FACILITY FOR RARE ISOTOPE BEAMS

The spectrometers of FRIB and the corresponding physics program

Remco G.T. Zegers

NSCL J I N A Department of Physics and Astronomy NSF MICHIGAN STATE UNIVERSITY

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- Spectrometers at NSCL
    - For reaccelerated beams (planned)
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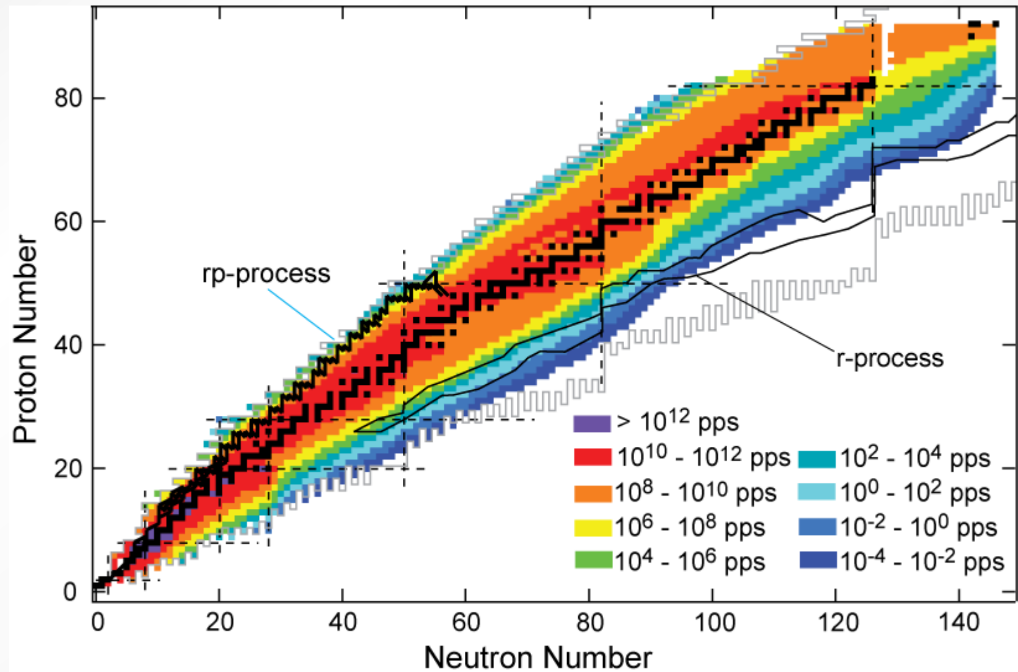
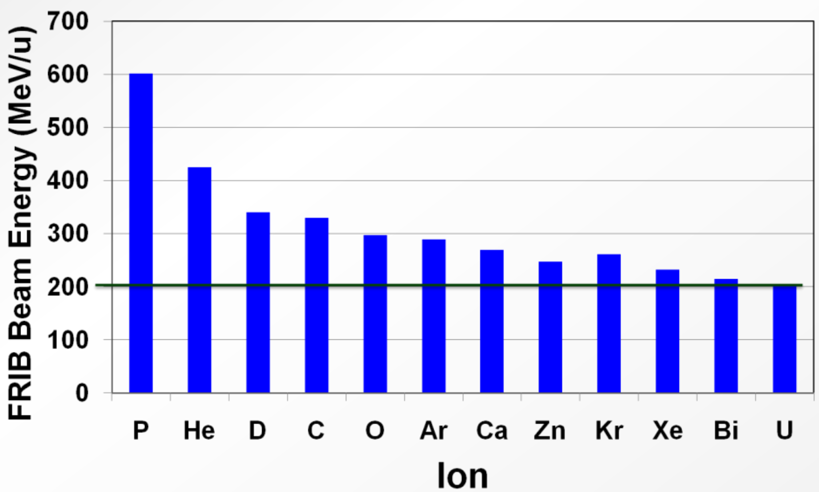
- The choice of beam energy and spectrometer rigidity
- A High-Rigidity Spectrometer for FRIB

The reach of FRIB

- FRIB will greatly extend the reach for studying rare isotopes
- Exciting prospects for study of nuclei along the drip line to A=120(compared to A=24)
- Production of most of the key nuclei for astrophysical modeling

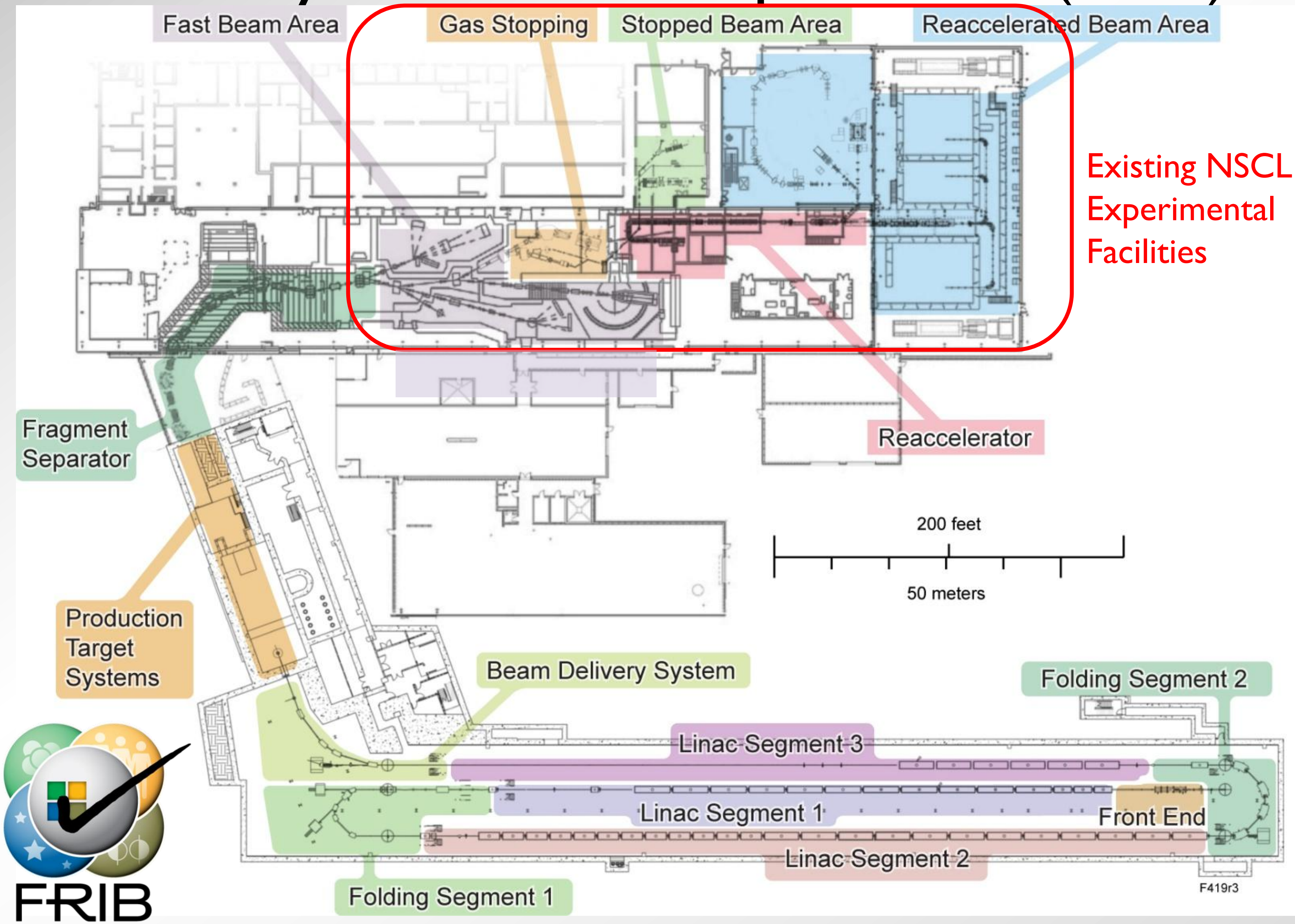




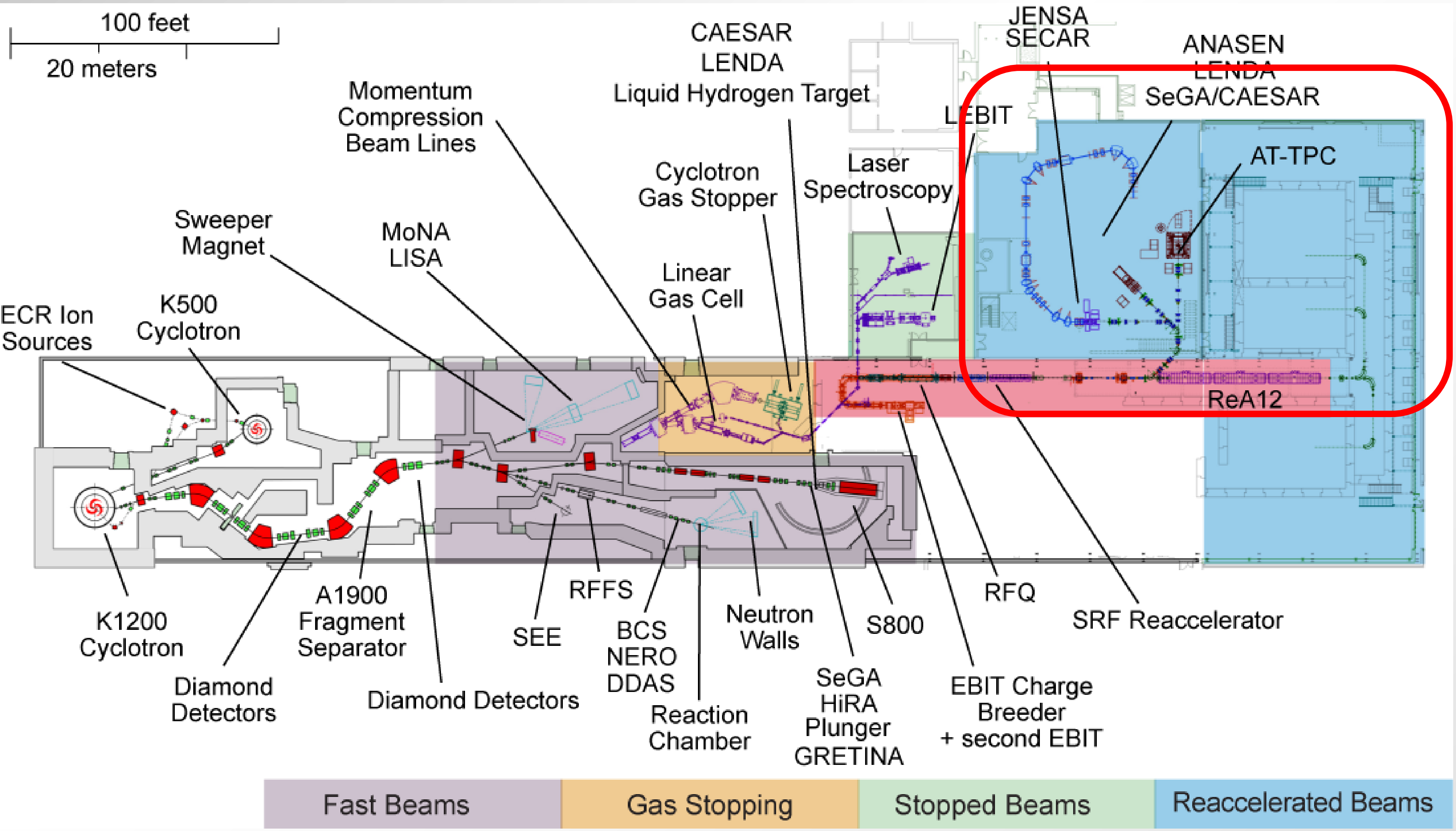
200MeV/u Beam energy (upgrade?)

