Letter of Intent

I. Study of Isomeric Beams, Lifetimes and Masses (ILIMA)

ILIMA Collaboration

April 2004

Abstract

Precision measurements of nuclear masses and lifetimes of stored exotic nuclei at relativistic energies and studies with isomeric beams are proposed. The planned experiments are triggered by the successful experimental program at the present FRS-ESR facilities. The new Super-FRS-CR-NESR facility will yield access to interesting nuclei near and at the driplines which can not be accessed with the present facilities.

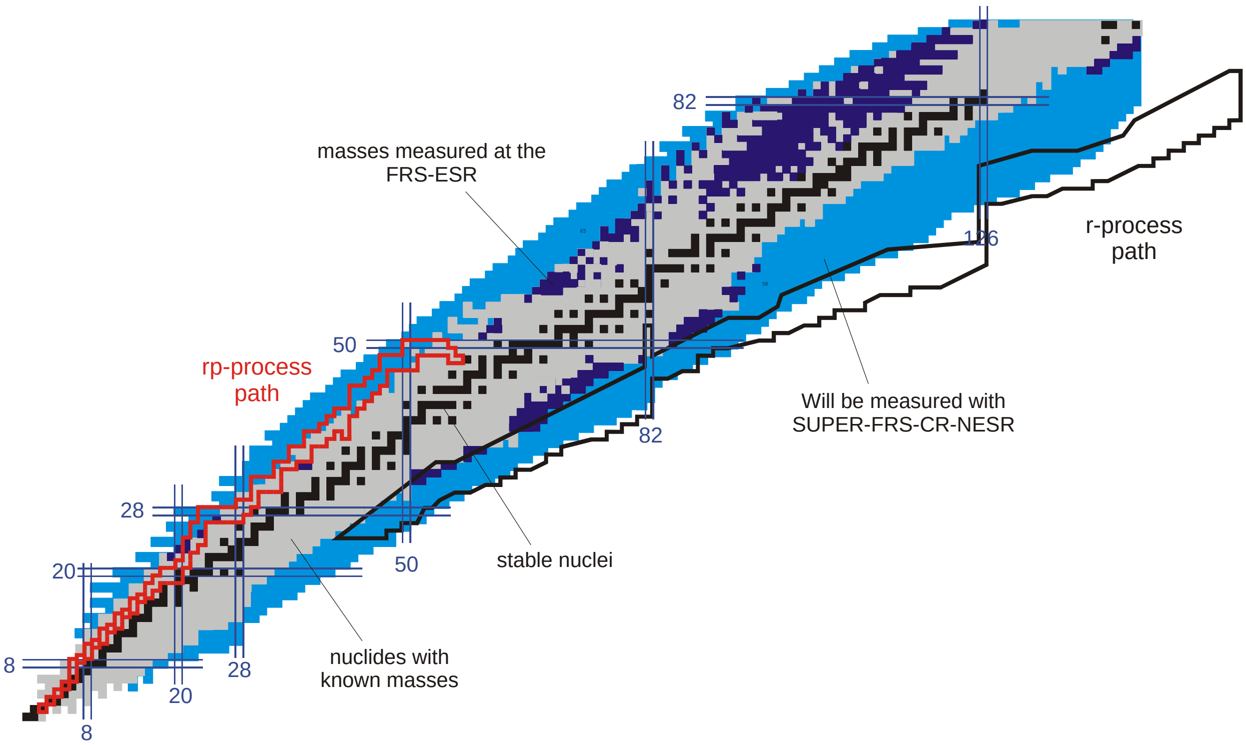

Figure 1. The chart of nuclides with known and unknown masses. The range of the mass measurements performed presently in the storage ring ESR at GSI is marked as a dark-blue area. Nuclides with still unknown masses which will become accessible with the new facilities, the SUPER-FRS, the double-storage ring system of CR and NESR, are indicated by the light-blue area. Astrophysical r- and rp-processes are indicated as well.

