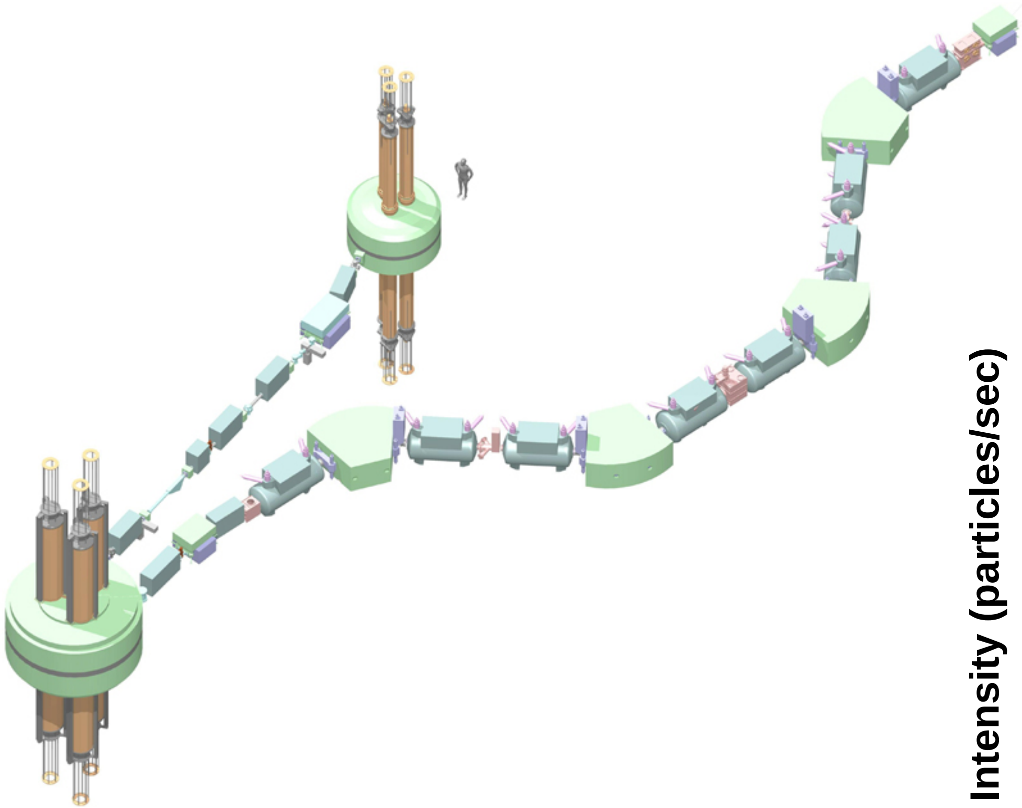
National Superconducting Cyclotron Laboratory

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

280 employees, incl. 41 undergraduate and 52 graduate students, 24 faculty (+ 3 open faculty positions)

New CCF user group formed in 2001: 700 registered members (439 from 101 US institutions, 261 from 113 foreign institutions and 35 countries) as of Feb. 17, 2006

Key Elements of Coupled Cyclotron Facility

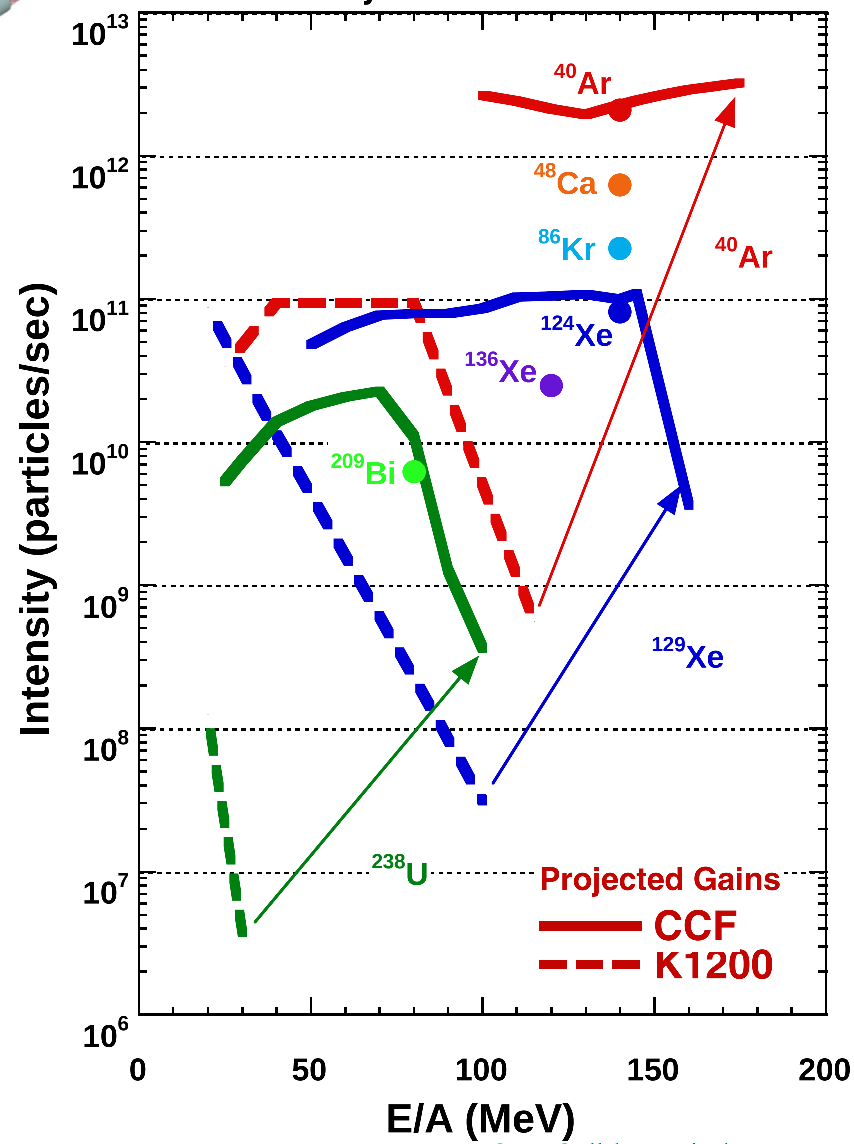


Coupling of superconducting K500 and K1200 cyclotrons provides large intensity gains

Additional gains in rare isotope beam intensities from superconducting A1900 fragment separator – the largest-acceptance fragment separator world-wide (technology adopted by RIKEN)

Completed in 2001 – on schedule and within budget

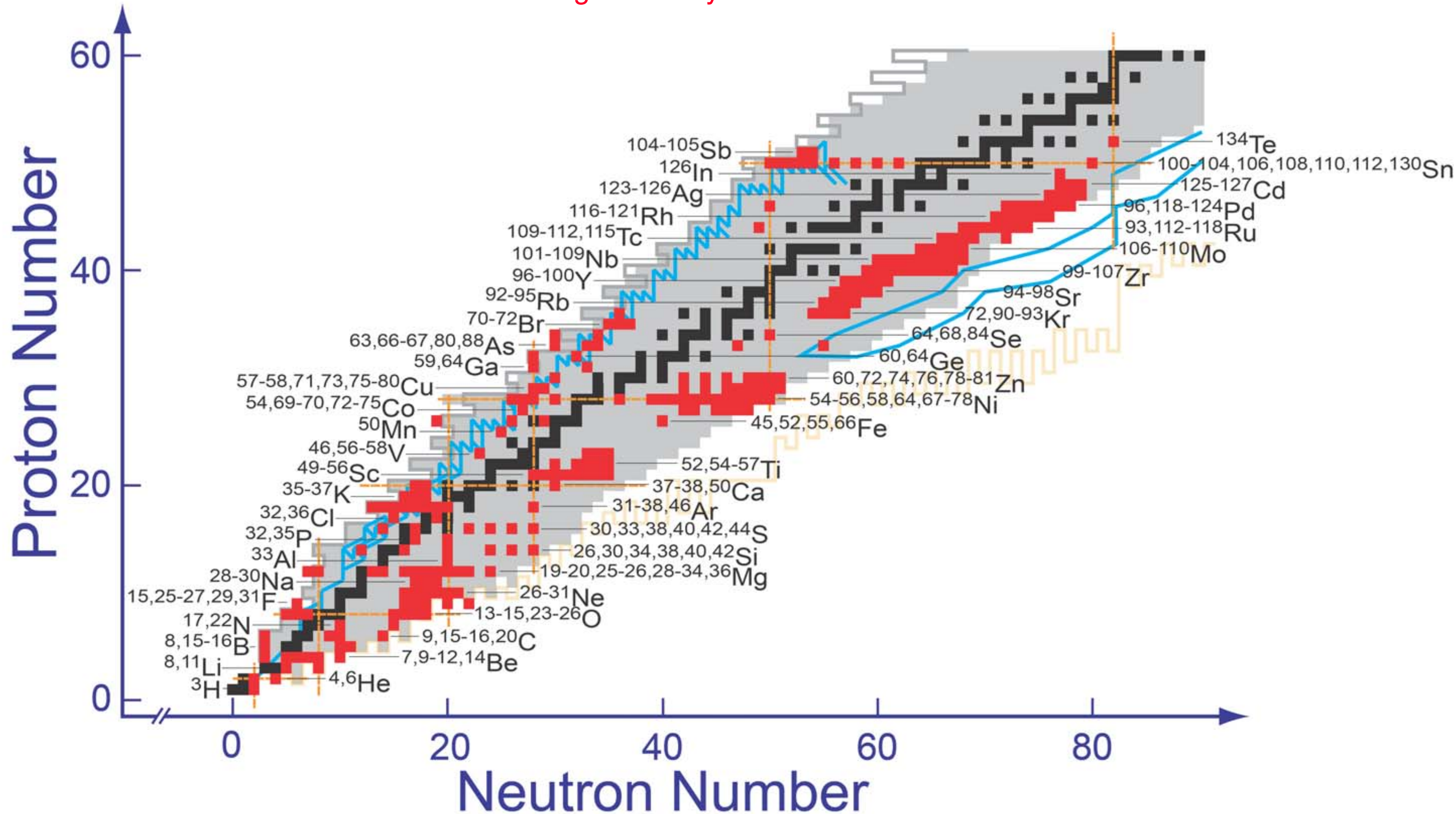
Projected gains in primary beam intensity: CCF vs K1200



Beams Produced with CCF/A1900

Research program requires large number of beam tunes

2001 through 2005: 503 invited talks by NSCL users and staff, 426 papers in refereed journals, including 68 in Physical Review Letters



Major Research Thrusts

- Production of nuclei with unusual ratios of protons to neutrons and the measurement of their properties

  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}Ni, ^{78}Ni, ^{100}Sn, ^{132}Sn…

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

  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 JINA

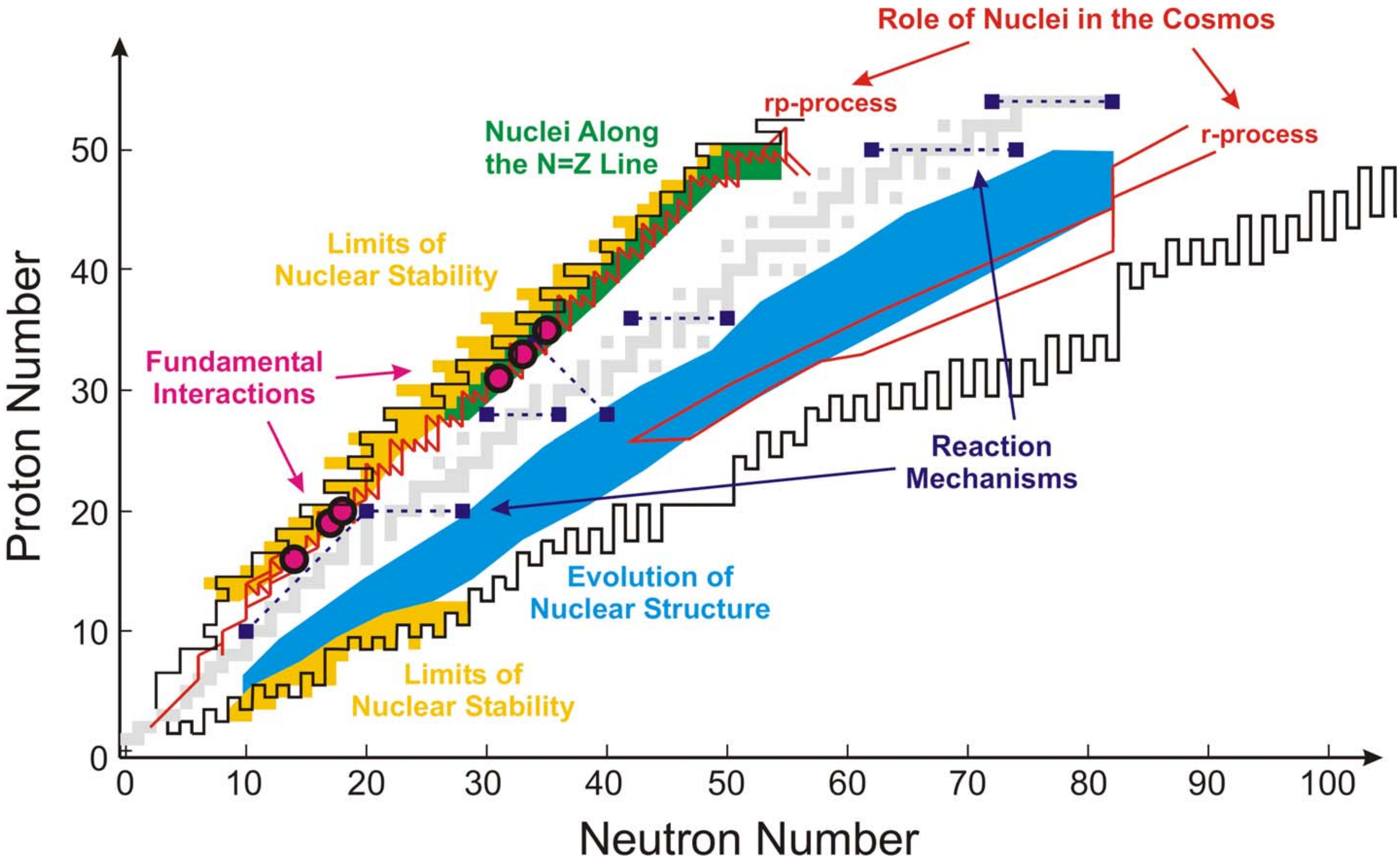
  What is the equation of state (EOS) of neutron-rich nuclear matter?

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

Alignment with 3 of the 5 key questions identified in the 2002 NSAC LRP: What is the structure of the nucleon? What is the structure of nucleonic matter? What are the properties of hot nuclear matter? What is the nuclear microphysics of the Universe? What will be the new Standard Model?

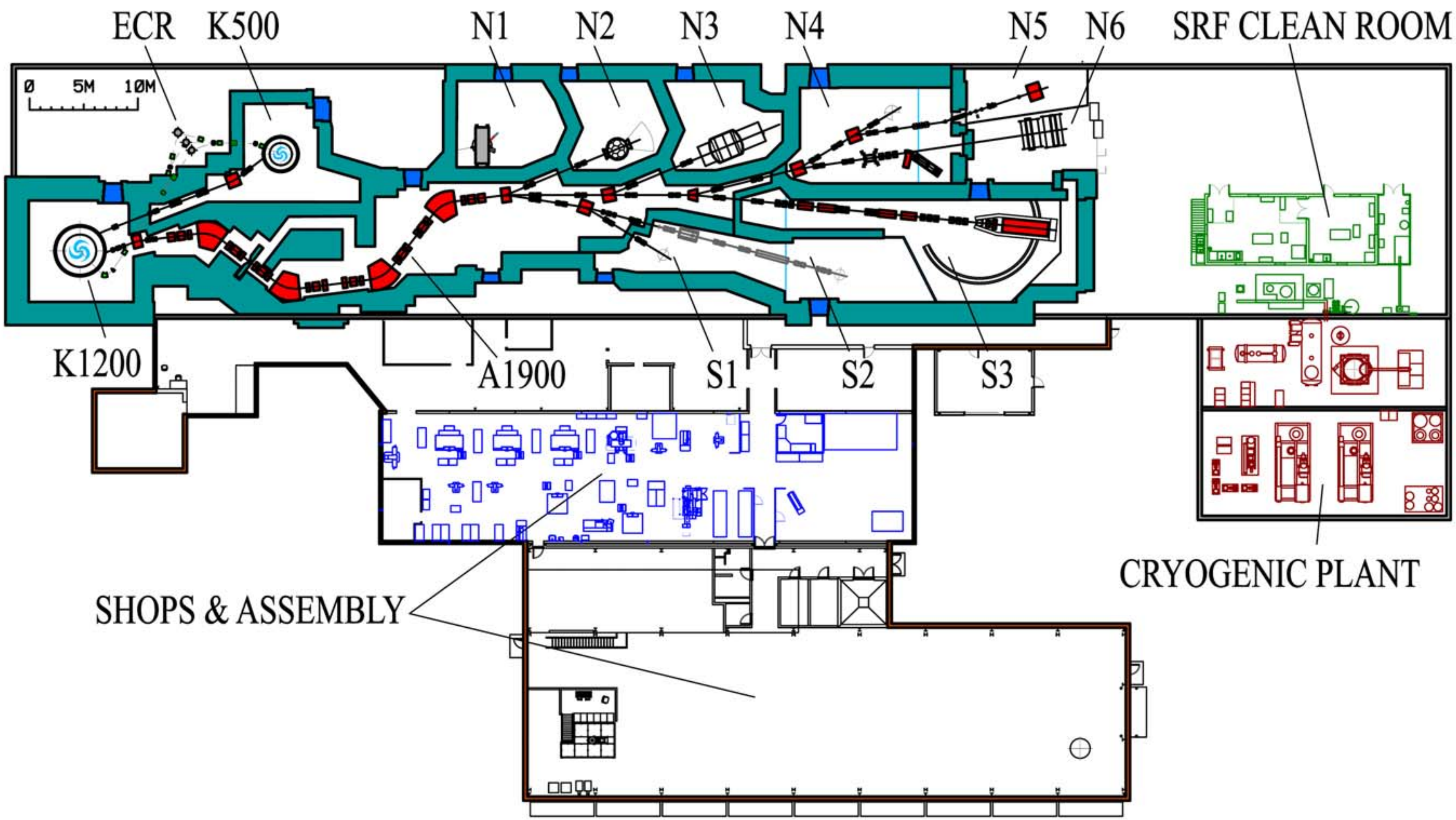
Scientific Program

With CCF running well, the 5-year perspective is superb



NSCL Technical Facilities

State-of-the-art apparatus: A1900 fragment separator, 4π-Array, 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, …



Attractive Features of Fast Beams of Rare Isotopes

produced by projectile fragmentation or fission and separation in flight

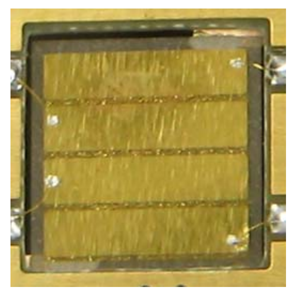
- Economic production of medium-energy (E/A > 20 MeV) beams of rare isotopes, without reacceleration
- Chemistry-independent separation and transport to experiment
  - Short beam development times
  - Negligible losses from decay (separation and transport in microseconds)
- Increased luminosity from use of thick secondary targets (typical factors of 10^3-10^4)
  - Enhanced scientific reach
- Reduced background from beam tracking
  - Use of particle tagging and cocktail beams
- Efficient particle detection from strong forward focusing

Diamond Detectors for Particle Tracking

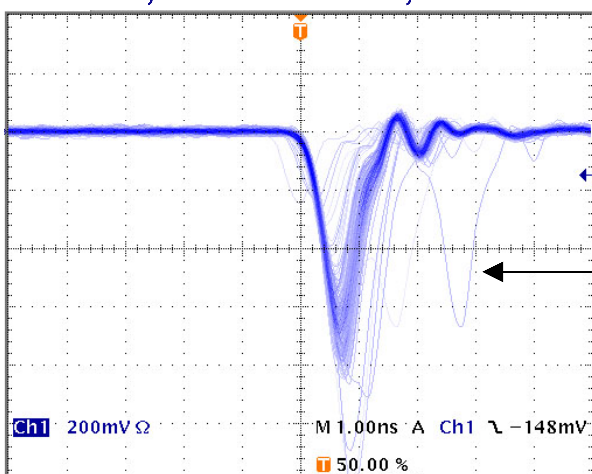
Development of ultra-fast, radiation-hard detectors for timing and particle tracking made from single-crystal diamond. Diamonds are grown by chemical vapor deposition (CVD) on iridium at MSU's Keck Microfabrication Facility.

