NSCL – snapshot in time

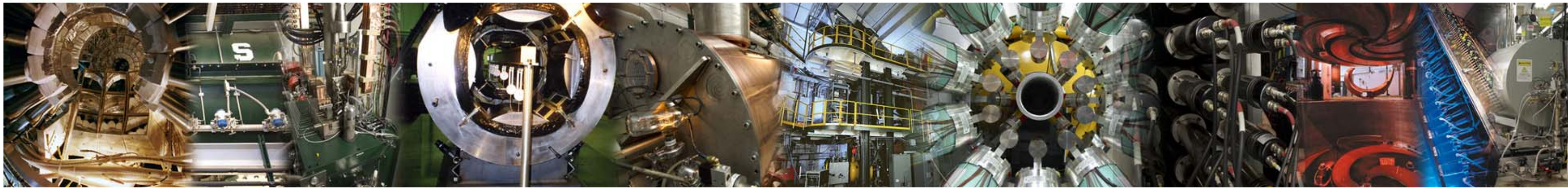
Premier national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

302 (274) employees, incl. 56 (35) undergraduate and 58 (57) graduate students, 31 faculty – over 700 users

as of May 16 (Aug. 4), 2008

- 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)

NSCL Timeline

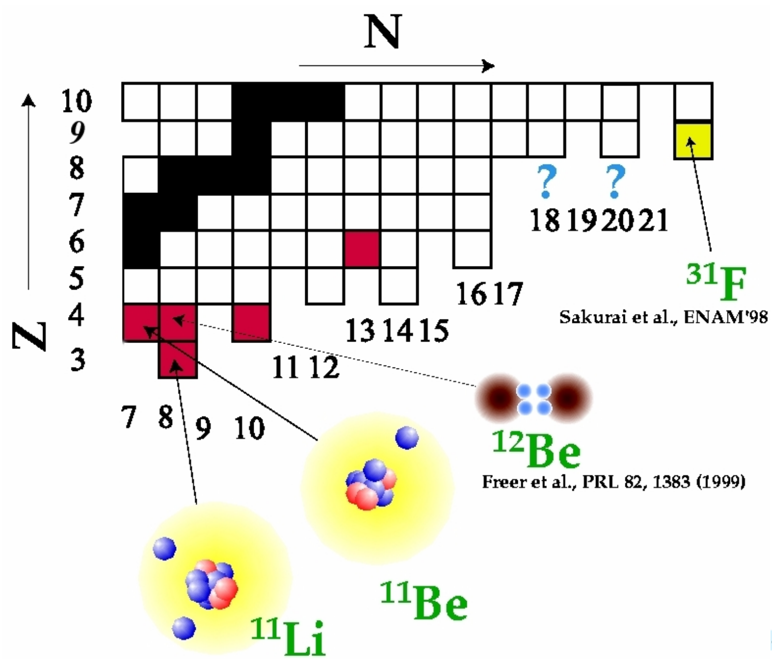


- **1958** — MSU hires accelerator expert to design and build a sector-focused cyclotron
- **1961** — NSF approves 50 MeV cyclotron
- **1965** — 50 MeV Cyclotron with single-turn extraction operational
- **1975** — NSF approves construction of superconducting cyclotron magnet prototype
- **1977** — K500 superconducting Cyclotron approved by NSF
- **1978** — Nuclear Science Advisory Committee (NSAC) recommends construction of NSCL as a national user facility
- **1982** — Experimental program with stable heavy ion beams from K500 cyclotron
- **1989** — Experimental program with stable heavy ion beams up to 200 MeV/u from K1200 cyclotron
- **1990** — Rare isotope beam program with fast beams generated in second generation A1200 fragment separator
- **2001** — Rare isotope beam program with Coupled Cyclotron Facility
- **2002** — In-house superconducting rf design fabrication, testing capability
- **2005** — Experimental program with rare isotope beams stopped in a gas cell, after fragmentation of heavy-ion beams, extracted and delivered to Penning trap
- **2010** — Experimental program with reaccelerated rare isotope beams following fragmentation of heavy-ion beams and gas stopping

Major Research Thrusts at NSCL (1)

Properties of nuclei with unusual ratios of protons to neutrons*

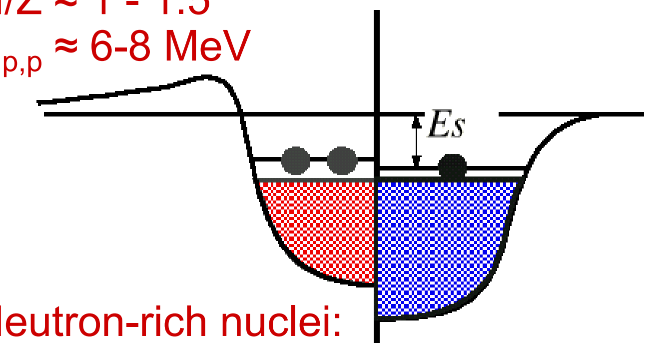
* Connection to Mesoscopic Theory Center at MSU



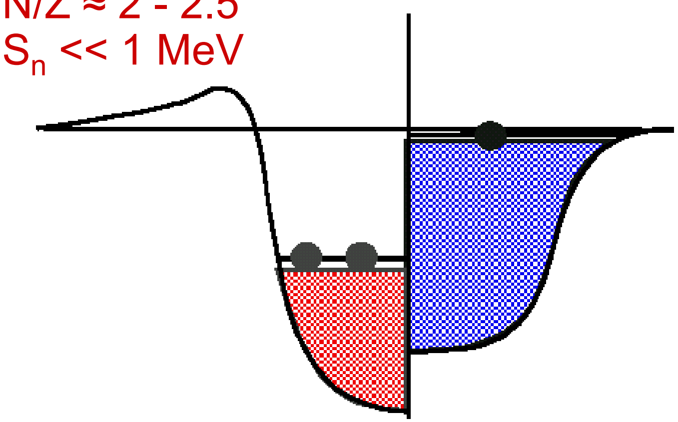
Limits of nuclear existence

Properties of nuclei with extreme ratios of protons and neutrons (e.g., skins and halos)

Stable nuclei:
$N/Z \approx 1 - 1.5$
$S_{p,p} \approx$ 6-8 MeV

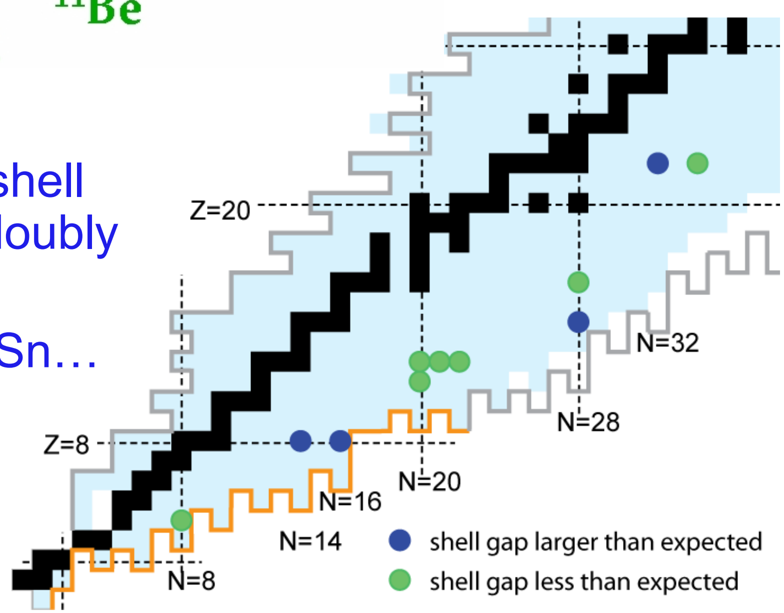


Neutron-rich nuclei:
$N/Z \approx 2 - 2.5$
$S_n \ll 1$ MeV



Modification of shell structure, new doubly magic nuclei:

^{48}Ni, ^{78}Ni, ^{100,132}Sn…



Major Research Thrusts at NSCL (2)

Exploration of the nuclear processes responsible for the chemical evolution of the universe through the ongoing synthesis of most elements in the cosmos*

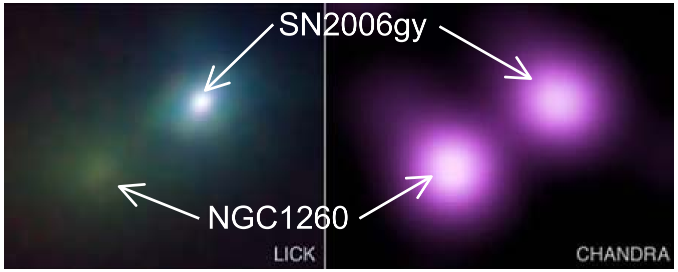
* Connection to JINA (Joint Institute for Nuclear Astrophysics)

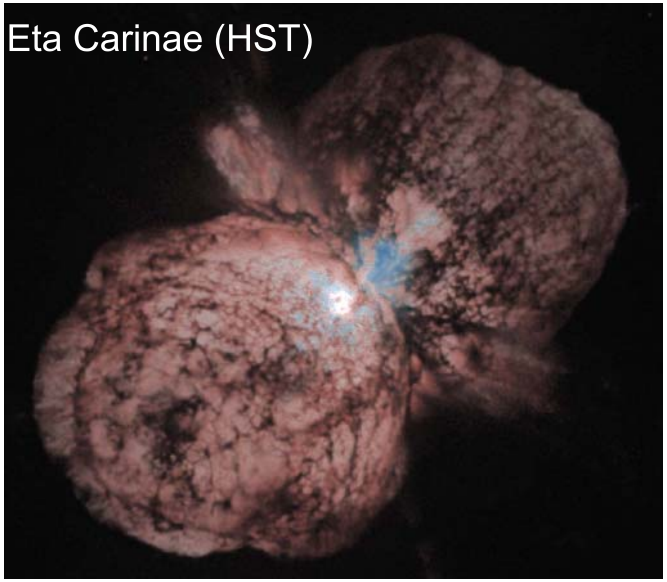
- Where are most of the nuclei heavier than iron made? – r-process nuclei: masses and half-lives…
- How do supernovae explode? – GT strengths…
- Are Type 1a SN good standard candles?

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

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

<u>NASA (May 7, 2007):</u>
Brightest supernova ever observed





Major Research Thrusts at NSCL (3)

Exploration of the isospin dependent properties of hot nuclear matter and how they affect supernovae and neutron star properties*

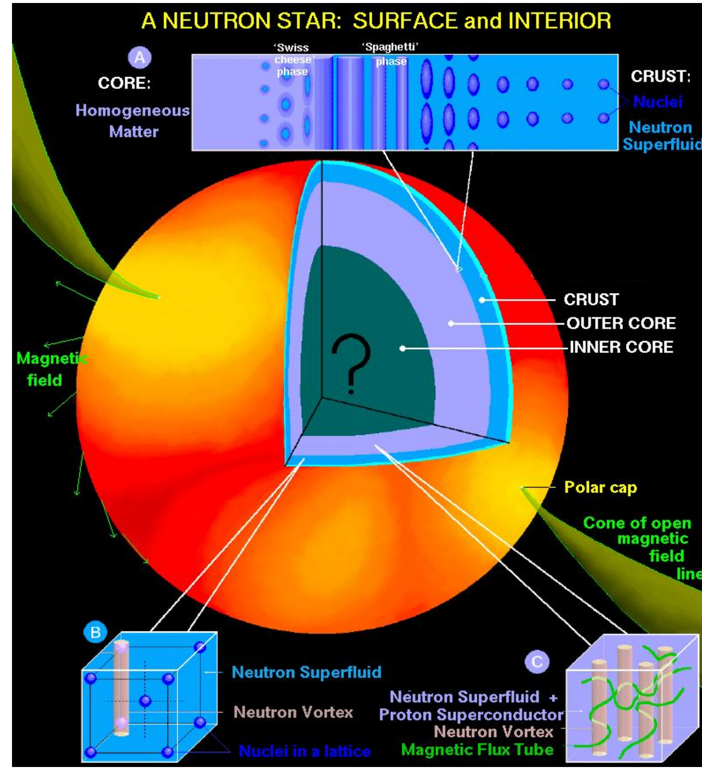
* Connection to JINA (Joint Institute for Nuclear Astrophysics)

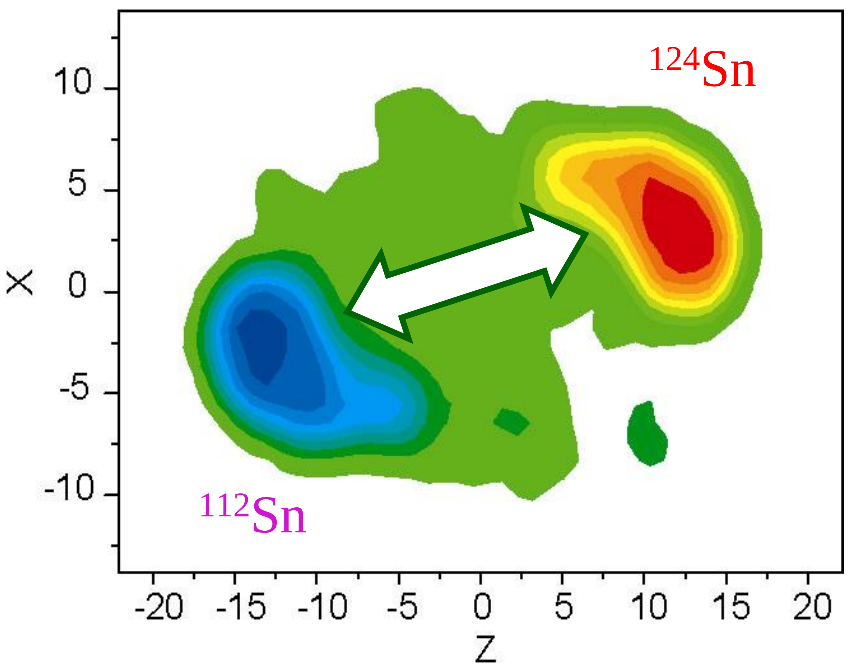
What is the equation of state (EOS) of neutron-rich nuclear matter?

– Constrain the symmetry energy term of the EOS

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 approach: Investigate isospin diffusion in nucleus-nucleus collisions

$$R_i = \frac{2O_{PN} - O_{PP} - O_{NN}}{O_{PP} - O_{NN}}$$

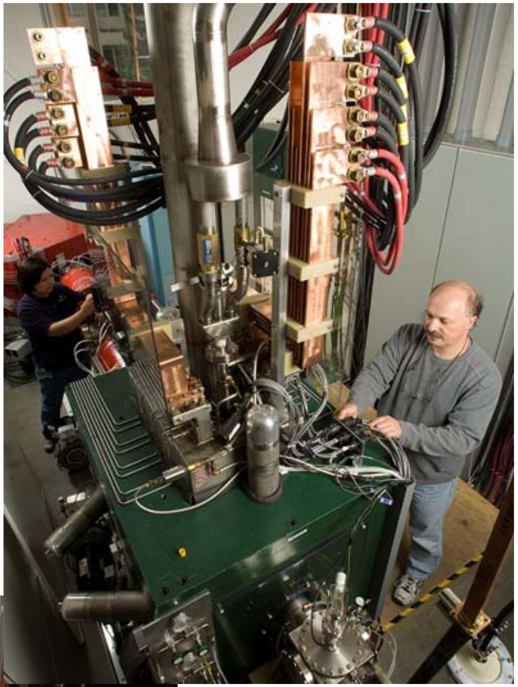
O = isospin observable, representing the ratio of protons and neutrons of the emitted matter, e.g.: $\ln(Y(^7Li)/Y(^7Be))$

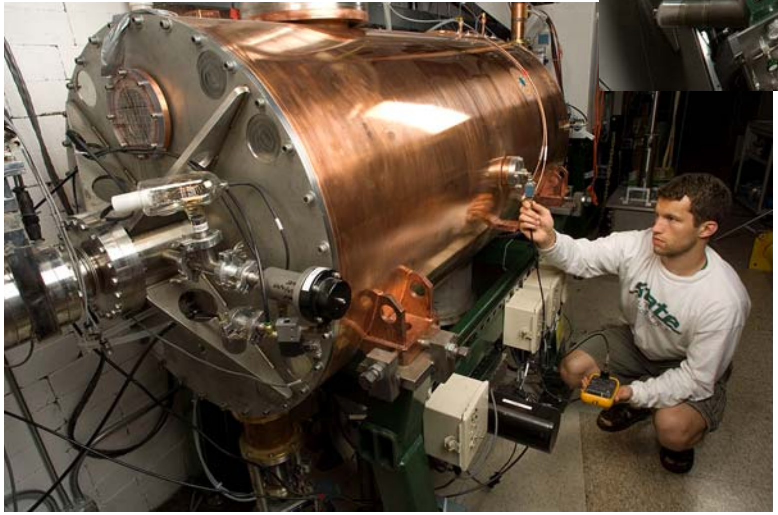
Major Research Thrusts at NSCL (4)

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

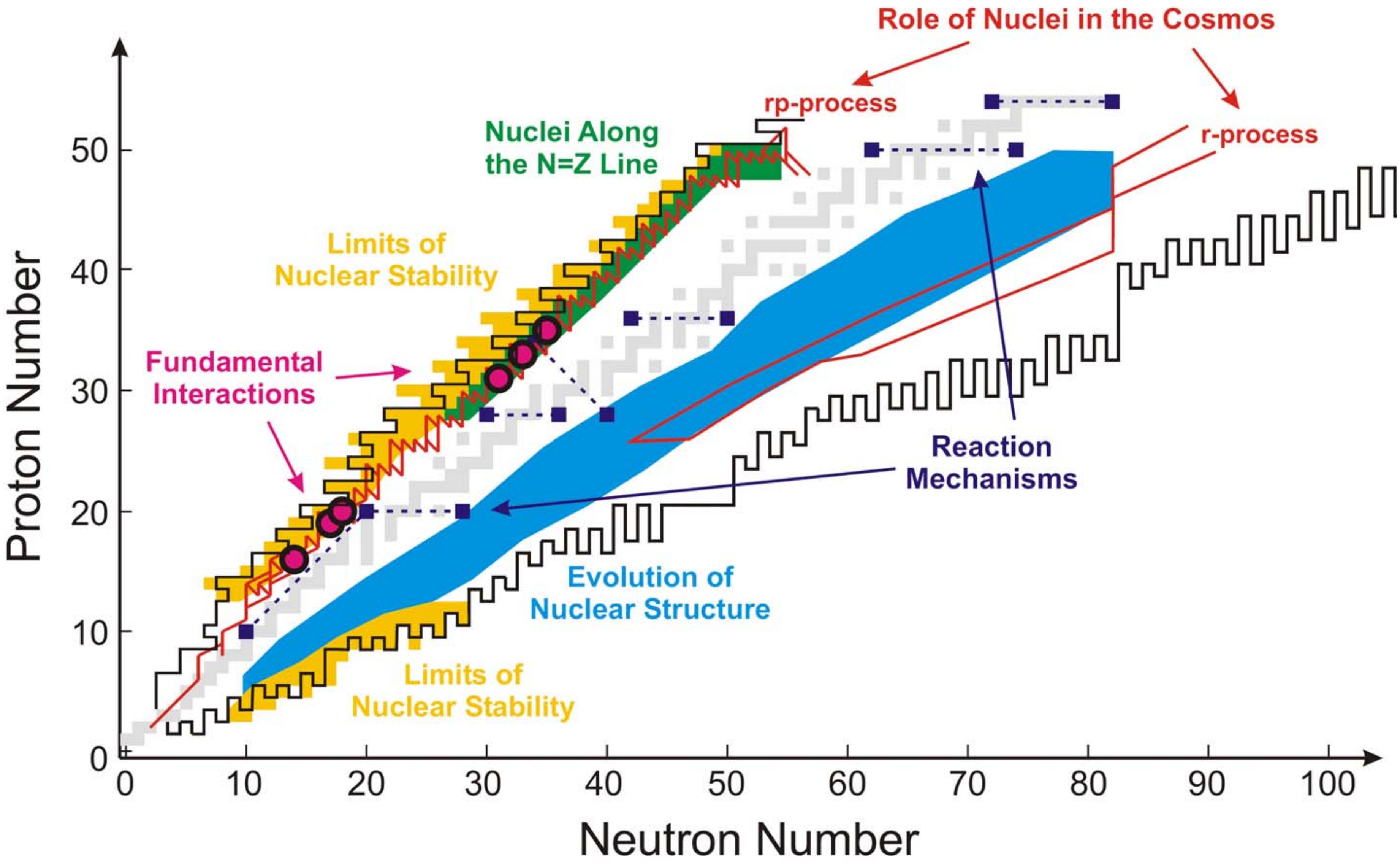
* Member of USPAS (U.S. Particle Accelerator School)

