Low Energy Nuclear Experiments

Ben Kay, Argonne National Laboratory
National Nuclear Physics Summer School, 8-19 July 2019
Overview, part 1 (general properties of nuclei, mostly macroscopic)

What can experimentalists determine about a nuclear system in the lab?

- History ... the isotopes, the facilities we use
- What can we measure/is observable?
- Questions to ask about the nucleus
  - How much do they weigh?
  - What size are they?
  - What shape are they?

Attempt to use many accessible examples from recent literature, leaning towards the study of exotic nuclei where possible
Overview, part 2 (mostly direct reactions, not so exotic, microscopic)

The connection between direction reactions and nuclear structure

• History
• Reactions, reaction types, direct reactions
• Observables
• Energies, momentum
• Spectroscopic factors, occupancies (in context of ‘modern’ [but stable-beam] examples)
• Other reactions (pairing, cluster, charge exchange)

Attempt to steer clear of reactions for reaction’s sake, rather using them as a meaningful tool to gain insights into topical nuclear structure properties
Overview, part 3 (mostly direct reactions, quite exotic, microscopic)

The connection between direction reactions and nuclear structure

- History
- Exotic beams
- Kinematics
- Spectrometers (with a focus on solenoidal spectrometers)
- A few examples from the last few years (2014, 2017, 2017, 2019) (what drove them, reaction choices, results, commentary)
Reading

• Slides from past schools (NNPSS [Heather Crawford's are exemplary], EBSS) are impressive (next slide for references)

• Books are good, but often dense and not always transparent (on direct reactions, my personal favorites are N. K. Glendenning’s *Direct Nuclear Reactions*, and C. A. Bertulani and P. Danielewicz’s *Introduction to Nuclear Reactions*).

• Great papers (some of the older ones can be wonderfully pedagogical, others far less so). I will attempt to highlight some as I go through.
Past schools ... slides on reactions


https://people.nscl.msu.edu/~zegers/ebss2011/cizewski.pdf (J. Cizewski of Rutgers, NSCL 2011) ... 10th in EBSS series

http://www.phy.anl.gov/atlas/EBSS2012/NuclearReactions-ExperimentII.pptx

http://fribusers.org/documents/2013/ebssLectures/reactions1.pdf (Grigory Rogachev of FSU, LBNL 2013) ... 12th


http://aruna.physics.fsu.edu/ebss_lectures/F_Lecture2.pdf (Ben Kay of Argonne, FSU 2015) ... 14th

https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_1.pdf (Alan Wuosmaa of UConn, NSCL 2016) ... 15th
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_2.pdf


And soon, these slides ... 17th
Part 1: General overview
Isotopes, masses, sizes, shapes
Isotopes

Proton number, \( Z \)

Neutron number, \( N \)

https://people.nscl.msu.edu/~thoennes/isotopes/
Isotopes

Proton number, $Z$ vs Neutron number, $N$ diagram with annotations for different processes:

- Radioactive Decay
- Mass Spectroscopy
- Light Particles
- Fission
- Fusion/Transfer
- Spallation
- Projectile Fragmentation/Deep Inelastic

https://people.nscl.msu.edu/~thoennes/isotopes/
Isotopes

1892

Proton number, Z

Neutron number, N

Discovery of $^{68}$Br in secondary reactions of radioactive beams

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Abstract
The proton-rich isotope $^{68}$Br was discovered in secondary fragmentation reactions of fast radioactive beams. Proton-rich secondary beams of $^{70,71,72}$Kr and $^{80}$Br, produced at the RIKEN Nishina Center and identified by the BigRIPS fragment separator, impacted on a secondary $^{80}$Be target. Unambiguous particle identification behind the secondary target was achieved with the ZeroDegree spectrometer. Based on the expected direct production cross sections from neighboring isotopes, the lifetime of the ground or long-lived isomeric state of $^{68}$Br was estimated. The results suggest that secondary fragmentation reactions, where relatively few nucleons are removed from the projectile, offer an alternative way to search for new isotopes, as these reactions populate preferentially low-lying states.

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1937

World pop: 2.3 B
Gas: 16 cents/gal.
Isotopes

THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. Some 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.

2010: first year in which more than 100 isotopes were discovered

Second World War

5-year running average

Isotope-discovery technique

- Light particle reactions
- Neutron reactions
- Fusion
- Fragmentation/spallation

Stable and naturally existing radioactive isotopes

Predicted, but as yet unconfirmed, isotopes

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First challenge for an experimentalist is to make/probe the nucleus you want to study ...
Isotopes

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E.g. fusion(-evaporation)

$^{122}\text{Ce}$ discovered via $^{64}\text{Zn} + ^{64}\text{Zn} \rightarrow ^{122}\text{Ce} + \alpha + 2n$

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**Diagram**: Illustrates the process of nuclear fusion and evaporation, showing the transition from beam nucleus to fusion, compound formation, and fission. The diagram includes a nuclear chart with points representing known isotopes and a trajectory indicating the path of discovery.

**Additional Notes**:
- **Isotope Discovery**: In the past 100 years, isotope discovery has increased with each introduction of new technology. A timeline shows the number of isotopes discovered over time, with a peak around 1980.
- **Rare-Isotope Accelerators**: New facilities such as SPIRAL2 in Caen, France, and J-PARC in Japan are under development to advance the search for rare isotopes.
- **Nuclear Stability**: The stability of nuclei is a focus, with the limit of nuclear existence being pushed further with higher-energy accelerators.
- **Applications**: The discovery of new isotopes has implications for medicine and other fields, with the potential for improved understanding of nuclear processes and fundamental physics.

**References**:
- J. F. Smith et al. PLB 625, 203 (2005)
E.g. fusion(-evaporation)

\[ ^{122}\text{Ce} \text{ discovered via } ^{64}\text{Zn} \]

- **Example** fusion(-evaporation)

122Ce discovered via 64Zn

---

**Figure 4.3:**

- **Choice of reaction**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Threshold</th>
<th>Energy</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion</td>
<td>-</td>
<td>8 MeV</td>
<td>0</td>
</tr>
</tbody>
</table>
| Fission  | -         | 0.75 MeV | 1/2-

**Figure 4.4:**

- **Target nucleus**
- **Fusion**
- **10^{-12}s**
- **Compound formation**
- **Fast fission**
- **Rotation**

**Figure 4.5:**

- **Yrast line**
- **Unresolvable states**
- **Discrete states**

**Figure 4.6:**

- **Energy**
- **Particle evaporation threshold**
- **Groundstate**
- **Spin**

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**Comment:**

2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.

