GSI-ESAC/RIB/NUSTAR/MATS

Letter of Intent
for

Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged ions

MATS Collaboration

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Abstract

We propose high-precision mass measurements and trap assisted spectroscopy of short-lived radionuclides using an advanced trapping system and highly-charged ions. Trapping devices are versatile tools for nuclear physics experiments with radioactive ions and are becoming more and more important at accelerator facilities. The proposed setup will allow mass measurements on radionuclides with a so far unrivaled accuracy. The mass is one of the most fundamental properties of a nuclide, being a unique "fingerprint", and its measurement contributes to a variety of fundamental studies including tests of the Standard Model and the weak interaction.

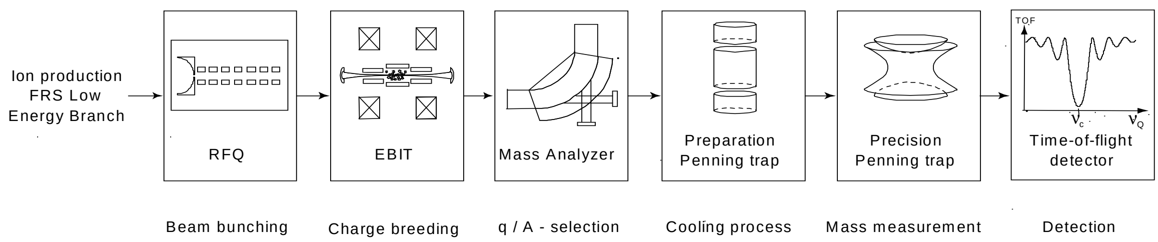

Figure 1: Schematic view of the components of the MATS setup.

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1. Physics case

1.1 Introductory note

In the Letters of Intent “SPARC” and “HITRAP” it is also proposed to study highly-charged ions for atomic-electron binding energies, QED tests and similar, however in a complementary way yielding levels of accuracy of the order of 10^{-10} and better.

1.2 Introduction and overview

Ion traps play an important role not only in high-precision experiments on stable particles but also on exotic nuclei. Besides accurate mass measurements they have recently been introduced to nuclear decay studies and laser spectroscopy as well as to tailoring the properties of radioactive ion beams [Klu03]. This broad usage of trapping devices at accelerator facilities is based on the manifold advantages of a three-dimensional ion confinement in well controlled fields: First, the extended observation time is only limited by the half-life of the radionuclide of interest. Second, the ion beam performance can be improved by, *e.g.*, ion accumulation and bunching, which allows an effective use of rare species. Third, stored ions can be cooled and manipulated in various ways, even polarization and charge breeding of the ions are possible.

It must be noted that these approaches are complementary to the ones pursued at the other branches of the Super-FRS, having specific advantages and unique capabilities rather than leading to a duplication of efforts. For instance, precision measurements in ion traps provide the most accurate mass values, which are needed as calibration points for the ILIMA program proposed for the storage ring branch. There, the program aims at mapping the mass surface and looking for nuclear structure effects, whereas here atomic masses can be measured with the highest possible precision, which opens up new fields such as probing the Standard Model to the highest levels of accuracy.

1.3 Research objectives

Mass measurements at the Low-Energy Branch of the Super-FRS offer the unique possibility to extend our knowledge of masses by several nuclides in the region around the doubly magic nuclei ^{78}Ni and ^{132}Sn. In these regions the knowledge on nuclides and their properties is very limited and many masses far away from stability are still unknown and will remain unknown in the next years. New phenomena as for instance shell quenching may arise, the closeness of the continuum and a reduction of spin-orbit splitting being two of several competing possible reasons [Dob96]. The yields available at the Super-FRS for neutron rich nuclei provide an excellent opportunity for high-precision mass measurements in these mass regions where many nuclides can be addressed for the first time. In addition, high-resolution and high-precision measurements are required in the case of low-lying isomeric states to make a clear identification, e.g. to resolve the discrepancies between theoretical predictions and experimental data for the ground and first isomeric state in ^{131}Sn [Fog99]. Recent shell model calculations [Bro02] showed, that the first isomeric state should be at about 50 keV, which is much less than the accepted value of about 250 keV and still lower than earlier predictions of less than 140keV [Gen99]. To resolve such states a resolving power of above 10^7 is required which can be easily reached while using highly-charged ions. The accurate masses will serve as reliable calibration points for mass measurements planned at the ring branch. At the present SIS-18 facility such measurements suffer from unaccurate or even wrong mass values, which were mostly obtained using decay-spectroscopy techniques.
Very precise mass values with uncertainties of the 10^{-8}-level or even better for specific unstable nuclides are important to test symmetry concepts in nuclear physics and to uncover