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

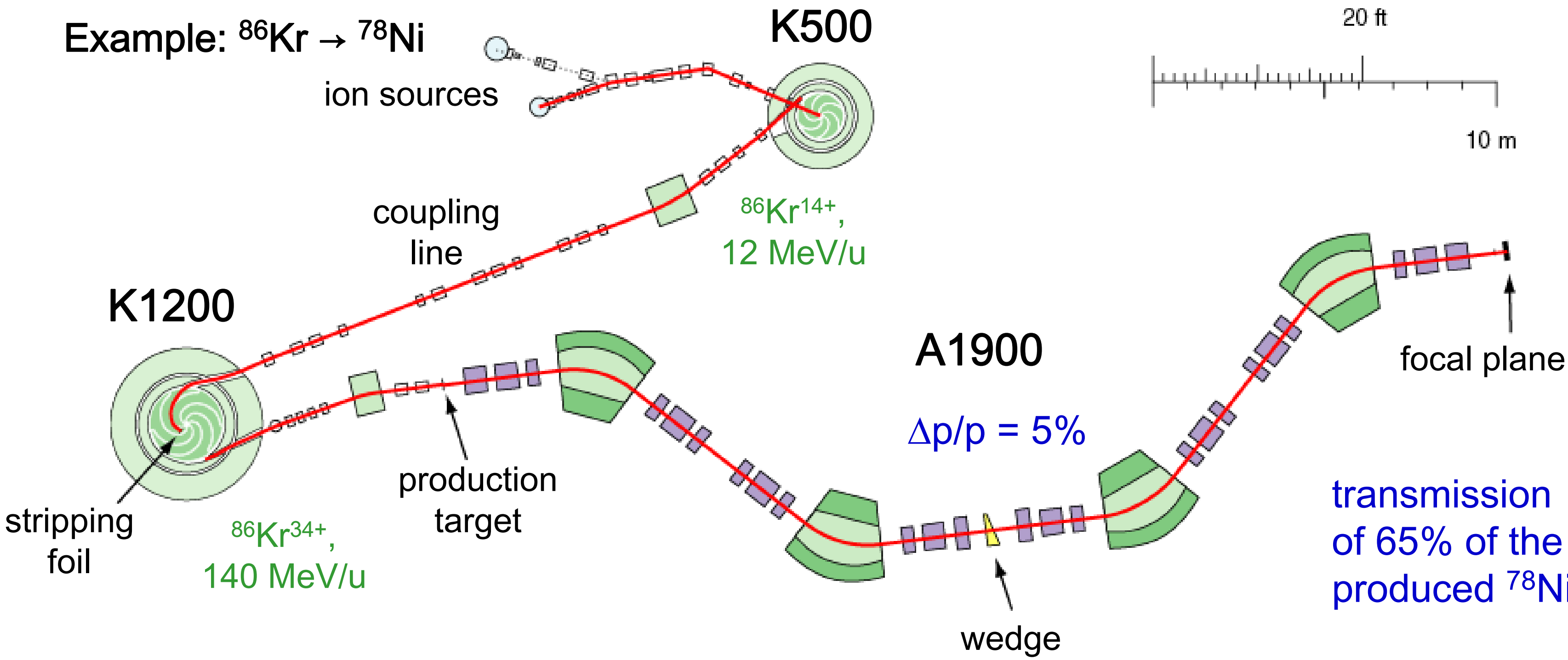


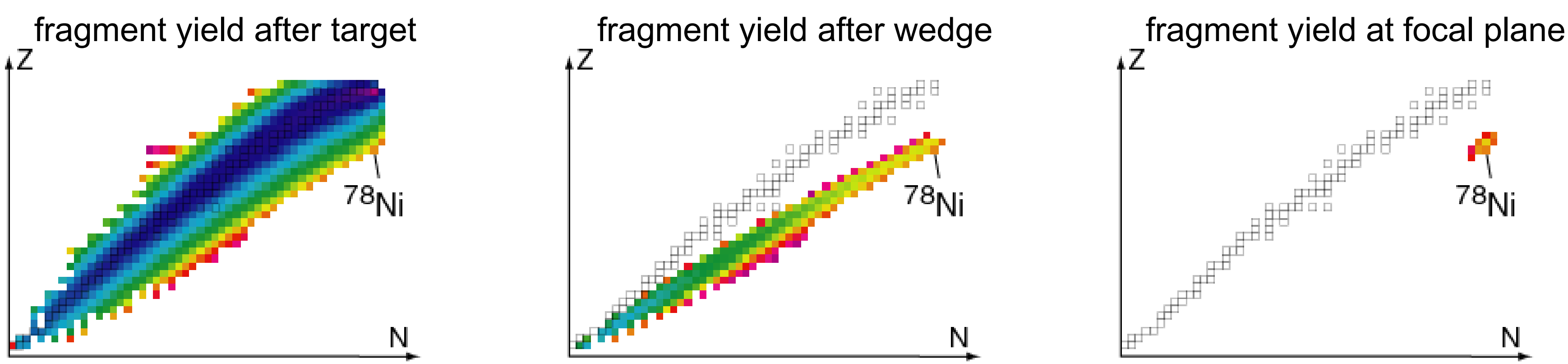


NSCL Science Program (next 5 years)



In-Flight Production of Rare Isotopes at NSCL

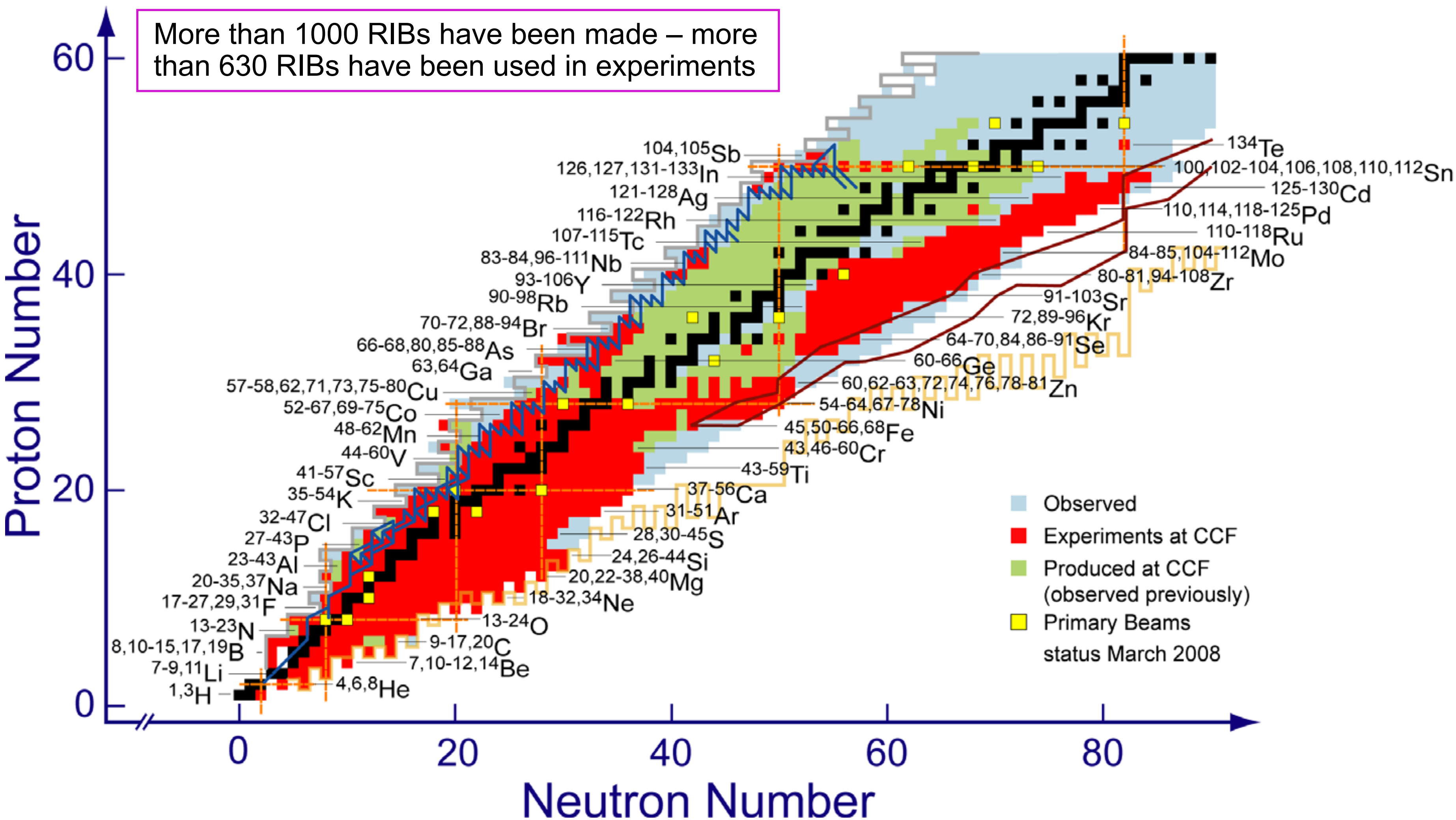




Rare Isotope Beams Produced at NSCL

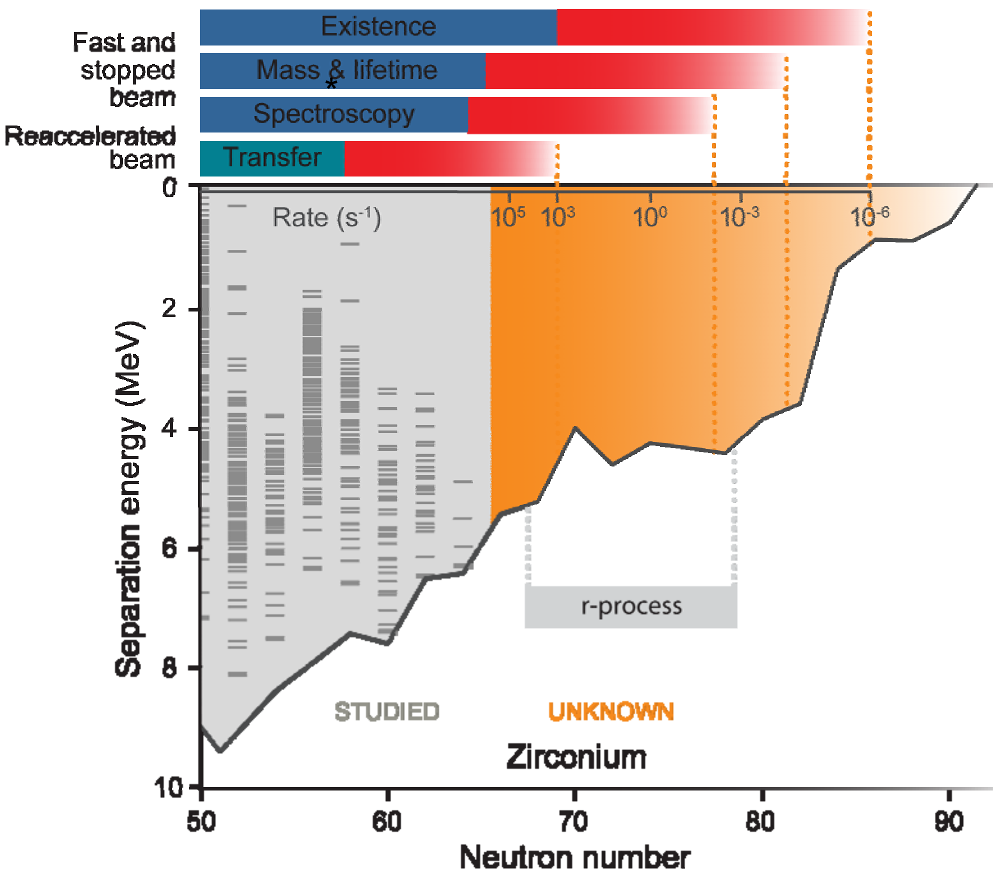
Research program requires large number of beam tunes and, hence, reliable and predictable operations (CCF availability > 90%)

Increasing science pressure to move towards heavier nuclei



Scientific Reach of Heavy Ion Drivers

Measurements for the rarest nuclei provide the most important leverage to constrain theoretical models



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

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

Exotic Decays – Search for di-proton Decay

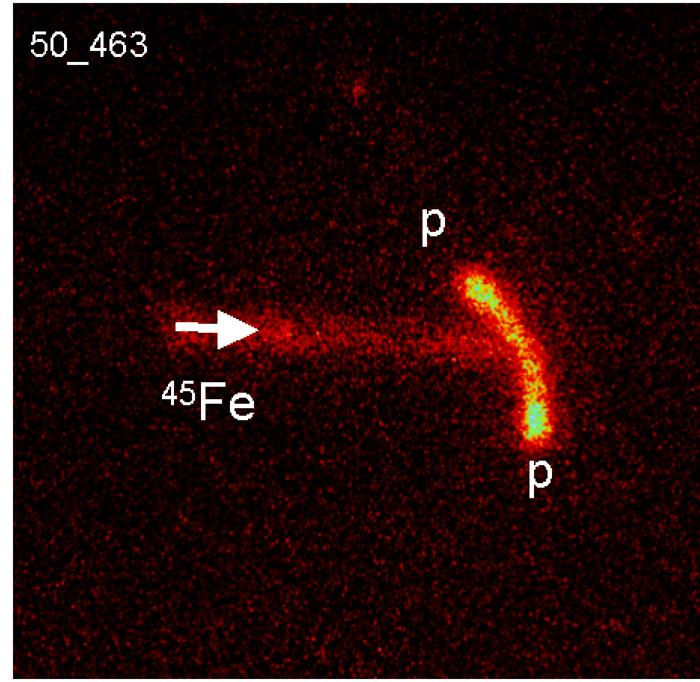
K. Miernik et al., PRL99 (2007) 192501

<u>^{45}Fe is a known 2-proton ground-state emitter</u>

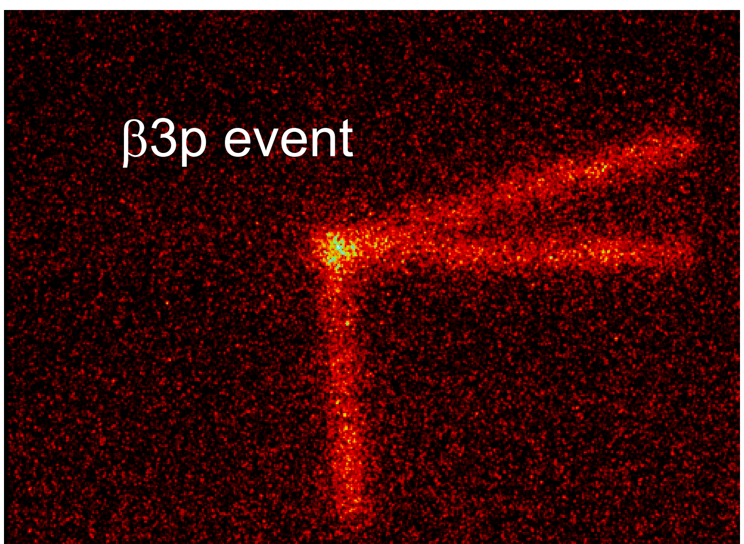
- What is the correlation between the two emitted protons
  - Di-proton (^{2}He) or p+p?

<u>Experiment with optical time projection chamber</u>

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



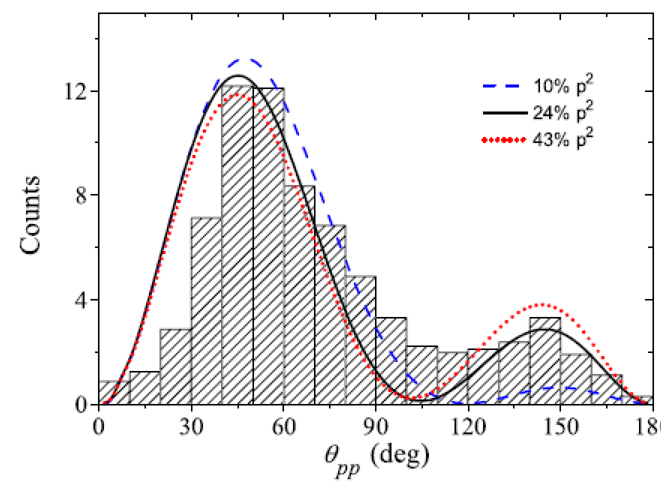
M. Pfützner (Warsaw) et al.



