Exotic Nuclei

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OUTLINES

- What are exotic nuclei?
- Why are they interesting?
- Production mechanisms.
- Accelerators.
- Targets.
- How to separate?
- How to identify?
- Summary.
What are exotic nuclei?
Chart of the Nuclides (decay modes)
What are exotic nuclei?

- Nuclei far from the $\beta$-stability valley;
- Nuclei at the border of nucleon stability;
- Nuclei (resonances) beyond the border of stability;
- Superheavy nuclei;
- Nuclei with unusual form – superdeformed;
- Nuclei with n- or p-”halo” or “skin”;
- Nuclei with unusual structure – nuclear fullerene;
- Nuclei with unusual density distribution – bubble nuclei
- ...
Extended Chart of the Nuclides

Andrew Westphal, Space Sciences Laboratory U. C. Berkeley
Why are they interesting?
Why are they interesting?

- The borders of nuclear stability: $B_n = 0; B_p = 0$;
- How heavy can be the nuclei?
- Properties of exotic nuclei – spectroscopy, masses;
- Astrophysics;
- New decay modes;
- Unusual structures of nuclei;
- Mechanisms of reactions with exotic nuclei;
- Synthesis of even more exotic;
- Resonances beyond stability lines;
- Fundamental interactions;
- Electrodynamics of extreme fields;
- $\beta$–beams;
- Applications;
- ..........
Collective effects and nuclear shells
Nuclei with unusual density distribution – bubble nuclei

Nuclei with unusual density distribution – bubble nuclei
Nuclei with unusual structure

Neutron halo, Borromean nuclei

\[ ^{9}\text{Li} + n \quad \text{Barely Unbound} \]
\[ n + n \quad \text{Barely Unbound} \]
\[ ^{9}\text{Li} + n+n \quad \text{Bound} \]

Nuclear fullerene

\[ Z=120, \ A=298-300 \]
60 $\alpha$-particles
+ 60 neutrons
Superheavy nuclei

- 1966: A. Sobiczewski, F.A. Gareev, B.N. Kalinkin: next “magic numbers” are Z=114, N=184;
- 1966: V.M. Strutinsky; “shell correction” method;
- 1967: H.B. Meldner: next “magic numbers” are Z=114, N=184.

Accuracy of predictions:
- Spontaneous fission half-life: $T_{1/2} \ast 10^{\pm 10}!!$
- $\alpha$-decay: $T_{1/2} \ast 10^{\pm 10}!!$
Chart of the Nuclides (life-times)
SuperHeavy Elements
$\beta$-пучки ($^6\text{He}$, $^{18}\text{Ne}$)

**Ion production**
- Proton Driver
  - SPL
- Ion production
  - ISOL target & Ion source
- Beam preparation
  - Pulsed ECR
- Ion acceleration
  - Linac
- Acceleration to medium energy
  - RCS

**Acceleration**
- PS & SPS
  - Acceleration to final energy

**Neutrino source**
- $^6\text{He}\rightarrow^6\text{Li} e^- \bar{\nu}$
  - Average $E_{\text{cms}} = 1.937 \text{ MeV}$
- $^{18}\text{Ne}\rightarrow^{18}_9\text{F} e^+ \nu$
  - Average $E_{\text{cms}} = 1.86 \text{ MeV}$
Production mechanisms
Exotic isotope production mechanisms

- **Projectile fragmentation**
  - $v_{product} = v_{beam}$

- **Spallation**
  - few MeV/u

- **Fusion-fission**
  - ~1 MeV/u
  - ~10-25 MeV/u (new: inverse)

- **Abraision-fission**
  - $v_{product} = v_{beam}$

- **Coulomb fission**
  - > 200 MeV/u
  - $v_{product} = v_{beam}$

- **Fusion-evaporation**
  - $E_R = \frac{m_p}{m_p + m_t} E_P$
Сепаратор PN1 (Lohengrin)
ILL, Grenoble, France

- $\Phi_n \approx 5 \cdot 10^{14} \text{n/cm}^2/\text{s} \rightarrow 1 \text{ mg }^{235}\text{U} \rightarrow 10^{12} \text{fission/s};$
- Изучение экзотических ядер;
- Изучение деления ядер.
CARIBU (2 mg $^{252}\text{Cf} \rightarrow 10^9$ fiss/s)
ISOL or In-flight production
# Pros for ISOL & In-Flight

| **In-flight:** | Provides beams with energy near that of the primary beam  
|               | ✓ Individual ions can be identified  
|               | ✓ Luminosity (intensity x target thickness) gain of 10,000  
|               | (one week experiment* = 3 x 10^{-18} barn)  
| GSI           | Efficient (can be close to 100%)  
| RIKEN         | Fast (100 ns)  
| NSCL          | Chemically independent separation  
| FRIB          | Production target is relatively simple  
| GANIL         | Broad range of RIBs  
| ANL           | RIBBAS  
| ...           |

| **ISOL:**      | Better separation of the selected nuclei  
| HRIBF          | Good beam quality (emittance)  
| ISAC           | Small beam energy spread  
| SPIRAL         | Post-acceleration allows to vary RIB energy  
| ISOLDE         | Can use chemistry (or atomic physics) to limit the elements released  
| SPES           | 2-step targets provide a path to MW targets  
| EURIOSOL       | ...  

