NSCL – Ongoing Activities and Future Perspectives

Premier national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

302 employees, incl. 56 undergraduate and 58 graduate students, 30 faculty – over 700 users

Largest campus-based nuclear physics laboratory in the U.S. – 10% of U.S. nuclear science Ph.D.s

Nuclear physics graduate program ranked #2 (behind MIT) as of May 16, 2008
Major Research Thrusts at NSCL

• **Production of nuclei with unusual ratios of protons to neutrons and measurement of their properties** – connection to mesoscopic science*

  What are the limits of nuclear existence? What are the properties of nuclei with extreme ratios of protons and neutrons (neutron skins and halos)? Modification of shell structure, new doubly magic nuclei: \(^{48}\text{Ni},^{78}\text{Ni},^{100}\text{Sn},^{132}\text{Sn}…\)

• **Exploration of the nuclear processes responsible for the chemical evolution of the universe through the ongoing synthesis of most elements in the cosmos** – connection to astrophysics**

  Where are most of the nuclei heavier than iron made? How do supernovae explode? Are Type 1a SN good standard candles?

• **Exploration of the isospin dependent properties of hot nuclear matter and how they affect supernovae and neutron star properties** – connection to astrophysics**

  What is the equation of state (EOS) of neutron-rich nuclear matter?

• **Exploration and tests of novel superconducting accelerator and beam transport concepts and the dynamics of high-intensity beams***

  One of the few universities that graduates accelerator physics/engineering PhDs

* Mesoscopic Theory Center at MSU
** JINA (Joint Institute for Nuclear Astrophysics
*** Member of USPAS (U.S. Particle Accelerator School)
In-Flight Production of Rare Isotopes at NSCL

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

Production target $^{86}\text{Kr}^{14+}, 12\text{ MeV/u}$

K500

Coupling line

K1200

Stripping foil $^{86}\text{Kr}^{34+}, 140\text{ MeV/u}$

A1900

$\Delta p/p = 5\%$

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

Fragment yield after target

Fragment yield after wedge

Fragment yield at focal plane

C.K. Gelbke, May 23, 2008, Slide 3
Rare Isotope Beams Produced at NSCL

Research program requires large number of beam tunes and, hence, reliable and predictable operations (CCF availability > 90%)

Increasing science pressure to move towards heavier nuclei

More than 1000 RIBs have been made – more than 630 RIBs have been used in experiments
R&D: Neutron-Rich Isotopes from $^{208}$Pb at 86 MeV/u

R&D issues:
- Are charge states an issue – and if so at what level?
  - Achieved isotopic identification of $A \sim 200$ nuclides
- Determine production cross sections
- Access to new new isotopes?

First Experiment (10/2007):
- $^{208}$Pb (86 MeV/u, 1 pA) on Be and Ni targets
- $B_\rho$ - ToF $\Delta E$ - E
  - Verification of PID via $\gamma$-decay of known isomers + charge states of primary beams

First Results:
- Particle ID possible
- Good A,Z,Q resolution
- New isomers identified

O. Tarasov et al.
Scientific Reach of Heavy Ion Drivers
Measurements for the rarest nuclei provide the most important leverage 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

C.K. Gelbke, May 23, 2008, Slide 6
Discovery of $^{40}$Mg, $^{42,43}$Al, and $^{44}$Si in 2007


Enhanced selectivity from two-stage separator:

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

RFFS (Radio-Frequency Fragment Separator)

difference in time of flight ⇔ difference in rf phase

High implantation rate of undesirable isotopes can limit the rate of desirable implantations

This problem is particularly serious for very proton-rich even for highly segmented detector systems like the NSCL beta counting station

Courtesy Daniel Bazin
Exotic Decays – Search for di-proton Decay

K. Miernik et al., PRL99 (2007) 192501

$^{45}$Fe is a known 2-proton ground-state emitter

- What is the correlation between the two emitted protons
  - Di-proton ($^2$He) or p+p?

Experiment with optical time projection chamber

- First direct angular and energy correlation measurement in 2-proton decay
- First observation of $\beta$-delayed 3-proton decay

M. Pfützner (Warsaw) et al.

- 87 2p-events
- 38 $\beta$-delayed events
  - Good agreement with 3-body model of Grigorenko, Zhukov
NSCL Science Program
(next 5 years)
Evolution of Shell Structure

Provides an improved understanding of the nature of the effective interactions and operators used in nuclear structure models

– Insight into tensor and 3-body forces in nuclei (e.g., Otsuka, et al.)
– The continuum plays an important role in weakly bound nuclei (e.g., Nazarewicz, Zelevinsky, et al.)

