q/A-resolution of about 1/150 is sufficient to select the highly charged rare radioactive ions from rest gas contaminants.

In addition, the separator beam line has to match the beam behind the mass slit into the acceptance of the RFQ. It should also have the ability to transfer a 60 keV q beam back to the ISOLDE main beam line in order to deliver high charge state ions to the solid state experiments. This transfer is done in front of the RFQ (figure 2). The achromatic separator consist of an electrostatic and a magnetic bender. The electrostatic bender compensates the energy dispersion of the magnetic bender. In order

to reduce the energy dispersion at the mass slit to zero, the second order aberrations have to be corrected by appropriate magnet pole curvatures. The third order aberrations are diminished by an electrostatic octupole, which is placed at the beginning of the system due to space restrictions [17]. The resolving power of this system depends on the emittance of the injected beam. In order to provide a resolving power of 150, which is sufficient to separate all isotopes from residual gas ions, the EBIS emittance has to be lower than 10π mm mrad at 20 kV extraction potential.

3. Accelerator components of REX-ISOLDE

For the first experiments it is planned to accelerate ions with a charge-to-mass ratio of 1/4.5 from 5 keV/u to a final energy between 0.8 and 2.2 MeV/u. The linear accelerator of REX-ISOLDE consists of different types of resonant structures to meet the requirements of the experiments. The RFQ and IH-structure take the ions to an intermediate energy of 1.2 MeV/u where they are postaccelerated or decelerated by the 7-gap resonators. Except of the 7-gap resonators the LINAC is similar to the GSI-HLI LINAC [27] and to the CERN LINAC 3 [28]. All structures operate at 101.28 MHz the half of the frequency of the CERN proton LINAC and with 10% duty cycle. The transverse design acceptance of the REX-ISOLDE LINAC is large in comparison to the EBIS emittance. This conservative design of the acceptance is based on typical extraction emittances from an ECR sources. The macrostructure of the accelerated ions will have a typical bunch width of 100 μs and a pulse distance of 20 ms. The microstructure will have a pulse width depending on the final energy between 1.9 ns at 2.2 MeV/u and 13 ns at 0.8 MeV/u (cw-beam). The time between the pulses will be 10 ns.

3.1. The 4-rod RFQ

In the first stage the ions are accelerated from 5 keV/u to 300 keV/u by a 4-rod RFQ. Efficient acceleration of low energy ion beams with this special type of RFQ has been well tested [29,30]. The rf quadrupole field provides transverse focusing for the low energy ions while an aperture modulation of the four rods performs smooth bunching of the injected dc-beam and acceleration. In the 4-rod-design the strong separation of rod sections in shaper, buncher and accelerator of the Los Alamos design was revoked [31] to achieve short structures. The REX-ISOLDE RFQ is a progressive development derived from the GSI HLI-RFQ [32] and from the RFQ of the Heidelberg high-current injector [33]. The RFQ tank is 3 m long and has a diameter of 0.32 m. The modulation of the four electrodes had to be optimized for a specific charge-to-mass ratio and for a specific input and output velocity. In order to gain efficient adiabatic bunching and optimum output emittances of the RFQ, we choose a rather low injection energy of 5 keV/u. The lay-out of the RFQ is conservative and we therefore expect that for the maximum voltages between the rods even charge-to-mass ratios larger than

$1/6.5$ can be accelerated. This will be important if heavier ions will be used in future experiments. The electrode voltage has been reduced to 42 kV in comparison to the first design in order to reduce the rf-power requirement.

For the design of the REX-RFQ the assumed normalized injection emittances have been $\varepsilon_{x,y} = 0.61\pi$ mm mrad. The final transverse emittances are $\varepsilon_{x,x'} = 0.68\pi$ mm mrad and $\varepsilon_{y,y'} = 0.67\pi$ mm mrad assuming 95% transmission. The resulting emittance growth is only 11%. In longitudinal direction the phase spread and the energy spread are $\Delta\varphi = \pm 14°$ and $\Delta W/W = \pm 1.5\%$. Thus, the longitudinal emittance of $\varepsilon_{\text{long}} = 1.89$ keV/u ns is very small. Regarding the particle dynamics, we introduce a so called "matching-out section" at the high-energy end of the REX-ISOLDE RFQ, which is an analogue to the matching-in section. In the matching-out section the focusing strength is reduced stepwise at the last cells of the accelerator. This leads to decreased beam slopes at the exit of the RFQ and thus reduces the required field gradients of the following matching section between RFQ- and IH-accelerator.