400 kW Beam power

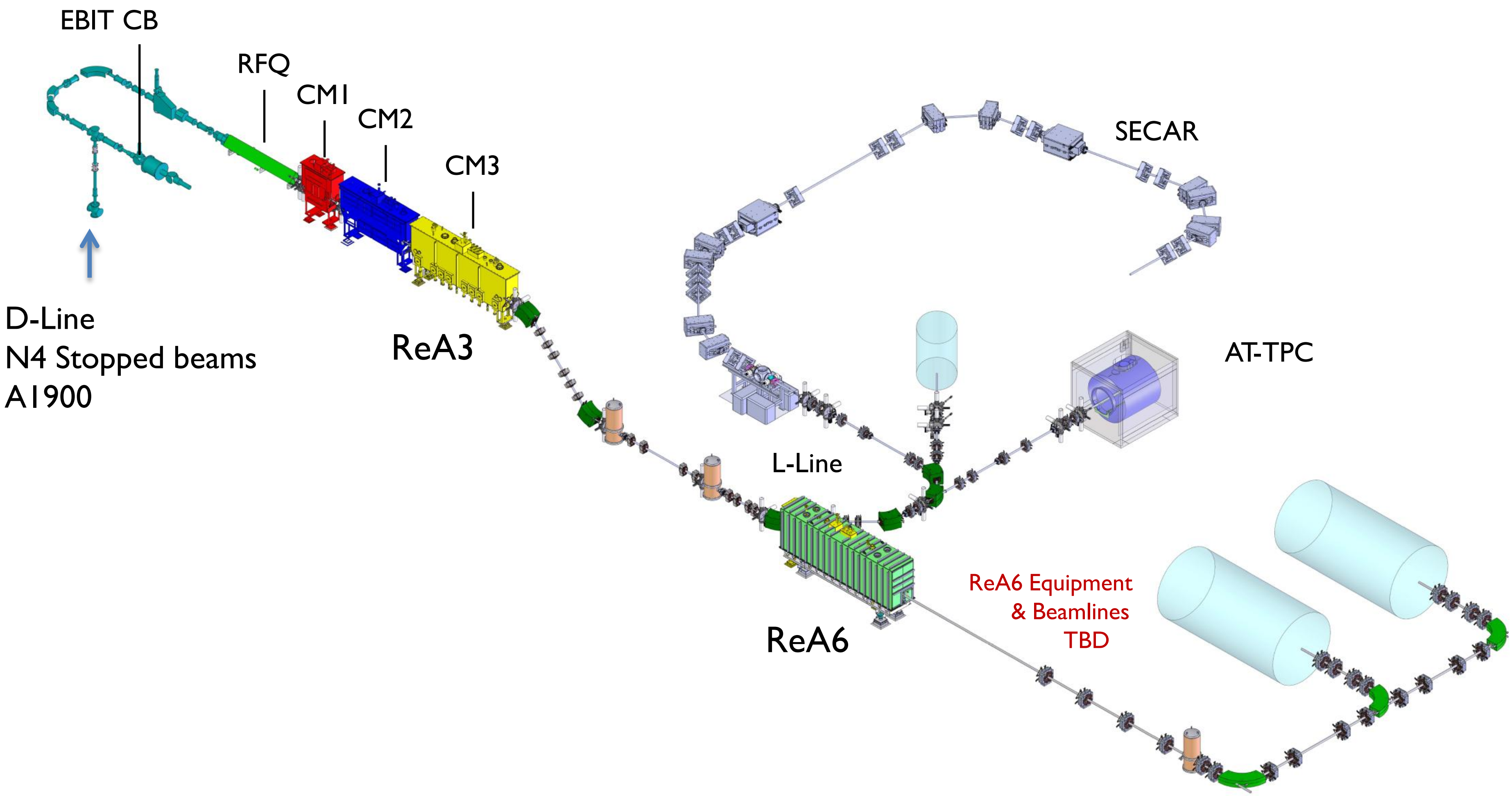
Facility for Rare Isotope Beams (FRIB)



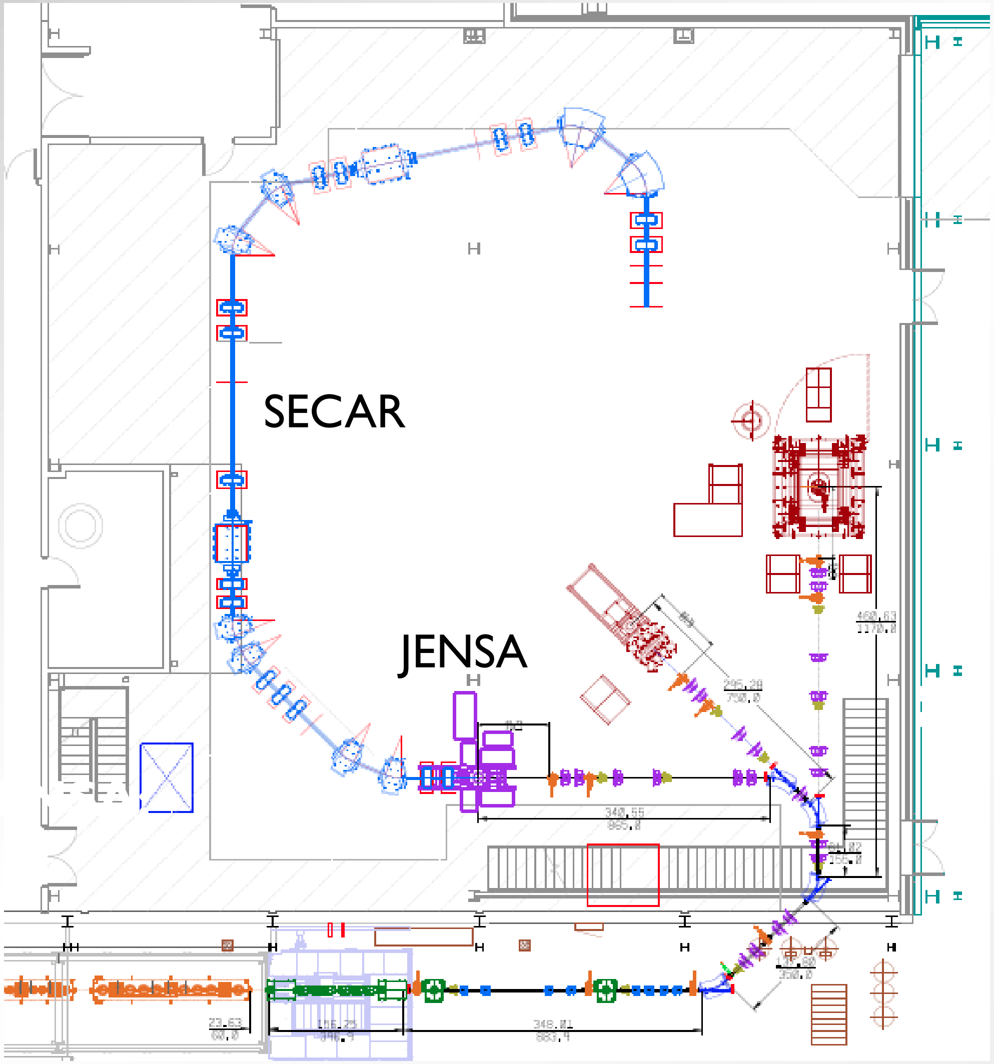
Spectrometers for reaccelerated beams



Re-accelerator and Associated Beam Lines and Experimental Equipment



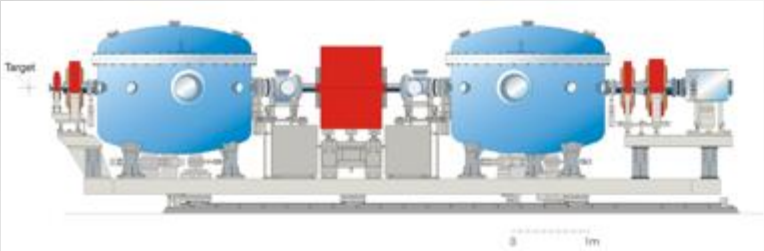
Separator for Capture Reactions (SECAR)



Based on design of St. George separator at Notre Dame U.

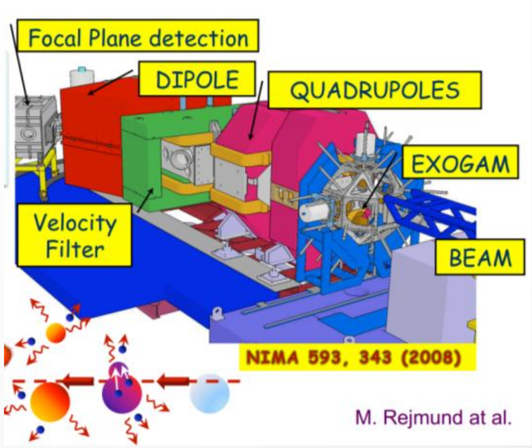
Collaboration of ANL-CSM-JINA-LSU-McMaster-MSU-ND-ORNL-PNNL

ReA12 – Recoil separator

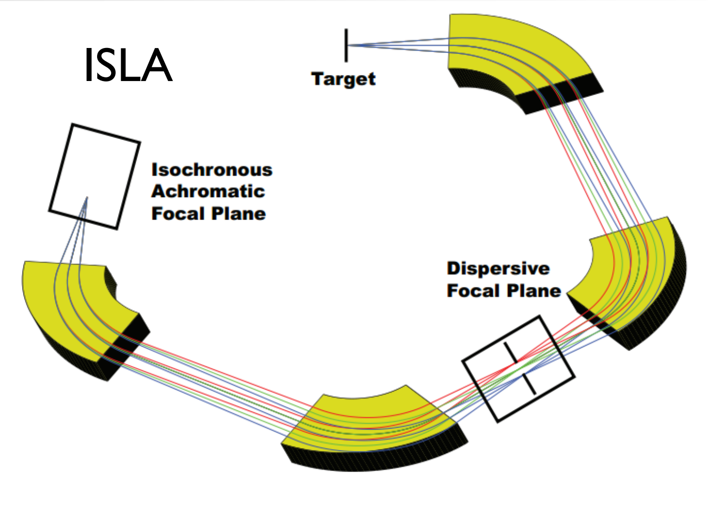


Electro-Magnetic Mass Analyzer (EMMA)

