ISOLDE Highlights and the HIE- ISOLDE Project

Karsten Riisager
Aarhus University / INTC chair
ISOLDE Facility

- ISOLDE is the CERN radioactive beam facility.
- “Oldest running experiment” at CERN
- Provides low energy or post-accelerated beams
- > 800 Users from > 200 Institutions, 50 experiments / year

Linac4 PSB upgrade (2020)

- Intensity (2uA -> 6uA)
- Energy (1.4 -> 2GeV)
Prehistory + today

- First ISOL beam: Copenhagen 1951
- ISOLDE approved 1964
- First radioactive beam 1967, positioned at SC (worth a visit !)
- Several upgrades until SC was closed 1990
- Restart at PS-Booster in 1992
- Two hall enlargements, REX in 2001, HIE in 2015....

- ISOLDE Collaboration (16 members) have MoU with CERN

- Proposals through INTC to Research Board

- Fruitful collaboration with many other radioactive beam facilities

- 132 active experiments, 117 theses 2012-2016
ISOLDE Targets

- Main challenge: extracting the $10^{-1} - 10^{12}$ nuclei (one isotope) produced in the reaction from the $10^{23}$ nuclei in the target

- Targets:
  - UCx, SiC, Ta, LaCx, CaO, ZrO...

- The diffusion into the ion source is controlled by the target and transfer line temperature
Ion Sources

- **Hot-cavity**
  - W heated at > 2000 C
  - High ionization efficiencies for some nuclei

- **Plasma**
  - Electrons are extracted from a hot cathode and accelerated into a low pressure plasma
  - When passing through the plasma, the atoms get ionized with very high efficiency (up to 50%)

- **LASER – RILIS** (Resonance Ionization Laser Ion Source)
  - Used at ISOLDE since 1994
  - Based on the selective ionization of a single atomic species
Gain in yield due to p energy increase

Yield: \[ Y = I \times X \times \sigma \times \text{Efficiencies} \]

- Increase in proton energy from 1/1.4 GeV to 2 GeV will increase the cross section and thus the yield.

H. L. Ravn et al., NIM B 88 (1994) 441
Produced Nuclei: 50 y Experience

- Over 20 target materials (carbides, oxides, solid metals, molten metals and molten salts) operated at high temperature
- 3 types of Ion-sources: Surface, Plasma, laser
- > 1000 nuclides of 75 chemical elements produced → B (BF$_2$) and Ge (GeS)
Research with radioactive nuclides

Techniques: all available at ISOLDE

Nuclear physics and atomic physics

Material science and life sciences

Nuclear astrophysics

Fundamental interactions

Nuclear physics

Decay spectroscopy

Decay spectroscopy

Laser spectroscopy

Beta-detected NMR

Nucleon transfer reactions

Coulomb excitation

Transition probability

Spin, parity

Half-life

Mass

Radii

Electromagnetic moments

B_n = 0
Decay spectroscopy (IDS, TAS, ..)
Coulomb excitation (MINIBALL)
Transfer reactions (T-REX, Scattering)
Electromagnetic Properties (COLLAPS, CRIS, NICOLE)
Polarized Beta-NMR (VITO, COLLAPS)
Masses (ISOLTRAP)
Applications:
- Solide state (Collections)
- Life Science (collections & VITO)

First Beams Oct 2015

Post-accelerated Exps (5.5 MeV/u); Low Energy (30-60kV) Exps, Machine elements
Recent Highlights and types of experiments
**βp in halo $^{11}$Be nuclei: Quasi-free n $\rightarrow$ p decay**

- βd observed in $^6$He & $^{11}$Li halo nuclei decay directly to the continuum $\rightarrow$ simpler mode in 1n-halo nuclei $\rightarrow$ βp
- $^{11}$Be best case to search for βp, $Q_{\beta p} = 280.7$ keV
- Expected B.R. $3 \times 10^{-8}$ assuming direct decay
  