- 87 2p-events
- 38 β-delayed events

Simple ^{2}He decay ruled out

Good agreement with 3-body model of Grigorenko and Zhukov



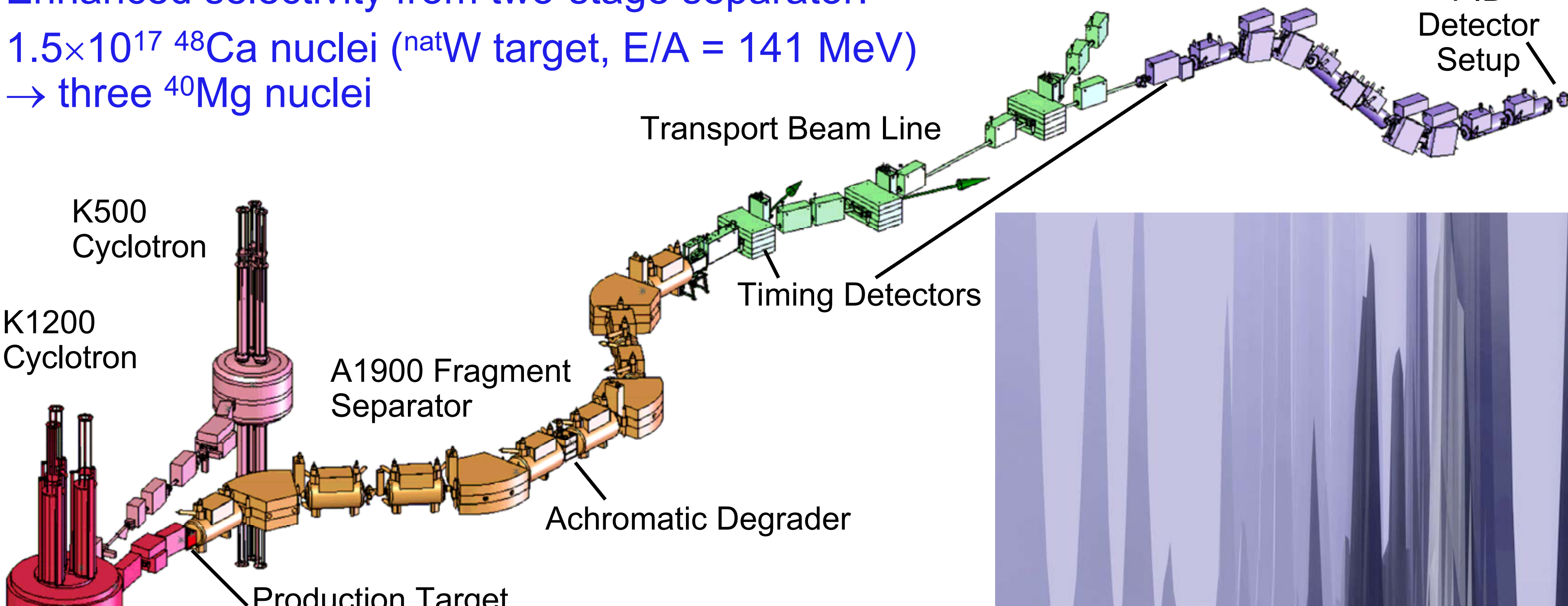
Discovery of ^{40}Mg, ^{42,43}Al, and ^{44}Si in 2007

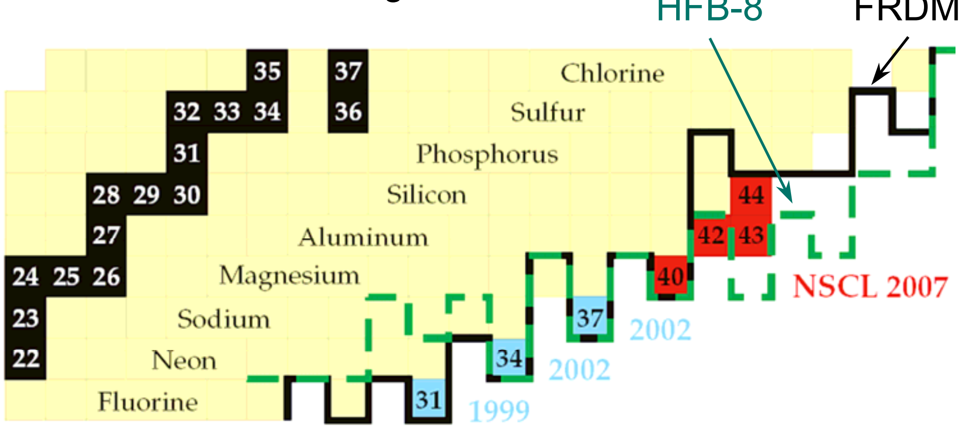
Baumann et al., Phys. Rev. C75 (2007) 064613; Nature 449 (2007) 1022

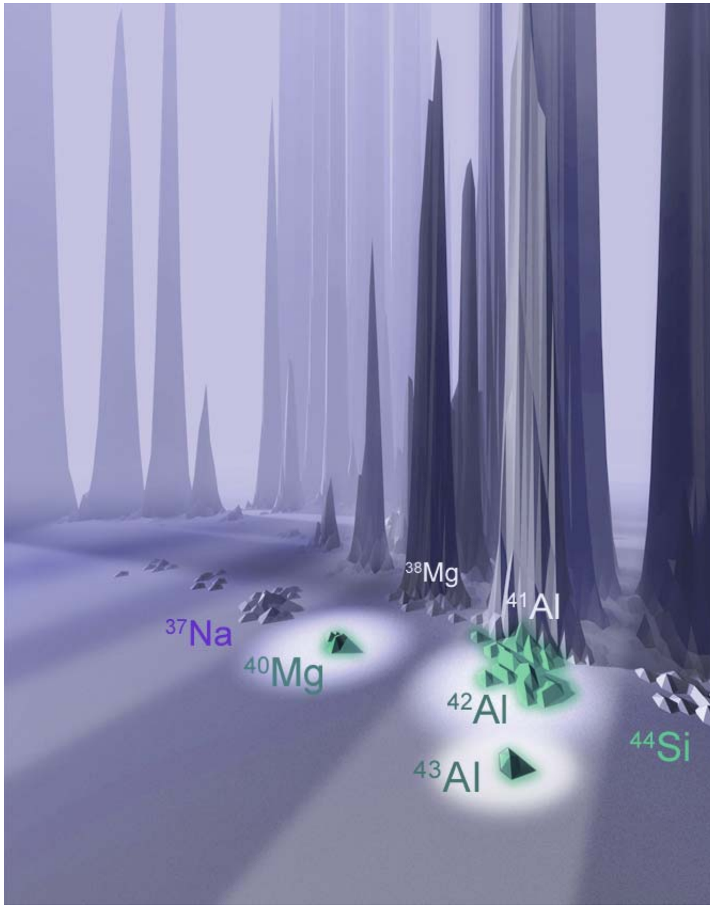
Enhanced selectivity from two-stage separator:

1.5×10^{17} ^{48}Ca nuclei (^{nat}W target, E/A = 141 MeV)

$\rightarrow$ three ^{40}Mg nuclei

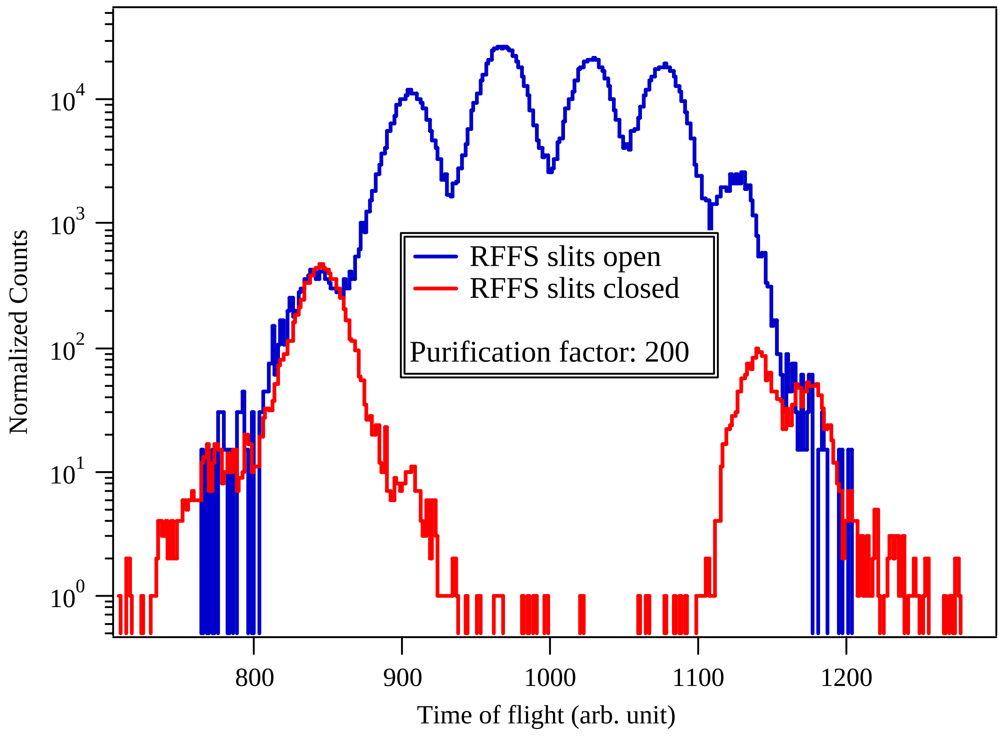




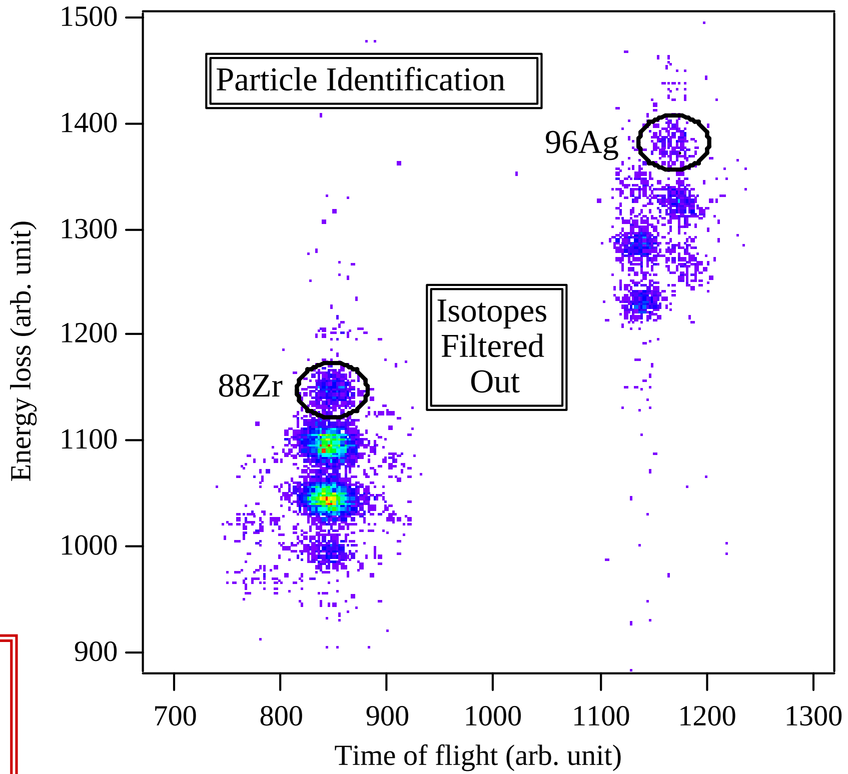


RFFS (Radio-Frequency Fragment Separator)

difference in time of flight ⇔ difference in rf phase



Background suppression via velocity selection



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

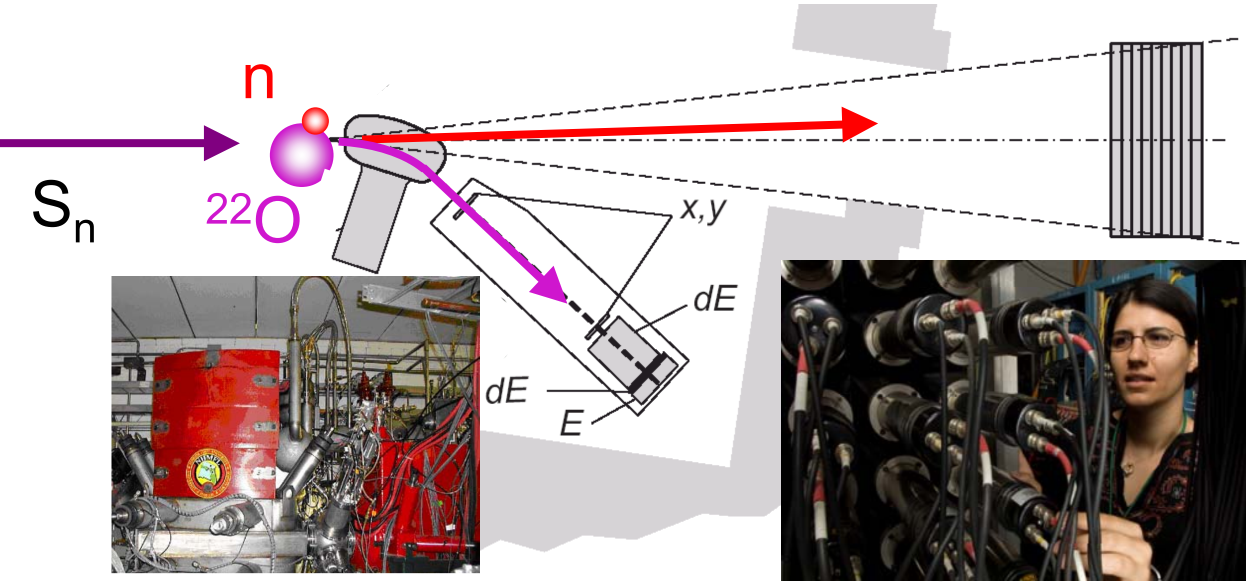
This problem is particularly serious for very proton-rich isotopes – even for highly segmented detector systems like the NSCL beta counting station

Courtesy Daniel Bazin

N =14 Gap in Neutron-Rich Oxygen Isotopes

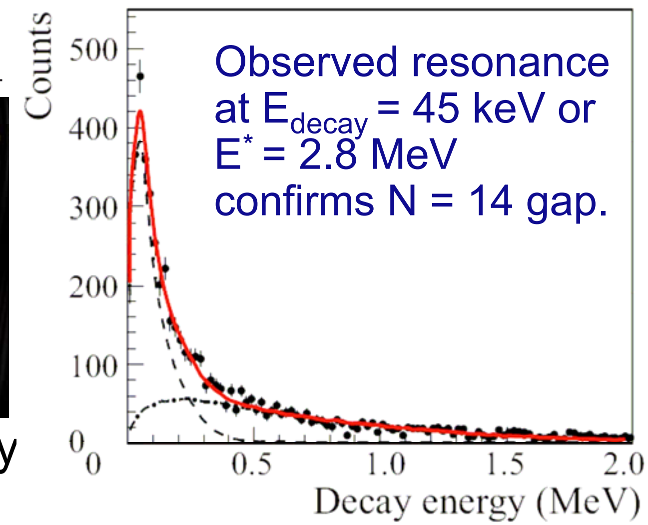
A. Schiller *et al.*, Phys. Rev. Lett. 99, 112501 (2007)

Prediction of large shell gap for N =14 in oxygen isotopes close to the neutron dripline