Low level frequency tuning and flatness measurements have been done. The measured flatness of the voltage distribution along the rods without the end cells is below 1%. The Rp value is 140 kΩm with a quality factor of 3900. First power tests have shown a rather short time for conditioning up to 80 kW and a very low reflection rate (-30 dB), which means a very good coupling of the transmission line to the RFQ. Figure 6 shows the power resonator ready for beam tests.

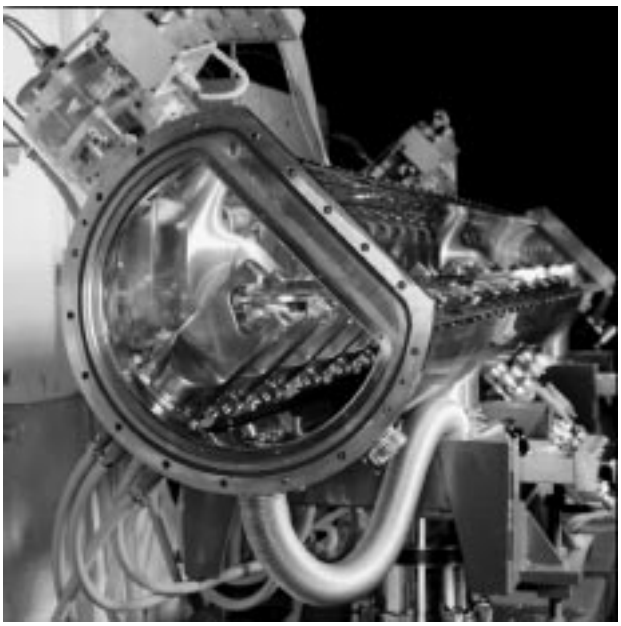

Figure 6. The REX-RFQ at the Munich test beam line.

3.2. The matching section

The very special beam dynamics concept of the IH-structure requires a rather small phase spread of the ion bunches and a converging beam in both transverse directions at the entrance of the IH-resonator. In order to match the beam from the RFQ into the acceptances of the IH-structure a section consisting of two magnetic quadrupole triplet lenses and a rebuncher is required. The first triplet lens focuses the beam through the rebuncher and produces a waist for diagnostics. The second triplet lens matches the beam to the transverse acceptance of the IH-structure. The aperture of the lenses is 3 cm and the maximum gradient is about 60 T/m. The rebuncher is a three gap split ring resonator with a peak voltage of 40 kV which has to match the phase spread of $\pm 15^\circ$ to the phase spread acceptance of $\pm 10^\circ$ of the IH-structure. Measurements at the power resonator resulted in a quality factor of 3500 and a shunt impedance of 4.5 MΩ/m. In order to reach the peak voltage 2 kW rf-power will be required.

3.3. The IH-structure

The Interdigital-H-type (IH)-structure is an efficient drift-tube structure with special beam dynamics (Combined Zero Degree Structure, KONUS) [34]. The IH-structure of REX-ISOLDE is a short version (1.5 m, 20 gaps) to similar structures like the GSI HLI-IH-structure [35] or "tank 1" of the lead LINAC at CERN [28]. After an initial accelerating section with a 0°-synchronous particle structure the ions drift through a magnetic quadrupole triplet lens for transverse focusing. Then the particles

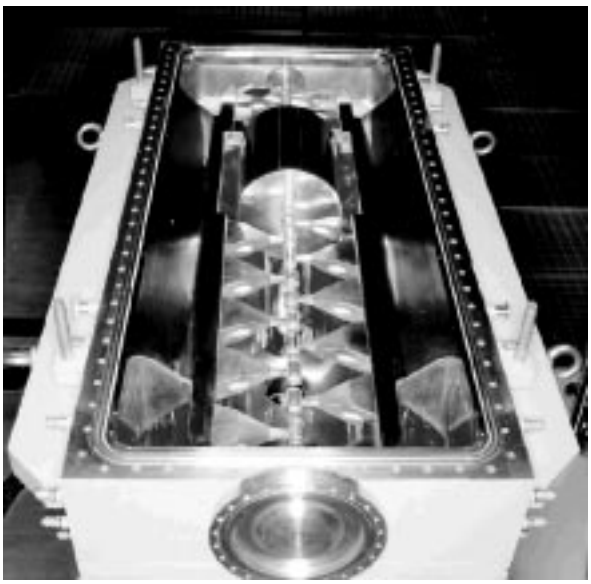

Figure 7. The REX-IH-structure prepared for low-level measurements.