Detector successfully tested up to particle rate of $5 \cdot 10^7$ /s

tracking detector (10x10 mm)

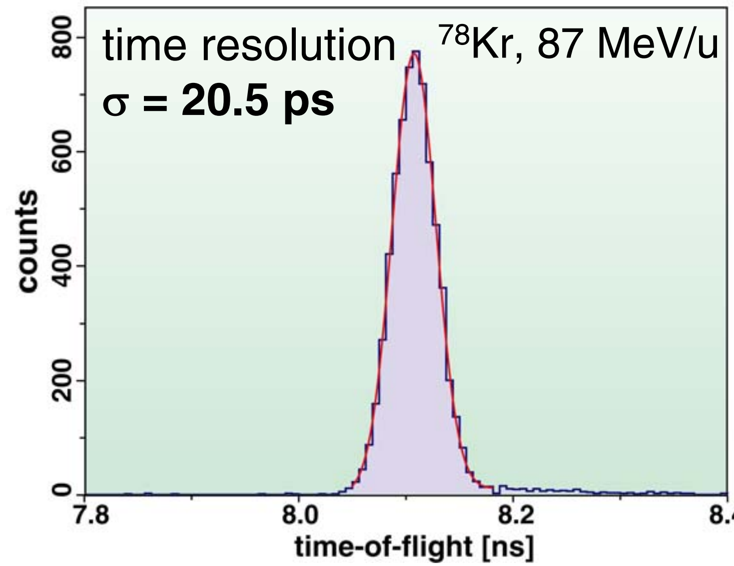


^{76}Ge, 100 MeV/u, 10^6 /s



2nd particle within one cyclotron extraction pulse

signal risetime: ~ 0.5 nsec

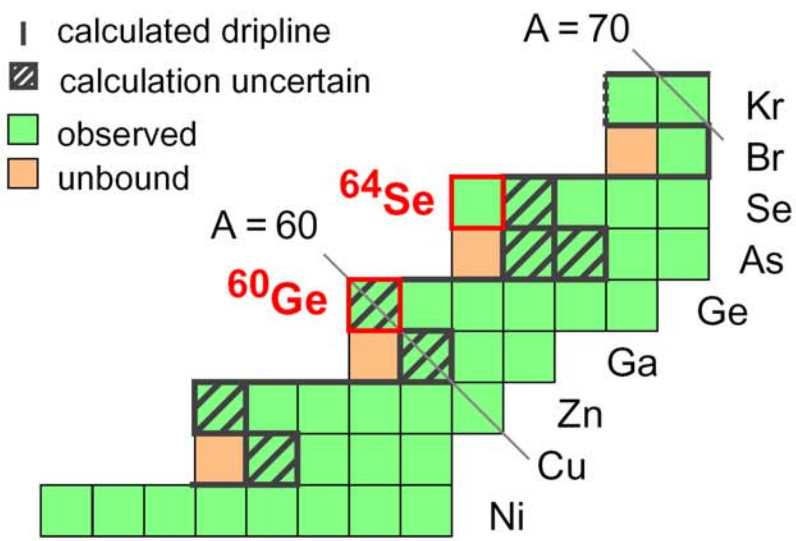


Intrinsic detector resolution: σ = 15 ps

A. Stolz et al., Diamond & Related Material, in press

First Observation of ^{60}Ge and ^{64}Se

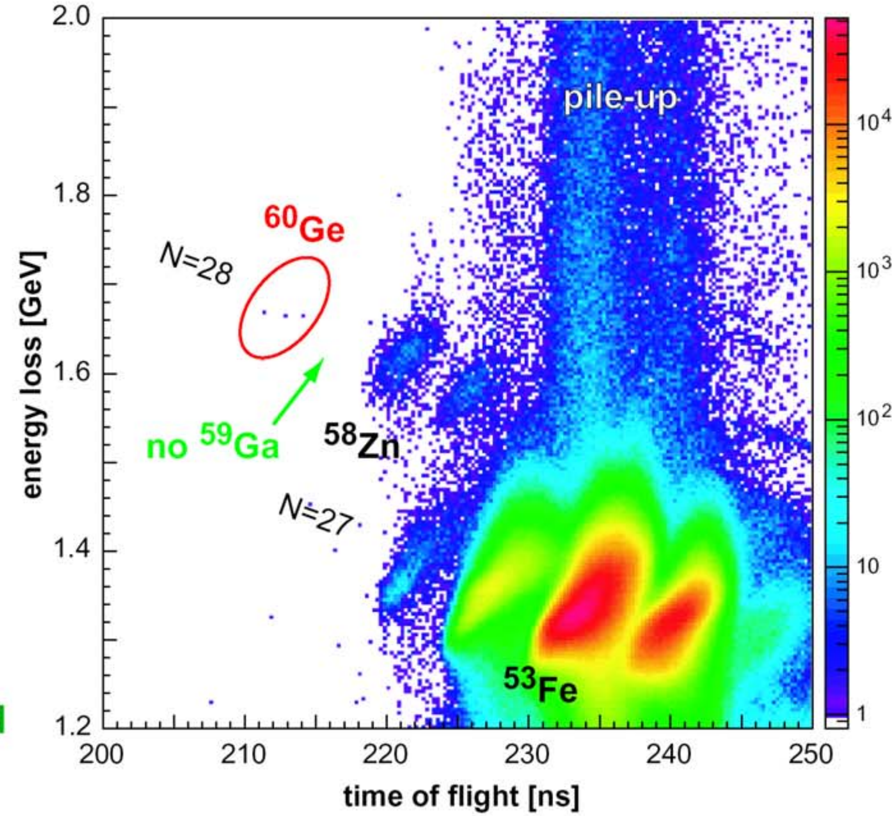
A. Stolz et al., Phys. Lett. B 627 (2005) 32



Particle identification plot in A1900

primary beam: ^{78}Kr, 140 MeV/u

target: ^{9}Be, 610 mg/cm2



3 events of ^{60}Ge, 4 events of ^{64}Se observed

^{60}Ge is heaviest N=28 isotone

half-life limits:

$T_{1/2}(^{60}\text{Ge}) > 110$ ns, $T_{1/2}(^{64}\text{Se}) > 180$ ns

cross sections (< 1 pb) smaller than expected

Non-observation of ^{59}Ga and ^{63}As

half-life limits: $T_{1/2}(^{60}\text{Ge}) < 40$ ns

Coulomb Excitation of ^{72}Kr

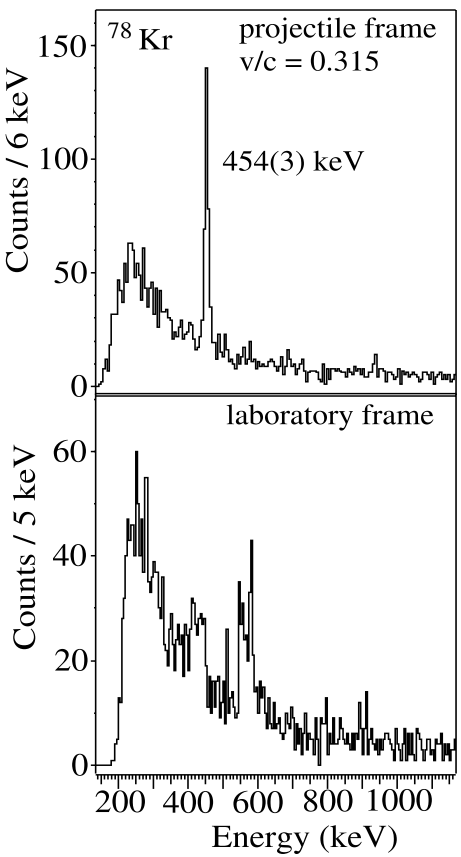
A. Gade et al., Phys. Rev. Lett. 95, 022502 (2005)

Heaviest N=Z nucleus for which $B(E2;0_1^+ \rightarrow 2_1^+)$ has been measured

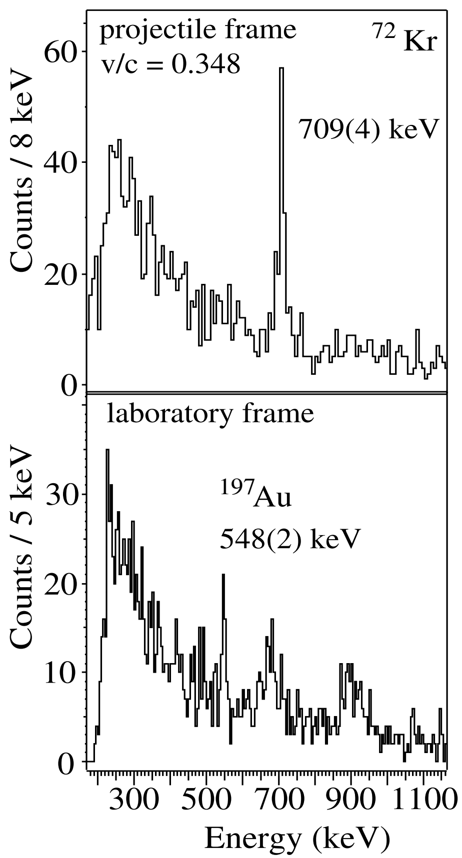
$B(E2;0_1^+ \rightarrow 2_1^+)$ = 5000(650) e^{2}fm^4

Comparison to theory → oblate ground state, |β| = 0.33

Test case: ^{78}Kr



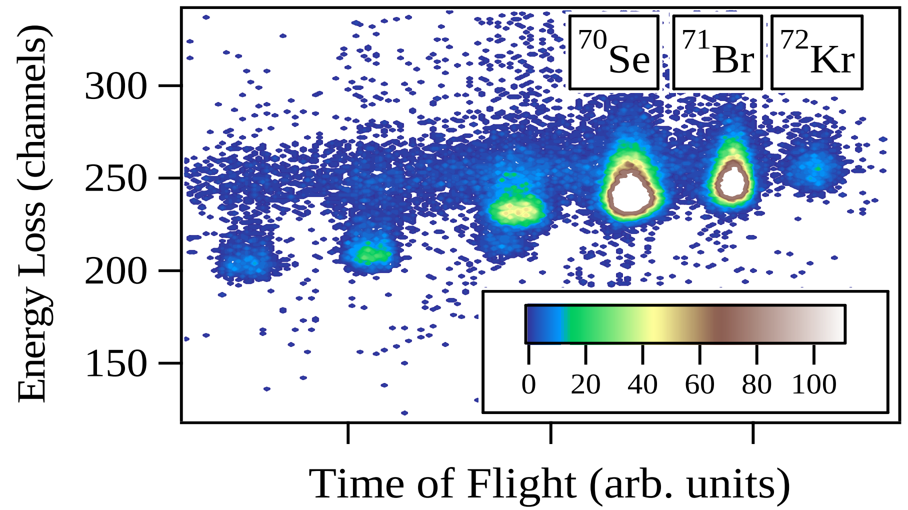
Measurement: ^{72}Kr



S800 + SeGA

Purity of ^{72}Kr beam was only 1.7%

- Event-by-event tracking with clean PID in S800
  - Improved purity with future RF separator (under construction)



Exploring ^{42}Si

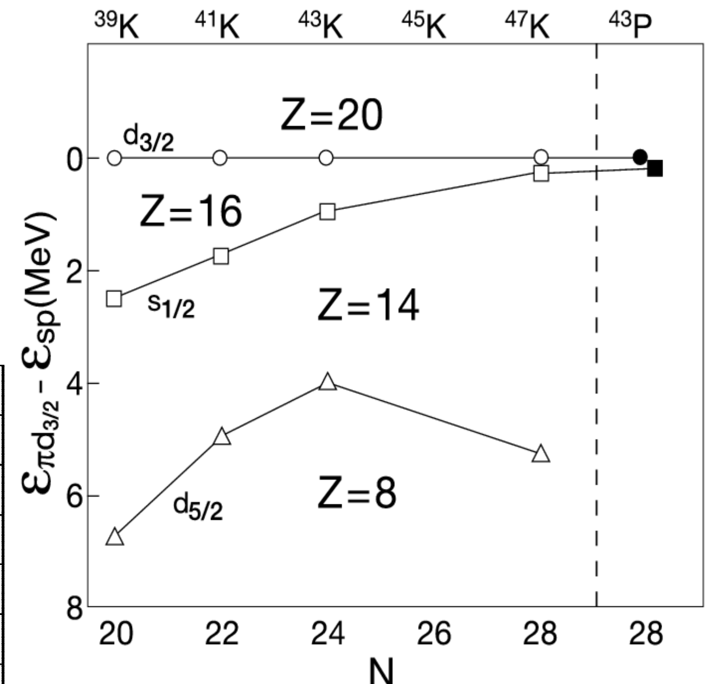
J. Fridmann et al., Nature 435, 922 (2005)

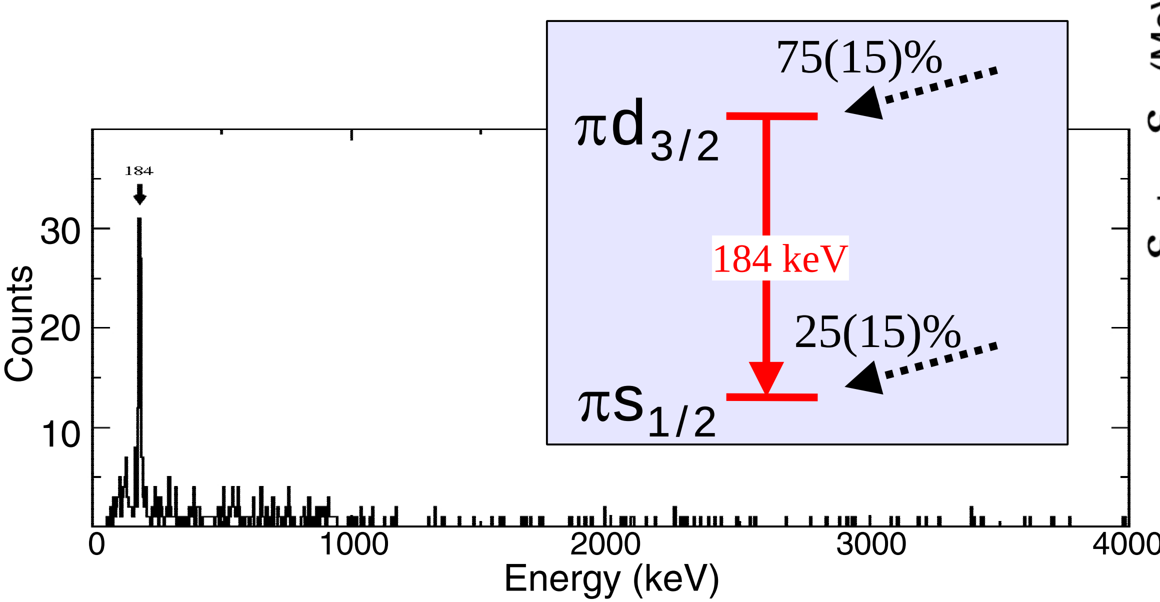
S800 + SeGA: $^{48}Ca \rightarrow {}^{44}S \rightarrow {}^{43}P$

Only one low-energy γ-ray transition is observed $\rightarrow$ near degeneracy of $\pi d_{3/2}$ and $\pi s_{1/2}$ states

Relative population of the two states determines that excited state has higher orbital angular momentum $\rightarrow$ ordering of the $\pi d_{3/2}$ and $\pi s_{1/2}$ states

Small 2p-knockout cross section to ^{42}Si
$\rightarrow$ Z=14 gap persists for N = 28 at ^{43}P

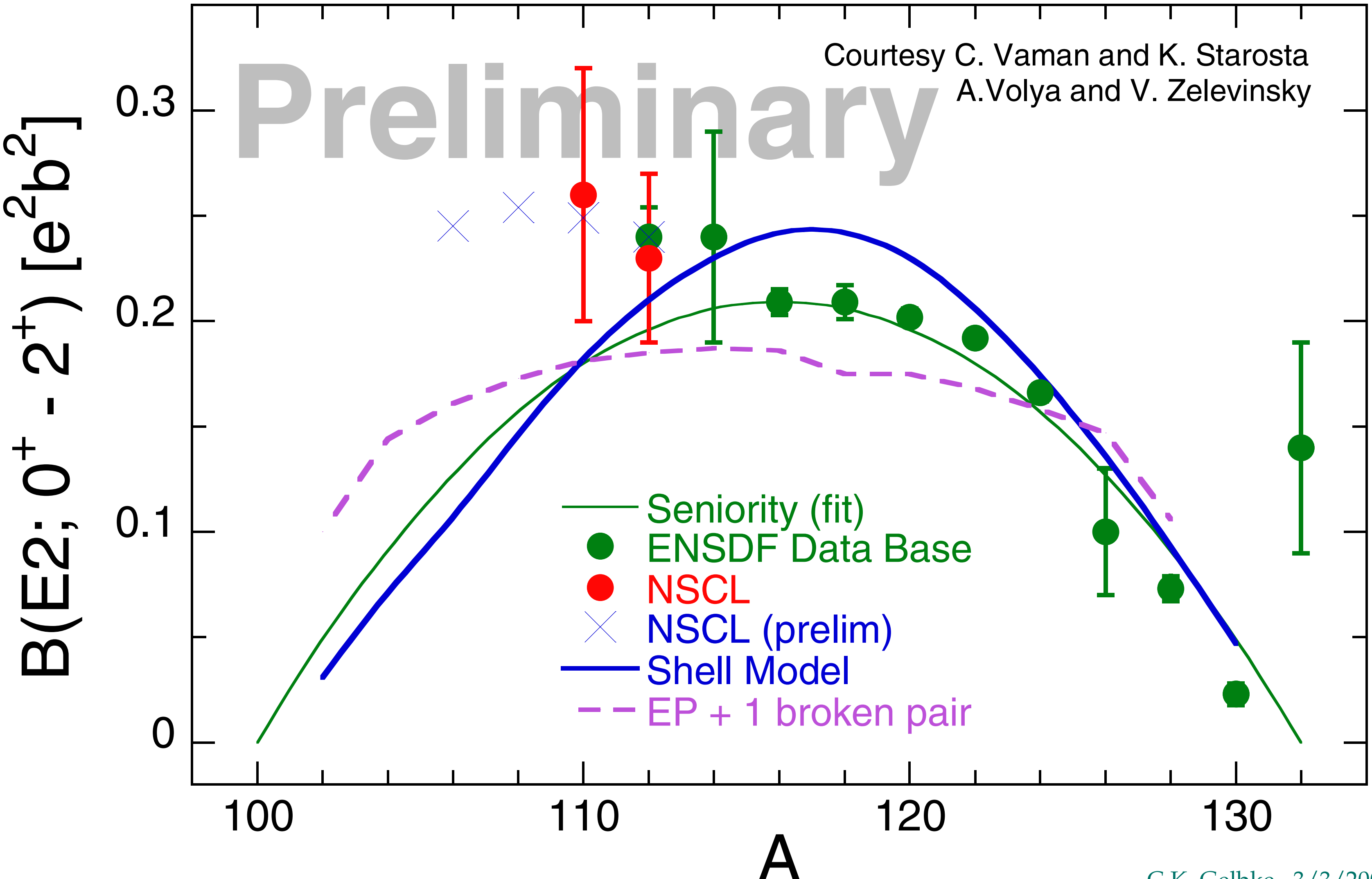




Breaking of Z=N=50 Core Near ^{100}Sn?

