# ION TRAP PROJECT AT IGISOL AND r-PROCESS STUDIES*

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The IGISOL facility at the Department of Physics of the University of Jyväskylä (JYFL) is delivering radioactive beams of short-lived exotic nuclei, in particular the neutron-rich isotopes from the fission reaction. These nuclei are studied with the nuclear spectroscopy methods. In order to substantially increase the quality and sensitivity of such studies the beam should undergo beam handling: cooling, bunching and isobaric purification. The first two processes are performed with the use of an RFQ cooler/buncher. The isobaric purification will be made by a Penning trap placed after the RF-cooler element. This will yield a substantial background reduction in the nuclear decay spectroscopy experiments and enable studies of much more exotic nuclei, like the ones belonging to r-process path. This contribution describes the current status of the project.

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## 1. Introduction

A project for improving the quality of radioactive ion beams produced at IGISOL [1], aiming at the enhancement of the quality of experiments, has been started in 1997 [2, 3]. The goal was to decrease the beam energy spread $\Delta E$ by 2 orders of magnitude, transverse emittance $\xi$ by a factor of 10 and increase the mass resolving power $R = M/\Delta M$ by two orders of magnitude, reaching $10^5$. The latter means a possibility of rejecting even

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isobaric contaminants, obtaining a pure monoisotopic beam. This improvement will be achieved due to radioactive beam handling, which consists of three steps: beam cooling (which improves both $\Delta E$ and $\xi$), bunching and purification (due to high $R$). The first two steps are done with the use of an RFQ cooler/buncher. The beam purification is performed applying a cylindrical Penning trap (see [4]).

## 2. Project description

Main features of the project are described in Ref. [5]. The RFQ cooler/buncher [6] exists at JYFL already. Its performance: $\Delta E = 0.6$ eV, $\xi \approx 1$–$2\,\pi$ mm mrad, transmission TR> 60 % and cooling time around 1 ms. Bunching possibility was also demonstrated.

The above device has been connected to the collinear laser spectroscopy set-up. The new bunched beam method provides a source of cooled ion bunches (FWHM: 15 $\mu$s) at a repetition rate down to 1 Hz. This results in a background suppression by a factor of $7 \times 10^4$ in the bunch-gated photon spectrum. The new method appears to be at least an order of magnitude more sensitive than the previous method of coincident ion/photon detection. It has been applied recently for the first time in experiments with radioactive isotopes (Ti, Hf and Zr) to measure their isotope shifts and hyperfine structures.

In a Penning trap, ions are confined in three dimensions by a superposition of static electric quadrupole and homogeneous magnetic fields. The magnetic field confines the ions in two dimensions in a plane perpendicular to the field direction. Since strong field is required for the beam purification, it is created by means of a superconducting magnet. A confinement in the third, magnetic field direction (parallel to the trap axis) is done by a quadrupole electric field. This field is created by a set of cylindrical (ring) electrodes in such a way that the central part of the electrode set is put to a negative potential, whereas the outer electrodes are at positive potential. This way an axial potential well for the ions with a minimum at the trap center is formed for positively charged species. To achieve an isobaric purification, mass-selective buffer gas cooling technique [7] will be used. This process can have a high mass resolving power, of the order of $10^5$, which permits to reject even isobaric contaminants [4]. This is particularly important for the experimental program at IGISOL, which in a future will be centered on exotic neutron-rich nuclei, produced in fission. The isobaric purification will allow for rejecting of all unwanted members of the isobaric chain, leaving only a species of interest. This will significantly improve signal-to-background ratio, sensitivity and precision of the experiments, and will extend the range of the isotopes investigated.

Summarising, the task of the purification Penning trap at IGISOL is to:

1. accept cooled (continuous or bunched) beams from the RFQ cooler/buncher,
2. perform the isobaric purification,
3. deliver clean, monoisotopic bunched beams for nuclear spectroscopy investigations, precise nuclear mass measurements and laser spectroscopy experiments.

The nuclear spectroscopy experiment will utilize a variety of gamma, X-ray and particle detectors. The bunched monoisotopic beam from the trap will be transferred to a measurement position and implanted in a collecting foil or a movable tape surrounded by the above-mentioned detector set-up.

The precise nuclear mass measurements of radioactive ions will be done using a second Penning trap. It will be placed directly after the purification trap in the same superconducting magnet. A trap of a cylindrical type will be used, which should assure the measurement accuracy of $10^{-6}$–$10^{-7}$. It will enable mass measurements of many neutron-rich isotopes not reachable anywhere else (*e.g.* of refractory elements) and will significantly broaden experimental program at IGISOL.

As an extension of the conventional decay spectroscopy studies, nuclear spectroscopy in a Penning trap interior ("in-trap" spectroscopy) is foreseen. This means placing the detectors of a needed type directly inside the trap and positioning the radioactive sample in front of them. Such a scheme has following advantages over conventional spectroscopy:

(a) radioactive sample (ion cloud) constitutes a very thin, small size radioactive source with no backing, free of intensity attenuation, energy degradation and backscattering problems,

(b) due to a proper detector placement one can substantially decrease, in a given detector, background contribution from other types of radiation, *e.g.* gamma background in the electron spectrum. The latter can be achieved by placing the electron detector relatively far away (inside the trap) from the source, minimizing the solid angle for gammas while having still very high efficiency (solid angle of 50 %) for detecting electrons which are guided by the magnetic field. In particular, this would be beneficial for the conversion electron and beta spectroscopy,

(c) efficient passive shielding for a background radiation with the magnet cryostat.