---

Radioactive ion beam facilities

(Magenta - In-flight production
Black - In-target (ISOL) production

(Left) Original source unsure (perhaps Brad Sherrill)
... RI beams

~10 MeV/u (3-20 MeV/u), >100s pps (and up to 100s MeV/u)

(Beam rates are very crude estimates from various sources, illustrative, likely ~1-2 orders of mag. off)
RIB facilities, ISOL at e.g. CERN, TRIUMF, ...

Examples of ISOL facilities:
- TRIUMF (Canada)
- SPIRAL/SPIRAL2 (France)
- REX-ISOLDE/HIE-ISOLDE (CERN)
- iTHEMBA - future radioactive-beam facility (South Africa)
- JYFL (Finland) - IGISOL

Typically:
- Light, energetic ion
- Thick, hot target
- Ion source
- Separator
- Post acceleration
- Lower beam energies
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In-flight / fragmentation at e.g. NSCL

Examples of fragmentation facilities:
- NSCL (USA) → FRIB
- RIKEN (Japan)
- GANIL (France)
- GSI (Germany)

Typically:
- Ion source
- Heavy, energetic ion
- Thin, light target
- Separator
- Higher beam energies

https://www.nscl.msu.edu/public/virtual-tour.html
In-flight / fragmentation at e.g. NSCL

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In-flight / fragmentation at e.g. RIBF, RIKEN

In-flight / fragmentation at e.g. RIBF, RIKEN

RIKEN RI Beam Factory (RIBF)

Old facility

- RIPS
  - 60-100 MeV/nucleon
- GARIS
  - -5 MeV/nucleon
- SHE
  - (e.g. Z=113)
- Accelerator
- RILAC
- AVF
- IRC
- RRC
- SRC

New facility

- CRIB (CNS)
  - <10 MeV/nucleon
- BigRIPS
  - 350-400 MeV/nucleon
- Experiment facility
- To be funded
- In phase II
- SCRIT
- ZeroDegree
- SAMURAI
- SLOWRI
- RI-ring

Intense (80 kW max.) H.I. beams (up to U) of 345AMeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007

An unrivaled combination for direct reaction studies

- **Stable beams** at high intensity and energies up to 18 MeV/u
- **In-flight beams** approx. $10 < A < 50$ at energies up to 15 MeV/u
- **Reaccelerated CARIBU beams** at energies up to ~15 MeV/u
- **Low energy CARIBU beams** for ‘stopped beam’ measurements

E.g. "ISOL" and in-flight at Argonne

[Diagram of beam lines and facilities]
E.g. "ISOL" and in-flight at Argonne

An unrivaled combination for direct reaction studies

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- Reaccelerated CARIBU beams at energies up to ~15 MeV/u
- Low energy CARIBU beams for 'stopped beam' measurements

3 Z, protons
N, neutrons

www.anl.gov/atlas
Primary beam from ATLAS, a few to 20 MeV/u, < few pμA
CARIBU

- Fission fragments stopped in high purity He
- Ions transported by RF fields, DC gradients, and gas flow
- Fast and essentially universal
Production of $N = 126$ nuclei

Accessing new regions: deep-inelastic reactions to reach the far north-east of the nuclear chart

Armbruster et al.

The Science:
- Nuclear shell structure at the extremes
- $r$-process: second abundance peak, fission recycling and termination
- Fission barriers of neutron-rich nuclei and symmetry energy
- Connection of hot-fusion SHE island and mainland

Production through deep-inelastic reactions

Efficient thermalization, extraction and separation through a CARIBU like large gas catcher and separator

Coming soon to the "BGO" area...
More than one beam!?  

**Higher demand for ATLAS beam time resolved ...**

- The nation’s premier stable beam facility *(but longer experiments, higher demand ...)*
- Unique RI beams at ideal energies *(naturally longer experiments, higher demand ...)*

... why not run both at the same time?
“Multi-user” facility

Higher demand for ATLAS beam time resolved …

- The nation’s premier stable beam facility (but longer experiments, higher demand …)
- Unique RI beams at ideal energies (naturally longer experiments, higher demand …)

... why not run both at the same time?
Key point:
No compromise made – each beam is optimal

Future alt. ECR

Modified injection and LEBT

LE beam lines

100 ms

82 ns

 sooner

e.g. CARIBU beam at 10 MeV/u

e.g. stable beam at 6 MeV/u

Pulsed switchyard
Non-hadronic probes ...
Atoms consist of a tiny, dense nucleus made of protons and neutrons, surrounded by a cloud of orbiting electrons. In a neutral atom, the number of electrons balances the number of protons. Protons and neutrons are very much heavier than electrons by a factor of about 1836, so the vast majority of the mass of an atom is contained within the nucleus. The number of protons in a nucleus $Z$—also called the atomic number—defines the element to which it belongs, and associated with each element is a symbol, e.g. carbon $= C$, magnesium $= Mg$, lead $= Pb$, which we generically denoted by $X$. Though all nuclei of a given element will have the same number of protons $Z$, they may have different numbers of neutrons $N$, giving different mass numbers $A = Z + N$. These are called isotopes.

If we want to refer to a particular sort of nucleus, with specific $Z$ and $N$, we use the word nuclide, denoting a particular nuclide by $A_{ZXN}$. Since the element symbol $X$ uniquely specifies the number of protons, $Z$ and $N$ are often neglected.

Nuclear physics has a wide number of different applications in science and industry. These include producing electricity through nuclear fission, aiding medical diagnosis in positron emission tomography (PET), identifying the existence of recent near-Earth supernovae [3], and working out the age of individual cells within...
Nuclear playground

The 3D Nuclide Chart
Total Binding Energy

https://people.physics.anu.edu.au/~ecs103/chart3d/
Nuclear cartography: patterns in binding energies and subatomic structure

As we move further away from the stable nuclides, the half-lives get progressively shorter. Most radioactive nuclides decay with half-lives in the range of microseconds to years. One example is fluorine-18, which $\beta^+$ decays with a half-life of 110 minutes. Fluorine-18 can be used for medical imaging in PET. Fludeoxyglucose is a fluorine containing molecule, which acts like glucose within the body. Fludeoxyglucose containing $^{18}$F is put into the body and accumulates where glucose uptake is fastest—in, for example, glucose hungry cancerous tumours. When $^{18}$F decays it emits a positron. The positron is the antiparticle of an electron, and when the two meet they annihilate, producing two high energy photons that are emitted in opposite directions.