VAMOS



ISLA

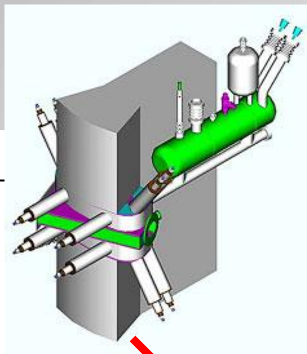


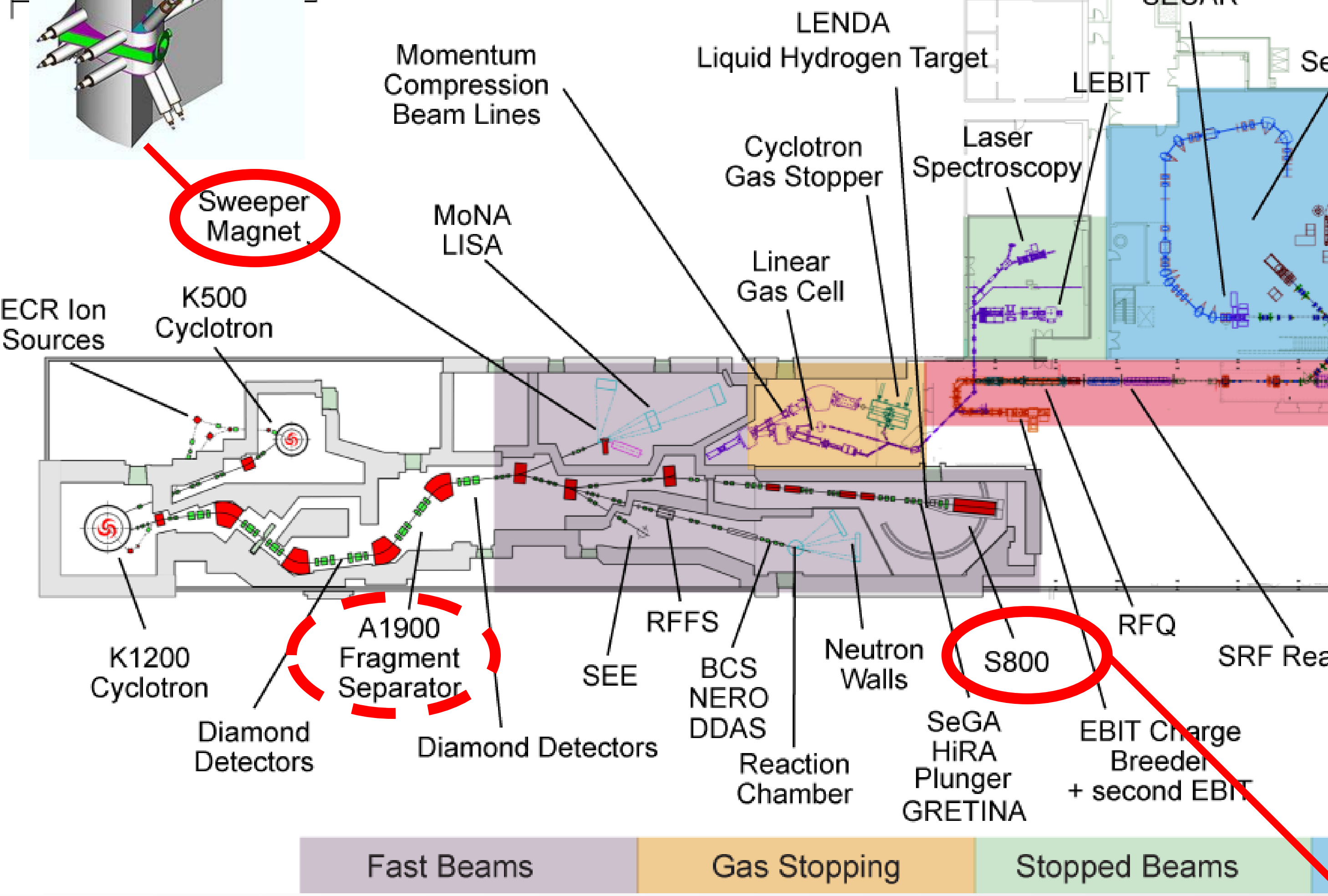
Berkeley Gas-filled Separator

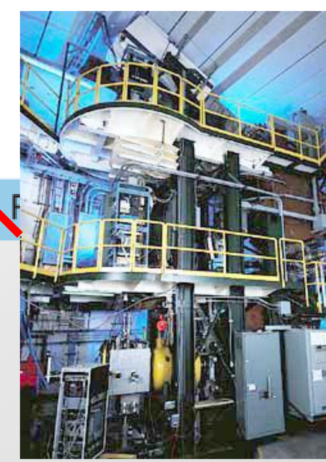
Gas-filled separator SASSYER

Isochronous Spectrometer with Large Acceptance (ISLA)

Spectrometers for fast beams at NSCL



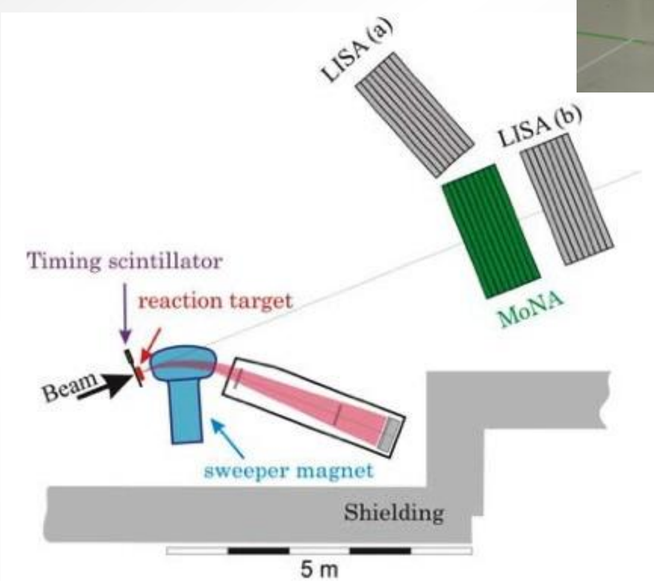


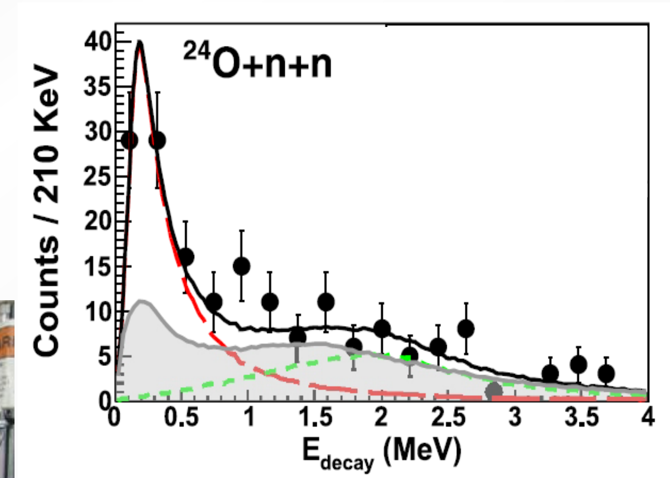


The magnetic rigidity of the S800 and Sweeper are limited to ~4 Tm.

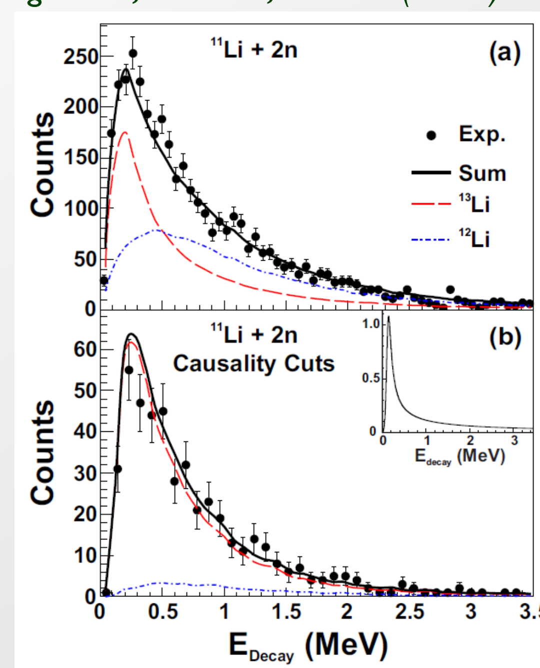
Sweeper Magnet + MoNA-LISA

Primary physics program:
Decay Spectroscopy at and beyond the Neutron Dripline
Sweeper: Low-Resolution, Large Acceptance spectrometer





First observation of ^{26}O ground state
E. Lunderberg et al., PRL 108,142503 (2012)

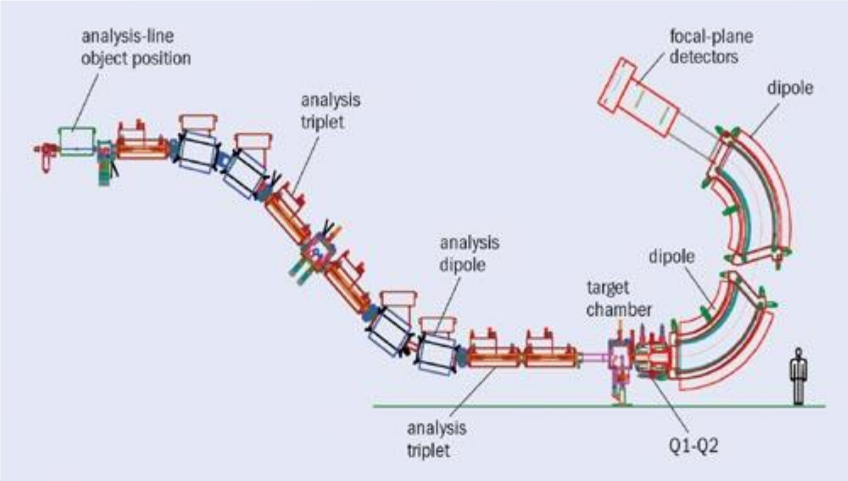


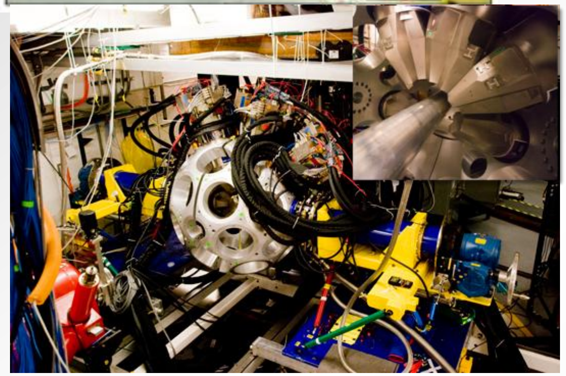
Strong Motivation for spectrometer at FRIB