Stable nuclei:
\[ \frac{N}{Z} \approx 1 - 1.5 \]
\[ S_{p,p} \approx 6-8 \text{ MeV} \]

Neutron-rich nuclei:
\[ \frac{N}{Z} \approx 2 - 2.5 \]
\[ S_n \ll 1 \text{ MeV} \]
Continuum Shell Model (Oxygen Isotopes)

Experimental information is needed to pin down the interactions


sd space, HBUSD interaction, single-nucleon reactions
Prediction of large shell gap for $N = 14$ in oxygen isotopes close to the neutron dripline

Observed resonance at $E_{\text{decay}} = 45$ keV or $E^* = 2.8$ MeV confirms $N = 14$ gap.

Low Energy Beam Ion Trap (LEBIT)

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

Since 2005: accurate masses for more than 30 isotopes of more than 10 elements:

\[^{32,33}\text{Si}, {^{29,34}\text{P}}, {^{37,38}\text{Ca}}, {^{40-44}\text{S}}, {^{63-65,65m}\text{Fe}}, {^{64-66}\text{Co}}, {^{63-64}\text{Ga}}, {^{64-66}\text{Ge}}, {^{66-68,80}\text{As}}, {^{68-70,81,81m}\text{Se}}, {^{70m,71}\text{Br}}\]

G. Bollen et al., PRL 96 (2006) 152501; P. Schury et al., PRC 75 (2007) 055801;
R. Ringle et al., PRC 75 (2007) 055503
M. Block et al., PRL accepted

\[f_{\text{RF}} \text{ [Hz]} -2528609.5\]

\[^{44}\text{S}[\text{CH}]^+\]

T\(_{1/2}\) = 123 ms

\[^{44}\text{S}\]:

\[\text{ME}_{\text{LEBIT}} = -9205(5) \text{ keV}\]

– 25-fold improvement over SPEG 2007:

\[\text{ME} = -9100(130) \text{ keV}\]

– Disappearance of N = 28 magic number?

C.K. Gelbke, May 23, 2008, Slide 14
Examples of Precision Mass Measurements

Stop high-energy fragments in helium-gas cell, extract, purify, and store in 9.4-Tesla Penning trap

\[ ^{38}\text{Ca}: 0^+ \rightarrow 0^+ \beta^+-\text{emitter} \]
- new candidate for the test of the conserved vector current (CVC) hypothesis

\[ \text{ME}_{\text{LEBIT}} = -22058.53(28) \text{ keV} \]
\[ \delta m = 280 \text{ eV}, \delta m/m = 8 \cdot 10^{-9} \]
- 17-fold improvement over AME 03: \( \delta m = 5 \text{ keV} \)

\[ ^{68}\text{Se}: \beta^+-\text{emitter} \]
- more important rp-process waiting point nucleus than previously thought

\[ \text{ME}_{\text{LEBIT}} = -54189.3(5) \text{ keV} \]
\[ \delta m = 530 \text{ eV}, \delta m/m = 8 \cdot 10^{-9} \]
- 35-fold improvement over CPT 2004: \( \text{ME} = -54232(19) \text{ keV} \)

C.K. Gelbke, May 23, 2008, Slide 15
Nuclear Spectroscopy with Knockout Reactions

Different $P_{\parallel}$-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)$^2$
In stable nuclei, a reduction of $R_s=0.6-0.7$ 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 : Theory (Eikonal + SM)


\[ R_S = \frac{\text{exp}}{\text{th}} \]

- $R_S (e,e'p): S = S_p - S_n$
- $R_S p\text{-knockout}: S = S_p - S_n$
- $R_S n\text{-knockout}: S = S_n - S_p$

C.K. Gelbke, May 23, 2008, Slide 18
Evidence for Shell Breaking near $^{56}$Ni

The $^{57}$Cu-$^{57}$Ni mirror pair is the heaviest T=$1/2$ system studied to date

- Measurement of spin expectation value with $\beta$-NMR technique: $<\sigma> = -0.78 \pm 0.031$
- Value is inconsistent with the assumption of an inert doubly-magic $^{56}$Ni core

NSCL Beta Counting System (BCS)

High-sensitivity system for correlating fragment implants with subsequent $\beta$-decays on an event-by-event basis
- Suited for use with cocktail beams

1 fragment implant detector:
- $4 \times 4$ cm$^2$ active area, 1 mm thick
- 40 1-mm strips in x and y

6 calorimeter detectors:
- $5 \times 5$ cm$^2$ active area, 1 mm thick
- 16 strips in one dimension

BCS combined with 12 Ge-detectors from SeGA

Prisciandaro et al. NIM A 505, 140 (2003).
Doubly Magic $^{78}\text{Ni}$ Accelerates Heavy Element Synthesis

rp-process occurs at $T > 10^9$ K and $\rho_{n,\text{free}} > 10^{20}$ cm$^{-3}$

Particle identification

- Different types of nuclei in the beam

$^{78}\text{Ni}$

Model calculation for heavy element synthesis (r-process in supernova explosion)

- Measured half-life of $^{78}\text{Ni}$ with 11 events: $T_{1/2}$ is 3-4 times shorter than predicted
- $^{78}\text{Ni}$ is the most neutron rich of the 10 possible classical “doubly-magic” nuclei in nature
- Models produce excess of heavy elements with new (shorter) $^{78}\text{Ni}$ half-life
- Result: $110^{+100}_{-60}$ ms

→ Heavy element synthesis in the r-process proceeds faster than previously assumed

P.T. Hosmer et al.