As experimentalists we can:

- **Determine the decay mode**
- **Determine the half life**
- **Determine the mass, binding**
- **Reaction cross sections**
- **Moments**
- **Transition rates / energies**

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What can one observe, why is it tough?

• As you will have heard over the workshop, there are only a handful of physical properties of nuclei one can probe and link to models.

• For a low-energy experimentalists the challenges are many ... as we've just seen only about 4% of the nuclei predicted to be bound are stable, the rest we have to make ...

• The best probes are typically nuclei themselves ...

• Then there is the connection to theory and understanding, what we measure are not always instructive without model-dependent conversions (plenty of discussions in lectures 2 and 3).
To begin at the beginning …

The Geiger-Marsden Experiment

To begin at the beginning …

The Geiger-Marsden Experiment

The plum-pudding idea seemed reasonable: this result would fit expectations

- A 0.1 Ci radium source
- \( \sim 10^{10} \) α particles per second (\( \sim 1 \) nA of \(^4\)He)
- α particles of 7.7 MeV (\( \sim 1.9 \) MeV/u)
- A gold foil of 0.00004 cm thick (\( \sim 0.8 \) mg/cm²)
- A telescope was used to look at flashes of light on a zinc sulphide screen

E. Rutherford, Philosophical Magazine 21, 669 (1911)
This has *all the same* ingredients a modern nuclear reaction experiment:

- A beam
- A target
- A chamber
- Reaction products
- A detector
- *... deduce something about the gold ... its* SIZE, *that's* it's bound,...

**The Geiger-Marsden experiment**

- A 0.1 Ci radium source
- ~$10^{10}$ $\alpha$ particles per second (~1 nA of $^4$He)
- $\alpha$ particles of 7.7 MeV (~1.9 MeV/u)
- A gold foil of 0.00004 cm thick (~0.8 mg/cm$^2$)
- A telescope was used to look at flashes of light on a zinc sulphide screen

"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." — E. Rutherford.
Neutrons, strong force, shell structure

Still not quite the nucleus ... what's missing

✓ What is the positive charge? Protons (Rutherford)
✓ What else is in there? Neutrons (Chadwick)
✓ How does it stick together? (A strong nuclear potential)

Hugely exaggerated cartoon on the atom. On this scale the nucleus would be a tiny period at the center.
**Neutrons, strong force, shell structure, shapes**

- **Shapes** (all nucleons, collective)

- **Single-particle** (inert cores, valence nucleons)

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**Figure 1.1** [ Colour ] Schematic ordering of single-particle orbitals as reproduced by a variety of different central potentials. The colour coding follows quantum number \( l \). The so-called magic numbers are circled in the far right-hand column, whereas they appear as brackets in all others. The numbers adjacent to the levels with the spin-orbit term indicate the \( j \) of those states. Figure taken from [6].

Infinite square well

Saxon Woods

Harmonic oscillator

Nuclear Shell Structure

N/Z ~1-1.6

Neutron-rich nuclei

N/Z ~3

"Normal"

"Exotic"
Magic systems still the pillars of our understanding

78\textsuperscript{Ni} revealed as a doubly magic stronghold against nuclear deformation

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May 2019 ... Taniuchi et al., Nature 569, 53 (2019)
Masses
**Binding energy**

Here we focus our discussion on two concepts - fusion and fission, the processes by which stars burn, and the abundances of chemical elements. This illustrates the role binding energy per nucleon plays in radioactive decays.

The binding energy per nucleon is shown as a function of the mass number in Figure 1. The data for binding energies per nucleon are taken from the Atomic Mass Data Center [6, 7]. The curve has a characteristic peak, which is the peak of the curve, and indicates the approximate boundary between which fusion and fission are energetically favourable.

The binding energy per nucleon is the energy required to break up a nucleus into its constituent nucleons. It is calculated by subtracting the mass of a nucleus from the sum of the masses of its constituent nucleons, then dividing the result by the number of nucleons in the nucleus. The binding energy per nucleon is given by the following equation:

\[
B = \frac{M_n - \sum m_i}{N}
\]

where \( B \) is the binding energy per nucleon, \( M_n \) is the atomic mass of an atom, \( m_i \) are the masses of a proton, neutron, and electron respectively, \( N \) is the number of nucleons.

The symbol \( m_p \) is the mass of a proton, \( m_e \) is the mass of an electron, \( Z \) is the atomic number which includes the mass of atomic electrons, and \( N \) is the number of nucleons.

The masses of nuclides from high school physics: the masses of nuclides are introduced in section 3. These are two different visualizations of the nuclide chart, which includes the mass of atomic electrons, such as the noble gases. In section 4 we present the properties of nuclides as a nuclide chart. This illustrates the role of the nuclide chart.
Binding energy

Wikimedia Commons (left) and NuDat2.0 (right)
**Terms and data**

**Nuclear mass:** $m(Z,N)$

**Binding energy per nucleon**

**Mass excess:** $\{Zm_p + Nm_n - m(Z,N)\}c^2$

**Separation energies, $S_p$ and $S_n$ ($S_{2p} + S_{2n}$)**

[difference in binding energies e.g. $S_n = \{m(Z,N-1) + m_n - m(Z,N)\}c^2 = B(Z,N) - B(Z,N-1)$]

**Atomic mass unit (mass of nucleon):** 931.49410242(28) MeV/c²

Mass databases compile these ...
Terms and data

e.g. [https://www-nds.iaea.org/amdc/](https://www-nds.iaea.org/amdc/), the 2016 mass evaluation
Various techniques to determine mass

- **Q-values**
  - Decays
  - Kinematics \( Q = \sum m_i - \sum m_f \)

- **ToF**
  - Spectrograph
    \[ qvB = \left(\frac{y_{m_0}}{L_{\text{path}}/\text{ToF}}\right)^2 \]
  - Multi-reflection (MR-TOF)
    \[ E = \frac{1}{2}mv^2 = qeU \Rightarrow \frac{m}{q} \propto t^2 \]

- **Dispersion**
  - Spectrograph

- **Frequency**
  - Penning trap
  - Storage rings

---

Slide stolen from Chris Chiara, ARL, who was inspired by others ...
Precision, time, resolution

Modern techniques:
- **TOF** (fast, low precision)
- Storage rings (fast, many measurements at once)
- **MR-TOFs** (fast, high resolution)
- Penning traps ("slow", high resolution, high precision)

*Plot from Rodney Orford, LBNL and proud Canadian*
THE MASS AND LOW-LYING LEVEL STRUCTURE OF $^{17}$C

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Received 14 September 1977

Spectra of $^{17}$C ions from the $^{48}$Ca($^{18}$O, $^{17}$C)$^{49}$Ti reaction at 102 MeV were recorded with a Q3D spectrograph. The lowest state observed, assumed to be the ground state of $^{17}$C, has a mass excess of $21023 \pm 35$ keV. An excited state of $^{17}$C was also observed at an excitation energy of $292 \pm 20$ keV.

