Nuclear physics:
the ISOLDE facility

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on behalf of the CERN ISOLDE team
www.cern.ch/isolde
Outline

- Forces inside atomic nuclei
- Nuclei and QCD, nuclear models
- Nuclear landscape
- Open questions in nuclear physics

- ISOLDE facility
- Radio-isotope production
- Physics of ISOLDE
- Examples of experimental setups
- Physics case: “island of inversion”
Nuclear physics today
Forces acting in nuclei

- **Coulomb force** repels protons

- **Strong interaction** ("nuclear force") causes binding which is stronger for pn-systems than nn-systems

- Neutrons alone form no bound states (exception: neutron stars (gravitation!))

- **Weak interaction** causes β-decay
Nuclei and QCD

- Different energy scales
- In nuclei: non-perturbative QCD, so no easy way of calculating
- Have to rely on nuclear models (shell model, mean-field approaches)
- Recent progress: lattice QCD
Nuclear landscape

- About 300 stable isotopes: nuclear models developed for these systems
- 3000 radioactive isotopes discovered up to now
Properties of radio-nuclides

Different neutron-to-proton ratio than stable nuclei leads to:

- New structure properties
- New decay modes

=> Nuclear models have problems predicting and even explaining the observations

Example - halo nucleus $^{11}$Li:

- Extended neutron wave functions make $^{11}$Li the size of $^{208}$Pb
- When taking away 1 neutron, the other is not bound any more ($^{10}$Li is not bound)
Open questions in nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

**Observables:**
Ground-state properties: mass, radius, moments
Half-lives and decay modes
Transition probabilities

**Main models:**
Shell model (magic numbers)
Mean-field models (deformations)
Ab-initio approaches (light nuclei)

(NuPECC long-range plan 2010)
ISOLDE: CERN radio-nuclide factory
Radioactive-ion beam facilities

- Renaissance of nuclear physics:
  - access to nuclei with new proton-to-neutron ratios
  - testing ground for nuclear models
  - allows many applications
Radioactive-ion beam facilities

- 1967: ISOLDE-CERN: first ISOL-type facility
- Now:

![Map of radioactive-ion beam facilities worldwide](image)
ISOLDE – short history

First beam October 1967

Upgrades 1974 and 1988

New facility June 1992
ISOLDE at CERN
ISOLDE within CERN accelerators
ISOLDE elements

Isotope production via reactions of light beam with thick and heavy target

Production – ionization – separation
ISOTOPE production

$1 \text{ GeV } p \rightarrow 238U \rightarrow \text{spallation} \rightarrow 201\text{Fr} + \text{fragmentation} \rightarrow 11\text{Li} + X + 235\text{U} \rightarrow \text{fission} \rightarrow 143\text{Cs} + 89\text{Y}$
Targets

- Over 20 target materials and ionizers, depending on beam of interest
- U, Ta, Zr, Y, Ti, Si, ...
- Target material and transfer tube heated to 1500 – 2000 degrees
- Operated by robots due to radiation
Ionization

- Surface
- Plasma
- Lasers

Diagram showing atom and ion with laser beams, fast electrons, and energy levels.
Production, ionization, extraction

Ion energy: 30-60keV

Target
Target+ vacuum+ extraction

robots
Separation

Magnet separators (General Purpose and High Resolution)
Post-acceleration

- REX accelerator
- Rf acceleration
- A/q selection
- Increase in charge state
- Ion trapping and cooling

