Recent Results from ISOLDE and new Opportunities with HIE- ISOLDE

Mark Huyse
IKS, K.U.Leuven, Belgium
The many lives of ISOLDE

The first 40 years of physics at ISOLDE

ISOLDE PHYSICS WORKSHOP
AND
USERS MEETING
December 17 - 19, 2007

Prof. Bjorn JONSON (Chalmers University of Technology)
CERN accelerator complex

1.2x10^{13} pps 1 or 1.4 GeV p
RIB - Production reactions

- Spallation
- Fragmentation
- Fission
  - n- (thermal or energetic), p-induced
  - Photofission (e-beam)
- Fusion
Target - Ion-source matrix

ISOLDE Target distribution 2007

- UC 66.9%
- Sn 4.8%
- CaO 2.9%
- SIC 8.6%
- Pb 0.3%
- HfD 0.9%
- Ti 4.6%
- Ta 5.7%

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Surface & plasma ionization

Surface Ionization

Ionization by electron impact

atom
ion

hot metal surface

continuum
vacuum

ionization energy
< 5-6 eV

ground state
work function
conduction band
Fermi energy

continuum
ionization energy
< electron impact energy

ground state

fast electrons

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Laser ionization

Laser Ionization

- laser beams
- atom
- ion
- continuum
- ionization energy < 9-10 eV
- excited states
- ground state

Target Ion Source Unit

Distance to Target: 20m

CERN

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ISOLDE Table of elements

ION SOURCE:
+ SURFACE —
+ hot PLASMA cooled LASER

<table>
<thead>
<tr>
<th>H</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>F</th>
<th>Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
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<td>Be</td>
<td>K</td>
<td>Ca</td>
<td>Sc</td>
<td>Ti</td>
<td>V</td>
<td>Cr</td>
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<tr>
<td>Na</td>
<td>Rb</td>
<td>Sr</td>
<td>Y</td>
<td>Zr</td>
<td>Nb</td>
<td>Mo</td>
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<tr>
<td>Mg</td>
<td>Sr</td>
<td>Ba</td>
<td>La</td>
<td>Hf</td>
<td>Ta</td>
<td>W</td>
</tr>
<tr>
<td>Rb</td>
<td>Cs</td>
<td>Ba</td>
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<td>Hf</td>
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<td>Ra</td>
<td>Ac</td>
<td>Rf</td>
<td>Db</td>
<td>Sg</td>
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<td></td>
<td></td>
<td></td>
<td>Ce</td>
<td>Pr</td>
<td>Nd</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Th</td>
<td>Pa</td>
<td>U</td>
</tr>
</tbody>
</table>

SURFACE
- hot PLASMA
  cooled LASER

112 113 114 115

113

Ion Source:

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ISOLDE yields, 2006

So far >600 radioactive isotopes of >60 elements @ 60 keV

http://isolde.web.cern.ch/ISOLDE/
October 2001: a new dimension

Post acceleration by REX-ISOLDE
up to 3 MeV/u
**REX-ISOLDE OVERVIEW**

**Nier-spectrometer**
- Select the correct A/q and separate the radioactive ions from the residual gases.
- A/q resolution ~150

**EBIS**
- Super conducting solenoid, 2 T
- Electron beam < 0.4 A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity 6·10^10 charges
- A/q < 4.5

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- Super conducting solenoid, 2 T
- Electron beam < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity 6·10^10 charges
- A/q < 4.5

**REX-trap**
- Cooling (10-20 ms)
- Buffer gas + RF
- (He), Li,...,U
- 10^8 ions/pulse
- (Space charge effects >10^5)

**Linac**
- Length 11 m
- Freq. 101 MHz (202 MHz for the 9GP)
- Duty cycle 1ms 100 Hz (10%)
- Energy 300 keV/u, 1.2-3 MeV/u
- A/q max. 4.5 (2.2 MeV/u), 3.5 (3 MeV/u)