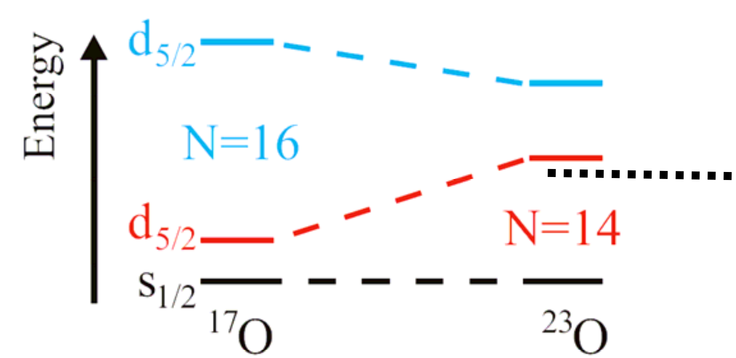
Sweeper magnet

Modular Neutron Array



MoNA

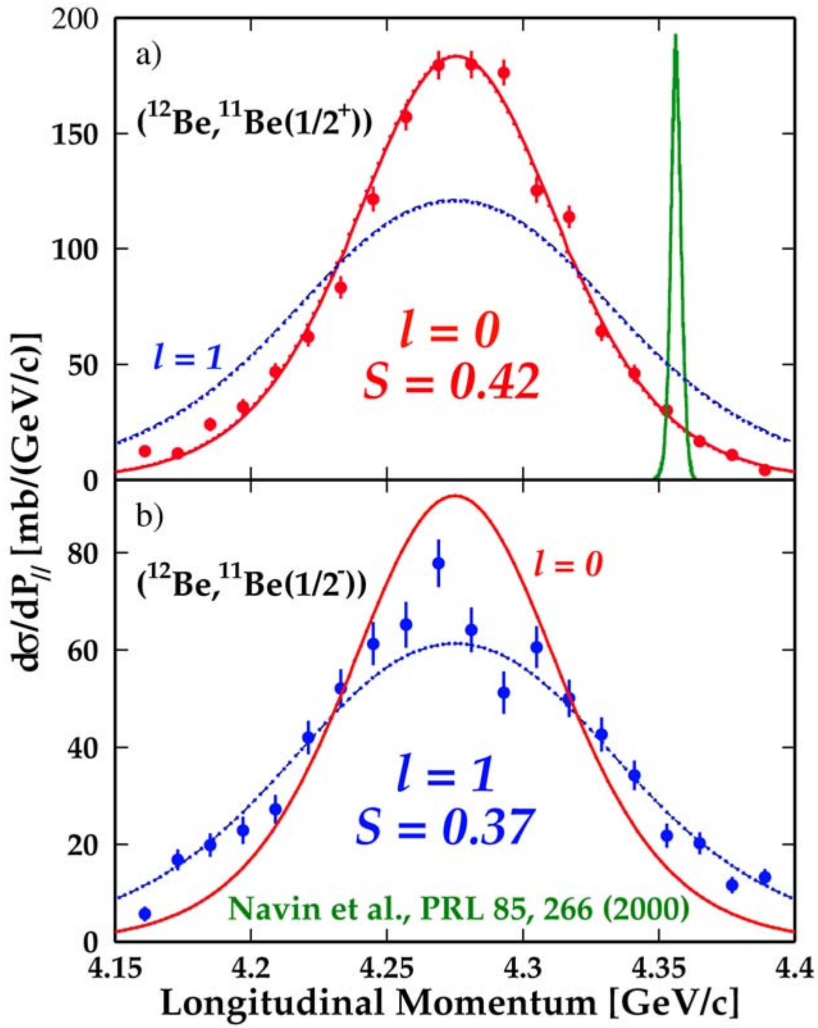
(Modular Neutron Array) Institutions

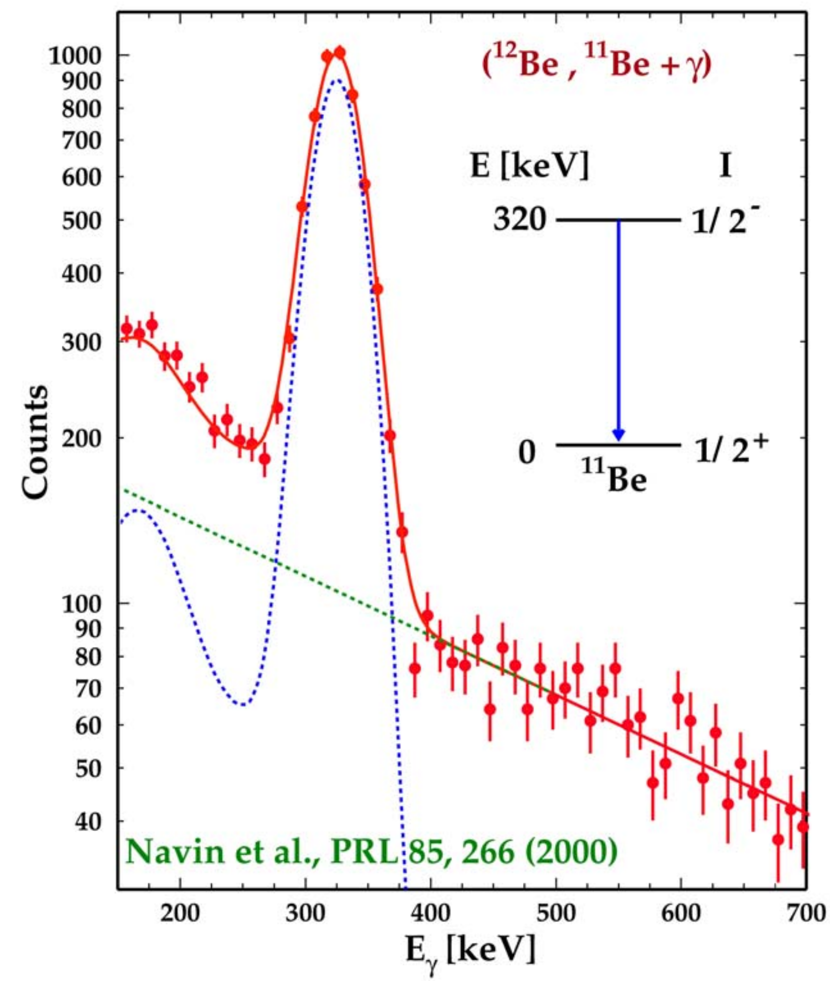


Nuclear Spectroscopy with Knockout Reactions

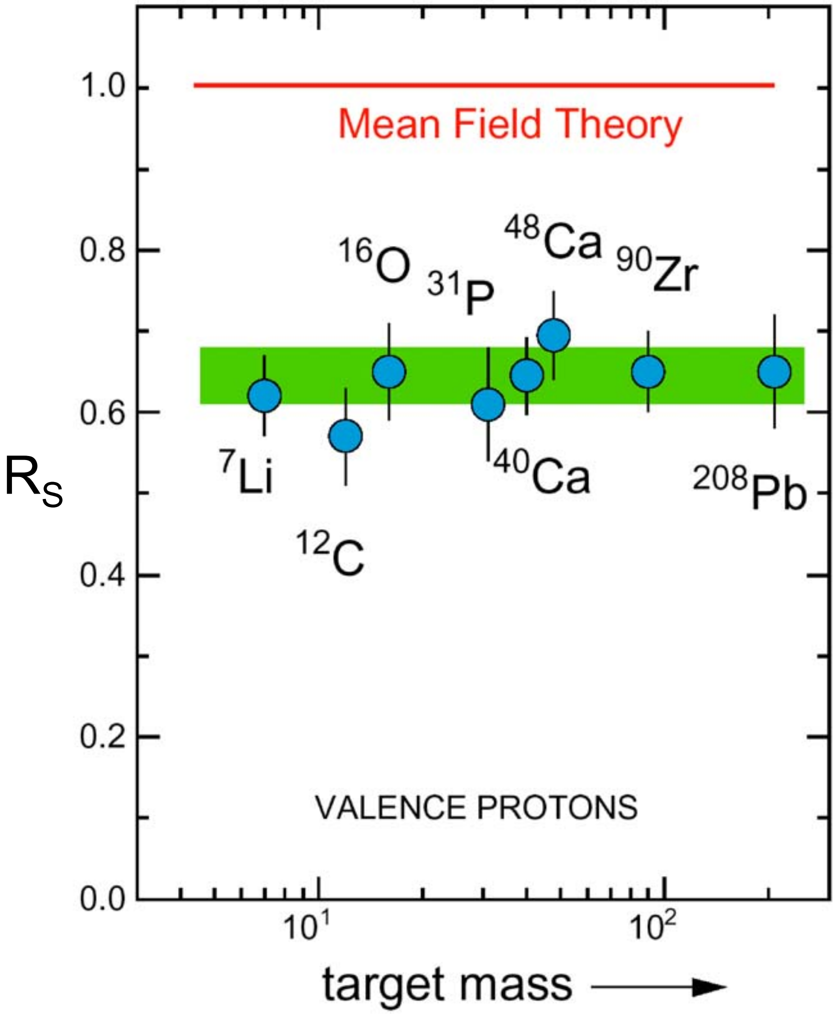
Measure $P_{||}$-distributions for individual states, tagged by γ-rays: cross section is sensitive to wavefunction; shape identifies l of knocked-out nucleon

→Breakdown of N=8 shell closure in ^{12}Be: only 32% $(0p)^8$ and 68% $(0p)^6$-$(1s,0d)^2$





Occupation of Single-Particle States



Shell model: Deeply-bound states are fully occupied by nucleons. At and above the Fermi sea, configuration mixing leads to occupancies that gradually decrease to zero.

Correlation effects (short-range, soft-core, long-range, tensor, coupling to vibrational excitations): Beyond effective interactions employed in shell model and mean-field approaches. Occupancies will be modified.

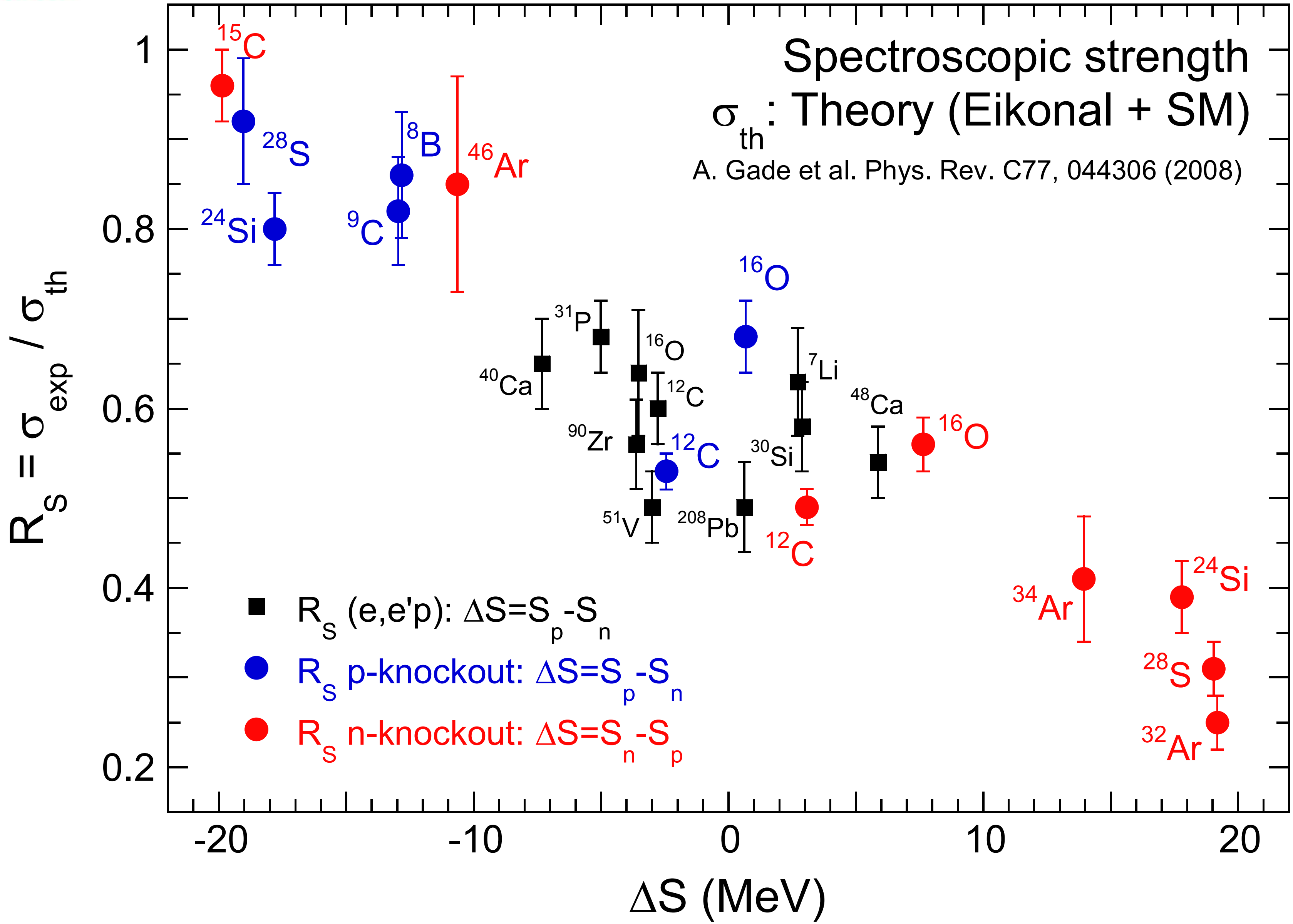
Reduction factor with respect to the shell model:

$$R_s=C^2S_{exp}/ C^2S_{th}$$

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

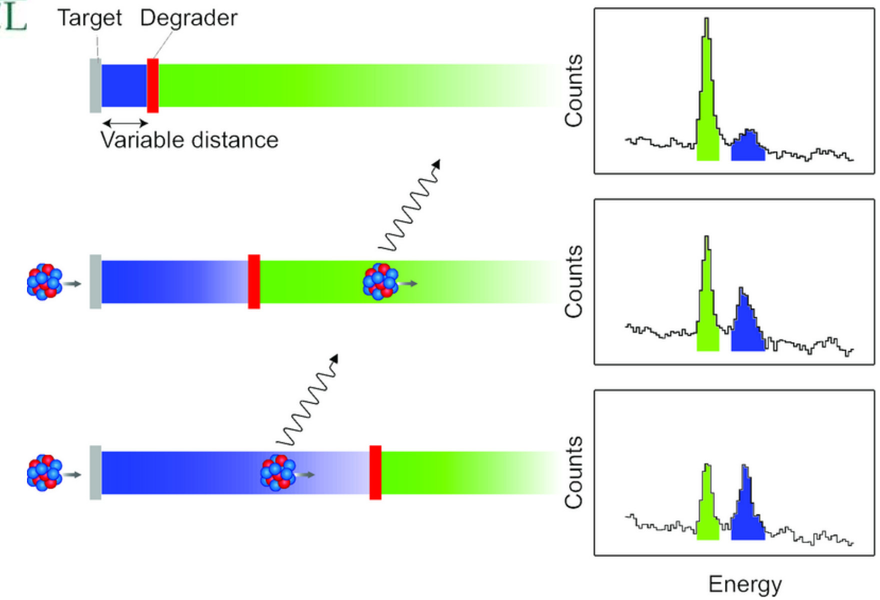
V. R. Pandharipande *et al*, Rev. Mod. Phys. 69, 981 (1997)
W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci. 52, 377 (2004).

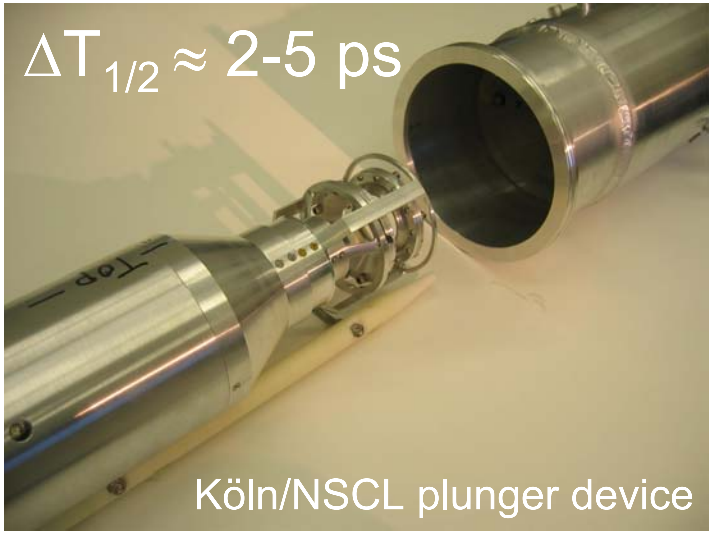
Expanded Purview from Rare Isotopes



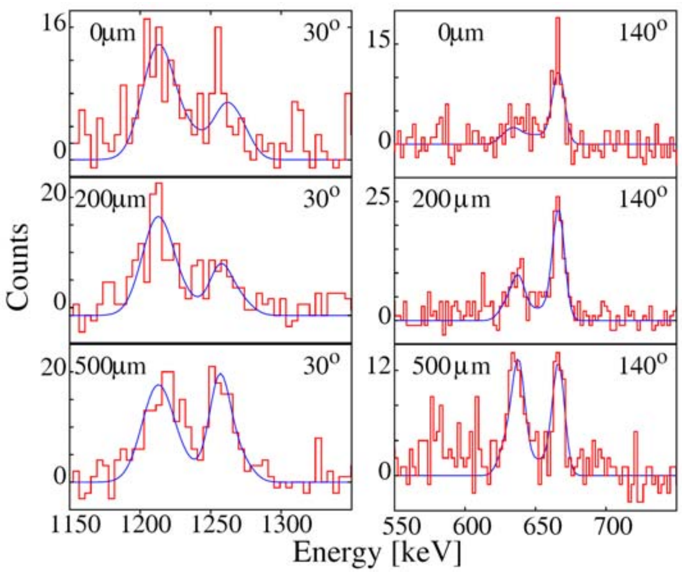
Recoil Distance Method for Knock-Out Reactions

Michigan State University
Advancing Knowledge. Transforming Lives.

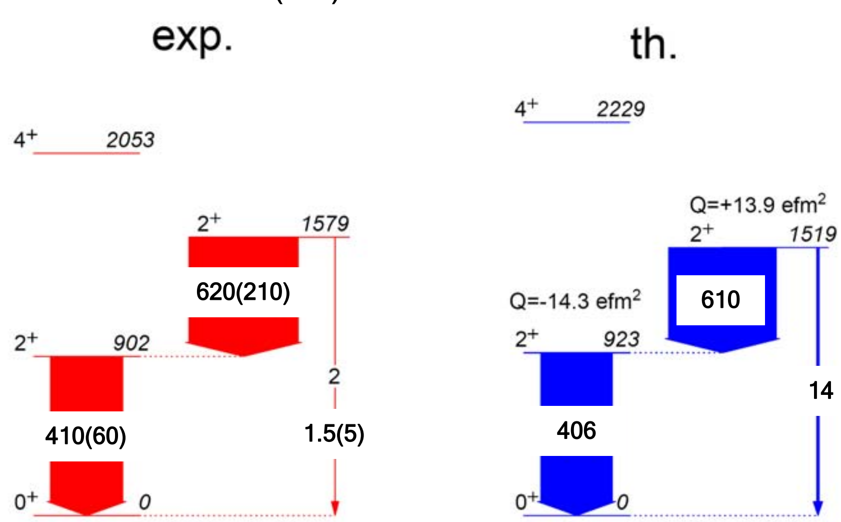




Transition rates for N=Z ^{64}Ge



B(E2) values in e^2fm^4



A. Dewald et al., Phys Rev. Lett. 99 (2007) 042503

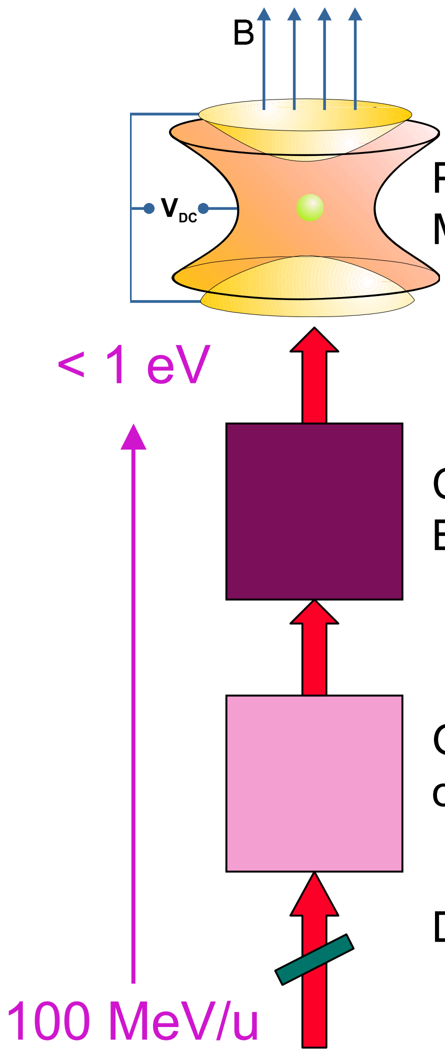
Low Energy Beam Ion Trap (LEBIT)

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}Si, ^{29,34}P, ^{37,38}Ca, $^{40-44}$S, $^{63-65,65m}$Fe, $^{64-66}$Co, $^{63-64}$Ga, $^{64-66}$Ge, $^{66-68,80}$As, $^{68-70,81,81m}$Se, ^{70m,71}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 100 (2008) 132501

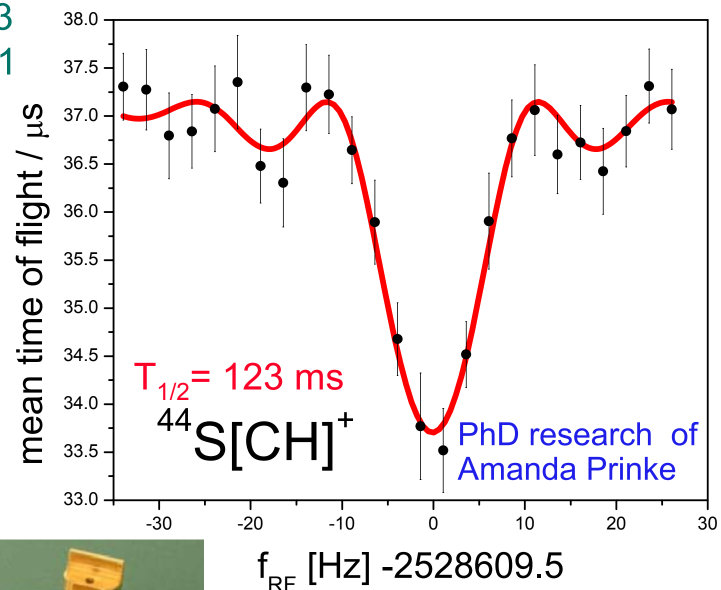


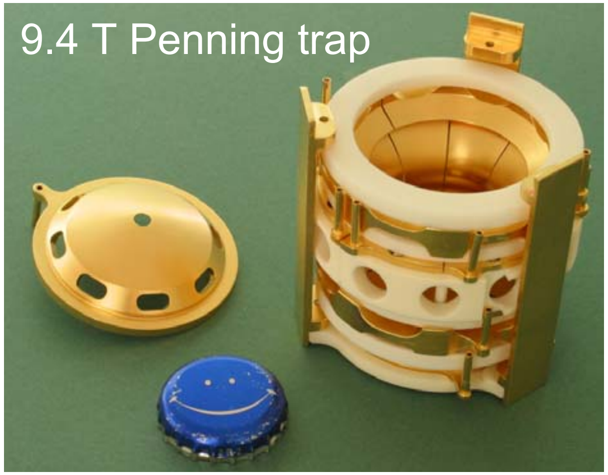
Penning Trap Mass Spectrometry

Cooling and Bunching

Gas stopping of fast ions

Degrader



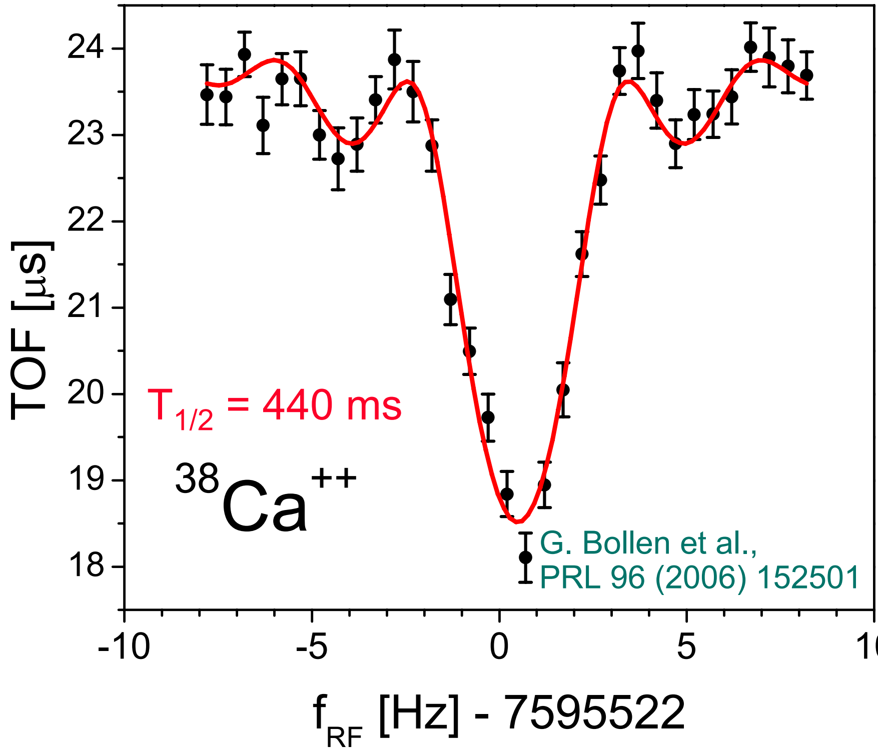


^{44}S:
ME_{LEBIT} = -9205(5) keV

- 25-fold improvement over SPEG 2007: ME = -9100(130) keV
- Disappearance of N = 28 magic number?