3MeV*A beam to experiment
## Production and selection example

<table>
<thead>
<tr>
<th>Facility</th>
<th>C11</th>
<th>C13</th>
<th>C15</th>
<th>C17</th>
<th>C18</th>
<th>C19</th>
<th>C20</th>
<th>C21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5730 y</td>
<td>2.449 s</td>
<td>0.747 s</td>
<td>193 ms</td>
<td>95 ms</td>
<td>46 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 ms</td>
<td>b</td>
<td>b</td>
<td>b</td>
<td>b</td>
<td>b</td>
<td>b</td>
<td>b</td>
<td>b</td>
</tr>
<tr>
<td>B13</td>
<td>17.36 ms</td>
<td>13.8 ms</td>
<td>10.5 ms</td>
<td>200 Ps</td>
<td>5.08 ms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B14</td>
<td>2.36 ms</td>
<td>0.9 MeV</td>
<td>0.3 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B15</td>
<td>8.5 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B16</td>
<td>0.5 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes:
- **Be14**: 4.35 ms 0+
- **Li11**: 8.5 ms 3/2-
- **Li12**: 2.3 MeV 3/2-
- **He10**: 0.3 MeV 0+
Decay spectroscopy
Coulomb excitation
Transfer reactions
Laser spectroscopy
Beta-NMR
Penning traps

**Experimental hall**

Target stations
HRS & GPS

PS-Booster
1.4 GeV protons

3\times10^{13} \text{ ppp}

Collection points

Travelling setups

MINIBALL and T-REX

Post-accelerated beams

Travelling setups

Post-accelerated beams

MINIBALL and T-REX

Post-accelerated beams

Travelling setups

Post-accelerated beams

MINIBALL and T-REX

Post-accelerated beams
Facility photos
Experimental beamlines
More than 700 nuclides of over 70 chemical elements delivered to users – by far largest choice among ISOL-type facilities (experience gathered over 40 years)
Physics topics

**Nuclear Physics**
- Nuclear Decay Spectroscopy and Reactions
- Structure of Nuclei
- Exotic Decay Modes

**Atomic Physics**
- Laser Spectroscopy and Direct Mass Measurements
- Radii, Moments, Nuclear Binding Energies

**Applied Physics**
- Implanted Radioactive Probes, Tailored Isotopes for Diagnosis and Therapy
- Condensed matter physics and Life sciences

**Fundamental Physics**
- Direct Mass Measurements, Dedicated Decay Studies - WI CKM unitarity tests, search for b-n correlations, right-handed currents

**Nuclear Astrophysics**
- Dedicated Nuclear Decay/Reaction Studies
- Element Synthesis, Solar Processes

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Laser and beta-NMR spectroscopy

**Detection method depends on the case** => optimised for best S/N ratio

*Observables:* Hyperfine structure, isotope shifts, Nuclear Magnetic Resonance

*Information:* ground-state spin (+parity assignment), charge radius, moments

=> Probing single-particle and collective properties
Laser and beta-NMR spectroscopy
Penning-trap mass spectrometry

Observable: cyclotron frequency
Information: mass
=> shell structure, deformations

$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$

**determination of cyclotron frequency**
$(R = 10^7)$

**removal of contaminant ions**
$(R = 10^5)$

**Bunching of the continuous beam**

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**ISOLTRAP setup**

**Reference ion source**

**ISOLDE**
60 keV ion beam

**RFQ cooler and buncher**

**HV platform**

**ToF**
MCP 1

**MCP 2**

**MCP 3**

**Precison Penning trap**
$B = 6T$

**Preparation Penning trap**
$B = 4.7T$
Penning-trap mass spectrometry
Coulomb excitation

Miniball setup

Observables: Transition energies and intensities
Information: reduced transition matrix elements
=> Study collectivity and deformations
Coulomb excitation
Transfer reactions

Miniball + T-REX setup (Si detector barrel): gamma detectors and particle identification

Typical reactions: one or two-nucleon transfer (d,p), (t,p)

Observables
- energies of protons (+ E_g)
- angular distributions of protons (+ γ-rays)
- (relative) spectroscopic factors

Information:
- (single-particle) level energies
- spin/parity assignments
- particle configurations

study single-particle properties of nuclei

=> Similar configurations = large overlap of wave functions = Large probability of transfer reaction
“Island of inversion”: discovery

Nuclear shell model developed on stable nuclei works very well until 1975: mass measurements of neutron-rich Ne, Na, Mg isotopes => trend in binding energies can be only explained by large deformation and thus no shell closure at N=20

=> Collapse of the backbone

Mass measurements at PS-CERN
**Island of inversion: explanation**

**Decreased N=20 shell gap**
*(or even disappeared)*

**Increased correlations**

*In low-lying excited states and even in the ground state, neutrons occupy higher (intruder) orbitals before the usual shell is closed.*

**Inversion of the usual level filling**

But for nuclei with more protons, N = 20 is again a magic number.