are rebunched using a negative synchronous phase ($\Phi_s \approx -30°$) in the first three gaps behind the quadrupole triplet, followed by a second accelerating section with $\Phi_s \approx 0°$. The triplet lens has an aperture of 22 mm and a length of 299 mm. The required field gradients are about 55 T/m. Due to the small aperture the pole tips were made from normal soft iron. The maximum energy gain of about 0.9 MeV/u which is required corresponds to 4.05 MV effective resonator voltage or 5.04 MV absolute voltage. Assuming a shunt impedance of 250 MΩ/m, the total peak power consumption will be 70 kW. Figure 7 shows the power resonator with the drift tube structure and the inner tank triplet lens.

A new feature of the REX-ISOLDE-IH resonator is the possibility to vary the final energy between 1.1 and 1.2 MeV/u by adjusting the gap voltage distribution via two capacitive plungers and by adjusting the rf-power fed into the resonator. The lower final energy of the IH-structure is important for deceleration of the ions down to 0.8 MeV/u, since the deceleration from 1.2 MeV/u down to 0.8 MeV/u through the 7-gap resonators would perform a non-acceptable phase spread at the target which could not be reduced in a rebuncher without losses. This new concept has been examined thoroughly by bead perturbation measurements with a down scaled model (1:2) [36]. Figure 8 shows the principle of the variation of the gap voltage distribution. Moving the piston at the low energy side towards the drift tubes the capacity and the gap voltage are increased. Consequently, the gap voltages at the high energy side decrease relative to the voltages at the low energy side. Reduction of the rf-power will lead to the right gap voltage distribution for the final energy of 1.1 MeV/u.

A comparison between the reference gap voltage distribution given by particle dynamics calculations, the measured distribution at the model and the power resonator have shown significant discrepancies to calculations with MAFIA within 2%. Thus, for the power resonator slight changes of the undercut geometry and of the drift tube structure have to be done in order to increase the resonator frequency which was to low for operation in the 1.1 MeV/u mode.

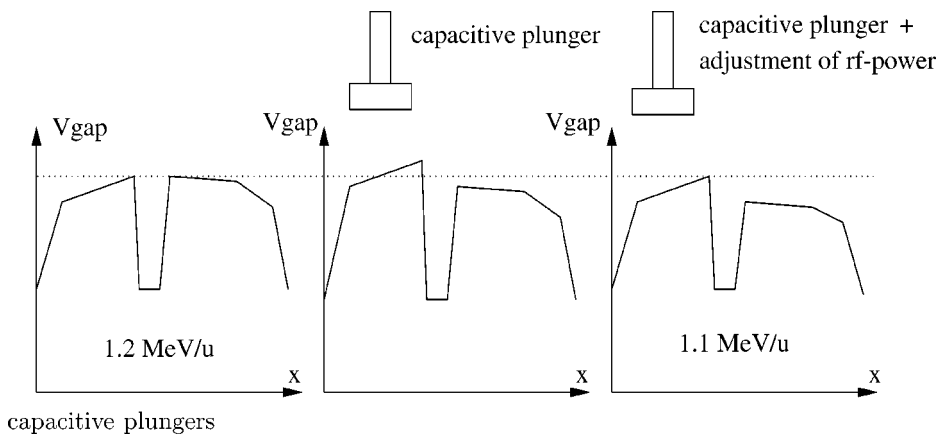

Figure 8. Principle of changing the final energy of the IH-structure by adjusting the capacitive plungers.

For beam dynamics calculations and drift tube design of the IH-structure normalized injection emittances of $\varepsilon_{x,x'} = 0.59\pi$ mm mrad, $\varepsilon_{y,y'} = 0.56\pi$ mm mrad and $\varepsilon_{\text{long}} = 2.31$ keV/u ns have been assumed. The accepted energy/phase spread are $\pm 10°/\pm 3.4\%$, respectively. The final emittances of the present design are $\varepsilon_{x,x'} = 0.59\pi$ mm mrad, $\varepsilon_{y,y'} = 0.63\pi$ mm mrad and $\varepsilon_{\text{long}} = 2.65$ keV/u ns. The final energy/phase spread is $\pm 7°/\pm 1.2\%$.