**Total efficiency : 1 - 10%**
## World ISOL accelerated beams

<table>
<thead>
<tr>
<th>FACILITY</th>
<th>DRIVER</th>
<th>POWER (kW)</th>
<th>USER BEAMS ACCELERATED</th>
<th>ENERGY (MeV/u)</th>
<th>PHYSICS REACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOUVANE-LA-NEUVE</td>
<td>30 MeV</td>
<td>6</td>
<td>$^6$He, $^7$Be, $^{10,11}$C, $^{13}$N, $^{15}$O, $^{16}$F, $^{18,19}$Ne, $^{35}$Ar</td>
<td>10</td>
<td>cyclotron,</td>
</tr>
<tr>
<td>(BELGIUM) 1989</td>
<td>protons</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear structure</td>
</tr>
<tr>
<td>HRIBF Oak Ridge (USA)</td>
<td>100 MeV</td>
<td>1</td>
<td>$^{7}$Be, $^{17,18}$F, $^{69}$As, $^{76-79}$Cu, $^{67,83-85}$Ga, $^{80}$, $^{82-86}$Ge, $^{69}$As, $^{83-84}$Se, $^{92}$Sr, $^{118,120,122,124}$Ag, $^{128}$, $^{132-134}$Sn, $^{129,132,134,136}$Te</td>
<td>2 - 10</td>
<td>tandem (-ve ion source)</td>
</tr>
<tr>
<td>1997</td>
<td>p, d, $\alpha$</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear Structure, Astrophysics</td>
</tr>
<tr>
<td>ISAC TRIUMF (CANADA)</td>
<td>500 MeV</td>
<td>50</td>
<td>$^{8,9,11}$Li, $^{11}$Be, $^{18}$F, $^{20-22,24-29}$Na, $^{23}$Mg, $^{26}$Al</td>
<td>1.5 - 5</td>
<td>linac,</td>
</tr>
<tr>
<td>2000</td>
<td>protons</td>
<td></td>
<td></td>
<td></td>
<td>Astrophysics, Condensed matter, Nuclear Structure</td>
</tr>
<tr>
<td>SPIRAL GANIL (FRANCE)</td>
<td>100 MeV/u</td>
<td>6</td>
<td>$^{6,8}$He, $^{14,15,19-21}$O, $^{18}$F, $^{17-19,23-26}$Ne, $^{33-35,44,46}$Ar, $^{74-77}$Kr</td>
<td>2 - 25</td>
<td>cyclotron,</td>
</tr>
<tr>
<td>2001</td>
<td>heavy ions</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear structure, Astrophysics</td>
</tr>
<tr>
<td>REX ISOLDE (CERN)</td>
<td>1.4 GeV</td>
<td>3</td>
<td>$^{8,9}$Li, $^{10-12}$Be, $^{10}$C, $^{17}$F, $^{24-29}$Na, $^{28-28,30}$Mg, $^{61-62}$Mn, $^{61-62}$Fe, $^{68}$Ni, $^{67-73}$Cu, $^{74,76,78,80}$Zn, $^{70}$Se, $^{88,92}$Kr, $^{96}$Sr, $^{108}$In, $^{106,108,110}$Sn, $^{100,102,104,122,124,126}$Cd, $^{138,140,142,144}$Xe, $^{140,142,148}$Ba, $^{148}$Pm, $^{183}$Sm, $^{186}$Eu, $^{182,184,186,188}$Hg, $^{202,204}$Rn</td>
<td>0.3 - 3</td>
<td>linac,</td>
</tr>
<tr>
<td>2001</td>
<td>protons</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear structure, Condensed matter, Astrophysics</td>
</tr>
</tbody>
</table>

So far 63 radioactive isotopes of 24 elements
Users & Science

- 450 users
- 25 countries; 100 institutions
- 175 projects (4 years)
A rich basket

- Solid-state studies
- Mass measurements
- Moments and radii
- Decay studies
  - Coulomb excitation
  - Elastic scattering
  - Transfer reactions
The many lives of ISOLDE

Thanks to

– The primary beams of CERN
  • Almost the whole nuclear chart is available when combined with e.g. $^{238}\text{U}$

– Continuous target-ion source techniques
  • Laser ion source

– Innovative beam manipulation
  • Rex concept

– Innovative experimental set-upps
  • Collaps, ISOLTRAP, MiniBall, Witch, …

– Strong users community
The fifth decade of ISOLDE
## Technical goals for HIE-ISOLDE

### ENERGY: REX energy upgrade and increase of current capacity
- Energy upgrade in 3 stages: 5.5 MeV and 10 MeV/u and lower energy capacity

