Experiments for the $r$ process at IGISOL

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IGISOL at JYFL Accelerator Laboratory
JYFL Accelerator Laboratory

www.jyu.fi/accelerator

Image: Google
JYFL Accelerator Laboratory

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- Located at the Department of Physics, University of Jyväskylä
- Three accelerators (K130 and MCC30 cyclotrons and 1.7 MV Pelletron)
- Over 6000 h beamtime every year
JYFL Accelerator Laboratory

- Pelletron
- MARA
- RITU
- Reactions
- RADEF
- cLinac
- K130
- MCC30
- IGISOL-4
The IGISOL facility

IGISOL - a fast and universal method to produce radioactive beams

J. Årje, J. Äystö et al., PRL 54 (1985) 99


MCC-30

K-130

Offline ion source

Mass number A

RFQ

Cooler & Buncher

A. Nieminen et al., PRL 88 (2002) 094801

Target chamber

Production method:
30 MeV p beam on U or Th

JYFLTRAP

Mass measurements & Post-trap spectroscopy

Mass measurements for the r process at IGISOL
"...we found that uncertainties in nuclear masses and fission properties need to be reduced in order to better constrain the role of NS-NS mergers on the chemical evolution of r-process elements using LIGO/Virgo's detections."


M.R. Mumpower et al., PPNP 86 (2016) 86
Mass measurements - JYFLTRAP

7 T superconducting solenoid

**PURIFICATION TRAP**
- select the ions of interest for mass measurements or decay spectroscopy

**PRECISION TRAP**
- mass measurements using TOF-ICR (time of flight ion cyclotron resonance) or PI-ICR (phase-imaging ICR) techniques
Mass measurements

Ion’s cyclotron resonance frequency:

\[ \nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m} \]

B determined using a reference ion:

\[ m = \frac{\nu_c^{\text{ref}}}{\nu_c} (m_{\text{ref}} - m_e) + m_e \]

THIS IS VALID BOTH FOR TOF-ICR AND PI-ICR METHODS
Mass measurements

**TOF-ICR**
- $\nu_c$ determined from the time-of-flight spectrum

**PI-ICR**
- $\nu_c$ determined from the phase $\phi$ of the ions after a phase accumulation time $t$

$$\nu = \frac{\phi + 2\pi n}{2\pi t}$$

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Roosbroeck et al., PRL 92, 112501 (2004)

$T_{RF} = 900 \text{ ms} + 3000 \text{ ms}$ for cleaning

100 ms accumulation time
Neutron-rich nuclides measured at JYFLTRAP

More than 200 neutron-rich nuclides measured so far

Focus of this talk
• Rare-earth region
• $^{132}$Sn region (shortly)
• $^{78}$Ni region (shortly)
Rare-earth region
Formation of the rare-earth abundance peak

See also: talk by N. Vassh “Lanthanide production in r-process nucleosynthesis” last week

**FISSION RECYCLING?**

**DEFORMATION FUNNELING THE FLOW?**

S. Goriely et al., PRL 111 (2013) 242502

M. Mumpower et al., PRC 85 (2012) 045801.
M. Mumpower et al., PPNP 86 (2016) 86.
E(2+) energies and a kink at N=100

\[ \frac{E(4^+)}{E(2^+)} \approx 3.3 \]

rigid rotor

Z. Patel et al., PRL 113 (2014) 262502
Two-neutron separation energies $S_{2n}$

M. Vilén et al., PRL 120, 262701 (2018)

Onset of deformation

No kink at $N=100$
Neutron separation energies $S_n$

6 nuclides measured for the first time!

Less odd-even staggering
- Lower for $N=96,98,100,102$
- Higher for $N=97,99,101$

Measured with JYFLTRAP:
$^{156,158}$Nd ($Z=60$), $^{158,160}$Pm ($Z=61$), $^{162}$Sm ($Z=62$), $^{162,163}$Eu ($Z=63$), $^{163-166}$Gd ($Z=64$), $^{164}$Tb ($Z=65$)
Neutron pairing metrics $D_n$

$$D_n(N) = (-1)^{N+1} [S_n(Z, N + 1) - S_n(Z, N)] = 2\Delta^3(N)$$

Empirical neutron pairing gap a.k.a. odd-even staggering parameter

Experimental neutron pairing weaker than predicted by theoretical models when approaching the midshell!

$M. \; Vilén \; et \; al., \; PRL \; 120, \; 262701 \; (2018)$
Impact on the r-process calculations

New $S_n$ values result in smoother calculated abundance distributions and in a better agreement with the observed pattern.

- **(a)** Merger with two 1.35$M_{\odot}$ neutron stars. ($Y_e = 0.016$, initial $s/k_B \sim 8$)

- **(b)** A low-entropy, hot wind ($Y_e = 0.15$, $s/k_B = 10$)

Changes up to 25% observed. Mainly due to revised neutron-capture rates.

Baseline: AME16 exp. + FRDM12

Neutron-capture rates: TALYS
Region close to $^{132}$Sn: In isotopes
Neutron-rich indium isotopes

$^{129,131}$In and their isomers already measured at IGISOL3

J. Hakala et al., PRL 109, 032501 (2012)
A. Kankainen et al., PRC 87, 024307 (2013)

✓ $^{128}$In and $^{130}$In measured at IGISOL4
✓ Post-trap decay spectroscopy

Dipolar Ramsey cleaning method:
clean samples for mass measurements and post-trap decay spectroscopy

Region close to $^{78}\text{Ni}$
Interesting region both for nuclear structure and astrophysics

NUCLEAR STRUCTURE
Evolution of the Z=28 and N=50 shell gaps? Shape coexistence?

Core collapse supernovae


Neutron star crust

R.N.Wolf et al., PRL 110, 041101 (2013)
Several new masses measured

For example masses of $^{70}\text{Co}$ and $^{74,75}\text{Ni}$ measured for the first time!

![Graphs showing mean TOF (μs) vs. RF frequency (Hz) for $^{70}\text{Co}^+$ and $^{75}\text{Ni}^+$ with $N_{\text{ions}} = 299$ and 314, respectively.]

Analysis ongoing!
Decay spectroscopy for the r process at IGISOL
First determination of $P_{2n}$ above $A=100$: $^{136}\text{Sb}$

R. Caballero-Folch, I. Dillmann et al., arXiv:1803.07205 [nucl-ex]

- JYFLTRAP to select $^{136}\text{Sb}^+$ ions
- $P_{2n}=0.31(5)\%$ is a factor of 20 smaller than predicted by FRDM + QRPA

J. Agramunt et al., NIMA 807(2016) 69
Total Absorption Spectroscopy (TAS)

TAS on $^{87,88}\text{Br}$ and $^{94}\text{Rb}$: observed gamma decays above $S_n$!

J. L. Tain et al., PRL 115 (2015) 062502
MONSTER (MOdular Neutron SpectrometeTER) NuSTAR@FAIR

- 8 modules at IGISOL
- Liquid scintillator detector
- Gamma-neutron separation from pulse shape
- First online tests later this year using $^{85}$As ($P_n = 59.4(24)\%$)

*T. Martínez et al., Nuclear Data Sheets 120 (2014) 78*
Versatile programme to study neutron-rich nuclei at IGISOL

Mass measurements:
- PI-ICR commissioned
- MR-TOF to be installed later this year

Decay studies:
- Isotopically or even isomerically pure beams for experiments
- New phase-dependent cleaning method

Production:
- Neutron-induced fission?
- Multinucleon transfer reactions?
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B. Bastin, S. Giraud et al., GANIL

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