3.4. The 7-gap resonators

The high-energy section of the REX-ISOLDE LINAC consists of three 7-gap resonators similar to those built for the high-current injector at the MPI für Kernphysik in Heidelberg [37]. These special types of spiral resonators are designed and optimized for synchronous velocities of $\beta_s = 5.4$, 6.0 and 6.6% [38]. The 7-gap resonator is a compromise between maximum reachable accelerating voltage and maximum flexibility in the transit time factor. The resonator has a single resonance structure, which consists of a copper half shell and three arms attached to both sides of the shell. Each arm consists of two hollow profiles, surrounding the drift tubes and carrying the cooling water (see figure 9).

High power tests have been performed [39] in order to check the capability of achieving the design voltage of 1.74 MV at 90 kW rf power. These tests were carried out with a test beam. It appeared that the resonators exceed their design voltage at which the measured voltages are between 1.77 and 1.88 MV. This corresponds

Figure 9. Photograph of the REX-ISOLDE 7-gap resonators.

Table 1
Measured parameters of the power type resonators, f = frequency, Z = shunt impedance, U_0 = voltage. The shunt impedance and the resonator voltage are determined by beam tests.

Parameter	5.4%	6.0%	6.6%
f (MHz)	101.28	101.28	101.28
Q-value	5620 ± 110	5420 ± 110	5580 ± 110
Z (MΩ/m)	62.5 ± 4.0	59.7 ± 3.6	59.5 ± 3.5
U_0 (MV)	1.77 ± 0.05	1.81 ± 0.05	1.88 ± 0.05

with a shunt impedance between 59.5 and 62.5 MΩ/m. Table 1 shows the measured parameters of the three power type resonators.

The development of the resonators was accompanied by MAFIA calculations. It could be demonstrated that the frequency of 7-gap-resonators can be calculated with an accuracy of better than 1%. The calculated quality factor Q and shunt impedance Z come out consistently a factor of two too high. The power losses inside a 7-gap-resonator are also calculated in order to check the cooling water requirements. These investigations have shown that about 75% of the rf power is dissipated at the resonance structure, half of which is lost at the arms, which therefore have to be cooled very effectively. The output of the IH-structure is matched with a triplet lens to the first 7-gap resonator. Between the first and the second resonator there is an additional doublet for transverse focusing. Detailed beam dynamics calculations have been performed, showing normalized acceptances of 1.2π mm mrad for the (x, x')-plane and 3π mm mrad for the (y, y')-plane. The bunchlength of the fully accelerated beam (2.2 MeV/u) is 2.4 ns at the target, which can be further improved – if necessary – by a rebuncher before the target.

3.5. *The beam diagnostics*

The necessity for beam monitoring after every accelerating element of the REX-ISOLDE facility demands requirements specific for the beam observation system.

The beam diagnostics system has to: (1) monitor the beam intensity profile, (2) work in a wide range of beam intensities: from a few particles per second (pps) for the radioactive beams up to a few nA for stable pilot beams used for tuning and testing, (3) work in a wide range of beam energies from 60 keV to a few MeV/amu, (4) provide a timing signal to measure the time structure of the beam.

Considering various possibilities for beam diagnostics and the requirements listed above, a simple and universal configuration has been developed based on the detection, by a position sensitive MSP/MCP amplifier, of the accelerated secondary electrons (SE) produced by the beam impinging onto a foil.

The beam impinges at an angle of 45° onto an Al foil, introduced into the beam by a pneumatic feedthrough. The emitted SE are accelerated by a strong and uniform

electrical field (up to 10 kV/cm) applied between the foil and a transparent grid electrode. The grid and the MSP input electrode are grounded and the accelerated SE travel in a field free region till the MSP detector. When leaving the foil most of the SE have an energy of about 1 eV. Therefore, the acceleration by the strong electrical field that is perpendicular to the foil surface ensures a minimal spread of the SE in lateral direction during the passage towards the detector. After amplification by the MSP or MCP, the electron cascade strikes a phosphor screen. The flashes of fluorescent light are observed by a CMOS or CCD camera, which is coupled to a personal computer via a special interface allowing storage and analysis of the observed light intensity pattern.

The low-intensity beam monitoring system is incorporated with a set of collimators and a conventional Faraday cup for pilot beam measurements. Numerous tests of the beam diagnostics prototype were performed with various radioactive sources and beams with intensities ranging from 1 nA to a few hundreds particle per second and energies ranging from 50 keV to 3 MeV/amu. The measured spatial resolution of the system is better than 1 mm. The experiments with α- and β-radioactive beams showed that the system performs well for radioactive beams. A test with a pulsed beam show that the time resolution of the MSP signal is better than 1 ns. The system operates under manageable background conditions when placed closed to RF accelerating cavities. A detailed report on these tests will be published in [40].