Coulex of neutron-deficient Sn isotopes

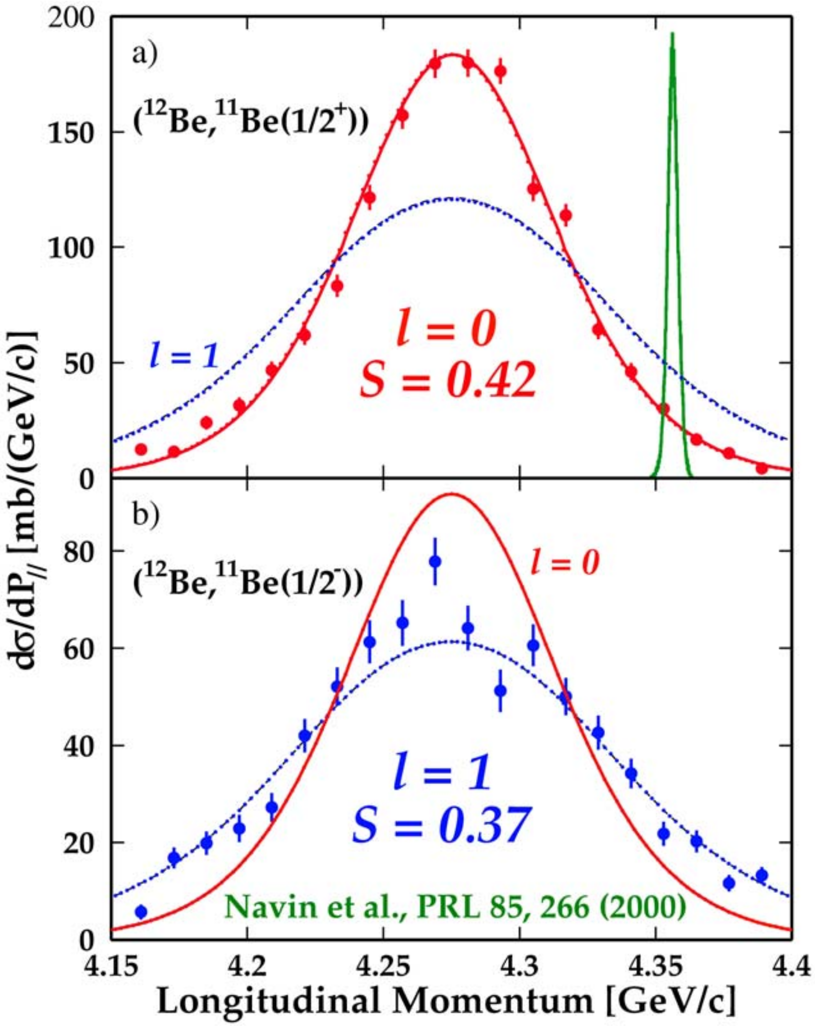
Emerging discrepancy: do we need to open the proton space near ^{100}Sn
or do we need to improve the effective interaction?

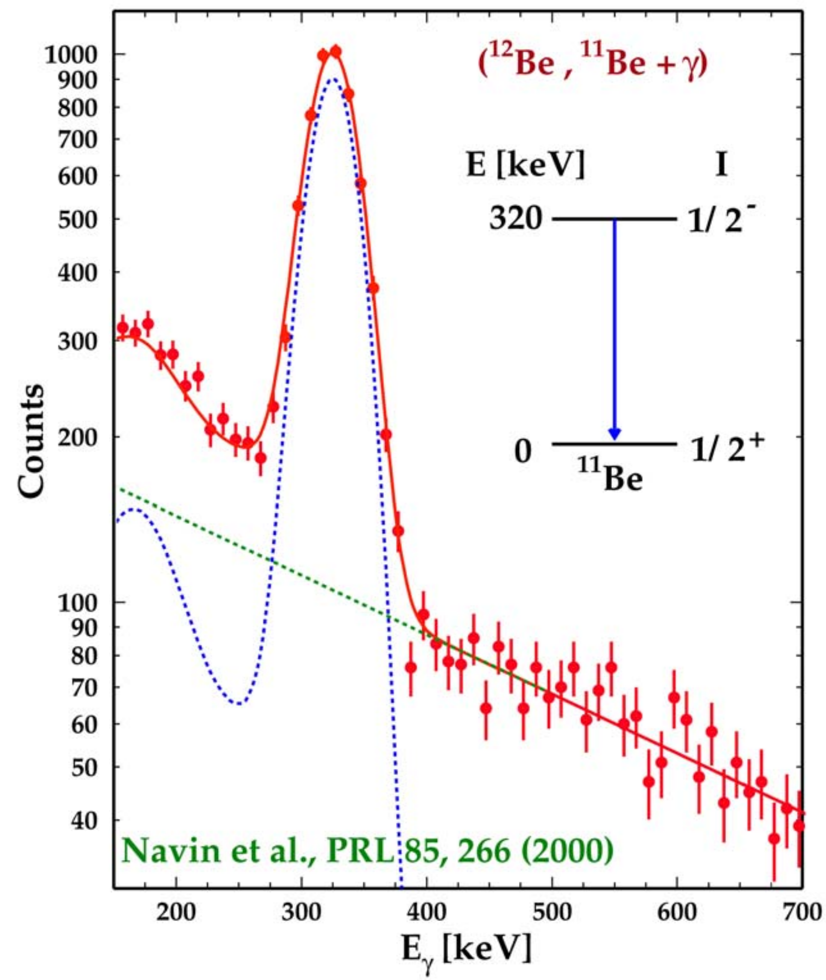


Nuclear Spectroscopy with Knockout Reactions

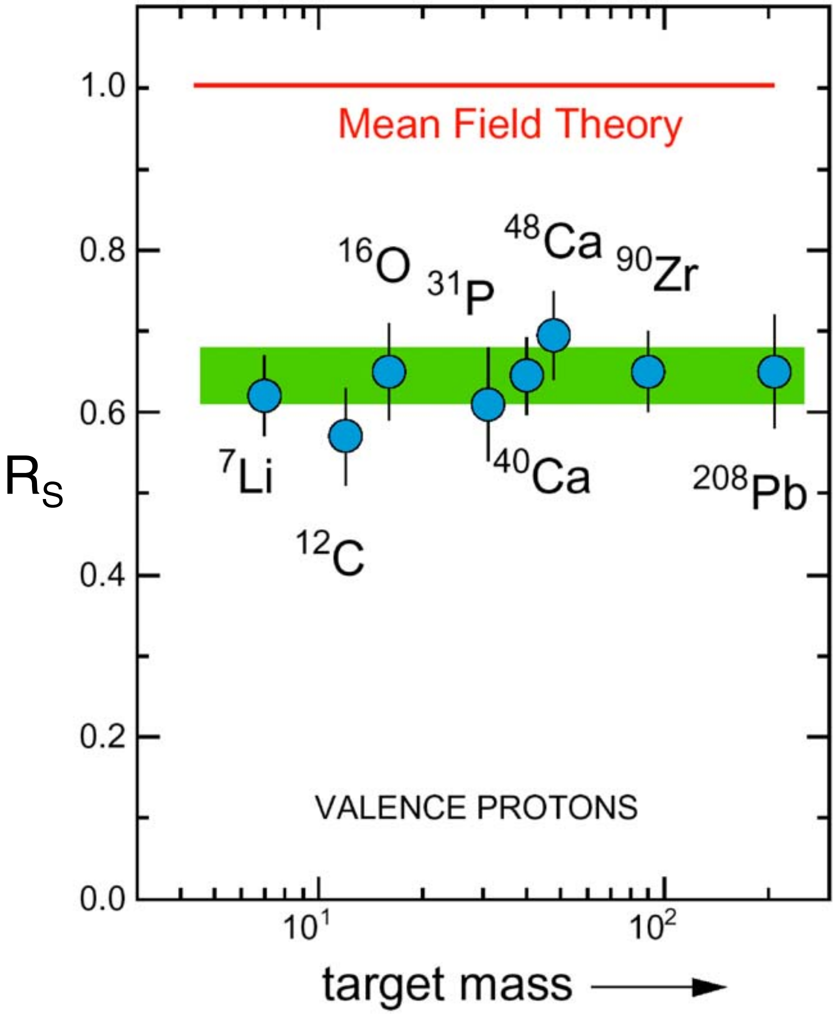
Different $P_{||}$-distributions for individual states, tagged by γ-rays: cross section is sensitive to wavefunction; shape identifies l of knocked-out nucleon

→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 and coupling to vibrational excitations): Beyond effective interactions employed in shell model and mean-field approaches. Occupancies will be modified.

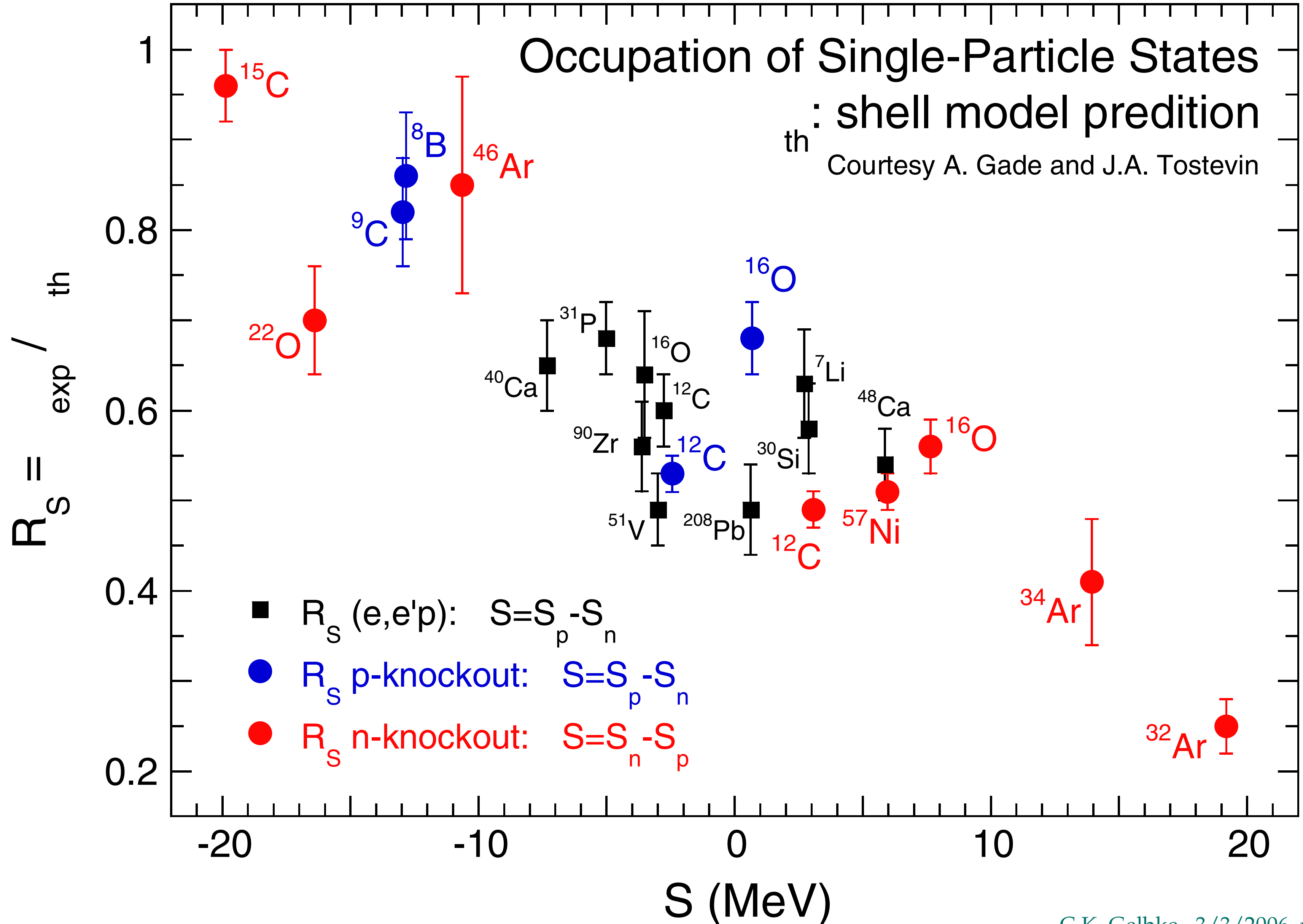
Reduction factor with respect to the shell model:

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

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

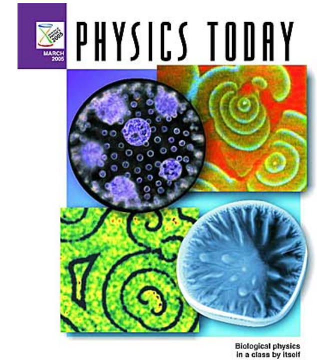
V. R. Pandharipande *et al*, Rev. Mod. Phys. **69**, 981 (1997)
W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci. **52**, 377 (2004).

Expanded Purview from Rare Isotopes



MoNA (Modular Neutron Array)

MSU, FSU, Marquette U., Central Mi. U., Concordia College at Moorhead, Hope College, Indiana U. South Bend, Wabash College, Western Mi. U., Westmont College



T. Feder, Physics Today March 2005, p.25

Issues and Events

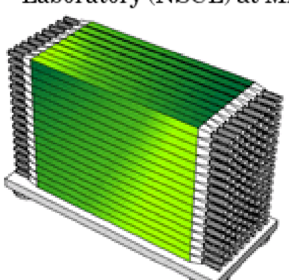
Undergraduates Assemble Neutron Detector

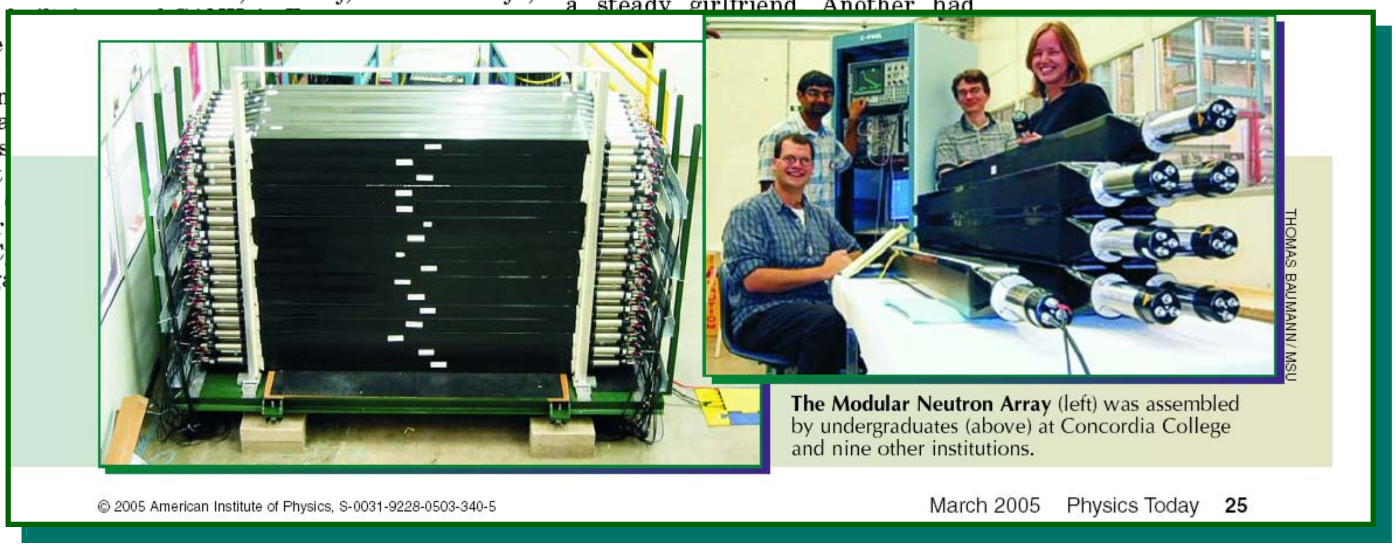
Spreading the construction of a detector across several institutions brings project visibility to participants.