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1 Physics case

1.1 Research objectives

Nuclear masses and lifetimes of exotic nuclei in ground and isomeric states are basic quantities which are essential for the understanding of nuclear structure and the creation of the elements in stars.

Nuclear masses are of fundamental interest, because they reflect the complex interaction of the nucleons and the forces acting among them in the nuclear medium. From systematic precision measurements, i. e., the variation of neutron (proton) number along isotopic (isotonic) chains, important information can be derived, like location of driplines, the development of shell closures, the changes in shapes and pairing. Such investigations are indispensable for testing the predictive power of nuclear models and refining their theoretical foundations. Today the challenge is to measure the masses and lifetimes of exotic nuclei up to the limits of nuclear stability. New experimental developments involving storage rings yield access to measurements of bare and few-electron ions in the laboratory, thus under conditions that prevail in hot stellar environments.

A great research potential is that not only ground state properties can be studied but also those of isomeric states, which are populated in projectile fragmentation and fission reactions at relativistic energies. Isomers with long half-lives usually result from specific structural features, related to angular momentum quantum numbers or shape degrees of freedom. These features may themselves result from the breaking of several nucleon pairs. In a general sense, the study of multi-quasiparticle isomers gives an opportunity to quantify the characteristics of the pair field. The experimental possibilities will dramatically expand with the availability of isomeric beams that can be used for secondary nuclear reactions, which will open novel ways to explore the nuclear landscape. A great novelty is the possibility of neutron radioactivity from high energy isomers in very neutron-rich nuclei. Furthermore, so-far unknown, long-lived isomers close to the drip-lines can alter astrophysical pathways. Due to their range of half-lives, isomers also offer special access, through their decay, to otherwise inaccessible states. The ability to store isomers and separate them from their ground states, hence to measure their half-lives and excitation energies, and thereafter to measure their reaction modes and decay modes, has wide implications for future nuclear structure investigations.

The proposed investigations at the new facility will focus on:

- mapping of large areas of the unknown mass surface:
  - near and at the driplines, investigate pairing among loosely bound nucleons;
  - $N \approx Z$ nuclei, investigate the role of the neutron-proton pairing and to test a restoration of SU(4) symmetry in heavy nuclides;
  - in the region of shell closures, e.g. around doubly magic nuclides ^{48}Ni, ^{78}Ni, ^{100}Sn;
  - along specific chains of isotopes and isotones, explore predicted shell quenching away from stability;
  - at the pathways of nucleosynthesis in stars (r- and rp-process), in particular waiting points;
- lifetimes of highly-charged ions, their decay modes and branching ratios;
- mass-resolved isomeric states and related nuclear properties;
- the production of and investigations with pure isomeric beams.

1.2 Experimental concept

Mass measurements of exotic nuclei are a challenge because of the low production cross sections and the inherent large emittance and longitudinal momentum spread of the radioactive ion beam. A further difficulty arises from the fact that the most interesting nuclei near the drip lines are short-lived and thus limit the preparation and observation times.

Two methods have been developed at GSI for accurate mass measurements of stored exotic nuclei at relativistic energies: *'Schottky Mass Spectrometry (SMS)'* for cooled beams of longer-lived isotopes [1], and *'Isochronous Mass Spectrometry (IMS)'* for hot beams of short-lived fragments [2]. Both methods, well established in previous experiments, are based on precise measurements of the revolution frequency which unambiguously characterizes the mass-to-charge ratio of the circulating ions.

In the SMS the velocity spread of the relativistic hot fragment beams is reduced by electron cooling. For IMS the ring optics is tuned to an isochronous mode such that the different velocities are exactly compensated by different trajectories.

These two experimental methods are especially well-suited to measure effectively a large part of the mass surface in one run. In this way the systematic errors can be kept small if the reference masses for the calibration are reliable. The corresponding mass measurements in the Penning trap system of the Low-Energy Branch of the Super-FRS will yield complementary results and are predestinated to provide very accurate new reference masses. The Penning trap experiments will have the highest accuracy for the longer-lived nuclei and the isochronous method in the storage ring will yield access to very short-lived isotopes down to microsecond range.