$S_n = \{m(Z,N-1) + m_n - m(Z,N)\}c^2 = B(Z,N) - B(Z,N-1) = Q$ (with knowledge of other masses and beam energies)

e.g. TOF (and magnetic spectrograph)

K1200

TOF start

transfer hall

10 m

TOF stop

S800

B_{\rho} meas.

K500

A1900

Energy Loss [arb. units]

increasing \frac{K}{Z}

constant Z

Time-of-flight [ns]

460

500

520

increasing Z

40000

30000

20000

10000

10

10^2

10^3

5000

e.g. Z. Meisel, Phys. Rev. C 93, 035805 (2016)
**e.g. Penning traps**

A somewhat de-facto approach for 30+ years

Ion confined in strong B field (radial confinement), with electrodes providing a potential for axial confinement and manipulation

*Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)*
Ion motion in Penning trap

Segmented Ring electrode allows for:
1. Driving of orbital motions through a dipole excitation
2. Interconversion of orbital motions through a quadrupole excitation at $\omega_c$

$\omega_c = \omega_- + \omega_+$

$\omega_- \sim 1.6 \text{ kHz} \quad \text{Mass independent}$

$\omega_+ \sim 1 \text{ MHz} \quad \text{Mass dependent}$
Penning trap mass measurements

\[ \vec{F} = -\nabla (\mu \cdot \vec{B}) = -\frac{E_{rad}}{B} \frac{\partial B}{\partial z} \hat{z} \]

\[ \omega_+ >> \omega_- \]

Leads to Time-Of-Flight Ion-Cyclotron-Resonance (TOF-ICR) method of mass measurements

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)
Penning trap mass measurements

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)
Penning trap mass measurements

TOF drift tube

MCP

Leads to Time-Of-Flight Ion-Cyclotron-Resonance (TOF-ICR) method of mass measurements

\[ \vec{F} = - \mu \vec{B} \]

\( B \text{ field [T]} \)

\( \text{distance} \)

\( \text{TOF (s)} \)

\( \text{Frequency -1121310 (Hz)} \)

\( 156\text{Pr} \)

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)
PI-ICR technique

General concept: Determine the cyclotron frequency of trapped ions by measuring the phase advance of ions over a period excitation free motion

- Use a position-sensitive detector to determine ion position

\[
\omega_c = \frac{qB}{m_{ion}} = \frac{\phi_c + 2\pi N}{t_1}
\]
WORLDWIDE EXPLOSION OF PENNING TRAP PROJECTS

Operating facilities

Facilities under construction or test

Planned facilities

Penning traps … popular? (last 10 days)

PHYSICAL REVIEW C 100, 014304 (2019)

Mass measurements of neutron-rich isotopes near N = 20 by in-trap on-the-fly decay with the ISOLTRAP spectrometer

P. Ascher,1,7 N. Althubiti,2,3 D. Atanasov,4,5 K. Blaum,1,8 F. Cakirli,5 S. Grévy,1 F. Herfurth,6 S. Kreim,4 P. Ascher,1,*, N. Althubiti,2,3 D. Atanasov,4,† K. Blaum,4 R. B. Cakirli,5 S. Grévy,1 F. Herfurth,6 S. Kreim,4 D. Lunney,7

TRIUMF [5,16] but as shown recently, the first known bubble nucleus [20,21].

This trap was used to further cool the ions and center the ions radially in the trap via their cyclotron motion in the magnetic solenoidal magnet. The ring electrode of the Penning trap is used for the two sides. The high temperatures produced by the laser can give access to long-lived isomers that are not produced or formed in the target. Cooling by the Penning trap is necessary for the mass spectrometer. A sketch of the setup, consisting of four ion traps, is given in Fig. 1.

The ions were first trapped for about 5 ms in the helium-based trochoidal, before being sent to the ISOLTRAP mass spectrometer. A sketch of the setup, consisting of four ion traps, is given in Fig. 1.

FIG. 1. Two-neutron separation energies of 31P, 32S, and 34Mg [1]. For the first time the possibility of 32S and 34Mg with the mass spectrometer was studied.

The understanding and description of forbidden decays provides interesting challenges for nuclear theory and experiment. In this paper, we focus on the second forbidden unique decay scheme of 34Mg (adapted from [17]), populating mostly the 1+4p state. A position-sensitive detector was used to trigger dedicated studies to see if 34Al would be in the island of two-phonon states. A summary of the results is given in Table 1.

Table 1. Summary of the results for the 34Al decays [41].

The measurement of the 34Al β-decay and EC energy is an important input for the improved calculations of the 138La and 138Ce Q values. Before the 138La β-decay process and interest in the antineutrino anomaly [11,12]. The long half-life has enabled the use of 138La for the measurement of the 34Al β-decay and EC energy, improving the precision compared to the values obtained in the most recent atomic mass measurements.

The ISOLDE facility at the National Superconducting Cyclotron Laboratory (NSCL) in East Lansing, Michigan, has been used for the measurement of the 138La β-decay and EC energy. The ISOLDE facility is equipped with a large number of radioactive ion beams and has been used for a variety of studies involving the measurement of nuclear masses. The ISOLDE facility is the ideal place for the measurement of the 138La β-decay and EC energy, as it is equipped with a large number of radioactive ion beams and has been used for a variety of studies involving the measurement of nuclear masses.

In this paper, we focus on the second forbidden unique decay scheme of 34Mg (adapted from [17]), populating mostly the 1+4p state. A position-sensitive detector was used to trigger dedicated studies to see if 34Al would be in the island of two-phonon states. A summary of the results is given in Table 1.

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Ions cycle back and forth. A time separation occurs such that $t \sim \sqrt{m/q}$. Fast. High resolution.