"The undergraduates come running." So says Ruth Howes about student participation in the Modular Neutron Array, or MoNA, a detector large part by undergraduate majors. Howes, chair of the department at Marquette Ur in Milwaukee, Wisconsin, sa unusual and significant that can work on MoNA without their home institutions. The was installed last summer National Superconducting C Laboratory (NSCL) at Michiga

The facilities offering the biggest competition for MoNA, he adds, are GSI in Darmstadt, Germany, RIKEN in Tokyo,

rectly through their physics departments. "Increasingly, undergraduate physics departments are seeing nontraditional students," says Howes. "One of my undergraduates had been a funeral director. He was 30 and had a steady girlfriend. Another had



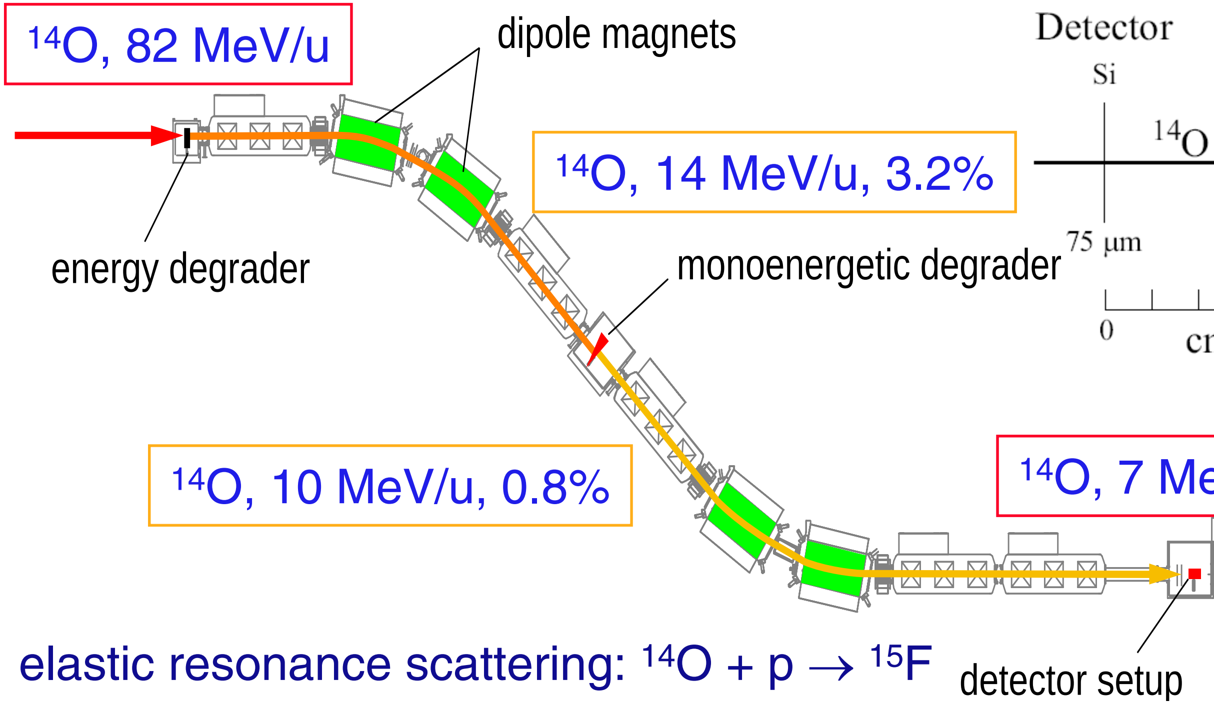


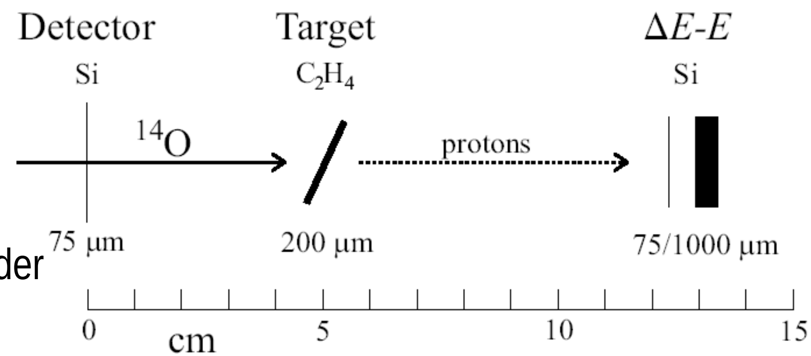
The Modular Neutron Array (left) was assembled by undergraduates (above) at Concordia College and nine other institutions.

"At NSF, the MoNA collaboration is considered a big success" (Brad Keister, NSF Program Director)

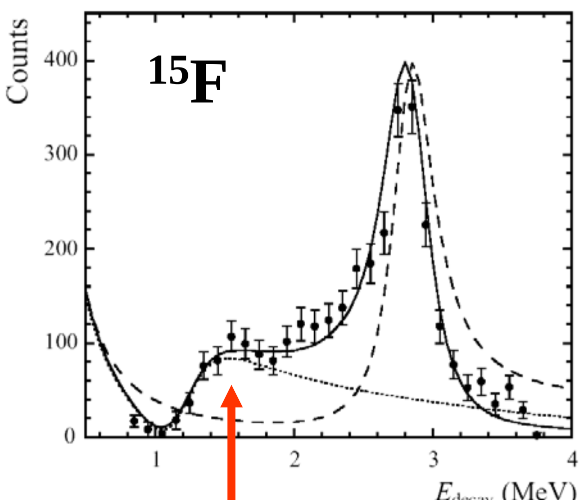
"That's what NSF is about" (Bob Eisenstein, NSF Assistant Director in 2001)

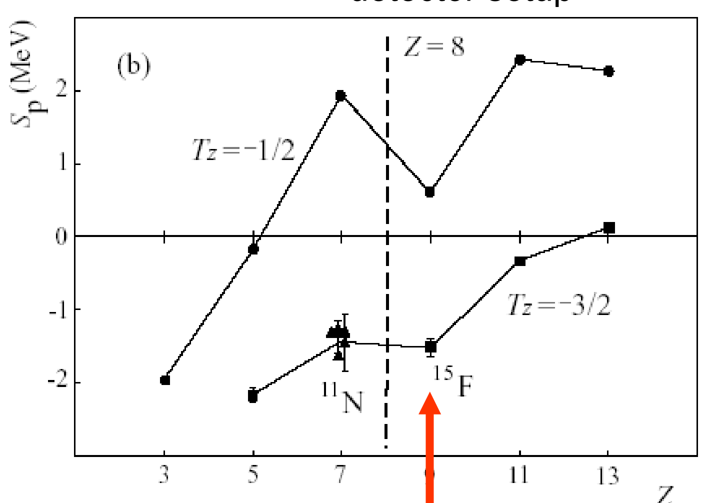
Momentum Compression of Fragmentation Beams





elastic resonance scattering: ^{14}O + p → ^{15}F





W.A. Peters et al., Phys. Rev. C68, 034607 (2003)

Improved value for $E_{G.S.}$ →

Disappearance of the Z=8 Shell

NSCL Beta Counting System (BCS)

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

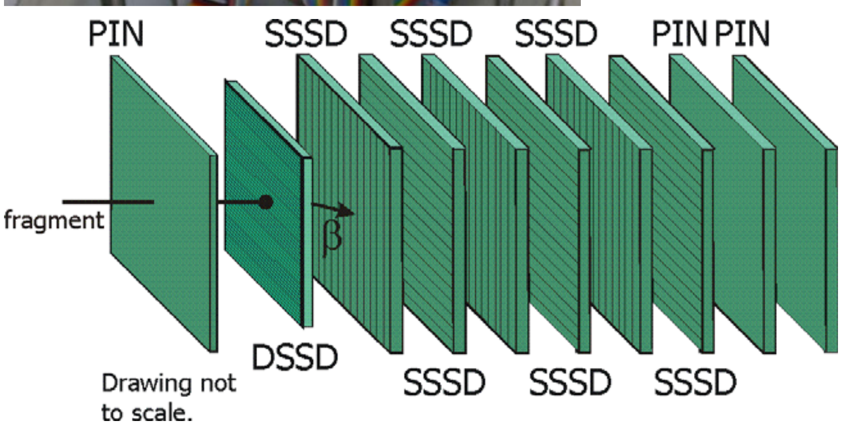
– Suited for use with cocktail beams

1 fragment implant detector:

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

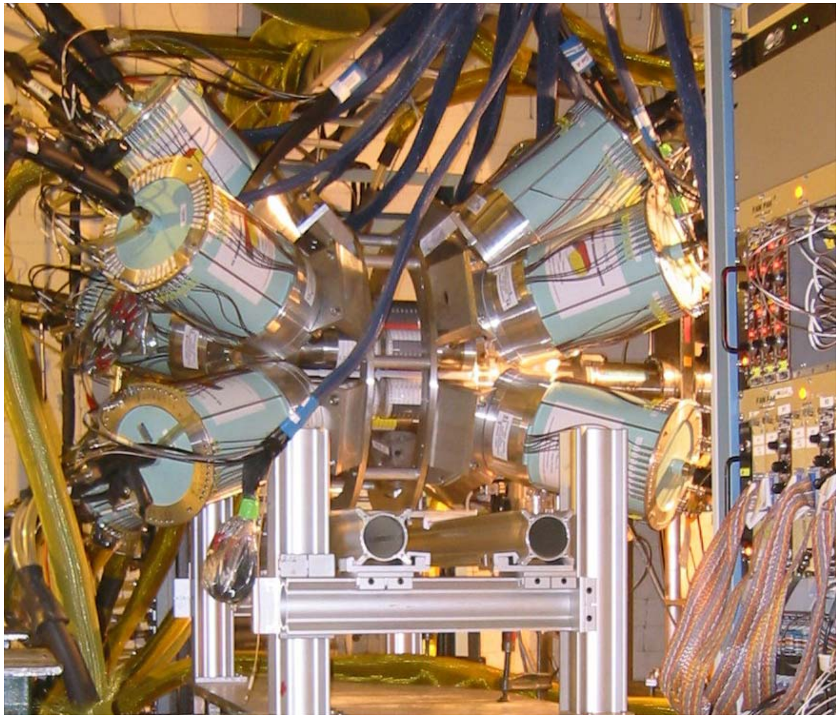
6 calorimeter detectors:

– 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

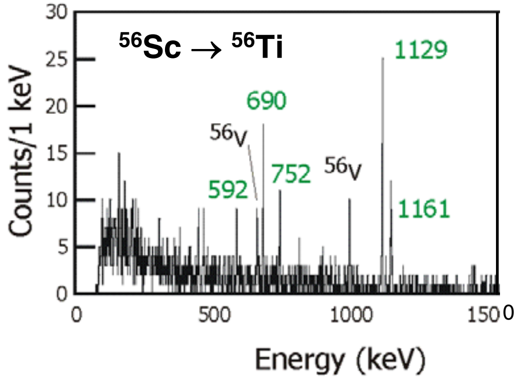


No N=34 Shell Gap for Ti Isotopes

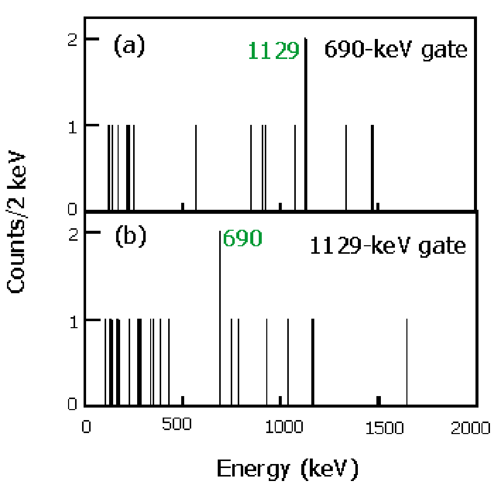
Shell model with GXPF1 effective interaction suggested that N=34 may become a magic number for Ca and Ti isotopes

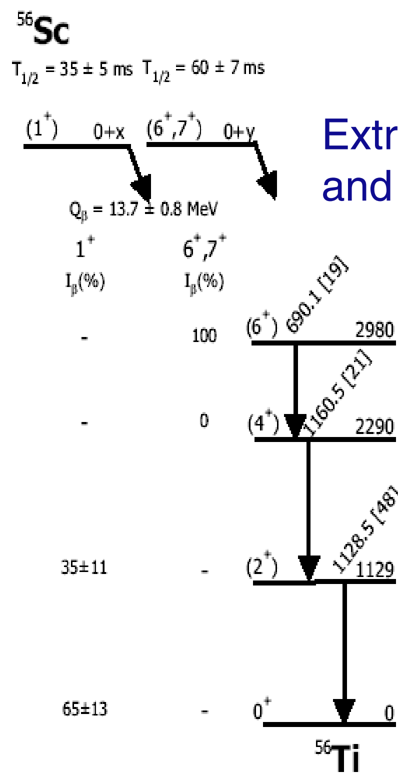
High-sensitivity experiment (0.05/s) reveals low value of $E(2^+)$ in ^{56}Ti, inconsistent with predicted shell gap

Delayed γ-ray spectrum

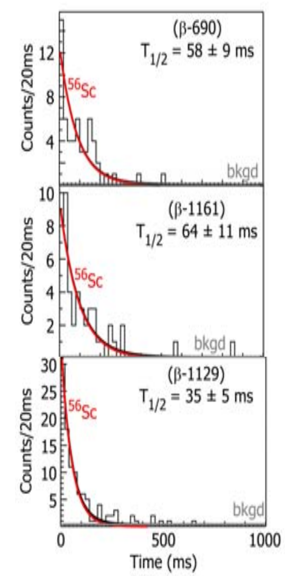


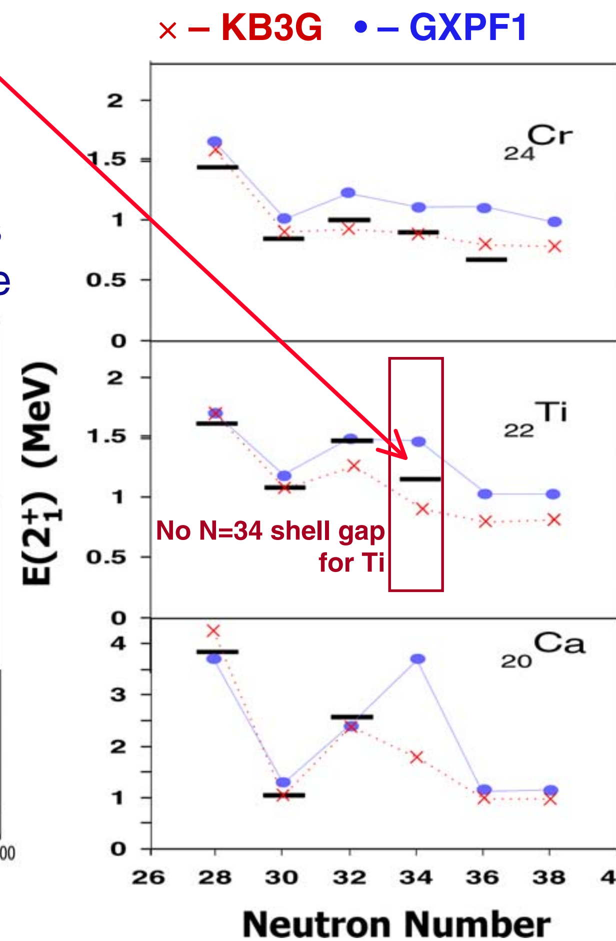
Coincidence spectra





Extracted lifetimes and decay scheme



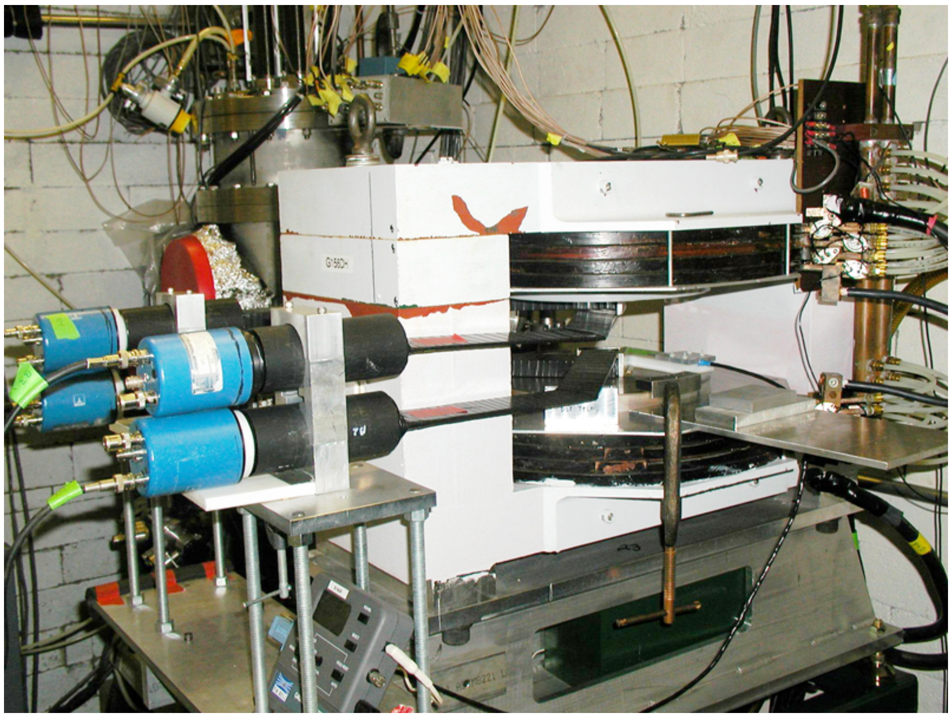


Liddick et al., PRL 92, 072502 (2004); PRC 70, 064303 (2004)

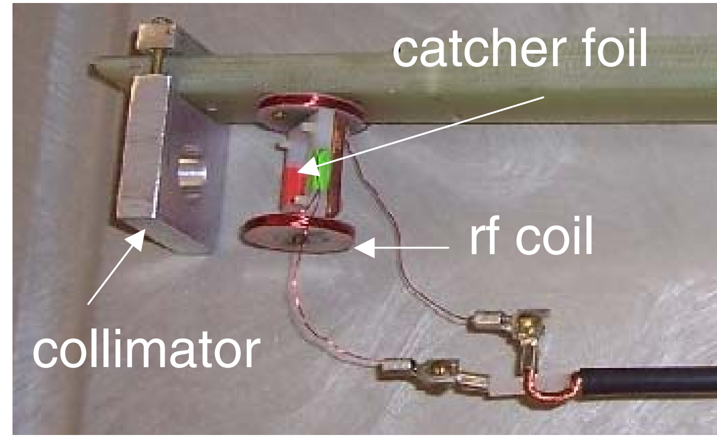
Beta-NMR Apparatus

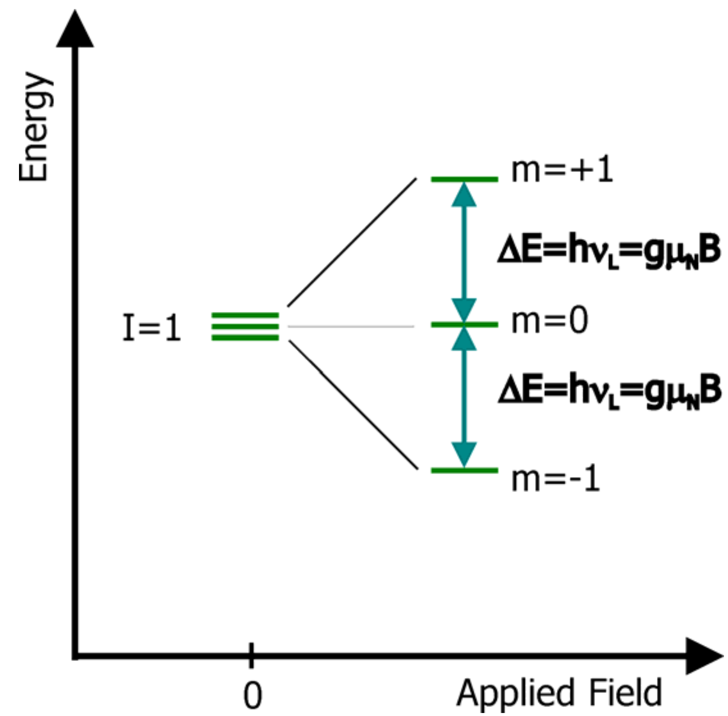
Small dipole magnet equipped with an rf coil and beta telescopes for nuclear moment measurements

- 10 cm magnet gap; B_{max} = 5000 Gauss, cooled catcher



Mantica et al., NIM A422, 498 (1999)





