Exotic nuclei

Christoph Scheidenberger
GSI Darmstadt
Overview

Part 1:
What are exotic nuclei? Why study? Key questions

Part 2:
Production and separation of exotic nuclei in the laboratory

Part 3:
Examples: halo nuclei, 2-proton radioactivity, superheavy elements

Part 4:
Exotic nuclei in nuclear astrophysics

Part 5:
Future opportunities at FAIR
1. Introduction
Discovery of isotopes

J. J. Thomson (1913)

High-resolution mass-spectrographs

F. W. Aston (~1915...1925)
* identification of 212 isotopes
* systematics:
→ "packing fraction"
Development of nuclear models

**Discovery of mass excess:**

Masses deviate from whole numbers

![Image](image.png)

**First (collective) model:**

Liquid-drop model by C.F.v.Weizsäcker, H. A. Bethe (1935/36)

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume energy</td>
<td>$\sim A^{(*)}$</td>
</tr>
<tr>
<td>Surface</td>
<td>$\sim A^{2/3}$</td>
</tr>
<tr>
<td>Coulomb</td>
<td>$\sim -\frac{Z^2}{A^{1/3}}$</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>$\sim -\frac{(Z - A/2)^2}{A}$</td>
</tr>
</tbody>
</table>

(*$R \sim A^{1/3}$)

C. F. v. Weizsäcker  
Z. Phys. 96, 431 (1935)  
H. A. Bethe  
Rev. Mod. Phys. 8, 81 (1936)
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Chart of (stable) nuclei

- 270 stable nuclides in nature
- 50 radioactive nuclides in nature
- 320 nuclides in total

Z (protons) → N (neutrons)
Shell effect in stable nuclei

Number of stable isotopes/isotones

--->

magic numbers
**Development of nuclear models (II)**

**Single-particle shell model (1949):**

Individual properties:
- e.g.: excitation energies, magnetic moments

Based on Schrödinger equation:

\[
H = \sum_i \left[ -\left( \frac{\hbar}{2m} \right) \cdot \Delta_{ii} \right] + \sum_{i<j} V_{ij}
\]
Chart of (known) nuclei

- stable
- $\beta^+$-decay
- $\beta^-$-decay
- $\alpha$-decay
- p-decay
- spont. fiss.

126 magic numbers

Exotic nuclei
Nuclear radii do not increase as $A^{1/3}$

1) Nuclear Radius:

Textbooks say: $R \approx 1.3 \text{ fm} \times A^{1/3}$

I. Tanihata et al., NPA654, 235 (1999)

.....valid only for nuclei near stability
2) Magic numbers:

According to standard textbooks:

\[ 2, 8, 20, 28, 50, 82, 126 \]

New “halo-driven” magic numbers

A. Ozawa et al., PRL 84, 5493 (2000)
Many more bound nuclei exist than anticipated.

**blue** - about 3000 known isotopes

Available today

Unknown territory, some 6000...9000 isotopes expected to exist
New and unexpected „exotic“ phenomena

Neutron halo in nuclei
Exotic places where they are produced

Nov. 1986


SN1987A
What is the meaning of „exotic“

exotic places

exotic composition

exotic properties

→ sufficiently many reasons to study exotic nuclei!
### Key questions

<table>
<thead>
<tr>
<th>General questions:</th>
<th>Properties of nuclei:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits of stability, heaviest elements</td>
<td>“Weight” (mass excess)</td>
</tr>
<tr>
<td>Understanding of nuclear forces, isospin dependence</td>
<td>“Size” (matter and charge radii)</td>
</tr>
<tr>
<td>Magicity and shells far-off stability</td>
<td>“Shape” (deformation)</td>
</tr>
<tr>
<td>New phenomena and new decay modes</td>
<td>Half-life, decay modes</td>
</tr>
<tr>
<td>Nucleosynthesis and elemental abundances</td>
<td>Electrical and magnetic moments, spins</td>
</tr>
<tr>
<td></td>
<td>Single-particle structure</td>
</tr>
<tr>
<td></td>
<td>Collective phenomena (giant dipole resonance)</td>
</tr>
</tbody>
</table>
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**Challenge:** understand solar system element and mass abundances

Where, when and how are the elements produced?
Understand the observed distribution, qualitatively and quantitatively!
Why no elements $Z>92$, why no masses $A>240$?

