A variety of physics using radioactive beams at ISOLDE and HIE-ISOLDE @ CERN

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CERN (Switzerland) and KU Leuven (Belgium)
CERN’s Radioactive Ion Beam (RIB) facility

50% of protons at 1.4 GeV, (2 μA) from PS Booster.
Unique worldwide: high energy (1.4 GeV) protons onto a thick target, e.g. $^{238}$U

The protons split up the heavy nucleus in one of three ways
- Fission
- Fragmentation
- Spallation
Producing purified beams: RILIS

- **Resonance Ionization Laser Ion Source** (since 1994)
- **Selective and efficient ionization of one particular element** (e.g. Tin)
  
  - CAN ALSO BE USED FOR SPECTROSCOPY

![Diagram of RILIS setup]

**Proton beam**

**Isotope Mass selection with dipole magnets**

**Isotope Element selection with lasers**
A diverse research program in 15 experimental set-ups

ISOLDE PIE 2018

- ~ 35 % low-energy RIB’s for nuclear structure
- Nuclear structure from ground state properties 22%
- Nuclear structure from beta decay 14%
- Solid state physics 12%
- Biophysics 6%
- Medical physics 4%
- TISD 4%
- Coordinators reserve 6%
- ~ 20 % other
- HIE ISOLDE 32%
- Scattering chamber @Miniball 11%
- Coulomb excitation @Miniball 12%
- Transfer T-REX@Miniball 4%
- Transfer @ ISS 5%
- ~ 35 % accelerated RIB’s for nuclear and astrophysics

HIE-ISOLDE

An accelerator of Radioactive Ion Beams (RIB’s)
Now 3 experimental set-ups available

Period 2015-2018
HIE-ISOLDE
superconducting LINAC accelerates RIB’s
up to 9.5 MeV/nucleon

Since 2001:
REX-ISOLDE NC Linac accelerates RIB’s to
2.8 MeV/nucleon

40-60 keV RIB from ISOLDE
Recent highlights from HIE-ISOLDE
Safe Coulex on $^{132}\text{Sn}$

$^{132}\text{Sn}$, 5.49 MeV/u, $3 \times 10^5$ ions/s

$\rightarrow$ Precision on B(E2) improved by more than factor 10!

$^{132}\text{Sn}$ is doubly magic and spherical

$\rightarrow$ Enhanced B(E2) as compared to $^{130-134}\text{Sn}$ confirmed

$\rightarrow$ Enhanced B(E3)
ISOLDE Solenoidal Spectrometer

- 4T superconducting (former MRI) solenoid from UQ hospital, Brisbane to ISOLDE in 2017

**Helical orbit spectrometer principle**

*Target* on the field axis + array of Si detectors.

*MEASURE*: position $z$, cyclotron period $T_{\text{cyc}}$ and energy $E_p$ of emitted protons from transfer reaction

Suffers no kinematic compression of the Q-value spectrum.

Linear relationship between $E_{\text{cm}}$ and $E_{\text{lab}}$
Spring-Summer 2017: construction of proper shielding around ISS

Nov. 2017: Field mapping and beam transmission tests

Sept. 2018: Successful commissioning with stable 22Ne beam and the HELIOS Si-detector array from Argonne Nat. Lab.

October 2018: Two successful RIB experiments
  ➢ Transfer reactions using the maximum HIE-ISOLDE beam energies
EXP #1 IS621 – $^{28}$Mg(d,p)$^{29}$Mg Angular distributions results

Dave Sharp, Liam Gaffney

3.10$^5$ $^{28}$Mg/s
9.5 MeV/u

FWHM <115keV

Angular distributions extracted for 9 states up to 4.32 MeV (2 unbound).

Compared to DWBA calculations to make preliminary assignments – calculations extrapolated for unbound states.
EXP#2 IS631 - $^{206}$Hg(d,p)$^{207}$Hg set up

- $5.10^5$ $^{206}$Hg/s
- 7.4 MeV/u (purity > 98 %)

- 30 deuterated polyethylene targets (165 mg/cm²) (to deal with target degradation)
- Special target ladder (automatic moving)
Experiments with low-energy RIB’s

- **Masses**
  - ISOLTRAP (Penning trap + MR-TOF-MS)

- **Decay spectroscopy**
  - Isolde Decay Station (IDS) since 2015

- **Moments, radii and spins**
  - LASER SPECTROSCOPY (COLLAPS, CRIS, RILIS)

- **Material research** with short lived isotopes
  - Emission channeling, PAC, β-NMR, Mossbauer
Recent highlights from low-energy ISOLDE

Franchoo et al., PRC64 (2001) decay of Ni isotopes at LISOL (LLN)

Lowering of $\pi f_{5/2}$ when filling $\pi g_{9/2}$
(due to strong p-n interaction, enhanced due to tensor force)

→ Inversion of levels predicted from $^{75}$Cu onwards

I. Stefanescu et al., PRL 100 (2008)

Coulex at REX-ISOLDE up to $^{73}$Cu
→ 5/2- level is single-particle like!

