HIE ISOLDE: opportunities, challenges and importance

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- Importance: key questions in nuclear physics, nuclear astrophysics, fundamental interactions and condensed matter

- Challenges: experiments with radioactive ion beams to answer these questions

- Opportunities: HIE-ISOLDE - new and higher quality beams, higher energy
Research with Radioactive Isotopes

- Decay and laser-spectroscopy
- Moments and mass measurements
- Solid-state physics experiments
- Coulomb excitation
- Transfer reactions
- Heavy-ion fusion reactions

HIE – ISOLDE: challenges

Known Nuclei (2006)

Isospin Symmetry
Pairing
Exotic decays

Shape coexistence

Specific radioactive probes for solid-state and bio-medical studies

Bound Nuclei

r-process and r-p process

Ab Initio Calculations
Halos and Skins

Magic Numbers
Evolution of Shell Structure
Weak Binding N>>Z
Diffuse Surfaces
HIE – ISOLDE: technical options (see talk M. Lindroos)

✓ ENERGY:
  Energy upgrade to 10 MeV/u and lower energy capacity

✓ INTENSITY: ISOLDE proton driver beam intensity upgrade
  strongly linked to PS Booster improvements including linac4

✓ QUALITY: ISOLDE radioactive ion beam quality: broader spectrum and
  higher quality (purity, emittance, time structure)

HIE – ISOLDE: opportunities

✓ Wide spectrum of radioactive ion beams
✓ Wide energy range: from rest to 10 MeV/u
✓ Pure beams occupying a small phase space: allows for low-intensity RIB experiments
✓ Isomeric beams: nuclear spin degree of freedom

Intensity and quality upgrade and the extended variety of beams will create new opportunities to the current research programs (cfr. K. Riisager)
This presentation mainly focuses on the higher energy capabilities
HIE – ISOLDE: opportunities

1. Testing Ab-Initio Calculations - Halos and Skins
2. Evolution of Shell Structure
3. Shape coexistence
4. Exotic decays
5. Nuclear Astrophysics
6. Solid-State Physics

- Atomic physics: ID 93
- Bio-medical and medical applications: ID 44
1. Testing Ab-Initio Calculations

- RMS Radii of nuclei cfr. $^{11}\text{Li}$, $^{9,10}\text{Be}$ (abstract ID 96)

- Nuclear Moments cfr. $^{9,11}\text{Li}$ (ID 20)

- Electroweak Matrix Elements

- Transfer reactions
Transfer reactions

• REX-ISOLDE

d($^8$Li,$^9$Li)p - 3.15 MeV/u, $\sim$10$^5$/s
Tengborn et al.

d($^9$Li,$^{10}$Li)p - 2.77 MeV/u, $\sim$10$^5$/s
Kirsebom et al.

• Reaction studies with He beams:
  • $^4$He($^6$He,$^4$He)$^6$He @ LLN
  • p($^8$He,d)$^7$He @ SPIRAL-GANIL
  • $^{12}$C($^8$He,$^7$H-$^3$H+4n)$^{13}$N @ SPIRAL-GANIL

• Reaction studies with Li beams:
  • d($^8$Li,$^9$Li)p @ ANL:
Two neutron removal reaction: $p(^{11}\text{Li},^9\text{Li})t$

Active target - GANIL

I. Tanihata et al. PRL 100, 192502 (2008)

(see talk R. Raabe ID 75)
Two-neutron transfer reactions: radioactive beam onto a radioactive target

\( ^3H(^{30}Mg,^{32}Mg)^1H \)

\( ^{30}Mg \) 
\( ^{32}Mg \) 

MINIBALL germanium detector

Si barrel detector

(1115 ± 60) keV

(13 ± 48) keV

IS470: Kathrin Wimmer
1. Test of Ab-Initio calculations – Halos and Skins

• Study properties of bound and un-bound states in light-mass(halo) nuclei – open quantum systems

**HIE-ISOLDE opportunities**

• Transfer reactions using heavier beams (A>8): \(^3\text{H}(^9\text{Li},p)^{11}\text{Li},\) \(^3\text{H}(^{12}\text{Be},p)^{14}\text{Be}\) and heavier masses (C, N and O)