physics beyond the Standard Model (SM) of particle interaction. Examples are the isospin symmetry, which allows very precise mass predictions using the isobaric-multiplet mass equation IMME, the search for scalar currents that are not predicted in the SM by precision beta-neutrino correlation experiments, and a test of the conserved-vector-current hypothesis, a postulate of the SM. The mass accuracy needed in these cases is only achievable with direct mass measurements in Penning traps.

2. Experimental techniques

2.1 Experimental setup

We propose a novel combination of an electron beam ion trap (EBIT) and a Penning trap mass spectrometer at the Low-Energy Branch of the Super-FRS, which exploits the advantages of highly-charged ions for high-precision mass measurements. A schematic drawing of the proposed combination is shown in the figure below.

A major advantage of the EBIT consists in the possibility of spectroscopic measurements during the charge-breeding time. High-resolution spectrometers in the x-ray, VUV and visible region can collect data used to determine the fine and hyperfine structure of the ions [Bei98, Cre96, Cre98, Bei01] in the trap. These methods have been refined in the last decade and yield information not only on the atomic structure, but on isotopic shifts [Tup03] and nuclear size effects such as magnetization distribution as well. The Heidelberg charge-breeding EBIT will also be tested with the current EBIT laser spectroscopy setup at MPIK.

2.2 Mass measurements

The mass measurement of an ion confined in a Penning trap is carried out via a determination of the cyclotron frequency $\nu_c = qB/(2\pi m)$, where q and m are the charge and the mass of the ion and B is the magnetic-field magnitude. The mass of an ion is obtained from the comparison of its cyclotron frequency ν_c with that of a well-known reference mass (ideally ^{12}C since the unified atomic mass unit is by definition 1/12 of the mass of that nuclide). The advantage of using highly-charged ions becomes immediately obvious since the cyclotron frequency scales linearly with the charge of the ion. The resolving power achieved is approximately equal to the product of the cyclotron frequency and the excitation duration T_{ex} and the accuracy scales with the resolving power. The relative statistical mass uncertainty is then given by

$$\delta m/m \approx m \,/\, (T_{ex}\, q\, B\, N^{1/2}) \qquad (1) \qquad \text{(SI units)}$$

where N is the number of detected ions. In order to obtain a high accuracy, *i.e.* a low mass uncertainty, high cyclotron frequencies through strong magnetic fields or high charge states, and long observation times are desirable. For radioactive ions far from stability the observation time is limited by the half-life while the number of detected ions is depending on the production yield and the available beam time. Since highly-charged ions have higher cyclotron frequencies the resolving power and the accuracy are increased; or vice versa, a high-precision mass measurement can be performed in a much shorter time as compared to the case of singly-charged ions, which gives access to very short-lived nuclides. Figure 2 shows the advantage of using highly-charged ions with respect to the accuracy in the case of an ion with mass 100 in a 7 T strong magnetic field.