The lifetimes of stored nuclei can be obtained with two independent methods. The first one is to measure directly the intensity changes of the stored ion beams. The second is based on the fact that daughter and mother nuclides differ by their mass-to-charge ratio. Then the resulting daughter nuclei can be recorded with particle detectors placed near the orbit of mother nuclides. Both methods yield redundant information by simultaneous measurement of the decay of mother and the population of daughter nuclides.

Nuclei in isomeric states were already observed throughout the campaign for mass and life-time measurements with the present FRS-ESR [3,4] facility due to superb resolution obtained with stored cooled beams. Using the $B\rho$-ΔE-$B\rho$ separation method, isotopic pure beams can be injected and stored in the rings. Depending on the half-life and excitation energy of isomeric states a pure isomeric beam can be prepared.

1.3 Competitiveness

The unique opportunity of the FAIR facility is the combination of the in-flight separator SUPER-FRS and a system of storage rings CR-RESR-NESR. The SUPER-FRS will be an ideal tool to provide short-lived nuclides of all elements for precise mass and half-life measurements in the new storage rings. Unique investigations of decay modes and half-lives of stored bare and highly charged nuclides are possible. Another unique feature of the new facility will be to give access to pure isomeric beams.

The present status of the knowledge of atomic masses [5] and the large area of hitherto unknown masses, which will become accessible with the new facility, is illustrated in Figure 1. The light blue area covers those nuclides where direct mass measurements will be possible with the FAIR facility. The lifetimes will be measured simultaneously with mass measurements. Most of these nuclides can only be investigated with the new facility.

2 Experimental techniques

2.1 Experimental setup

The combination of the Collector Ring (CR) and the New Experimental Storage Ring (NESR) is designed for fragment beams and will accept the full phase space of the secondary beams delivered by the SUPER-FRS. The efficient storage of fission fragments will give access in particular to exotic neutron-rich nuclei. The goals for the mass resolving power and accuracy are about 10^6 and 20–50 keV, respectively. We have already achieved these values for SMS in previous experiments, whereas for IMS still some improvements are required.

Experiments involving nuclei with very short half-lives, less than 0.5 s down to the μs range, will be performed in the CR operated in the isochronous mode. In addition to conventional diagnostic detectors, the experimental equipment in the CR will include time-of-flight detectors and very sensitive resonant Schottky probes, both enable precise revolution frequency measurements in a very short time. An independent measurement of the lifetimes will be performed by measuring the daughter nucleus in particle-identification detectors placed near the closed orbit of the stored beam.

An important feature of the new ring system is the short cooling time of about 1 s for all fragment species an ideal condition for SMS in the NESR. These cooling times will be a factor of 5 shorter than for the current ESR. The task of the CR is the efficient collection and fast precooling of secondary beams to a relative momentum spread of 10^{-4} and an emittance of $\varepsilon = 1\ \pi$ mm mrad before the exotic nuclei are transferred to the NESR. This high beam quality is achieved by bunch rotation and subsequent stochastic cooling within 500 ms, for a typical fragment beam characterized by an initial momentum spread of ±1.75%. The fact that the beam has been precooled in the CR will considerably reduce the time for electron cooling in the NESR. With this precooling it will be possible to reduce the emittance by electron cooling to $\varepsilon < 0.1\ \pi$ mm mrad with a relative momentum spread of $\Delta p/p < 10^{-4}$ for an intensity of 10^{8} fully stripped uranium ions within another 100 ms. These parameters are an upper limit and considerably lower values for the emittance and momentum spread will be achieved for lower intensities. The mass and half-life measurements will be performed using Schottky probes. The experimental setup is schematically illustrated in Figure 2.