**Name: island of inversion**

This hypothesis has to be tested/confirmed experimentally.
Mg spins and moments

Spins, parities and magnetic moments => single-particle nature

Laser and beta-NMR spectroscopy on 29-33Mg
With COLLAPS setup

\[ \text{pf shell: } p_{\frac{1}{2}}, f_{\frac{3}{2}}, p_{\frac{3}{2}}, f_{\frac{5}{2}} \]
\[ \text{sd shell: } d_{\frac{3}{2}}, s_{\frac{1}{2}}, d_{\frac{5}{2}} \]

N=20

29Mg

29Mg outside the “island”
31,33Mg inside; with 2 nucleons across N=20

Mg Coulomb excitation

Coulomb excitation on 30,32Mg with MINIBALL setup

World results for Mg Coulomb excitation:
only ISOLDE can provide pure e.m. excitation ("safe Coulex")

Excitations across N=20 will increase collectivity, due to more active nucleons and thus more correlations

Increase in collectivity from 30Mg to 32Mg (N=20)

32Mg, transfer reaction

Two-neutron \((t,p)\) transfer reactions on 30,32Mg

Allow finding 1st excited 0+ state and probing its nature: “normal” spherical structure or deformed structure based on 2 neutrons excited across \(N=20\)

existence of excited 0+ state in 32Mg at 1058 keV

cross section to populate 32Mg excited 0+ state points to its similarity to 30Mg ground-state, i.e. spherical structure made of orbitals below \(N=20\)

32Mg, transfer reaction

Coexistence of spherical and deformed states

Coexistence of spherical and deformed states

30Mg 32Mg

0+ 2+

E0  E2

inversion

confirmed

normal sd configurations

intruder fp configurations

30Mg 31Mg 32Mg

0+ 2+

0+ 2+
Mg: laser spectroscopy

Laser spectroscopy with COLLAPS

HFS structure of $^{21}$Mg observed in $\beta$-decay asymmetry

Smallest radius at $N=14$, not $N=20$: Migration of the shell closure

D. Yordanov et al, in preparation
What did we learn?

- Normal sd configuration
- 2 neutrons in pf shell
- Mixed configuration

- Already at N=19 neutrons occupy higher orbits
- Transition to island of inversion is sudden
- Spherical and deformed shapes coexist at low energies
- Deformed ground states show mainly 2 neutrons across N=20 (in pf shell)
- New magic number (N=14 or N=16) appears
- Theories start agreeing with experiment

=> Mechanism driving the island connected to tensor part of nuclear interaction
=> There can be other islands like this one
(but interaction details need to be worked out based on more experiments)
Summary and outlook

- Nuclear physics describes the atomic nucleus
- Since several decades radioactive-beam facilities have given access to many short-lived nuclei
- These nuclei have different properties than stable nuclei on which nuclear models were based
- Open questions include the description and prediction all observed properties and theoretical connection to QCD
- ISOLDE facility at CERN provides many radio-nuclides
- Various setups look at the nuclear physics, fundamental studies and applications
- Complementarily of methods is well seen in the famous “island of inversion” region
- One answer brings new questions ...
Thank you for your attention
Example – island of inversion

Decreased N=20 shell gap
(or even disappeared)
Increased correlations

In low-lying excited states and even in the ground state
neutrons occupy higher (intruder) orbitals before the usual shell is closed

Inversion of the usual level filling
But for nuclei with more protons N = 20 is again a closed shell