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)
- **Stable beams** at high intensity and energies up to 18 MeV/u
- **In-flight beams** approx. $10 < A < 50$ at energies up to 15 MeV/u
- **Reaccelerated CARIBU beams** at energies up to ~15 MeV/u
- **Low energy CARIBU beams** for ‘stopped beam’ measurements
Deformed, neutron-rich nuclei

CARIBU allows access to terra incognita: What stabilizes these deformed shapes? What role does the structure of these nuclei have on the r-process abundance?
Detailed spectroscopy
Detailed spectroscopy

Understanding REP formation

Masses measurements necessary to gain insights into what environment produces the observed abundance peaks

General classification:
Hot: \((n, \gamma) \rightleftharpoons (\gamma, n)\)
Cold: no equilibrium, competition between decay and neutron-capture
Understanding REP formation

Masses measurements necessary to gain insights into what environment produces the observed abundance peaks

General classification:
Hot: \((n, \gamma) \rightleftharpoons (\gamma, n)\)
Cold: no equilibrium, competition between decay and neutron-capture

REP (Rare-Earth Peak)
Masses, mass models

**Monte Carlo Mass Corrections (MCMC): “reverse engineering” the masses**

![Masses, mass models](image_url)

Brief detour (1) ...

$\beta^+ \text{ decay}: \, p \rightarrow n + e^+ + \nu_e$

$\beta^- \text{ decay}: \, n \rightarrow p + e^- + \bar{\nu}_e$
Brief detour (1) ...

$\beta^+ \text{ decay: } p \rightarrow n + e^+ + \nu_e$

$\beta^- \text{ decay: } n \rightarrow p + e^- + \bar{\nu}_e$
Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012.
Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012.

Precise masses ⇒ precise Q value.
The second recommendation specifically targets the development and deployment of a ton-scale neutrinoless double beta decay experiment. Demonstration experiments at the scale of 100 kg are currently underway to identify the requirements and candidate technologies for a larger, next-generation experiment, which is needed to be sensitive to postulated new physics. An ongoing NSAC subcommittee is helping to guide the process of the down-select, from several current options to one U.S.-led ton-scale experiment.

Since neutrinoless double beta decay measurements use the atomic nucleus as a laboratory, nuclear theory is critical in connecting experimental results to the underlying lepton-number violating interactions and parameters through nuclear matrix elements, which account for the strong interactions of neutrons and protons. Currently, there exists about a factor of two uncertainty in the relevant matrix elements, but by the time a ton-scale experiment is ready to take data, we expect reduced uncertainties as a result of the application to this problem of improved methods to solve the nuclear many-body physics.
(Neutrino-less) double beta decay

The search is on ... what does the future hold?

\[ [T_{1/2}^{0\nu}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2 \]
Knowing the Q value is essential

$$Q^5! \quad \left[ T_{1/2}^{0\nu} \right]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2$$

Sizes
Neutron and weak-charge distributions of the $^{48}$Ca nucleus

G. Hagen$^{1,2,*}$, A. Ekström$^{1,2}$, C. Forssén$^{1,2,3}$, G. R. Jansen$^{1,2}$, W. Nazarewicz$^{1,4,5}$, T. Papenbrock$^{1,2}$, K. A. Wendt$^{1,2}$, S. Bacca$^{6,7}$, N. Barnea$^{8}$, B. Carlsson$^{3}$, C. Drischler$^{9,10}$, K. Hebeler$^{9,10}$, M. Hjorth-Jensen$^{4,11}$, M. Miorelli$^{6,12}$, G. Orlandini$^{13,14}$, A. Schwenk$^{9,10}$ and J. Simonis$^{9,10}$

What is the size of the atomic nucleus? This deceptively simple question is difficult to answer. Although the electric charge distributions in atomic nuclei were measured accurately already half a century ago, our knowledge of the distribution of neutrons is still deficient. In addition to constraining the size of atomic nuclei, the neutron distribution also impacts the number of nuclei that can exist and the size of neutron stars. We present an $ab$ initio calculation of the neutron distribution of the neutron-rich nucleus $^{48}$Ca. We show that the neutron skin (difference between the radii of the neutron and proton distributions) is significantly smaller than previously thought. We also make predictions for the electric dipole polarizability and the weak form factor; both quantities that are at present targeted by precision measurements. Based on $ab$ initio results for $^{48}$Ca, we provide a constraint on the size of a neutron star.
Sizes

• Sizes of nuclei along with their mass (binding) is a fundamental property of the nucleus
• Radius links to size of the nuclear potential
• Matter and charge radii are similar for most nuclei, but dramatic differences seen in exotic systems
• Neutron skins
• Matter radii, neutron structure, can modify charge radius (or center-of-mass motion)?
• Shapes of nuclei can result in changes in charge radii
• ..... a series of examples ... via dramatic examples
**Proton, neutron, matter**

\[ r_c^2 = \frac{1}{Z} \int \rho_c(r) r^2 d^3r \]

- Can be probed via elastic scattering, isotope shifts (precise)
- Matter distributions (radii) through interaction cross sections, or hadronic scattering reactions (less precise)
- A global picture of something like \( r = r_0 A^{1/3} \) emerges (\( r_0 \sim 1.15-3 \text{ fm} \))

*Krane’s text book ... Rolf’s slides from this school*
Proton, neutron, and matter:

- Can be probed via elastic scattering, isotope shifts (precise).
- Matter distributions (radii) through interaction cross sections, or hadronic scattering reactions (less precise).
- A global picture of something like $r = r_0A^{1/3}$ emerges ($r_0 \approx 1.15-3$ fm).

History: Charge Distributions

In the '70s, a large data set was acquired on elastic electron scattering (mainly from Saclay) over a large $Q^2$-range and for a variety of nuclei. A "model-independent" analysis provided accurate results on charge distribution well described by mean field Density-Dependent Hartree-Fock calculations.