**Solar system abundances**

Abundance of Si is normalized to $10^6$

Lodders (2003)
E.g., discover and understand the formation of the first stars and galaxies, chemical evolution of galaxies, measure the geometry of the Universe and the distribution of (dark) matter, investigate the evolution of galaxies and the production of elements by stars, and the process of star and planet formation.
Radioactive nuclei tell us: elements are synthesized in stars

$^{26}\text{Al}$ half-life $7.8 \times 10^5$ y

Stars are still making atoms

R. Diehl, C. Dupraz, K. Bennett et. al.,
A&A 298 (June, 1995) 445
Element synthesis processes

- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- vp – process
- p – process
- α - process
- fission recycling
- Cosmic ray spallation
- pyconuclear fusion
- + others

Radioactive ("exotic") nuclei
Our telescopes in nuclear physics

We can look into the interior of stars!

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2. Production
Nuclear reactions to produce exotic nuclei

Fragmentation, spallation

Coulomb dissociation, fission

Compound nuclei, fusion
Production reactions

- **Fusion**
  - $^{70}_{\text{Zn}} \rightarrow 208_{\text{Pb}} \rightarrow 277_{\text{Ni}}$

- **Fission**
  - $^{238}_{\text{U}} \rightarrow ^{78}_{\text{Ni}}$

- **Fragmentation**
  - $^{124}_{\text{Xe}} \rightarrow \text{Be} \rightarrow ^{100}_{\text{Sn}}$

Legend:
- Stable nucleus
- Proton rich nucleus
- Neutron rich nucleus

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Exotic nuclei
Technical concepts to produce exotic nuclei

**In-flight**
- Heavy Ions
- Storage Collider Rings
- g/cm²
- ~ 1 ms
- 1-1000 MeV

**ISOL**
- Light Ions or Neutrons
- Ion Source
- ~ 0.1 s
- 10-100 keV

**Hybrid (in-flight + ISOL)**
- Heavy Ions
- Stopper Ion-guide
- ~ ms

---

**Elements**
- Universal
- Chemically difficult
- Universal (?)

**Separation time**
- < 1 ms
- 0.1 s~
- ~ ms

**Selectivity**
- pure beams
- contaminants possible
- pure beams (?)

**Intensity**
- moderate
- high
- moderate

**Energy of secondary beam**
- 50-1500 A MeV
- 10 - 100 keV

**Options**
- Storage rings
- Post-Acceleration (1....10 A MeV)
World view of radioactive-beam facilities

- ISOL-type facilities
- In-flight separation

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Exotic nuclei
The exotic beam facilities at GSI

Laboratory tour at GSI: Thursday afternoon
Production of exotic nuclei by projectile fragmentation

$^{209}\text{Bi}$, $\beta \approx 0.85$

4 cm Be, $\beta \approx 0.70$

Fragmentation, invented at LBNL in the 1980's

Produktionsraten: $10^5$/sek. ... $10^{-5}$/sek. ($\approx 1$/Tag)

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Spallation and fission of uranium

\[ ^{238}\text{U} \ (1 \text{ A GeV}) + ^{1}\text{H} \]
Production mechanisms and cross sections

$^{40}\text{Zr}$ produced in $^{238}\text{U} + \text{Pb} 1 \text{ AGeV}$

<table>
<thead>
<tr>
<th>Neutron number</th>
<th>Cross section / mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
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<tr>
<td>55</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
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</tbody>
</table>

- Fission
- Fragmentation
Nucleo"synthesis" by spallation of cosmic rays

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Exotic nuclei
Big-RIPS in RIKEN (Japan, near Tokyo)

BigRIPS 1st stage
BigRIPS 2nd stage

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Exotic nuclei
Separation principle: $B_\rho - \Delta E - B_\rho$ method

Magnetic rigidity: $B_\rho = \gamma \nu * A/Z$

$V_{\text{Fragment}} \sim V_{\text{Projectile}} \quad A/Z \sim \text{const.} \quad \text{Magnetic-rigidity analysis of energy loss yields single isotope!}$
**Separation principle: B_ρ-ΔE-B_ρ method**

Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

Production target: $^{86}\text{Kr}^{14+}, 12 \text{ MeV/u}$

Focal plane transmission of 65% of the produced $^{78}\text{Ni}$

Fragment yield after target

Fragment yield after wedge

Fragment yield at focal plane
Separation and identification at the FRS

Production target

Sci-1

Time-of-Flight (ToF)

Sci-2

Detectors

- Scintillator
- MUSIC (Ioniz. Chamber)
- MWPC

Identification of fragments

Principle

\[ B_\rho = \gamma V \times \frac{A}{Z} \]

- ToF: \( \gamma V \)
- \( \Delta E \): \( Z \)
- \( B_\rho \): \( A \)
Experimental area at the Fragment Separator FRS
Identification and experiments with few atoms per week

In-flight identification (B_q, TOF, ΔE)

$^{129}$Xe (1095 AMeV) + $^9$Be

$^{100}$Sn

$^{99}$In

$^{101}$In

$^{102}$Sn

$^{103}$Sn

$^{101}$In

$^{100}$In

$^{99}$In

$^{98}$In

$\Delta E$ (arb. units)

M/Q * 1000 (u/c)

$T_{1/2} = (0.94 \pm 0.54) \text{ s}$

$Q_β = (3.4 \pm 0.2) \text{ MeV}$

$\sigma = 11 \text{ pb}$

(7 atoms)

R. Schneider
J. Friese, 1995

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Exotic nuclei
ISOL target and ion source

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Exotic nuclei
Ionisation mechanisms

Surface ionization
- Atom
- Ionization energy: <5-6 eV
- Ground state

Laser ionization
- Atom
- Ionization energy: <9-10 eV
- Ground state

Ionization by electron impact
- Atom
- Fast electrons
- Ionization energy: < electron impact energy
- Ground state
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Nuclear chart @ CERN-ISOLDE

- $B_p = 0$
- $B_F = 4\text{MeV}$

- rp-process
- r-process

- $B_n = 0$

- Stable nuclides
- $\alpha$, $\beta^+$ - decay
- $\beta^-$ - decay
- $\alpha$ - decay
- Spontaneous fission
- $p$ - decay
3a. Superheavy elements
Superheavy elements

Key questions:

• where are the upper limits of the periodic table of elements?

• why do SHE exist?

• where is the next proton magic number?

• what atomic and nuclear properties do they have?
Chemical element 112: Copernicium (Cn)

- Officially named in 2009 by IUPAC
- “The idea was to go backwards, to honor someone who was not greatly honored in his lifetime.” – Sigurd Hofmann
- Hofmann wanted to highlight the contribution of nuclear chemistry to other fields, astrophysics in particular
- Element was first produced at GSI in 1996 by fusion of zinc and lead

Synthesis and identification of SHE at SHIP

kinematic separation in flight

identification by $\alpha-\alpha$ correlations to known nuclides

Date: 09-Feb-1996
Time: 22:37 h

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Cross section systematics (1n evaporation residue)

Times needed to observe on average 1 event:
- Present sensitivity: limit $\approx 1$ pbarn
- Beam dose: $1.5 \times 10^{18}$ projectiles
Status of worldwide SHE research

Background: calculated shell correction energies $E_{\text{shell}}$ of SHE

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Exotic nuclei
The inner electrons move at relativistic speed in the strong electric field of the high-Z nucleus:

\[ \frac{v}{c} \sim Z \alpha \sim \frac{100}{137} \rightarrow \beta \sim 0,7 \]

example \( {}^{106}\text{Sg} \):

- \( \beta = 0.77 \)
- \( \gamma = 1.58 \)
- \( r = 0.63 \, r_0 \)

\[ \rightarrow \text{s,p-electrons are attracted closer to the nucleus} \]
\[ \rightarrow \text{spin-orbit splitting} \]
\[ \rightarrow \text{high electron-density near nuclear surface} \]
\[ \rightarrow \text{screening of nuc.charge for outer (d,f) electrons} \]

**Chemistry of Transactinides**

- electron configuration, ionic radii, binding energies
- chemical properties (redox potential, volatility, complex formation, periodicity of chem.properties,...)