### INTENSITY: ISOLDE proton driver beam intensity upgrade - strongly linked to PS Booster improvements including linac4
- Faster cycling of the booster
- New target stations for ISOLDE
- New targets
- New target handling system

### QUALITY: ISOLDE radioactive ion beam quality – more than half already financed through the ISOLDE collaboration
- Smaller longitudinal and transverse emittance
  - Done – RFQ cooler operational
- RILIS upgrade and LARIS construction
  - Done
- Charge breeder upgrade
- Better mass resolution
- Continue target and ion source developments
Upgrade of the on-line RILIS

Diode Pumped Solid State Nd:YAG Lasers as replacement of Copper Vapor Lasers:

- **CVL**
  - Green Beams: 45 W @ 511 nm
  - Yellow Beams: 35 W @ 578 nm

- **SSL**
  - Green Beams: 92 W @ 532 nm
  - UV Beam: 18 W @ 355 nm
  - IR Beam: 45 W @ 1064 nm

Ga ion beam has been produced with the SSL

Improvement of ionization efficiency by SSL:
- Two dye lasers were applied at 1\textsuperscript{st} step of excitation - x 2.2
- More power could be delivered to HRS target at the 2\textsuperscript{nd} step of excitation

And CVLs are still available for runs...
Shape coexistence in the Pb region

$^{182}$Pb: $T_{1/2}$ 55 ms 1 count/min


Resonant Laser Ionization
Pb: H. De Witte et al. PRL 98 (2007) 112501
Po: T. Cocolios et al., under analysis

ISOLDE; more than 30 years ago
ISCool: RFQ-Cooler

- Results + further studies
  - High transmission efficiencies
    - Space charge limits (up to $10^8$/s)
  - 10 x decrease in emittance
  - Easy beam tuning
  - Bunching
    - New applications (see further)
  - Yield measurements: continuous vs. bunched
  - Losses due to trapping time

<table>
<thead>
<tr>
<th>Ion</th>
<th>transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li$^+$</td>
<td>17%</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>27%</td>
</tr>
<tr>
<td>K$^+$</td>
<td>60%</td>
</tr>
<tr>
<td>Cs$^+$</td>
<td>70%</td>
</tr>
</tbody>
</table>

$^{75}\text{Ga}$
Continuous photon counting

Photons gated by ion bunch
Spin assignment from in-source laser spectroscopy

A.F. Lisecky, B. A. Brown, M. Horoi, EPJ Direct 2005

Yield of $^{75}$Cu $\sim 5 \times 10^4$/uC
5 out of 6 peaks resolved

Kieran Flanagan et al.
Beam manipulation in REXTRAP and REX-EBIS

Jarno Van De Walle et al.
The proposed HIE-LINAC

3 stages installation

Matteo Passini

Review panel of HIE-LINAC R&D work
15-16 June 2009

7/05/2009
### Beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy (MeV/u)</td>
<td>Initially 3, finally 1.2</td>
</tr>
<tr>
<td>Final energy (MeV/u)</td>
<td>5.5 (stage 1) 10.0 (stage 2) and low energy capacity (stage 3)</td>
</tr>
<tr>
<td>$A/q$</td>
<td>3 to 4.5 (presently limited by IH1)</td>
</tr>
<tr>
<td>Intensity</td>
<td>&lt;2 enA (much smaller in case of exotic beams)</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>10% (CW with new ECR, new RFQ and new IH1 structure)</td>
</tr>
<tr>
<td>Length available</td>
<td>25m (including the RFQ)</td>
</tr>
<tr>
<td>Energy Variability</td>
<td>From 1.2 up to 10 MeV/u, maybe with deceleration</td>
</tr>
</tbody>
</table>
The proposed HIE-LINAC layout
What becomes possible with the upgrade

• Intensity
  – Not a step function but important for all users
• Quality of the beam
  – ISCOOL
• Energy of the beam
  – Solid-state physics
Solid-state physics

Diffusion in highly immiscible systems

Beta-NMR with tilted-foil polarization
What becomes possible with the upgrade

- **Intensity**
  - Not a step function but important for all users
- **Quality of the beam**
  - ISCOOL
- **Energy of the beam**
  - Solid-state physics
  - Nuclear physics
    - Decay studies
Rare charged-particle decay studies

Implantation-decay tagging
Successfully used at LLN, TRIUMF, KVI

Andrei Andreyev, Riccardo Raabe et al.

