Rare isotopes: Probing many-body physics and the origin of the elements

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Who we are - NSCL and FRIB Laboratory

>780 employees, incl. >40 faculty, >121 graduate and >100 undergraduate students

- NSCL is funded by the U.S. National Science Foundation to operate a user facility for rare isotope research and education in nuclear science, nuclear astrophysics, accelerator physics, and societal applications
- FRIB will be a national user facility for the U.S. Department of Energy Office of Science – when FRIB becomes operational, NSCL will transition into FRIB
Outline

- Development of a comprehensive model of atomic nuclei – How do we understand the structure and stability of atomic nuclei?
- Understanding the origin of elements and nature of extreme astrophysical environments
- Use of atomic nuclei to test fundamental symmetries (e.g. search for new couplings)
- Applied isotope science – opportunities with rare (or energetic) isotopes
The territory: Nuclear Landscape

256 “Stable” – no decay observed
3307 total in the NNDC Database
Over 7000 predicted to exist
Lofty goal: Comprehensive model of nuclear structure and reactions

- A comprehensive and quantified model of atomic nuclei does not yet exist.
- In recent years, enormous progress has been made with measurements of properties of rare isotopes and developments in nuclear theory and computation.
- Access to key regions of the nuclear chart constrains models and identifies missing physics.
- Theory identifies key nuclei and properties to be studied.

A. Gade, FRIB Science, EDM Topical Program, August 2019
Challenge: Nuclei from NN interactions

- How do we model atomic nuclei? QCD ... but we need approximations

Theory

- Modern approaches to NN potentials include
  - QCD-inspired EFT (chiral interactions)
  - Lattice QCD

Figure from N. Ishii, S. Aoki, T. Hatsuda, PRL 99, 022001 (2007)

M. Savage
Calcium isotopes – where ab-initio, configuration interaction models and density functionals meet

- How many Ca nuclei exist? $^{58}\text{Ca}$ was observed in experiments a while ago – Experiment: just found $^{59}\text{Ca}$ and $^{60}\text{Ca}$. Theory: The jury is still out …

Coupled-cluster calculations based on chiral EFT

$^{60}\text{Ca}$ weakly bound/unbound, $^{61-62}\text{Ca}$ are located right at threshold

State-of-the-art energy density functionals

Calcium isotopes bound out to about $^{70}\text{Ca}$

C. Forssen et al., Physica Scripta T152 014022 (2013)
The nucleon driplines bound the nuclear chart and provide the fundamental information on which combinations of protons and neutrons can be made into a bound system. They are a critical benchmark for any model that aspires to predict nuclear binding/masses across the nuclear chart.

- $^{47}\text{P}$, $^{49}\text{S}$, $^{52}\text{Cl}$, $^{54}\text{Ar}$, $^{57}\text{K}$, $^{59;60}\text{Ca}$, and $^{62}\text{Sc}$, the most neutron-rich isotopes of the respective elements, were observed for the first time.
- The discovery of the above isotopes favors models that predict $^{70}\text{Ca}$ to be bound.

Method: Produce them and identify them!
What it took: Many years of work at NSCL

Most recent isotope discoveries in this region (2009/2013)

- $^{76}$Ge beam on W and Be at NSCL (130 MeV/u)
- Cross sections and systematics studies

O.B. Tarasov et al., NIM A 620, 578-584 (2010) : A new approach to measure momentum distributions

$^{64}$Ti, $^{67}$V, $^{69}$Cr, $^{72}$Mn, $^{70}$Cr, $^{75}$Fe

- $^{82}$Se beam on W and Be at NSCL (140 MeV/u)
- Cross sections and systematics studies


From that: $^{60}$Ca search is realistic at RIBF/RIKEN
Density functional theory and many-body perturbation theory based on potentials from EFT have advanced to predict the limits of existence based on advances statistical treatments.