First observation of ^{13}Li Ground State
Z. Kohley et al., PRC (Vol. 87, 011304(R))

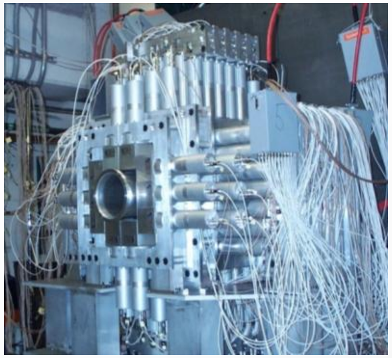
S800 Spectrometer

High resolution (dispersion matching)
Medium Momentum Acceptance (dp/p=5%)
Large Angular Acceptance (20 msr [120x170 mrad])
Bending Angle/Radius 150^0/2.8 m
QQDD layout

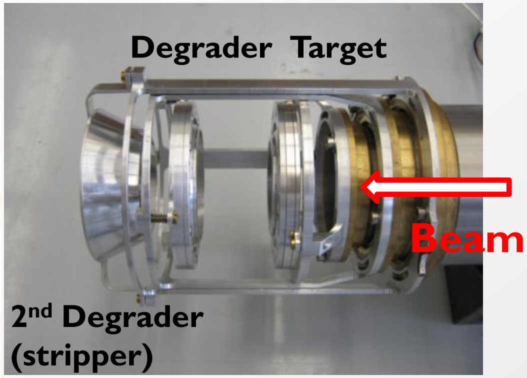




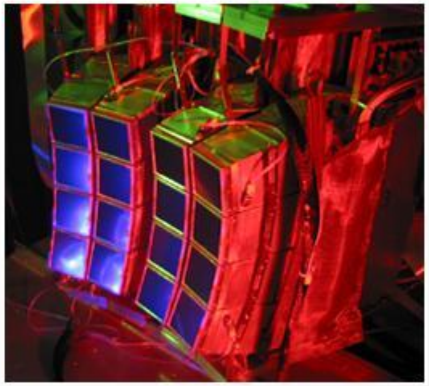
Gretina



CAESAR



TRI-foil PLunger for EXotic beams

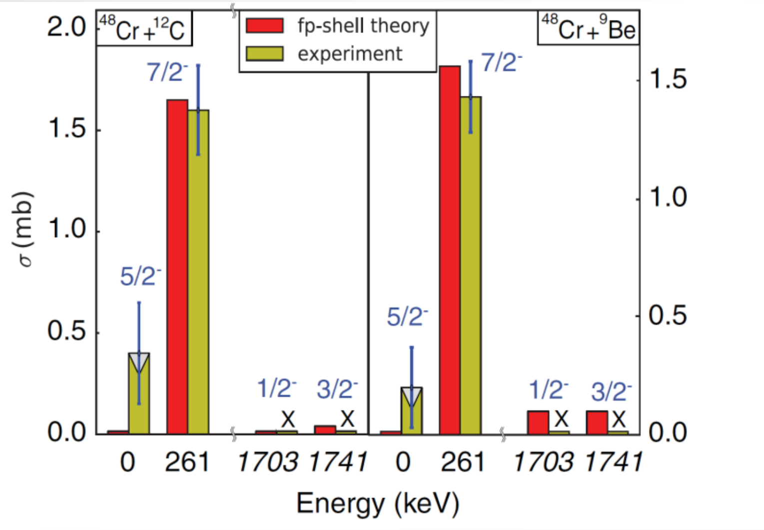


HiRA

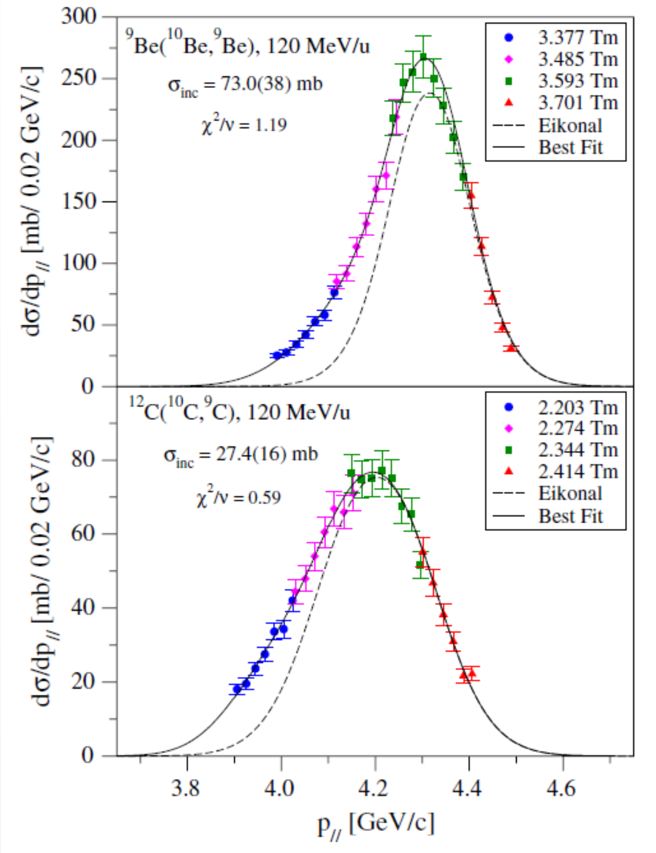
LENDA

Physics with the S800 spectrometer: in-beam γ-ray spectroscopy I

- Spectroscopy of the nuclear wave function – probing single particle structure
  - Sensitive to hole configurations: One- and two-nucleon knockout reactions
  - Sensitive to particle configurations: C and Be-induced one-nucleon pickup reactions
  - Inelastic scattering
  - …



Heavy-ion induced pickup using fast beams with γ-ray tagging
S. McDaniel et al., PRC 85, 014610 (2012)

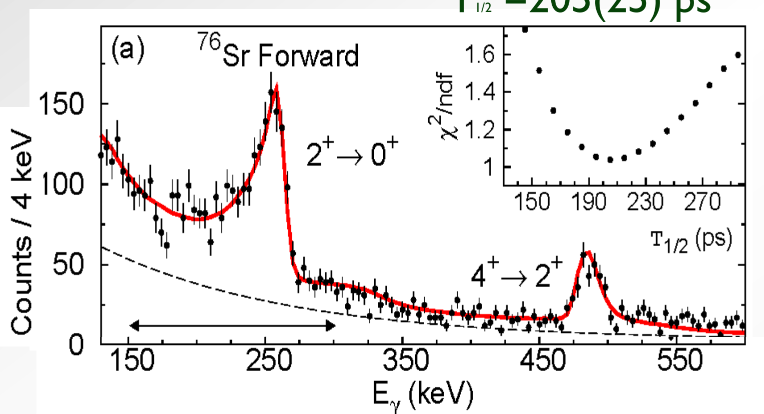


Knockout reactions from p-shell nuclei: Tests of ab initio structure models *G.F. Grinyer, et al., PRL106, 162502 (2011)*

Physics with the S800 spectrometer: in-beam γ-ray spectroscopy II

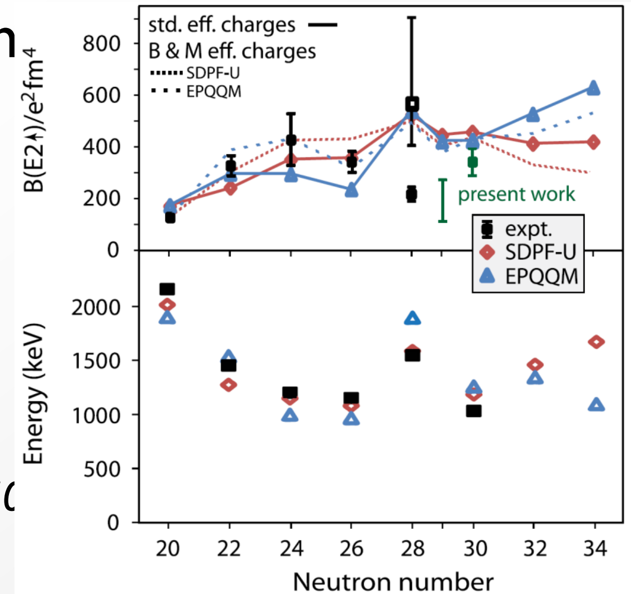
- Exploring the collectives degree of freedom
  - Intermediate-energy Coulomb excitation
  - Excited-state lifetime measurements

$T_{1/2}$ =205(25) ps

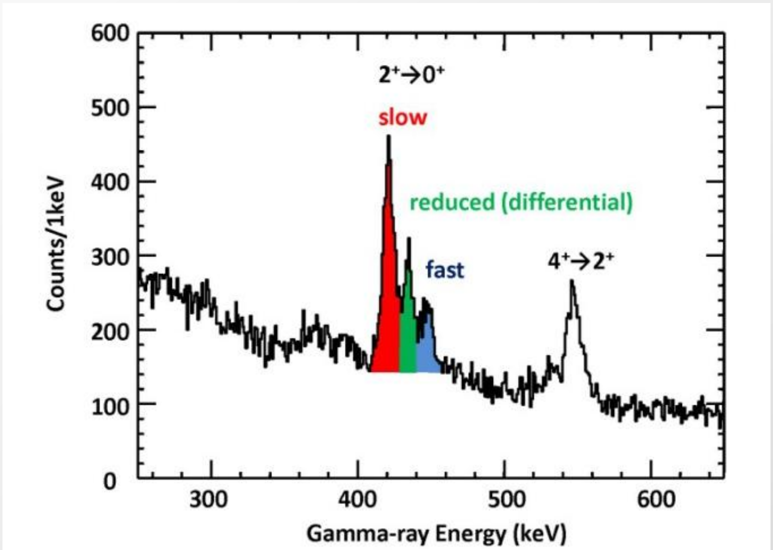


Line-shape life-time measurement of ^{76}Sr
A. Lemasson et al., Phys. Rev. C *85,041303 (R) (2012)*

Studies of Quadupole Collectivity in Coulomb excitation of $^{47}Ar/^{48}Ar$
R. Winkler, PRL 108, 18250 (2012)



Tri-foil plunger experiment with GRETINA
H. Iwasaki et al. (^{74}Kr)