Glenn Seaborg during his visit to GSI
Theory predictions: relativistic vs. non-relativistic calculations

**Consequences**

- Shift of energetic and spacial distribution of electronic orbital on an absolute and relative scale
- Change of electronic ground state configurations and the ionization energies
- Change of atomic- and ionic radii
- Change of availability of electronic orbitals for chemical bonding
- Change of bonding energies in molecular bonds
- Change of contribution of ionic- and covalent part in the bonding

**Group 6 elements**

![Graph showing the energy levels of Group 6 elements: Cr, Mo, W, and Sg.](image)

V. Pershina 8/98, Declusax

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**Exotic nuclei**
Confirmation by chemistry

3 events for $^{269}\text{Hs}$ (2 events for $^{270}\text{Hs}$) confirm the SHIP-data

determination of the chemical Properties of Hassium
Hot fusion advances the field

Produced at DUBNA by 48-calcium + target

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Future perspectives

Element confirmation

58Fe + 248Cm \rightarrow 306^{122}\star

54Cr + 248Cm \rightarrow 302^{120}\star

48Ca + 249Bk \rightarrow 297^{117}\star

48Ca + 244Pu \rightarrow 292^{114}\star

Nuclear structure
Accurate masses
Transfer reactions

Pb/Bi targets
Actinide targets

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Exotic nuclei
3b. 2-proton radioactivity
Discovery of a new type of radioactivity

- Production of nuclei at the proton dripline
- Study of the 2-proton emitter $^{45}\text{Fe}$
Emission of two protons from nuclear states

Sequential

\begin{align*}
(Z,N) & \rightarrow (Z-1,N) \\
(Z,N) & \rightarrow (Z-2,N)
\end{align*}

Democratic

\begin{align*}
(Z,N) & \rightarrow (Z-1,N) \\
(Z,N) & \rightarrow (Z-2,N)
\end{align*}

2p radioactivity

\begin{align*}
(Z,N) & \rightarrow (Z-2,N)
\end{align*}

- \( ^{22}\text{Mg}^* \), \( ^{26}\text{Si}^* \) – Cable et al., 1983
- \( ^{35}\text{K}^* \) – Äystö et al., 1985
- \( ^{31}\text{Cl}^* \) – Borge et al., 1990
- \( ^{14}\text{O}^* \) – Bain et al., 1996
- \( ^{18}\text{Ne}^* \) – Gómez del Campo et al., 2000
- \( ^{6}\text{Be} \) – Bochkarev et al., 1989
- \( ^{12}\text{O} \) – Kryger et al., 1994
- \( ^{18}\text{Ne} \) – ?
- \( ^{35}\text{K}^* \) – Äystö et al., 1985
- \( ^{31}\text{Cl}^* \) – Borge et al., 1990
- \( ^{14}\text{O}^* \) – Bain et al., 1996
- \( ^{18}\text{Ne}^* \) – Gómez del Campo et al., 2000
- \( ^{6}\text{Be} \) – Bochkarev et al., 1989
- \( ^{12}\text{O} \) – Kryger et al., 1994
- \( ^{18}\text{Ne} \) – ?

Not observed before!

Predicted candidates:
- \( ^{19}\text{Mg} \), \( ^{45}\text{Fe} \), \( ^{48}\text{Ni} \), \( ^{54}\text{Zn} \)
Ground state energies of $^{45}\text{Fe}$, $^{44}\text{Mn}$, $^{43}\text{Cr}$

<table>
<thead>
<tr>
<th>Author</th>
<th>$Q_{2p}$ [MeV]</th>
<th>$T_{1/2}$ [$\mu$s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown</td>
<td>$1.15 \pm 0.09$</td>
<td>$2 - 300$</td>
</tr>
<tr>
<td>Ormand</td>
<td>$1.28 \pm 0.18$</td>
<td>$0.01 - 100$</td>
</tr>
<tr>
<td>Cole</td>
<td>$1.22 \pm 0.05$</td>
<td>-</td>
</tr>
</tbody>
</table>
Experiment at the FRS

Beam current (SEETRAM)

Target 4 g/cm² Be

Degrader 1 3.2 g/cm² Al

Degrader 2 3.6 g/cm² Al

TOF 1, 2, 3 (scintillators)


IN-FLIGHT IDENTIFICATION OF IONS

\[
B_{\rho_{3,4}} \Rightarrow \frac{A}{v} / Z \]

\[
\text{TOF 1,2,3} \Rightarrow v \}

\Rightarrow A/Z

\Delta E \Rightarrow Z

\]