More Examples of Mass Measurements

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



^{38}Ca: $0^+ \rightarrow 0^+$ β^+-emitter

– new candidate for the test of the conserved vector current (CVC) hypothesis

ME_{LEBIT} = -22058.53(28) keV

δm = 280 eV, $\delta m/m = 8\cdot10^{-9}$

– 17-fold improvement over AME 03: δm = 5 keV

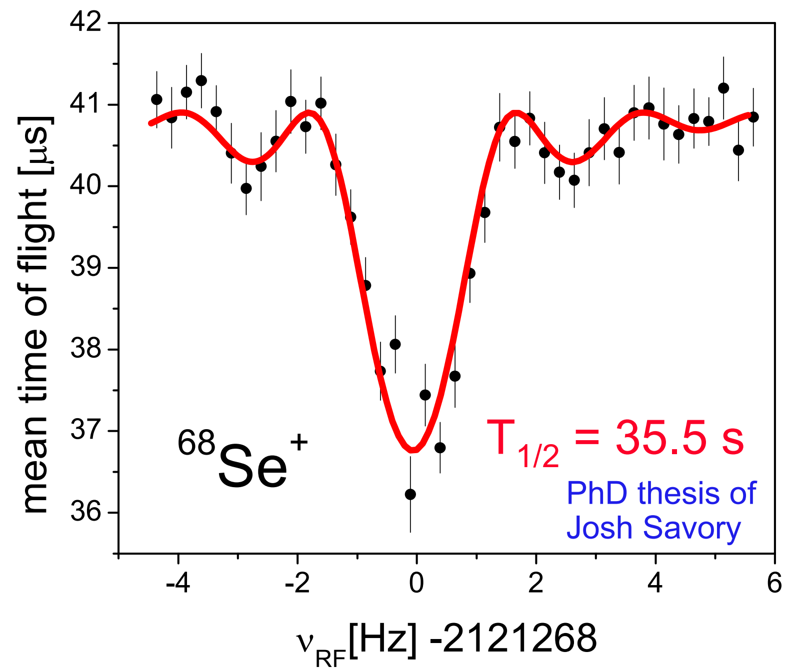
^{68}Se: β^+-emitter

– more important rp-process waiting point nucleus than previously thought

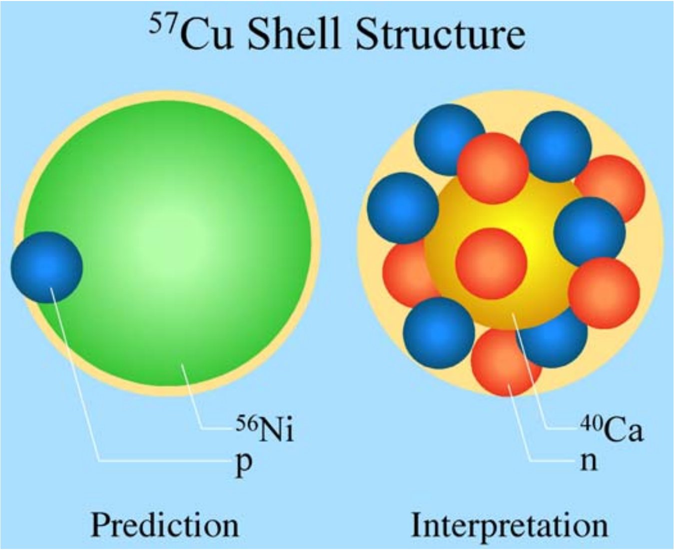
ME_{LEBIT} = -54189.3(5) keV

δm = 530 eV, $\delta m/m = 8\cdot10^{-9}$

– 35-fold improvement over CPT 2004: ME = -54 232(19) keV)



Evidence for Shell Breaking near ^{56}Ni

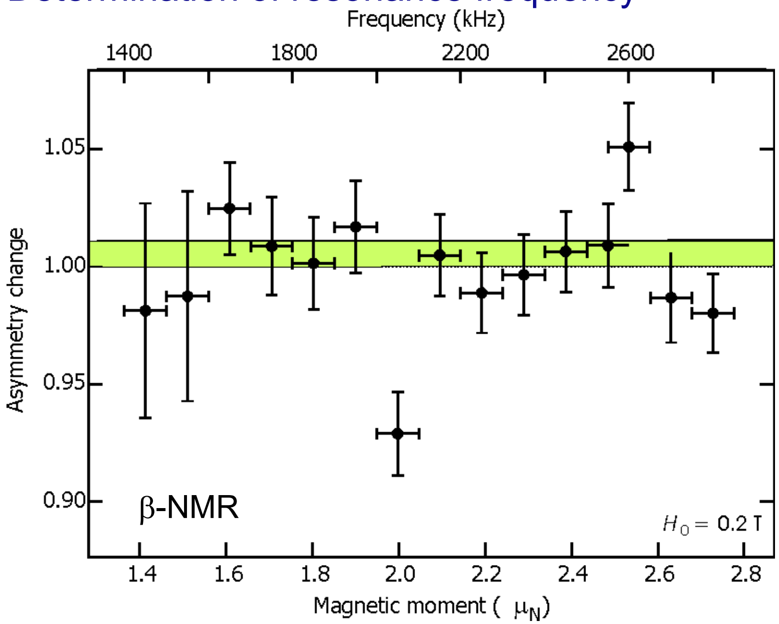


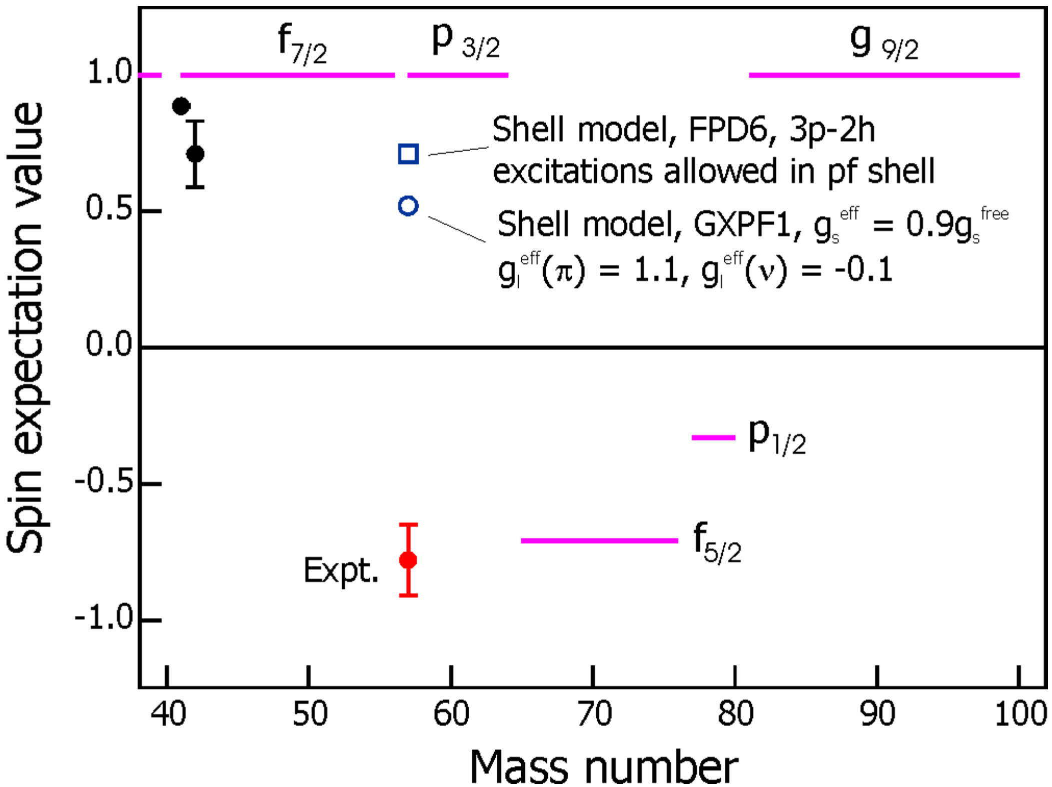
The ^{57}Cu-^{57}Ni mirror pair is the heaviest T=1/2 system studied to date

- Measurement of spin expectation value with β-NMR technique: <σ> = -0.78±0.031
- Value is inconsistent with the assumption of an inert doubly-magic ^{56}Ni core

Minamisono et al., Phys. Rev. Lett. 96 (2006) 102501

Determination of resonance frequency





NSCL Beta Counting System (BCS)

High-sensitivity system for correlating fragment implants with subsequent β-decays on an event-by-event basis

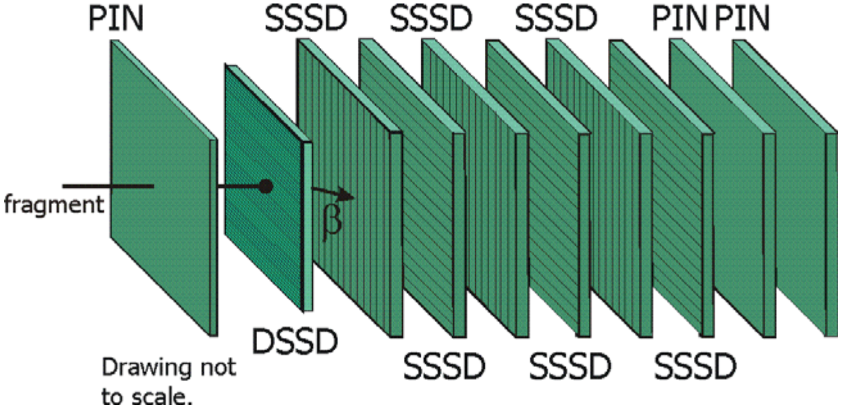
- Suited for use with cocktail beams

1 fragment implant detector:

- 4×4 cm^2 active area, 1 mm thick
- 40 1-mm strips in x and y

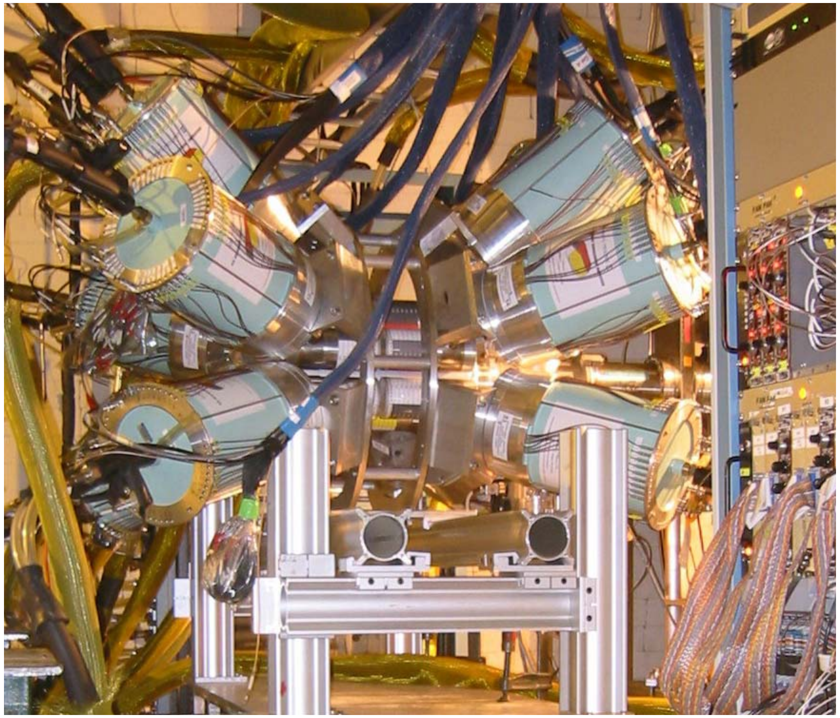
6 calorimeter detectors:

- 5×5 cm^2 active area, 1 mm thick
- 16 strips in one dimension



Prisciandaro et al. NIM A 505, 140 (2003).

BCS combined with 12 Ge-detectors from SeGA



Doubly Magic ^{78}Ni Accelerates Heavy Element Synthesis

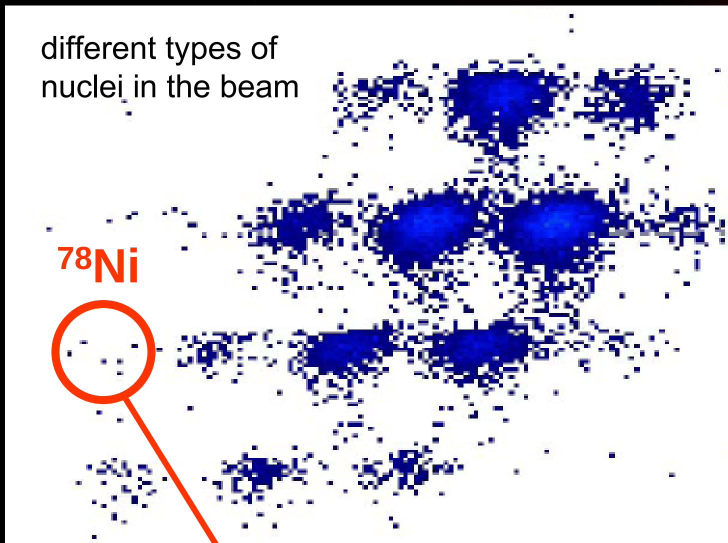
NSCL

MICHIGAN STATE UNIVERSITY

Advancing Knowledge. Transforming Lives.

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

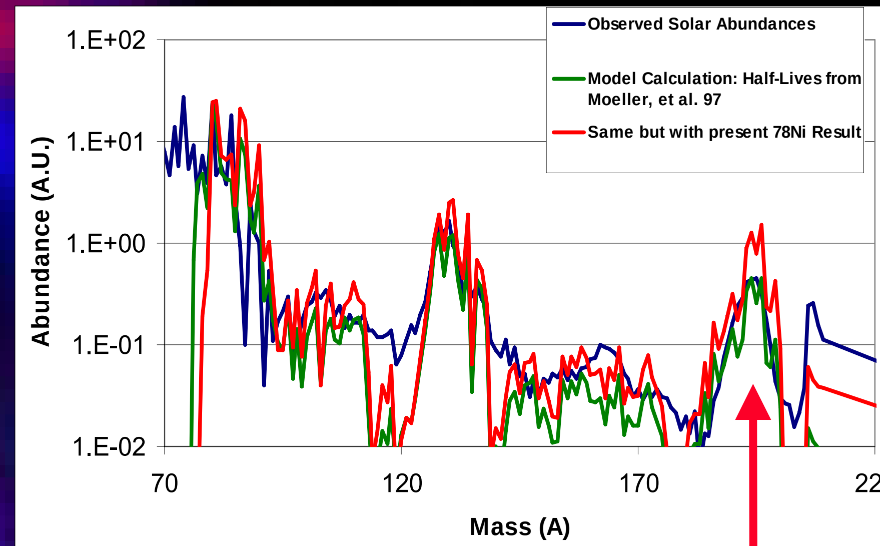
Particle identification



Measured half-life of ^{78}Ni with 11 events –
$T_{1/2}$ is 3-4 times shorter than predicted

^{78}Ni is the most neutron rich of the 10 possible classical "doubly-magic" nuclei in nature

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



models produce excess of heavy element with new (shorter) ^{78}Ni half-life

Result: 110 $^{+100}_{-60}$ ms

P.T. Hosmer et al.
Phys. Rev. Lett. 94 (2005) 112501

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

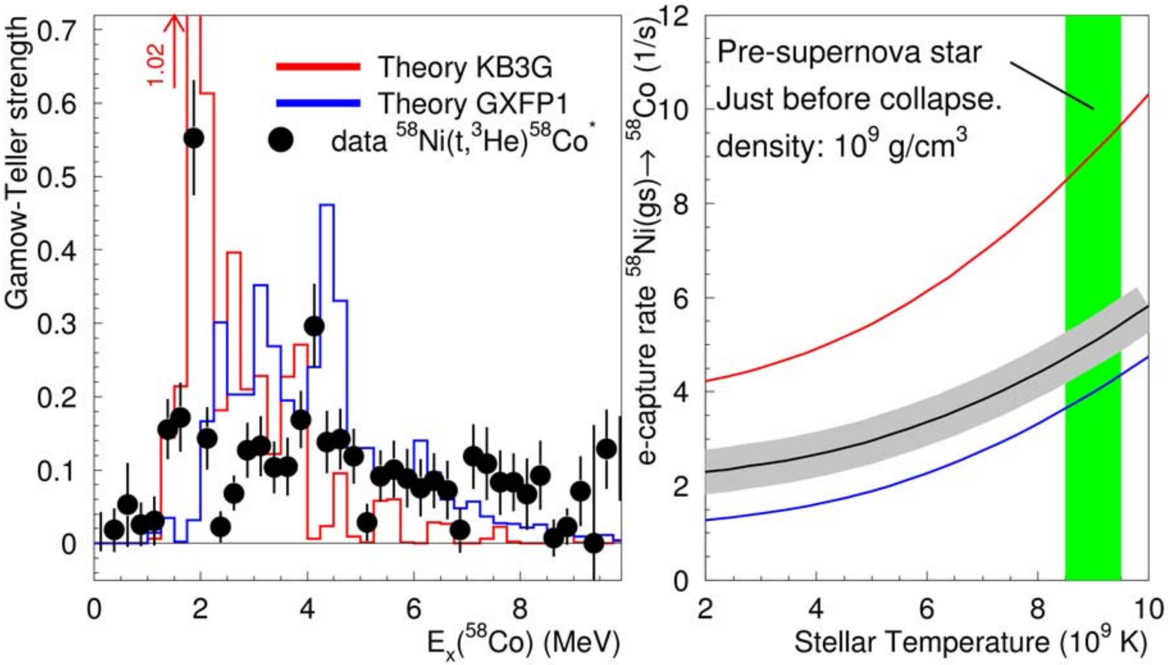
Spin-Isospin Response of Nuclei

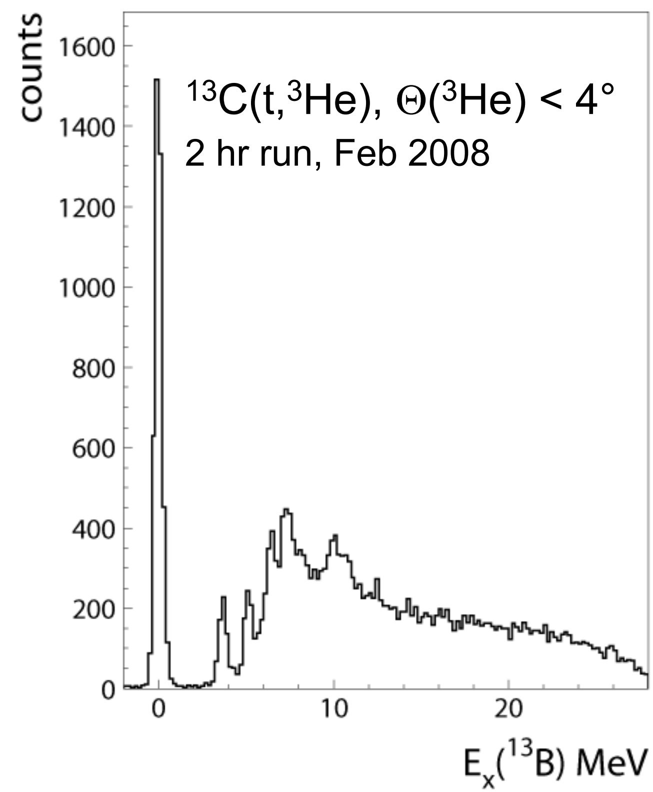
Weak transition rates are important for stellar evolution

