Experiments at NSCL

Who we are

Nuclear science thrusts

Production of rare isotopes at NSCL

– Projectile fragmentation and separation
– Experimental consideration with fast beams

Selection of physics highlights

– Probing the limits of nuclear existence
– Ground-state half-lives and importance for nuclear astrophysics
– High-precision mass measurements
– In-beam spectroscopy – knockout, Coulomb excitation, excited-state lifetime measurements, tests of reaction dynamics, charged-particle spectroscopy
– Beyond the n-dripline: Spectroscopy of neutron-unbound states
– Charge-exchange reactions and EC rates

Very brief: NSCL’s future – reaccelerated beams and laser spectroscopy
NSCL – fast facts

National user facility for rare isotope research and education
– nuclear science, accelerator physics, nuclear astrophysics, societal applications

Selected to establish the facility for rare isotope beams FRIB
433 employees, incl. 36 faculty, 70 graduate and 58 undergraduate students
as of January 2, 2011

August 2009
Where we are
Research areas

**Evolution of Nuclear Structure**
- At and beyond the nucleon driplines
- Changes in shell structure, level schemes & collectivity
- Nuclear wave functions through direct reactions
- Spin-isospin response of nuclei through charge exchange reactions

**Fundamental Interactions & Precision Measurements**
- Mass measurements, IMME, CVC hypothesis
- Precise measurements of nuclear radii & moments (new)
- Search for new interactions & couplings (new)

**Reaction Dynamics**
- The nuclear equation of state
- Study of reaction mechanisms

**Role of Nuclei in the Cosmos**
- Origin of the elements, supernovae, X-ray bursts
- Neutron stars and nuclear equation of state

**Accelerator physics**
Research all over the nuclear chart
Motivation and experimental reality

Motivation to study rare isotopes:
• Limits of nuclear existence
• Modifications to magic numbers
• Extreme charge and mass distributions
• Astrophysical reaction rates

- Experimental task: Quantify changes encountered in rare isotopes and measure observables that are calculable and can serve to discriminate between theories
- Experiments?! Largely done in inverse kinematics with a beam of exotic nuclei
- New precision techniques have been developed in past decade to enable experimental study of these most exotic nuclei
- Unfortunate fact of life: The nuclei with the largest $N/Z$ ratio accessible are light nuclei and they have low beam rates
Production of rare isotopes by projectile fragmentation

Adapted from A. Stolz
Nuclei produced by fragmentation

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

We need a filter device to select single isotopes

Adapted from A. Stolz
NSCL’s A1900 fragment separator

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

- K500
- K1200
- $^{86}\text{Kr}^{14+}$, 14 MeV/u
- coupling line
- stripping foil
- $^{86}\text{Kr}^{34+}$, 155 MeV/u
- production target
- Be, 480 mg/cm$^2$
- focal plane

A1900
- 4 dipole magnets to filter the fragments
- 24 quadrupole magnets to focus the beam

Adapted from A. Stolz
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

- **K500**: Ion sources (RT-ECR, SC-ECR)
  - $^{86}\text{Kr}^{14+}$, $^{86}\text{Kr}^{14+}$, $^{86}\text{Kr}^{14+}$, 14 MeV/u
- **K1200**: Stripping foil
  - $^{86}\text{Kr}^{34+}$, 155 MeV/u
- **A1900**: Production target
  - Be, 480 mg/cm²

**Fragment yield after target**

**Fragment yield at image-2**
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

- Ion sources
- Coupling line

K500

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

K1200

- Stripping foil: $^{86}\text{Kr}^{34+}$, 155 MeV/u
- Production target: Be, 480 mg/cm$^2$

A1900

- Image-2
- Degrader: Al, 200 mg/cm$^2$

Fragment yield after target

Fragment yield at image-2

"we need a degrader in the middle of the separator to achieve isotopic separation"

Adapted from A. Stolz
Selection of the beams of interest

A1900

energy loss in degrader depends on
• nuclear charge (proton number) of fragment
  → different isotopes can be separated
• velocity (momentum) of fragment
  → degrader needs a wedge shape

Adapted from A. Stolz
Production and separation end-to-end

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

- Ion sources: RT-ECR, SC-ECR
- Coupling line: $^{86}\text{Kr}^{14+}, 14\text{ MeV/u}$
- Stripping foil: $^{86}\text{Kr}^{34+}, 155\text{ MeV/u}$
- Production target: Be, 480 mg/cm²
- Wedge: Al, 200 mg/cm²

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

- Fragment yield after target
- Fragment yield after wedge
- Fragment yield at focal plane

Adapted from A. Stolz
Selectivity is key!