Name: island of inversion

This hypothesis has to be investigated experimentally
Results – island of inversion

- Laser and NMR spectroscopy
- Laser spectroscopy

Transfer reactions

\[ \Delta L = 0 \Rightarrow 0^+ \rightarrow 0^+ \]

Decay
Results - island of inversion

=> Theories can now reproduce most results
=> Mechanism driving the island connected to tensor part of nuclear interaction
=> There can be other islands like this one
(but interaction details need to be worked out based on more experiments)
- **Spin** (orbital+intrinsic angular momentum), **parity** ($I^\pi$)
- Nuclear **$g$-factor** and **magnetic** dipole **moment** ($g_I$ and $\mu_I$)
  - Electric quadrupole moment ($Q$)
  - **Charge radius** ($\langle r^2 \rangle$)

**Give information on:**
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

<table>
<thead>
<tr>
<th>Spin Orbit</th>
<th>Parity</th>
<th>$g_I$ and $\mu_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2$^+$</td>
<td>$I^\pi$</td>
<td>$</td>
</tr>
<tr>
<td>0d$_{3/2}$</td>
<td></td>
<td>$\mu = +0.54$</td>
</tr>
<tr>
<td>1s$_{1/2}$</td>
<td></td>
<td>$0d_{3/2}$</td>
</tr>
<tr>
<td>0d$_{5/2}$</td>
<td></td>
<td>$1s_{1/2}$</td>
</tr>
</tbody>
</table>

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<th>Spin Orbit</th>
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<tbody>
<tr>
<td>3/2$^+$</td>
<td>$I^\pi$</td>
<td>$</td>
</tr>
<tr>
<td>0d$_{3/2}$</td>
<td></td>
<td>$\mu = +1.83$</td>
</tr>
<tr>
<td>1s$_{1/2}$</td>
<td></td>
<td>$0d_{3/2}$</td>
</tr>
<tr>
<td>0d$_{5/2}$</td>
<td></td>
<td>$1s_{1/2}$</td>
</tr>
</tbody>
</table>

**Electric Quadrupole Moment ($Q$):**
- $Q=0$: spherical
- $Q>0$: prolate
- $Q<0$: oblate

**Charge Radius ($\langle r^2 \rangle$):**
- Volume
- Deformation
- Pairing
## Production process

### Table:

<table>
<thead>
<tr>
<th>Element</th>
<th>Charge</th>
<th>Mass</th>
<th>Energy</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be14</td>
<td>0+</td>
<td>5730</td>
<td>4.35</td>
<td>n, n, 2n,...</td>
</tr>
<tr>
<td>B13</td>
<td>3/2-</td>
<td>2.449</td>
<td>1.93</td>
<td>0+</td>
</tr>
<tr>
<td>B14</td>
<td>2-</td>
<td>0.747</td>
<td>10.5</td>
<td>0+</td>
</tr>
<tr>
<td>B15</td>
<td>0-</td>
<td>193</td>
<td>95</td>
<td>0+</td>
</tr>
<tr>
<td>B16</td>
<td>0-</td>
<td>5.08</td>
<td>200 Ps</td>
<td>0+</td>
</tr>
<tr>
<td>B17</td>
<td>0-</td>
<td>46</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>

### Diagram:

- **Hot Cell**
- **Robot Control**
- **Robots**
- **GPS Target**
- **Proton Beam**
- **GPS Separator**
- **Control Room**
- **HV Platform**
- **COLLAPS**
- **COMPLIS**
- **COLTRAP**

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**Legend:**
- C:
- Li:
- He:
- Bn: n, n, 2n,...
Fast-timing gamma spectroscopy

Gamma spectroscopy with BaF2 crystals (very fast response, <ps lifetime studies)

=> Transition energies and probabilities, deformations
Mg: fast-timing

fast timing $\beta\gamma\gamma(t)$ using BaF$_2$ detectors

$\Rightarrow$ level lifetimes in 30,31,32Mg

(transition probabilities)