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

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

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





NSCL

Spin-Isospin Response of Unstable Nuclei

$^{7}Li(^{34}P,^{34}Si^{*})^{7}Be^{*}$ at 100 MeV/n in inverse kinematics

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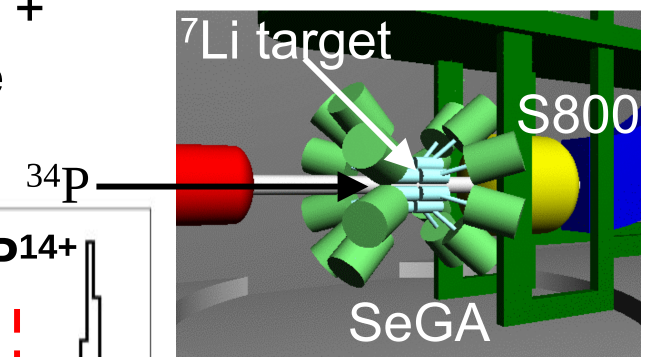
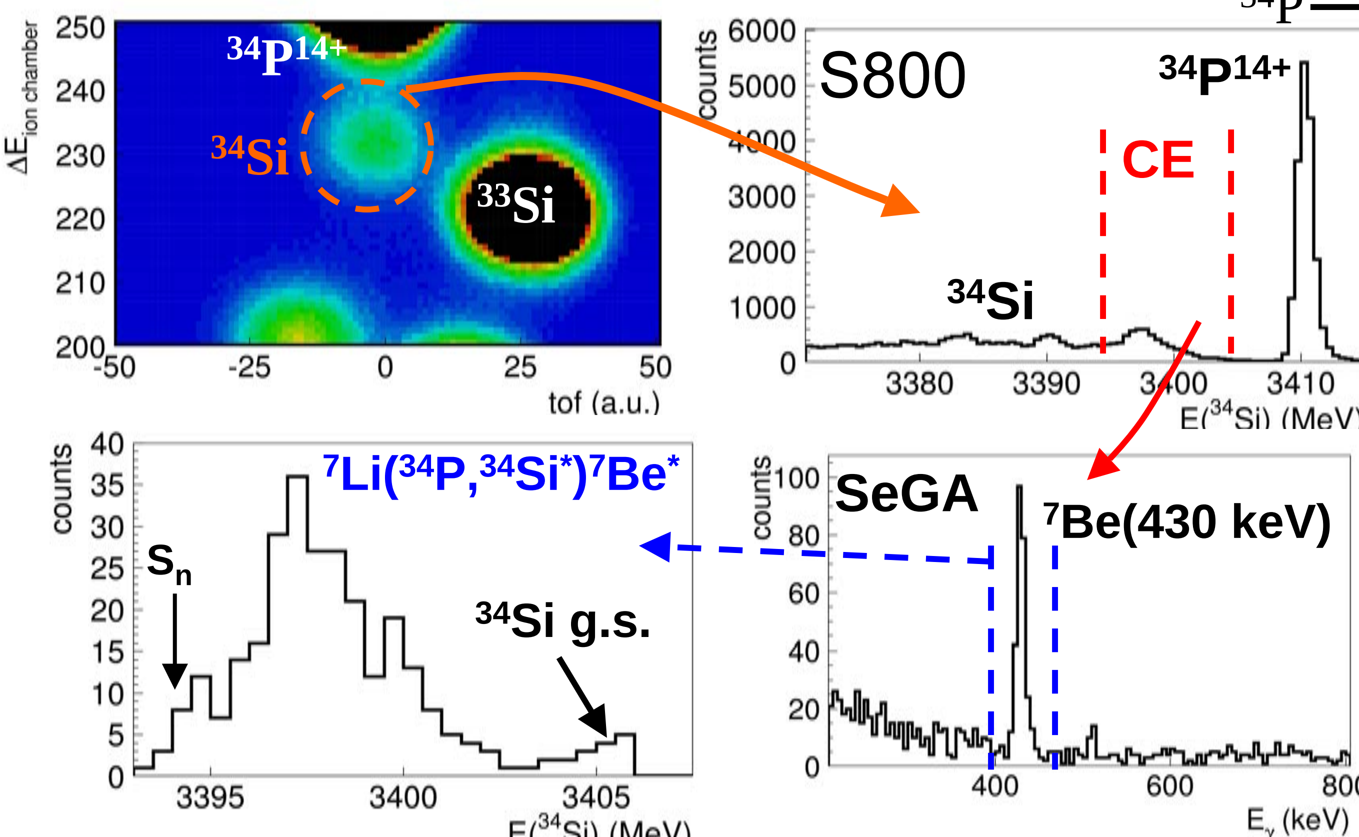
(^{7}Li,$^{7}Be^{*}$) in inverse kinematics: extract isovector response of unstable nuclei

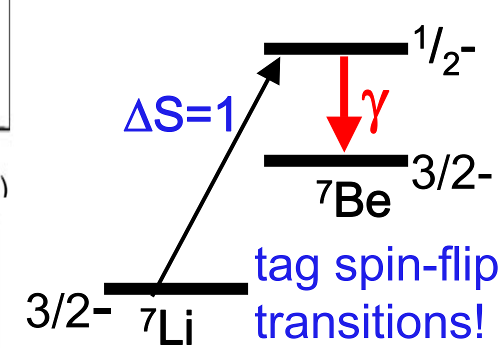
- Selects ΔS = 1 transitions with small background (≤ 1%)
- S800 spectrometer (dispersion-matched mode) + SeGA for coincidence with $^{7}Be^{*}$(430 keV) γ-line

  ≈ 1 MeV energy resolution for E*

R. Zegers et al.







preliminary

New $^{32}Cl(p,\gamma)^{33}Ar$ Rate

Accelerated Energy Generation in X-ray Bursts

NSCL

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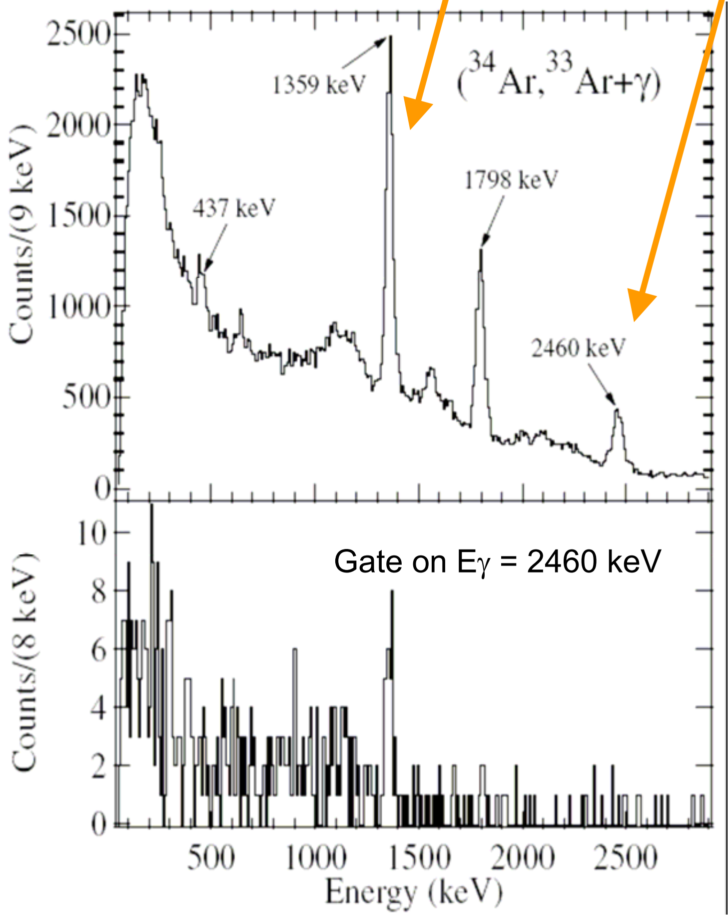
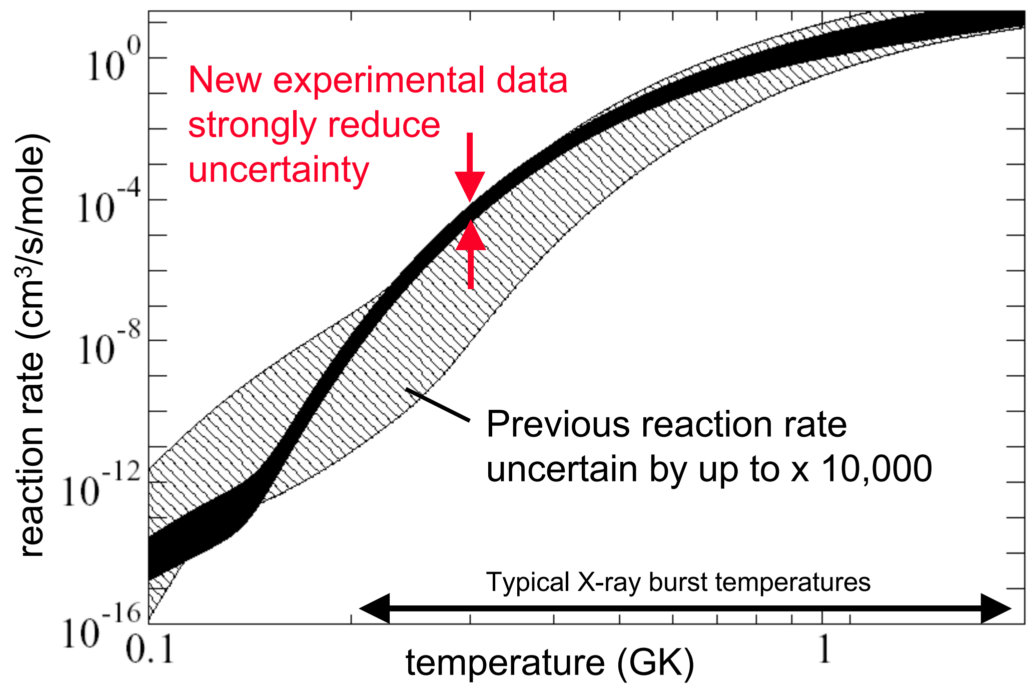
p-capture on ^{32}Cl producing ^{33}Ar is an important step in the rp-process powering thermonuclear explosions on surfaces of accreting neutron stars (X-ray bursts)

γ-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 $^{32}Cl(p,\gamma)^{33}Ar$ stellar reaction rate by 3 orders of magnitude



Clement et al. PRL 92, 172502 (2004)

Most rp-process nuclei can be studied at NSCL

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) – pre-proposal to DOE
- Si-detector array for low-energy astrophysics experiments (Blackmon) – MRI-proposal accepted for funding
- Two beam lines with monochromators for gas stopping –cryogenic linear cell and cyclotron gas stopper (Bollen, Morrissey) – first line complete by 2009

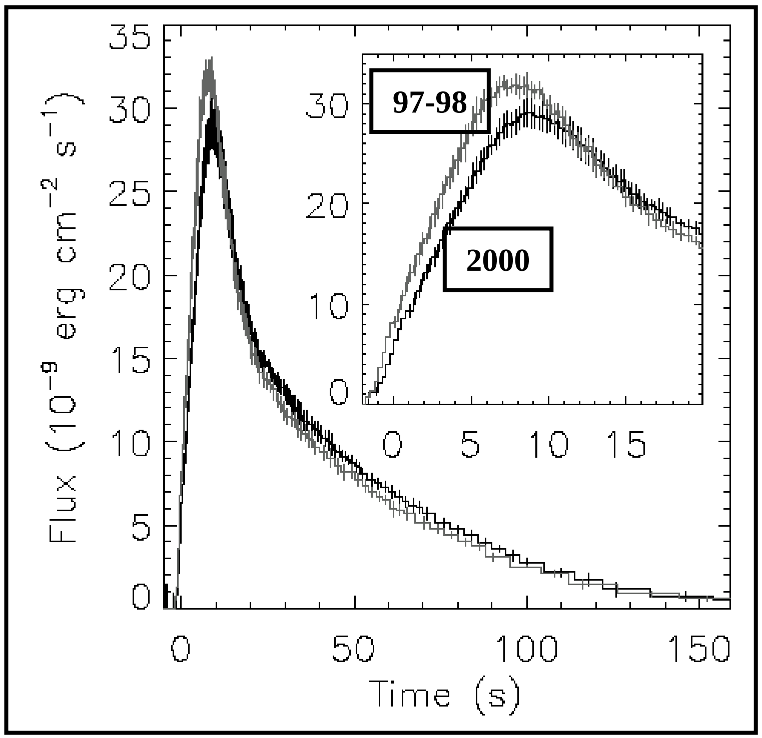
ReA3 – 3.2 MeV/u reacceleration facility (easily upgradeable to higher energy):

- 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
- Construction of mezzanine for reaccelerator – completed
- Commissioning of reaccelerator expected to start in 2010

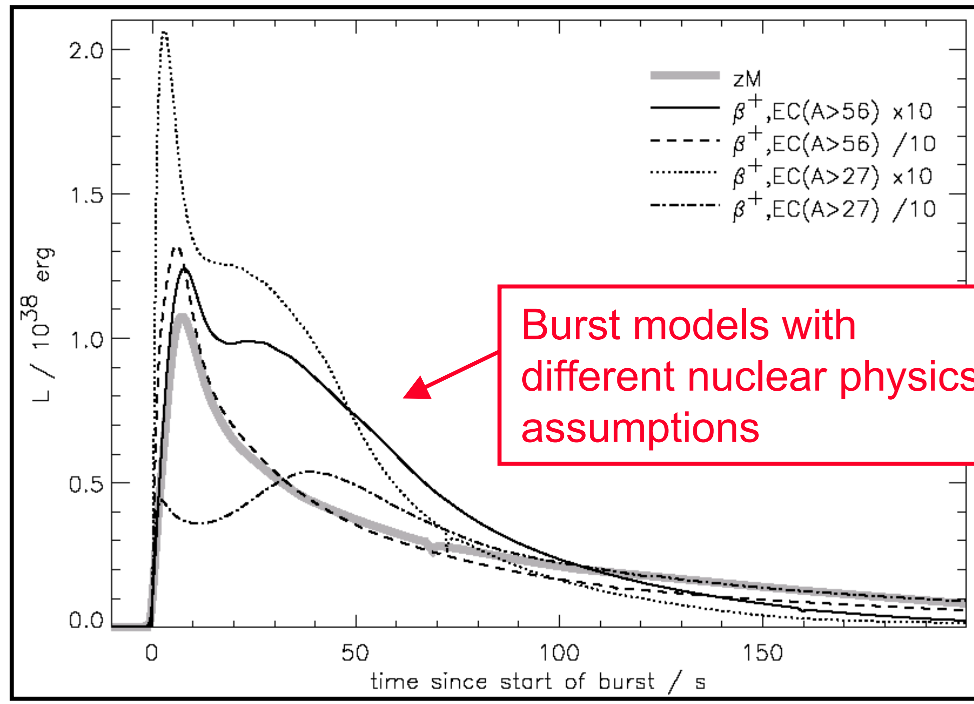
X-Ray Burst Light Curves

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

Laser Spectroscopy at NSCL

NSCL

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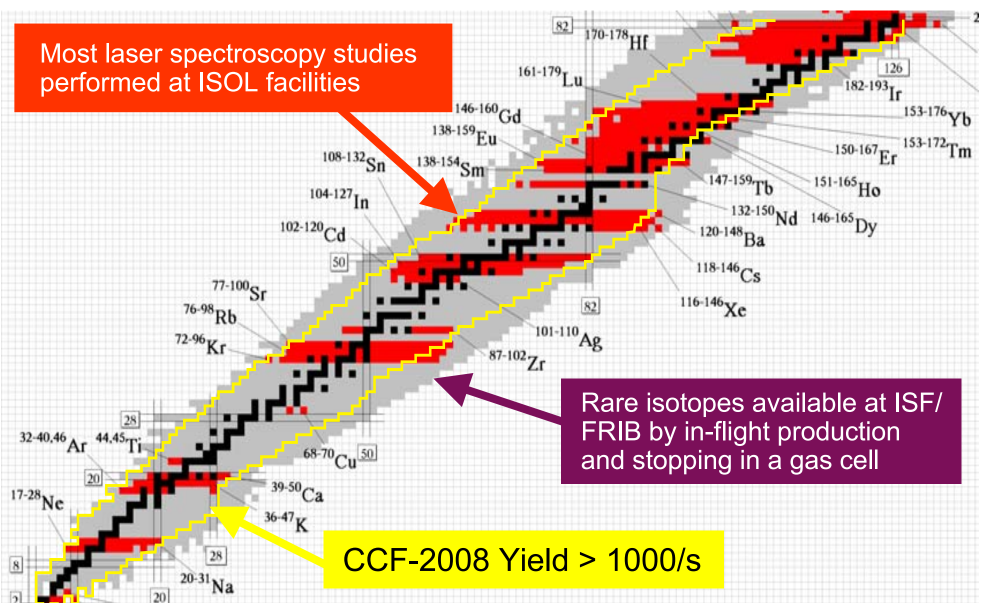
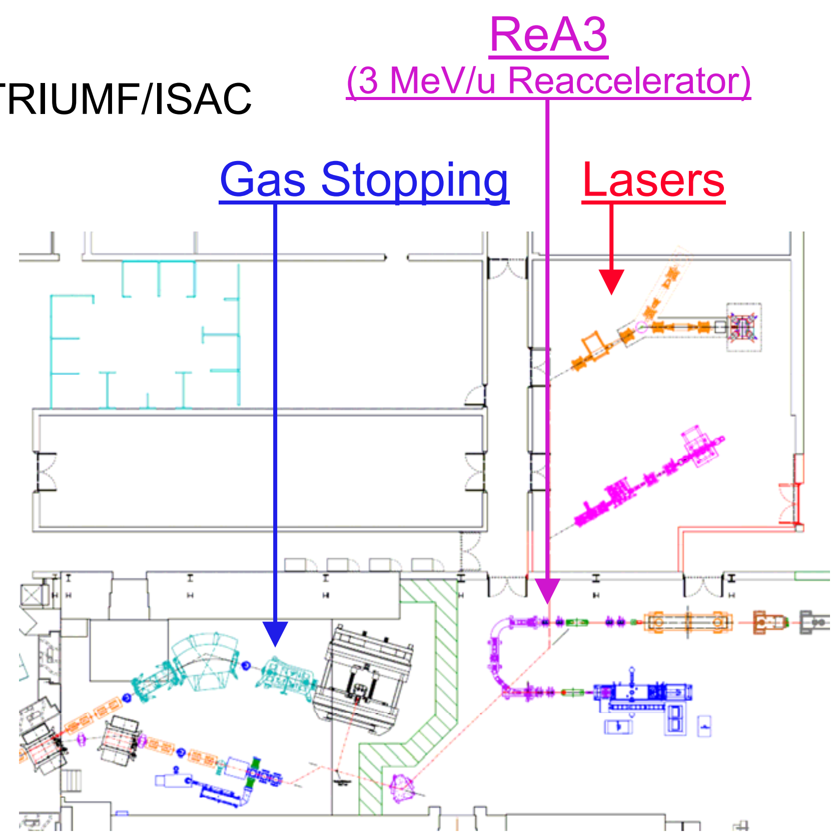
- Evolution of nuclear sizes and shapes across long chains of isotopes
  - Isotope shifts, charge radii, nuclear moments (m, Q)
  - Method applicable to nuclides over wide range of $T_{1/2}$ values
- Projectile fragmentation plus gas stopping
  - Broad range of refractory elements with Z<50 that have been previously inaccessible
- Complements programs at ISOL facilities:
  - CERN/ISOLDE, JAEA, Jyväskylä/IGISOL, TRIUMF/ISAC



