Astrophysics Experiments at FRIB

Dan Bardayan (ORNL)
FRIB Layout

Target

Folding Segment 1

Isotope harvesting

Fast beams:
- Charge exchange
- Drip line
- Knockout, Coulex
- TOF masses
- Decay studies

Gas Stopping

Linac Segment 1

Fast Beams

ReA3 Reaccelerator

ReA6,9,12 Reaccelerator

Gas stopped beams:
- Mass measurements
- Laser spectroscopy

ReA3 reaccelerated beams:
- Astrophysical rates
- Lighter nuclei transfer
- Coulex

ReA6-12 reaccelerated beams:
- High spin
- Transfer reactions
- \( \gamma \)-spectroscopy

Linac Segment 2

Beam Delivery System

Linac Segment 3

Front End

Reaccelerated Beam Area

Fast Beams

Gas Stopping

Fragment separator

Isotope harvesting

Target

FRIB

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

Sherrill NN2012

, Slide 2
The Reach of FRIB

Separated fast beam rates
http://groups.nscl.msu.edu/frib/rates/

Proton Number

Neutron Number

rp-process

Number of isotopes

Estimated Possible
New from FRIB
Known Isotopes

Atomic Number

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Nuclear Structure 2012 - Sherrill, Slide 12
FRIB: a game changer for nuclear astrophysics

rp-process in X-ray bursts/Novae/Supernovae
- Direct reaction rates (SECAR)
- Indirect reaction rate studies
- Masses and p-drip line

s-process in AGB stars
- Harvesting of targets for n-capture on branchpoints

Supernova cores
- Electron capture rates with charge exchange reactions

p-process in supernovae
- Direct reaction rates

Explosive Si burning in supernovae ($^{44}$Ti, ..)
- Reaction rates (SECAR)
- Indirect reaction rate studies

r-process
- $\beta$ decay properties
- Masses
- Indirect neutron capture rate studies
- Fission barriers

Neutron star crusts
- Fusion reactions of n-rich isotopes
- Electron capture rates with charge exchange
- Masses
- Complete mapping of n-drip line

Rare isotopes are common in many astrophysical scenarios. FRIB is critical to address a broad range of astrophysics questions.
Capture reactions on n-deficient rare isotopes in the cosmos

**X-ray bursts**

**Accreting White Dwarfs**
- Novae
- He-detonations
- Ia Supernovae

**Supernovae**
- Expl. Burning
- vp-process?

- SECAR is optimized for direct measurement of \((p,\gamma)\) and \((\alpha,\gamma)\) rates on rare isotopes at highest beam intensities available
- JENSA enables indirect measurements at lower beam intensities or of weaker resonances

**FRIB reach for**
> 10^7 pps reaccelerated beams

Late stellar burning?
A recoil separator is necessary to directly measure proton-capture reaction in inverse kinematics

Ideal Method

- Very high efficiency.
- Focal plane detectors see low count rates.
- Extremely clean.

Technically Challenging!

- Projectiles / Recoils ~ $10^{10}$-$10^{12}$
- Momentum equal, velocities differ slightly

Result for 206 keV resonance:

SECAR Recoil Separator at NSCL/FRB at MSU

SECAR under design (G. Berg, M. Couder) (DOE Office of Science)

Inspired by St. George at Notre Dame

To be completed Fall 2013

Large multi-institutional collaboration: (ANL, CSM, JINA, LSU, McMaster, MSU, ND, ORNL, PNNL)
JENSA: Jet Experiments for Nuclear Structure and Astrophysics
(Colorado School of Mines, ORNL, LSU, NSCL, UT, Notre Dame + others)

- Large-area Si detector array
- High pressure laval nozzle
Active targets for \((p,p), (\alpha,p), \text{ etc...}\)

Direct \((\alpha,p)\) measurements

\[ ^{17}\text{O}(p,\alpha) \]

- The spectra were accumulated over 6 hours.
- Intensity of \(^{14}\text{N}\) beam was \(\sim 5 \times 10^5\) pps (35.6 MeV).

Forward detectors

Excitation function for \(^{14}\text{N}(\alpha,p)^{17}\text{O}\)

ANASEN

AT-TPC

120 cm
Knockout, transfer, $\beta$ decay with $\gamma$s

Study of $\gamma$-rays provide powerful probe of nuclear structure of exotic nuclei important for astrophysics.