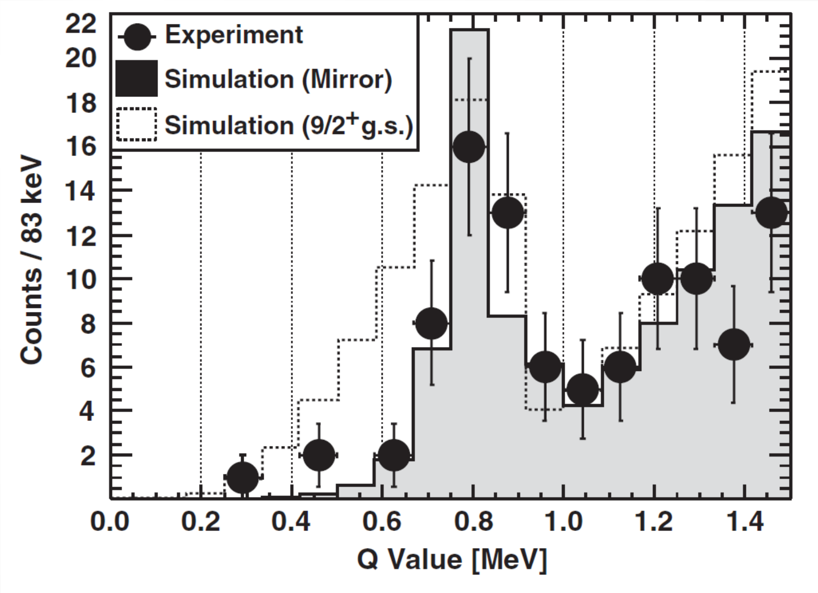


Physics with the S800 spectrometer: in-beam particle-decay spectroscopy

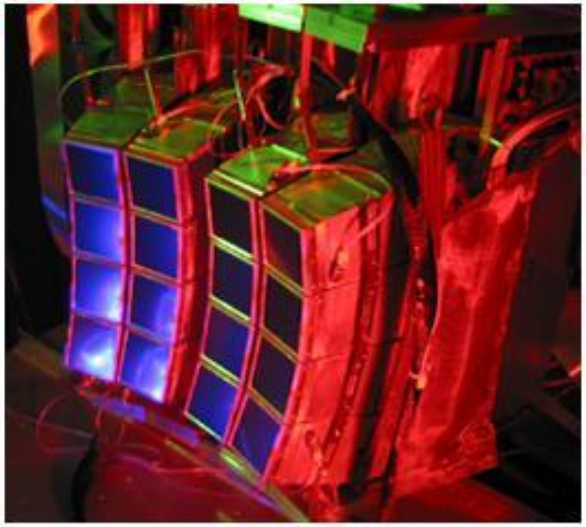
Direct measurement of the ground-state one-proton decay from ^{69}Br using the High Resolution Array at the S800

Ground-state proton decay of ^{69}Br and implications for the ^{68}Se rp process waiting point

A.M. Rogers et al., PRL 106, 252503 (2011)

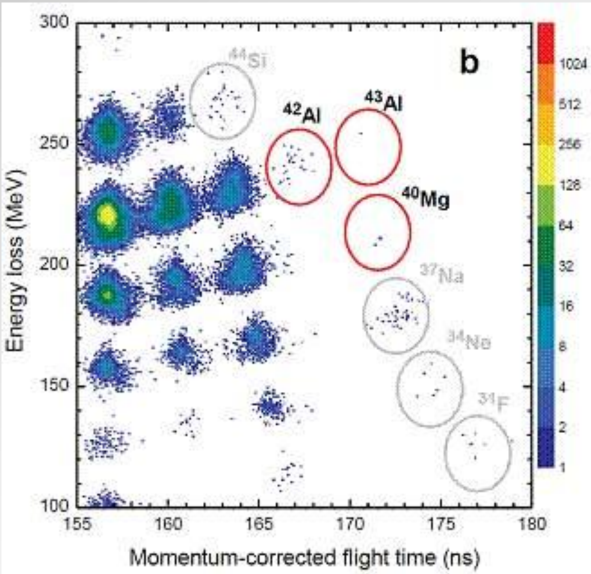


Relative-energy spectrum for the $^{69}Br \to p + ^{68}Se$ reaction; best fit is achieved assuming a ^{69}Br $3/2^-$ ground state with $S_p = -785_{-40}^{+34}$ keV

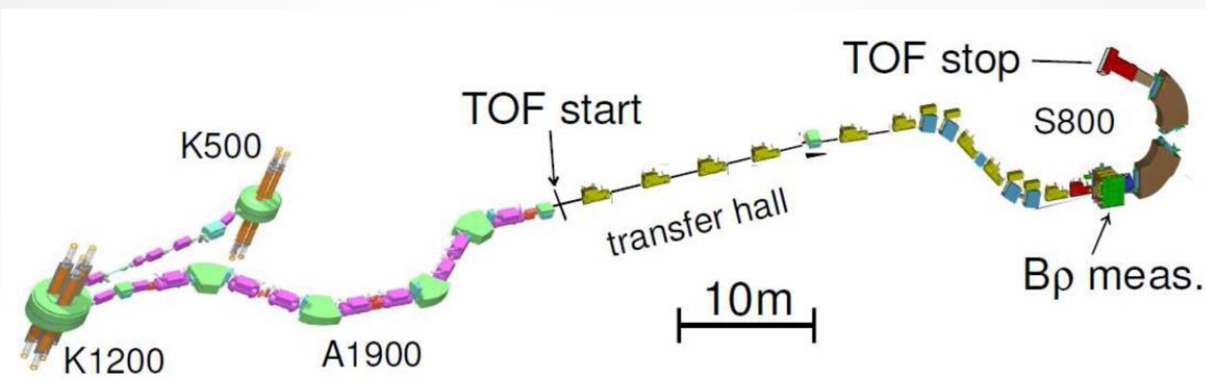


HiRA

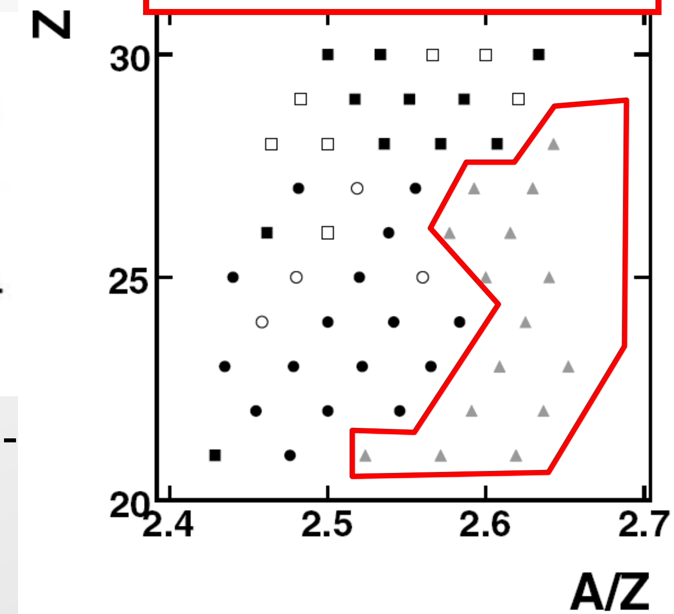
Isotope discovery and masses



T. Baumann et al., *Discovery of 40Mg and 42Al*, Nature 449, 1022 (2007).
Used A1900+S800 two-stage separator technique

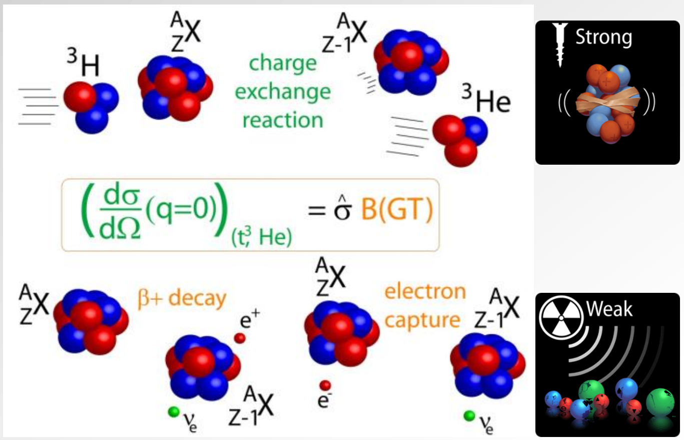


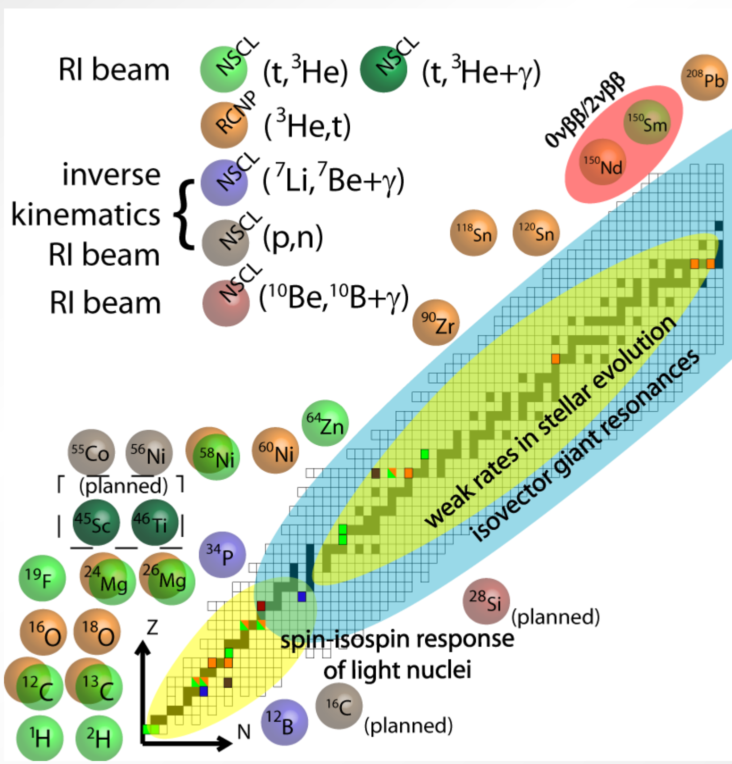
New (4) or improved (12)
masses dm ~ 200-800 keV