Identifying rare isotopes is like finding one person from among everyone on this planet.

total world population estimate (August 2007): 6,600,000,000

typical beam intensity: 1 pnA = 6.3 \cdot 10^9 \text{ particles / sec}

Adapted from A. Stolz
Primary beams available at NSCL
Exotic beams produced at NSCL

More than 1000 RIBs have been made – more than 680 RIBs have been used in experiments.
Facility layout and experimental end-stations
Complementary approach: fast, stopped and reaccelerated rare isotope beams
Nuclear existence

• What combinations of protons and neutrons can make up bound systems?
Establishing the limits of nuclear existence at NSCL

Two-stage separator
CCF + A1900 + S800 analysis line

O. B. Tarasov et al., PRC 75, 064613 (2007)

48Ca fragmentation

76Ge fragmentation

O. B. Tarasov et al., PRL 102, 142501 (2009)
O. B. Tarasov et al., PRC 80, 034609 (2009)
Nuclear existence – highlights

Physics highlights at the limits

- Discovery of $^{40}\text{Mg},^{42,43}\text{Al},^{44}\text{Si}$: Bound $^{42}\text{Al}$ implies dripline extends further than believed

- Evidence for a new “island of inversion” around $^{62}\text{Ti}$ (?)
  - From measured cross section systematics: Modifications to the underlying shell structure of these very neutron-rich may not be included in most mass models

- 15 new isotopes from $^{76}\text{Ge}$ beam
  - O. B. Tarasov et al., PRL 102, 142501 (2009)
  - O. B. Tarasov et al., PRC 80, 034609 (2009)

- 4 new isotopes from $^{48}\text{Ca}$ beam
  - O. B. Tarasov et al., PRC 75, 064613 (2007)
Beta-decay properties

- Nuclear structure
- Nuclear astrophysics
Beta-decay and information on the most exotic nuclei

Beta-decay spectroscopy provides information at the extremes of the nuclear chart to be confronted with theory:
- Half-lives
- Q values (masses)
- Absolute branching ratios
- Excited states in daughter nuclei
- Microsecond isomers

NSCL’s approach – fast-fragment implantation and event-by-event decay correlation – is highly sensitive and reaches the most exotic nuclei, e.g.
- Half-lives (few ions per day)
- Excited states in daughter nuclei (few ions/min)

New data helped discriminate between different shell model configuration spaces

Adapted from S. N. Liddick
Half-life of the doubly magic r-process nucleus

Particle identification

different types of nuclei in the beam

78Ni

Measured half-life of 78Ni with 11 events
This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

Result: 110 $^{\pm100}_{-60}$ ms

P.T. Hosmer et al.
PRL 94, 112501 (2005)

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

Observed Solar Abundances
Model Calculation: Half-Lives from Moeller, et al. 97
Same but with present 78Ni Result

models produce excess of heavy elements with new (shorter) 78Ni half-life

$\rightarrow$ Heavy element synthesis in the r-process proceeds faster than previously assumed

$\cdots$ one step towards a better understanding of the origin of the elements in the cosmos

Adapted from H. Schatz
Mass measurements

- Fundamental symmetries
- Nuclear structure
- Nuclear astrophysics
Masses – what are they good for?

**Nuclear structure**

Two-neutron separation energy: \( S_{2n} = M(Z,N) - M(Z,N-2) \)

Shell closures and deformation from separation energies (\( m/m < 10^{-5} \))

Astrophysics (Nucleosynthesis)
- \( r \) process (\( m/m < 10^{-5}, m < 10 \text{ keV} \))
- \( rp \) process (\( m/m \sim 10^{-7} \))

Fundamental interactions and symmetries (\( m/m < 10^{-8} \))
- CVC
- CKM

[Diagram showing two-neutron separation energy with shell and sub-shell deformation.]
Penning trap mass measurements

**Penning Trap**

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

Mass measurement via determination of cyclotron frequency

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

from characteristic motion of stored ions

Mass excess: $-22058.53(28)$ keV

$\delta m = 280$ eV, $\delta m/m = 8 \cdot 10^{-9}$
LEBIT Results

rp-process waiting point and isospin symmetry along the N=Z line

\[ {^{68}\text{Se}}^+ , T_{1/2} = 35.5 \text{ s} \]

CVC tests

\[ {^{38}\text{Ca}}^{++}, T_{1/2} = 440 \text{ ms} \]

Mass measurements at the dripline

\[ {^{70}\text{Br}}^+, T_{1/2} = 2.2 \text{ s} \]