- $^{57}\text{Cu}(d,n)^{58}\text{Zn}(\gamma)$ – Montes et al.
- $^{26}\text{P}\left(\beta\right)^{26}\text{Si}(\gamma)$ – Wrede et al.
- $^{23}\text{Al}(\beta)^{23}\text{Mg}(\gamma)$ – Zhai et al.
Reach of FRIB – Will Allow Modeling of the r-Process

- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields

Current reach
First experiments

FRIB reach for half-lives

Known half-life
FRIB reach for (d,p)

N=126
RISAC Key Nuclei

Future Reach

(70) Yb
(69) Tm
(68) Er
(67) Ho
(66) Dy

FRIB
Facility for Rare Isotope Beams
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Michigan State University

Nuclear Structure 2012 - Sherrill, Slide 14
We now have several robust, self-consistent r-process models.

To test them against observations → Need nuclear data now!
Mass sensitivity

Sensitivity of calculated r-process abundances to n-separation energies with different mass models.

Brett, Bentley, Paul, Surman, Aprahamian (2012).
New NSCL stopped beam area

Stopped beam delivered to ReA3 for charge breeding in EBIT and subsequent reacceleration, or into the new stopped beam area.

Stopped beam area to include:

- BECOLA - beam cooler and laser spectroscopy beam line
- LEBIT - high precision Penning trap mass measurements

Reconfiguration in progress
Entire system to be placed on 60 kV
Operational in < 1 year

CARIBU – $^{132}$Sb

Time of Flight (ns)

4 s excitation

Applied Frequency (Hz)

668.065.0  668.065.5  668.066.0  668.066.5
Stopped beams – decay

Improved half-life model resulted in significant change in r-process calculation.

Madurga et al., PRL 109, 112501 (2012)
Individual n-capture rates important


\[ ^{130}\text{Sn} \text{Rate x 10} \]

\[ ^{132}\text{Sn} \text{Rate x 10} \]

\[ ^{130}\text{Sn}(d,p) - \text{Kozub et al., PRL (in press)} \]

\[ ^{130}\text{Sn}(n,\gamma) \]

\[ \begin{align*}
^{130}\text{Sn} & \rightarrow \text{FRDM} \\
^{130}\text{Sn} & \rightarrow \text{HFB} \\
^{130}\text{Sn} & \rightarrow \text{RMFT}
\end{align*} \]

\[ [\text{Rauscher et al., PRC 57, 2031 (1998)}] \]
Transfer reactions on exotic beams

(d,p) as surrogate for neutron-transfer (d,n), ($^3\text{He}$,$^4\text{He}$), etc...
Need separator for forward going recoils at 10 MeV/u
An expanded fast beam area for high-rigidity beams, including a High-Rigidity Spectrometer (~7 Tm – compared to 4 Tm achievable with the S800) will expand the discovery potential and greatly increase the efficiency of the measurements because higher beam intensities for the most exotic neutron-rich nuclei can be achieved.

Very tentative sketch of high-rigidity fast beam area at FRIB.
Overview

• The opportunities provided by FRIB to study a remarkably broad range of astrophysical questions is compelling.

• The advances made in astrophysical modeling and observations require precise nuclear data to keep up.

• FRIB should be rapidly and vigorously pursued – need state of the art experimental instruments (and theory) to take advantage of the opportunities.

• Thanks to all those I borrowed slides from and sorry for omissions.
Expeditious construction of the Facility for Rare Isotope Beams (FRIB) is the highest nuclear physics priority for the nuclear astrophysics community. Rare isotope data obtained with the unprecedented capabilities of FRIB will be key to the understanding of the origin of the elements, stellar explosions, and the nature of neutron stars.

FRIB data will satisfy the nuclear data needs of state of the art astrophysical model calculations, and will be needed to understand observations with present and future ground and space based observatories.

The urgency of these motivations was reiterated in the 2012 Decadal Study of the National Research Council “Exploring the Heart of Matter”. We endorse the urgency for constructing FRIB expressed in the report in the strongest possible terms.
Updated Layout of ReA3 and ReA6

ReA3 energy maximum is 3 to 6 MeV/u; ReA6 maximum is 6 to 9 MeV/u

- ReA3 and ReA6 cryomodule construction are funded by MSU
- ReA3 experimental area beamlines will be installed and commissioned in FY2013
  - SECAR will be a DOE-funded project
- ReA6 experimental area beam lines and equipment will be driven by user needs and generation of proposals to agencies