The US Facility for Rare Isotope Beams and Its Science

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Outline

• Why Rare Isotope beams?
• Where will it be located?
• The facility in brief:
  – its rare isotope production methods,
  – its scientific agenda,
• Summary and outlook

• Acknowledgement on slides: Konrad Gelbke (FRIB Director), Brad Sherrill (FRIB Chief Scientist), Thomas Glasmacher (FRIB Project Director), FRIB team at NSCL, and Bill Lynch.
Rare Isotope Nuclear Science Context

• Stable nuclei: $N/Z \approx 1 - 1.5$, $S_p \approx S_n \approx 6 - 8$ MeV
  – Homogeneous admixture of protons and neutrons
  – Good mean-field description & “single-particle” picture
  – Large gaps between major shells (magic numbers)
  – Empirical shell-model interactions

• Very neutron-rich nuclei: $N/Z \approx 2 - 2.5$, $S_n << 1$ MeV
  – Extended neutron distributions – neutron skins & halos
  – Proximity of the Fermi surface – coupling to the continuum
  – Redefinition of magic numbers
  – Unknown shell-model interactions

• Studies of rare isotopes are crucial for developing reliable models of nuclei and their reactions
  – Link to mesoscopic science – deriving the properties of complex systems from their simple building blocks
    » Nuclei are finite droplets of a two-component Fermi-liquid subject to the strong, weak and Coulomb interactions
    » Nuclei far from stability are open quantum systems that exhibit strong coupling to the continuum
World view of rare isotope facilities

China: CSR in Lanzhou
BRIF & in Beijing

Black – production in target
Magenta – in-flight production
Michigan State University
57,000 people; 92 sq km; $1.8B annual revenue; 552 buildings
Timeline for NSCL – FRIB

- 1958: MSU hires first accelerator expert
- 1961: NSF approves sector focused K50 cyclotron
- 1965: Research with K50; single turn extraction
- 1975: NSF approves superconducting cyclotron magnet prototype
- 1977: NSF approves K500 cyclotron
- 1982: Research with stable beams from K500
- 1989: Research with stable beams from K1200
- 1990: Research with fast rare isotope beams from A1200
- 1996: NSF approves coupled cyclotron facility (CCF)
- 2001: Research with fast rare isotope beams from CCF
- 2002: Infrastructure for SRF linac R&D
- 2005: Research with trapped rare isotope beams
- 2006: MSU funds ReA3 reaccelerator project
- 2008: DOE selects MSU to establish FRIB
- 2010: Research with reaccelerated rare isotope beams from ReA3
- 2018: FRIB operations
FRIB FOA Specifications (DOE)

• 200 MeV/u, 400 kW superconducting heavy-ion driver linac

• Initial capabilities should include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration

• Capable of world-class scientific research program at start of operation

• Accommodate 400-500 users per year

• Designed, built and commissioned for a total project cost of \( \leq 550 \text{ M}$ in escalated ("then year") dollars

• Funding Constraints
Main FRIB production mechanism: Production of Rare Isotopes in Flight

1. Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight.

2. Cooling by evaporation.
How it all fits together …
Details still evolve due to ongoing value engineering process
Key Collaborators

- ANL
  - Liquid lithium charge stripper
- BNL
  - Plasma window & charge stripper
- FNAL
  - Diagnostics
- JLab
  - Cryogenics systems design
- LBNL
  - ECR ion source; beam dynamics
- ORNL
  - Diagnostics, controls
- SLAC
  - Cryogenics, SRF multipacting
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, SRF
- INFN
  - SRF technology
- Texas A&M
  - Heavy ion beam tests
- IMP
  - Magnets, ECR ion source
- COSYLAB
  - Machine protection controls
- Budker Institute, INR Institute
  - Diagnostics
FRIB Linac Performance

200 MeV/u Beam energy
400 kW Beam power

FRIB Beam Energy (MeV/u)

Ion

P  He  D  C  O  Ar  Ca  Zn  Kr  Xe  Bi  U
FRIB will produce more than 1000 NEW isotopes at useful rates (4500 available for study; compared to 1700 now). Rates are available at http://groups.nscl.msu.edu/frib/rates/
The Scientific Agenda of FRIB

Properties of nucleonic matter
- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks

Nuclear processes in the universe
- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter

Tests of fundamental symmetries
- Effects of symmetry violations are amplified in certain nuclei

Societal applications and benefits
- Bio-medicine, energy, material sciences, national security
Some selected science programs

- Search of Dripline nuclei: study of nuclei along the drip line to mass 120 (compared to 24)
- Evolution of nuclear radii
- Mass measurements
- Laser spectroscopy
- Evolution of shell structure
  - Knockout process
  - Transfer reactions
- Astrophysics
  - rp process
  - r process
  - Density dependence of the symmetry energy
- …
Nuclear radii near the driplines: development of skins and halos

- Measurement of interaction radii (fast beams)

I. Tanihata,

Large radii enabled by the weak binding of valence nucleons near the driplines.

$^{11}$Li has valence orbits as large as $^{208}$Pb
**Mass measurements: Low Energy Beam Ion Trap (LEBIT)**

stopped fragments in helium-gas cell, extract, purify, and store in Penning trap

- Measurements of masses, moments, fission barriers, and deformations provide guidance for the development of an energy density functional with significant predictive power

**Penning Trap Mass Spectrometry**

- Cooling and Bunching
- Gas stopping of fast ions
- Degrader

Since 2005: accurate masses for more than 30 isotopes of more than 10 elements: $^{33}$Si, $^{29}$P, $^{34}$P, $^{37,38}$Ca, $^{40-44}$S, $^{63-65}$Fe, $^{64-66}$Co, $^{63-64}$Ga, $^{64-66}$Ge, $^{66-68,80}$As, $^{68-70,81,81m}$Se, $^{70m,71m}$Br

G. Bollen et al. PRL 96 (2006)152501

\[ \delta m = 280 \text{ eV} \]
\[ \delta m/m = 8 \cdot 10^{-9} \]

\[ ^{38}\text{Ca}^{++} \]

$0^+ \rightarrow 0^+ \beta^+\text{-emitter}$
Laser Spectroscopy at NSCL/FRIB (Stopped beams)

• Evolution of nuclear sizes and shapes across long chains of isotopes
  – Isotope shifts, charge radii, nuclear moments ($\mu$, $Q$)
  – Method applicable to nuclides over wide range of $T_{1/2}$ values

• Projectile fragmentation plus gas stopping
  – Broad range of previously inaccessible refractory elements with $Z<50$
Evolution of Shell Structure

- Needed for an improved understanding of the nature of the effective interactions and operators used in nuclear structure models

- Shell gaps change near driplines
  - Insight into tensor and 3-body forces in nuclei (e.g., Otsuka, et al.)
  - Diffuse surfaces influence S.O. term
  - The continuum plays an important role in weakly bound nuclei (e.g., Nazarewicz, Zelevinsky, et al.)

- Further surprises are likely
What are the valence orbits and their occupancies? Knockout & Transfer reactions

Knockout result: strong dep. of SF on how deeply bound is the valence nucleon
Transfer result: no strong dep. of SF on asymmetry

- Provides test of nuclear structure theories
- Important for astrophysical applications
Major Advance in Nuclear Astrophysics

FRIB is designed to address important scientific questions in nuclear astrophysics identified in NSAC’s 2007 Long Range Plan

– What is the origin of the elements in the cosmos
  » Synthesis of neutron-rich nuclei heavier than iron: r-process
  » Gamma-ray emitters in supernovae
  » Isotope harvesting for s-process studies

– What are the nuclear reactions that drive stellar explosions
  » Synthesis of proton-rich nuclei: rp-process
  » Weak interactions in supernovae

– What is the nature of neutron stars and dense nuclear matter
  » Nuclear processes in the crusts of neutron stars
  » Symmetry energy term of equation of state of nuclear matter
The separation energy for $^{69}\text{Br} \rightarrow p + ^{68}\text{Se}$ governs the two proton capture rate on $^{68}\text{Se}$.

It was determined by directly measuring relative energies of the proton and $^{68}\text{Se}$ decay products.

Assuming the $J^\pi=3/2^- \ (l=1)$ ground state from $^{69}\text{Se}$ and mirror symmetry, the data indicate a separation energy of $S_p = -785 \pm 40 \text{ keV}$.