β angular distribution: $W(\theta) = 1+AP\cos\theta$

- Isotropy after pumping and equalization of m-state population

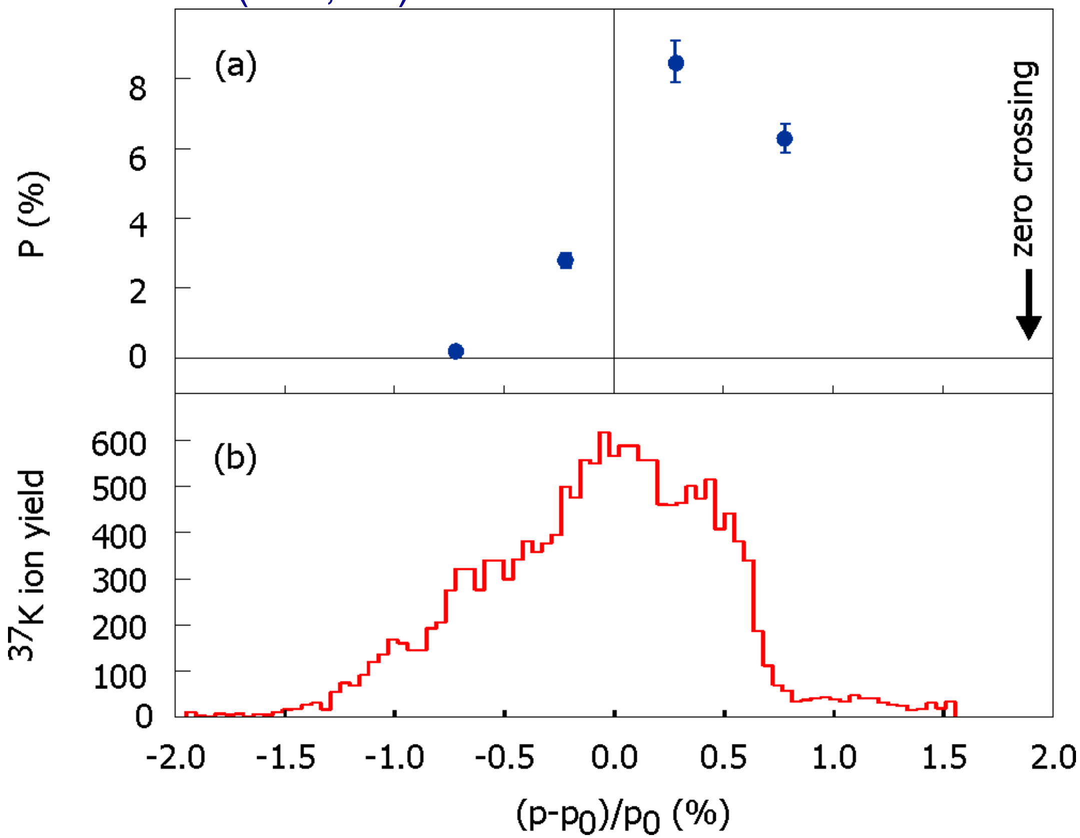
Polarization of Rare Isotope Beams

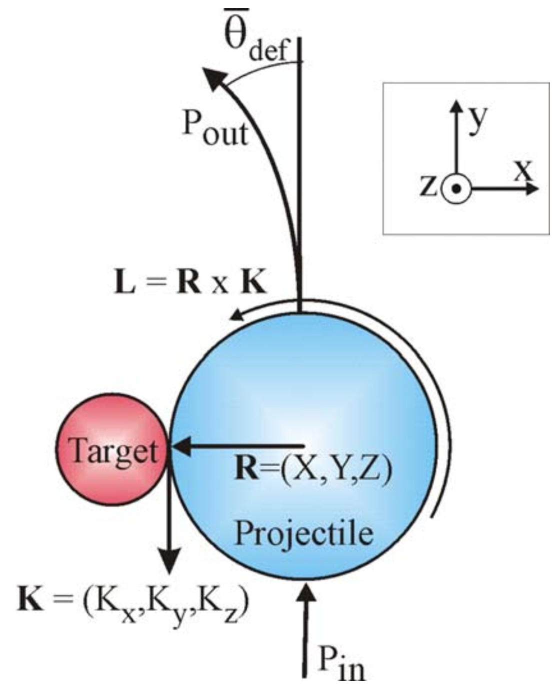
Single-nucleon pick-up produces polarization maximum near the peak of the momentum distribution*

→ Tool for measuring nuclear moments of key neutron-deficient nuclei near N = Z

* For projectile fragmentation, the polarization is maximal in the wings of momentum distribution: Asahi *et al.*, PLB 251, 488 (1990)

$^{9}Be(^{36}Ar,^{37}K)$ @ 155 MeV/A





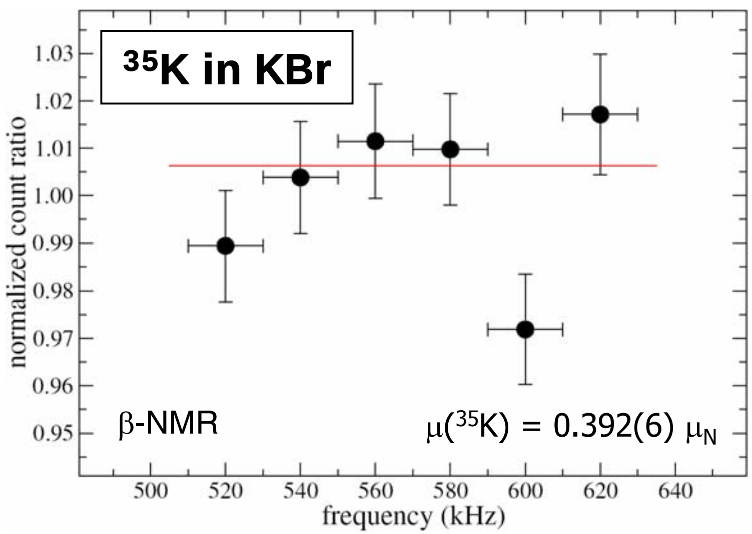
Groh et al., PRL 90, 202502 (2003)

Magnetic Moment of ^{35}K

The ^{35}K-^{35}S mirror pair is the heaviest T=3/2 system studied to date

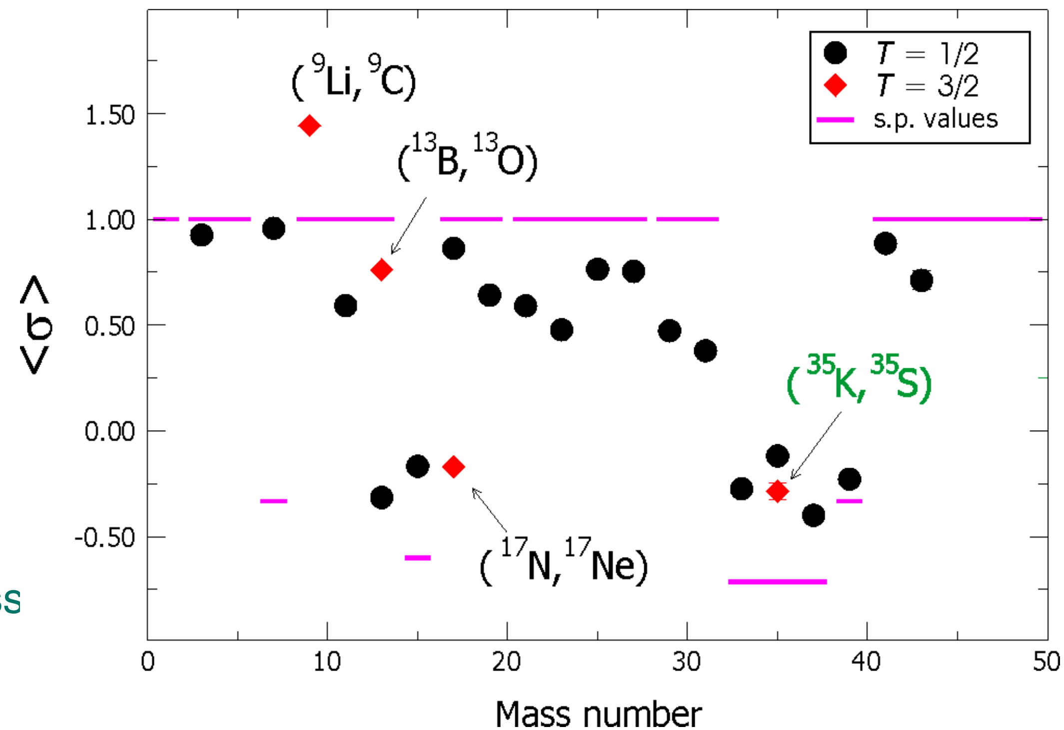
– Measured spin expectation value, <σ> = -0.284±0.040, agrees with T=1/2 systematics

Measured resonance curve

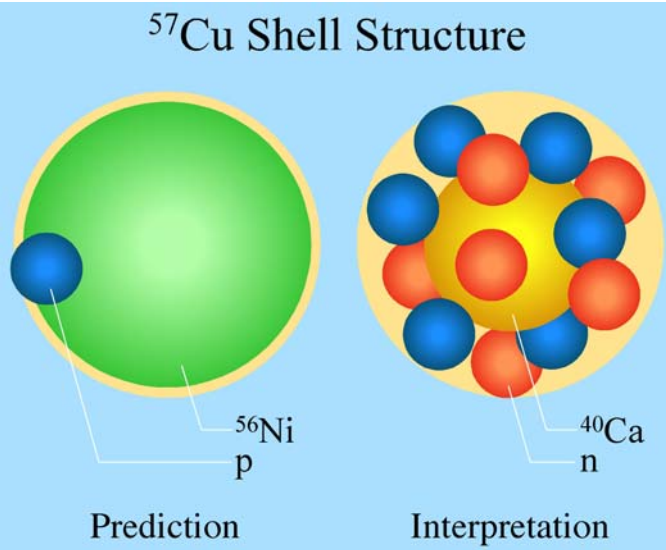


Mertzimekis et al., Phys. Rev. C in press

Spin expectation values



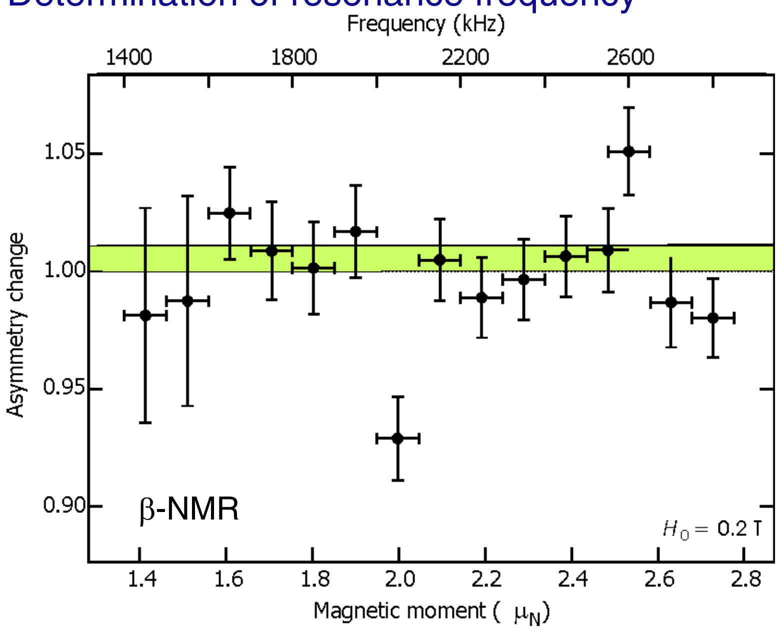
Evidence for Shell Breaking near ^{56}Ni



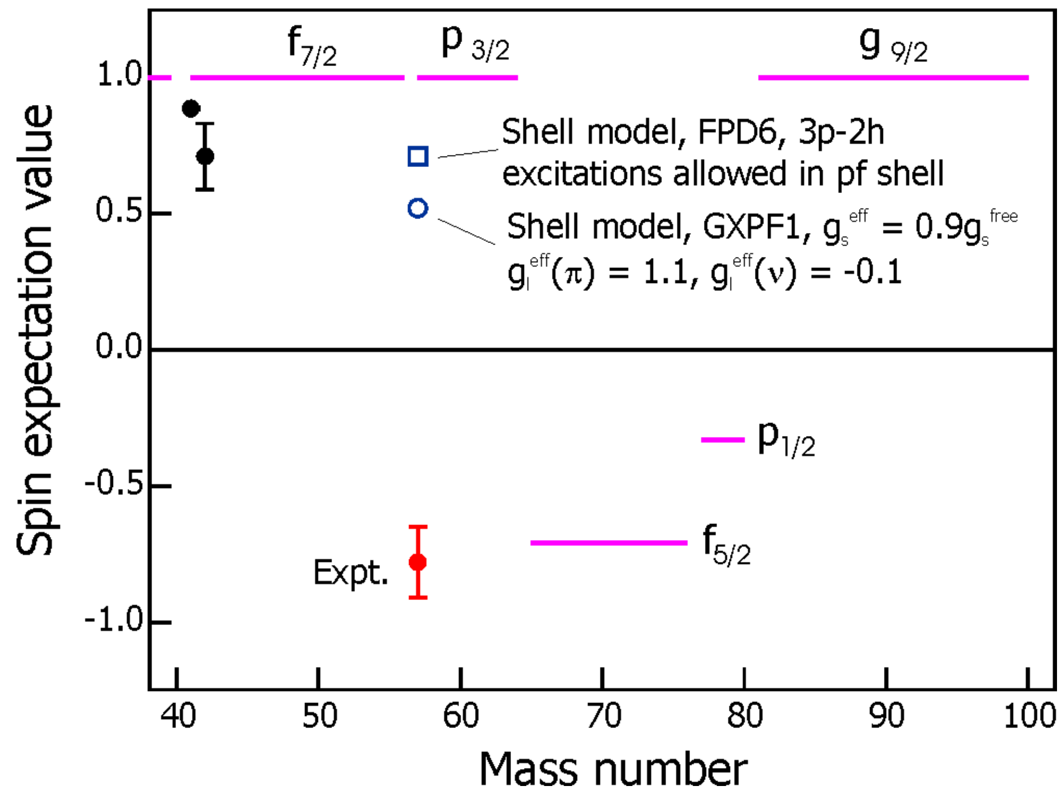
The ^{57}Cu-^{57}Ni mirror pair is the heaviest T=1/2 system studied to date

- The measured spin expectation value, $\langle\sigma\rangle$ = -0.78±0.031, is inconsistent with the assumption of an inert doubly-magic ^{56}Ni core

Determination of resonance frequency



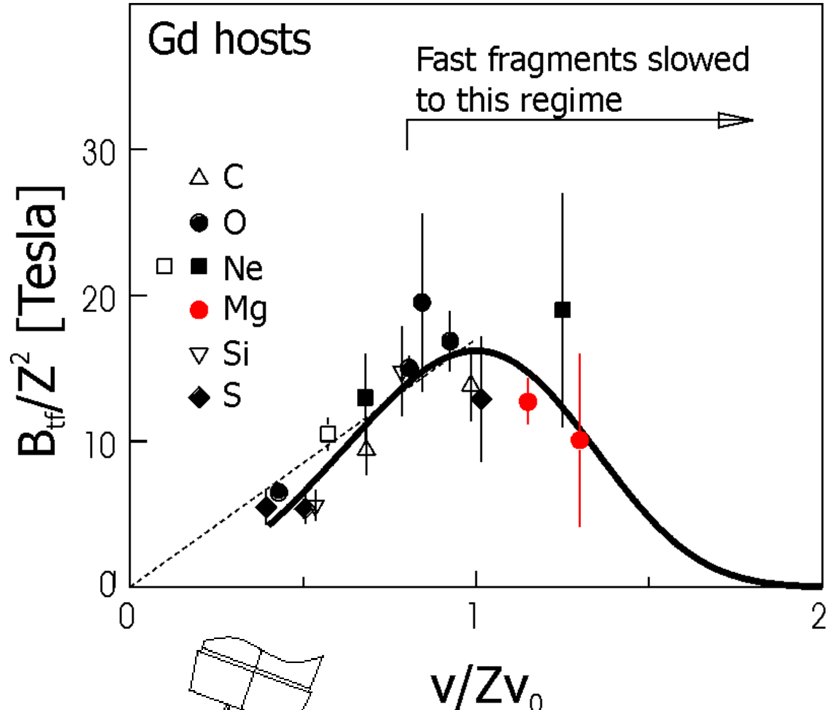
Minamisono et al., Phys. Rev. Lett. in press



High-Velocity Transient Field Method

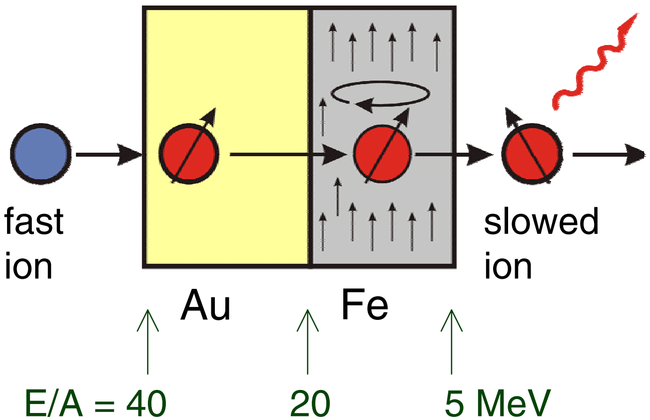
Perturbation of γ-ray angular distribution by Δθ due to interaction of magnetic moment (g=μ/I) in large hyperfine field

$$\Delta\theta = g\phi \qquad \phi = -\frac{\mu_N}{h}\int_{T_1}^{T_2} B_{tf}(t)\, e^{-t/\tau}\, dt$$

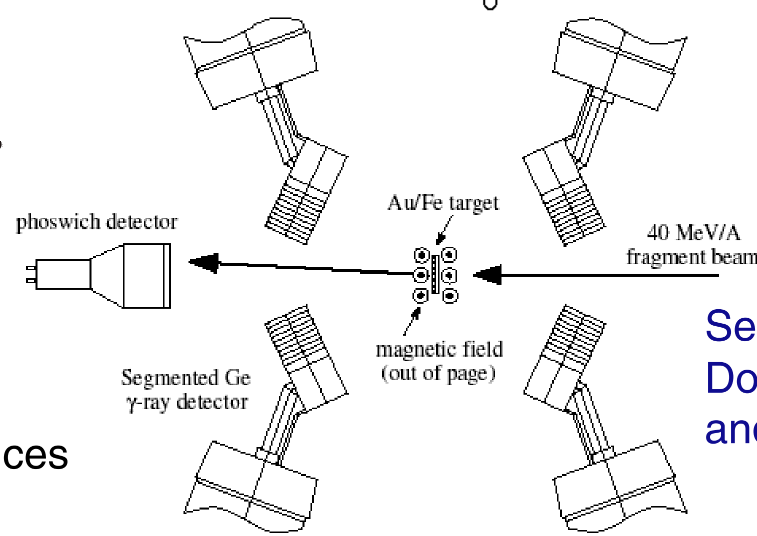


Fast fragment velocities are too large for transient field measurements

Use thick Au interaction target to slow down and Coulomb excite the secondary beam and pass through magnetized Fe layer to induce transient field



