Eur. Phys. J. A **13**, 247–253 (2002)

THE EUROPEAN
PHYSICAL JOURNAL A

Present and future experiments with stored exotic nuclei at relativistic energies

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Received: 1 May 2001

Abstract. Pioneering experiments with stored and cooled exotic nuclei at relativistic energies have been performed using the combination of the fragment separator FRS with the storage-cooler ring ESR. Exotic nuclei created in peripheral collisions are spatially separated in-flight and injected into the storage ring for high-precision mass and unique lifetime measurements. Lifetimes of stored bare and few-electron nuclei have been measured to study the influence of the electron density on the β decay. This condition, relevant for stellar plasma, can now be systematically investigated in the laboratory for the first time. Characteristic experiments of the present FRS-ESR system are presented and perspectives for a next-generation facility are briefly outlined.

PACS. 29.30.-h Spectrometers and spectroscopic techniques – 29.20.Dh Storage rings – 06.30.Dr Mass and density – 21.10.Tg Lifetimes

1 Introduction

Strong motivations for the investigation of exotic nuclei are to extend our knowledge of nuclear structure to unknown regions far from the valley of stability and to explore the limits of the existence and creation of matter in the laboratory and in the cosmos. The interest in studying exotic nuclei has motivated worldwide the commissioning of new secondary nuclear beam facilities. Special effort has been devoted to experiments using radioactive nuclei at energies above the Coulomb barrier. The study of rare nuclei is an important challenge and has revealed exciting new nuclear properties which are not present close to the valley of beta stability. However, beam quality, low intensity, and the available energy range of exotic nuclear beams are the main restrictions of existing facilities. Therefore, new proposals for large-scale next-generation facilities with more powerful driver accelerators providing several orders of magnitude higher projectile intensities and energies up to several hundreds MeV/u are launched in America, Asia, and Europe [1–3]. A recent NUPECC report addresses the physics thrusts and the key features of the future facilities [3].

An advantage of exotic nuclear beams at relativistic energies is that the reaction products are bare or few-electron systems. Indeed, the selection of the projectile energy can be used to prepare the fragments in desired ionic charge-state distributions. This situation allows experiments under conditions which prevail in stellar plasma and are therefore relevant for basic astrophysical studies [4,5].

The superior experimental conditions with relativistic secondary beams have been demonstrated at the fragment separator FRS [6] with the identification of about 150 new fragments among them the two doubly magic nuclei ^{78}Ni [7], ^{100}Sn [8]. New nuclear structure properties of halo nuclei [9,10] and deeply bound pionic states in heavy ions [11] have been discovered using the FRS as a high-resolution spectrometer.

In this contribution we will concentrate on mass and half-life measurements of relativistic projectile fragments performed with the unique combination of the FRS and the experimental storage ring ESR [12,13]. This article will be terminated by an outlook presenting the first plans for a next-generation European in-flight facility at GSI.

2 Mass measurements

Stable beams of relativistic heavy ions provided by the synchrotron SIS with a maximum magnetic rigidity (Bρ) of 18 Tm are converted into exotic nuclei in the production target at the entrance of the FRS. The FRS separates the fragments in-flight and injects them into the ESR for precise mass determination, performed by measuring the revolution frequency of the stored circulating ions. The ESR is equipped with an electron cooler [14] and can store ions in the range of $(0.5 \le B\rho \le 10)$Tm, corresponding to $(3 \le E \le 833)$ MeV/u for $m/q = 2$. The storage time of the nuclei (τ_{st}) is limited by atomic collisions with atoms of the residual gas (pressure $\le 10^{-10}$ mbar) and with the electrons of the cooler. τ_{st} can range from hours up to days depending on the velocity and the charge state of