- Previous attempt gave unconclusive result with
  
  BR = $2.5(25) \times 10^{-6}$; Borge et al., J. Phys G 40 (2013) 035109

A 200 keV $10^{-8}$ proton branch is challenging to detect $\rightarrow$ Detect $^{10}$Be daughter by AMS

- Contaminations measured to be negligible.
- B.R. = $8.4(6) \times 10^{-6}$ Consistent with previous results
- New resonance in $^{11}$B $\rightarrow$ OTPC

- The new decay mode is a consequence of halo structure, peripheral decay of the neutron halo + intense super allowed transition near $Q$-value observed in other neutron rich drip line nuclei. Riisager et al, Phys Lett. B732 (2014) 305
New Permanent setup: IDS

Very versatile Setup

From proton rich $^{20}\text{Mg}$ to very neutron rich $^{132}\text{Cd}$
Extent of the Island of Inversion: β-decay of $^{34}$Mg

Results GANIL-LISE: Rotaru, Grevy PRL 2012

$^{34}$Mg

- Long lived isomer in $^{34}$Al of $J^\pi = 1^+$ ($T = 26(1)$ ms)
- $0^+$ at 2719 keV in $^{34}$Si

Results 2015

- 2 times > yield
- Improved setup
- $T_{1/2}$ of $^{34}$Mg
- $B(E2; 2^+ \rightarrow 0^+)$ in $^{34}$Si
- Identification of isomeric state and gs,
  Lica et al., PRC 95 (2017) 021301

$^{34}$Mg β-decay

$T_{1/2}$ (364.5 keV) = 44.3(3) ms

Counts / ms

Time (1 ms/ch)
ISOLTRAP mass spectrometer

- Study of the onset of collectivity at N=40 deformation in n-rich chromium beams $^{50-63}\text{Cr}$

M. König et al., 142, 95 (1995).

Courtesy of V. Marica
Laser spectroscopy

- Probe the hyperfine structure of the energy levels of the electron
  - Scan the laser frequency of the resonant transition

- Nuclear observables extracted with model-independence:
  - Change in mean square charge radii: $\left\langle r^2 \right\rangle^{A,A'}$
  - Magnetic dipole moment: $I$
  - Electric quadrupole moment: $Q_S$
  - Nuclear spin: $I$
Exploring the nature of N=32

- Collinear laser Spectroscopy study of Ca-isotopes: $^{40-52}$Ca
- Change in nuclear size produces a shift in the hfs.

Level scheme for resonance excitation

4p2P₂

393.4 nm

4s2S₂

$^{49}$Ca (I = 3/2)

$^{51}$Ca (I = 3/2)

$^{52}$Ca (I = 0)

Relative Frequency (MHz)

Counts/proton pulse

Hyperfine structure spectra

Ca
393.4 nm

20  22  24  26  28  30  32

Relative Frequency (MHz)

Counts/proton pulse

Ca
40  42  44  46  48  50  52

Ca

ISOLTRAP: Mass of 54Ca and 3-body forces

- Confirmation of N=32 as magic number far from stability
- Validation of three-body forces using chiral perturbation theory

2-neutron separation energy (MeV)

Mass models

Neutron number

R. F Garcia Ruiz
Quadrupole moment of $^{219}\text{Fr}$

- HFS of short-lived $^{219}\text{Fr}$ measured
  - $t_{1/2} = 22$ ms
  - Linewidth of 20(1) MHz
- $Q_s = -1.21(2)$ eb
- $\beta_2 = 0.094$

- Spherical up to $N=126$ $\rightarrow$ Sudden deformation in $gs$ for $^{219-225}\text{Fr}$
  - Strongly negative to strongly positive $Q_s$
  - Changing influence of Coriolis mixing on prolate-deformed structures

Atomic properties of Astatine

- Determination of ionising potential
- Identification of new atomic transitions
- Comparison with atomic theory
- Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP

$\text{IP(At)} = 9.31751(8) \text{ eV}$

Nature Com. 14May2013
DOI 10.1038
Emission channeling at ISOLDE

30-60 keV radioactive ions

single crystal or epitaxial film

decay particles: conversion electrons, $\beta^-, \beta^+, \alpha$

2-dimensional position- and energy-sensitive detector

2D emission patterns characterize specific lattice sites of the emitting atoms
ESS W-target – release test
Post-accelerator: REX-ISOLDE