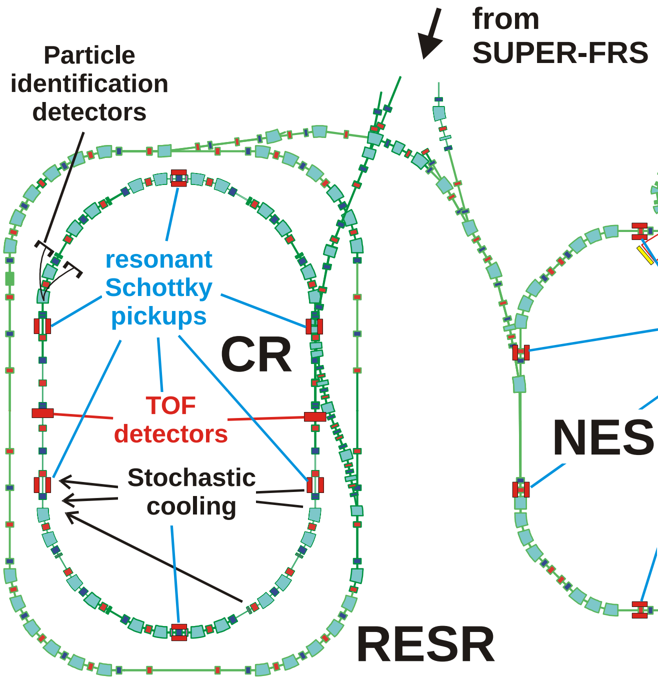

Figure 2. The storage ring facilities for direct mass and half-life measurements and studies with isomeric beams. Exotic nuclei separated with the Super-FRS will be injected into the Collector Ring CR. Mass and half-life measurements of very short-lived nuclides (down to few tens μs) will be performed in the CR operated in isochronous mode. Longer-lived nuclides (longer than 1 s) will be stochastically precooled in the CR and be transferred via RESR to the NESR. Here, they will be further cooled by electron cooling and Schottky Mass Spectrometry will be applied. Movable particle-identification detectors for the independent half-life measurements will be installed after one of the dipole magnets in the CR and NESR.

2.2 Mass and life-time measurements in the NESR

The measurements in the NESR will be performed with well-cooled beams ($\Delta v/v < 10^{-6}$). The cooling time limits the access to nuclei with lifetimes larger than 1 s. The revolution frequencies of all ion species stored simultaneously are obtained nondestructively by a Fourier transformation of the correlated signals which they induce in pick-up probes at each turn.

An example of SMS is illustrated in Figure 3 with a part of a typical Schottky frequency spectrum of cooled bismuth fragments at 370 MeV/u. Isotopes with previously known and unknown masses are marked in the spectrum by the blue and red labels, respectively. The high kinetic energy of the projectile fragments stored into the ESR allows to measure the masses in bare, H-like, and He-like charge states, a feature which yields redundancy in particle identification, calibration, and mass measurement. An illustration of the mass resolution achieved and of the ultimate sensitivity down to single ions is presented in the inset. The mass peaks of one ion each of the ground and isomeric states of ^{143}Sm ions are clearly resolved. A resolving power of 7.5×10^{5} was achieved and masses of more than 500 nuclides were measured with a typical accuracy of 30 keV in one experiment. The achieved ultimate sensitivity down to single stored ions will allow mass measurements of extremely exotic nuclides with very low production cross-sections.