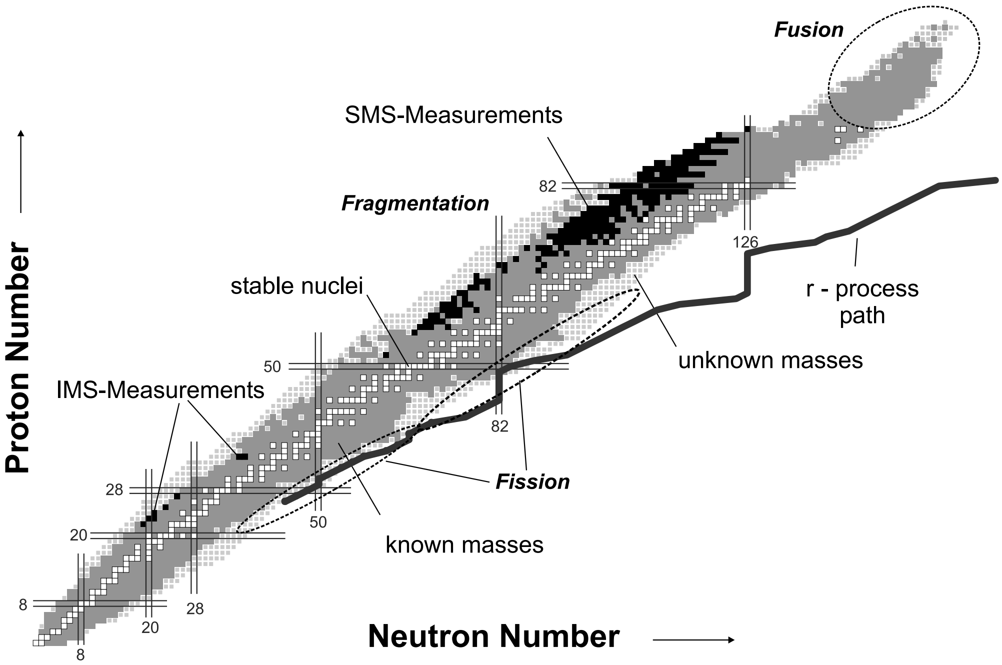

Fig. 1. New mass measurements covered in FRS-ESR experiments. In experiments with ^{209}Bi projectile fragmentation we extended the known mass surface for neutron-deficient nuclei from Pa down to Rh by applying Schottky Mass Spectrometry (SMS). Short-lived light fragments produced via fragmentation of ^{84}Kr projectiles were used in the IMS experiment.

the stored ions. The phase-space density of the stored ions can be drastically reduced by the electron cooling, *e.g.*, the relative velocity spread of a low-intensity cooled beam can be less than 10^{-6}.

Our mass measurements with stored fragments in the ESR cover a large area of proton-rich nuclei which includes also members of α-chains linked by precise Q_α values but not yet connected to the backbone of known masses. An overview of the new mass surface covered by our measurements with ^{209}Bi and ^{84}Kr projectiles is shown in fig. 1. The isotopes with masses known before our experiments as well as those where new mass measurements were performed are indicated in the chart of nuclides. The most efficient production processes for exotic nuclei in different regions of the chart of nuclides and the astrophysical r-process path are indicated. Fragmentation is the most universal tool up to uranium whereas for the heaviest elements fusion is the successful way to access new nuclei. Neutron-rich nuclei of medium mass can be efficiently created by fission, *e.g.*, projectile fission of ^{238}U.

Depending on the nuclear half-life, two methods are employed to perform precise mass measurements of stored ions circulating in the ESR: 1) Mass spectrometry using cooled ion beams (Schottky Mass Spectrometry (SMS)). 2) Mass spectrometry of hot fragments by operating the ESR in the isochronous mode without electron cooling (Isochronous Mass Spectrometry (IMS)).

2.1 Schottky mass measurements with cooled fragments

Schottky spectroscopy is widely used for beam diagnosis in circular accelerators and storage rings. The induced signals of the stored circulating ions in non-destructive probes are recorded and analyzed. Already in our pilot experiments with cooled projectile fragments [13,15,16] we have applied Schottky diagnostics and since then we have gradually developed this technique for the requirements of precision mass spectrometry [17–19]. Details of the experimental setup and analysis are presented in [20].

The stored and cooled ions circulate in the ESR with revolution frequencies of about 1.9 MHz. The data-acquisition system digitizes the Schottky signals with a sampling rate of 640 kHz. The data are sequentially recorded on tape, *i.e.*, the time information of the events can be advantageously employed in the data analysis. Fast Fourier transformation of the data can be performed off-line in order to obtain the revolution frequencies of the stored ions as well as the half-life information of the radioactive species. Furthermore, undesirable drifts of the experimental conditions can be corrected in the off-line analysis. In the recent SMS experiment we used ^{209}Bi projectiles and set the magnetic fields of the FRS and ESR and the cooler voltage corresponding to a constant $B\rho$ value of 6.5 Tm, *i.e.*, for the measurements of fragments with different isospins we only changed the incident energy of the primary beam. Such conditions have the advantage that the ion-optical performance of the ESR lattice is preserved during the complete experiment. The selected energy range allowed an optimum performance of the electron cooler and, in addition, presented the opportunity to measure the masses of bismuth fragments in bare, H-like, and He-like charge states.