Identified ions

Trigger, \( \Delta E \)

Si telescope

7 x 300 \( \mu \)m

511 keV

Implantation and decay spectroscopy

Nal barrel

511 keV

Identified targets

58Ni, 650 A MeV

4×10⁸ ions/s

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Exotic nuclei
Identification of $^{45}$Fe

2115 events in 8117 min. (5.6 d)
6 events $^{45}$Fe

M. Pfützner et al.,
The $^{45}$Fe experiment at GANIL

**LISE 3 Separator at GANIL**

- **Target**
- **Cyclotrons**
- **CSS1**
- **CSS2**
- **SISSI**
- **Ion source**
- **Selection according to mag. rigidity**
- **Velocity selection**
- **Identification in A and Z**

- **$^{58}$Ni @ 75 MeV/A on nickel target**
- **High primary beam intensity: 3-5μA**

**Exotic nuclei**

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Results from GANIL experiment

Decay energies

$t < 15 \text{ ms}$

$Q_{2P} = 1.14 \pm 0.05 \text{ MeV}$

$\text{FWHM} = 0.06 \text{ MeV}$

$t > 15 \text{ ms}$

Decay times

$^{45}\text{Fe}$

$T_{1/2} = 4.7^{+3.4}_{-1.4} \text{ ms}$
2p-decay of $^{45}$Fe in a 3-body model

![Graph showing 2p-decay of $^{45}$Fe in a 3-body model with various decay rates and half-lives.](image-url)
3c. Halo nuclei
Halo nuclei

- Radii measurements
- Momentum measurements
- Complete kinematic measurements
Halo nuclei

1-neutron halos

1-proton halo

Halo or skin?

2-n halos (Borromean)
Examples and simple imagination

Borromean rings – Borromean nuclei
(sign of an Italien noble family)

$^{11}\text{Li}$  $^{11}\text{Be}$
Discovery of halo phenomenon: absorption measurements

\[ \sigma_R = -\frac{1}{t} \ln \left( \frac{R_{in}}{R_{out}} \right) \]

I. Tanihata et al., PRL 55 (1985) 2676
Interaction cross sections of n-rich nuclei

I. Tanihata et al.,

B. Blank et al.,
Radial density distributions

ground state densities:

g.s. densities $\times r^2$:

Theory: H. Lenske
Spectroscopy by one-nucleon knockout reactions

“Sudden collision”: $\Delta t_{\text{collision}} \ll \Delta t_{\text{orbit}}$

Reaction time $\Delta t_{\text{collision}} \approx 10^{-22} \text{ s}$

Internal motion $\Delta t_{\text{orbit}} \approx 10^{-21} \text{ s}$

$\Rightarrow p_{\text{core}} = -p_n$

$\Rightarrow$ Measurement of momentum of halo-nucleon

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Exotic nuclei
Transformation of wave function to momentum space

Relation of space and momentum is given by Heisenberg’s uncertainty principle:
\[ \Delta p \cdot \Delta x \approx \hbar \]
Example: Carbon isotopes

\[ ^{A}C + C \rightarrow ^{A-1}C + x \]

E \approx 900 \text{ MeV/u}

FRS@GSI
High resolution momentum measurements - proton-halo in $^8\text{B}$

$^{12}\text{C} + \text{Be} \rightarrow ^8\text{B}$

$^{8}\text{B} + \text{C} \rightarrow ^7\text{Be}$

**Discovery of a proton-halo nucleus: $^8\text{B}$**

1.4 GeV/u $^8\text{B}\rightarrow\text{C}$

Mean-Field & RPA

- $^7\text{Be}(3/2^-,0.0^+)\ p_{3/2}: 71\%$
- $^7\text{Be}(3/2^-,0.0^+)\ p_{1/2}: 13\%$
- $^7\text{Be}(3/2^-,0.0^+)\ f_{7/2}: 11\%$
- $^7\text{Be}(3/2^-,0.0^+)\ f_{5/2}: 5\%$
- $^7\text{Be}(1/2^-,0.420)\ p_{3/2}: 15\%$

H. Lenske et al., Prog. Part. Nucl. Phys. 46 (2001)
When/where do halos form?

Small nucleon separation energy → close to drip-lines

Low orbital angular momentum (l=0,2)

Asymptotic form of wave function:

\[ \Psi(r) \sim \exp[-(2\cdot\mu\cdot S_{2n})^{1/2}\cdot r/\hbar] \]

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Exotic nuclei

Kinematical complete experiments

$40^\text{Ar}$ primary beam

Beam cocktail (all unstable !)