Mass measurements of very n-rich isotopes in scandium-nickel region via their time of flight *A. Estrade et al., PRL 107,172503 (2011)*

nuclear charge-exchange reactions as a probe of weak transition strengths





Astrophysics – weak reaction rates

t,^{3}He | t,^{3}Heγ | ^{3}He,t | p,n

(Neutrinoless) Double beta decay

t,^{3}He | ^{3}He,t

Shell evolution in light systems

t,^{3}He | ^{3}He,t | ^{7}Li,^{7}Beγ

Giant resonances and the macroscopic properties of nuclear matter

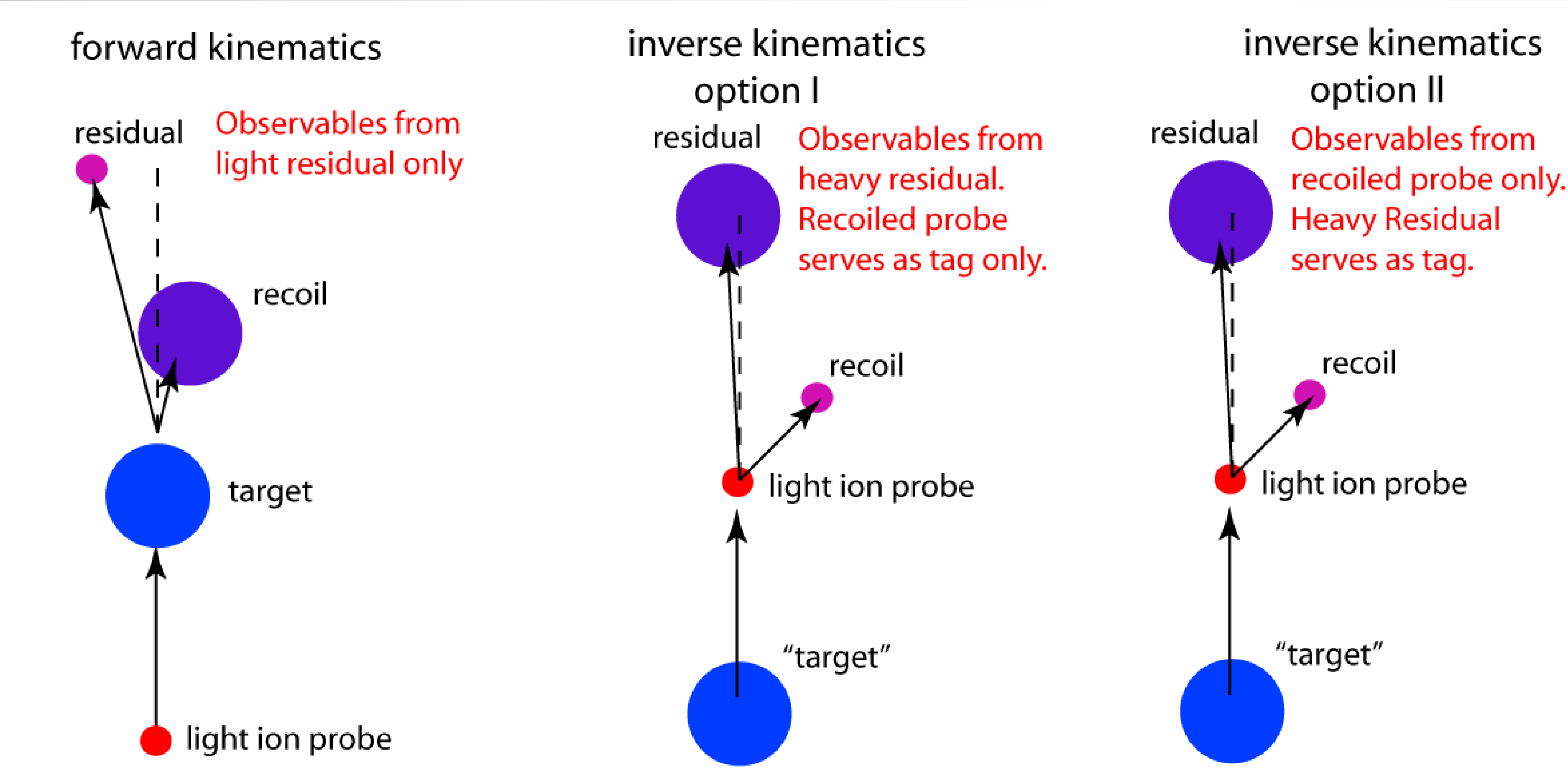
t,^{3}He | ^{3}He,t | p,n | ^{10}Be,^{10}Bγ

Novel probes for isolating particular responses

^{7}Li,^{7}Beγ | ^{10}Be,^{10}Bγ | t,^{3}Heγ

Studies of the charge-exchange reaction mechanism

t,^{3}He | ^{3}He,t



e.g. $(t,{}^{3}He)$

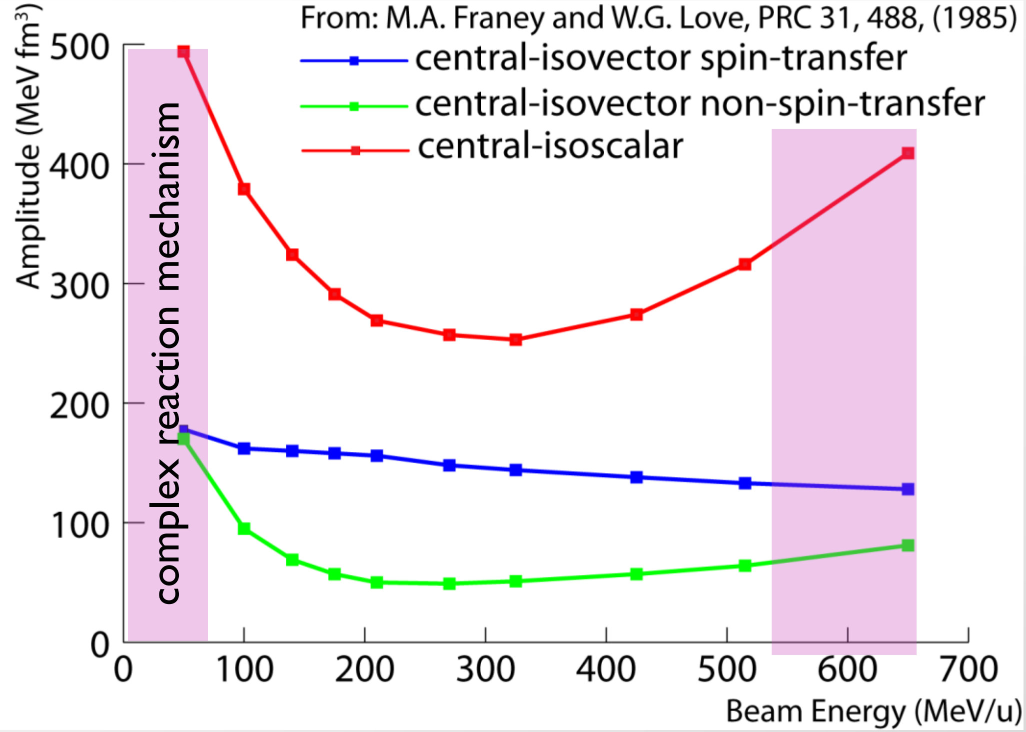
e.g. $({}^{7}Li\ {}^{7}Be)$

e.g. (p,n)

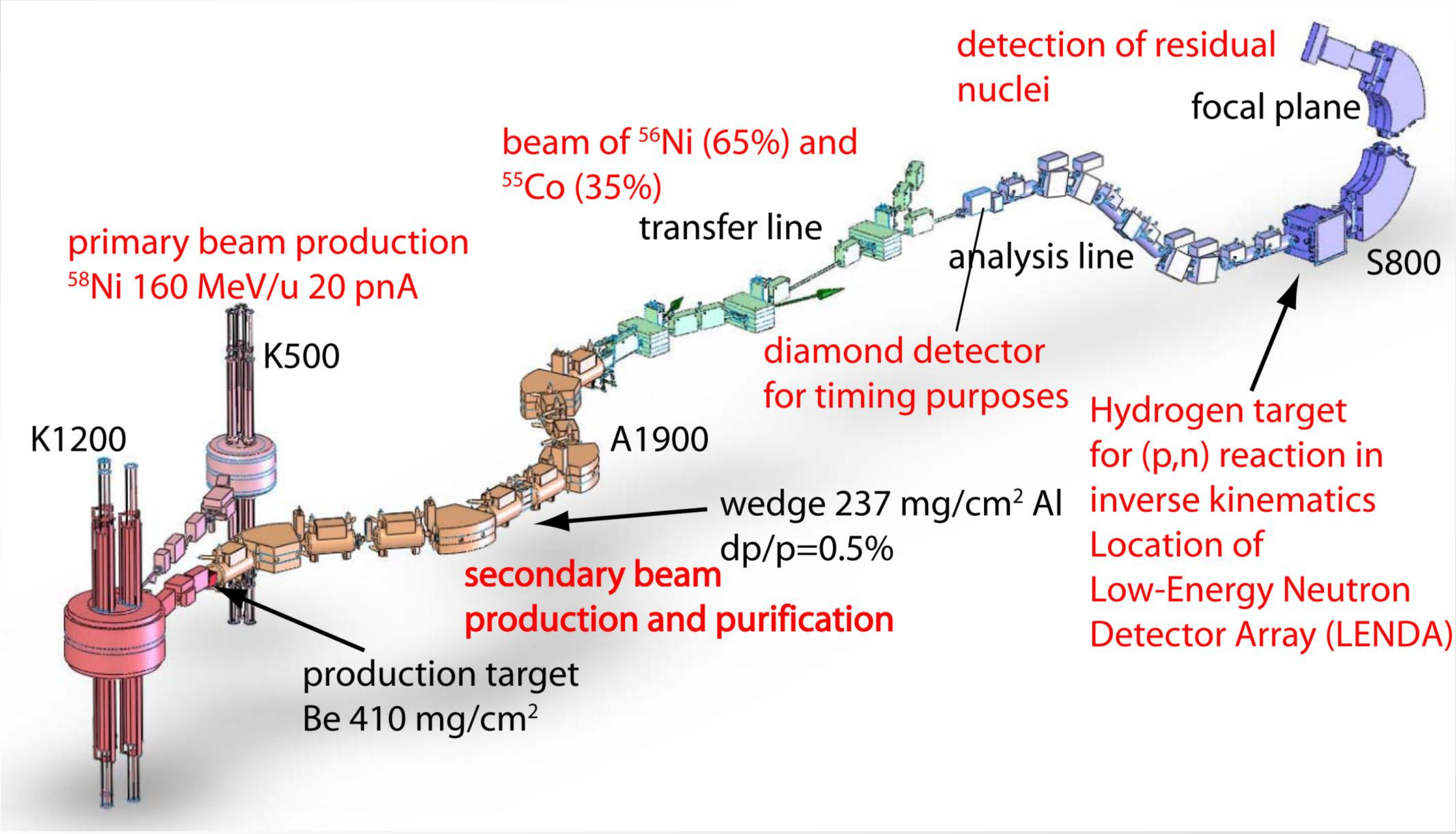
charge-exchange reactions

- spin-isospin response of nuclei at low (structure) and high excitation energies (giant resonances)
- applications in astrophysics (electron-captures, β-decay, neutrino interactions) and astro neutrino physics
- map the isovector part of the nucleon-nucleon effective interaction, including tensor contributions
- (neutrinoless) double β-decay