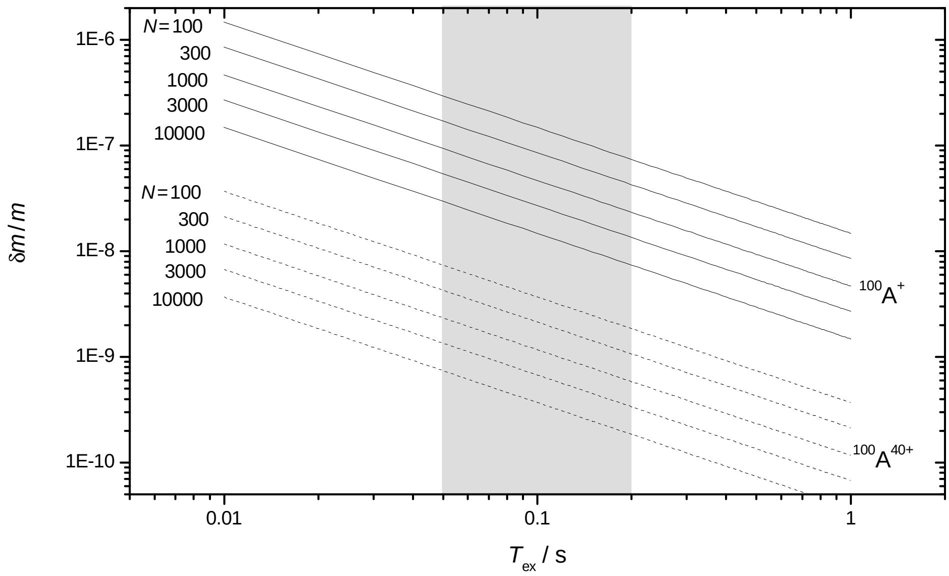

Figure 2: The achievable mass uncertainty (see Eq. 1) for a nuclide with mass A = 100 u as a function of the excitation time in the Penning trap (B = 7 T) for two sets of charge states and different numbers of detected ions. The upper set of curves belong to singly charged ions, the lower set of curves to ions in the charge state 40+. The grey shaded area corresponds to an excitation time T_{ex} of 50-200 ms.

For the Penning trap system a superconducting magnet of 6 to 9 T with field homogenity of 10^{-7}-10^{-8} in the two trapping regions is required. For the detection, i.e. the observation of the masses of the confined ions, either a Fourier Transformation Ion Cyclotron Resonance (FT-ICR) method [Sch92] or a Time-of-Flight (TOF) method [Grä80] can be used. Whereas the observation of the image currents is non-destructive, the TOF detection of the cyclotron resonance is destructive.

2.3 Charge breeding

At present the only electron beam ion source trap in operation for charge breeding of short-lived radionuclides is REX-ISOLDE/CERN for post-acceleration experiments.[1] With a 5 keV electron beam and a current of 0.5 A a current density of >200 A/cm^2 throughout a 0.8 m long trap region can be obtained in the charge breeder. With these parameters *e.g.* the REXEBIS trap at ISOLDE/CERN can hold ~6x10^9 charges for an electron-beam charge-compensation of 10%. The most dominant charge states for some typical ions, charge bred for 20 ms in an EBIT with the parameters given above, are listed in Tab. 1. Figure 3 shows the breeding time as a function of charge state for some selected elements.

Table 1: Peak charge-state after 20 ms breeding time.

Element	Charge-state		Element	Charge-state
$_{8}$O	7^+		$_{20}$Ca	12^+
$_{11}$Na	9^+		$_{36}$Kr	16^+
$_{12}$Mg	9^+		$_{37}$Rb	18^+
$_{18}$Ar	11^+		$_{51}$Sb	19^+
$_{19}$K	11^+		$_{54}$Xe	21^+

[1] Another facility is planned in the framework of the TITAN project at TRIUMF, which is also aiming for high-precision mass measurements, but on radionuclides produced at the TRIUMF ISOL facility.