This implies that 2 proton capture through $^{69}\text{Br}$ is can be neglected in standard X-ray burst network calculations.
FRIB Capability to Address r-Process

Asymmetry dependence of fission barriers

(d,p) for (n,γ)

NSCL experiments including 78Ni

Known β-decay

FRIB reach for β-decay properties

Masses

RISAC benchmark

FRIB reach

N=126

(70) Yb
(69) Tm
(68) Er
(67) Ho
(66) Dy
Asymmetry Term of the Equation of State

Highly relevant for supernovae and neutron star properties

- Neutron star radii, neutron skins of nuclei, and isospin diffusion processes are sensitive to the asymmetry term of the EOS
  - At $\rho = 2\rho_0$, up to 70% of the pressure in neutron star crusts comes from the asymmetry energy

Possible measurements:
- Asymmetric nucleus-nucleus collisions
  » Isospin diffusion (isotope ratios)
  » $\pi^+/\pi^-$ emission ratios
- Neutron skins
FRIB Reach For Crust Processes

- Fast and stopped beams provide unique reach for much of the nuclear physics of neutron star crusts

Gupta et al. 2006
Summary

• FRIB, a powerful new US rare isotope facility is being designed at MSU.
• The current schedule indicates a possible early completion date of 2018.
• This new facility will provide important capabilities for studies of
  – Properties of nucleonic matter
  – Nuclear processes in the universe
  – Tests of fundamental symmetries
  – Societal applications and benefits
• Many programs at FRIB should be able to start using CCF beams and transition smoothly to FRIB operations upon FRIB completion.
Transition from NSCL to FRIB Operations

- Minimal perturbation of the experimental area when transitioning from CCF to FRIB operations

Existing MSU Cyclotron Driver and Target operates until FRIB Driver and Target are operational.
NSCL’s Pre-FRIB Facility Plan

Equipment will be in place for experiments with FRIB
What are the valence orbits and their occupancies?

1 probe: Knockout Reactions with fast beams

- Different $P_{||}$-distributions for individual states, tagged by $\gamma$-rays: cross section is sensitive to wavefunction; shape identifies $l$ of knocked-out nucleon
  - Breakdown of N=8 shell closure in $^{12}$Be: only 32% (0p)$^8$ and 68% (0p)$^6$-(1s,0d)$^2$
2nd probe: Transfer reactions (Fast or reaccelerated beams)

Results indicate that

\[
\frac{d\sigma}{d\Omega}_{\text{Exp}} = S F_{\text{LB-SM}} \cdot \frac{d\sigma}{d\Omega}_{\text{ADWA}}
\]

- Global potentials and Johnson-Soper App.
- Consistent with shell model to within 20% for ground states for stable and exotic nuclei and 30% for excited states, using CH89 opt. pot.
- Provides test of nuclear structure theories
- Important for astrophysical applications
Explosive Nucleo-Synthesis Paths

r and rp-processes involve exotic nuclei

Isotopes with known masses

rp-process in x-ray bursts

A=64-72 waiting point region

Nickel (28) → Calcium (20)

Tin (50) → Tellurium

Lead (82) → Platinum

Mass number 195

Mass number 130

Number of neutrons

Number of protons

r-process responsible for about half of the heavy elements

Hendrik Schatz
Physics Today, Nov. 2008 p. 40

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Betty Tsang, 8/1/2011, Slide 32
FRIB will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth). FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

Cost: $640M; construction start: 2013; completion: 2020
One motivation: Test some common assumptions used to describe stable nuclei theoretically

- Nuclear can be approximated by protons, neutrons, and their pair-wise interactions
- Nuclear radii follow the formula $r = r_0 A^{1/3}$ (Equation 1.2 Wong *Introductory Nuclear Physics*)
- The nuclear force has a saturation property where each nucleon can only interact with a few of its neighbors and the total binding energy increases linearly with $A$.
- Nuclei obey a shell model with magic numbers 2, 8, 20, 28, 50, etc.
- Resonance properties, etc.
Assumptions used in stable nuclei fail for exotic nuclei

- Nuclei can be approximated by protons, neutrons, and their pair-wise interactions

- Nuclear radii follow the formula \( r = r_0 A^{1/3} \) (Equation 1.2 Wong Introductory Nuclear Physics)

- The nuclear force has a saturation property where each nucleon can only interact with a few of its neighbors and the total binding energy increases linearly with \( A \).

- Nuclei obey a shell model with magic numbers 2, 8, 20, 28, 50, etc.