The key parameter in Schottky mass spectrometry is the quality of cooling reflected by the magnitude of ve-

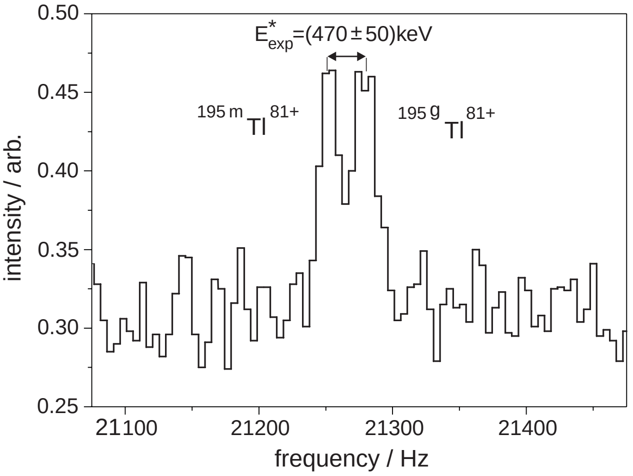

Fig. 2. Mass-resolved ground and isomeric states of ^{195}Tl^{81+}. The measured excitation energy is (470 ± 50) keV and the achieved mass resolution was 7.5×10^5. Remarkable is also the fact that each Tl peak represents only one single ion.

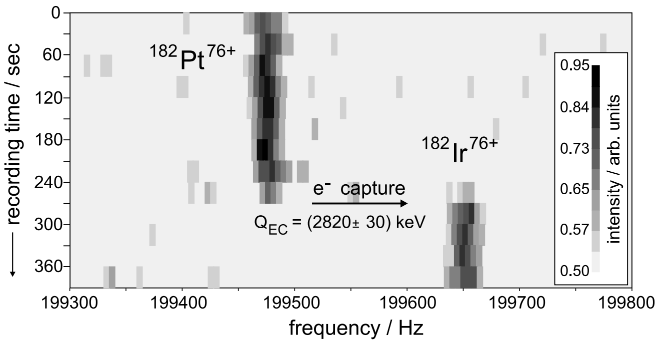

Fig. 3. One single ^{182}Pt^{76+} ion decays via electron capture to ^{182}Ir^{76+}. The measured mass difference for this case is (2820 ± 30) keV.

locity spread. The time for cooling of the hot projectile fragments was of the order of 10 s with an electron current of 50–400 mA. The cooling time is inversely proportional to the electron current. However, one has to compromise with respect to the storage lifetime due to atomic electron capture collisions.

An example of mass-resolved ground and isomeric states are presented in fig. 2 for ^{195}Tl^{81+}. The measured excitation energy of (470 ± 50) keV is in excellent agreement with the spectroscopy data from literature (482 ± 0.2) keV [21]. Note that the obtained mass resolution in these spectra reached $7{\times}10^5$. Remarkable is also the fact that each Tl peak represents only one ion.

The time information in the Schottky spectra gives also the unique possibility to follow the decay of a single stored ion as is illustrated in fig. 3. One ^{182}Pt^{76+} ion decays via electron capture to ^{182}Ir^{76+}. The measured mass difference for this case is (2820 ± 30) keV. This Q-value could be better determined in our measurement than it was previously known (2920 ± 140) keV [22].

2.2 Isochronous mass measurements with hot fragments

Exotic nuclei with half-lives shorter than the cooling time can be investigated by the time-of-flight techniques where the ESR is operated in the isochronous mode [23,24]. In this case, the magnetic fields of the ESR quadrupole and hexapole magnets are set such that the revolution frequency of an ion species becomes independent of its velocity, *i.e.*, cooling is not required anymore.