3.5.1. The parallel plate avalanche counter

A parallel plate avalanche counter (PPAC) was developed serving as an efficient and spatially sensitive forward angle detector to monitor the radioactive beam behind the target [41]. The PPAC has a compact design with an active diameter of 4 cm and a low effective thickness of $\sim$1 mg/cm^2 to prevent the radioactive ions from being stopped and to avoid large angle scattering. This reduces background of other detectors in the target area originating, e.g., from electrons emitted after β-decay of the nuclei in the beam with typically high energy. The detector is operated with a small gas flow at typical pressures of 4–10 mbar of isobutane and with voltages of $\sim$600 V.

The spatial resolution in x and y direction of 1.6 mm is obtained using two thin mylar foils anodes on each of them evaporated aluminum strips of 1.6 mm width (the spatial resolution is given mainly by the width of the strips). In order to cover a large dynamical range of possible counting rates the read out of signals is carried out in two different operating modes: At rates less than $\sim 10^5$ s^{-1} per strip the signals can be read out from the ends of a delay line event by event, where as at rates of 10^4–10^9 s^{-1} the current measured on all anode strips are recorded. The dynamic range reaches down to α particles and should not be restricted for very heavy ions. Moreover with a rise time of signals of approximately 5 ns in the event by event read out mode the PPAC can be serve also as a fast trigger detector.

4. The experimental area

4.1. The MINIBALL

γ-ray spectroscopy after Coulomb excitation or transfer reactions will be one of the main techniques for the envisaged nuclear structure and astrophysics experiments at REX-ISOLDE. To utilize the elaborate and precious radioactive beams in the most effective way a new Ge detector array the MINIBALL – optimized to gain highest full-energy peak efficiency – is actually assembled. MINIBALL consists of a new generation of six-fold encapsulated segmented Ge-detectors. In a compact configuration without Anti-Compton shieldings the array is well suited for low to medium γ-ray multiplicity ($M_\gamma \sim 10$) events. In its final implementation the array will consist of 42 Ge-detectors. Subgroups of 3 and 4 detectors in one common cryostat will allow flexible geometrical arrangements to accommodate specific experimental requirements.

Based on the design of the individually encapsulated EUROBALL cluster detectors [43], the company EURISYS (Strasbourg, France) developed for the MINIBALL project sixfold azimuthally electrically segmented Ge-detectors. Although the bombarding energy of 2.2 MeV/u will be relatively small, the reaction products will have typical recoil velocities of 5% c. Due to the close distance between target and Ge-detectors and the large opening angle γ-spectroscopy would suffer from significant Doppler shift and -broadening of the deexcitation γ-rays. Therefore, the position resolution introduced by the segmentation is an essential requirement for the Ge-detectors. Prototype tests resulted in an energy resolution of 2.1 keV (central contact) and 2.45 keV (individual segments) at $E_\gamma = 1.33$ MeV, thus matching the performance of conventional detectors.

The assembly of MINIBALL will take place in two phases. The first phase will comprise 18 sixfold segmented Ge-detectors, housed in six cryostats. These detectors are scheduled to be available for experiments in early 2000. In a second phase the array will be augmented and completed with additional 24 detectors. These detectors may be even 12-fold segmented by introducing a longitudinal segmentation.

Improved position resolution for γ-ray detection will be gained from a radial position detection. Flash ADC measurements enable a detailed pulse shape analysis and a radial position resolution of the first γ-interaction of about 5 mm is achieved. In order to combine this feature with a modern concept of electronical signal processing, MINIBALL will be instrumented only with digital electronics based on flash ADCs and DSPs. Moreover, the digital electronics is preserving the energy resolution of conventional analogue high-resolution spectroscopy electronics at substantially higher count rates.

A new data acquisition and analysis system [44] has been developed on the basis of the GSI frontend system MBS [45] combined with the ROOT framework from CERN [46] for the backend visualization. The system has been successfully tested at the Garching accelerator laboratory. Thus, for the first experiments at REX-ISOLDE in early 2000, a powerful detector system equipped with modern electronics and read out by a high-performance data acquisition system will be available.

4.2. The target chamber

A target chamber with its associate equipment has been built especially according to the geometrical requirements of the MINIBALL setup as the result of compromises between the minimum volume necessary to house particle detectors and beam controls and the maximum volume that can be easily surrounded with Ge-detectors. A thin spherical Aluminum structure has been chosen to minimize γ-absorption and scattering. A removable top lid yields easy access to the interior of the chamber that houses a turnable wheel with target holders, a Faraday cup and a beam collimator. The chamber has been built and successfully vacuum tested as a contribution of the Strasbourg group.

