Probing nuclei at the limits of nuclear landscape

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Abstract. Light- and heavy ion beams from the K=130 cyclotron are used to produce nuclei far from stability at the Accelerator Laboratory of the Department of Physics of the University of Jyväskylä (JYFL), Finland. Novel instruments at the target and focal-plane areas of a gas-filled recoil separator for in-beam tagging measurements are available for probing structures of very neutron deficient and very heavy nuclei. Bunched and cooled radioactive beams from the IGISOL system are available for studies of nuclear ground-state properties by employing Penning traps and laser systems. Recent results from measurements at these two facilities are presented. Future plans will also be introduced.

1. Introduction
The Accelerator Laboratory at JYFL has been nominated to be the Finnish Centre of Excellence in Nuclear and Accelerator Based Physics by the Academy of Finland for the period of 2006-2011. The status covers research and development work as well as ion beam applications at the Accelerator Laboratory of JYFL and theoretical nuclear physics activities carried out at JYFL. The K130 Cyclotron accelerates light and heavy ion beams, provided by two ECR sources and one multi-cusp source for heavy and light ions, respectively. The total beam time on target has exceeded 6000 hours a year for many years. In this report some recent highlights related to experimental nuclear structure studies performed by the combined Gamma and RITU groups (Nuclear Spectroscopy Group) and by the IGISOL group will be presented.

2. Some highlights from the Nuclear Spectroscopy Group

Figure 1. JUROGAMII+RITU+GREAT facility

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The main activity of the Nuclear Spectroscopy Group has been on making use of the powerful JUROGAMII+RITU+GREAT facility (see figure 1). JUROGAMII is a $\gamma$-ray array placed at the target position of RITU. RITU is an in-flight gas-filled recoil separator which separates the fusion products from other recoils. At the focal plane a GREAT spectrometer measures recoils, decay products (\(\alpha\)'s, \(\beta\)'s and protons), $\gamma$-rays and electrons. Spectroscopic studies have successfully been performed covering a broad area of the nuclear landscape. The nuclei at the N=Z line below A=100, the neutron-deficient rare earth nuclei (A = 117-160), the proton drip-line nuclei in the vicinity of Z = 82 and the heaviest elements (nobelium) have been examined. In these studies the Recoil Gating (RG), Recoil Decay Tagging (RDT) and Recoil Isomer Tagging (RIT) methods have been utilized.

The program to explore nuclear structure at the proton drip line in the lead region has been extensive. One intriguing question is the survival of shape coexistence when approaching the proton drip line. Following the successful development of Zr beams by the ECR group, the JUROGAM II array at RITU was employed in an RDT experiment to observe prompt $\gamma$ rays from $^{180}$Pb. Excited states were populated via the cold $^{92}$Mo($^{90}$Zr,2n)$^{180}$Pb reaction. The measured production cross-section was only 10 nb. All the excited states of $^{180}$Pb are proton unbound. In figure 2 is shown level systematic of the neutron deficient lead isotopes. From the systematics it can be seen that the intruding prolate structures still persist in the very neutron deficient $^{180}$Pb.

At JYFL persistent work has been performed in the Nobelium region [5-10]. In in-beam $\gamma$-ray spectroscopy studies one of the limiting factors has been the permitted total counting rates at the

\[E_{\gamma} \text{ [keV]}
\]

\[A \]

\[180 \ 182 \ 184 \ 186 \ 188 \ 190 \ 192 \ 194 \ 196 \ 198 \ 200 \ 202 \ 204 \ 206 \ 208 \]

\[0^+ \ 2^+ \ 4^+ \ 6^+ \ 8^+ \ 10^+ \ 12^+ \]

\[spherical \ oblate \ prolate \]

\[10^+ \ 12^+ \ 14^+ \ 16^+ \ 18^+ \ 20^+ \ 22^+ \ 24^+ \ 26^+ \]

\[E_{\gamma} \text{ [keV]}
\]

\[A \]

\[180 \ 182 \ 184 \ 186 \ 188 \ 190 \ 192 \ 194 \ 196 \ 198 \ 200 \ 202 \ 204 \ 206 \ 208 \]

\[0^+ \ 2^+ \ 4^+ \ 6^+ \ 8^+ \ 10^+ \ 12^+ \]

**Figure 2.** Level systematic of lead nuclei with A < 208. The data are taken from the works [1-4]
target position. The combination of digital electronics with JUROGAMII enables low cross-section in beam experiments at high total $\gamma$-ray counting rates for heavy nuclei. A successful in-beam spectroscopy run was carried out, for the first time, for $^{246}$Fm produced in the $^{208}$Pb($^{40}$Ar,2n)$^{246}$Fm reaction with a cross-section of approximately 10 nb, which is the lowest cross-section so far to be studied in-beam in the heavy-element region (figure 3) [11].