• Showing that an isotope is bound or not impacts predictions

L. Neufcourt et al., PRL 122, 062502 (2019)
Calcium isotopes – what is important?
For the example of the coupled cluster approach

3-nucleon forces

C. Forssen et al., Physica Scripta T152, 014022 (2013)

The particle continuum (e.g. asymptotics of wave functions, correlations)

Measured properties of most neutron-rich Calcium isotopes will reveal missing ingredients in interactions and many-body approaches.
Access to Calcium isotopes now and at FRIB

- Calcium isotopic chain \((Z=20)\) is crucial
- FRIB provides access to the relevant neutron-rich Ca isotopes with intensities sufficient to measure important observables
  - Masses, half-lives, decay properties, single-particle and collective degrees of freedom
  - Structure of heavy Ca isotopes will quantify the role of the 3N forces and weak binding
- In general: Long isotopic chains are essential
  - Evolution of nuclear properties can be benchmarked as a function of isospin
The neutron-rich Ca isotopes beyond $^{48}\text{Ca}$ provide textbook examples of structural evolution.

Theory suggests a sensitivity of the detailed structure to the inclusion of a variety of many-body correlations, including 3N forces.

Understanding the nuclear force – Calcium isotopes, where we are and where we can go.
Some nuclei are special: “Designer Nuclei” as selective probes of certain aspects

- Not all nuclei are equally important to constrain nuclear models
  - Nuclear theory, computational physics and experiment work in concert to identify key nuclei and properties

- FRIB can produce nuclei with desired N/Z and nucleon separation energies to amplify effects of interest
  - Access to nuclei with exotic decay modes, e.g. 2-proton or 2-neutron radioactivity – sensitive to pairing and spatial correlations
  - Access to nuclei with extreme skins (>0.5 fm) – benchmark for isovector interactions/functionals, crucial for understanding neutron stars

Nuclei can be selected to highlight a particular aspect of the nuclear many-body problem

From K. Miernik et al., PRL 99, 192501 (2007)

Nuclei with large neutron skins
A note on nuclear reactions

- Nuclear reactions are an essential tool for the extraction of crucial information for nuclear structure physics and nuclear astrophysics.

- The required beam energy range spans from keV/u (astrophysics) to above 200 MeV/u for heavy-ion reactions that will constrain the nuclear equation of state.

FRIB will provide the full range of beam energies required to exploit nuclear reactions for nuclear structure and astrophysics.

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A. Gade, FRIB Science, EDM Topical Program, August 2019
Some challenges formulated for nuclei that highlight their role as open QS:

- What is the interplay between mean field and correlations around the emission threshold?
- What are properties of many-body systems around the reaction or decay threshold?
- What is the origin of cluster states, especially those of astrophysical importance?
- How to understand tunneling of complex systems?
- Which nuclear states are most impacted in continuum coupling?
Data on rare isotopes and their reactions are required to elucidate many astrophysical scenarios.
Nuclear data is needed to understand the many nucleosynthesis processes

- Big Bang nucleosynthesis
- pp-chain
- CNO cycle
- triple alpha
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- νp - process
- p - process
- α - process
- fission recycling
- Cosmic ray spallation
- pyconuclear fusion

Black - data on rare isotopes needed to model process

Sample reaction paths

Needed: masses, $T_{1/2}$, β-delayed particle emission probabilities, location of capture resonances, reaction rates if possible, …
Nuclear Astrophysics - Spectroscopy of proton-rich $^{58}\text{Zn}$

Nuclear reaction flow powers X-ray bursts through important waiting point $^{56}\text{Ni}$

Explore the nuclear structure and search for resonance

$^{56}\text{Ni}$ and $^{57}\text{Cu}$ are in a $(\text{p},\gamma)-\gamma,(\gamma,\text{p})$ equilibrium; variations of $^{57}\text{Cu}(\text{p},\gamma)\text{Zn}^{58}$ affect the eff. lifetime of $^{56}\text{Ni}$

$^{57}\text{Cu} + \text{p}$

Reaction rate dominated by $2^+$ resonances

C. Langer et al., PRL 113, 032502 (2014)

A. Gade, FRIB Science, EDM Topical Program, August 2019
Spectroscopy of $^{58}$Zn and reduced uncertainty in important reaction rate

C. Langer et al., PRL 113, 032502 (2014)

Experimental results and level scheme $^{58}$Zn

$^{57}$Cu($d$,n)$^{58}$Zn @ 75 MeV/u

Resulting astrophysical rate

$^{57}$Cu(p,$\gamma$)$^{58}$Zn rate uncertainty highly reduced!

