EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2007-021
INTC-P-231
April 23, 2007

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Off-Line Tests and First On-line Installation of the Laser Ion Source Trap LIST – Application for CVC Test and CKM Unitarity

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Introduction: History and Motivation

The laser ion source RILIS at ISOLDE/CERN [Klu85] has developed into an extraordinary fruitful tool for efficient and selective radioactive ion production of a wide spectrum of elements [Kos03]. The advantages of RILIS in comparison to conventional ion sources ensure its leading role for the majority of the ISOLDE experiments. However, there is still one limiting condition observed, which restricts its application and usefulness:

Isobaric selectivity, the key argument for RILIS use, is high but nevertheless limited by the competing process of surface ionization on the necessarily hot surfaces inside the transfer tube/atomizer funnel. Thus investigation of lowest production rate isotopes far off stability using RILIS is hampered, particularly, if easily surface ionizable isobars, e.g. from alkali metals in the neighborhood, are present.

Further enhancement of ISOLDE RILIS performance with respect to the range of accessible elements and also the efficiency and selectivity is presently under way by investigating new atomizer materials which have an extremely low work function. In this way, the necessary temperature for efficient atomization is lowered and surface ion

contaminations are strongly reduced. So far, the ratio of the wanted laser ions to contaminating surface ions has been investigated using Ta, Nb or TaC atomizer materials, all exhibiting low electron emission work function of around 4 eV. Both Niobium and TaC have the additional advantage of high electron emissivity, which leads to the formation of a stronger trapping of ions in a thermal plasma and hence should increase the useable ion yield. For all cases suppression of unwanted surface ions lies between minimum two and maximum three orders of magnitude for the typical temperature range used, strongly decreasing for higher temperatures due to the increase in surface ionization. Very recently additional investigations have been started at the ISOLDE off-line test separator on new materials with still lower work functions, using the transportable University of Mainz Titanium-Sapphire laser system. The first tests already showed promising results and will be continued in May 2007 at the University of Mainz RISIKO test separator, using a standard ISOLDE target unit [Öst06].

The contaminating surface ions, which generate high isobaric interference for quite a number of isotopes of interest, can be further reduced by utilizing the pulse structure of the laser ionization process. Unfortunately the precise time structure of the laser beam and the generated laser ions is smeared out by the comparably low energy primary acceleration and its variation inside the crucible, resulting in an ion peak structure of typically a few 10 μs duration and with a tailing to higher delays. By setting a time window of between 10 to 20 μs lengths, a suppression of surface ions of about a further factor of 10 has been demonstrated [Fed06].

Design and performance of the laser ion source trap LIST

Isobaric suppression of the laser ionization process can be significantly enhanced by decoupling the processes of atomization and laser ionization. For this purpose the location of ionization must be transferred out of the atomizer channel into a region without any surrounding hot walls and surface ions must be hindered to enter. The heated source channel remains to serve as a self-collimating atomic beam source, delivering a rather well collimated beam profile. Any ions emerging from the chamber are pushed back or removed by a repeller aperture set onto a potential of a few 10 volts. Since this repeller might serve as an extractor for electrons, which could again lead to unwanted and unselective ionization processes in front of the chamber, a careful adjustment of this voltage is mandatory and possibly even a second electrode on low negative potential might be required in front of the orifice.

As an unavoidable side effect, the ionization in front of the orifice channel leads to a significant reduction in efficiency, due to the divergence of the initial atomic beam distribution. To account for this, a somewhat enlarged laser beam size of about 5 mm must be used. Within this area saturation of all optical excitation steps for a “typical” resonance ionization ladder with the accessible laser powers in the range of 100 mW and above can be expected. Nevertheless spatial beam quality decreases by the enlarged beam size and a no

longer well defined ionization volume. To compensate for both the reduction and the unwanted emittance increase we proposed the installation of a segmented radio frequency trap close to the atomizer, immediately after the repeller electrodes and around the location of ionization (see Fig. 1) [Bla03, Wen04]. In this so called laser ion source trap (LIST), the photo ions are produced free of any background, radially confined by the RF potential and longitudinally trapped through an axial DC potential. By introducing a helium buffer gas bunching, cooling and storage of the laser ion cloud is possible. Due to the low buffer gas pressure of only about 10^{-3} mbar no disturbing effects of the acceleration high voltage has been observed, whilst also gas consumption is very limited. The extraction of the ions as a clean and well controlled ion pulse is achieved by switching a number of the DC electrodes from trapping conditions to release. A sketch of the LIST device together with the axial potential distribution is given in Figure 1:

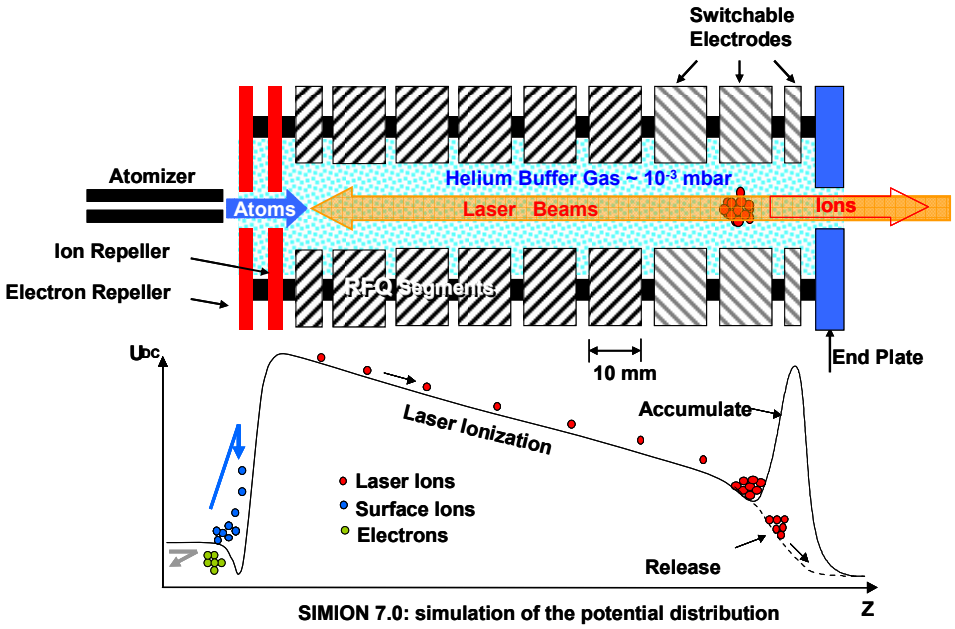

Fig. 1: Sketch of the LIST gas filled segmented FRQ ion trap and the axial potential distribution, showing both the trapping and release mode.

In extensive tests at Mainz, the individual parameters governing the operation of the LIST have been investigated, leading to the optimization of its design and the determination of its most suitable geometry and operation conditions [Wies05]. The LIST performance could be specified during these studies in respect to ionization efficiency, time structure of ion bunches, surface ion suppression, emittance and maximum trap capacity, most of these parameters in direct relation to the corresponding numbers for direct RILIS operation at the University of Mainz RISIKO mass separator and using the UMz Ti:Sa laser system (see Tab. 1). Currently, the main problem of unsatisfying ionization efficiency remains, which stands actually at about 1% of the RILIS efficiency. Nevertheless, there are promising ideas and adaptations concerning the optimization of the atomizer geometry, which will be installed in 2007 and should significantly improve this value. The results obtained for trapping capacity,

time structure and emittance show that their requirements are already met. Sharp Gaussian shaped ion bunches with a FWHM of just a few microseconds are delivered, containing up to $4 \cdot 10^6$ ions per bunch at an emittance of well below 5 π mm mrad [Wen07]. As an example time structures for Ca laser ion pulses from the LIST as function of the gas pressure are shown in Fig. 2.

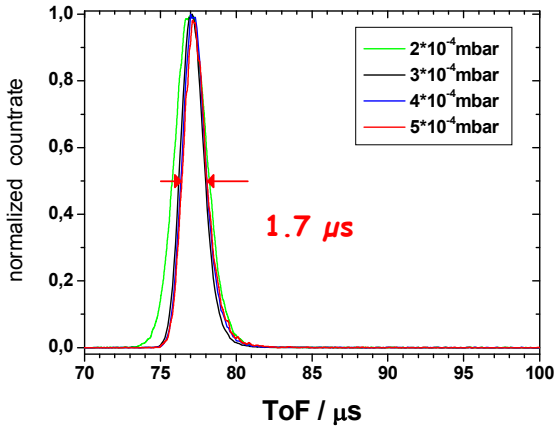

Fig.2: Time structure of a Ca laser ion pulse from the LIST.