T. Otsuka et al, PRL 95, 232502 (2005)
Inversion of the $\pi f_{5/2}$ and $\pi p_{3/2}$ levels in $^{75,77}$Cu

Collinear laser spectroscopy on bunched beams (ISCOOL)

Model-independent spin determinations: 5/2

Magnetic moments: proton occupies $\pi f_{5/2}$

Experimental sensitivity improved by factor 200

K.T. Flanagan et al., PRL 103 (2009)

$^{71,73,75}$Cu

R.P. de Groote et al., PRC 96 (2017)

$^{73,75,77}$Cu

Experimental sensitivity improved by another factor 300
Shape coexistence in Hg isotopes (1972 – 1986)

Hg: $Z=80$


Huge increase in the charge radii of neutron-deficient $^{181,183,185}$Hg ($N=101,103,105 \rightarrow$ neutron mid-shell)

$\Delta r = 0.7$ fm!

Shape coexistence established in $^{185}$Hg!

Microscopic description remained unexplained for more than 30 years!

Remove more neutrons: what happens??
Shape coexistence in Hg isotopes

Combining resonance laser ionisation in the RILIS ion source with detection in 3 different experimental stations!

Hg mean square charge radii

FIRST large scale MCSM calculations in this heavy mass region (Otuska et al.)

→ origin of the staggering is understood microscopically!

Due to enhanced (tensor) interaction between $vi_{13/2}$ and $\pi h_{9/2}$

→ Favors occupations of these orbits, leading to increased deformation and lowering of the energy

$E_{\text{mon}} = f(j_p, j_n)n_{\pi}(j_p)n_{\nu}(j_n)$

E(1+) intruder isomer energy in $^{34}$Al

$^{34}$Mg, 700 ions/s

1p-1h intruder state at $E = 46.6$ keV
**Search for $^{229}$Th isomer energy**

M. Verlinde et al., submitted to PRC

Requirement: $^{229}$Ac should take substitutional site in CaF

**Method: Emission Channeling**

Idea to measure radiative decay energy:
- Produce intense beam of $^{229}$Ac
- $^{229}$Ac decays into the $^{229m}$Th isomer (13%)
- To block Internal Conversion decay
  - implantation in wide bandgap material CaF (12 eV)
  - radiative decay dominates!

* Measure the radiative decay energy (VUV)
  - CaF is transparent for VUV radiation

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229Ac
\[ \beta \ (13\%) \]

229Th
\[ \lambda \sim 159 \text{ nm (VUV)} \]
\[ t_{1/2} \sim \text{hours} \]

E \sim 8 \text{ eV} \ (IC, 7 \mu s)

3/2^+

5/2^+


Courtesy P. Van Duppen, L. Pereira et al.
Outlook to the future
The EPIC Project: Exploiting the Potential of ISOLDE at CERN
(not yet approved by CERN)

The EPIC project comprises of 6 key upgrades (in no particular order):

- The addition of two new target stations and a high resolution mass separator
- Improvement of the existing beam dumps
- Provide 2 GeV protons to ISOLDE
- The addition of a second experimental hall
- Installation of a storage ring beyond the HIE-ISOLDE post accelerator
- An upgrade of the non-superconducting part of HIE-ISOLDE (REX-part)
New opportunities with EPIC@CERN for the (European) (Nuclear) Physics Community

- **Upgrade of the HIE-ISOLDE pre-accelerator (REX)**
  - higher A/Q (up to 5.5) so more intense heavy beams, with a variable time structure and up to 10 MeV/u also for those around Pb.

- **Higher RIB beam intensities (gain factor 2 to 50)**
  - thanks to the LHC intensity upgrades (LIU) at CERN
    - Higher proton beam intensity from booster (from 2 → 4 μA)
    - Higher proton beam energy (from 1.4 → 2 GeV) from booster

- **Two new (additional) target stations + a new low-energy hall**
  - Have multiple *simultaneous* beams for users (low/high energy)

- **Improved mass separation capabilities**
  - Purer beams are better for *efficient* reacceleration

- **A new storage ring for short-lived, light and heavy ions**
  - New perspectives for precision studies in nuclear, atomic and astrophysics
Conclusions

◆ ISOLDE now provides slow and accelerated RIB’s (up to ~10 MeV/u) for more than a dozen permanent experiments (and a few travelling setups) for studying:
  ◆ Nuclear physics
  ◆ Nuclear astrophysics
  ◆ Solid state physics
  ◆ Bio-physics
  ◆ Fundamental interactions and symmetries

◆ Future upgrades are under discussion in the framework of the EPIC Project (Exploiting the Potential of ISOLDE @ CERN)

First ISOLDE-EPIC workshop: December 3-4
followed by the Annual ISOLDE Users Meeting on December 5-6

Many more results and details in several contributions at this conference