The Fe layer is polarized and induces the transient field



Setup for measuring Doppler-shifted γ-rays and angular distributions

Measurement of g(2⁺) Factor for $^{38,40}S$

High-Velocity Transient Field Method

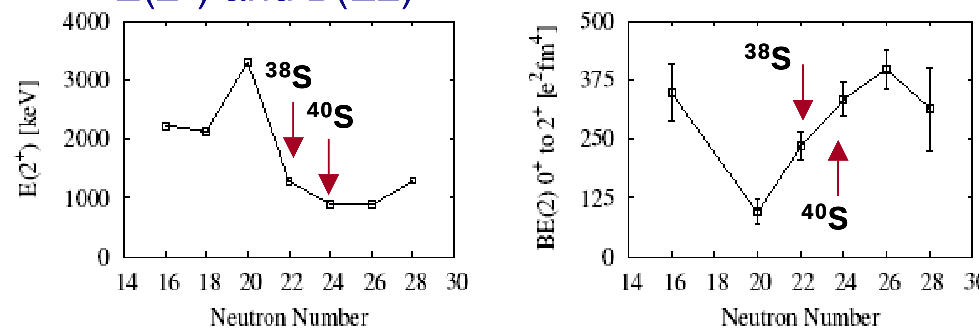
Observed small g factors

→ spin contributions dominate

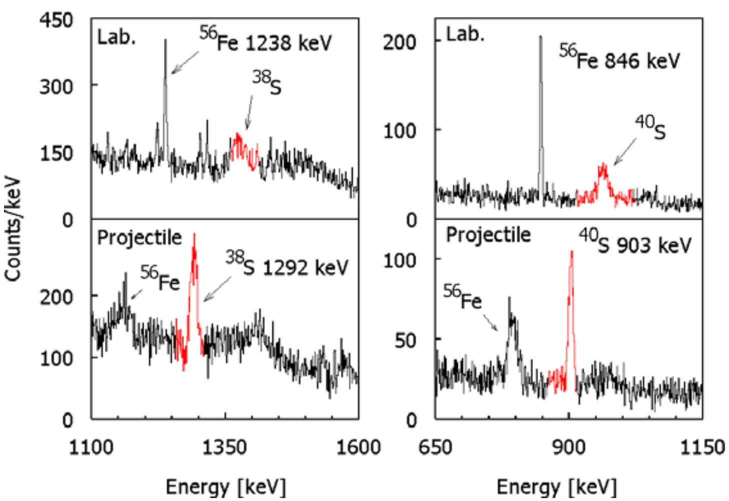
→ protons <u>and</u> neutrons contribute to onset of deformation

Nuclide	g_p(th)	g_n(th)	g(th)	g(exp)
^{38}S	+0.298	-0.301	-0.0026	+0.13(5)
^{40}S	+0.276	-0.241	+0.035	-0.02(6)

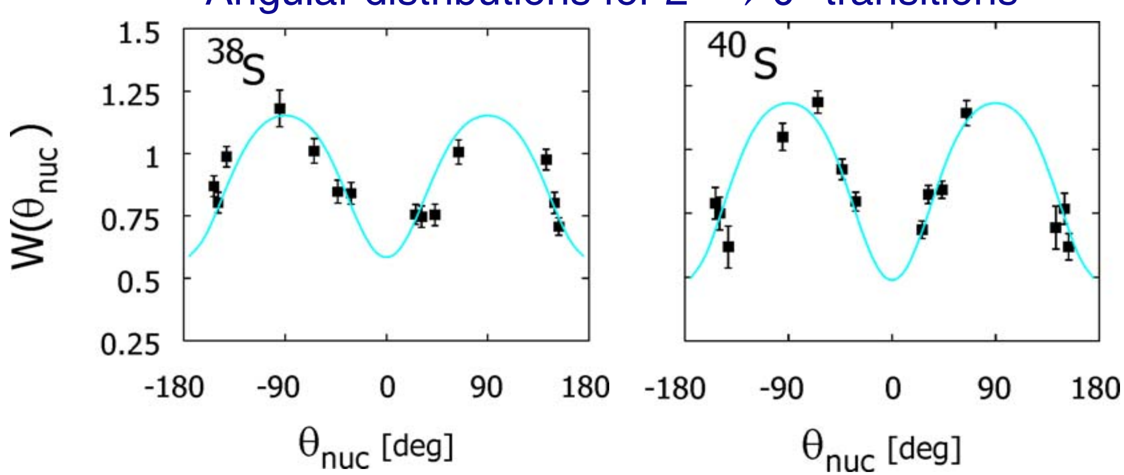
E(2⁺) and B(E2)



Doppler-corrected spectra



Angular distributions for $2^+ \rightarrow 0^+$ transitions

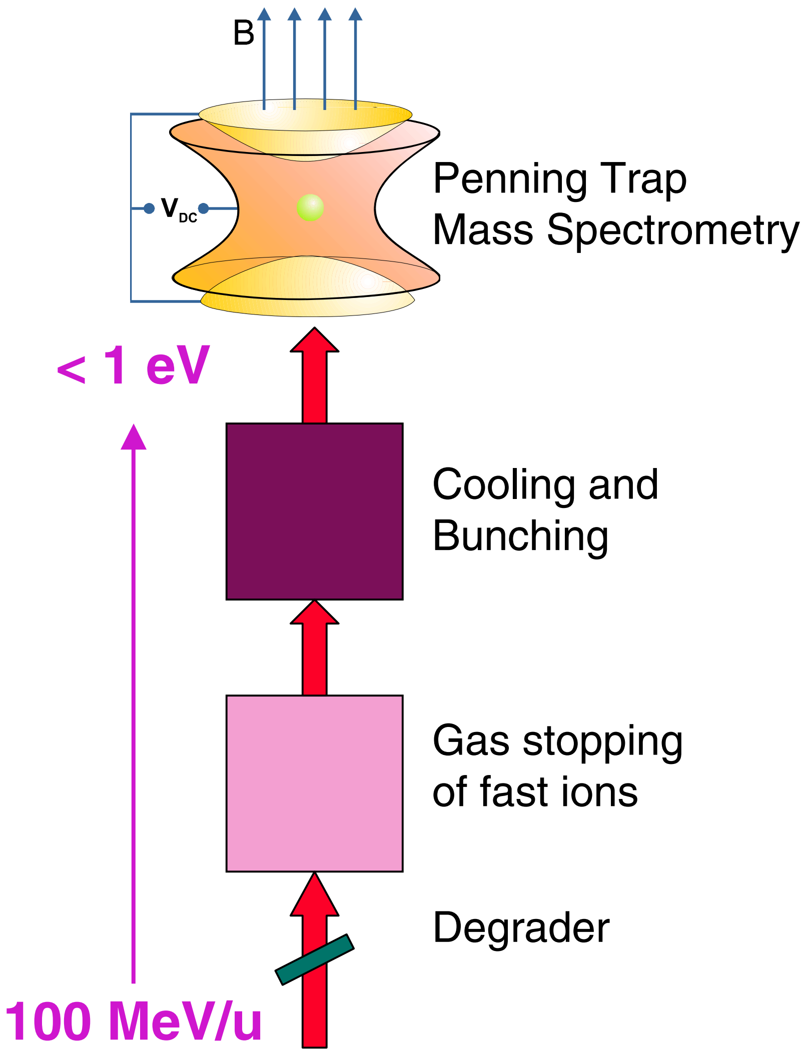


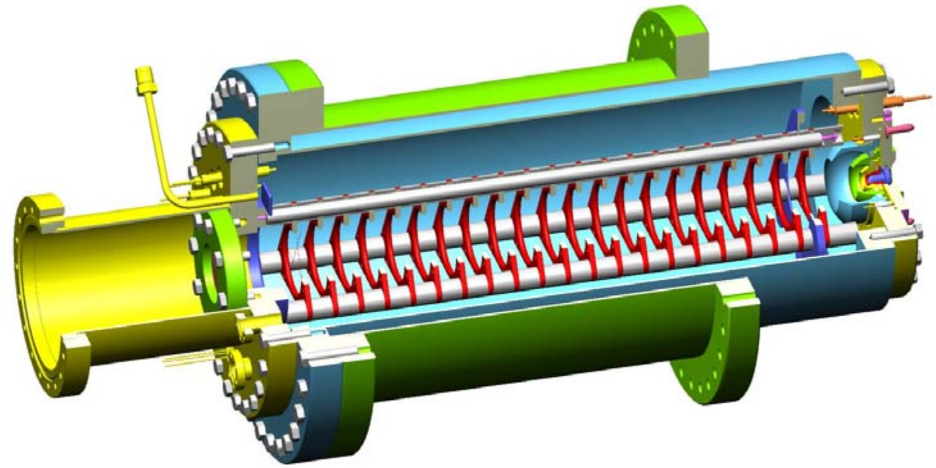
Davies et al., Phys. Rev. Lett. in press

The Low Energy Ion Beam Project LEBIT

Stop rare isotopes of ~100 MeV/A in ultra-pure He gas cell (~1 bar, 50 cm)

– High precision mass measurements since May 2005: ^{37}Ca, ^{38}Ca, ^{65}Ge, ^{66}As, ^{67}As, ^{80}As, $^{81m+g}$Se



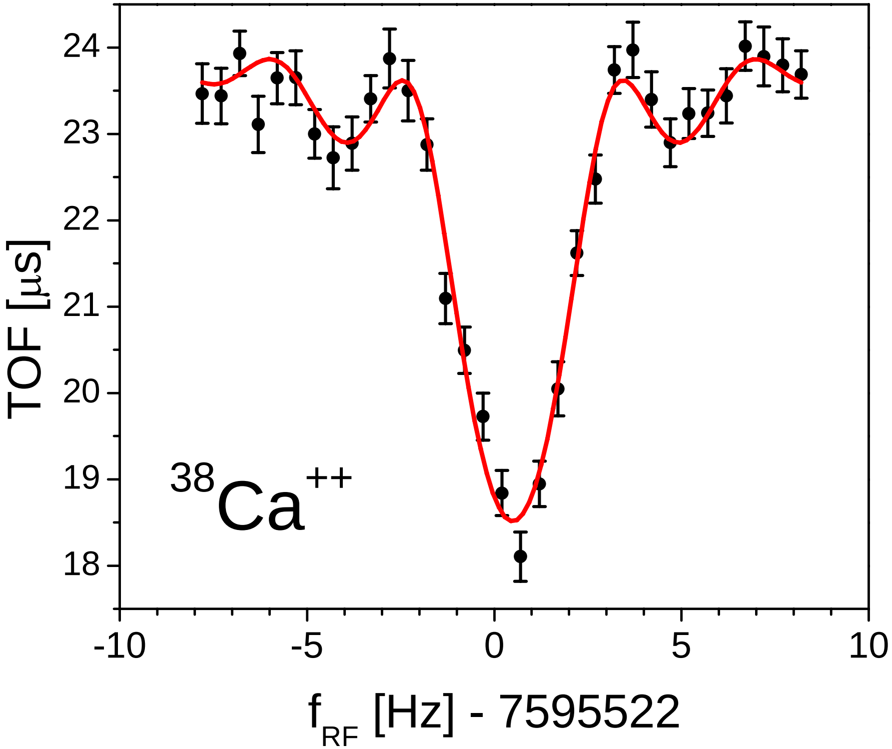


High precision 9.4 T Penning trap

NSCL

Precision Mass Measurements

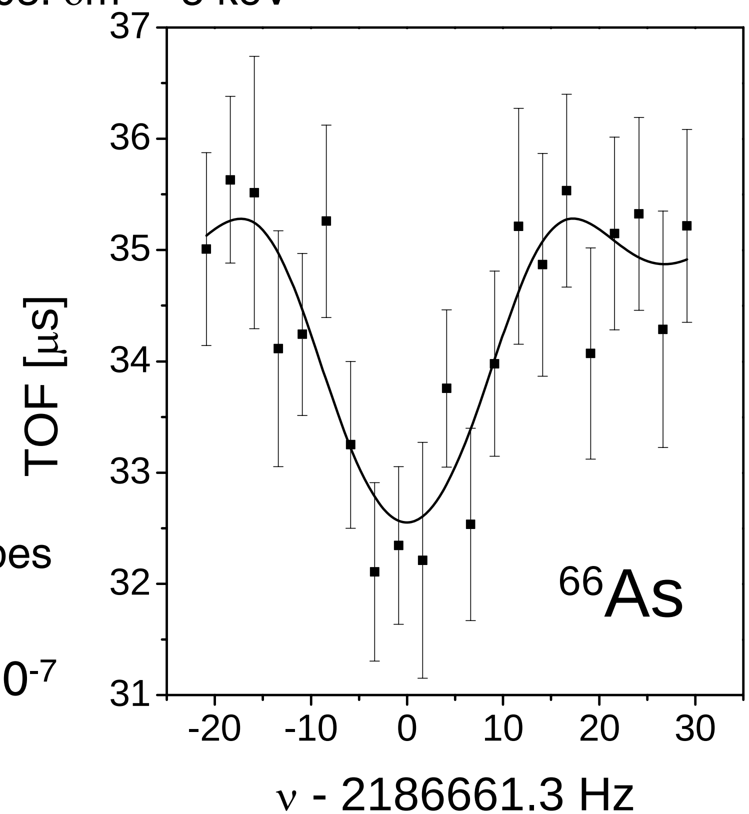
MICHIGAN STATE UNIVERSITY
Advancing Knowledge. Transforming Lives.



^{38}Ca: $T_{1/2}$ = 440 ms, $0^+ \rightarrow 0^+$ β^+-emitter
- new candidate for the test of the conserved vector current (CVC) hypothesis

ME_{LEBIT} = -22058.53(28) keV

δm = 280 eV, δm/m=$8 \cdot 10^{-9}$
- AME 03: δm = 5 keV

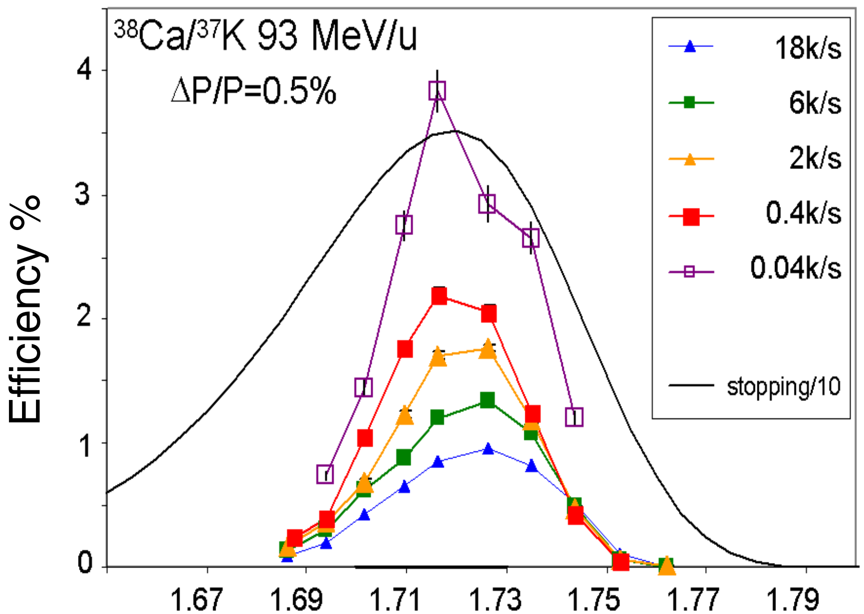


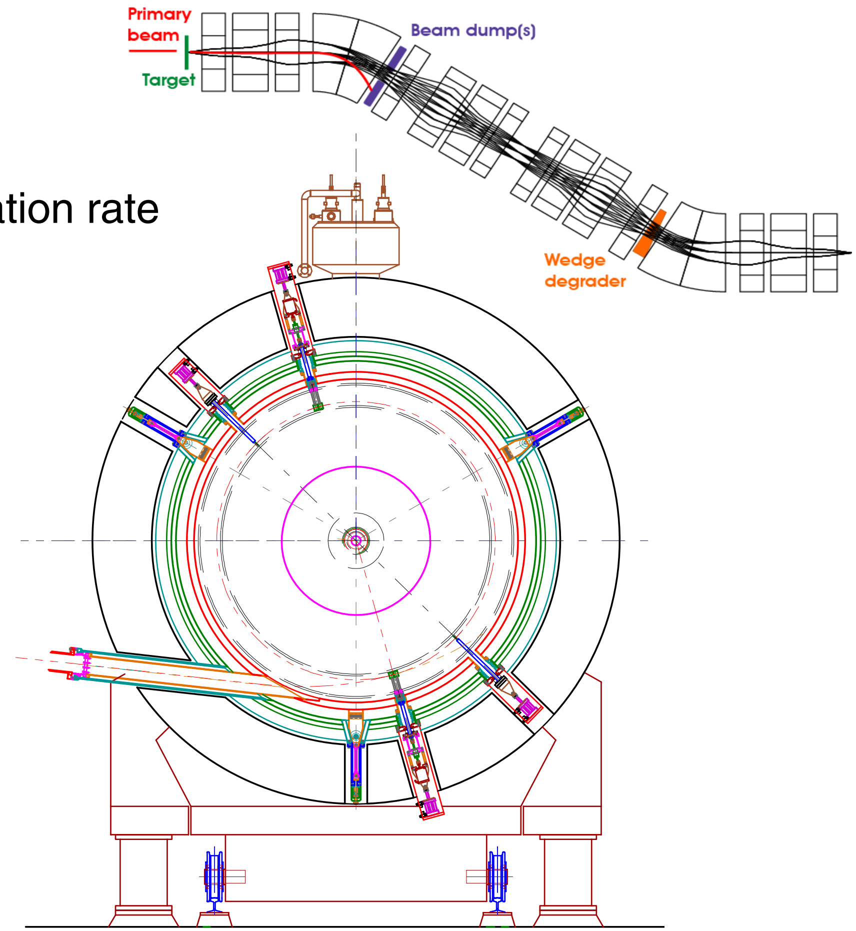
^{66}As: $T_{1/2}$ = 96 ms
- one of the two shortest-lived isotopes investigated in an ion trap up now

LEBIT: δm ≈ 20 keV, δ m/m ≈ 3×10^{-7}
- 20-fold improved masses in region critical to rp process

Beam Separation and Manipulation (DOE, NSF, MSU)

- Range compression studies
- Capture and extraction from a gas cell
  - Typical stopping fraction: ~ 0.2 – 0.5
  - Extraction efficiency decreases with implantation rate





Planned R&D:

– Develop improved gas-stopping scheme for rare isotopes from projectile fragmentation: gas-filled cyclotron magnet for high (>10^8/s) beam intensities and fast (<10 ms) extraction

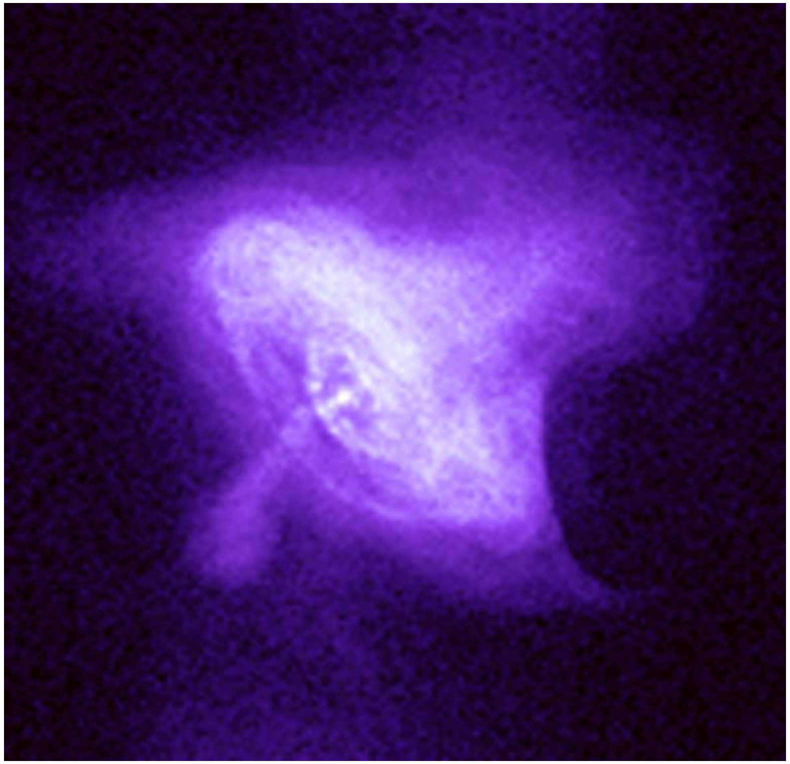
– Develop high efficiency charge breeder