- Krane's textbook... Rolf's slides from this school.
FORM FACTORS OF NUCLEI AT LOW ENERGY

Elastic scattering $\rightarrow W^2 = M^2 \rightarrow Q^2 = 2M(E-E') \rightarrow Q^2$ and $\nu$ are correlated

$$d\sigma/d\Omega \ (\text{and not } d\sigma/d\Omega dE) = \sigma_M F_0^2(q)$$

- For a point charge with charge $Z$ one has $F_0(q) = Z$.
- For a charge with a finite size $F_0(q)$ will be smaller than $Z$, because different parts of $\rho(r)$ will give destructive contributions in the integral that constitutes $F_0(q)$.
- Often one includes the factor $Z$ in $\sigma_M$ and not in $F_0$, such that $F_0(0) = 1$.

$$F(q) = \frac{4\pi}{Zq} \int \rho(r) \sin(qr) r dr$$

Scatter from uniform sphere with radius $R$ at low $q$: $\sin(qr) = qr - (1/6)(qr)^3$

1st term disappears (charge normalization)
2nd term gives direct $R_{RMS}$ measurement (for $q$ low enough)
At higher $q$ pattern looks like slit scattering with radius $R$

Krane’s text book ... Rolf’s slides from this school
<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>$E_x$ [MeV]</th>
<th>$J^\pi$</th>
<th>$S$ ($e,e'$)</th>
<th>$r_0$ [fm]</th>
<th>$S$ ($d,3\text{He}$) literature</th>
<th>$S$ ($d,3\text{He}$) reanalysis</th>
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</thead>
<tbody>
<tr>
<td>$^{12}\text{C}$</td>
<td>0.000</td>
<td>3/2$^-$</td>
<td>1.72(11) [43]</td>
<td>1.35(2)</td>
<td>2.98 [44] 1.72</td>
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<tr>
<td></td>
<td>2.125</td>
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<td>0.26(2)</td>
<td>1.65(2)</td>
<td>0.69 0.27</td>
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<td>5.020</td>
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<td>0.20(2)</td>
<td>1.51(2)</td>
<td>0.31 0.11</td>
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<td>$^{16}\text{O}$</td>
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<td>1.27(13) [45]</td>
<td>1.37(3)</td>
<td>2.30 [46] 1.02</td>
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<td>6.320</td>
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<td>2.25(22)</td>
<td>1.28(2)</td>
<td>3.64 1.94</td>
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<tr>
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<td>1.27(2)</td>
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<td>2.239</td>
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<td>1.18(3)</td>
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<td>3.498</td>
<td>2$^+$</td>
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<td>1.12(3)</td>
<td>0.30 0.19</td>
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<td>$^{40}\text{Ca}$</td>
<td>0.000</td>
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<td>2.58(19) [49,50]</td>
<td>1.30(5)</td>
<td>3.70 [51] 2.30</td>
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<td></td>
<td>2.522</td>
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<td>1.03(7)</td>
<td>1.28(6)</td>
<td>1.65 1.03</td>
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<tr>
<td>$^{51}\text{V}$</td>
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<td>0.37(3) [3]</td>
<td>1.30(3)</td>
<td>0.73 [52] 0.30 [5]</td>
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<td>1.554</td>
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<td>2.675</td>
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<td>0.33(3)</td>
<td>1.32(3)</td>
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<td>0.49(4)</td>
<td>1.34(3)</td>
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<td>1.32(3)</td>
<td>1.80 [53] 0.60 [54]</td>
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<td>1.25 0.30</td>
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<td>1.86(14)</td>
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<td>3.90 1.20</td>
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<td>1.745</td>
<td>5/2$^+$</td>
<td>2.77(19)</td>
<td>1.30(2)</td>
<td>8.90 2.40</td>
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<td>$^{142}\text{Nd}$</td>
<td>0.000</td>
<td>5/2$^+$</td>
<td>1.39(23) [55]</td>
<td>1.29(9)</td>
<td>2.33 [56] 1.25</td>
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<tr>
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<td>0.145</td>
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<td>3.14(43)</td>
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<td>6.28 3.79</td>
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<td>1.118</td>
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<td>0.56(7)</td>
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<td>1.300</td>
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<td>0.11 0.07</td>
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<td>0.000</td>
<td>1/2$^+$</td>
<td>0.68(6) [57]</td>
<td>1.23(3)</td>
<td>1.15 [58] 1.03</td>
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<tr>
<td></td>
<td>0.203</td>
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<td>1.10(9)</td>
<td>1.27(9)</td>
<td>1.77 0.99</td>
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<td>0.616</td>
<td>5/2$^+$</td>
<td>0.32(3)</td>
<td>1.23(8)</td>
<td>0.52 0.44</td>
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<td>0.52(5)</td>
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<td>0.66 0.37</td>
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<td>1.470</td>
<td>11/2$^+$</td>
<td>3.58(32)</td>
<td>1.25(9)</td>
<td>6.94 5.21</td>
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<tr>
<td>$^{208}\text{Pb}$</td>
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<td>1/2$^+$</td>
<td>0.98(9) [57]</td>
<td>1.25(8)</td>
<td>1.8 [59] 1.5</td>
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<td></td>
<td>0.350</td>
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<td>2.31(22)</td>
<td>1.23(8)</td>
<td>3.8 2.2</td>
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<td>6.85(68)</td>
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<td>1.670</td>
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<td>2.93(28)</td>
<td>1.19(8)</td>
<td>3.5 3.1</td>
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<td></td>
<td>3.470</td>
<td>7/2$^+$</td>
<td>2.06(20)</td>
<td>1.15(9)</td>
<td>3.5 2.9</td>
<td></td>
</tr>
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</table>
The first measurement of the momentum distribution of the unstable nuclei was reported by Kobayashi et al. [15]. The charge-changing cross section is defined as the total cross section of changing the number of protons from a projectile to a nucleus. The reaction cross sections have been determined mostly by the transmission type measurement. The inelastic scattering here is defined as the excitation of the nucleus to its bound excited states without the emission of nucleons. The interaction cross section is measured by the transmission measurement by detecting the same number of nuclei. The details of the transmission measurements can be seen in previous review papers [1,13]. Recent developments with these methods are reviewed in Section 6. The knowledge that can be obtained by combining nucleon and density distribution studies made after the last review [1] are presented. Not only the nucleon distribution but also the radius and the charge-changing cross sections is one of the interesting possibilities.

For a Borromean halo (most of the two neutron halos) the correlation between two-halo neutrons are important to be understood. One is the spatial correlation so called di-neutron correlation. The other is the mixing of the orbitals with different parity. Recent studies on these directions are presented in Section 8.

Analogies are found in certain nuclear bindings such as the three rings are linked even though no two-ring pairs are linked. The pairing of neutrons continues with a half-life of 0.1 s due to the nickname "Borromean nucleus". These exotic nuclear phenomena are interesting to explore.