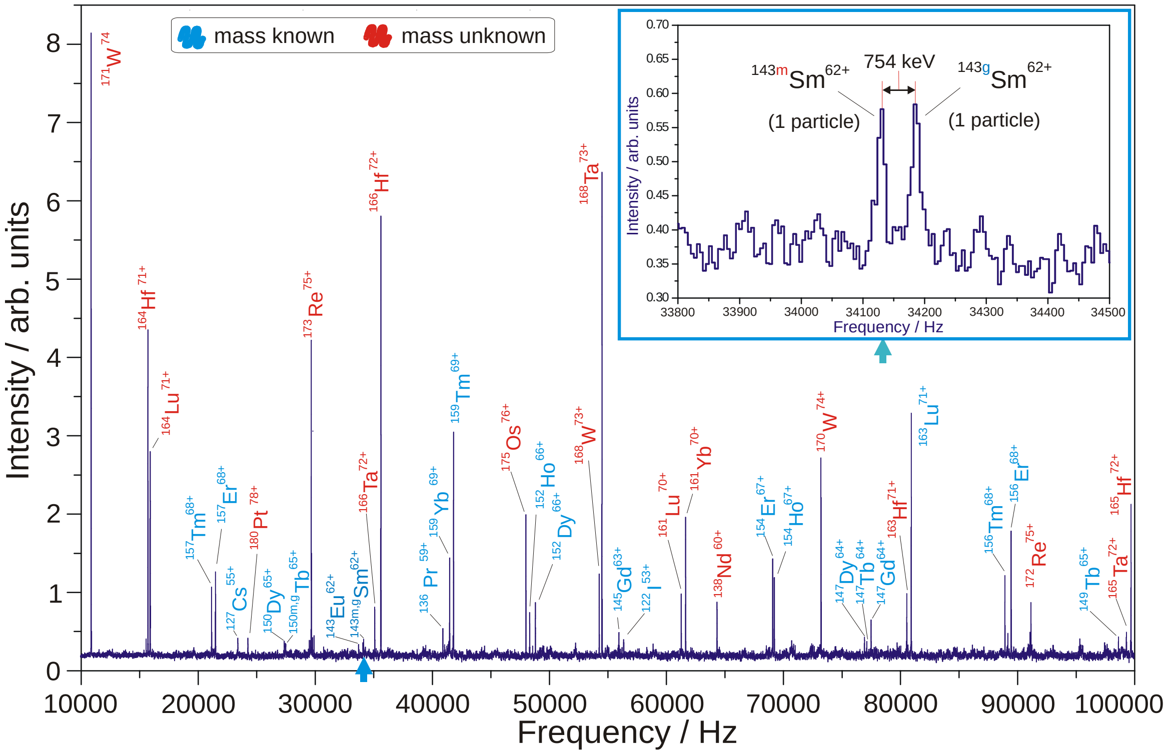

Figure 3. Typical frequency spectrum of cooled bismuth fragments from the FRS injected into the ESR at 370 MeV/u. The inset shows a frequency spectrum obtained from only two bare ^{143}Sm ions, one in the ground state, ^{143g}Sm, the other one in the isomeric state, ^{143m}Sm.

The area of the Schottky frequency peak is proportional to the number of stored particles and their charge squared. This allows a simultaneous determination of half-lives by measuring the change of the areas. The power of the method is demonstrated in Figure 4 where sequential Schottky spectra are plotted. In the left part of the figure each partial spectrum was recorded for one second. In the first two seconds stochastic precooling was used followed by electron cooling. The decaying of the isomeric state of ^{207}Tl^{81+} ions ($T_{1/2}$ = 1.5 s) and the growing intensity of the ^{207}Pb^{81+} ions, the daughter nuclides of the bound β-decay of ^{207}Tl^{81+}, can be clearly seen. In this experiment the branching ratio of the continuum β-decay and bound β-decay of fully ionized ^{207}Tl^{81+} atoms was measured for the first time. In the right panel of Figure 4 the decay of the ground state of ^{207}Tl^{81+} ions to the lead ions is shown over several minutes.