– Investigate beam-cooling for improved and cost-efficient high-resolution mass separation

Rapid Neutron Capture Process (r-process)

Synthesis of about half of all nuclei heavier than Fe

- Occurs at temperatures greater than 10^9 K and free neutron densities greater than 10^{20} cm^{-3}
- Astrophysical site not yet known; may be associated with type II supernovae, merging neutron stars, or other yet to be determined sites



X-ray image of Crab Nebula (Chandra)

Optical image of Crab Nebula (Mt. Palomar)

Doubly Magic ^{78}Ni Accelerates Heavy Element Synthesis

MICHIGAN STATE UNIVERSITY
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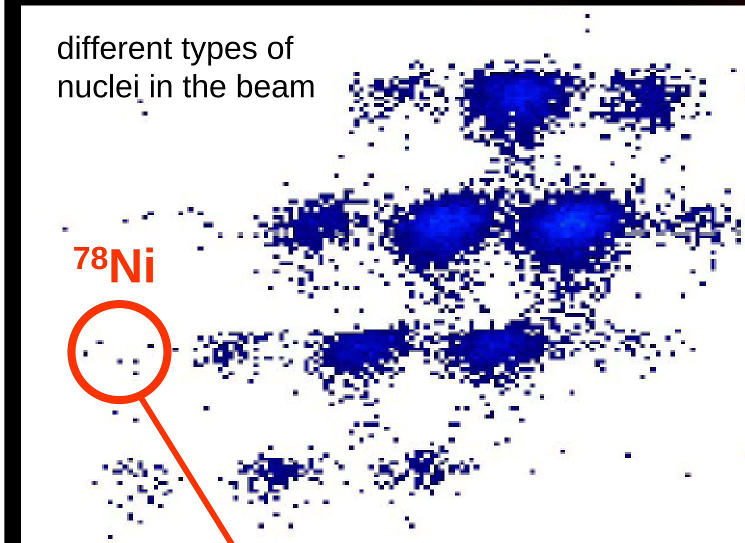
NSCL

Particle identification

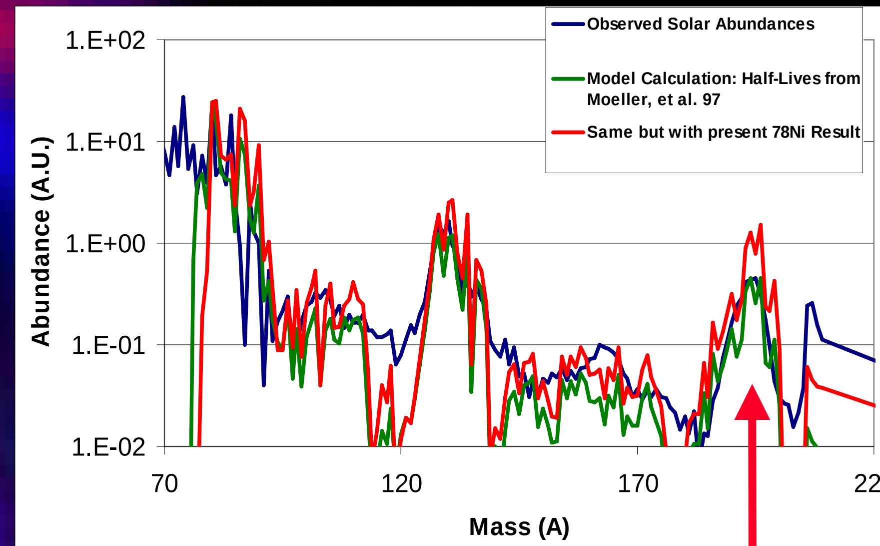


Measured half-life of ^{78}Ni with 11 events
This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

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

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

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



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

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

… one step towards a better understanding of the origin of the elements in the cosmos

Spin-Isospin Response of Nuclei

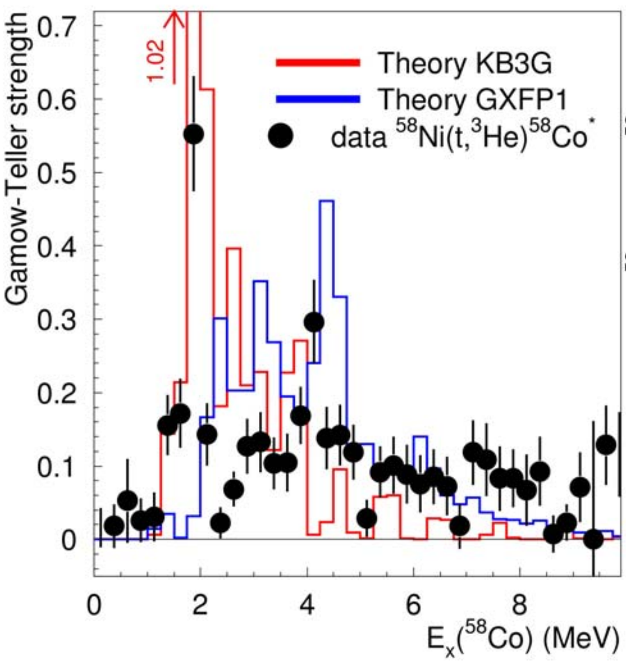
Weak transition rates are important for stellar evolution

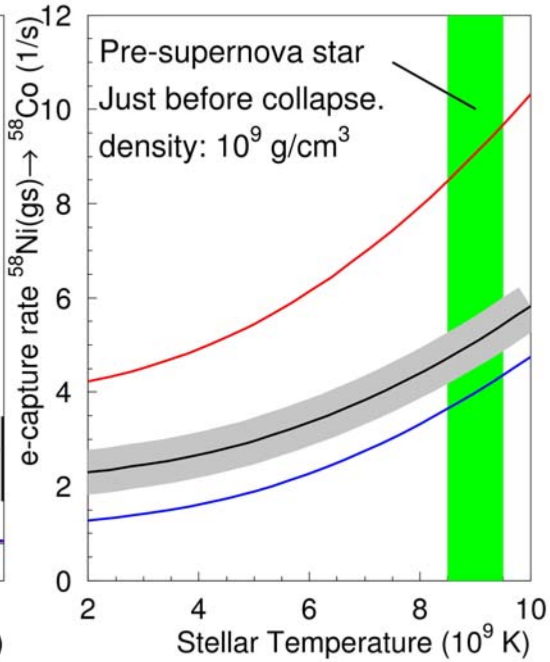
Measure of Gamow-Teller strengths via charge exchange reactions

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

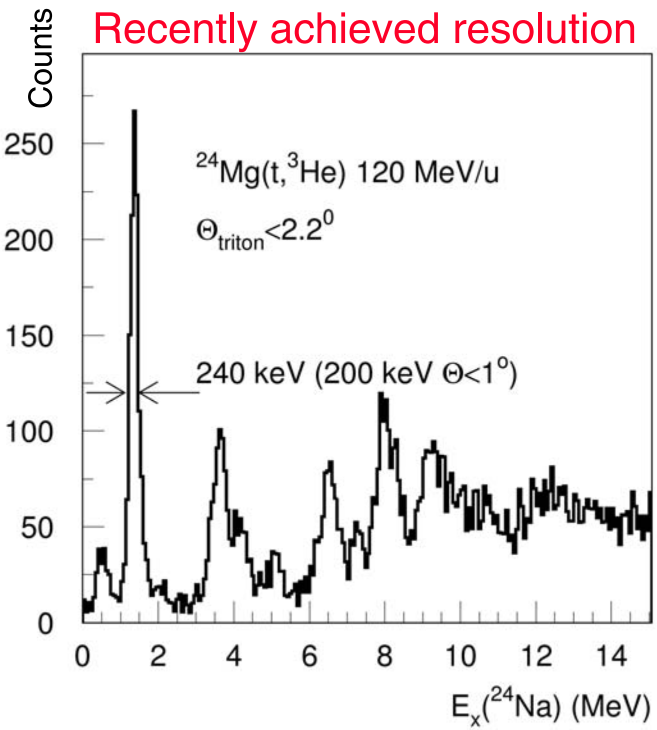
R.G.T. Zegers, et al.

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





Recently achieved resolution



The Equation of State (EOS) of Nuclear Matter

The EOS for symmetric matter has been constrained by nucleus-nucleus collision experiment, but little is known about symmetry energy term

Experimental constraints on EOS of symmetric nuclear matter

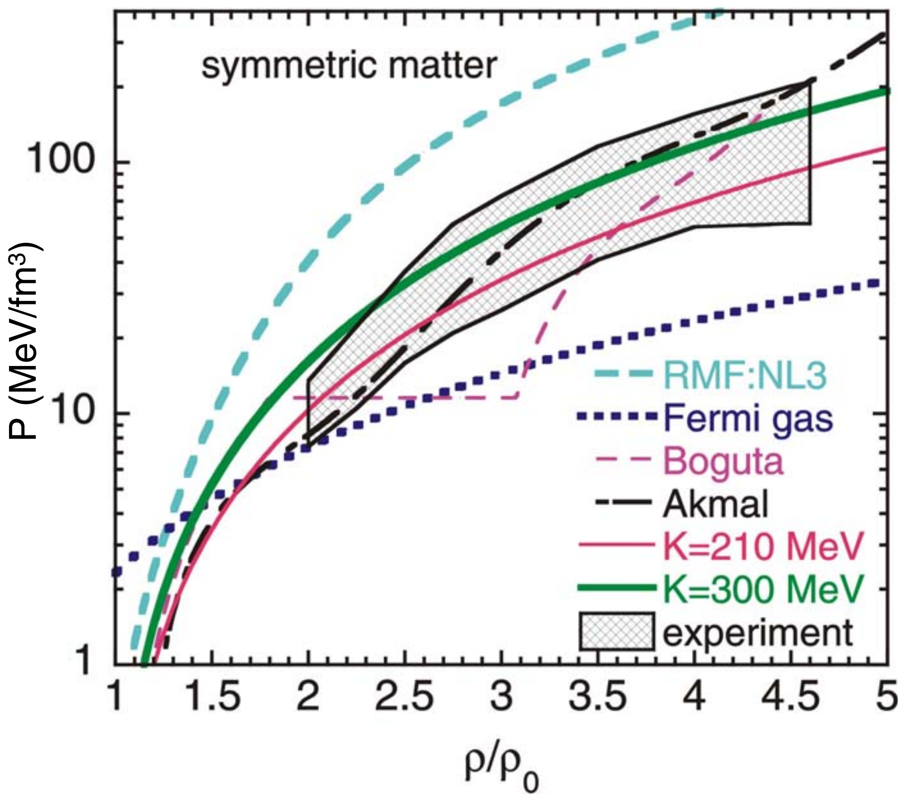
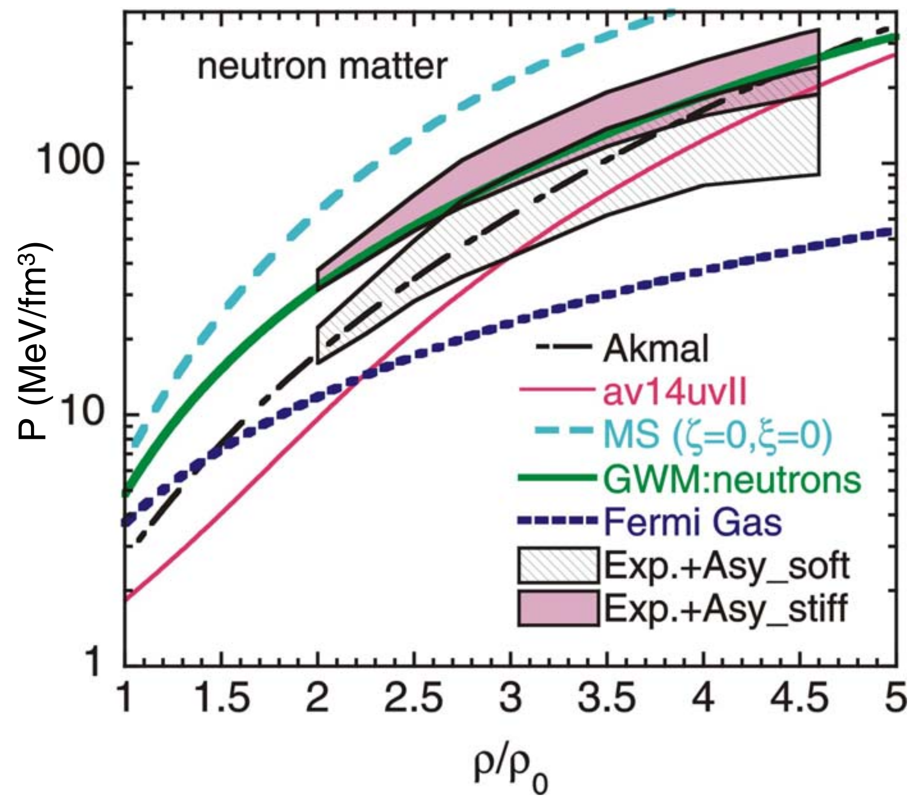


Illustration of uncertainties for EOS of neutron matter



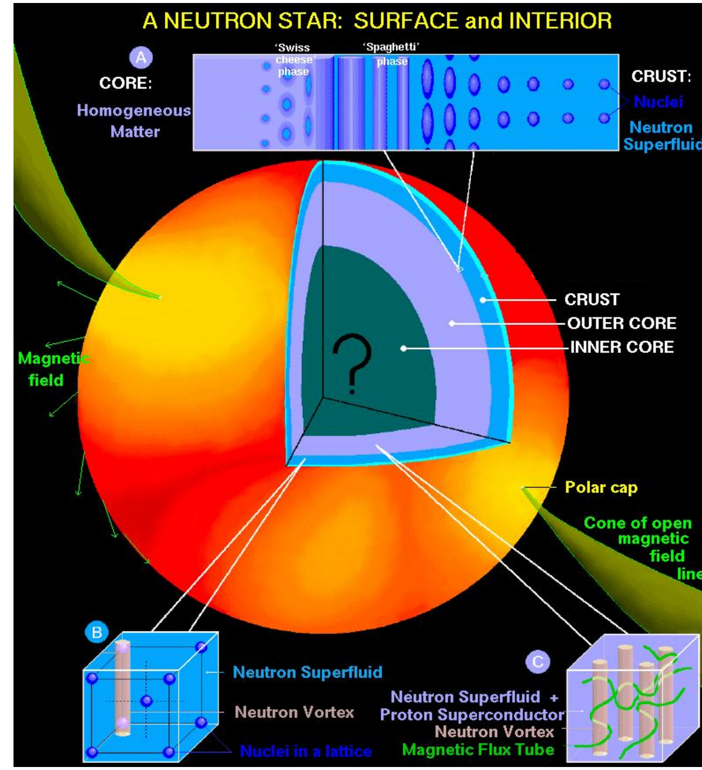
P. Danielewicz, R. Lacey, and W.G. Lynch, Science 298,1592 (2002)

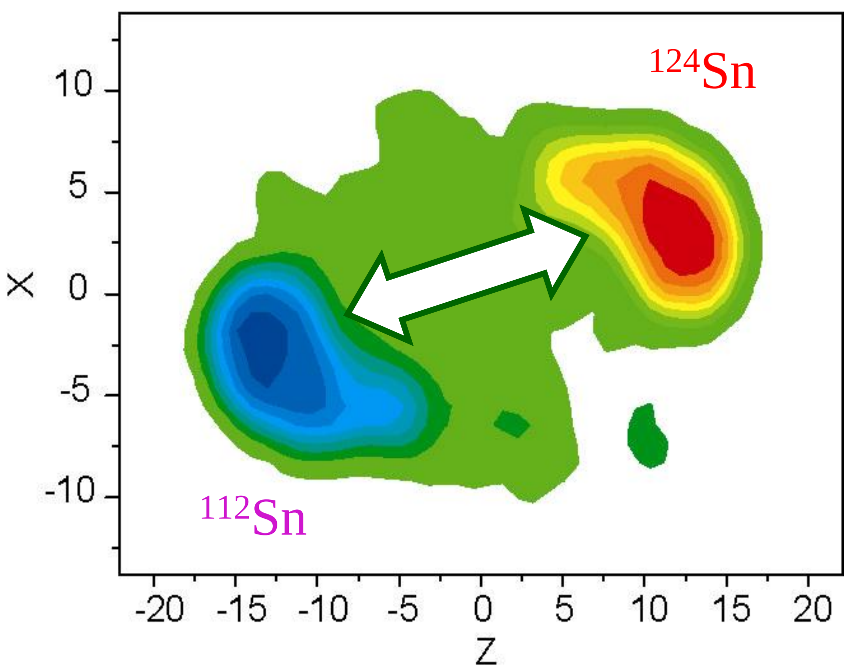
The Density Dependence of the Nuclear Asymmetry Energy

Neutron star radii, neutron skins of nuclei, and isospin diffusion processes are sensitive to the asymmetry term of the EOS

At $\rho = 2\,\rho_0$, more than 70% of the pressure in neutron star crusts comes from the asymmetry energy

→ Asymmetric nucleus-nucleus collisions offer the only option to explore the asymmetry term of the EOS at $\rho \neq \rho_0$



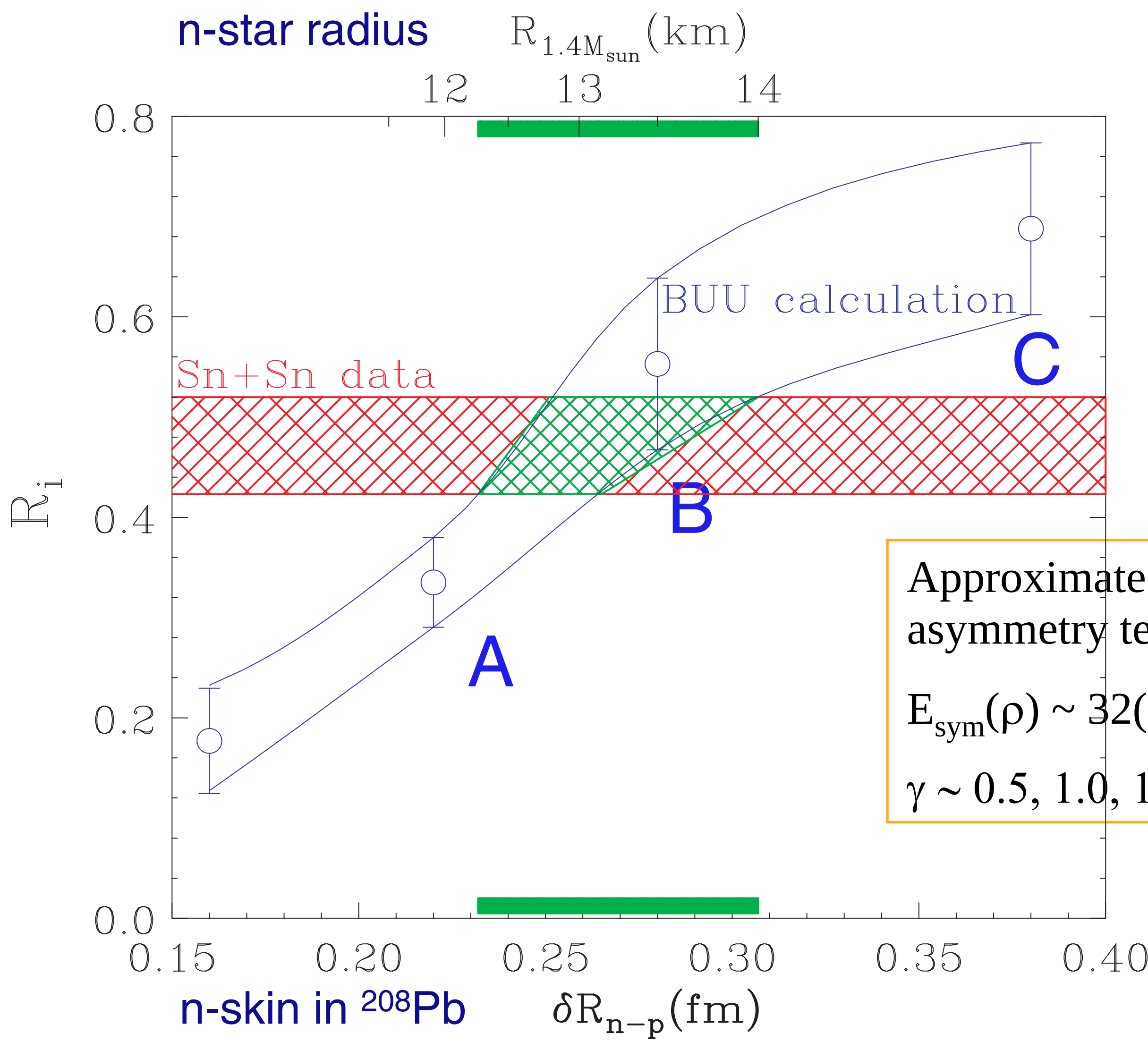


Possible approach: Investigate isospin diffusion in nucleus-nucleus collisions

$$R_i = \frac{2O_{PT} - O_{PP} - O_{TT}}{O_{PP} - O_{TT}}$$

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

Isospin Diffusion Data Constrain $E_{sym}(\rho)$



M.B. Tsang et. al.,
PRL 92, 062701 (2004)