C.K. Gelbke, May 23, 2008, Slide 21
Recoil Distance Method for Knock-Out Reactions

Köln/NSCL plunger device

Transition rates for N=Z $^{64}$Ge

B(E2) values in e²fm⁴

$\Delta T_{1/2} \approx 2-5$ ps


C.K. Gelbke, May 23, 2008, Slide 22
How Do Supernovae Explode?
Type 1a supernovae are used as standard candles
GT strengths, r-process …

NASA (May 7, 2007)

SN2006gy (in NGC1260, $2.4 \times 10^8$ light yrs from earth) is the brightest supernova ever observed

Explosion of a super-massive star (like Eta Carinae, in Milky Way, $7.5 \times 10^3$ light yrs from earth) that did not collapse into a black hole as had been expected (?)
Spin-Isospin Response of Nuclei
Weak transition rates are important for stellar evolution

Measure Gamow-Teller strengths via charge exchange reactions
(R.G.T. Zegers et al.)

- NSCL: \((t,^3\text{He})\) at \(E/A = 120\) MeV: \(0.8-1 \times 10^7/s \ 3\text{H}\) via fragmentation of \(^{16}\text{O}\)
  - Resolution \(\sim 200\) keV: better than \((n,p)\), comparable to \((d,^2\text{He})\)
- Accompanying \(^3\text{He},t\) program at RCNP, Osaka

Proof of principle: measured GT strength constrains theoretical uncertainties of e-capture rates in pre-supernovae

\[ ^{13}\text{C}(t,^3\text{He}), \theta(^3\text{He}) < 4^\circ \]
2 hr run, Feb 2008
Spin-isospin response of unstable nuclei

\((^7\text{Li}, ^7\text{Be}^*)\) in inverse kinematics: extract isovector response of unstable nuclei

- Selects \(\Delta S = 1\) transitions with small background (\(\leq 1\%\))
- S800 spectrometer (dispersion-matched mode) + SeGA for coincidence with \(^7\text{Be}^*(430 \text{ keV})\) \(\gamma\)-line

\[\approx 1 \text{ MeV energy resolution for } E^*\]

R. Zegers et al.

C.K. Gelbke, May 23, 2008, Slide 25
Novae and Type I X-ray Bursts

**Normal X-ray bursts:** Thermonuclear explosions on the surface (~ 4 m) of accreting neutron star binaries: rp-process

**X-ray super-bursts:** Re-ignition of the ashes in the neutron star’s crust (~ 20 m), carbon-burning and photo-dissociation of heavier nuclei

New $^{32}\text{Cl}(p,\gamma)^{33}\text{Ar}$ Rate Accelerates Energy Generation in X-ray Bursts

Most rp-process nuclei can be studied at NSCL

$p$-capture on $^{32}\text{Cl}$ producing $^{33}\text{Ar}$ is an important step in the rp-process powering thermonuclear explosions on surfaces of accreting neutron stars (X-ray bursts)

$\gamma$-rays from predicted 3.97 MeV state establish level energy of 3.819(4) MeV

2 orders of magnitude improvement in uncertainty of level energy reduced uncertainty of calculated $^{32}\text{Cl}(p,\gamma)^{33}\text{Ar}$ stellar reaction rate by 3 orders of magnitude

New experimental data strongly reduce uncertainty

Gate on $E_\gamma = 2460$ keV

Clement et al. PRL 92, 172502 (2004)
X-ray Burst Theory versus Observation

Measure the properties of nuclei that have a strong influence on the light curves

(NASA’s RXTE)

GS 1826-24 burst shape changes

Burst models with different nuclear physics assumptions

Galloway et al. 2003
Woosley et al. 2003
NSCL Facility Plan
(next 3 years)

Existing state-of-the-art experimental apparatus:

- A1900 fragment separator, 92-inch chamber, S800 magnetic spectrograph, large aperture sweeper magnet spectrograph, large area (2×2 m²) position sensitive neutron detectors, segmented Ge and Si-strip-CsI arrays, β-NMR and β-counting station, Gas cell (1 bar He) for stopping rare isotopes, 9.4 Tesla Penning Trap, RF fragment separator…