Neutron shell closure at N=28

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

Precise masses for 36 isotopes of 12 elements

- \(^{25}\text{Al}\)
- \(^{26,32,33}\text{Si}\)
- \(^{29}\text{P}\)
- \(^{34}\text{P}\)
- \(^{37}\text{Ca}\)
- \(^{38}\text{Ca}\)
- \(^{40-44}\text{S}\)
- \(^{63-65}\text{Fe}\)
- \(^{65m}\text{Fe}\)
- \(^{66}\text{Fe}\)
- \(^{64-67}\text{Co}\)
- \(^{63,64}\text{Ga}\)
- \(^{64-66}\text{Ge}\)
- \(^{66,68}\text{As}\)
- \(^{80}\text{As}\)
- \(^{68-70}\text{Se}\)
- \(^{81}\text{Se}\)
- \(^{81m}\text{Se}\)
- \(^{70m}\text{Br}\)
- \(^{71}\text{Br}\)

Discovery of new Isomer in \(^{65}\text{Fe}\)

Savory et al., PRL102 (2009) 132501
Block et al., PRL100, (2008) 132501
Bollen et al., PRL96 (2006) 152501
Kwiatkowski et al., PRC81 (2010),058501
Ferrer et al., PRC81 (2010) 044381
Ringle et al., PRC80 (2009) 064321
Kwiatkowski et al., PRC80 (2009) 051302
Ringle et al., PRC75 (2007) 055503
Schury et al., PRC75 (2007) 055801

Adapted from G. Bollen
Probing nuclear physics via reactions

• Experimental considerations
• Experimental equipment
Studying nuclei and their reactions – typical parameters

- Fast exotic beams allow for
  - thick secondary targets
  - event-by-event identification
  - Clean trigger

- Example
  \[ \sigma = 100 \text{ mbarn} \]
  - \( N_T = 10^{21} \)
  - \( N_B = 3 \text{ Hz} \)
  - \( N_R = 26/\text{day} = 3 \times 10^{-4} \text{ Hz} \)

- \( N_R = \sigma \times N_T \times N_B \)
  - \( \sigma \) Cross section
  - \( N_T \) Atoms in target
  - \( N_B \) Beam rate
  - \( N_R \) Reaction rate

\[ v/c = 0.3 - 0.4 \]
Equipment for coincidence spectroscopy

- SeGA
- CAESAR
- MoNA - LISA
- Sweeper
- GRETINA (2012)
In-beam spectroscopy

- Nuclear structure
- Nuclear astrophysics
- Reaction dynamics
Experimental reality – fast beams

- v/c > 0.3

beam → target → reacted beam

- Experimental tasks
  - Particle spectroscopy
    - Identification of the reaction residues
  - γ-ray spectroscopy
    - Identify the final state
    - Tag the inelastic process

- Light target for wave-function spectroscopy
  → location of single-particle orbits, identifies orbital angular momentum l, occupation number

- Nucleon knockout reactions

- High-Z target as electromagnetic probe
  → reduced matrix elements

- Intermediate-energy Coulomb excitation

Use photons to tag the final state
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

$\rightarrow$ Breakdown of N=8 shell closure in $^{12}\text{Be}$: only 32% $(0p)^8$ and 68% $(0p)^6\cdot(1s,0d)^2$
Collectivity from intermediate-energy Coulomb excitation

- $^{68}\text{Se} + ^{197}\text{Au}$ using SeGA-S800
- Motivation: $N=Z$ nuclei are a challenge for theory – subtle interplay of deformation-driving proton and neutron orbits leads to rapid shape changes and shape coexistence
- Experimental input is needed to constrain different theories

First measurement of the $B(E2)$ strength in $^{68}\text{Se}$ - good agreement was found with a novel parameter-free beyond-mean-field approach using the D1S Gogny interaction.

$^{68}\text{Se}$ was found to be transitional between $\gamma$-soft ($^{64}\text{Ge}$) and oblate deformation ($^{72}\text{Kr}$)

A. Obertelli et al., PRC 80, 031304(R) (2009).
Precision excited-state lifetime measurements

- Model-independent method to determine electromagnetic transition strengths between nuclear states using the Doppler shift
- A variety of reactions can be employed to populate states of interest

Example: Lifetime of the $2^+$ states measured in $^{62,64,66}$Fe $\rightarrow$ B(E2) values deduced as measure of quadrupole collectivity. The results show an increase in collectivity due to occupancy of $dg$ orbits

W. Rother et al., PRL in press

Direct reactions, e.g., knockout, nucleon exchange reactions

Inelastic scattering

Plunger device (used with SeGA@S800)

Adapted from H. Iwasaki
Constraining rp-process powering of X-ray bursts

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).

\[1359 \text{ keV (34 Ar, 33 Ar+\gamma)}\]

\[437 \text{ keV (1798 keV)}\]

\[2460 \text{ keV (1392 keV)}\]

\[\gamma\text{-rays from predicted 3.97 MeV state establish level energy of 3.819(4) MeV}\]

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.