Possible repetition rates of the trap range from the typical 11 kHz of the conventional RILIS system down to less than one bunch per second. Due to a long lifetime of the ions inside the trap of more than 200 ms, cooling times between a minimum of ~ 1 ms up to several tens of ms will be feasible, depending on the needs. In our first demonstration measurements at the University of Mainz RISIKO mass separator, comparing Ga laser ions with Ga surface ions, a suppression of surface ions of about 3 orders of magnitude could be demonstrated [Sch06]. A compilation of the presently reached values for the most important specifications of the LIST, obtained on stable Ga isotopes is given in Table 1.

Table 1: Specification of the LIST as determined in test measurements, predominantly at the University of Mainz RISIKO mass separator.

	LIST @ Mainz	**RILIS @ Mainz / ISOLDE**
Efficiency	$5{,}4 \cdot 10^{-4}$	$1{,}5 \cdot 10^{-2}$ (at Mainz)
Selectivity	>1000	10
Pulsewidth	< 10 µs	> 50 µsec
Trapping capacity	$4 \cdot 10^6$	-

Based on these values, a successful installation and utilization of the LIST at ISOLDE with the primary goal of suppressing isobaric contaminations in the beam already seems possible. The proper adaptation of a suitable device into an ISOLDE target/ion source unit will be prepared during summer/autumn 2007 at Mainz, resulting in a first prototype ISOLDE LIST target unit. For this purpose refined and simplified constructions of the trap have been

and will be designed, which will allow for the necessary remote installation of the power supplies and will require only a limited number of vacuum feed throughs and which should be sufficiently radiation resistant. A technical drawing of such a design, i.e. LIST version 3, is given in Figure 3. It allows for separation of RFQ (AC) and DC voltages and can be operated with as few as 5 vacuum feed throughs, which are available in a standard ISOLDE target unit.

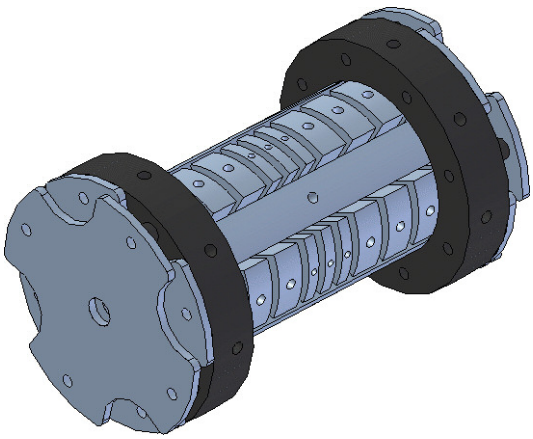

Figure 3: Technical drawing of LIST, version 3.

The first demonstration of the operation of the LIST is foreseen at the ISOLDE off-line test separator during the winter shut-down 2007/2008. For this purpose the University of Mainz Ti:Sa laser system will again be transported to CERN and a determination of all parameters of the LIST should be possible in a measurement campaign of about 4 weeks duration. During this period the laser system will also be available for further investigations concerning source and material development, in close collaboration with the ISOLDE RILIS and target/ion source group. A precise schedule for these measurement will be set up in correspondence to the results on the ongoing activities at Mainz university in May and possibly further work in autumn this year. Following the successful development and demonstration off-line up to Feb. 2008 we foresee a first on-line demonstration using the ISOLTRAP Penning trap mass spectrometer [Kel03] during spring 2008, directed towards tackling a physics case of outstanding relevance:

The physics case: test of the CVC or the CKM unitarity

ISOLTRAPs mass measurements have already significantly contributed to the test of fundamental relations like the Constant Vector Current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [Muk04, Kel04, Har05a, Har05b, Geo07a]. These investigations require an accuracy in the mass determination presently only achievable by Penning trap mass spectrometry. Nuclear beta decay is a unique laboratory for investigations of the weak interaction. Of special interest are the superallowed $0+ \rightarrow 0+$ nuclear β decays where the axial-vector decay strength is zero. The transition rate *Ft* for these decays should be nucleus independent if the vector current is a conserved quantity (CVC

hypothesis). In this case the vector coupling constant G_V can be extracted and be used together with value for G_μ extracted from muon decay to determine the V_{ud} element of the CKM quark-mixing matrix, which is a key for testing the unitarity of the CKM matrix and hence for the Standard Model itself.