- Resonance properties, etc.

- Three body forces are important

- Only true for \( N\sim Z \) nuclei; \(^{11}\text{Li}\) has valence orbits as large as \(^{208}\text{Pb}\)

- This is only true for the stable isotopes found in nature. Some heavy isotopes of mid-mass nuclei may accept 20+ nucleons with little change in BE

- Magic numbers change depending on relative \( A/Z \)

- Neutron number can dramatically change the values away from stability
Driving towards the dripline: e.g. discovery of $^{40}$Mg, $^{42,43}$Al, & $^{44}$Si


Enhanced selectivity from two-stage separator:

- $1.5 \times 10^{17}$ $^{48}$Ca nuclei ($^{\text{nat}}$W target, E/A = 141 MeV)
  → three $^{40}$Mg nuclei (fast beams)


\[ \sigma = C \exp \left( \frac{\langle B' \rangle}{\tau} \right) \]
The Rapid Neutron Capture Process (r-process)

Occurs at $T > 10^9$, $\rho_{\text{neutron}} > 10^{20}$ cm$^{-3}$

- Open questions:
  - Where does nature produce about half of the heavy elements beyond Fe? Supernovae or N-Star mergers?
  - What is the actual nuclear reaction sequence?
  - What does the abundance pattern tell us about the astrophysical environment?

- Needed: Data
  - Nuclear experimental data (masses, half-lives) plus improved nuclear theory
  - Precision observations of abundance patterns produced by the r-process in nature

Price & Rosswog 2006

Crab Nebula

Mt Palomar

Chandra

Supernovae: Neutrino-driven wind? Prompt explosions? Shocked O-Ne-Mg cores?

Nucleosynthesis in gamma ray burst accretion disks?
Details of the FRIB Accelerator

Superconducting RF cavities
4 types
≈ 344 total
$E_{peak} \approx 30 \text{ MV/m}$

$B=0.04 \quad \beta = 0.08 \quad \beta = 0.2 \quad \beta = 0.5$
Scientific Reach of Heavy Ion Drivers
Measurements for the rarest nuclei are needed to constrain theoretical models

In-flight production allows chemistry-independent separation
- Short beam development times
- Negligible losses from decay (separation and transport in microseconds)

Fast beams have the furthest reach
- Use of thick targets provides large luminosity gains (typically by 10^3-10^4)
- Avoid losses (> 10) incurred by gas-stopping and reacceleration
- Enhanced efficiency by use of cocktail beams (ion-by-ion PID & tracking)

→ Nuclei very far from stability can be reached only with fast beams

Experiments with reaccelerated beams (e.g., transfer reactions) typically require beam intensities of 10^3-10^4 s^{-1} (production rates > 10^4 s^{-1}) or more
- Reaccelerated beams from in-flight production can reach many new states in nuclei closer to stability
- Needed for fusion reactions

* For simplicity, the transfer reaction limit in this graph assumes no losses from gas stopping, extraction, and reacceleration
Support surface buildings

Linac tunnel
~40 ft below grade

Grade (ground) level
FRIB Linac Performance

200 MeV/u Beam energy
400 kW Beam power

FRIB Beam Energy (MeV/u)

Ion

P  He  D  C  O  Ar  Ca  Zn  Kr  Xe  Bi  U
A heavy-ion driver can also accelerate light ions needed for an ISOL facility
Extrapolation of cross-sections of drip-line nuclei

Existence of $^{40}$Mg but non-existence of $^{39}$Na establishes the n-drip line at $N=28$

Predicted cross-sections:

$\sigma(^{40}$Mg)$\sim 4-8\times 10^{-11}$ mb
$\sigma(^{39}$Na)$\sim 0.4-6\times 10^{-11}$ mb

Predictions in arXiv:0705.0349 changed from $\sigma(^{40}$Mg)$\sim 4\pm 1\times 10^{-10}$ mb to $4\pm 8\times 10^{-11}$ mb

$\sigma = C \exp(<B'/\tau)$

$Y(Z, N) = cA^{3/2}\exp[(N\mu_n + Z\mu_p - F)/T]$
Mass measurements of neutron rich rare isotopes with cross-sections

Experimental Uncertainties ~15% $\sigma$ corresponds to 200 keV; comparable to TOF method