4.2.1. The compact disk detector array

The purpose of a particle detector array inside MINIBALL is to facilitate the Doppler shift correction by measuring the source momentum. Therefore, the particle detector should fulfill the following requirements:

- Large solid angle to make maximum use of the weak beams.
- High granularity to provide sufficient angular resolution.
- Resistance to radiation damage.
- Performance under intense background from β-emitters.
- Easy access for target and detector replacement.

In addition, sufficient energy and timing resolution should be aimed at. A particle identification option might also be of interest.

The answer to all this demands is a double sided silicon strip detector array, which has been especially designed for the MINIBALL target region. It consists of a 160 discrete elements on four silicon wafers called sectors. In addition, a thin variant of this device is available that can be backed by a thick silicon detector to provide a ΔE–E telescope set-up. Prototypes of the silicon detectors have been produced and tested with an alpha-source. The energy resolution was 25 keV for ^{241}Am α-particles. The preamplifiers have been manufactured and tested as well as cabling and connectors.

Moreover, a test of the whole set-up including the front-end electronics has successfully been performed at the Cyclotron Research Centre at Louvain-la-Neuve, Belgium. A radioactive ion-beam of more than 10^6 ions per second has been used to test the system under “real life” conditions and all specifications have been verified in this way. The energy resolution was 0.7% and a timing resolution of 1 ns has been achieved.

5. Physics program

Among the wide field of physical perspectives opened up by the availability of radioactive beams provided by REX-ISOLDE, the physics program pursued will be centered around the following three key issues, each arising some intriguing questions.

- Nuclear structure
  - ∗ How are level schemes, B(Eλ)-values and quadrupole deformations changed in a region close to the drip line?
  - ∗ What is the most appropriate nuclear model far away from stability?
  - ∗ Do there exist new regions with extreme nuclear deformation?
  - ∗ Are there new collective modes to be found with stable octupole, oblate or triaxial nuclear shape?
  - ∗ Neutron halo nuclei: how many are there and do more forms exist?
- Nuclear astrophysics
  - ∗ The production of primordial matter during the early universe: how did the process proceed through the bottlenecks, e.g., through the ^{35}Ar(p, γ) reaction?
  - ∗ What is the magnitude of the astrophysical S-factor, and how can we contribute to the solar neutrino problem?
- Solid state physics
  - ∗ How will radioactive implantation, creating point defects and impurities, on a deep level in the semiconductor affect its properties?

In order to approach these questions, first-generation experiments at REX-ISOLDE have been proposed that will be briefly sketched in the following sections.

5.1. Nuclear structure

5.1.1. Studies of nuclei close to semimagic shells of $N = 20$ and 28

Quite different predictions of the nuclear shell model [12,48] are obtained, when going from the valley of stability to neutron rich nuclei, showing the uncertainty in predicting the nuclear forces, in particular their isospin dependence. For example, in [12] a change in the nuclear potential from a more box-shaped Woods–Saxon potential to a more parabolic harmonic potential is predicted, resulting in a lowering of the low-l single-particle energies and an increase in energy of the high-l-levels. These modifications finally lead to changes in the magic numbers and hence new predictions of the preferred regions of nuclear deformation. On the other hand, relativistic mean-field theories do not confirm these changes [48]. Furthermore, information on semi-magic nuclei is of particular importance for the determination of the monopole component of the nuclear interaction as their simple structure makes realistic calculations possible. Thus, it is interesting to study the level structure and the quadrupole deformation in a systematic way near neutron-shell closures for neutron-rich nuclei.

A second phenomenon makes the situation even more complicated. Due to the strong neutron-proton interaction a strong core polarization occurs near closed shells, resulting in low-lying intruder states [49]. These are strongly deformed 2p2h configurations which coexist besides the more spherical configurations and may even become the ground state.

A pioneer experiment using relativistic Coulomb excitation confirmed this neutron 2p2h intruder structure of the ground state in the case of ^{32}Mg, where a low-lying first excited 2^+-state (886 keV) with a large B(E2)-value of 426 ± 34 e^2 fm^4 has been measured, corresponding to a large deformation of $\beta_2 = 0.5$ [47]. Triggered by this finding a new region of well-deformed nuclei has been identified in a series of intermediate energy Coulomb excitation experiments at MSU [50,51] in the neutron-rich sulfur isotopes at and near the $N = 28$ shell closure. The importance of intruder configurations has been shown in a systematic study of the chain of neutron-rich Si-isotopes (^{32,34,36,38}Si) [52] as well as for neutron-rich Ne and Mg isotopes [53].