2+ state lifetime:

\[ B(E2; 0^+ \rightarrow 2^+) = 327(87) \ e^2\text{fm}^4, \]

Deformed ground state

Spherical ground state

1789 keV level established: candidate for deformed 0+ configuration in 30Mg

30Mg: E0 transition

E0 decay of 30Mg electron spectrometer

Identification of 0+ state at 1789 keV; small mixing amplitude with spherical ground state => deformed state

30Mg: spherical 0+ ground-state, deformed 1st 0+ state (2 neutrons across N=20) => shape coexistence

### Results – decay of light nuclei

#### Even a neutron rich-nucleus emits charged particles

- **$^{11}\text{Li}_8$**
  - $\frac{3}{2}^-$
  - $E = 20.6$ MeV
  - $T_{1/2} = 8$ ms
  - 1966

- **$^{9}\text{Be}+2\text{n}$**
  - $E = 7.315$ MeV
  - 1979

- **$^{10}\text{Be}+\text{n}$**
  - $E = 0.320$ MeV
  - 1974

- **$^{9}\text{Li}+\text{d}$**
  - $E = 8.982$ MeV
  - 1980

- **$^{8}\text{Li}+\text{t}$**
  - $E = 15.72$ MeV
  - 1983

- **$^{17}\text{Li}$**
  - $E = 17.91$ MeV
  - 1996
<table>
<thead>
<tr>
<th>Atoms</th>
<th>Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>shell model:</strong> e⁻ fill quantized energy levels</td>
<td><strong>Description:</strong> shell model (but not only): p and n separately fill quantized energy levels</td>
</tr>
<tr>
<td><strong>Quantum numbers</strong></td>
<td><strong>Quantum numbers</strong></td>
</tr>
<tr>
<td>$n, l, m_\ell, s, \text{parity } (-1)\uparrow$</td>
<td>$n, l, m_\ell, s, \text{parity } (-1)\uparrow$</td>
</tr>
<tr>
<td><strong>Lowest en. levels</strong></td>
<td><strong>Lowest en. levels</strong></td>
</tr>
<tr>
<td>max. $S$ possible (due to Coulomb force): $J= L+S= \Sigma l_i + \Sigma s_i$ or $J= \Sigma j_i = \Sigma (l_i +s_i)$</td>
<td>min. $S$ possible (due to strong force pairing): $J = \Sigma j_i = \Sigma (l_i +s_i)$</td>
</tr>
<tr>
<td><strong>Spin-orbit coupling</strong></td>
<td><strong>Spin-orbit coupling</strong></td>
</tr>
<tr>
<td>weak</td>
<td>strong</td>
</tr>
<tr>
<td>for 3 electrons in a $d$ orbital</td>
<td>for 3 nucleons in a $d$ orbital</td>
</tr>
<tr>
<td>$\uparrow \uparrow \uparrow \leftarrow \leftarrow$</td>
<td>$d_{3/2}$ $d_{5/2}$ $\uparrow \leftarrow \uparrow$</td>
</tr>
<tr>
<td>calculated by solving Schrödinger equation with central potential dominated by nuclear Coulomb field</td>
<td>not easily calculated; nucleons move and interact within a self-created potential</td>
</tr>
</tbody>
</table>

**Energy levels**
Nuclear potential

![Graph showing nuclear potential vs distance between proton and neutron. The x-axis represents distance in units of 10^{-13} cm, and the y-axis represents potential energy in units of 10^6 eV. The graph includes a line and several data points, illustrating the potential energy changes as a function of distance.]
Nucleon-nucleon interaction

distance > 1 fm

π-meson

distance < 0.5 fm

three-body forces?
Nuclei and QCD

Scales: 1 GeV 100 keV

In nuclei: non-perturbative QCD, so no easy way of calculating
Binding energy per nucleon

sun energy

fusion

H

He

B

8 (MeV)

reactor energy

fission

U

Fe

particle number → A
Valey of stability

**The Valley of Stability**

Nuclei with excess nucleons move down the valley toward stability. The neutron side of the valley is poorly understood - scientists aren’t sure where the dripline lies.