Reaction products after target

$M^* - M = \sum_{i<j} \frac{E_i E_j - m_i m_j c^4 - p_i p_j c^2}{Mc^4}$

$M = \sum m_i$

Exotic nuclei
Angular correlations reveal inner structure

He: p-states
Li/Be: different parity states
Energy and angular correlations

$^5$H obtained in proton knockout:

$^6$He $\rightarrow$ p + $^3$H + n + n

Measured three-body correlations (projections of energy and angle) are analyzed via a Jacobi coordinate system and an expansion with a restricted set of hyperspherical harmonics:

- angle between relative momenta $\theta_{nn}$
- energy sharing $\varepsilon = E_{nn}/E_{total}$ between sub-systems
- spin and parity of the state

Measured correlations are consistent with a 3-body microscopic calculation assuming $J^\pi = 1/2^+$

M. Meister et al., PRL 91 (2003) 2504
Neutron skins in Na-isotopes

Total interaction cross sections measured at 950 MeV/u \(^{13}\text{Na} \rightarrow \text{C}\)

RMS charge radii from isotope-shift measurements, e.g. G. Huber et al., Phys. Rev. C 18 (1978) 2342

Stable, skin and halo nuclei

- **Stable Nucleus**
- **Halo Nucleus**
- **Skin Nucleus**

Legend:
- Proton Density
- Neutron Density
Terra incognita: lithium isotopes beyond the drip-line

~300 MeV/u $^{11}\text{Li,}^{14}\text{Be} + \text{liq.}H_2 \rightarrow ^9\text{Li}+n, ^{11}\text{Li}+n, ^{11}\text{Li}+2n$

Previous results confirmed: $^{10}\text{Li}$ is known as virtual s-state ($a = -22$ fm) with an excited state at 0.5 MeV and $\Gamma = 0.5$ MeV.

$^{12}\text{Li}$ is observed as a virtual s-state with scattering length $a = -11$ fm.

$^{13}\text{Li}$ is seen as a broad 3-body resonance state at 1.5 MeV.

Newly observed $^{12}\text{Li}$ and $^{13}\text{Li}$

Yu. Aksyutina et al., publication in preparation
4. Some links to nuclear astrophysics
Where, when and how are the elements produced?
Understand the observed distribution, qualitatively and quantitatively!
Why no elements $Z>92$, why no masses $A>240$?
Formation of heavy elements by s- and r-process

- s-process terminates at $^{209}$Bi
- r-process produces the heaviest elements (Th, U)
- p-process produces ~30 n-deficient isotopes, which cannot be formed by s- or r-process
Explanation of s-process abundance maxima

\[ N_A \propto \frac{1}{\langle \sigma \rangle_A} \]  

small n-capture cross sections lead to large abundances and vice versa

- Temperature-averaged n-capture cross sections needed!
- Near stability
beta-decay to bound final states

Neutral atom:

Continuum-state $\beta$-decay

Bare nucleus:

Bound-state $\beta$-decay

$\lambda_b / \lambda_{tot}$ (%)

$^{81+_1} \text{Tl}$

K. Takahashi
and K. Yokoi,
ADNDT 36 (1987)
Bound-state beta decay of $^{207}\text{Tl}^{81+}$

Half-life $T_{1/2} = 271 \pm 2$ sec.