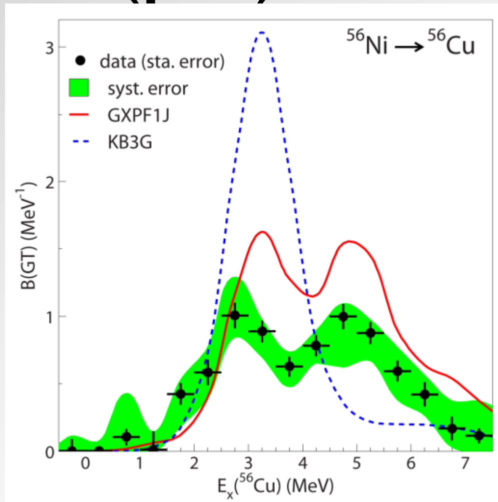
- different beam energies
- different probes with special selectivity

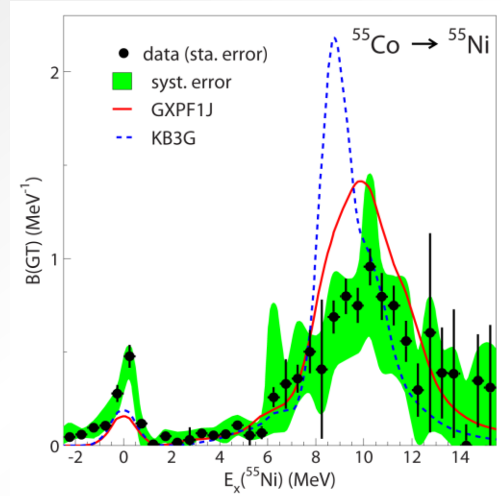


^{56}Ni(p,n) experiment at 110 MeV/u in inverse kinematics

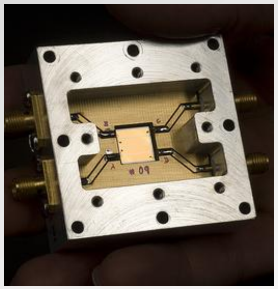


(p,n) in inverse kinematics



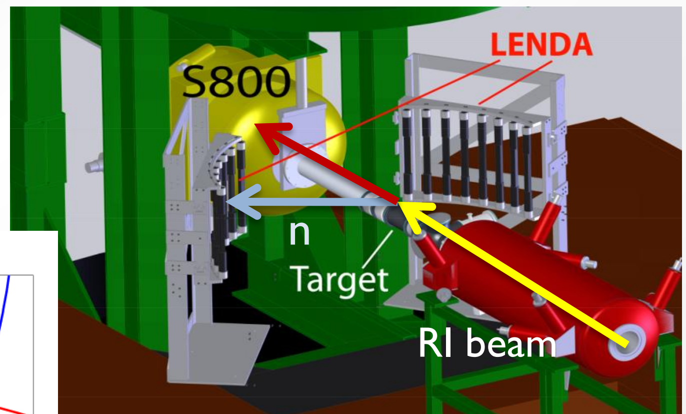


30 cm



Diamond detector

Beam particle timing



Low Energy Neutron Detector Array (LENDA)

neutron detection

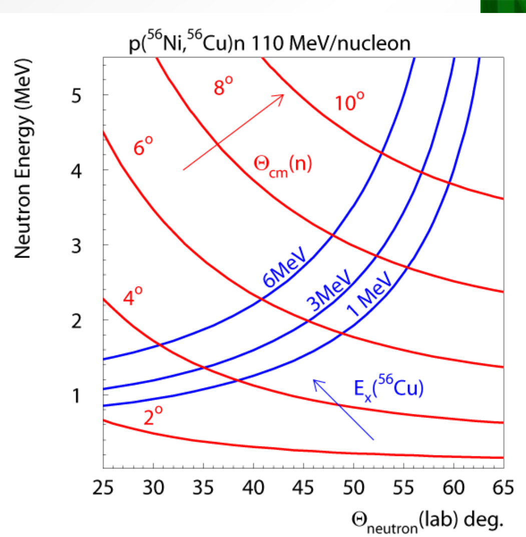
Plastic scintillator

24 bars 2.5x4.5x30cm

150 keV < E_n < 10 MeV

ΔE_n ~ 5% $\Delta\theta_n < 2°$

efficiency 15-40%



Liquid Hydrogen target

"proton " target

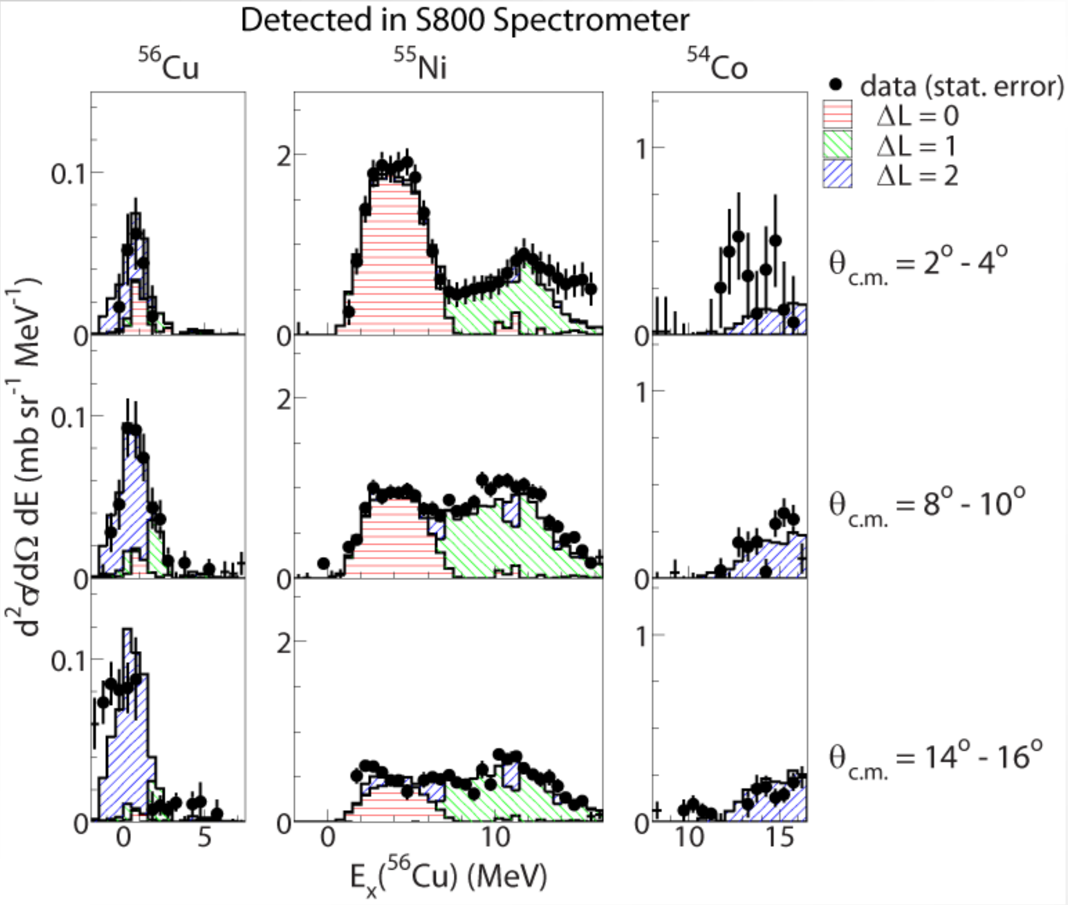
65 mg/cm^2 (~7 mm)

~3.5 cm diameter

T=20 K ~1 atm

M. Sasano et al., Phys. Rev. Lett. 107, 202501 (2011),Phys. Rev. C 86, 034324 (2012)

Some details

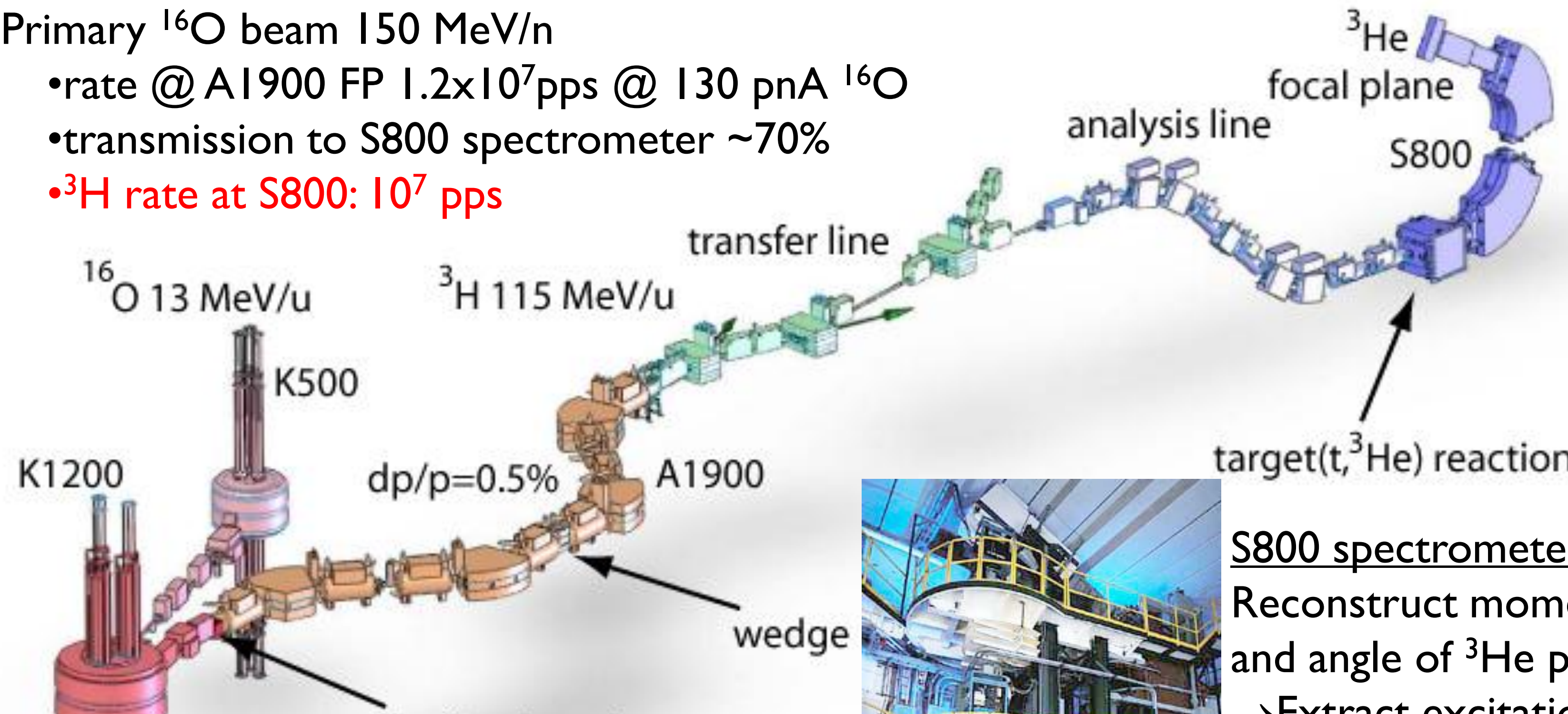


- Reconstruction of excitation energy and scattering angle from detection of slow neutron in LENDA only
- Detection of heavy residual (^{56}Cu or one of its decay products) in spectrograph serves as tag for CE reaction.
- Analysis similar to (p,n) experiment in forward kinematics
- required good PID capability in S800, but momentum/angle resolution not as critical.