Mass of $^{75}$Cu
AW03:
$636.75 \pm 0.98$ MeV
Compared to
$636.94 \pm 0.40$ MeV

Tsang et al: PRC 76 (2007) 041302(R)
Observational Precision Data Emerging

• r-process enhanced metal poor stars reveal properties of single r-process events and r-process enrichment history of the Galaxy

![Graph showing relative abundance of elements](image)

- Different abundances
- Nearly identical abundances

**CS22892-052 (HST)**


John Cowen, private communication
Selected Alternatives: “V2b” with “C-bend” Layout for Stages 2 and 3

Preseparator

Mass Selection Slits

Wedges

Second and Third Separator Stage

Beam Dump

Production Target

M. Hausmann, 27 July 2010, C02
Technical Requirements and Scope

• Intercept primary beam at well-defined location

• High power capability up to 400 kW
  – High power density: ~ 10 MW/cm$^3$, c.f. 0.4 kW/cm$^3$ for 1 MW SNS target

• Long-lived or rapidly replaceable
  – 1 year desirable
  – Remote-handling capable

• Compatible with other subsystems
  – Fragment separator layout, optics
    » Must meet Fit, Form, Function

• Safe to operate

• Technical risks
  – High power density
  – High radiation
Rotating Water-filled Aluminum-shell Dump
Preferred Concept

- Beam dump absorbs 100% of primary beam and > 90% of rare isotopes
- Concept of rotating water-filled aluminum-shell dump
  - Heavy-ion beam penetrates rotating shell and stops in water
  - Water cools rotating shell
  - Produced activity is diluted by large volume and water is filtered
    » Activity is removed from loop
    » Better radiological safety
    » Potential for “isotope harvesting”
- Concept chosen because
  - Large-power-density risk retired
  - Life expectancy is sufficient
  - Supporting infrastructure is based on established concepts
    » Water loop, filtration; HOG system
Such tests are enabled by the Reach of FRIB

- FRIB will produce more than 1000 NEW isotopes at useful rates (4500 available for study; compared to 1700 now)
- Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting of unusual isotopes for a wide range of applications

Rates are available at http://groups.nscl.msu.edu/frib/rates/
Stoppers Rare Isotope Beams

- Two momentum compression beam lines
- Three complementary stopping stations
  - Cyclotron gas stopper
    » Best for light and medium heavy isotopes
    » $B_{\text{max}} = 2.3T$, $r_{\text{inj}} = 0.95$,
      $p_{\text{He}} = 50-250$ mbar
    » $I > 10^8/s$, $T_{1/2} < 50$ms
  - Cryogenic linear gas stopper
    » Best for heavy isotopes
    » $L = 1.5$ m, $p < 300$ mbar
    » $I < 10^7/s$, $T_{1/2} > 100$ms
  - Solid stopper
    » For special elements and very high beam rates
    » Example: $^{15}$O, $I > 10^{10}$/s
Energy upgrade of ReA3
High priority for NSCL/FRIB user community

ReA3 (commissioning in 2011)

Upgrade path to ReA6 requires minor disruption of ReA3 operations
Upgrade path from ReA6 to ReA12 is non-disruptive
Phase 2 High Bay Addition
Construction complete by Fall 2011: needed for implementing ReA12 science capability
Occupation of Single-Particle States

- Shell model: Deeply-bound states are fully occupied. At and above Fermi sea, configuration mixing leads to reduced occupancies.

- Correlations (short-range, soft-core, long-range, coupling to vibrational excitations…) are not treated in shell model and can modify single-particle state occupancies.

- Reduction factor with respect to the shell model: $R_s = C_{\text{exp}}^2 / C_{\text{th}}^2$

- In stable nuclei, $R_s = 0.6 - 0.7$ has been established from $(e,e')p$ reactions

V. R. Pandharipande et al., Rev. Mod. Phys. 69, 981 (1997)

Expanded Purview from Rare Isotopes

Spectroscopic strength

$\sigma_{th}$: Theory (Eikonal + SM)