- The NSCL is currently developing an innovative facility for efficiently stopping and accelerating rare isotopes produced and separated in flight
  - Ongoing design and construction of gas stopper, EBIT charge breeder, RFQ, 3.2 MeV/nucleon SC linac (easily upgradeable to higher energy)

- World unique capability by 2010
  - Detectors for science program at conceptual stage e.g., \(^{30}\text{P}(p,\gamma)^{31}\text{S}\); (p,p) excitation functions, (p,α) reactions …
Ongoing Developments

New experimental apparatus:
- Digital electronics for enhanced resolution with SeGA (Starosta) – completion in 2008
- High-efficiency gamma-ray detector array (Gade) – completion by early 2009
- Low-energy neutron array for charge exchange reactions in inverse kinematics (Zegers) – tests with prototype modules in summer 2008, full array complete late 2009 (delayed by NSF budget shortfall)
- Laser spectroscopy area (Mantica) – completion by 2011
- Time projection chamber: dual use as active target for low energy experiments and for fast beam nucleus-nucleus collision experiments (Bickley) – MRI-proposal submitted
- Si-detector array for low-energy astrophysics experiments (Blackmon) – MRI-proposal submitted
- Two beam lines with monochromators for gas stopping – cryogenic linear cell and cyclotron gas stopper (Bollen, Morrissey) – first line complete by 2009
- New experimental area for reaccelerated beams – complete by spring 2009

Reacceleration facility (easily upgradeable to higher energy):
- Advanced EBIT charge breeder (collaboration with MPI Heidelberg, TRIUMF) – construction started, ongoing refinements of e-beam optics
- RFQ – being built at U. of Frankfurt
- 3.2 MeV/nucleon SC linac – long-lead items ordered, cavity construction started, prototype testing underway, ongoing refinements of cryostat design
- Construction of mezzanine for reaccelerator – complete by spring 2008
- Commissioning of reaccelerator expected to start in 2010
Laser Spectroscopy at NSCL

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

• Projectile fragmentation plus gas stopping
  – Broad range of refractory elements with $Z<50$ that have been previously inaccessible

• Complements programs at ISOL facilities:
  – CERN/ISOLDE, JAEA, Jyväskylä/IGISOL, TRIUMF/ISAC

Most laser spectroscopy studies performed at ISOL facilities

Rare isotopes available at ISF by in-flight production and stopping in a gas cell

CCF-2008 Yield > 1000/s


Reaccelerator
Gas Stopping
Lasers
NSCL Building Additions

Experimental area for reaccelerated beams
NSCL Long-Range Vision

“Blue Book” proposed building a 200 MeV superconducting linac driver

- 200 MeV linac endorsed by Rare Isotope Science Assessment Committee of the National Research Council of The National Academies
  (December 2006)

- #2 priority recommendation for the 2007 Long Range Plan for Nuclear Science is “construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics”
  (May 2007)

- Rare Isotope Beam Task Force recommends “that DOE and NSF proceed with solicitation of proposals for a FRIB based on the 200 MeV, 400 kW superconducting heavy-ion driver linac at the earliest opportunity”
  (August 2007)

- All recommendations are consistent with the vision laid out in the Blue Book
Large ISF Intensity Gains over NSCL’s CCF (ISF=FRIB)

Superb improvement over most advanced fragmentation capability in North America
Two site options...

New South Campus Facility allows unconstrained optimization

Upgrade at NSCL site: constrained by space available, but less costly by ~ $100 M; will need further optimization...
Breaking News
FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Nuclear Physics

Facility for Rare Isotope Beams
Funding Opportunity Number: DE-PS02-08ER41535
Announcement Type: Initial
CFDA Number: 81.049

Issue Date: 05/20/2008
Letter of Intent Due Date: Not Applicable
Pre-Application Due Date: Not Applicable
Application Due Date: 07/21/2008
FRIB/ISF at NSCL

- NSCL is a leading rare-isotope research facility
  - One of three nuclear-science flagship facilities in the US (RHIC at BNL, CEBAF at JLab, NSCL at MSU)

- One of the few university-based national user facilities
  - Big Science in an open academic environment offers unique synergy between cutting edge research and education
  - MSU educates more than 10% of the nation’s nuclear science PhD’s; its nuclear science graduate program is ranked #2 in U.S. (behind MIT)
  - Best in class operations, high-quality faculty & staff

- Excellent prospects for the near-term (5-10 years) future
  - Significant investment by MSU into reaccelerator project

- An upgrade with a 200 MeV/nucleon driver linac would ensure continued leadership for the coming decades
  - Builds on existing strength and experience in operating the premier rare isotope user facility in the U.S.
  - Near-perfect match to existing facility and human resources infrastructure
  - Continued hands-on education of nuclear science work-force via cost-effective synergy of education and research