• Higher energy (Q-value, higher cross sections, thicker targets, better angular momentum sensitivity, less model dependent analysis) and higher intensity

• Using active targets (also in the heavier mass region e.g. nickel and lead (see talk R. Raabe ID 75)

• Charge radii and moments (laser spectroscopy) (ID 22, 96)

• Decay studies using calorimetric detectors (ID89)
2. Evolution of Shell Structure

\[ V_{so} = -V_0 \frac{1}{r} \frac{\partial U(r)}{\partial r} \ell.s \]

\[ \rho(r) \]

\[ \frac{\partial \rho(r)}{\partial r} \]

Nuclear Shell Structure

- \( P_{3/2} \)
- \( f_{5/2} \)
- \( i_{13/2} \)
- \( P_{3/2} \)
- \( h_{9/2} \)
- \( f_{7/2} \)
- \( d_{3/2} \)
- \( h_{11/2} \)
- \( i_{1/2} \)
- \( s_{1/2} \)
- \( g_{7/2} \)
- \( d_{5/2} \)
- \( g_{9/2} \)

- \( N=5 \)
- \( N=4 \)
- \( 126 \)
- \( 112 \)
- \( 82 \)
- \( 70 \)
- \( 50 \)

Dobaczewski et al.
Phys Rev Lett 72 (1994) 981

Otsuka et al.
Phys Rev Lett 95 (2005) 232502
Measurements of one-neutron transfer on stable nuclei outside N=82

Evolution of Shell Structure studied with transfer reactions

Expect turnaround in trend, if tensor force drives changes, for higher Z.

Recent studies in the Sb region using Sn(α,t)

Radioactive beams with high yields:
132Sn, 134Te

Radioactive beams unique to ISOLDE with high yields:
146Gd, 148Dy, 150Er

Testing outside Z=50 using beams of n-deficient Sn isotopes
Testing outside N=126 using beams like 206Hg, 210Po, 212Rn and 214Ra
Evolution of shell structure studied with transfer reactions

Transfer reactions need higher energy

\[ ^{\text{32}}\text{Mg}(d,p)^{\text{33}}\text{Mg} \]

\[ ^{\text{132}}\text{Sn}(d,p)^{\text{133}}\text{Sn} \]
2. Evolution of Shell Structure

- Identify energy gaps, spin, parity and the single-particle strength outside an inert core

**HIE-ISOLDE opportunities**

- Transfer reactions requires higher energy (5 - 10 MeV/u) for adequate cross sections, angular momentum-transfer assignments and minimise dependency on reaction models (ID 33)
- Few-nucleon transfer reactions: production and study of medium spin states (ID 14)
- Wide spectrum of RIB available: study trend along closed proton/neutron shells
- Higher intensity allows decay, mass measurement and laser spectroscopy studies towards the neutron and proton drip lines (see talk K. Flanagan-ID 7, M. Kowalska-ID 85 and ID 20, 31, 53)
3. Shape co-existence in the lead region

Mean square charge radii

Potential energy surface

H. De Witte et al. PRL 98 (2007) 112501

Shape co-existence in the lead region studied with Coulomb excitation

Coulomb excitation @ 3 MeV/u
\(^{184}\text{Hg}\) (3MeV/u) + \(^{112}\text{Cd}\)

Strongly-coupled matrix elements
Band mixing
Sign, magnitude of deformation

Nick Bree, Andrew Petts et al.

Energy (keV)
4.7 MeV/u $^{74}$Kr radioactive beam - SPIRAL

Shape co-existence studied with transfer reactions

- One-neutron transfer: $^2H(^{184}Hg,p)^{185}Hg$, $^2H(^{183m,g}Hg,p)^{184}Hg$ and other Pb, Po and Rn (isomeric) beams
- Two-proton transfer: $^3He(^{184}Hg,n)^{186}Pb$

I. Stefanescu et al., PRL98 (2007) 122701
3. Shape co-existence

- Coulex populates states strongly coupled to g.s. (e.g. non-yrast states)
- Distinction between prolate and oblate deformation
- Identify the microscopic (particle-hole) origin of shape-coexistence
- Determine the degree of collectivity and mixing
- Test of local symmetries