The Schottky analysis is replaced in IMS experiments by a time-of-flight detector placed in the straight section of the ESR opposite to the electron cooler section. The ToF detector measures the revolution time of the stored fragments for each turn by recording the emitted secondary electrons from a thin (17μg/cm^2) carbon foil coated by a CsI (10μg/cm^2) sandwich backing [25] to increase the electron yield. The energy loss and the angular straggling in this foil is very small and thus allows to trace the heavy ions over several hundred turns as demonstrated with fragments produced by fragmentation of ^{52}Cr and ^{84}Kr projectiles. A spectrum of revolution times of ^{84}Kr fragments is displayed in fig. 4. As in SMS, nuclides of known and unknown masses are included in the spectrum. However, the measured $\frac{m}{q}$ range in one revolution time spectrum is much larger (±7%) in one spectrum than in SMS. This condition makes the calibration more difficult due to the non-linearity of the revolution frequency as a function of the magnetic rigidity deviation [23].

The relative velocity spread of the stored ions was about 10^{-3}. Already in this pilot experiment we achieved a remarkable mass resolving power of $\frac{m}{\Delta m} = 1.1 \times 10^5$ (FWHM) and an accuracy of 70–90 keV for isotopes in the $A \approx 70$ mass region.

2.3 Results of the mass measurements

First results of our mass measurements have been presented in several publications, *e.g.*, refs. [20,26]. In the following, we show some representative comparisons between our data and theories to illustrate the present accuracy of different mass predictions for the isotones $N = 108$ and the isotopes of $Z = 82$ and $Z = 74$. The measured data are compared with the macroscopic-microscopic approach [27], with the extended Thomas-Fermi model with Strutinski integral [28], and with a microscopic mass formula [29] (see fig. 5).

The observed deviations in this comparison are much smaller than presently pure microscopic models can achieve, see ref. [26]. But, there are still basic improvements necessary, especially, near and at the shell closures ($Z = 82$, $N = 126$) and also for pairing energies. The latter feature is indicated by the residual odd-even staggering in the figures. The measured large mass surface of previously unknown territory will form a basis for refined models and improved nuclear structure knowledge.

In the future, direct mass measurements will be extended to shorter-lived nuclei using the isochronous

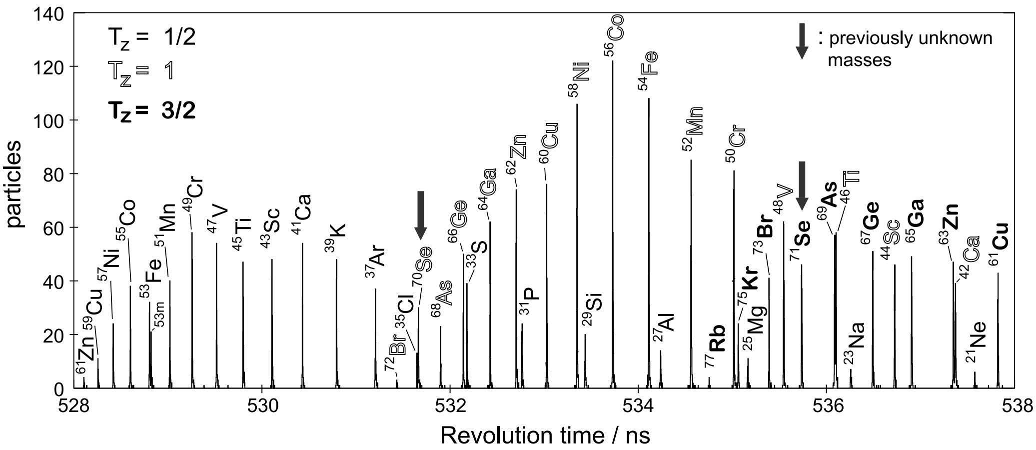

Fig. 4. Revolution-time spectrum from the ToF detector for hot short-lived ^{84}Kr fragments circulating in the isochronous magnetic lattice of the ESR. Nuclides with unknown masses are indicated by arrows and different fonts mark the different isospins (1/2, 1, 3/2) in the spectrum.