![Figure 3. Gamma-ray spectrum obtained for $^{246}$Fm](image)

2. Some highlights from the IGISOL group

One of the main research tools at JYFL is the IGISOL isotope separator facility (figure 4). Neutron-rich nuclei are produced using light ion induced fission reactions whereas the proton-drip line nuclei are probed employing the heavy ion induced fusion evaporation reactions. After ion guide the products are mass separated and transported to the radiofrequency quadrupole ion cooler and buncher which is followed by the JYFLTRAP tandem Penning trap. The ion cooler is used to improve the ion beam quality and bunch the beam for laser spectroscopy and the Penning trap. The Penning trap can be used for isobaric purification of the ion beams for nuclear spectroscopy experiments. It can also be employed for very precise (down to 1 keV/c²) mass measurement of the ions. These mass measurements have recently provided many data points for the CVC hypothesis and CKM unitarity tests [12, 13]. A new development is resonant laser ionization of atoms in the helium gas jet leaving the ion guide.

The collinear laser spectroscopy set-up, owned and operated by the Universities of Birmingham and Manchester, is connected to the IGISOL and can be considered as a part of the facility. In the experiments, the isotope shifts, nuclear electric quadrupole and magnetic dipole moments for short-lived isotopes of refractory elements such as hafnium, niobium, molybdenum and zirconium have been determined, an achievement that would have not been possible anywhere else in the world.
IGISOL group has studied extensively the evolution of shell gaps in different parts of chart of nuclei [15-18]. As an example in figure 5 two-neutron separation energies around neutron number 50 and covering the elements from cobalt up to zirconium are shown. At proton number $Z = 40$ the shell gap $N = 50$ is pronounced. When approaching the $Z = 28$ and $^{78}$Ni it can be noticed that $N = 50$ shell gap is again pronounced. Although more data points are needed this could be a sign of that the double magic structure persists in very neutron rich $^{78}$Ni.

**Figure 4.** The IGISOL facility floor level layout after the front end upgrade [14]. (1) Target chamber (2) K-130 cyclotron beam line (3) light ion beam dump (4) extraction chamber (5) dipole magnet (6) switchyard (7) radiofrequency cooler (8) JYFLTRAP (9) mini-quadrupole beam deflector (10) electrostatic deflector and beam line upstairs to collinear laser experiments and (11) beam lines for experimental setups.

**Figure 5.** Two-neutron separation energies as a function of proton number [15].
In figure 6 is shown results from the collinear laser spectroscopy studies and from the mass measurements for the neutron rich elements of $36 \leq Z \leq 42$ \cite{15-22}. At $N = 60$ a sudden increase of the obtained charge radii for higher neutron numbers for elements around zirconium can be seen. This has been interpreted as sign of rapid change from $\beta$ soft, weakly oblate to static strongly prolate ground state structures. This shape change as a function of neutron number is much smoother for Mo isotopes. The effect caused by this shape change can be seen as anomaly behavior in the two-neutron separation energies around neutron number 60.

3. Future plans

The highlight of the year 2009 was the advent of the new light-ion MCC30/15 cyclotron from NIIEFA, St. Petersburg and the commissioning of the new extension of the Accelerator Laboratory constructed in 2008-2009 (figure 7). First beams from the cyclotron were delivered on 11th November 2009. In the future the use of the new light-ion MCC30/15 cyclotron will release beam time for basic research, tests and service at the K130 cyclotron. The IGISOL facility is foreseen to move in to the new site. The IGISOL group is likely to be the main user of the new accelerator; however the IGISOL facility will also have access to the heavy ion beams provided by the K130 cyclotron through a connection from the old beam line to the new one. The move is expected to take place on the second half of 2010. This move will allow updating and improving the performance of the IGISOL facility.

The SAGE (combined electron and $\gamma$ spectrometer) and LISA (charge particle spectrometer) spectrometers were recently commissioned at JYFL. The SAGE spectrometer will allow to look for E0 transitions and to perform more comprehensive in-beam studies in the heaviest element region where the low energy transitions are highly converted. The LISA spectrometer will be
used to search for fast charge particle decays. The planned vacuum-mode mass separator MARA will be used for spectroscopic studies in the $A \sim 80$ region. The magnetic components for the MARA separator have been purchased but the most expensive part, the electric dipole, is waiting for funding.

**Figure 7.** The future layout of the JYFL accelerator laboratory. The new extension part is shown in the right lower corner. The IGISOL facility will move to this new extension. The new MARA separator will be placed alongside the existing RITU separator.

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