However, all of these experiments have been performed so far with the limited energy resolution of NaI scintillators.

Thus, a detailed nuclear level spectroscopy employing the Coulomb excitation and neutron-transfer process using MINIBALL as an efficient, high-resolution γ-detection setup to obtain more insight into the complex potential landscape of light neutron-rich nuclei and their single-particle structure will greatly enhance the experimental capabilities. In even–even nuclei, in addition to the excitation energy of the first 2^+-state and its collectivity, the position of the second 0^+ levels is of special interest to characterize the potential minima. The second 2^+ level will give information on the triaxiality, low-lying negative parity states on neutron skin vibrations and octupole shaped vibrations. In the odd nuclei, where so far only sparse information is available [54], identified Nilsson orbitals will test the extrapolation of the single-particle energies.

5.1.2. Studies of light neutron-rich nuclei

REX ISOLDE will also give interesting opportunities to investigate bound and unbound nuclei in the dripline regions. There is at present a large interest in investigations of the structural features of such nuclei. The reason for this is that light dripline nuclei have shown novel structural features that make them scientifically very attractive. One of the most striking discoveries was the observation that dripline nuclei could develop dilute, spatially very extended nuclear matter distributions referred to as nuclear halo states [55–57]. The prime example of a nucleus with a halo state as its ground state is ^{11}Li. Its halo belongs to the so-called Borromean halo states, where the three-body system (^{9}Li + n + n) is bound while the binary subsystems (^{10}Li and 2n) are unbound. The Borromean nuclei are of great current interest since they are situated at the threshold that separates the discrete and the continuous spectra. They are held together by forces that in neighboring nuclei give rise to scattering states, which leaves strong imprints on those states in form of final-state interactions. It is therefore important to get basic understanding of the continuum. In the following we list four different experiments, possible with the initial REX-ISOLDE energies, that will be of importance for a better understanding of the physics of halo states.

- A structural understanding of ^{11}Li leans strongly upon the structure of the low-energy states in ^{10}Li. Theoretical calculations, both within the shell-model and in three-body calculations suggest that an $1s_{1/2}$ state would form the ground state in ^{10}Li, an inversion of shell-model states similar to that in ^{11}Be. The present

status of the experimental investigations shows that the s state indeed forms the ground state but there is still a lack of information concerning the widths and energies of the low-lying states. (For references, see the above mentioned review papers and [58]. The beams which will become available at REX ISOLDE give rather unique opportunities to collect more precise spectroscopic data for ^{10}Li. The most favorable reaction to investigate the $1s_{1/2}$ state is offered by the d(^{9}Li,p)^{10}Li reaction while the ^{9}Be (^{9}Li,^{8}Be)^{10}Li reaction will emphasize the $0p_{1/2}$ state more. Both these reactions are characterized by very simple reaction mechanisms and measurements of protons and α particles in the one MeV energy range which will make the interpretation easy.

- The unbound nucleus ^{5}He has a $3/2^-$ ground state with the resonance energy 0.77 MeV. A broad $1/2^-$ state is present at about 4 MeV excitation energy [59]. In the ^{7}He case the $3/2^-$ ground state is known to be unbound with 0.44 MeV [59] and there are recent evidence for a state at about 3.3 MeV [60]. The latter state seems to be a $5/2^-$ state with a relatively complicated structure. The expected $1/2^-$ state is still not identified. There is a theoretical problem concerning the $\mathbf{l}\cdot\mathbf{s}$ force between the neutron and ^{6}He since this might be much larger than that between ^{4}He + n. The position of the $1/2^-$ resonance may help to resolve this problem and is also very important for a further understanding of ^{8}He, which has a structure that best can be described as a five-body, $\alpha + 4$n, system [61]. To shed light into this question a ^{6}He beam will be used to study the reaction ^{9}Be(^{6}He,^{8}Be)^{7}He. The data may give some input to the question of the clusterization in ^{7}He: is it best described as an $\alpha + 3$n system or as ^{6}He + n?
- A very successful method to study unbound nuclei is to perform resonance scattering reactions in inverse geometry. A recent example is provided by the unbound nucleus ^{11}N [62] which was observed in a ^{10}C+p reaction. This technique further offers the opportunity to learn about the quantum characteristics of the lowest excited states in ^{10}Li by investigating the isobaric analogue states in ^{10}Be. With ^{9}Li + p reactions one can distinguish the $T = 2$ states in ^{10}Be by measuring the resonance scattered protons. Their energy will lie in above 1 MeV and thus very easy to detect. The background of protons from $T = 1$ states is expected to be of the order 1%.
- The heaviest known one-neutron halo nucleus is ^{19}C. A systematic study of the momentum distributions of charged fragments after one-neutron breakup of ^{15,17,19}C has been performed at GSI [63]. An important ingredient in the interpretations of the data is the spin of the ground states of these nuclei. With the present REX energy one may get information about the spin of the ^{17}C ground state, which is not known. This is done by studying the reaction ^{16}C + p where the $T = 5/2$ states in ^{17}N will give the relevant information.