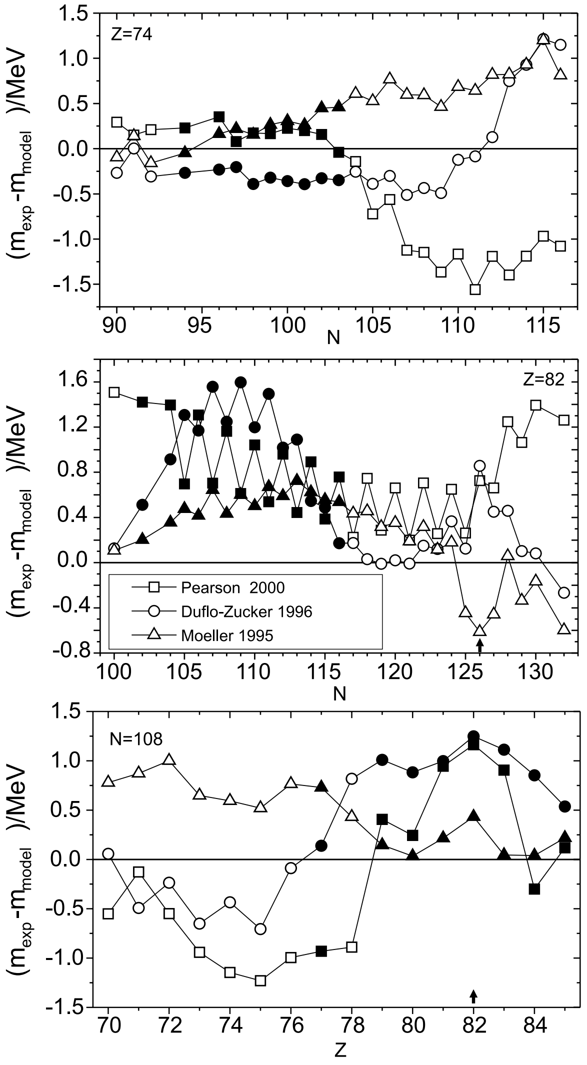

Fig. 5. Differences of the measured masses and some representative theoretical predictions [27–29] along the isotopes $Z = 74$, $Z = 82$ and isotones $N = 108$. The filled symbols represent the new masses measured in our FRS-ESR experiments.

method. However, there are also regions on the chart of nuclei where the Schottky mass spectrometry can still significantly contribute to an improved knowledge of the mass surface. A better mass resolution as well as the successful development of the stochastic cooling in the ESR [30], decreasing the cooling time for hot fragments, will considerably enhance the potential of Schottky mass spectrometry of cooled exotic nuclei. A resonant Schottky probe as it is successfully applied in the antiproton accumulator ring at CERN will also be a future experimental improvement towards shorter half-lives and higher sensitivity.

3 Lifetime measurements of stored relativistic ions

The constancy of the nuclear half-life was firmly established in experiments until Segré [31] and Daudel [32] pointed out in 1947 that the β decay and nuclear electron capture are dependent on the density of atomic electrons at the site of the nucleus. Summaries of the early studies in this field up to 1972 are given by Emery [33] and Crasemann [34]. A general conclusion is that in a complete description of the nuclear decay one has to consider the initial and final states of the nucleus *and* the atomic electrons.

Mass and half-life measurements both address fundamental properties of atomic nuclei. In the case of half-life measurements at relativistic energies, one has a unique possibility to study the nuclear decay as a function of the ionic charge state. Decay studies of bare and few-electron radioactive ions are of fundamental interest and are also relevant for the understanding of nuclear decay and reactions in stellar plasma. The possibility to access bare nuclei in the laboratory is experimentally also quite advantageous as demonstrated with our example with bare ^{195m}Tl nuclei where only the half-life prolongation due to the forbidden branch of internal conversion allowed to apply Schottky mass spectrometry. ^{195m}Tl as a neutral atom has a half-life of 3.6 s.

Spectroscopy at relativistic energies is a unique tool which allows for the first time systematic nuclear studies as a function of the atomic charge states. A programme of decay studies of bare and few-electron radioactive heavy ions has been started with the FRS-ESR facility [15,16].

Nuclei which are stable in the neutral state can become radioactive via β decay into bound states. This interesting decay mode was for the first time experimentally identified for bare $^{163}\mathrm{Dy}^{66+}$ nuclei stored in the ESR [4]. In a following experiment, the bound-state beta decay of $^{187}\mathrm{Re}^{75+}$ ions was studied [5]. This nucleus is of great importance as an astrophysical chronometer since the half-life of neutral $^{187}\mathrm{Re}^{0}$ atoms is 4×10^{10} years, a magnitude in the order of the lifetime of our Solar System. However, the reliability of such a clock is dependent on the corrections due to bound-state beta decay which is probable in the hot plasma of a star where the nuclei are then bare or highly ionized.