- Built @ different Universities
- Approved in 1994 as an experiment: “Radioactive EXperiment..
- First beams @ 2.2 MeV/u in Oct 2001
- Upgrade to 3.1 MeV/u completed in 2004
- REX Universal post-accelerator from He to Ra (A=224) > 100 different beams
- In 2006 a new hall extension in preparation for HIE-ISOLDE

1 Nature, 12 PRL, 6 PLB.....
Searching for pear-shaped nuclei at ISOLDE

The HIE-ISOLDE project (2010 -)

Energy: 4.5 – 10 MeV/u
Intensity: x4 in power
Beam Quality
Access to a wealth of spectroscopic information
- From the absolutes intensities of $4^+ / 2^+$ (multistep coulex)
  ⇒ Access to the sign of deformation

- Single particle information through the spectroscopic factors
- High energy needed to learn about the "l" transfer
High Energy Increase HIE-ISOLDE

Total efficiency: 1 - 10%

- 6x cryomodules (2x low-β, 4x high-β)
- 32x Nb-on-Cu QWRs (12x low-β, 20x high-β)
- 8x solenoids

IH structure

- 4.3 MeV/u A/Q = 4.3
- 5.5 MeV/u A/Q = 4.3

SC linac

- 10 MeV/u A/Q = 4.3
- 7.8 MeV/u A/Q = 4.3

2017

2015

2016

Penning trap

EBIS

A/q = 2.5 - 4.3

> 100 different beams
HIE-ISOLDE Phase 1 (2010-2016)

2 CMs: 5.5 MeV/u at A/q=4.3
HIE-ISOLDE Phase 2 (2017-2018)

MINIBALL

Cd-Si Detector
T-REX
SPEDE

Movable Setups

ISOL Solenoidal Spectrometer
Physics at HIE-ISOLDE

The new energy window gives the opportunity to address new physics questions

- 35 Experiments approved
  > 700 shifts

- Isospin symmetry
- Magic numbers far from stability
- Collectivity versus Single Particle
- Shape Coexistence
- Quadrupole and Octupole degrees of freedom
- Reaction for nucleo-synthesis studies
Radioactive beams @ 5.5 MeV/u

- HIE-ISOLDE stage 1 with 2 cryomodules producing physics
- First radioactive beams on 9 September 2016 $^{110}$Sn
- Coulomb excitation of $^{78}$Zn, $^{110}$Sn, $^{132}$Sn, $^{142}$Xe

Celebration 28 September 2016
Evolution of Quadrupole and Octupole collectivity in n-rich Xe

Physics aims
- transition and diagonal quadrupole MEs for higher spin states ($I^+ > 4^+$)
- $B(E3)$ values

Preliminary lifetimes measured at ILL with FATIMA
S. Ilieva

Octupole “magic” numbers

Doppler corrected with respect to Xe
Transfer reactions at the neutron Dripline

- Study of $^9\text{Li} (d,p)$ to study $^{10}\text{Li}$ resonances @ 6.8 MeV/u (2016)
- Study of $^9\text{Li} (t,p)$ to study @ 8.7 MeV/u:
  - $^{11}\text{Li}$ halo composition / 2n spectroscopic factor
  - Search for resonances just above the threshold on $^{11}\text{Li}$ predicted by 3-body models
  - Isotropic Neutron emission?

SAND:
- 30 (2x12+6) n-detectors
- 2° angular resolution,

Charge particle set-up: angular resolution 1-3°
- 1x S3 DSSD in forward direction covering angles 6 – 32°
- 5x DSSD telescopes surrounding target en forma pentagon 44 – 104°
- 1x DSSD telescope en backward direction 94 – 134°
Summary & Outlook

- ISOLDE operative since almost 50 years is in continuous transformation to stay at the forefront of nuclear physics research.
- Plenty of challenging physics at ISOLDE and HIE-ISOLDE!
- Many new devices and groups have been attracted by the increase of energy of the post-accelerated beams.
- HIE-ISOLDE stage 1 in operation with energies of 5.5 MeV/u for A/Q = 4. & 6.8 MeV/u for A/Q = 3.
- In 2017: third cryomodule connected reaching energies of 7.5 MeV/u for A/q = 4 and 3rd beamline.
- In 2018: energies up 10 MeV/u for A/q = 4.