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What becomes possible with the upgrade

- Intensity
  - Not a step function but important for all users
- Quality of the beam
  - ISCOOL
- Energy of the beam
  - Solid-state physics
  - Nuclear physics
    - Decay studies
    - Coulomb excitation
The Coulex program

- Mg
- Cu
- Ni
- Zn
- Sr
- Kr
- Ba
- Cd
- Xe
- Sn
- Mn
- Fe
- Hg
- Rn
- Se
- Sr
- Mn
- Fe

Diagram showing isotope locations on a nuclear chart.
Coulomb excitation

$^{182}\text{Hg}$

$^{184}\text{Hg}$

$^{186}\text{Hg}$

$^{188}\text{Hg}$

Nick Bree, Andrew Petts et al.

98$\pm$14

Hg x rays coincidences with $2^+_1 \rightarrow 0^+_1$

$^{112}\text{Cd}$ $2^+_1 \rightarrow 0^+_1$, $2^+_2 \rightarrow 0^+_1$

$4^+_1 \rightarrow 2^+_1$, $2^+_2 \rightarrow 2^+_1$

$4^+_1 \rightarrow 2^+_1$

Entries 628
Mean 186.6
RMS 146
Underflow 0
Overflow 0
Integral 572

pmrbeam

pmr

Hg x rays

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A step function in the Coulomb excitation studies

- Coulex will preferentially populated states strongly coupled to g.s.
  - Non-yrast states
- Distinction between prolate and oblate deformation
- Degree of collectivity and degree of mixing can be deduced
What becomes possible with the upgrade

• Intensity
  – Not a step function but important for all users
• Quality of the beam
  – ISCOOL
• Energy of the beam
  – Solid-state physics
  – Nuclear physics
    • Decay studies
    • Coulomb excitation
    • Nuclear reactions
Nuclear reactions for astrophysics

- Lower energies are needed
- Adopted instrumentation
  - See e.g. TUDA
A step function in transfer reaction studies

- Due to the higher energy
  - Higher cross sections
  - Better detection sensitivity
  - Less model dependence of spectroscopic factors
  - Dedicated recoil spectrometer

First experiment: $^2\text{H}^{(30}\text{Mg},p)^{31}\text{Mg}$ (REX-ISOLDE)

Courtesy Vinzenz Bildstein
Search for the second $0^+$ state in $^{32}\text{Mg}$ applying a two-neutron transfer reaction

$^3\text{H} (^{30}\text{Mg}, ^{32}\text{Mg}) ^1\text{H} @ 2 \text{ MeV/u}$

Tritium loaded Titanium foil
0.5 mg/cm$^2$ Ti foil
atomic ratio $^3\text{H}/\text{Ti}$ 1.5
Beam intensity $4 \times 10^4$ $^{30}\text{Mg}$/s

Kathrin Wimmer et al.
Roadmap to HIE-ISOLDE

- The HIE-ISOLDE project is a participative project
  - Direct member state contributions should be at least 50%
- The first phase has been launched
  - RFQ cooler
    - UK, Germany, France and Finland
  - RILIS replacement
    - Sweden
  - LINAC development and prototyping
    - Belgium
- Different grant requests are in progress
- Discussion at the CERN level on the MidTermPlan are ongoing
Thanks and you are all kindly invited to:

**NEW OPPORTUNITIES IN THE PHYSICS LANDSCAPE AT CERN**

11/13 May '09
Main Auditorium

Workshop to preview and discuss plans to diversify the scientific programme for non-LHC experiments.

Sessions:
- SPS Deep-Inelastic Scattering, including polarized targets
- SPS Rare-Isotope and COSY
- SPS Hadrons & Ions
- PS and Non-accelerator experiments
- Isolde
- sTOF
- Test Beams & Irradiation facilities
- Antiproton Decelerator (AD)
- Possible future developments
- Other facilities
- New Physics drivers at CERN

Organizing Committee

Contact: new-phys@cern.ch / http://isolde.cern.ch/news/51128/