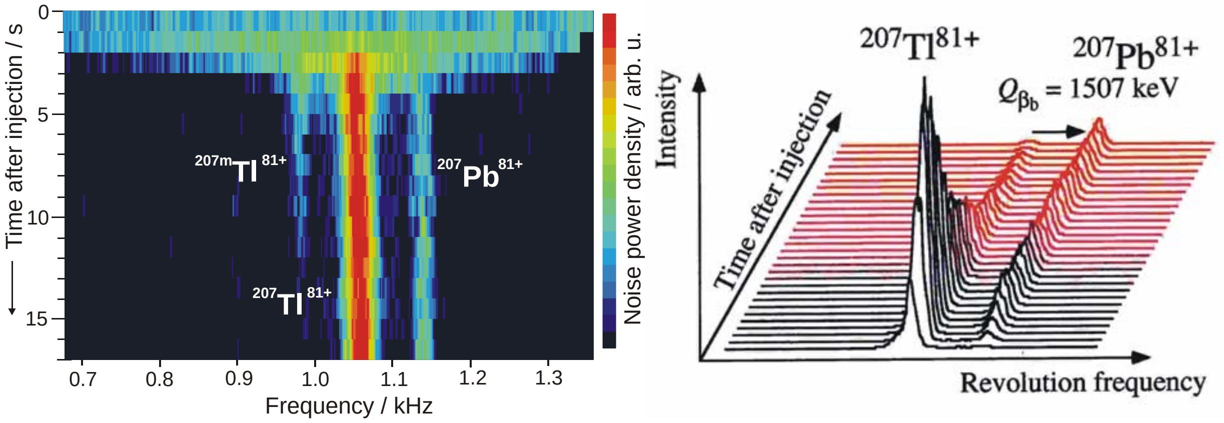

Figure 4: Sequential frequency spectra of stored ^{207}Tl^{81+} and ^{207}Pb^{81+} ions. In the left panel, the decay of an isomeric state of ^{207}Tl^{81+} ions and population of bound state beta daughter ^{207}Pb^{81+} are clearly seen. In the right panel, the decay of the ground state of ^{207}Tl^{81+} ions to the lead ions is shown over several minutes.

In order to increase the sensitivity and efficiency of this technique it is proposed to use several Schottky pick-ups in a correlated mode.

2.3 Mass and life-time measurements in the CR

Exotic nuclei with half-lives shorter than the cooling time are investigated by the IMS. A special mode of the CR is required, characterized by the property that the revolution frequency only depends on the mass over charge ratio of the isotope and is independent of the velocity of each individual ion. Thus, precise mass measurements can be performed without applying cooling. The revolution frequency is measured either by highly sensitive Schottky probes or by a time-of-flight (TOF) detector mounted in the storage ring aperture.

The prototype of the TOF detector is installed in the present ESR and has been successfully applied in recent mass measurements with uncooled short-lived krypton fragments and with uranium fission fragments. As in the SMS, nuclides of known and unknown masses are included in the revolution frequency spectra. A mass resolving power of 1.5×10^5 and an accuracy of 100 keV were obtained in first runs. Both characteristics can be improved with several position-sensitive TOF detectors and new pick-up probes.

In the isochronous mode, lifetimes from about 10 µs to about 1 ms can be measured with the time-of-flight detector and longer-lived nuclei with nondestructive pickup probes.

2.4 Production and study of pure isomeric beams

The combination of the SUPER-FRS with storage rings will provide access to pure isomeric beams. Already with the present FRS the Bρ-ΔE-Bρ separation method provides monoisotopic beams in the storage ring ESR as illustrated in Figure 5. In the left panel of this figure a Schottky spectrum is shown when the FRS is operated as a pure magnetic-rigidity analyzer. Applying the energy-loss separation with shaped degraders leads to a pure monoisotopic beam of ^{52}Mn circulating in the ESR (right panel).