Thanks for your attention!
Cd-nuclei: too simple or too complex?

N-Rich Cd isotopes of importance for the r-process:
- $^{129-131}$Cd masses determined @ISOLTRAP Atanasov, PRL115 (2015) 232501
- $\beta n$ with VANDLE @ IDS
- Radii and Q-moments @ COLLAPS

Simple Structure in Complex Cd isotopes: Q of $11/2^-$ States

Simplicity due to filling of the $h_{11/2}$. Expected for extreme shell model (6-odd) Contribution from degenerated orbitals Proton-core polarization

Yordanov, PRL 110 (2013) 192501

Parabolic behaviour!!! filling of the $h_{11/2}$ starting oblate and then prolate.

PRL 116 (2016) 032501
First Radioactive beams in 2015 @ 4 MeV/u

- Coulomb excitation of $^{74}$Zn and $^{76}$Zn studied at higher energy.
- Excitation energy domain enlarged!

- Large disagreement for $^{74}$Zn B(E2)
- Louchart PRC87 (2013) 054302 (AGATA) and Van der Valle PRC79 (2009) 014309
Experimental Techniques

Traps for masses

\[ \omega_c = \frac{qB}{m} \]

Talk by K. Blaum!

Lasers for radii & e-m moments

\[ \delta \nu_{IS}^{AA'} \propto \Delta |\Psi(0)|^2 \delta \left\langle r^2 \right\rangle^{AA'} \]

Talk by B. Cheal!

Versatile Decay Station: IDS

\[ N(t) = N_0 e^{-t/\tau} \]

Talk by S. Paulauskas, A. Andreyev!

Post-acceleration
For Reaccions studies

\[ R = \frac{B(E2, 4^+ \rightarrow 2^+)}{B(E2, 2^+ \rightarrow 0^+)} \]

Shapes

NuPECC meeting @ CERN, March 10-11, 2017
Shell Evolution in Ni-isotopes (IS555)

Large theoretical and experimental discrepancies. For Ni –isotopes beyond N=40.

Transfer reaction to characterize the 5/2^+ state in ^71Ni by looking to proton angular distribution with T-REX

NuPECC meeting @ CERN, March 10-11, 2017
Search for the new magic numbers above $^{208}\text{Pb}?$(IS550)

$Z = 114, 120$ or $126$

$N = 184$

- Shell closures indicated by an increase of fission barriers and half-lives
- Influence expected in quasi-nuclei

- Nuclei with $N \approx 184$ are still far
- Nuclei with $Z > 118$ are still unknown

Study of quasi-fission and fusion-fission with $^{94,95}\text{Rb}$ projectiles with Corset

$^{95}\text{Rb} + ^{209}\text{Bi} \rightarrow Z_1 + Z_2 = 120$, $N_1 + N_2 = 184$

Asymmetric component $\rightarrow$ transfer, quasi-fission
Symmetric component $\rightarrow$ fusion-fission
Coulomb excitation of $^{182}$Hg

- More and more precise matrix elements
- Type of deformation:
  - Quadrupole (oblate, prolate, triaxial or mixing)
  - Octupole
- Collectivity in the vicinity of closed shell nuclei
  - Nucleon-nucleon correlation
- Test local symmetries
NuPECC meeting @ CERN, March 10-11, 2017

129-131 Cd produced from UC, with neutron converter and cold quartz line, and ionized with RILIS.

R-process simulations of isotopic abundances in the core-collapse supernova scenario.

ISOLTRAP masses of n-rich cadmium isotopes

Data favour Core Colapse Supernova in this region

Atanasov, PRL115 (2015) 232501