With two different detector systems, the Schottky pick-up and a particle detector in the vicinity of the closed orbit, the mean value determined for the β_b^- half-life was 32.9 ± 2 years for $^{187}\mathrm{Re}^{75+}$. This result has a large impact on the reliability of the $^{187}\mathrm{Re}/^{187}\mathrm{Os}$ chronometer to determine the age of the universe. The theoretical prediction for the β_b^- of $^{187}\mathrm{Re}^{75+}$ is 14 years [35] which demonstrates that the theory even for the simple case of the decay of bare nuclei has to be improved. A way to support experimentally the progress in this field is to investigate more candidates in different ionic states with a large β^- enhancement due to bound-state decay.

With this goal, we started to study systematically the β_b^- decay channel in thallium isotopes with the combination of the FRS and ESR. $^{207,206}\mathrm{Tl}$ nuclei were produced by the fragmentation of $^{208}\mathrm{Pb}$ [37] in the FRS and separated by applying the $B\rho$-ΔE-$B\rho$ method [6]. The experiment required a very high separation performance to ensure that bare thallium fragments were injected in the ESR but no hydrogen-like lead fragments of the same mass number. This difficult requirement was achieved by the good resolution of the FRS. The bound-state beta decay was directly observed for the first time since mass difference of about 1.6 MeV allowed to separate mother and daughter nuclei in Schottky frequency spectra resulting from the stored and cooled nuclei. This experiment will provide unique information: of total and partial β_b^- lifetimes, the Q-value, and on the Fermi function of the β^- decay for the first time. Note that in the past this latter information could only be obtained for β^+- and orbital electron capture decay.

4 Outlook —next-generation in-flight facility

Although the present experimental programme at the SIS-FRS-ESR facilities has been quite successful and led to several basic new discoveries the field of research can be drastically extended by a next-generation facility which consists of a more powerful driver accelerator, a large acceptance in-flight separator, and a new storage-cooler ring system specially adapted to the large phase space and short half-lives of the exotic nuclear beams.

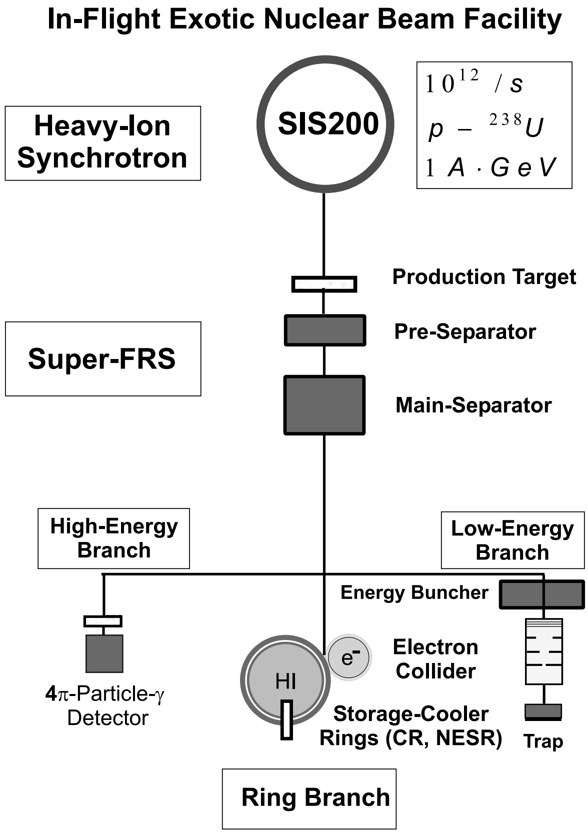

Fig. 6. Planned European in-flight exotic nuclear beam facility.

The planned design of the proposed facility at GSI is based on the proposal and the requirements of the NUPECC working group for the next-generation European in-flight facility [3]:

- Projectile fragmentation and projectile fission are the main production mechanisms. Fission of uranium projectiles, in particular, accesses the most neutron-rich isotopes. In order to provide secondary beams over the full range of the natural elements, primary beams of all stable isotopes up $^{238}\mathrm{U}$ have to be provided by the driver accelerator.
- Primary beam intensities should reach values of 2×10^{12} ions/s for all stable projectiles up to $^{238}\mathrm{U}$.
- Beam energies should extend into the regime of 1–1.5 GeV/u to yield fully ionized heavy projectiles and secondary beams for clean separation.
- The facility should have adequate instrumentation as: A large-acceptance fragment separator, an advanced setup for reaction studies, including a γ-array with tracking capabilities, a trap system, a heavy-ion storage- and cooler ring for precision experiments and reaction studies, including a small electron collider for structure research.