Branching $\beta_b/\beta_c = 0.224 \pm 0.004$

Q-value $Q_{\beta_b} = 1507 \pm 8$ keV

Assumption: \((n,\gamma) \leftrightarrow (\gamma,n)\) rate equilibrium

\[\lambda_{\gamma n} \propto T^{3/2} \exp \left( -\frac{Q_n}{kT} \right) \cdot \lambda_{n\gamma}\]

Example: \(N_n = 10^{24} /\text{cm}^3\), \(T_9 = 1\)
\[\Rightarrow Q_n = 2 \text{ MeV}\]

Neutron capture processes stall, and nucleus „waits“ for \(\beta^-\)-decay:

\[\rightarrow zX \rightarrow z+1X + e^- + \nu_e\]

\[\rightarrow \text{for every element, there is a so-called „waiting point“}\]

\[\rightarrow \text{r-process path determined by mass differences}\]
\[\rightarrow \text{abundances determined by half-lives}\]
Uncertainty between models and nuclear properties

Astrophysics modified

Nuclear physics modified

Are the fine details a reflection of the stellar site or of nuclear physics input?
Importance of mass measurements

- Nuclei far-off stability may show different phenomena than nuclei close to stability (magic numbers, shell quenching)
- Extrapolation of mass models to regions far from stability may introduce errors

D. Lunney, 2001
## Storage-ring mass spectrometry at FRS-ESR

**Production:**
- **Primary beams:** H, U, 100...1000 MeV/u
- **Reaction mechanisms:** Projectile fragmentation, ED and fission
- **Yields:** \( \sim 10^5/s \ldots 10^{-5}/s (=1/day) \)
- **Ionic charge states:** bare, H-, He-, Li-like

**Separation:**
- **Bρ-Analysis**
- **Bρ-ΔE-Bρ Method**

<table>
<thead>
<tr>
<th></th>
<th>IMS</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass resolving power ( m/\Delta m_{\text{FWHM}} )</strong></td>
<td>( 1 \cdot 10^5 )</td>
<td>( 1-2 \cdot 10^6 )</td>
</tr>
<tr>
<td><strong>Mass accuracy</strong></td>
<td>( \sim 100 \text{keV} )</td>
<td>( \sim 30 \text{keV} )</td>
</tr>
<tr>
<td><strong>Accessible half-lives</strong></td>
<td>( &gt; 10 , \mu s )</td>
<td>( &gt; 1 , s )</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>single ions</td>
<td>single ions</td>
</tr>
</tbody>
</table>

**Storage:**
- **Fast injection (bunch length \( \sim 400\text{ns} \))**
- **Storage times:** minutes .... hours
- **Cooling:** - stochastic (pre-)cooling
  - electron cooling

---

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Exotic nuclei
Mass Measurements at the Ring Branch

- **stable nuclei**
- **nuclides with known masses**
- **to be measured with SUPER-FRS-CR-RESR-NESR**
  - Conceptual Design Report, GSI 2001
- **observed nuclei**

Yu. Litvinov

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Exotic nuclei
5. Future opportunities at FAIR
FAIR – International Facility for Antiproton and Ion Research

GSI today

Future facility FAIR

SIS100/300

UNILAC

p-LINAC

SIS18

CBM

Rare Isotope Production Target

Super-FRS

Antiproton Production Target

Plasma Physics

Atomic Physics

RESR/CR

NESR

FLAIR

HESR

PANDA
Super-conducting FRS

Pre-separator

Main-separator

Low-Energy Branch

High-Energy Branch

Super-FRS

Ring Branch

Target

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Exotic nuclei
Comparison of FRS with Super-FRS

<table>
<thead>
<tr>
<th></th>
<th>$B_p \text{ max}$</th>
<th>$\Delta p/p$</th>
<th>$\Delta \Phi_x, \Delta \Phi_y$</th>
<th>Resolving power</th>
<th>Gain factor $^{19\text{C}}$</th>
<th>Gain factor $^{132\text{Sn}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRS</td>
<td>18 Tm</td>
<td>1.0 %</td>
<td>$\pm 13$, $\pm 13$ mrad</td>
<td>1500</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Super-FRS</td>
<td>20 Tm</td>
<td>2.5 %</td>
<td>$\pm 40$, $\pm 20$ mrad</td>
<td>1500</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Including primary rate: 250 20 000

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Exotic nuclei
Available today

More difficult to produce and separate (1 in $10^{18}$ atoms)

New territory to be explored with next-generation rare isotope facilities (BigRIPS, SuperFRS, FRIB Separator)

Nuclear Chart in 1966

Less than 1000 known isotopes

blue - about 3000 known isotopes
Rate estimates
Thank you for attention!

Enjoy the school and the NIC conference!
End