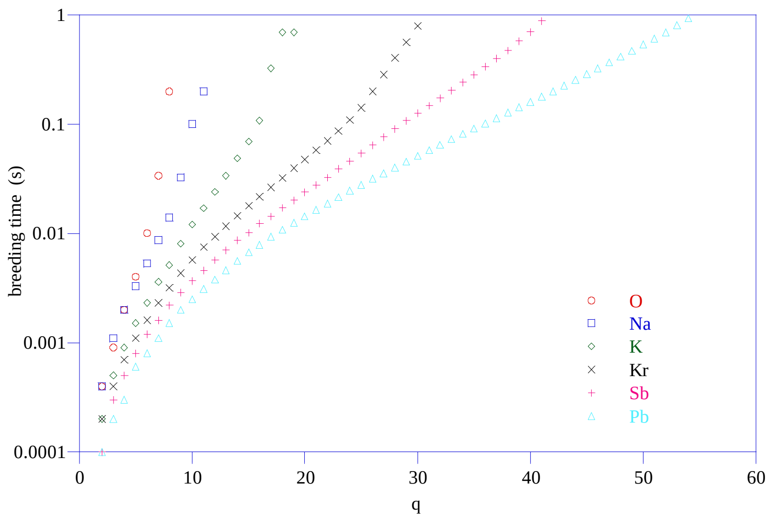

Figure 3: Breeding times as a function of the charge state for a current density of 200A/cm^2 (courtesy of F. Wenander).

Already with such an EBIT an enormous gain is achievable in short breeding times. However, for the proposed setup it is planned to use an EBIT like the device which is currently being built by the Heidelberg group, an apparatus which will be used at the TRIUMF ISOL facility. This machine will operate at 6T with a cryogen-free superconducting magnet. An electron beam current of 5A and the use of a non-immersed gun will result in much higher current density (of more than 10000 A/cm^2), beam energies of up to 60 keV, and much reduced charge-breeding times. This, in turn, allows the study of isotopes with still shorter lifetimes than the currently proposed techniques. Although the total trap length is reduced by a factor of two, the increased current yields a higher number of stored ions than the REXEBIS setup. Furthermore, the application of dielectronic recombination resonances for the purification of the main charge state of the trapped ions [Cres03] results in an increase of the effective yield and in a reduction of the background. For the Low-Energy Branch EBIT, a high-energy beam of 300 keV should also allow the production of hydrogenic ions of the heaviest available elements.

For the aforementioned reasons, we want to configure the charge-breeding EBIT at the Low-Energy Branch with the corresponding spectroscopic diagnostic tools, as they can deliver valuable information on the nuclear structure. A laser spectroscopy laboratory directly connected to the EBIT will indeed allow a wide range of new experiments inside of the trap, including nuclear polarization through optical pumping, laser cooling, etc. The necessary techniques are currently under development at the Heidelberg MPIK and should become mature for routine applications in the next two years.

2.4 Trap assisted spectroscopy

Finally, new approaches and an outlook for new developments in this field is given. Presently high-resolution electron spectroscopy is limited by the thickness of radioactive sources due to scattering in the source material. Thus it is intriguing to consider ions localized in a Penning trap as an ideal carrier-free source where energy loss or scattering do not influence the line shape. A cold ion ensemble can be quite precisely localized in the center (the corresponding cyclotron radius is typically of the order of 50µm) e.g. by side band cooling. We therefore propose to perform high-resolution spectroscopy of heavy elements in a Penning trap system

with high efficiency, concentrating on α- and electron spectroscopy. Exploiting the isobaric suppression capability of the first stage of the trap system (preparation trap) very pure sources can be obtained. The feasibility of in-trap conversion electron spectroscopy has already been successfully demonstrated at the REXTRAP Penning trap system at ISOLDE (CERN) [WEI02]. The conversion electrons emitted by the trapped ions within a confined cylindric volume are transported by the strong magnetic field of the trap through an ejection diaphragm to a detector placed behind the trap exit. In addition the 'shake-off' process of electrons can be investigated, since many electrons are emitted via this atomic process that occurs with high efficiency for outer electrons.
The physics goal of such measurements is to develop this new technique for the determination of lifetimes of 2^+ states in order to deduce the quadrupole moments of nuclei in a situation where presently no other experimental access exists, such as for superheavy elements. Knowledge on the deformation parameter β_2 or the quadrupole moment, respectively, are key ingredients for the theoretical description of heavy nuclei. From the α–spectra coincident with the electrons the shake-off process itself can be investigated for K, L, M and N shell electrons. Exploiting the coincidence condition betwen the α–particle and the carrier-free source a better understanding of shake-off processes can be achieved. Since the converted transitions are rotational states, the rotational energy and thus the spin can be inferred from the measured energy of the K and L lines. Therefore significantly more conclusive assignments during the construction of level schemes are achievable with such a technique especially in odd nuclei compared to the presently used α–spectroscopic methods.