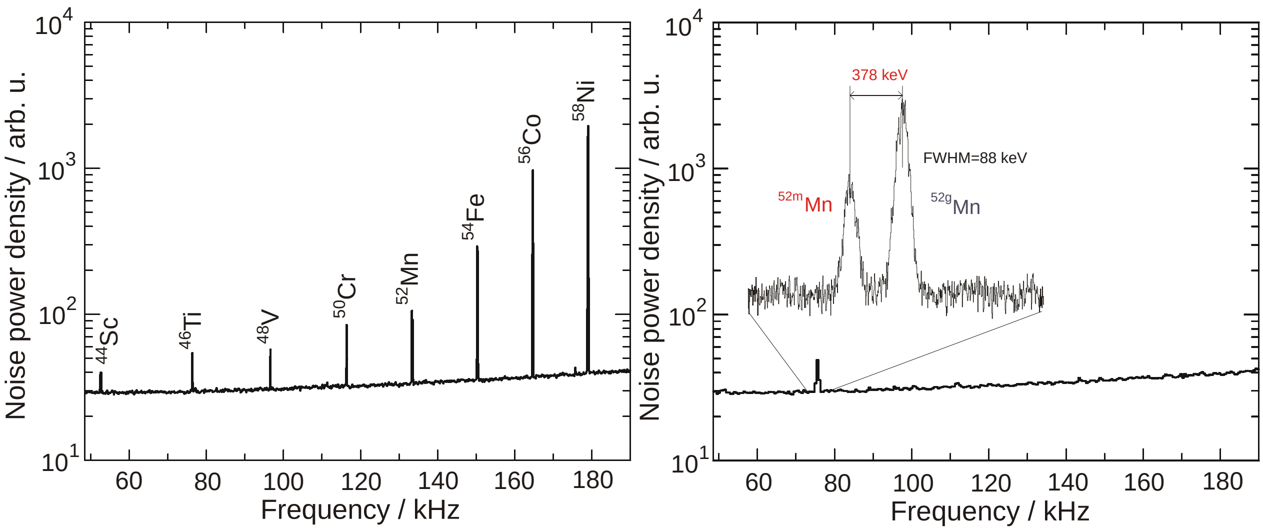

Figure 5: Schottky spectra of stored fragments in the ESR. Left panel, the FRS is used as a magnetic-rigidity analyzer resulting in an isotope-cocktail beam in the storage ring whereas the Bρ-ΔE-Bρ separation method provides monoisotopic beams as demonstrated for ^{52}Mn ions. The stored ^{52}Mn ions consists of nuclei in the ground and isomeric states which are resolved by SMS, see zoomed part in the right panel.

When a monoisotopic beam consisting of ions in the ground and isomeric states is stored and cooled in the ring, depending on the excitation energy it is possible to resolve the states as demonstrated by the mass-resolved ground and isomeric states of ^{52}Mn ions in Figure 5. In this case the excitation energy of the isomeric state is merely 378 keV.

Two ways are proposed to remove the ions in the ground state. First, one can use the mechanical scrapers installed inside the ring aperture to remove the ground state. This can be achieved either by moving the scrapers or by moving the beam. The latter can be done with a small change in velocity by the electron cooling force or by the use of selected RF excitation. This method is fast and the access to the pure isomeric beams can be achieved within a few seconds. Secondly, if the half-life of the isomeric state is significantly longer than the half-life of the corresponding ground state and, if it decays mainly via beta channel, then the purification is easy to achieve by storing the beam till the ground state decays completely.

2.5 Detector summary and data acquisition systems

The application of the three types of detectors for direct mass and lifetimes measurements in the NESR and CR rings is summarized in Table 1. For the studies with pure isomeric beams the detectors built for the in-ring reaction and scattering studies (see EXL LOI) will be used in addition to the equipment listed.

Table 1. Detectors needed for measurements of masses and lifetimes in the CR and NESR.

Detector	CR		NESR	
	masses	lifetimes	masses	lifetimes
time-of-flight	X	X		
Schottky pick-up	X	X	X	X
particle detector		X		X

The data acquisition systems for Schottky pick-ups in the CR and NESR can be designed based on the present experience. It must provide fast sampling of the raw data and store them online. It is important to record the measured frequencies without disturbing noise and background. Presently the sampling is achieved with 640 kHz 16bit ADC, which corresponds to 1.28 MB of raw data per second. About 100 GB of disk space is needed for one day of experiment per Schottky probe. This data acquisition and storage has been successfully applied in previous FRS-ESR experiments.