The nuclear charge radius is predominantly a measure of the center-of-mass motion of the charge carrying a neutron. The red shadows indicate the areas of motion of the protons; the blue shadows indicate the areas of motion of the neutrons. The nuclear charge density is an important parameter in nuclear theory, atomic theory, and laser trapping and probing in relatively simple systems (mass number A < 100) and in quantum systems in general (Jensen, Savajols, and Kanungo, 2013). In particular, the charge density is an important input for the interaction cross section that each proton is a point particle. In other words, only the general (Jensen, Savajols, and Kanungo, 2013) and in quantum systems in turn helps the development of effective models of structure, interactions, and reactions. This Colloquium is devoted to these subjects. Not only the nucleon distribution but also the density distribution studies made after the last review [1] are presented.

He isotopes

Which is larger charge radius? $^4$He, $^6$He, $^8$He?
Which is larger matter radius? $^4$He, $^6$He, $^8$He?
... and how were they determined?

Z.-T. Lu et al., Rev. Mod. Phys. 85, 1385 (2013)
Which is larger charge radius? 4He, 6He, 8He?

Which is larger matter radius? 4He, 6He, 8He?

... and how were they determined?

Colloquium: Laser probing of neutron-rich nuclei in light atoms

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(published 2 October 2013)
**He isotopes**

Which is larger charge radius? \(^4\)He, \(^6\)He, \(^8\)He?

Which is larger matter radius? \(^4\)He, \(^6\)He, \(^8\)He?
• Field shift, mass shift, and radius
E.g. $^8\text{He}$

He - Levels

- $^3\!\!^3P_{k,1,2}$
- $2\!\!^1P_2$
- $1\!\!^1S_0$

Spectroscopy

389 nm

- Trapping: 1993 nm
- 19.82 eV electron collision

work, $^9\text{He}$ nuclei were produced in a hot (750 °C) graphite target via the $^{12}\text{C}(^7\text{Li},^9\text{He})^1\text{N}$ reaction with a 100 pnA, 60 MeV beam of $^7\text{Li}$ from the ATLAS accelerator at Argonne National Laboratory. Neutral $^9\text{He}$ atoms diffused out of the target and were transferred in vacuum to the nearby atomic beam assembly in approximately 1 s. By detecting the characteristic $\beta$ decay, we established that $^9\text{He}$ atoms were transferred to the atomic beam assembly at the rate of $\sim 1 \times 10^6$ s$^{-1}$. Details on the production and transfer of $^9\text{He}$ atoms are given in [11].

Our design of the atomic beam assembly is based on a type of MOT system and is described in more detail in

Matter radii

- Matter radii can be determined from interaction cross sections

$$\sigma_I(p, t) = \pi \left[ R_I(p) + R_I(t) \right]^2$$

Table 1: Interaction cross sections ($\sigma_I$) of He isotopes ($\sigma_n$ in mb). The listed errors include statistical and systematic errors. The largest systematic errors were due to uncertainties in the estimation of scattering-out probabilities of non-interacting nuclei.

<table>
<thead>
<tr>
<th>Target</th>
<th>Be</th>
<th>$^4$He</th>
<th>$^6$He</th>
<th>$^8$He</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>498 ± 4</td>
<td>485 ± 4</td>
<td>757 ± 4</td>
<td>757 ± 4</td>
</tr>
<tr>
<td>C</td>
<td>550 ± 5</td>
<td>530 ± 5</td>
<td>722 ± 6</td>
<td>817 ± 6</td>
</tr>
<tr>
<td>$^8$He</td>
<td>850 ± 9</td>
<td>780 ± 13</td>
<td>1063 ± 8</td>
<td>1197 ± 9</td>
</tr>
</tbody>
</table>

$^4$He: He + $^4$He, $^6$He: He + $^6$He, $^8$He: He + $^8$He

Data from ref. [4]. The present value of $^8$He + C cross section agrees with the known value within quoted errors.

Which is larger charge radius? $^4\text{He}$, $^6\text{He}$, $^8\text{He}$?
Which is larger matter radius? $^4\text{He}$, $^6\text{He}$, $^8\text{He}$?

$^4\text{He}$

- $1.681(4) \text{ fm}$
- $1.63(3) \text{ fm}$

$^6\text{He}$

- $2.060(8) \text{ fm}$
- $2.33(4) \text{ fm}$

$^8\text{He}$

- $1.959(16) \text{ fm}$
- $2.49(4) \text{ fm}$

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$^{11}\text{Li}$ and $^{208}\text{Pb}$

$^{11}\text{Li}$ is the archetypal halo nucleus and $^{208}\text{Pb}$ is the archetypal doubly magic spherical magic nucleus ... which one is larger?
**11Li and 208Pb**

11Li is the archetypal halo nucleus and 208Pb is the archetypal doubly magic spherical magic nucleus ... which one is larger? About the same size!

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(Not sure who to credit for figure ... found as image online ...)

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TABLE I. Interaction cross sections (σ_I) in millibarns.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Be</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>6Li</td>
<td>651 ± 6</td>
<td>688 ± 10</td>
</tr>
<tr>
<td>7Li</td>
<td>686 ± 4</td>
<td>736 ± 6</td>
</tr>
<tr>
<td>8Li</td>
<td>727 ± 6</td>
<td>768 ± 9</td>
</tr>
<tr>
<td>9Li</td>
<td>739 ± 5</td>
<td>796 ± 6</td>
</tr>
<tr>
<td>10Li</td>
<td>1040 ± 60</td>
<td></td>
</tr>
<tr>
<td>7Be</td>
<td>682 ± 6</td>
<td>738 ± 9</td>
</tr>
<tr>
<td>8Be</td>
<td>755 ± 6</td>
<td>806 ± 9</td>
</tr>
<tr>
<td>9Be</td>
<td>755 ± 7</td>
<td>813 ± 10</td>
</tr>
</tbody>
</table>

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Recently, exotic-isotope beams, produced through the projectile-fragmentation process in high-energy heavy-ion reactions, were used to measure the interaction cross sections (σ_I) for all the known He isotopes. This novel technique of using exotic nuclear beams makes it possible to study systematically properties of unstable nuclei. In the present paper, we report the σ_I for all the known Li isotopes (6Li, 7Li, 8Li, 9Li, and 11Li) and 10Be, 11Be, and 12Be on the target nuclei Be, C, and Al at 790 MeV/nucleon. A firm basis has been practically established by use of a Glauber-type calculation to extract root mean square (rms) nuclear radii from the σ_I.

