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LETTER OF INTENT TO THE INTC

HIGH-PRECISION MASS MEASUREMENTS OF HIGHLY-CHARGED EXOTIC IONS WITH THE MASS SPECTROMETER ISOLTRAP

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We propose to combine the existing REX-ISOLDE electron beam ion source (REX-EBIS) and the Penning trap mass spectrometer ISOLTRAP at ISOLDE in order to exploit the advantages of highly-charged ions for high-precision mass measurements. A schematic drawing of the proposed combination is shown in Fig. 1.

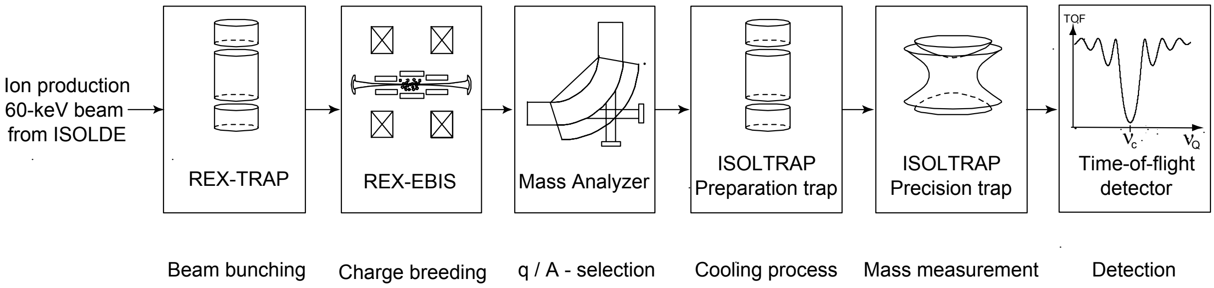

Figure 1: Schematic layout of the electron beam ion source (REX-EBIS) and the Penning trap system (ISOLTRAP).

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 efficient use of rare species. Third, stored ions can be cooled and manipulated in various ways; even charge breeding of the ions, as performed in REX-EBIS, and polarization are possible.

High-precision mass values and hence binding energies and *Q*-values of radioactive nuclides allow for important tests of symmetry concepts in nuclear physics and in the search of 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 conventional SM by precision beta-neutrino correlation experiments, and a test of the conserved-vector-current hypothesis, a postulate of the SM. In addition, masses of short-lived radionuclides are important for nuclear structure studies, for testing mass models far from stability and for reliable nucleosynthesis calculations in astrophysics. The relative mass accuracy needed in several of these cases is 10^{-8} or even below, only achievable with direct mass measurements in Penning traps.

For on-line mass measurements on short-lived radionuclides the ISOLTRAP Penning trap mass spectrometer installed at ISOLDE/CERN plays a prominent role. Atomic masses are determined with an uncertainty of 10^{-8} for nuclides that are produced with yields as low as a few 100 ions/s and at half-lives well below 100 ms. The scientific highlights include the mass measurements of ^{32}Ar ($T_{1/2}$ = 98 ms) and ^{74}Rb ($T_{1/2}$ = 65 ms). Both results provide important input for fundamental tests of the weak interaction, like test of the conserved vector current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Further details can be found in the INTC status report of the experiment IS413.

At ISOLTRAP the mass measurement is carried out via the 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 known reference mass (ideally ^{12}C since the unified atomic mass unit is by definition 1/12 of the mass of that nuclide). For beam purification and subsequent mass measurements ISOLTRAP uses two Penning traps places in superconducting magnets of 4.7 and 5.9 T field strength with a field inhomogeneity of 10^{-7}-10^{-8} in the precision trap [Bla03]. For the determination of the cyclotron frequency, *i.e.* the actual mass determination of the confined ions, a Time-of-Flight (TOF) method [Grä80] is in use.

The advantage of using highly charged ions is due to the higher cyclotron frequency that 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 precision scales with the resolving power. In particular, the relative statistical mass uncertainty is given by

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

where N is the number of detected ions. In order to obtain a high accuracy, *i.e.* a low mass uncertainty, high cyclotron frequencies due to strong magnetic fields or high charge states, and long interaction times are desirable. For radioactive ions far from stability the interaction 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, *e.g.* to the radionuclide ^{11}Li with $T_{1/2}$ = 9 ms. Figure 2 shows the advantage of using highly-charged ions with respect to accuracy in the case of ^{74}Rb with charged state 18+ in a 5.9 T magnetic field.