The proposed GSI facilities [38] will match all these requirements. The universal driver accelerator for all stable ions up to ^{238}U with a maximum energy of 1.5 GeV/u can be realized cost-effectively by synchrotrons provided the intensity limitation due to space-charge effects can be prevented by accelerating projectiles in low atomic charge states. Exactly this way is proposed by planning a 200 Tm synchrotron (SIS200)[38] (fig. 6).

The key instrument for rare-isotope physics will be a new multi-stage superconductive projectile-fragment separator, the Super-FRS, with large acceptance, particularly, for the efficient separation of fission fragments covering a large phase-space volume. The Super-FRS has a maximum magnetic rigidity of 20 Tm, a large momentum acceptance of ±2.5%, and angular acceptances of ±40 mrad and ±20 mrad in x- and y-direction, respectively. A new separator concept with two independent separator stages (pre- and main part, each equipped with shaped energy degraders) is necessary to cope with the high count rate and thus provides efficient background suppression. About 30–70% of the fission fragments produced at the production target will be available as spatially separated isotopic beams. This is a gain factor in pure transmission of more than 30 for the light uranium fission fragments, like ^{78}Ni. Together with the planned intensity increase for the primary beam the total gain factor will be more than 10^5 compared with the pioneer experiment of the discovery of ^{78}Ni.

The Super-FRS has three experimental branches (see fig. 6):

- A low-energy branch for decay studies and injection into traps,
- a high-energy branch for reaction studies
- a branch feeding exotic beams into a two-ring system for experiments with stored and cooled exotic nuclei.

The low-energy branch of the Super-FRS is equipped with an energy-bunching spectrometer and provides low-energy beams of in-flight separated exotic nuclei with a narrow energy distribution to allow for decay studies after implantation into silicon detector arrays and alternatively for efficient stopping in a gas cell. This branch will open up a broad and completely new field of experiments with short-lived isotopes ($T_{1/2} > 100$ ns). The whole spectrum of instrumentation and experimental techniques, which are in standard operation at modern ISOL facilities, such as Penning traps, magneto-optical traps (MOT), LASER spectroscopy etc., can be used favorably for short-lived species ($T_{1/2} > 1$ ms) and refractory elements.

The high-energy branch of the Super-FRS will include a reaction setup for structure studies in complete kinematics, measuring all outgoing particles and radiation. It will mainly consists of a powerful large dipole magnet (Big-ALADIN), a neutron detector(LAND), and a γ-array with tracking capability for in-beam spectroscopy.

In order to extend the pioneering experiments performed with the present combination of fragment separator FRS and the experimental storage ring ESR, an upgraded combination of a Collector Ring (CR) [39] and a New Experimental Storage Ring (NESR) are proposed. The ring combination will be optimized for short-lived projectile fragments, its main features are: 1) A large acceptance for exotic nuclear beams fully matched to the transmitted phase-space of the Super-FRS. 2) Fast cooling and stacking in the CR before the secondary beam is transferred to the NESR. The large momentum spread of the separated fragment beam of 5% requires a first momentum reduction by fast bunch rotation and subsequent adiabatic debunching [39] before the stochastic cooling of the CR can be applied. In the CR we will continue our scientific programme of IMS, *i.e.*, the ring lattice is also designed to be operated in the isochronous mode without any cooling. The stochastic cooling will be performed at 740 MeV/u thus a fast slowing-down stage in matter can be efficiently employed for very short-lived fragments to reach energies below 100 MeV/u for specific experiments in the NESR. The NESR will be equipped with an electron cooler and an internal target of high density up to 10^{14} atoms/cm^2 for reaction studies. Direct reactions with stored exotic nuclei in the internal target will be performed with the new facility which are not possible with the present low intensities available at the FRS-ESR.

A completely new experimental tool with unique possibilities for studies with exotic nuclei will be presented by the MINICOLLIDER [40], a low-energy electron–heavy-ion collider. Electrons of several hundred MeV interact with stored and cooled exotic nuclei.

Such a new facility will certainly improve the present knowledge of nuclear matter and will present also new features which are hitherto unexpected.

We gratefully acknowledge the work of our collaboration [20] and the help of M. Hausmann, Y. Litvinov, and T. Radon in preparing the figures for this article.

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