## 3. r-process study possibilities

One of main mechanisms of nucleosynthesis in astrophysics is the rapid neutron-capture process (r-process). It involves a great number of extremely neutron-rich, very short-lived isotopes which are usually hardly accessible with the conventional experimental techniques. Therefore, in order to obtain an important astrophysical information like the solar isotopic abundances, the nuclear structure properties (like masses, half-lives) entering the abundance calculations have to be taken from theoretical nuclear models. In order to improve the predictive power and to fine-tune the model parameters, an experimental information on the r-process nuclei is of extreme importance. The r-process nuclei can be produced in fission reaction, which is one of main production mechanisms at IGISOL. Unfortunately, the decay studies of so exotic species are always strongly hindered due to a huge background from isobaric contaminants. However, the Penning trap will be able to reject all the contaminating background, enabling studies of the pure radioactivity of interest. The range of accessible half-lives can be estimated basing on the performance of the ISOLTRAP Penning trap set-up at ISOLDE, CERN [8]. This set-up contains two Penning traps: one for the isobaric purification and one for the precise nuclear mass measurements. In one of the recent experiments, the mass of $^{74}$Rb (accuracy of $10^{-7}$) with $T_{1/2}$=65 ms was measured (see [9]). This indicates that the nuclei with half-lives above 50 ms should be available in the future for both nuclear spectroscopy and precise mass measurements also at IGISOL.

Fig. 1 shows a part of the nuclear chart covering the region where the $n$-rich nuclei are produced at IGISOL in a proton-induced fission of uranium. On the right-hand side, the chart ridge is following a typical r-process path (see *e.g.* [10]). Shaded squares mark the nuclei for which the half-life is known. Two criteria of availability of a given nucleus for studies at IGISOL with the ion trap system were arbitrarily assumed:

(a) production yield is above 1000 ions/day, and

(b) half-life is above 50 ms.

The theoretical production yields of Ref. [11] were used. In case where the experimental half-life was unknown, a theoretical one was taken from [12] and rescaled with the experimental values. As can be seen, after the IGISOL upgrade 73 new exotic $n$-rich nuclei will become accessible, 18 of them belonging to the r-process. Apart from that, there is a big number of nuclei which do not fulfil either production or half-life criteria. Nevertheless, it is quite possible that in the sufficiently clean experimental conditions and with the use of a high-efficiency detector set-up also the nuclei having production yields below 1000 ions/day can be studied. Moreover, most

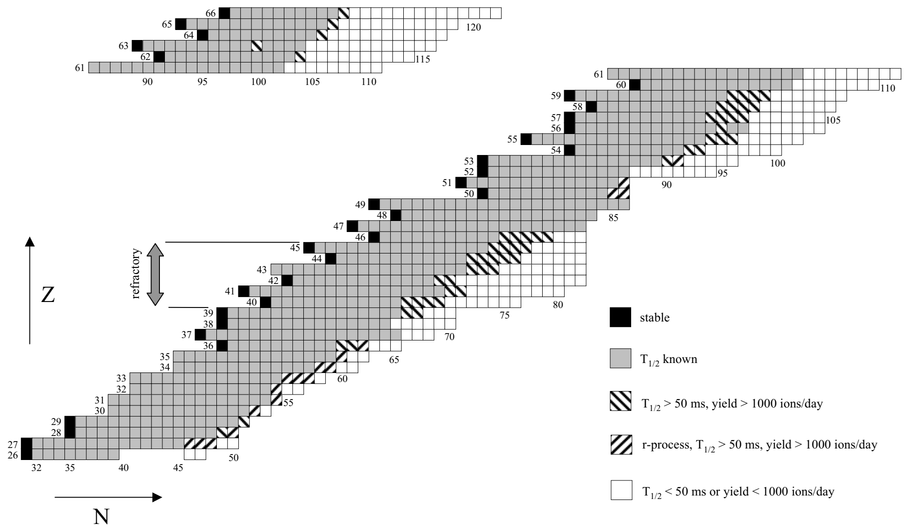


Fig. 1. Upgraded IGISOL production possibilities in fission reaction ($p + {}^{238}\mathrm{U} \rightarrow$ fission, $E_p = 25$ MeV)

probably the future ion trap developments will bring still faster scenarios for the beam purification process, thus pushing the half-life limit even below 50 ms. Therefore, the number of new $n$-rich nuclei available at IGISOL in a not very distant future may substantially exceed 73, and, respectively, 18 for the r-process, mentioned above.

## 4. Project status

At present, the superconducting $B = 7$ T magnet, the trap electrode structure and majority of vacuum components and electronics are existing. Control system will be based on PC computer, LabVIEW and CAN-bus, and is under development. Its part for the control of the RFQ cooler/buncher is ready. An alignment of the trap vacuum tube along the magnetic field lines in the magnet was performed. Also the trap injection and ejection beamlines were constructed and aligned with the trap vacuum tube. It is planned to test the purification trap with stable ions until the end of 2001. First experiments with radioactive ions will start after the end of the IGISOL shut-down in spring 2002.

The ion trap development at IGISOL is done in a collaboration with other nuclear physics laboratories grouped in an European network EXOTRAPS (JYFL is a coordinator of this network). The Penning trap system was created in close collaboration with GSI Darmstadt, where a similar trap project SHIPTRAP aiming at experiments with transuranium isotopes [13] is in preparation.

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