Previous reaction rate uncertain by up to x 10,000

Typical X-ray burst temperatures


Most rp-process nuclei can be studied at NSCL

Adapted from H. Schatz
Testing reaction dynamics

Sensitivity of the shape of the longitudinal momentum distribution in two-nucleon knockout to the spin of the final state → Spin determination in exotic nuclei

One-proton knockout reactions with detection of the proton:

\( ^9\text{Be} (^9\text{C}, ^8\text{B}+\text{X})\text{Y} \)

\( ^9\text{Be} (^8\text{B}, ^7\text{Be}+\text{X})\text{Y} \)

Accurate measurement of the diffractive breakup channel where the removed proton is at most elastically scattered.

Experimental results agree with eikonal reaction theory

Data from: A. Gade et al., PRL 99, 072502 (2007)

Data from: A. Gade et al., PRC 76, 024317 (2007)

E.C. Simpson et al., PRL 102, 132502 (2009)

D. Bazin et al., PRL 102, 232501 (2009)
Spectroscopy of neutron-unbound states
Neutron-fragment coincidence spectroscopy

In the proximity of the neutron dripline or beyond, excited states or even the ground state are not n-bound anymore -> decay neutron spectroscopy to characterize the unbound states!

\[ M_i = \sqrt{M_f^2 + M_n^2 + 2(E_f E_n - P_f P_n \cos \theta)} \]

\[ E^* = M_i - M_f - M_n \]
Spectroscopy of neutron-unbound systems

Example: $^{24}\text{O}$, Unexpected doubly magic nucleus

- In nuclei far from stability the first $2^+$ state can be unbound with respect to neutron emission.
- Excitation energy can be reconstructed by kinematic coincidence experiments of fragments with neutrons.
- Observed high excitation of first excited $2^+$ state is strong evidence for double magic nucleus.


C.R. Hoffman* et al., PLB 672, 17 (2009)

Adapted from M. Thoennessen
Spin-isospin response of nuclei

Nuclear structure and astrophysics information from charge-exchange reactions
Spin-isospin response of nuclei

- Charge-exchange reactions are an ideal tool to study the spin-isospin ($\Delta T=1, \Delta S=0,1$) response of nuclei
- Extraction of Gamow-Teller transitions strengths beyond the Q-value window for $\beta$-decay in a model independent way.

Adapted from R. Zegers
Testing shell model with respect to weak interaction strength

Measure of Gamow-Teller strengths via charge exchange reactions

- NSCL: \((t, ^3\text{He})\) at \(E/A = 120\) MeV: 0.4-1\(\times\)10\(^7\)/s \(^3\text{H}\) via fragmentation of \(^{16}\text{O}\)
  - Better resolution than \((n,p)\)
- Accompanying \((^3\text{He}, t)\) program at RCNP, Osaka, Japan

Proof of principle: measured GT strength constrain theoretical uncertainties of e-capture rates in presupernovae

Adapted from R. Zegers
In the future: Reaccelerated rare-isotope beams at NSCL (0.3-3 MeV/u for Uranium)

- Low-energy reactions important for nuclear astrophysics
- Transfer reactions, Coulomb excitation, fusion evaporation reactions, … for nuclear structure studies
In the future: Reaccelerated rare-isotope beams at NSCL and laser spectroscopy

BECOLA
• Charge radii and magnetic moments
• Provide polarized beams for
  • Tests of Maximal Parity Violation
  • Tests of Second Class Currents
  • Test of Time Reversal Symmetry

At ReA3 (0.3-3MeVu for Uranium):
• Low-energy reactions important for nuclear astrophysics
• Transfer reactions, Coulomb excitation, fusion evaporation reactions, ... for nuclear structure studies
Related literature

• The NSCL Laboratory and the FRIB Facility, A. Gade and C.K. Gelbke, Scholarpedia 5 (2010) 9651. [http://www.scholarpedia.org/article/The_NSCL_laboratory_and_the_FRIB_facility]


• NSCL- Ongoing activities and future perspectives, C.K. Gelbke, Prog. in Part. and Nucl. Phys 62 (2009) 307 and references within.