The data stream from the TOF detector is presently collected by a commercial digital oscilloscope (Tektronix TDS 7404) which has an analog bandwidth of 4 GHz, sampling rate of 20 GSamples/s (8 bit) and allows for a continuous measurement of up to about 2 ms. The data storage was done with a raid system. Future developments will certainly allow a higher data rate and more storage depth. It is obvious that all new detector developments can be performed and tested with the present FRS-ESR facilities.

3 Implementation

3.1 Organization and responsibilities

The ILIMA collaboration consists of scientists from 15 institutions of 8 countries. Main tasks for the implementation of the proposed program are listed in Table 2.

Table 2. Tasks and responsibilities.

Task	Group	Contact
Key experiments: - mass measurements - life-time measurements - isomeric beams	NPI St. Petersburg GSI JLU Giessen MSU JGU Mainz TU München Uni. Surrey CSNSM Orsay	Yu.N. Novikov Yu.A. Litvinov W. Plaß H. Schatz K.-L. Kratz T. Faestermann, P. Kienle P.M. Walker D. Lunney
Coupling of the Super-FRS with the CR and NESR	GSI	H. Weick, M. Winkler, A. Dolinski, P. Beller
Stochastic cooling in CR	GSI	F. Nolden
Electron cooling in NESR	GSI	M. Steck
Time-Of-Flight detectors	JLU Giessen	W. Plaß
Particle identification detectors	TU München	T. Faestermann
Resonant Schottky pick-ups	GSI JLU Giessen	C. Kozhuharov, Yu.A. Litvinov, F.Nolden W. Plaß
Software development	GSI	Yu.A. Litvinov

	NPI St. Petersburg SINS Warsaw Uni. Saitama Uni. Niigata	Yu.N. Novikov Z. Patyk T. Yamaguchi T. Ohtsubo
DAQ systems for Schottky pick-ups and data storage	GSI	C. Kozhuharov, Yu.A. Litvinov
DAQ systems for TOF detectors and data storage	JLU Giessen GSI	W. Plaß C. Kozhuharov, M. Matos
Theory: - Interpretation of data - New predictions - Improvement of theoretical models	GSI LANL SINS Warsaw NPI St. Petersburg TU Munich Uni. Thessaloniki	F. Bosch, S.Typel Th. Buervenich, D. Madland Z. Patyk Yu.N. Novikov P. Ring, D. Vretenar G.A. Lalazissis
Mass evaluation	CSNSM Orsay	G. Audi

3.2 Time schedule

The detectors will be designed and assembled before the building of the new storage rings. They will be tested in the existing ESR. The detectors are small in size and will be mounted inside the new rings during their construction on appropriate positions according to the ion-optical design and performance of the rings.

The measurements with short-lived nuclides will be possible with the IMS directly after the commissioning of the CR and the Super-FRS. With increasing projectile intensity, we will stepwise proceed towards the driplines. After commissioning of the RESR and NESR with primary beams we can start the full program.

Task/Milestone	Period	Cost estimate / k€
Adjustment of the ion-optical parameters of the CR for the isochronous mode	2004	
R&D of Schottky pick-ups in CR	2005-2006	500
R&D of Schottky pick-ups in NESR	2005-2006	300
Further development and construction of the time-of-flight detectors	2004-2006	200
R&D particle identification detectors	2004-2006	200
Technical Report	end of 2004	
Technical Design Report	end of 2005	
Software development	2004-2008	
Data acquisition systems for SMS	2004-2008	500

Total: 1700 k€

3.3 Beam time considerations

The proposed experiments will require the Super-FRS, CR, RESR and NESR facilities. For experiments on mass and half-life measurements in the CR, we can accept beam pulses each few hundred milliseconds. These experiments can partially be done in parallel with an independent program in the NESR.

Experiments in the NESR will require beam to be delivered every few seconds, every few minutes or even every few hours dependent on the task.

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