L.W. Chen, C.M. Ko, and B.A. Li,
PRL 94, 032701 (2005)

C.J. Horowitz and J. Piekarewicz,
PRL 86, 5647 (2001)

B.A. Li and A.W. Steiner,
nucl-th/0511064

Approximate representation of the various asymmetry terms used in BUU calcuations:

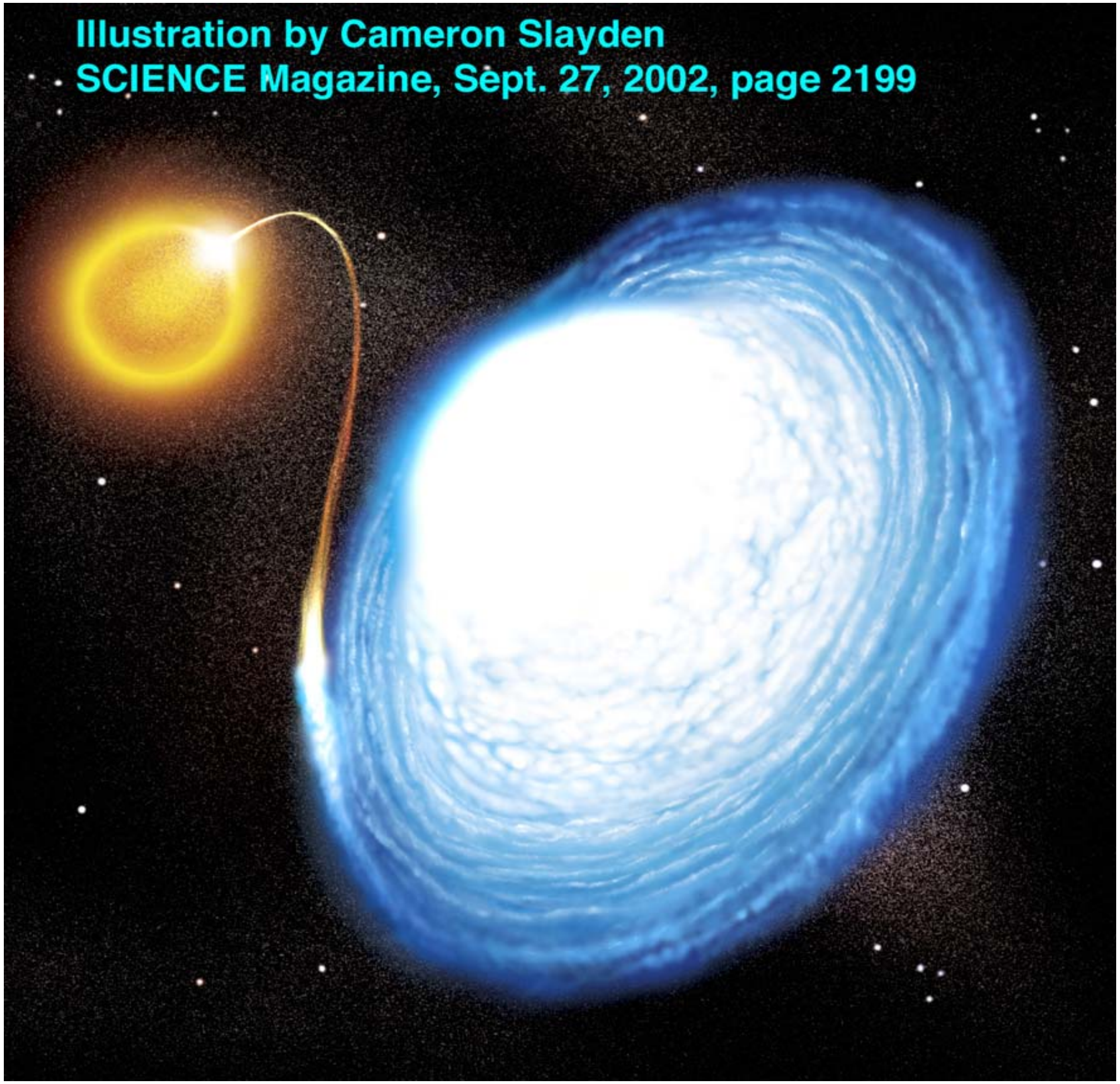
$E_{sym}(\rho) \sim 32(\rho/\rho_0)^{\gamma}\ [(\rho_n - \rho_p)/(\rho_n + \rho_p)]^2$

$\gamma \sim 0.5, 1.0, 1.6$ (for cases A, B, C)

Work in Progress:
M.B. Tsang

X-Ray Burst (Accreting Neutron Star)

2002 Physics Nobel Prizes: x-ray Astronomy and solar neutrinos



Normal bursts:

Thermonuclear explosions on the surface of accreting neutron star binaries: rp-process

Superbursts:

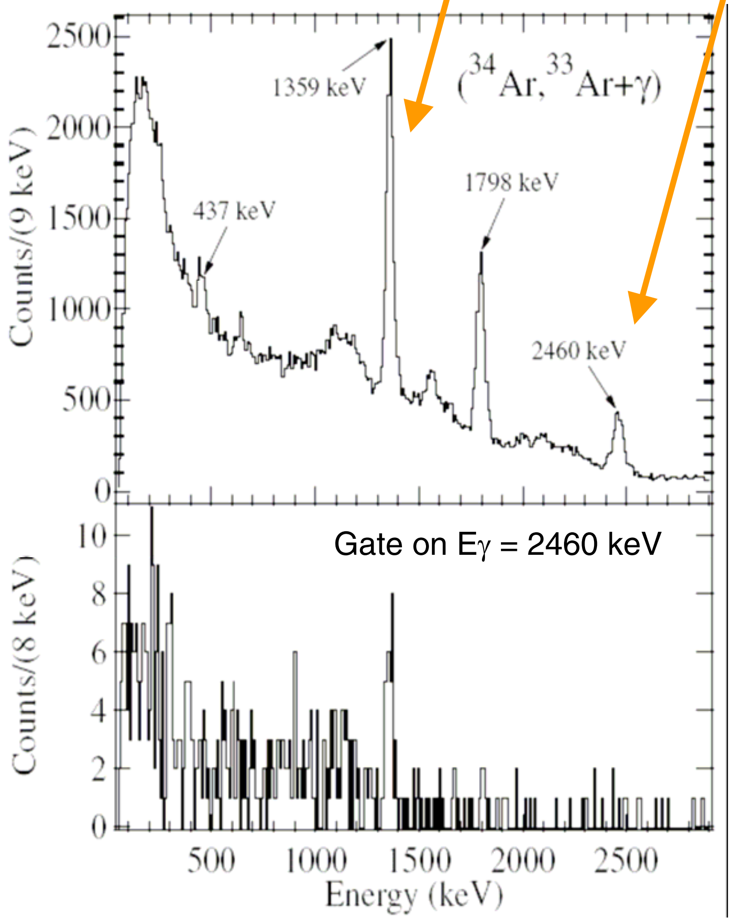
Re-ignition of the ashes in the neutron star's crust, carbon-burning and photodissociation of heavier nuclei

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

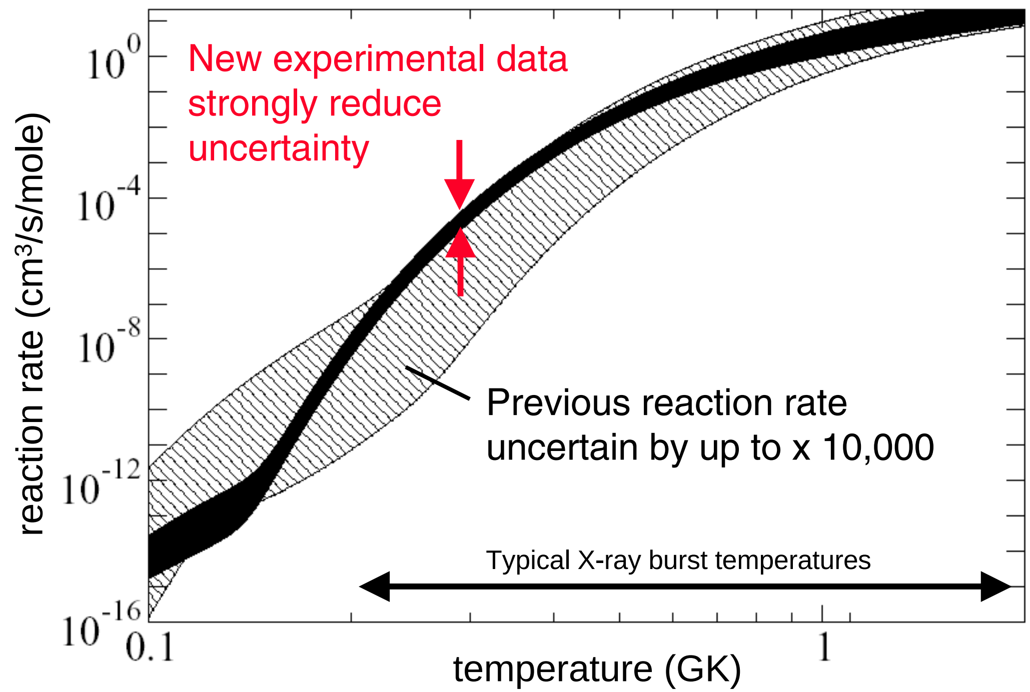
Most rp-process nuclei can be studied at NSCL

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*,)^{33}Ar stellar reaction rate by 3 orders of magnitude



Clement et al. PRL 92, 172502 (2004)

Accelerator Physics and Beam Dynamics

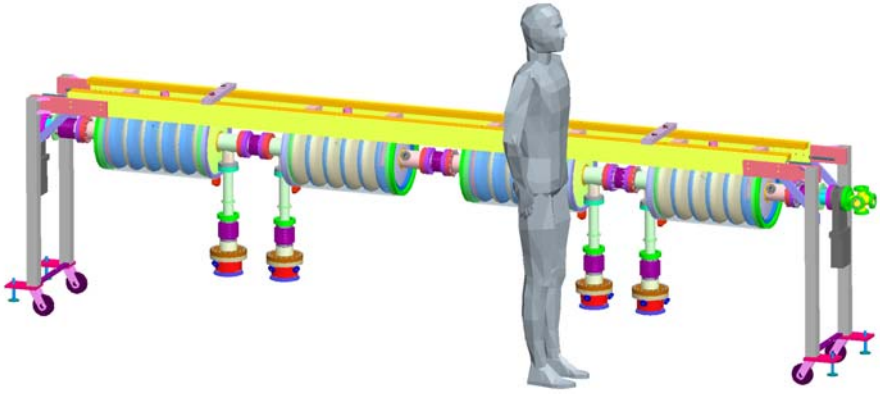
MSU is one of a few U.S. institutions that trains accelerator physics PhDs

Expertise in beam dynamics, beam transport systems, fragment separators, ion traps, ECR ion source technology, cyclotron technology, linac technology, including pertinent applications of superconductivity

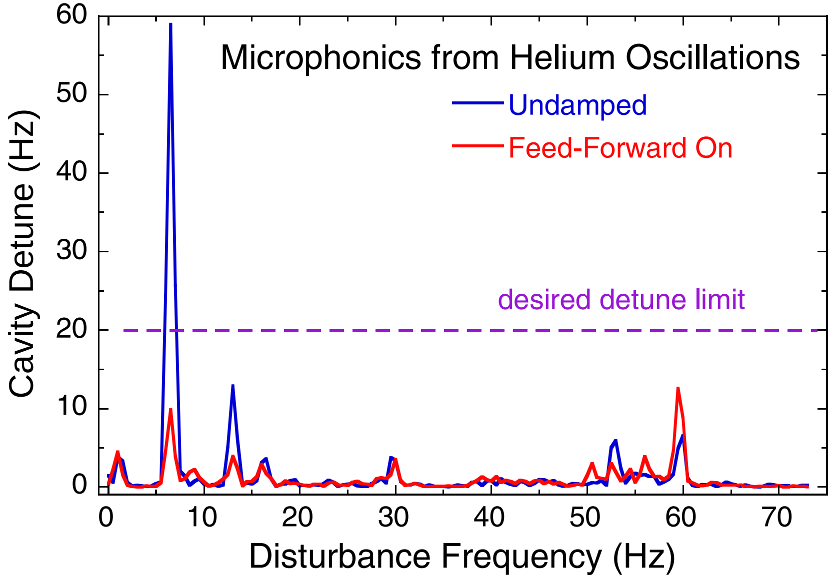
Well positioned to make contributions to new projects of national importance

Developed SRF infrastructure and expertise (funded by State of MI, MSU, DOE). All RIA driver linac SRF cavities prototyped – exceed specifications. Ongoing R&D: SRF cavities for FNAL; recirculating e-linac and high-field β=1 cavities (ILC)

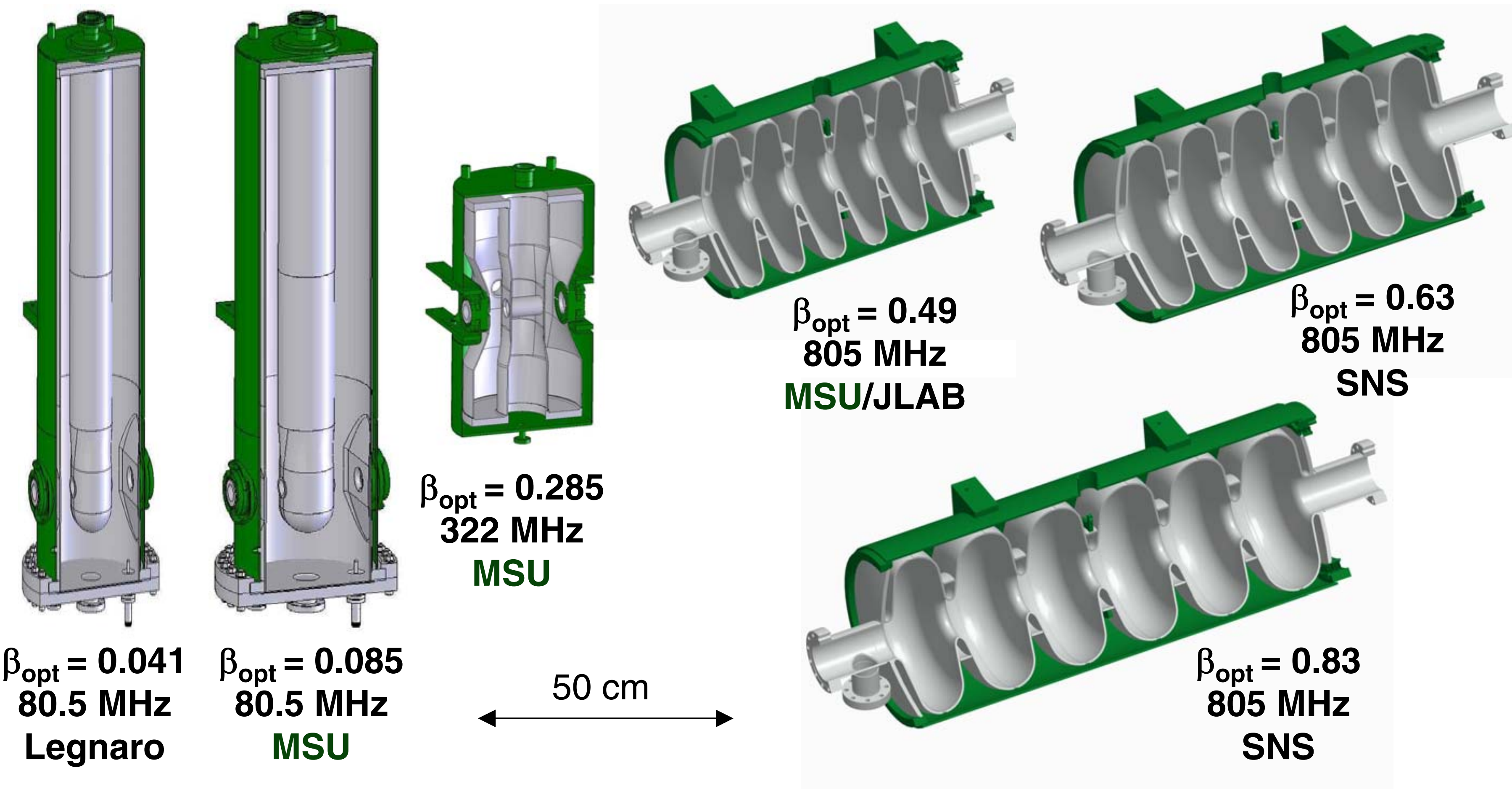
Important for development of future MSU-based nuclear science program.



Adaptive feed-forward cancellation of SRF-cavity microphonics developed by MSU reduces cavity detuning and RIA power cost by over $600,000/year



SRF Cavities for RIA Linacs (DOE, State of MI, MSU)



✓ Linac conceptual design complete, including end-to-end simulations* with errors

– 6 cavity types for driver & re-accelerator (→ low number of spares)

– All cavities prototyped – exceed design specs

* MSU, LANL, LBNL, ANL collaboration

Cost-effective Design of Cryostats (DOE, State of MI, MSU)

- ✓ Built & tested prototype for elliptical cavities (805 MHz), incl. feed-forward vibration control
- – Constructing prototype low-beta cryostat: $\lambda/4$ & $\lambda/2$ resonators + 9 T superconducting solenoid, 0.6 T quadrupole (tests in mid 2006)
- – Ready for linac construction