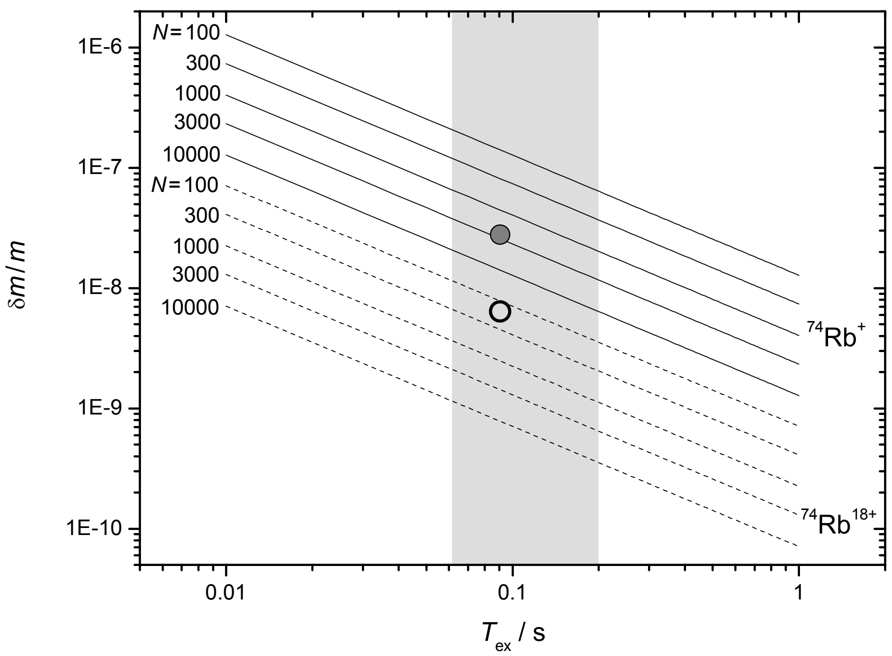

Figure 2: Mass uncertainty (see Eq. 1) for ^{74}Rb with a half-life of only $T_{1/2}$ = 65 ms as a function of the excitation time in the Penning trap (B = 5.9 T) for two sets of charge states and different numbers of detected ions. The upper set of curves belongs to singly charged ions, the lower set of curves to ions in the charge state 18+ which can be produced with the REX-EBIS within 20 ms. The grey-shaded area corresponds to an excitation time of about one to three times the half-life (T_{ex} = 60-200 ms). The grey dot gives the present accuracy limit obtained within ~7 radioactive beam shifts with ISOLTRAP in 2003 [Kel04]. The open circle indicates the accuracy limit of ISOLTRAP ($\delta m/m = 8\text{x}10^{-9}$) [Kel03], which can be reached exploiting highly-charged ions within one to two shifts for $^{74}Rb^+$.

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 0.5A 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 the REX-EBIS trap at ISOLDE/CERN can hold ~6x10^9 charges for an electron-beam charge-compensation of 10% [Wen01]. 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
$_{8}$O	7^+
$_{11}$Na	9^+
$_{12}$Mg	9^+
$_{18}$Ar	11^+
$_{19}$K	11^+
$_{20}$Ca	12^+
$_{36}$Kr	16^+
$_{37}$Rb	18^+
$_{51}$Sb	19^+
$_{54}$Xe	21^+

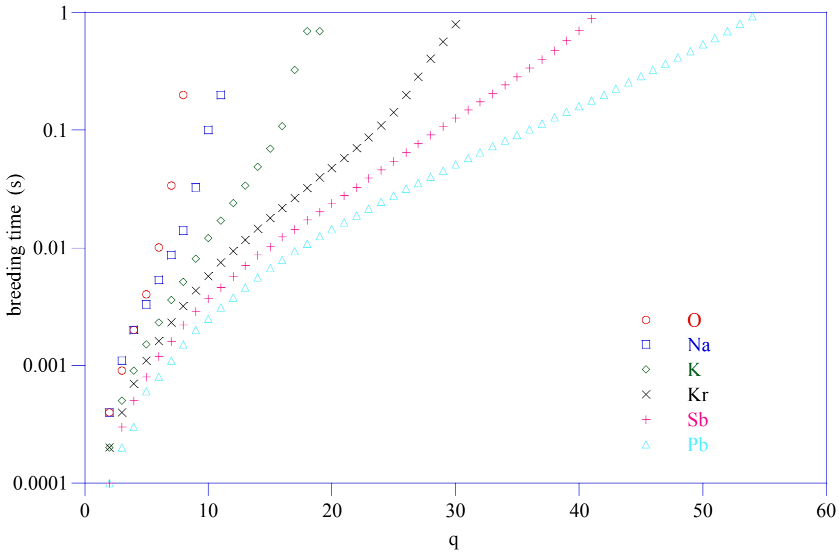

Figure 3: Breeding times as a function of the charge state for a current density of 200A/cm^2 (courtesy of F. Wenander [Wen01]).

As for the requirements with respect to ISOLTRAP, for a short storage time of only a few hundred milliseconds a vacuum of $p \leq 10^{-9}$ mbar should be sufficient, which is slightly better than our present vacuum conditions at the precision trap. We plan to improve the vacuum by adding getter pumps to the current ISOLTRAP system. Of course helium buffer gas cooling – at present in use at ISOLTRAP in the radiofrequency cooler and buncher and in the preparation Penning trap – can not be used in the case of highly-charged ions due to charge-exchange losses. Therefore, in a first step we plan to shoot through the buncher and to use

[1] Another facility is planned in the framework of the TITAN project at TRIUMF, which is also aiming for high-precision mass measurements on ISOL type produced radionuclides. First TITAN tests are scheduled for 2007.

evaporative cooling in the preparation trap, *i.e.* throwing away the hottest ions and reducing the overall efficiency by about two orders of magnitude. However, for high-precision mass measurements the number of ions stored in the precision Penning trap at a given time is reduced to one in order to avoid frequency shifts due to ion-ion interactions. In a second step the presently achieved efficiency can be re-established by adding electron and resistive cooling as planned in the HITRAP project at GSI for stable or long-lived isotopes [HIT03]. Also sympathetic cooling with laser-cooled ions might be an efficient way to prepare the ions.