5.2. *Nuclear astrophysics*

Radioactive ion beam experiments offer a unique opportunity to extend the experimental study of astrophysical nucleosynthesis processes towards unstable, short-lived

nuclei. These are of extreme importance in explosive environments like type-II supernovae (the final collapse of massive stars), novae (explosive hydrogen burning on the surface of white dwarfs in a binary stellar system) and X-ray bursts (explosive hydrogen burning on neutron star surfaces). Type-II supernovae are the site of the r-process (rapid neutron capture and β^- decay), which produced about half of the heavy elements (beyond the Fe-group) in nature and proceeds 15–35 units away from stability on the neutron-rich side. Explosive hydrogen burning on white dwarfs and neutron stars leads to the rp-process (rapid proton capture and β^+ decay), which can produce elements as heavy as S and Ar in novae, and up to Kr and beyond in X-ray bursts. The understanding of these processes requires a detailed knowledge of the nuclear-structure parameters of the involved isotopes. Because of the substantially different nature of these processes, different experimental approaches with radioactive beams are necessary for the study of the respective nuclear input parameters.

The r-process proceeds on the neutron-rich side of the line of stability and is mainly determined by an equilibrium of neutron captures and (γ,n)-reactions. In that case, the most important features which enter are nuclear masses (or neutron separation energies), β-decay half-lives and β-delayed properties like neutron emission and eventually fission (see, e.g., [64]). The onset of the r-process depends on the competition of (α,n)-reactions and neutron captures. It is highly important to understand the change from α-induced reactions to neutron captures and exactly at which mass numbers this transition occurs. For that reason, an experimental investigation of the size of α-induced and neutron capture reactions of neutron-rich nuclei in this mass range would be desirable. Typical reactions of interest would be ^{82}Ge(α,n) and ^{80}Zn(d,p).

The rp-process is determined by a sequence of proton-capture reactions and β^+-decays on the proton-rich side of stability. The understanding of this process requires a detailed knowledge of (p,γ)-, (p,α)-, (α,p)-reactions and β^+-decays. It involves flow impedances due to cyclic reaction sequences and waiting point nuclei and undergoes a transition at high densities and temperatures from a process dominated by proton-induced reactions to a process driven by (α,p)-reactions [65,66]. It turns out that the reaction flow is determined almost entirely by only a finite number of key reactions. So for temperatures above $T = 0.3 \times 10^9$ K the rp-process flux proceeds through the bottleneck reaction ^{35}Ar(p,γ), which is a breakout point of the S–Cl–Ar-cycle. The investigation of this reaction as one of the key reactions governing the rp-process is proposed as one of the first astrophysics experiments at REX-ISOLDE [67].

5.3. Solid state physics

The on-line isotope separator ISOLDE already has a long impact on the progress of “radioactive” solid state physics. The combination of producing a great variety of isotopically and chemically clean radioactive ion beams of rather high intensities and the possibility to implant the isotopes on-line has attracted a continuously increasing number of materials research projects, particular in the field of semiconductor physics. The installation REX-ISOLDE with a post-accelerator for energetic ion beams will

continue this development by opening up a new generation of "radioactive" solid state physics experiments at ISOLDE, simply due to the advantage of deeper implantations.

A first round of experiments at REX-ISOLDE will concentrate on the investigation of "Hydrogen in Semiconductors" with energetic radioactive beams [68]. Although the experiments on this topic performed so far have been very successful, the availability of post-accelerated ion beams will allow to improve the experimental conditions in a unique way by:

- preventing surface problems and enabling experiments inside a diode structure,
- monitoring the H-depth profile,
- enabling the comparison of PAC with other techniques,
- increasing the sensitivity,
- improving tracer techniques.

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