H.-J. Kluge, W. Nörtershäuser, Spectrochim. Acta B, 58 (2003)

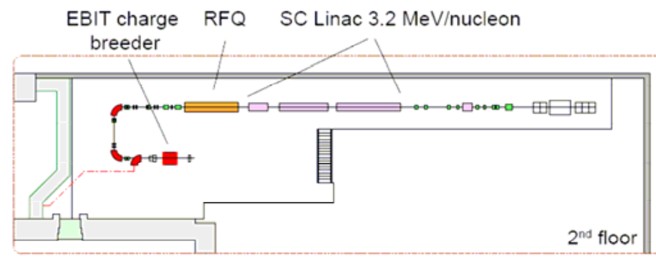


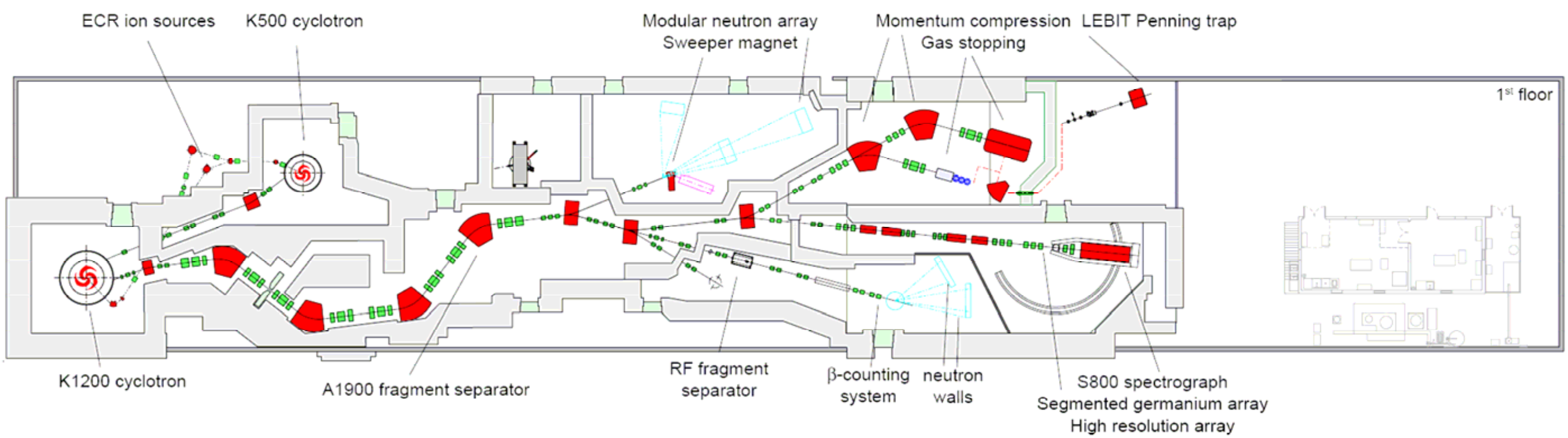
NSCL Facility Plan
(near term future)

Existing state-of-the-art experimental apparatus:

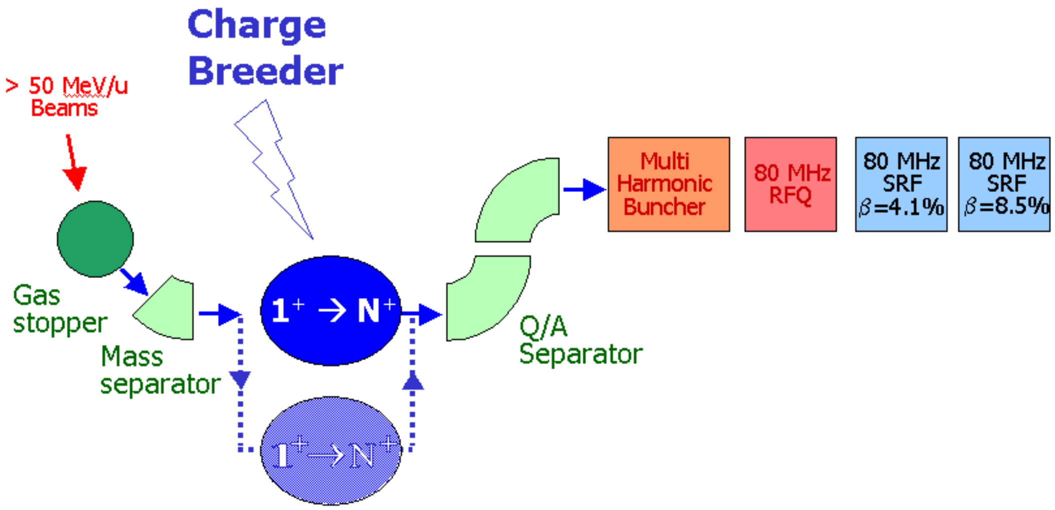
- A1900 fragment separator, 92-inch chamber, S800 magnetic spectrograph, large aperture sweeper magnet spectrograph, large area (2×2 m^2) position sensitive neutron detectors, segmented Ge and Si-strip-CsI arrays, β-NMR and β-counting station, Gas cell (1 bar He) for stopping rare isotopes, 9.4 Tesla 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, ReA3 (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., $^{30}P(p,\gamma)^{31}S$; (p,p) excitation functions, (p,α) reactions …





NSCL ReA3 Project



Attractive features of (N+) acceleration
- Only one frequency – 80 MHz
- No strippers
- Variable duty cycle
- All RF cavities on ground potential
- Less costly

Energy range 300 keV/u –3 MeV/u:
- Nuclear astrophysics and "safe" Coulex

Upgradeable to 12 MeV/u:
- Transfer and fusion-reactions

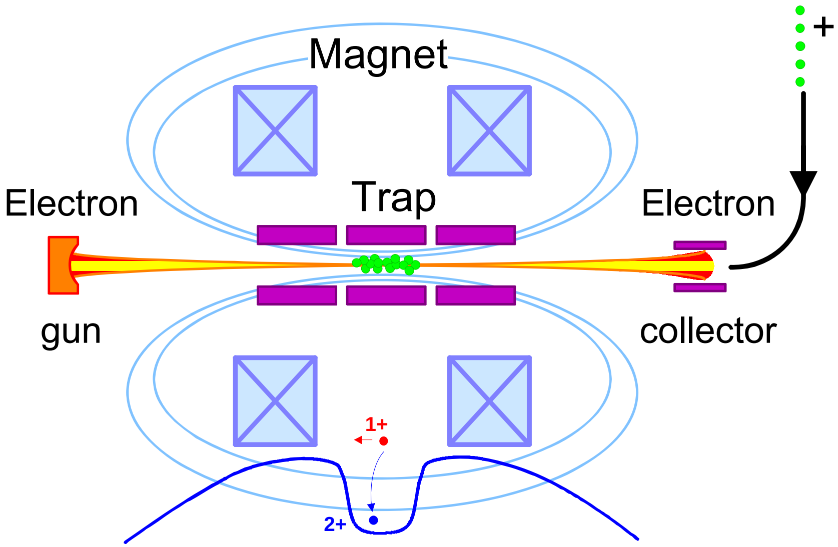
- EBIS/EBIT charge breeding (ε >50%) has higher efficiency than ECR charge breeding (ε <10%) for reacceleration of beams with rates expected for ISF and similar facilities
- An EBIS/EBIT based N+ scheme promises significant efficiency gains over conventional (and more expensive) 1+ schemes

	N+ scheme	1+ scheme	Gain: ε(N+)/ε(1+)	
ε (A<40)	> 55% (1 CS)	40% (1-2 CS)	1.5	3
ε (A=100)	> 45% (1 CS)	16% (3 CS)	3	10
ε (A=200)	> 35% (1 CS)	12% (4 CS)	3	12
Beam rate	> 10^9/s	>> 10^9/s	Multi-Cs	1 Cs

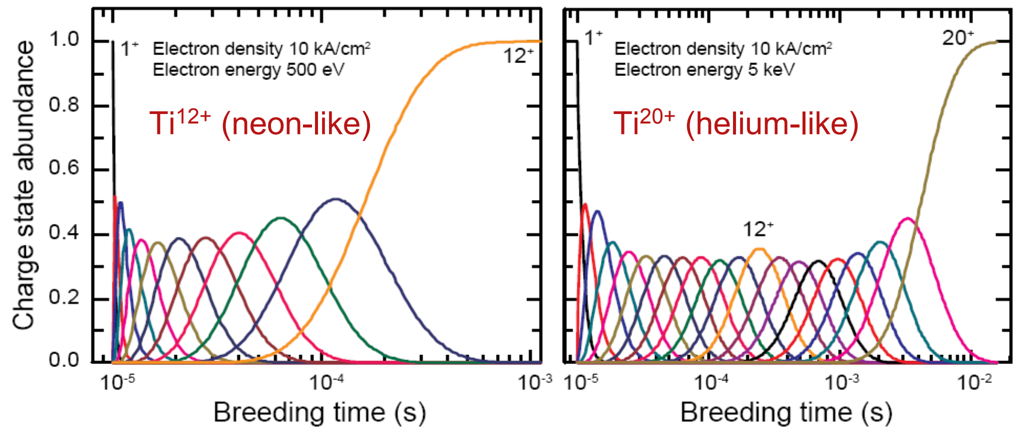
- EBIS/EBIT charge breeding has been used successfully at REX-ISOLDE

NSCL EBIT Charge-Breeder

Breeder requirements: breeding times ~ 10 ms, beam intensity 10^9 ions/s



High-intensity EBIT → fast and selective breeding



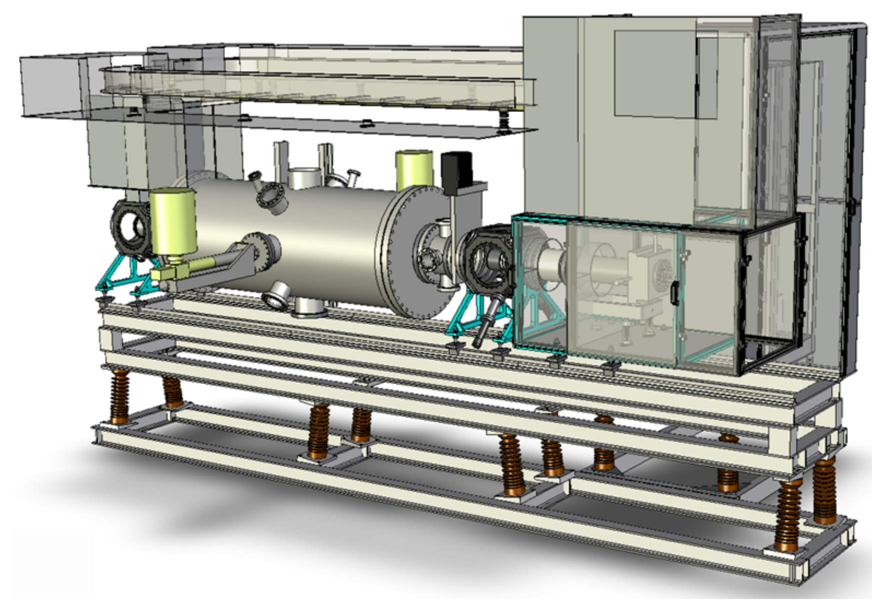
NSCL's EBIT Project:

Started from TITAN-EBIT at TRIUMF

- 10^4 A/cm^2, 6T, 60 kV

Modified design for increased acceptance

- larger trapping region (40 cm)
- variable B-field configuration (2T + 8T)
- higher current density (<10^5 A/cm^2)



Collaboration with MPI-K Heidelberg, TRIUMF

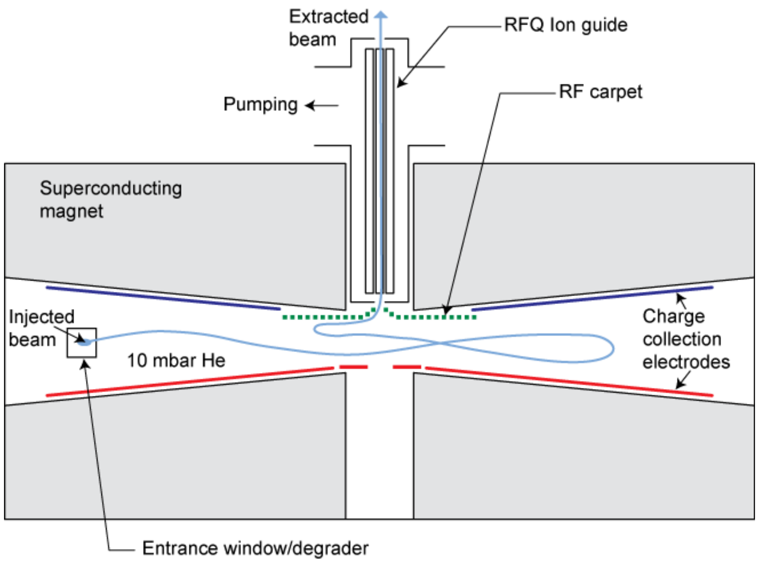
Advances in Gas Stopping

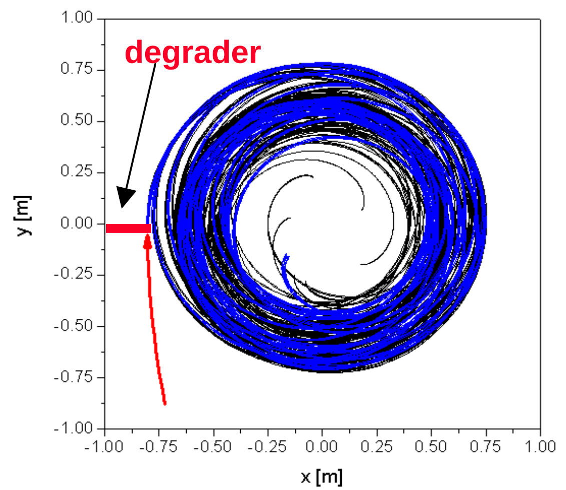
Linear gas cells are used at NSCL and RIKEN to stop fast fragmentation beams, but they have limitations at high beam rates, short half-lives, and low stopping power (light ions)

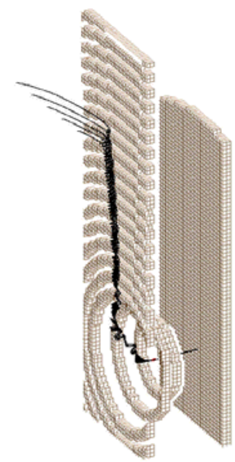
→ Need R&D combined with system performance evaluation

→ Plan for two beam lines with momentum compression and gas stopping

Cyclotron gas stopper project (NSCL/MSU)
– Gas-filled cyclotron magnet combined with RF ion guiding techniques