While the preparation trap is currently also used for purification of the ion ensemble as delivered by ISOLDE, note that in the proposed scheme there is an additional q/A selection step for the ion beam on its way from REX-EBIS to ISOLTRAP. The charge breeding at REX-EBIS provides further parameters for the reduction of contaminants. In addition, the selection of appropriate charge states of the ions of interest and the ions for the magnetic-field calibration will lead to closer mass doublets and thus to a further increase of accuracy.

A possible beam-line scheme for the transfer of highly-charged ions from the REX-EBIS to the ISOLTRAP experiment is shown in Fig. 4. In this scheme, developed by H. Haas [Haa04], the highly-charged ions can be transported to either the present high-voltage cage for other experiments or to ISOLTRAP, as discussed in this letter. Thus, the proposed beam line would serve several users.

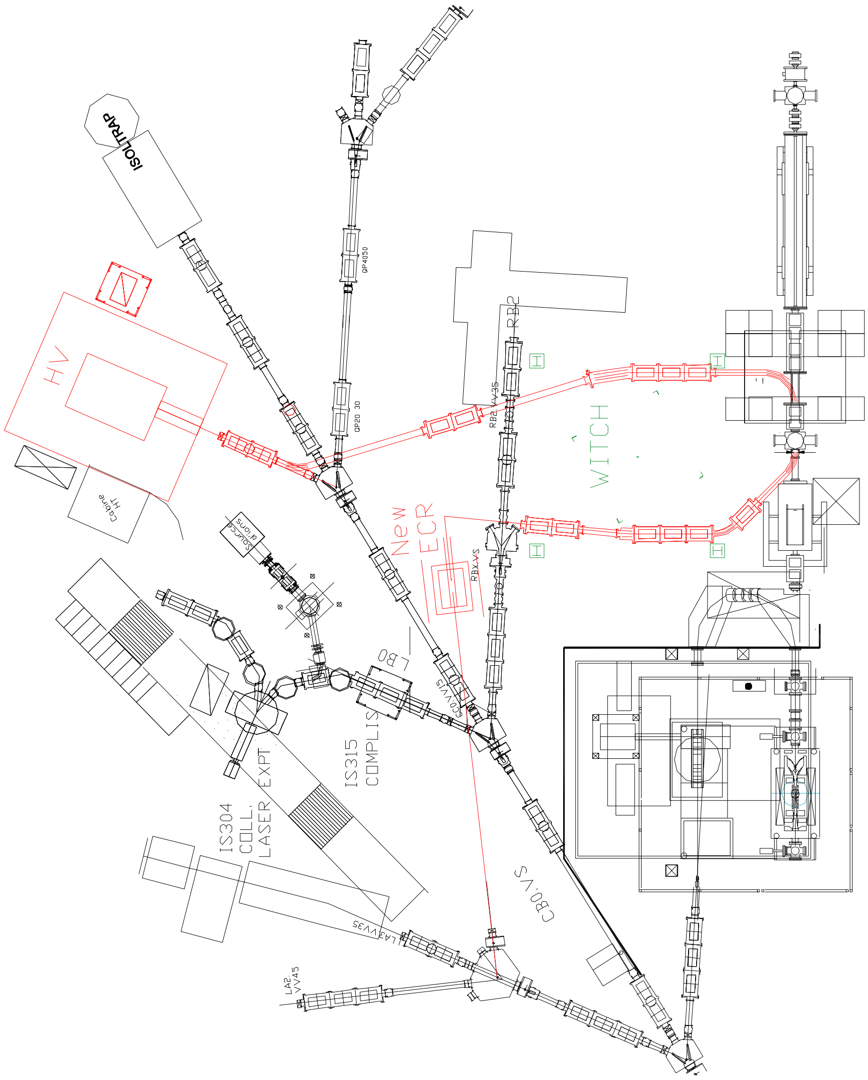

Figure 4: Beamlines for extraction and injection of the low energy high charge state ion beam of the REX facility suggested in this study (courtesy of H. Haas).

In conclusion, the unique combination of an electron beam ion source to produce highly-charged ions and a Penning trap mass spectrometer for high-precision mass measurements installed at ISOLDE/CERN will be the most powerful technique for mass spectrometry on short-lived exotic nuclei. Increased accuracies and a further reduction in the lower limit of the half-lives as compared to the present values are expected.

With this letter of intent we ask for a beam line connecting REX-EBIS and ISOLTRAP, which would be also of advantage for other members of the ISOLDE community. In addition, we ask for technical support and 30 shifts of stable beam from REX-EBIS to test the ion transfer as well as our setup with highly-charged ions after the installation of the new beam line.

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