## Cons for ISOL & In-Flight

### In-flight:
- GSI
- RIKEN
- NSCL
- FRIB
- GANIL
- ANL
- RIBBAS
- ...

- Very low cross section for n-rich of some elements
- Large energy and transverse emittances
- Fixed high energy
- Contamination by secondary products
  - large size and cost of fragment separators

### ISOL:
- HRIBF
- ISAC
- SPIRAL
- ISOLDE
- SPES
- EURIOSOL
- ...

- Finite time to get the RIB out of source ($t_{1/2} > 10$ ms)
- Some elements are tough to produce
- Large cost of high-temperature production target
- Chemistry is involved
Accelerators
Superconducting Ring Cyclotron K=2600
RIKEN, Japan

July 2018: $^{49}\text{S}$, $^{52}\text{Cl}$, $^{59}\text{Ca}$, $^{60}\text{Ca}$
RIKEN RI Beam Factory (RIBF)

Old facility

- RIPS
  - 60~100 MeV/nucleon

- GARIS
  - ~5 MeV/nucleon
  - SHE (eg. Z=113)

New facility

- fRC
  - several MeV/nucleon

- CRIB (CNS)

Accelerator

- AVF
- RRC
- SRC
- RILAC
- ZeroDegree
- SAMURAI
- SHARAQ (CNS)
- BigRIPS
  - 350~400 MeV/nucleon

Experiment facility

Intense Heavy Ion beams (up to U) up to 345AMeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007
Facility for Rare Isotope Beams, FRIB

Funded by DOE Office of Science & MSU
- 2022 completion,
- 2020 early completion

Key Features:
400kW beam power ($5 \times 10^{13} \ 238\text{U/s}$)
- Efficient acceleration (multiple charge states)

Separation of isotopes in-flight:
- Fast development time for any isotope
- Suited for all elements and short half-lives
FAIR, Germany

Ion Beams now
Z = 1 – 92
up to 2 GeV/nucleon

Ion Beams in the future
100 – 1000 fold intensity
Z = -1 – 92 antiprotons
up to 35 - 45 GeV/nucleon
KoRIA

Beam power: 400 kW; protons – 600 MeV; U – 200 MeV/A
Targets
FRIB Production Target and Beam Dump Area

Rare isotope beam production with beam power of 400 kW at 200 MeV/u from C to U

Technical Risk: High power density: ~ 20 - 60 MW/cm³
Multi-slice Target Concept FRIB

Cooled by thermal radiation
T ≈ 1800 - 1900°C

Multi-slice target heat exchanger

Shielding

Lifting frame

Target
Tritium target: $^{10}\text{He}$: 2n-transfer

\[ ^{8}\text{He} \quad 2n \quad ^{10}\text{He} \]

\[ ^{3}\text{H} \quad p \]
How to separate?
Background

- Primary beam;
- Scattered beam;
- Transfer (target-like) products;
- Neutrons;
- High-energy protons or alphas.
Super-FRS
FAIR, Germany
Comparison of FRS and Super-FRS

FRS → 69 m → Super-FRS

Degrader

170 mm

Degrader 1

380 mm

Degrader 2

129 m
Fragment-separator ACCULINNA-2: assembling and testing.
Cryogenic Stopping Cell for MR-ToF mass spectrometry
Velocity Filter “SHIP”
The gas-filled separator GFS-II
New gas-filled separator GFS-II: assembling
Gas-Catcher

**Linear gas stopper**

- Turbo pump 1600 l/s
- Extraction-RFQ
- Turbo pump 400 l/s
- Buffer gas cell

**Cyclotron gas stopper**

- Cryogenic linear gas stopper
- Solid stopper ion-source station
- Two momentum compression lines
How to identify?
Michigan State University (USA)
Example: $^{40}\text{Mg}$ Production, 120 pnA $^{48}\text{Ca}$ 140 MeV/u
Kinematical complete experiments

\[
m^* - M = \sum_{i<j} \frac{E_i E_j - m_i m_j c^4 + p_i p_j c^2}{M c^4}
\]
Detector system for identification of $^{10}\text{He}$ produced in reaction $^{8}\text{He}(t,p)$
Storage-ring mass spectrometry

Relativistic Heavy Ion Beam

Production Target

Degrader

FRS projectile fragment separator

ESR storage cooler ring

↑ 10m
SHIP-trap
New focal plane detector GABRIELA

GABRIELA - Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser
Summary
World view of rare isotope facilities

In-flight production, in target production
288 nuclides are stable or practically stable
3500 nuclides have been discovered (end of 2018)
9035 nuclides with $2 \leq Z \leq 120$ are predicted to be bound
Summary

- More than 3000 new nuclides have been discovered, more than 6000 of most exotic nuclei are awaiting to be discovered.

- The studies of exotic nuclei are especially important for nuclear structure, fundamental interactions and astrophysics.

- The next-generation facilities will provide excellent possibilities for research and education.

- There are many extremely technical problems on the way to new nuclei which must be solved by the next-generation scientists.
THANK YOU FOR YOUR ATTENTION!