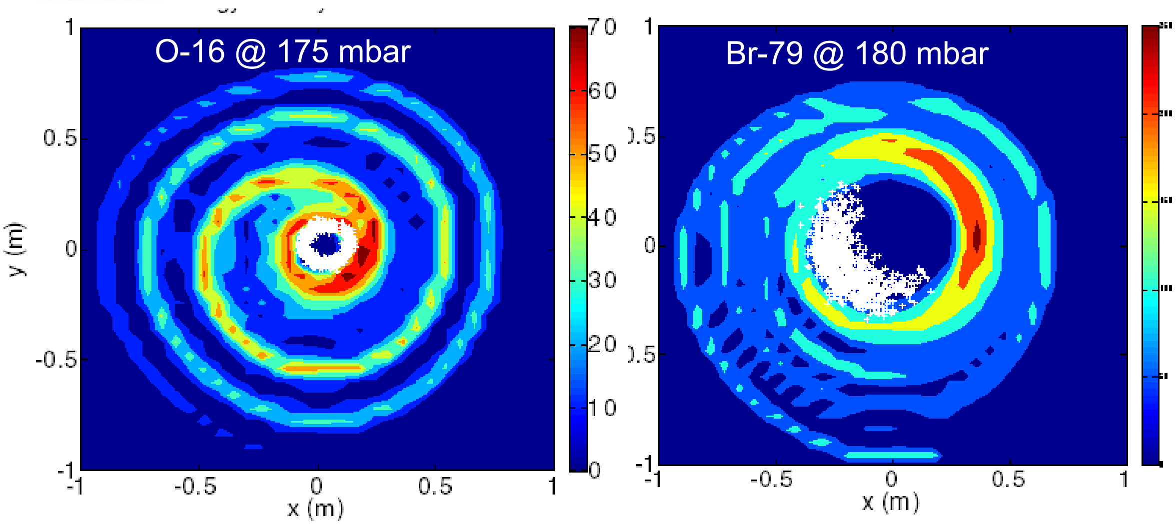


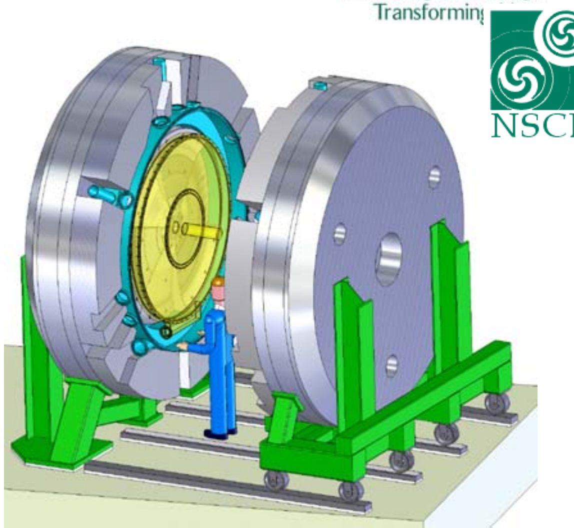


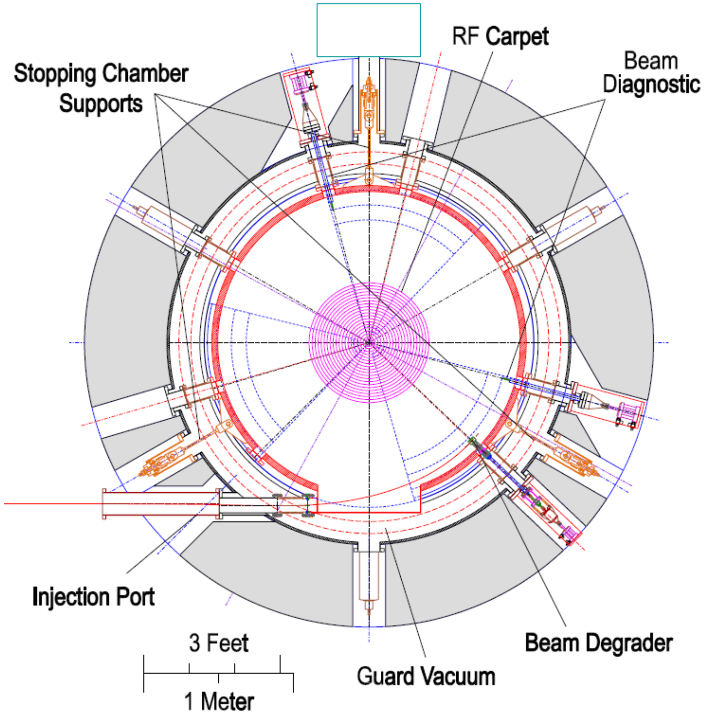
Expected benefits:
- Higher stopping efficiency
- Faster beam extraction
- Higher beam-rate capability

G. Bollen, D.J. Morrissey, S. Schwarz, NIM A550 (2005) 27
C. Guénaut et al., Hyperfine Interactions 173 (2006) 35
G. Pang et al., Proc. PAC07, 2007

Cyclotron Gas Stopper







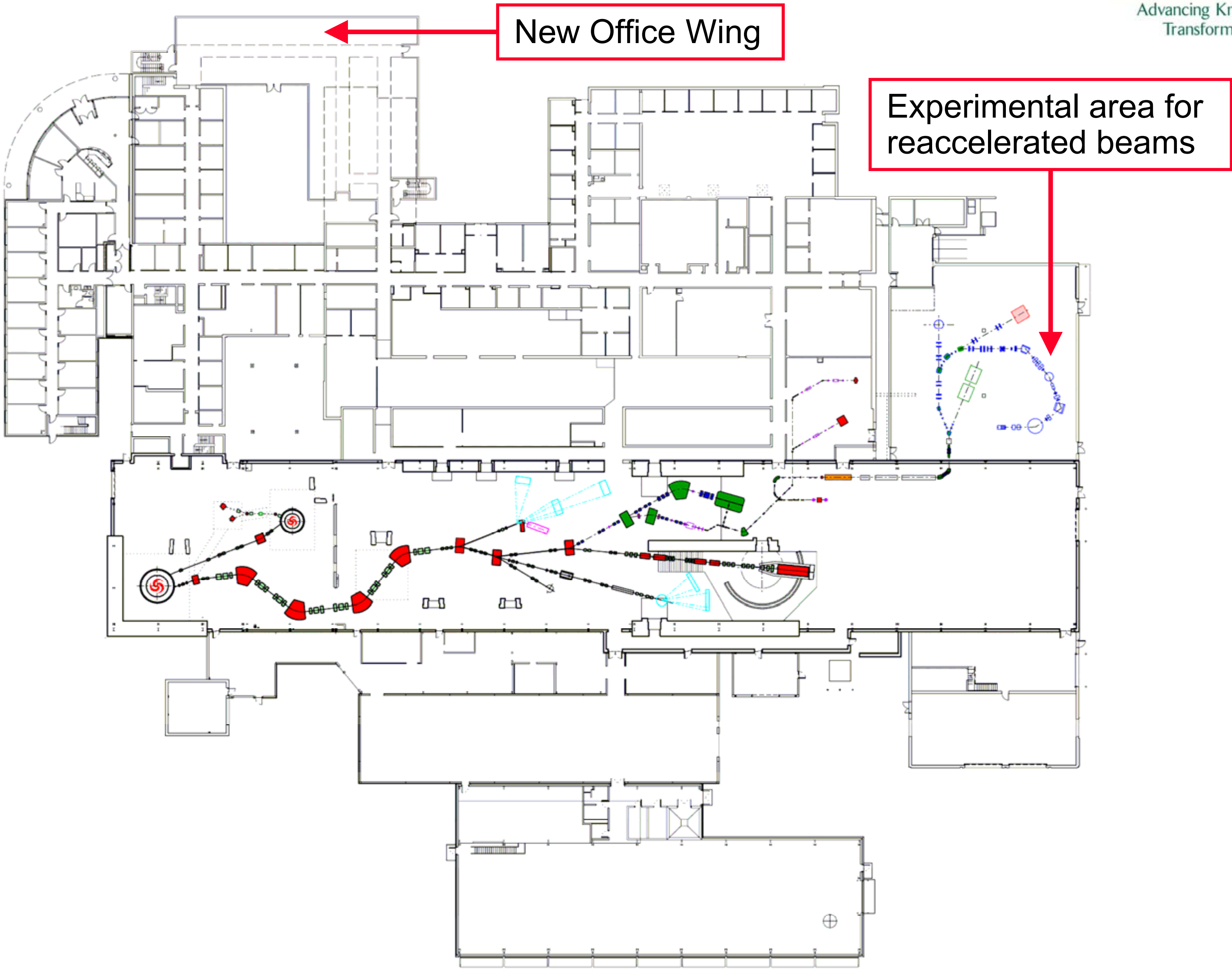
Best system for light and medium-heavy isotope beams

- Higher beam rate capability than linear stoppers
- Extraction times well below 50 ms

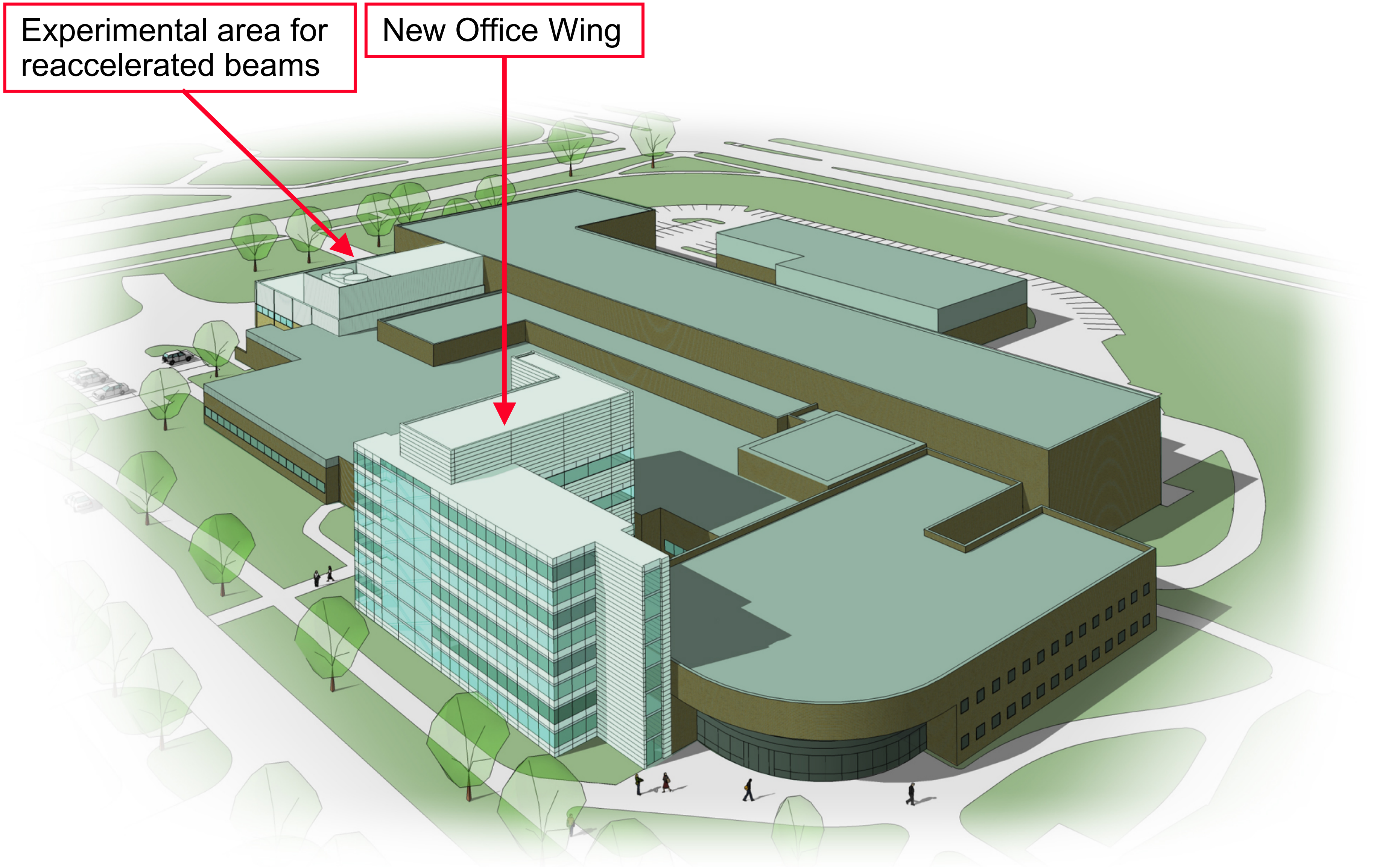
Extensive simulations to evaluate and optimize performance – incorporating

- Electromagnetic forces
- Stopping power, energy and angular scattering
- Evolution of charge states (largest uncertainty)

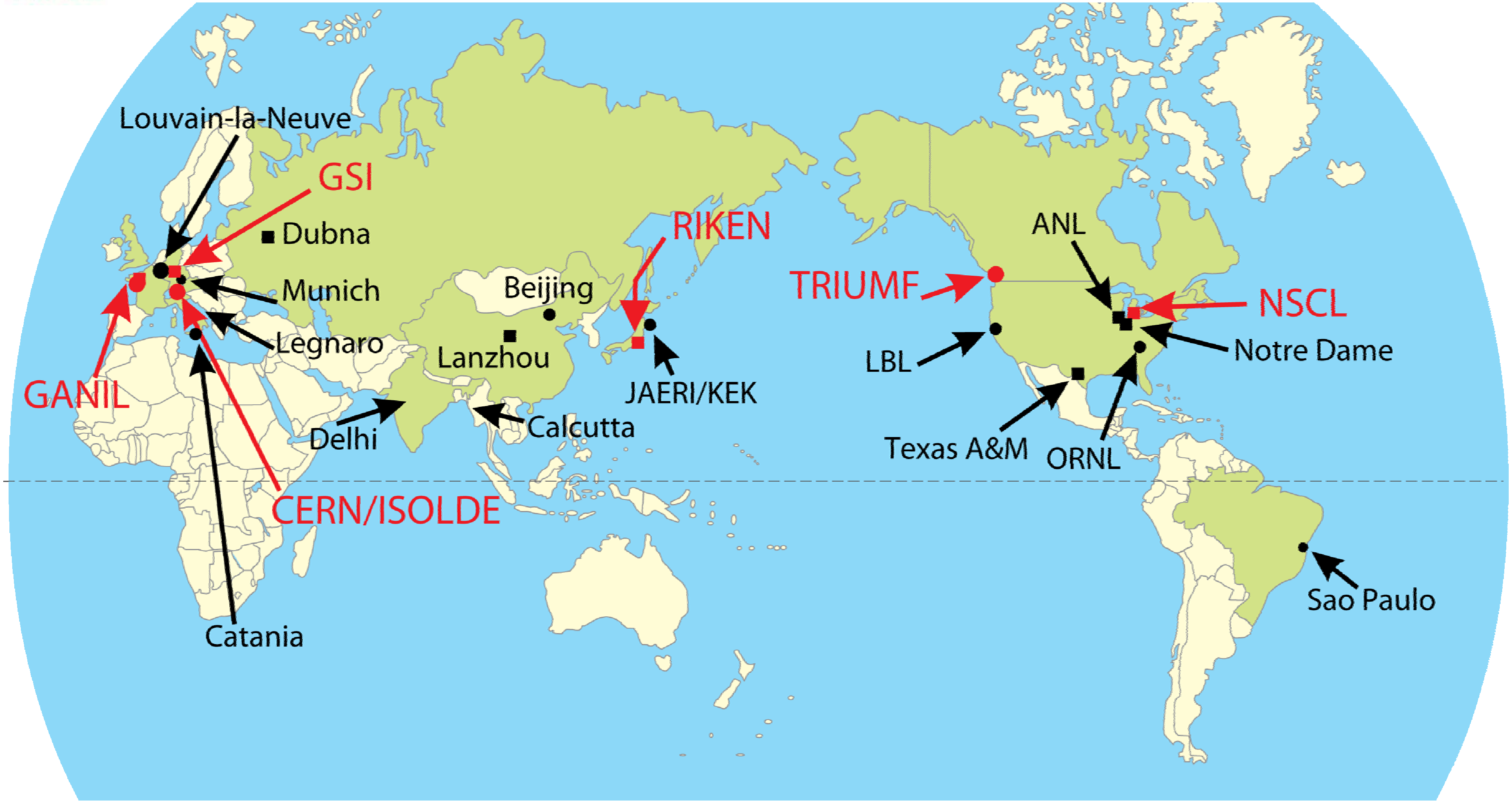
NSCL Ongoing Building Additions



How NSCL will look in a year from now



Rare Isotope Beam Capabilities Worldwide



The research opportunities with intense beams of rare isotopes are now widely recognized, and major investments into advanced RIB capabilities are being made world-wide: GANIL, GSI, RIKEN, TRIUMF, …

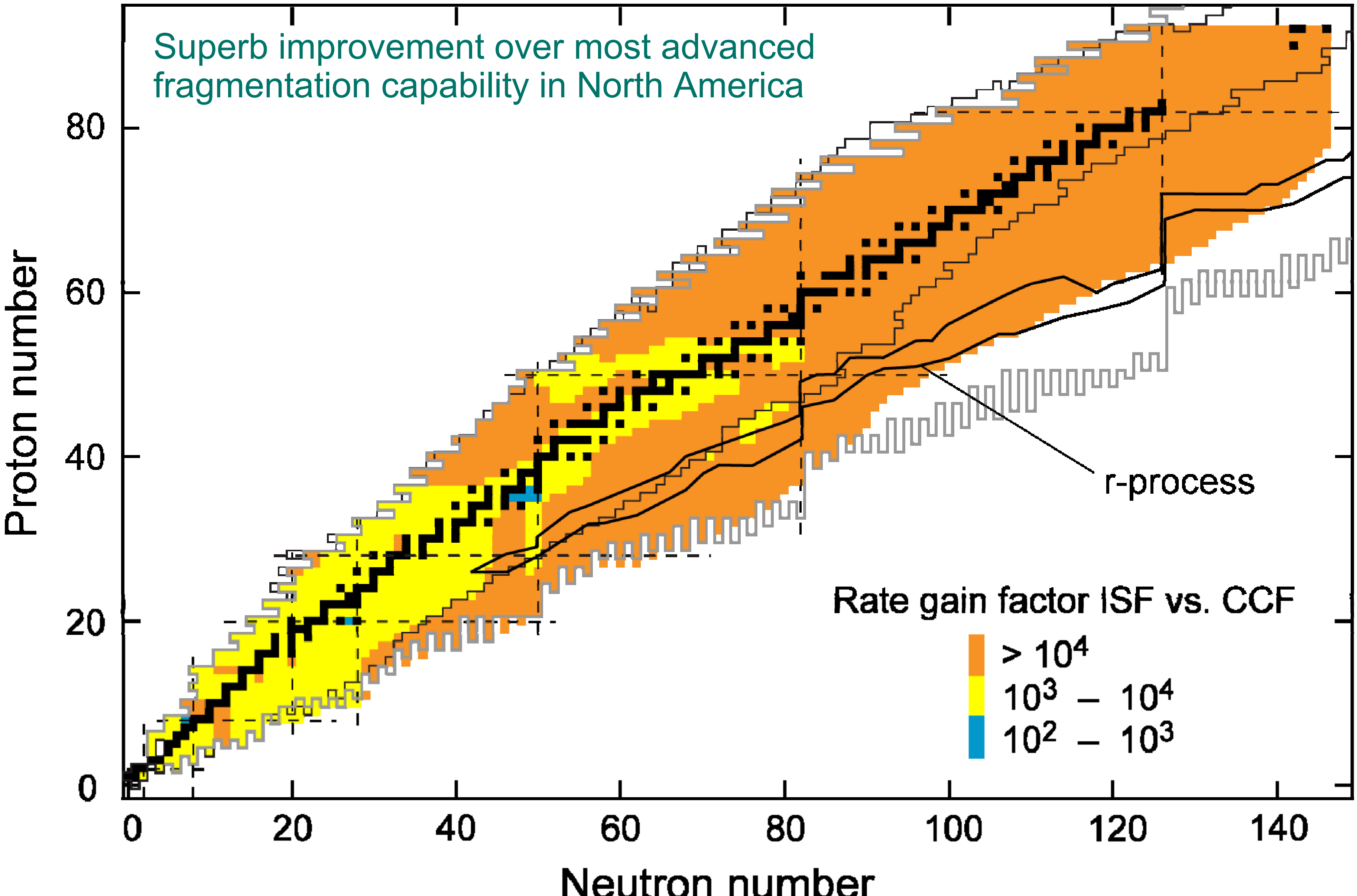
NSCL Long-Range Vision

"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



Ongoing Competition

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**

Why FRIB at NSCL

- NSCL is a leading rare-isotope research facility
  - It makes sense to make use of MSU's existing infrastructure in human and material resources
- One of the few university-based national user facilities
  - Largest nuclear physics faculty in the U.S.
  - Open academic environment offers best synergy between 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 – high user satisfaction
- Excellent prospects for the near-term (5-10 years) future
  - Significant investment by MSU into ReA3 reaccelerator project
- An upgrade with a 200 MeV/nucleon driver linac is needed to keep NSCL viable beyond 2017
  - Needed for continued hands-on education of nuclear science work-force via best possible synergy of education and research