- **β⁺** decay
- **N-Z**
- **β⁻** decay
Physics with radioactive-ion beams

**Nuclear physics**
- Strong interaction in many-nucleon systems
- Nuclear driplines

![Image of nuclear driplines]

\[ ? = \text{Mean field} \]

**Astrophysics**
- Nucleo-synthesis, star evolution
- Abundances of elements

![Image of stellar H, He, C, O, Si burning stars, supernovae]

**Fundamental studies**
- Beyond standard model (neutrino mass, ...)

**Applications, e.g.**
- Solid state physics, life sciences

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**34Ne:**
- 10 protons + 24 neutrons
- Does it exist?

<table>
<thead>
<tr>
<th>Shell</th>
<th>的态度</th>
</tr>
</thead>
<tbody>
<tr>
<td>fp-shell</td>
<td>28</td>
</tr>
<tr>
<td>sd-shell</td>
<td>20</td>
</tr>
<tr>
<td>p-shell</td>
<td>8</td>
</tr>
<tr>
<td>s-shell</td>
<td>2</td>
</tr>
</tbody>
</table>

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![Diagram of nuclear shells and abundances]
Modelling nuclear interaction

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Meson-exchange theory of Yukawa (1935)</td>
</tr>
<tr>
<td>2</td>
<td>Fujita-Miyazawa three-nucleon potential (1955)</td>
</tr>
<tr>
<td>3</td>
<td>First phase-shift analysis of $NN$ scattering data (1957)</td>
</tr>
<tr>
<td>4</td>
<td>Gammel-Thaler, Hamada-Johnston and Reid phenomenological potentials (1957–1968)</td>
</tr>
<tr>
<td>5</td>
<td>Bonn, Nijmegen and Paris field-theoretic models (1970s)</td>
</tr>
<tr>
<td>6</td>
<td>Tuscon-Melbourne and Urbana $NNN$ potential models (late 70’s–early 80’s)</td>
</tr>
<tr>
<td>7</td>
<td>Nijmegen partial wave analysis (PWA93) with $\chi^2$/dof~ 1 (1993)</td>
</tr>
<tr>
<td>8</td>
<td>Nijm I, Nijm II, Reid93, Argonne $v_{18}$ and CD-Bonn (1990s)</td>
</tr>
<tr>
<td>9</td>
<td>Effective field theory (EFT) at $N^3$LO (2004–)</td>
</tr>
<tr>
<td>10</td>
<td>Can we constrain parameters in EFT from lattice QCD? In the mesonic sector,</td>
</tr>
<tr>
<td></td>
<td>constraining EFT parameters from LQCD has been definitely demonstrated.</td>
</tr>
<tr>
<td></td>
<td>With petascale and soon exascale, this will happen in the baryonic sector as well!</td>
</tr>
</tbody>
</table>


REX post-accelerator

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 < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity $6\cdot10^{10}$ charges
- $A/q < 4.5$

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

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

Total efficiency : 1 -10 %
Nuclear shell model

Developed about 50 years ago for stable nuclei:
Some nuclides more stable and more difficult to excite than others

**Backbone of nuclear physics:** with closed-shell assumption

**Based on analogies to atomic shells, but differences:**
- No central potential but a self-created potential
- Nucleon-nucleon interaction has tensor (non-central) components
- Two kinds of nucleons
- In ground state: all odd number of protons or neutrons couple to spin 0
- Strong spin-orbit coupling changes magic numbers: 8, 20, 28, 50, ...
- No analytic form of nucleon-nucleon interaction in nuclear medium

**Challenges:** disappearing and migrating magic numbers =>
The backbone is not as well understood as we thought

Describes “single-particle” properties