$R_S = \frac{\sigma_{exp}}{\sigma_{th}}$

$R_S (e,e'p): \Delta S = S_p - S_n$

$R_S p$-knockout: $\Delta S = S_p - S_n$

$R_S n$-knockout: $\Delta S = S_n - S_p$

$\Delta S$ (MeV)
Accreting Neutron Stars: X-ray Bursts

- Normal X-ray bursts: thermonuclear explosions on the surface (~4 m) of accreting neutron stars
  - Calculated time structures are sensitive to unknown nuclear properties
- X-ray superbursts: re-ignition of the ashes in the neutron star’s crust (~20 m)
  - carbon burning and photo-dissociation of heavier nuclei

L. Keek, PhD Thesis 2008

~ 1 day observation time
Crusts of Accreting Neutron Stars

- Understanding of crust reactions offers possibility to constrain neutron star properties (core composition, $\nu$-emission…)

- Nuclear reactions in the crust
  - Determine its thermal properties
  - Influence (observable) transients
  - Directly affect superburst ignition

New Neutron-Rich Nuclei (Summary)

- 4 new isotope from $^{48}\text{Ca}^+\text{natW}$, E/A = 141 MeV
- 15 new isotopes from $^{76}\text{Ge}^+\text{Be}$, E/A = 130 MeV
- Higher than expected production rates of $^{55,56}\text{K}$, $^{57,58}\text{Ca}$, and $^{59-61}\text{Sc}$
- Evidence for a new “island of inversion” around $^{62}\text{Ti}$ (?)
  - Modifications to the underlying shell structure of these very neutron-rich through the strong, attractive proton-neutron interaction (?)

Expanded Purview from Rare Isotopes

Spectroscopic strength

\[ \sigma = \frac{\sigma_{\text{exp}}}{\sigma_{\text{th}}} \]

\( \Delta S = S_p - S_n \)

\( R_S \) (e,e'p): \( \Delta S = S_p - S_n \)

\( R_S \) p-knockout: \( \Delta S = S_p - S_n \)

\( R_S \) n-knockout: \( \Delta S = S_n - S_p \)

\( A. \text{ Gade et al., Phys. Rev. C77, 044306 (2008)} \)
Emerging Trends in r-Process Stars

- Only 1:1.2 Mio halo stars are r-process enhanced
  - Ongoing surveys such as SEGUE might find 1000s more

Apache Point

Sneden et al., Jan. 2009

Abundance Relative to Eu

Element Number

Ba  La  Ce  Pr  Nd  Sm  Eu  Gd  Tb  Dy  Ho  Er  Tm  Yb  Lu  Hf

55  60  65  70

r-solar  r-stellar  HD 115444  CS 22892-052  BD+17 3248

Betty Tsang, 8/1/2011, Slide 59
Rare Isotope Crust Processes

Gupta et al. 2006

- **Known mass**

- **rp-ashes**

- **56Fe**
  - 2.5 x 10^{11} g/cm^3

- **56Ar**
  - 1.5 x 10^{12} g/cm^3

- **68Ca**
  - 4.4 x 10^{12} g/cm^3

- **72Ca**
  - 4.8 x 10^{11} g/cm^3

- **106Pd**
  - 1.8 x 10^{12} g/cm^3

- **106Ge**
  - 4.8 x 10^{11} g/cm^3

- **34Ne**

Gupta et al. 2006
In-Flight Production of Rare Isotopes
Example: NSCL’s CCF

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

- Ion sources
- $^{86}\text{Kr}^{14+}$, 12 MeV/u
- Production target
- Stripping foil
- Coupling line
- K500
- K1200
- A1900

Transmission of 65% of the produced $^{78}\text{Ni}$

$^{86}\text{Kr}^{14+}$, 140 MeV/u

$\Delta p/p = 5\%$

Fragment yield after target

Fragment yield after wedge

Fragment yield at focal plane
or Fragmentation of 132 MeV/u $^{76}$Ge+$^9$Be
Editors’ Selection

15 new isotopes observed – unexpected deviations from $Q_g$-systematics

$Q_g = ME(Z_p, A_p) - ME(Z, A)$
Production of Rare Isotopes at Rest

1. Bombard a thick target of heavy nuclei with energetic light particles, e.g. 1 GeV protons, to achieve random removal of protons and neutrons or fission

2. Extract rare isotopes from the target material by diffusion or effusion; ionize and accelerate them to the desired energy → beam of high quality
Occupation of Single-Particle States

• Shell model: Deeply-bound states are fully occupied. At and above Fermi sea, configuration mixing leads to reduced occupancies.