→ Reliable prediction of A=56 in ashes
Neutron-capture process leading to elements heavier than iron


- Rapid neutron capture process, r-process
  - Fast, few seconds duration
  - Neutron density of $10^{20-28}$ n/cm$^3$
  - Runs out to where $(n,\gamma)$ and $(\gamma,n)$ are similar in rate
  - Adds 30-40 neutrons
  - Site: Unknown!

Origin of the heavy elements: One of 11 Science Questions for the 21st century
The neutron star merger event, GW170817, detected by LIGO/Virgo electrified our field

- The observation of GW170817 together with a kilonova, the afterglow from $\beta$-decaying rare isotopes, revealed neutron star mergers as a major source of the r process.
- This confirms Anna Frebel’s earlier conjecture based on abundance observations in an ultra faint dwarf galaxy that one site of the r process seems to be a rare and prolific event.

This defines better which nuclei are important for the r process.

The gravitational wave signal itself and the amount of r process material flung out are sensitive to the equation of state of nuclear matter.
FRIB’s reach for r-process studies
– Example: neutron-star merger scenario

-neutron capture rates

-β-delayed neutron emitters

Black line: FRIB production $10^{-4}$/s

Sensitive masses

(see this reference for other r-process scenarios)
Example – Time-of-flight (TOF) mass measurements reaching the r process

- Many masses measured at the same time, uses the fast rare isotope beams from fragmentation/fission directly, minimal decay and efficiency losses. Complements Penning trap mass measurements when modest precision is sufficient.

- Masses are deduced from the simultaneous measurement of an ion's time-of-flight, charge, and magnetic rigidity thorough a magnetic system of a known flight path.

- With the High-Rigidity Spectrometer (HRS) aspired for FRIB, this approach can reach a significant fraction of the nuclei relevant for the r-process.

Example: Masses determined at NSCL: Z. Meisel et al., PRL 114, 022501 (2015)
Example – precision masses

\[ f_c = \frac{\frac{q}{2\pi}}{m} B \]

from characteristic motion of stored ions

PENNING trap

- Strong homogeneous magnetic field of known strength B provides radial confinement
- Weak electric 3D quadrupole field provides axial confinement

Precision: \( \Delta m/m \sim 10^{-10} \)
Stay tuned for more exciting multi-messenger astronomy news

Latest @LIGO @ego_virgo update on #S190814bv labels it "NSBH". This means that, if confirmed, our candidate event *could* be an exciting new milestone: the first ever detection of a #NeutronStar #BlackHole merger. But, as always in science, we must be cautious... 1/5

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<thead>
<tr>
<th>Type</th>
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<tr>
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<td>BNS</td>
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<td>BBH</td>
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In a first, astronomers may have detected a black hole swallowing a neutron star

The LIGO and Virgo observatories appear to have picked up gravitational waves from a first-of-its-kind astronomical observation.
Rare isotopes put the Standard Model to the test

- Angular correlations in $\beta$-decay
  - Search for new particles and interactions
  - Mass scale for possible new particles is comparable with LHC
- Permanent electric dipole moments in atoms
  - Beyond
  - Dominance of matter over antimatter (CP violation)
  - 225Ra, 223Rn, 229Pa are special (several thousand times more sensitive than 199Hg)
- Parity non-conservation in atoms
  - Weak charge in the nucleus (Francium isotopes)

See talks posted for “Fundamental Symmetry Tests with Rare Isotopes” Workshop, UMassAmherst 2014 for more
Probing the Standard Model with the $\beta$ decay of $^6$He and $^{20}$F