Small nucleus-dependent corrections that are related to the presence of charge-dependent forces in the nucleus have to be applied when *Ft* is extracted from nuclear β decay. These corrections, the radiative correction δR and the Coulomb correction δC, have to be calculated [Har05a].

Until now the parameters of 12 superallowed β decays have been measured with high accuracy [Har05a, Har05b]. For many of the other potential candidates the knowledge of the Q_{EC}-value is limited, prohibiting an accurate determination of the *Ft* value. To reach an uncertainty level of 0.1% or better in the *Ft* value, an uncertainty of 0.1% or better is required for the half-life and branching ratio. But since the statistical rate function *F* is proportional to the fifth power of Q_{EC}, the Q_{EC} value must be determined with an uncertainty of less than 0.01%. This requires mass measurements of mother and daughter nuclei with relative uncertainties $\delta m/m \leq 1 \cdot 10^{-8}$.

For the 12 well-known cases the *Ft* values appear to be constant [Har05a, Hard05b], supporting CVC. However, the extracted V_{ud} together with the much smaller V_{us} and V_{ub} result in a CKM matrix that is not unitary by more than 2 standard deviations. One important point to be clarified here is the correctness of the calculated Coulomb correction δ_C. The well-known cases have quite low calculated Coulomb corrections in the order of 0.5%. Furthermore, to test new theoretical approaches as well as to probe CVC for higher *Z* it is necessary to extend the study of superallowed decays beyond *A* = 54 (Co).

Request for ^{62}Ga and ^{62}Zn

Both masses have been requested already in 2004 and 2005 by ISOLTRAP [Bla2002], but both runs failed due to an overwhelming contamination of $^{46}Ti^{16}O$ in the delivered ISOLDE beam, being up to six orders of magnitude more abundant than ^{62}Ga and thus three orders of magnitude above the background ratio that can be handled by ISOLTRAP (1:1000). Meanwhile the masses of ^{62}Ga and ^{62}Zn have been measured with the JYFLTRAP Penning trap mass spectrometer at Jyväskylä with an uncertainty of about $2 \cdot 10^{-8}$ [Ero06]. However, with the newly developed Ramsey excitation technique for the manipulation of the ion motion in the Penning trap [Kre07, Geo07b], ISOLTRAP is able to perform mass measurements on an uncertainty level of a few times 10^{-9}, thus still keeping highest interest in performing the experiment on ^{62}Ga. The LIST technique for the ionization of the radionuclides of interest is ideally suited to deliver the most background free ensemble, reducing the $^{46}Ti^{16}O$ background by three or more orders of magnitude. The production of ^{62}Ga with about a few thousand ions per second is sufficiently high to perform the mass measurement within 6 shifts, thus allowing for a considerable reduction in beam efficiency during this first operation of an ISOLDE LIST

target. Also the COLLAPS experiment and its proposal to investigate isotope shifts and nuclear charge radii of the neutron deficient Ga isotopes (including ^{62}Ga) [Bil07] would definitely benefit from the LIST technique and will place corresponding requests for the use of this unit after successful demonstration of operation.

Beam time request:

For the first commissioning and operation of the LIST target/ion source unit and its demonstration on the physics case of the ^{62}Ga high-precision mass measurement we request 15 shifts (9 shifts for the first on-line test, optimization, and specification of the LIST system and 6 shifts for the mass measurements) during 2008, utilizing a ZrO_2 target and the adapted RILIS/LIST ion source, which will be designed and installed following the off-line tests. A second commissioning run for the corresponding high-precision mass measurement on ^{62}Zn would require 12 shifts duration (again 9 shifts for the commissioning and only 3 shifts for the mass measurement due to the higher Zn yield). Most probably this would not only imply a simple laser wavelength change but also a target change to niobium foil, which might postpone this activity to a later stage, probably in 2009.

Table 2: ISOLDE beam time and target requests:

Nuclide	Target	Yield	Ion Source	Shifts
^{62}Ga	ZrO_2	$4\cdot10^3$	LIST	15
^{62}Zn	ZrO_2 or Nb	$2\cdot10^7$	LIST	12

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