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V. R. Pandharipande et al., Rev. Mod. Phys. 69, 981 (1997)
Origin of the Elements in the Cosmos

Particle Physics
Nuclear Physics (NSCL, FRIB)
Chemistry
Biochemistry

MAP (Microwave Anisotropy Probe)
NGST (Next Generation Space Telescope)
SIRTF (Space Infra Red Telescope Facility)
TPF (Terrestrial Planet Finder)
Rare Isotopes For Society

• Isotopes for medical research
  – Examples: $^{47}$Sc, $^{62}$Zn, $^{64}$Cu, $^{67}$Cu, $^{68}$Ge, $^{149}$Tb, $^{153}$Gd, $^{168}$Ho, $^{177}$Lu, $^{188}$Re, $^{211}$At, $^{212}$Bi, $^{213}$Bi, $^{223}$Ra (DOE expert panel)
  – MSU Radiology Dept. interested in $^{60,61}$Cu
  – $\alpha$-emitters $^{149}$Tb, $^{211}$At: potential treatment of metastatic cancer

• Reaction rates important for stockpile stewardship – non-classified research
  – Determination of extremely high neutron fluxes by activation analysis
  – Rare isotope samples for $(n,\gamma)$, $(n,n')$, $(n,2n)$, $(n,f)$ e.g. $^{88,89}$Zr
    » Same technique important for astrophysics
  – Far from stability: surrogate reactions (d,p), $(^3$He,$\alpha$ xn) …

Expansion options (beyond FRIB scope)

Example: NNSA Neutron Facility as proposed by LLNL
Examples of In-Flight Production Rates and impact on fast or reaccelerated beam measurements.

- Fast, stopped and reaccelerated beams are needed for effective science return on investment
  - High premium on efficiency for in-flight separation, stopping and reacceleration chain
  - High premium on efficient experimental apparatus
Harvesting at Beam Dump

- Beam dump absorbs 100 % of primary beam and > 90 % of rare isotopes

Possible primary beam Trajectories; all available at beam dump

Dump for primary beam

Br slits, adjustable

Selected fragment
Preliminary Performance Baseline Schedule for 2018 Early Completion – CD-4 in 2020

CALENDAR YEAR

ID | 2009 Q1 Q2 Q3 Q4 | 2010 Q1 Q2 Q3 Q4 | 2011 Q1 Q2 Q3 Q4 | 2012 Q1 Q2 Q3 Q4 | 2013 Q1 Q2 Q3 Q4 | 2014 Q1 Q2 Q3 Q4 | 2015 Q1 Q2 Q3 Q4 | 2016 Q1 Q2 Q3 Q4 | 2017 Q1 Q2 Q3 Q4 | 2018 Q1 Q2 Q3 Q4 | 2019 Q1 Q2 Q3 Q4 | 2020 Q1 Q2 Q3 Q4
---|---|---|---|---|---|---|---|---|---|---|---|---
1 | | | | | | | | | | | | |
2 | | | | | | | | | | | | |
3 | | | | | | | | | | | | |
4 | | | | | | | | | | | | |
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TPC covers schedule range

Early CD-4 •

CD-4 •

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University
Existing NSCL Site
FRIB will be build adjoined to NSCL
Existing NSCL Site
FRIB will be built adjoined to NSCL
Target Building Layout

- Target hot cell, subterranean
  - Production target
  - Fragment preseparator
  - Primary beam dumps
  - Remote handling equipment

- Support building highbay, grade level
  - Second and third stage of fragment separator
  - 50-ton bridge crane
  - Fragment separator power supplies

- Support building, subterranean
  - Nuclear ventilation
  - Non-conventional utilities
  - Control room
  - Remote handling gallery
  - Waste handling
Michigan State University
1. Bombard a thick target of heavy nuclei with energetic light particles, e.g. 1 GeV protons, to achieve random removal of protons and neutrons or fission

2. Extract rare isotopes from the target material by diffusion or effusion; ionize and accelerate them to the desired energy → beam of high quality
Such tests are enabled by the Reach of FRIB

- FRIB will produce more than 1000 NEW isotopes at useful rates (4500 available for study; compared to 1700 now)
- Theory is key to making the right measurements
- Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting of unusual isotopes for a wide range of applications

Rates are available at http://groups.nscl.msu.edu/frib/rates/