- The shape of the $\beta$ spectrum is sensitive to the different terms in the electroweak theory of $\beta$ decay that is embedded in the Standard Model
- Novel approach: Implant $^6$He produced from fragmentation deep (12 mm) into an inorganic scintillator, e.g. CsI(Na)
- This implantation approach eliminates effects such as back-scattering and out-scattering of $\beta$ particles on/from detectors (unique to NSCL due to the availability of high-energy $^6$He from fragmentation)

Second case: $^{20}$F, along the way, measured the $\beta$-decay half life very

- Such precise half lives are needed for the sufficiently precise determination of $ft$ values for mirror symmetry tests
- The new result is at variance with the two most precise previous results by 18 standard deviations $\rightarrow$ Puzzling controversy now resolved by ND measurement [PRC 99 015501 (2019)]

$\beta$ spectrum $^6$He

Red line is sum of Gaussians representing the results, characterized by $\sigma$ and weighted by $1/\sigma^2$ for each measurement

M. Hughes et al., PRC 97, 054328 (2018)
Research isotopes for (societal) applications

- Broad range of rare isotopes that can be made available for applications through harvesting at FRIB
  - In-flight production at 400 kW beam power by projectile fragmentation and fission provides widest range of rare isotopes
  - Commensal mode of operation: delivery of rare isotope beam to main user while harvesting unused rare isotopes for applications

Real-time radioisotope imaging – nutrient uptake in plants with $^{32}$P

S. Kanno et al., Phil. Trans. R. Soc. B 367, 1501 (2012)

Stockpile stewardship – cross sections involving rare isotopes are needed

A. Gade, FRIB Science, EDM Topical Program, August 2019
Applications of energetic isotopes – Heavy-ion irradiations (NSCL unique!)

• 20-year history of providing heavy-ion beams to researchers from JPL, Caltech, and WashU for the calibration of heavy-ion detectors sent on space missions:
  
  • 1997: Beam for calibration of the detectors for CRIS-ACE (Cosmic Ray Isotope Spectrometer for the Advanced Composition Explorer)
  
  • 2006: Beam for calibration of the low-energy and high-energy telescopes (LET and HET) for the Solar Energetic Particle instrument on the STEREO mission
  
  • 2016: Beam for calibration of the EPI-Hi high-energy particle detector for the Solar Probe Plus (now Parker Solar Probe) – Launched in August 2018

Parker Solar Probe makes a second orbit of the sun, captures solar wind on video

ASTROPARTICLE PHYSICS

Observation of the $^{60}$Fe nucleosynthesis-clock isotope in galactic cosmic rays


Iron-60 ($^{60}$Fe) is a radioactive isotope in cosmic rays that serves as a clock to infer an upper limit on the time between nucleosynthesis and acceleration. We have used the ACE CRIS instrument to collect $3.55 \times 10^9$ iron nuclei, with energies ~195 to ~500 mega-electron volts per nucleon, of which we identify 15 $^{60}$Fe nuclei. The $^{60}$Fe/$^{56}$Fe source ratio is $(75 \pm 2.9) \times 10^{-5}$. The detection of supernova-produced $^{60}$Fe in cosmic rays implies that the time required for acceleration and transport to Earth does not greatly exceed the $^{60}$Fe half-life of 2.6 million years and that the $^{60}$Fe source distance does not greatly exceed the distance cosmic rays can diffuse over this time, 81 kiloparsecs. A natural place for $^{60}$Fe origin is in nearby clusters of massive stars.

W.R. Binns et al., Science, April 2016 (10.1126/science.aad6004)
Applications of rare isotopes – Heavy-ion irradiations (NSCL unique!)

Also: HI irradiation of DNA
Oakland University, MI

Direct Formation of the C5’-Radical in the Sugar-Phosphate Backbone of DNA by High Energy Radiation

Amitava Adhikary, David Becker, Brian J. Palmer, Alicia N. Heizer, and Michael D. Sevilla
Department of Chemistry, Oakland University, Rochester, MI 48309
Discovery potential – new phenomena may be out there

FRIB will produce 80% of all (predicted) isotopes of elements up to Uranium

New territory to be explored at FRIB

About 3000 known isotopes

A. Gade, FRIB Science, EDM Topical Program, August 2019
Thank you