**HIE-ISOLDE opportunities**

- Higher energy:
  - Coulex: higher yields, multiple Coulex, higher sensitivity to the sign of Q
  - Transfer: higher sensitivity to angular momentum transfer, less model dependent spectroscopic factors (ANC’s), better detection sensitivity
- Wide spectrum of RIB available: pin down N,Z specific aspects of shape co-existence (ID 6, 18, 62, 74, 83)
- Higher intensity: possibility to study weak reaction channels
- **Isomeric beams:** investigate underlying particle mechanism
Discovery of $^{229}\text{Rn}$ and the Structure of the Heaviest Rn and Ra Isotopes from Penning-Trap Mass Measurements

- Systematic deviation from the general trend of $\delta V_{pn}$ values, probably induced by the octupole deformation.

**HIE-ISOLDE opportunities**
- Higher intensities: extended range of nuclei (cfr. talk M. Kowalska ID 85, M. Scheck ID 52)
4. Rare charge-particle decay studies

- Fission of $^{180}\text{Hg}$ observed in the beta decay of $^{180}\text{Tl}$
- Unexpected asymmetric mass split
  ($^{180}\text{Hg} \ (Z=80, \ N=100) = 2 \times ^{90}\text{Zr} \ (Z=40, \ N=50)$
- Cold fission, important for the end of the r-process

HIE-ISOLDE opportunities
- Higher intensities, other nuclei
- Higher energy: implantation – decay (absolute branching ratios) (ID 89)
5. Nuclear Astrophysics

X-ray bursts (rp-process)

- Dominated by \((p,\gamma)\) and \((\alpha,p)\) reactions
  - Direct \((p,\gamma)\) or \((^3\text{He},d)/(d,n)\) as surrogate of \((p,\gamma)\)
  - \((p,\alpha)\) as inverse of \((\alpha,p)\)

Supernovae (r-process)

- Dominated by \((n,\gamma)\) reactions
  - r-process pathway largely unknown
  - Understanding of shell evolution important

- \((d,p)\) as surrogate of \((n,\gamma)\)
  (J. Cizewski et al. NIMB 261 (2007) 938)

- Measure global properties such as mass and lifetime very far from stability
Heavy Element Synthesis

NOVA, X-RAY Bursts, Type I SN

Z \uparrow

rp process

IGNITION REACTIONS

hot CNO cycle

CNO cycle

Mg-Al cycle

Ne-Na cycle

26Si
27Si
28Si
25Al
20Al
33Al
26Mg
25Mg
24Mg

23Na
21Na
20Na
19Ne
18Ne
17F
16O
15O
14N
13N
12C

(\alpha,\gamma)
(p,\gamma)
(p,\alpha)
(p,\beta^+)

TUDA chamber

LEDA detector: 8 sectors \times 16 strips

incident beam

CH\textsubscript{2} target

recoil protons

Louvain-la-Neuve, Triumf
Successful pioneering study of time reverse $^{17}\text{F}(p,\alpha)^{14}\text{O}$ reaction IS424

**HIE-ISOLDE opportunities**

- Tunable energy to apply time reverse technique to other X-ray busters reactions
- Wide spectrum of RIB available
- Mass measurements, half life determinations: need for higher intensities
6. Solid-state physics

- How do minor impurities or defects influence the electrical and optical properties of different materials (e.g. in semiconductors, metals, oxides, high-Tc superconductors)? (the chemical nature and the structure of defects and the interaction between defects)

- Low energy beams (PAC, DLTS, Mossbauer, surface studies, emission channeling)
  see talks U. Wahl ID 63, L. Hemmingsen ID 90, 64, 86, 88, 94, 96

- Diffusion in highly immiscible systems

- $\beta$-NMR with tilted-foil polarization
  tilted foils
  also applicable for nuclear physics experiments (see talk G. Georgiev ID 65)
**Existing equipment:**
- MINIBALL segmented germanium detector array: Coulex, transfer, multi-nucleon transfer
- Silicon barrel detector and multi silicon detector system: transfer reactions

**Prototype / design / preliminary study phase:**
- Bragg detector: Coulex
- Separator: identification of the reaction products
- High resolution spectrometer: \((p,d), (t,p), (α,p),…\)
- Active target: direct reactions