The Li isotopes, except 11Li, and the Be isotopes were produced as secondary beams through projectile fragmentation of the 800-MeV/nucleon 11B accelerated by the Bevalac at the Lawrence Berkeley Laboratory. The beam of 11Li was produced from a 20Ne primary beam. The isotopes produced in a production target of Be were separated by rigidity with the beamline magnet system as described in previous papers.1,2 The rigidity-separated isotopes were further identified before incidence on a reaction target by velocity time-of-flight (TOF) and by charge (puls height in scintillation counters). No contamination more than 10^-3 was observed in any selected isotope beam.

The interaction cross section (σ_I) was measured by a transmission experiment using the large-acceptance spectrometer as in the measurement of the He isotopes. Here σ_I is defined as the total reaction cross section for the change of proton and/or neutron number in the incident nucleus. The obtained σ_I are listed in Table I. The largest systematic error on σ_I, up to about 0.3%, came from uncertainties in the estimation of the scattering-out probability of the nonin-
Nuclei ... neutron stars

Neutron rich matter in heaven and on Earth

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(Dated: July 8, 2019)

Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.

FIG. 3: Connecting the very small to the very big. Despite a difference in size of 18 orders of magnitude, the symmetry pressure $L$ controls both the neutron skin thickness of $^{208}\text{Pb}$ as well as the radius of a neutron star. On the left hand panel a large set of highly successful models are used to illustrate the correlation between $L$ and $R^\text{208}_{\text{skin}}$; figure adapted from Ref. [5]. The right hand panel displays the correlation between $L$ and neutron star radii for one of these models: “FSUGold” [6].
Neutron rich matter in heaven and on Earth

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(Dated: July 8, 2019)

Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.
Shapes (and sizes)
Characterization of the shape-staggering effect in mercury nuclei

**Shapes**

<table>
<thead>
<tr>
<th>$\beta_{\lambda\mu}$</th>
<th>$\beta_{20} &gt; 0$</th>
<th>$\beta_{20} &lt; 0$</th>
<th>$\beta_{240} &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{22} \neq 0$</td>
<td>$\beta_{30} \neq 0$</td>
<td>$\beta_{32} \neq 0$</td>
<td>$\beta_{20} \gg 0$</td>
</tr>
</tbody>
</table>

$R(\theta, \phi) = c(\alpha_{\lambda\mu})R_0 \left[ 1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right]$

**Multipole order: $2^\lambda$**

- $2^0 = \text{monopole - breathing mode}$
- $2^1 = \text{dipole - centre of mass shift}$
- $2^2 = \text{quadrupole - axial deformation}$
- $2^3 = \text{octupole - asymmetric deformation}$
- $2^4 = \text{hexadecapole - pinching}$
Shapes, spectroscopy

https://www.nndc.bnl.gov/nudat2/, quadrupole deformation ($\beta_2$)
Shapes, spectroscopy

https://www.nndc.bnl.gov/nudat2/, energy of the first excited 2+ state
**Strange shapes ... "pears"**

**Reflection Asymmetry**

*Microscopically driven...*

Intruder orbitals of opposite parity and $\Delta J, \Delta L = 3$ close to the Fermi level

\[
(l + 3)^{-\pi}_{(j+3)}
\]

Enhancement of octupole part of nucleon-nucleon force...

- Small energy gap
- High sub-state density

Heaviest nuclei

*Taken from L. P. Gaffney talk, EuNPC 2015*
It’s all gone ... pear shaped

See write up in Nature 497, 190 (2013) [by C. J. (Kim) Lister …] ... and the BBC
Take a look at the Ba isotopes

Reflection Asymmetry
Intruder orbitals of opposite parity and $\Delta J, \Delta L = 3$ close to the Fermi level $\varepsilon_F$

Enhancement of octupole part of nucleon-nucleon force...
-Small energy gap
-High sub-state density

Heaviest nuclei
Gamma ray tracking

Motivation of $\gamma$-ray tracking

Compton Suppressed

$\epsilon_{\text{ph}} \sim 10\%$  
$N_{\text{det}} \sim 100$  
$\Omega \sim 40\%$  
$\theta \sim 8^\circ$

Ge Sphere

$\epsilon_{\text{ph}} \sim 50\%$  
$N_{\text{det}} \sim 1000$  
$\Omega \sim 80\%$  
$\theta \sim 3^\circ$

Tracking Array

$\epsilon_{\text{ph}} \sim 50\%$  
$N_{\text{det}} \sim 100$  
$\Omega \sim 80\%$  
$\theta \sim 10^\circ$

- 50% of solid angle taken by the AC shields
- large opening angle $\rightarrow$ poor energy resolution at high recoil velocity
- too many detectors needed to avoid summing effects
- opening angle still too big for very high recoil velocity

Smarter use of Ge detectors

- segmented detectors
- digital electronics
- timestamping of events
- analysis of pulse shapes
- tracking of $\gamma$-rays

Pulse Shape Analysis
Gamma-ray Tracking

$\theta_{\text{eff}} \sim 1^\circ$  
$N_{\text{eff}} \sim 10000$

from Calorimetric to Position Sensitive operation mode
**Coulomb excitation of $^{144}$Ba**

- $^{144}$Ba lies in a region where suspected enhanced octupole correlations occur
  - where long-range interactions between $\Delta j = \Delta l = 3$ configurations, namely the $\pi h_{11/2} \otimes \pi d_{5/2}$ and $\nu i_{13/2} \otimes v f_{7/2}$, occur
- Coulomb excitation is a reliable probe to extract B(E3) values
  - $B(E3) = 48^{+25}_{-34}$ W.u., consistent with octupole collectivity

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**References**

- W. Nazarewicz et al., NPA 429, 269 (1984)
**Coulomb excitation of $^{144}$Ba**

- Enhanced octupole correlations firmly established in both $^{144}$Ba and $^{146}$Ba
- Suggests a ‘region’ not just isolated cases (how far does it extend?)
- Behavior of the dipole strength shows interesting behavior

\[ D_0 = c_{ld} Z A \beta_2 \beta_3 \]

\[ D_{\delta^p} = \frac{e}{3.6} \left( \frac{N}{A} \langle z \rangle_p - \frac{Z}{A} \langle z \rangle_n \right) \]

Summary

• The many varied techniques associated with determining even simple properties of nuclei can give tremendous insights ... and we have not even delved (much) into the microscopic structure of these systems yet ....

• ... next two lectures focus on single-particle structure as probed through direct reactions