In conclusion, the unique combination of an electron beam ion trap to produce highly-charged ions and a Penning trap mass spectrometer for high-precision measurements installed at the Low-Energy Branch of the Super-FRS will yield the most accurate results for masses of short-lived exotic nuclei and allows for a new field of in-trap experiments. Mass uncertainties below 10^{-8} can be obtained, which is at present at no existing trap facility possible. Furthermore, due to the extremely high yield of neutron-rich radionuclides, nuclei can be investigated which are much further away from the valley of stability than what is accessible at present at any other radioactive beam facility. Such a setup will open new ways of studying nuclear properties by x-ray and LASER spectroscopy of trapped ions and decays and transitions with high resolution.

References:

[Klu03] J. Kluge, K. Blaum, F. Herfurth, W. Quint, Physica Scripta T104 (2003) 167.
[Dob96] J. Dobaczewski *et al.*, Phys. Rev. C 53 (1996) 2809.
[Fog99] B. Fogelberg *et al.*, Phys. Rev. Lett. 82 (1999) 1823.
[Bro02] A. Brown, private communication (2002).
[Gen99] J. Genevey and J.A. Pinston, private communication (1999).
[Bei98] P. Beiersdorfer et al., Phys. Rev. Lett. **80** (1998) 3022-3025
[Cre96] J. R. Crespo López-Urrutia et al., Phys. Rev. Lett. **77** (1996) 826
[Cre98] J. R. Crespo López-Urrutia et al., Phys. Rev. **A 57** (1998) 879-887
[Bei01] P. Beiersdorfer et al., Phys. Rev. A **64** (2001) 032506
[Tup03] I. Tupitsyn, et al., Phys. Rev. A **68** (2003) 022511
[Cres03] J. R. Crespo López-Urrutia et al., Rev. Sci. Inst., accepted (2003)
[Sch92] L. Schweikhard *et al.*, Int. J. Mass Spectrom. Ion Proc. 120 (1992) 71.
[Grä80] G. Gräff *et al*., Z. Phys. A 297 (1980) 35.
[Wei02] L. Weissman et al., Nucl. Instr. Meth. (2002)

3. Implementation

3.1 Experimental area

Width: 3m Length: 8 m Height: 4 m

3.2 Radiation environment

No special requirements (experiments are performed with only a few ten ions per second)

3.3 Cost estimates

Superconducting magnet (without traps and electronics)	300 kEUR
EBIT	500 kEUR
RFQ cooler and buncher (without electronics)	200 kEUR
Electronics (for traps and buncher)	200 kEUR
Vacuum components (for highly-charged ions)	300 kEUR
Off-line ion source	60 kEUR
TOF-detector (with electronics)	20 kEUR
FT-ICR detector (with electronics)	50 kEUR
SUM	**1.630 kEUR**

3.4 Organisation and responsibilities

Mainz, Greifswald, Jyväskylä, Stockholm: Penning trap system
GSI, Munich: RFQ cooler and buncher
Heidelberg, GSI, Livermore, Seattle: EBIT
Giessen, Mainz, Orsay: Detection system and electronics
Mainz, Munich: Trap assisted spectroscopy

The conceptual layout of the setup and its components will be established as a combined effort with the LASER spectroscopy collaboration in order to efficiently use the available resources and to reach optimum performance and physics capabilities.

3.5 Time schedule

Overall preparation period: 4-5 years
The complete setup can be tested, operated, and optimized off-line with test ion sources.

3.6 Beam time considerations

The setup will be permanently installed at the Low-Energy Branch at GSI. Experimental campaigns of about 4 weeks per year (overall, split in periods of typically one week each) should be envisaged and will be ideally be combined with other experiments using reaccelerated beams and same or similar nuclides.