**Under study:**
- Neutron wall detector: \((^{3}\text{He},n),…\)
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Physics</th>
<th>Optimum energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d,p), (³He,α), (³He,d), (d,n),… transfer</td>
<td>Single-particle configurations, r- and rp-process for nucleosynthesis</td>
<td>10 MeV/u</td>
</tr>
<tr>
<td>(³He,p), (d,α), (p,t), (t,p)</td>
<td>pairing</td>
<td>5-10 MeV/u</td>
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<td>Few-nucleon transfer</td>
<td>Structure of neutron-rich nuclei</td>
<td>8 MeV/u</td>
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<td>Unsafe Coulomb excitation</td>
<td>High-lying collective states</td>
<td>6-8 MeV/u</td>
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<td>Compound nucleus reactions</td>
<td>Exotic structure at drip line</td>
<td>5 MeV/u</td>
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<tr>
<td>Coulomb excitation, g-factor measurements</td>
<td>Nuclear collectivity and single-particle aspects</td>
<td>3-5 MeV/u</td>
</tr>
<tr>
<td>(p,p'γ), (p,α), …</td>
<td>nucleosynthesis</td>
<td>2-5 MeV/u</td>
</tr>
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</table>
HIE-ISOLDE: uniqueness

- Large RIB beam variety: spallation, fission, fragmentation
- Universal acceleration scheme (REX-trap, EBIS)
- High quality beams: cooled and clean beams, isomeric beams
- Instrumentation: Penning traps, laser labs, silicon ball, MINIBALL detector, …
HIE-ISOLDE: importance, challenges and opportunities

- A unique facility for ISOL based radioactive ion beam research because of its large degrees of freedom in N and Z, in energy and in (to a certain extent) nuclear and atomic spin.
  - its wide spectrum of isotopes
  - broad energy range
  - high beam intensities and high beam quality

- Its aim is to answer important questions in
  - nuclear-structure physics
  - nuclear astrophysics
  - fundamental interaction studies
  - condensed matter research
  - atomic physics

Many thanks to:
P. Butler, Y. Blumenfeld, H. Fynbo, A. Goergen, M. Huyse, K. Riisager, N. Severijns, L. Hemmingsen, V. Amaral, U. Wahl,
Radioactive Ion Beams: In-Flight versus ISOL

In-Flight

- thin target
  - heavy ions
    - fusion
    - fragmentation
    - fission
- fragment separator
- storage ring
- μs

Experiments
- detectors
- spectrometers
- ...

Isotope Separator On Line (ISOL)

- high-temperature thick target
  - light & heavy ions, neutrons, electrons
    - spallation
    - fission
    - fragmentation
- ion source
- mass separator
- post accelerator
- ~ ms to s

50 MeV/u to 1 GeV/u

100 MeV/u
4. Octupole shapes and the Standard Model

Coulomb excitation populates odd and even-even Radon and Radium with N~134
See talk M. Scheck ID 52
4. Octupole shapes and the Standard Model

Tests of \( CP \) invariance in hadronic sector from static Electric Dipole Moment (EDM) of atom (best limits so far from \(^{199}\text{Hg}\) on \( \theta_{\text{QCD}}, d_d, C_T, C_S, \varepsilon_q^\text{SUSY}, \varepsilon^{\text{HIGGS}}, \chi^{\text{LR}} \)

M.V. Romalis et al., PRL 86 (2001) 2505

Expect enhancement (by \( 10^2 \)) of EDM in octupole radioactive nuclei, e.g. \(^{223}\text{Rn}, ^{225}\text{Ra}\)

Schiff moment is the quantity responsible for inducing an EDM in the electrons orbiting the nucleus:

\[
S \approx -\frac{2}{3} \left( \langle \hat{S}_z \rangle \frac{\langle \hat{V}_{\text{PT}} \rangle}{E_0 - E_i} \right)
\]

parity doublet

Octupole deformation

Dobaczewski and Engel, Phys. Rev. Lett. 94 (2005) 232502

L.I. Schiff, Phys. Rev. 132 (1963) 2194

HIE-ISOLDE opportunities

- High intensities, heavy isotopes
- Atomic parity violation studies (e.g. Ra): (ID 45)