The RI beam was a cocktail of ^{56}Ni and ^{55}Co-GT strengths measured from both. Spectrometer not run in dispersion-matched mode

Producing a triton beam for (t,^{3}He) experiments

Primary ^{16}O beam 150 MeV/n
- rate @ A1900 FP 1.2×10^{7}pps @ 130 pnA ^{16}O
- transmission to S800 spectrometer ~70%
- ^{3}H rate at S800: 10^{7} pps

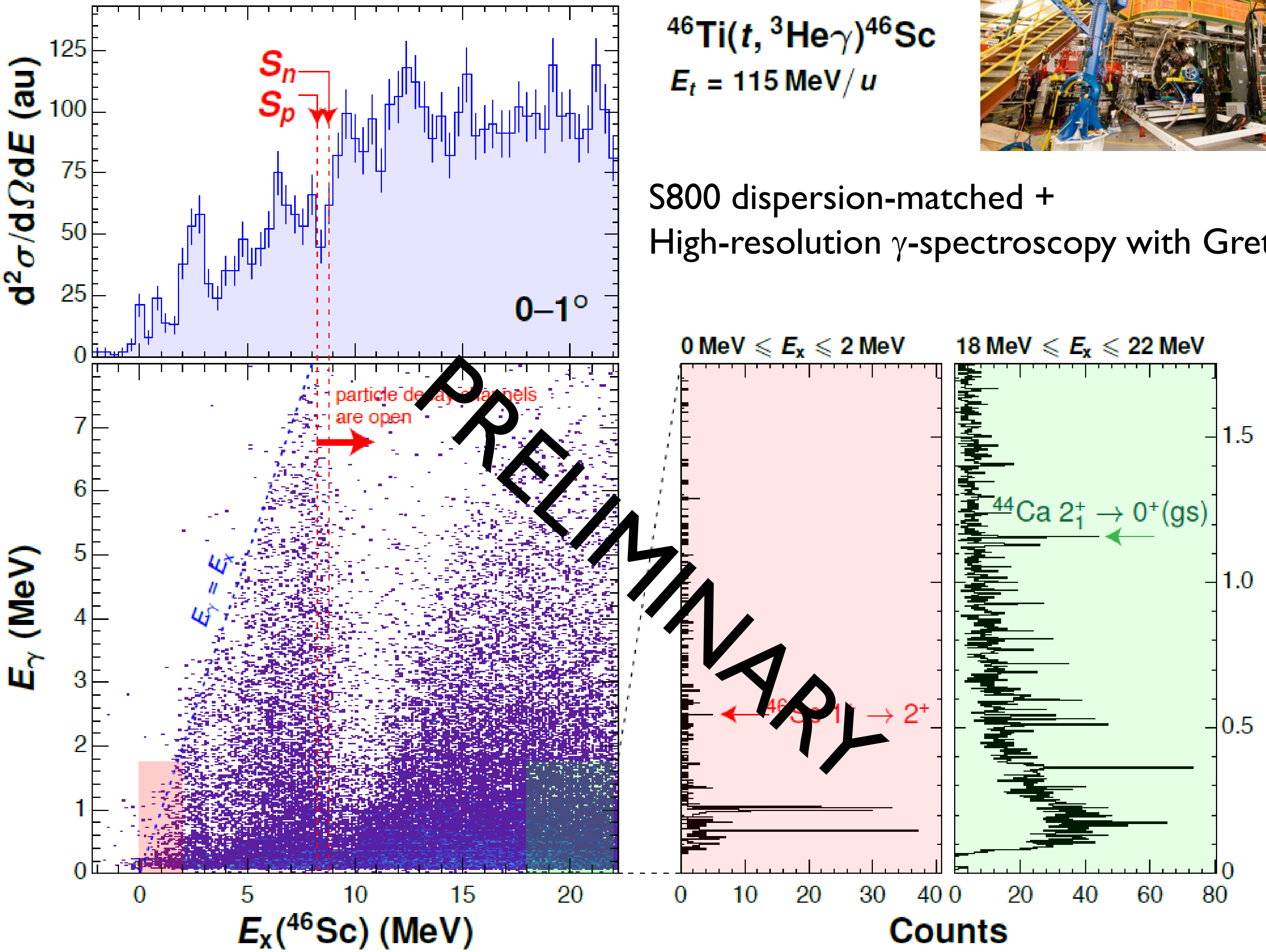


S800 spectrometer
Reconstruct momentum and angle of ^{3}He particle
→Extract excitation-energy and center-of-mass scattering angle from two-body kinematics

Thin wedge is needed to remove ^{6}He (^{9}Li)
Background channel ^{6}He->^{3}He + 3n

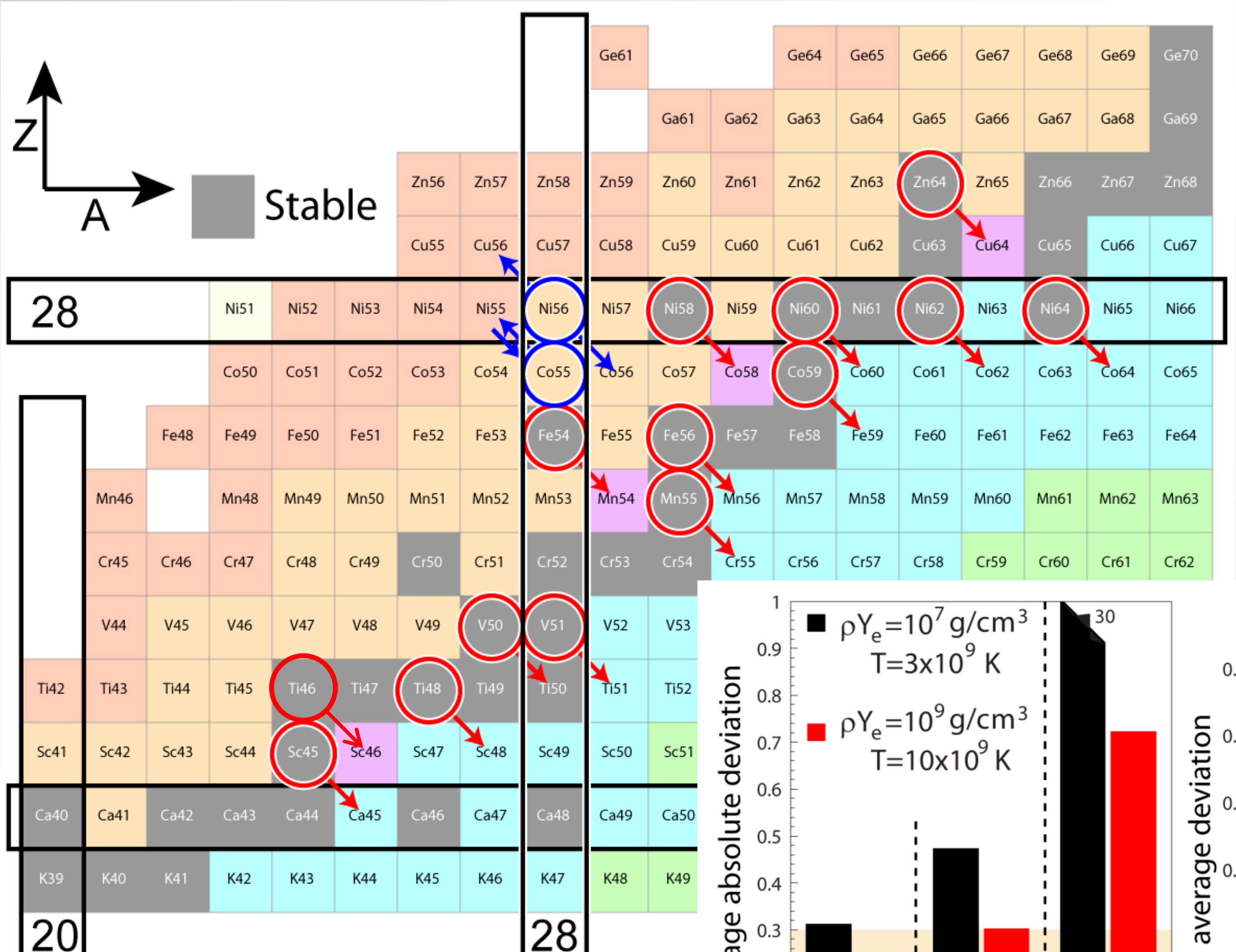
G.W. Hitt Nucl. Instr. and Meth. A 566 (2006), 264.

(t,^{3}He+γ)



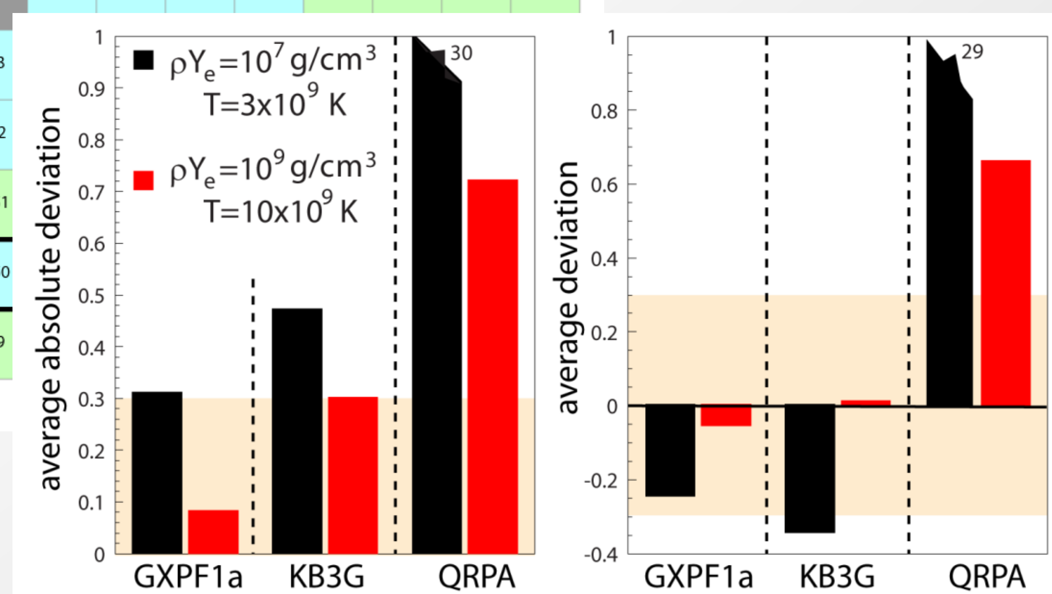
S800 dispersion-matched +
High-resolution γ-spectroscopy with Gretina

Astrophysical electron-capture rates on pf-shell nuclei



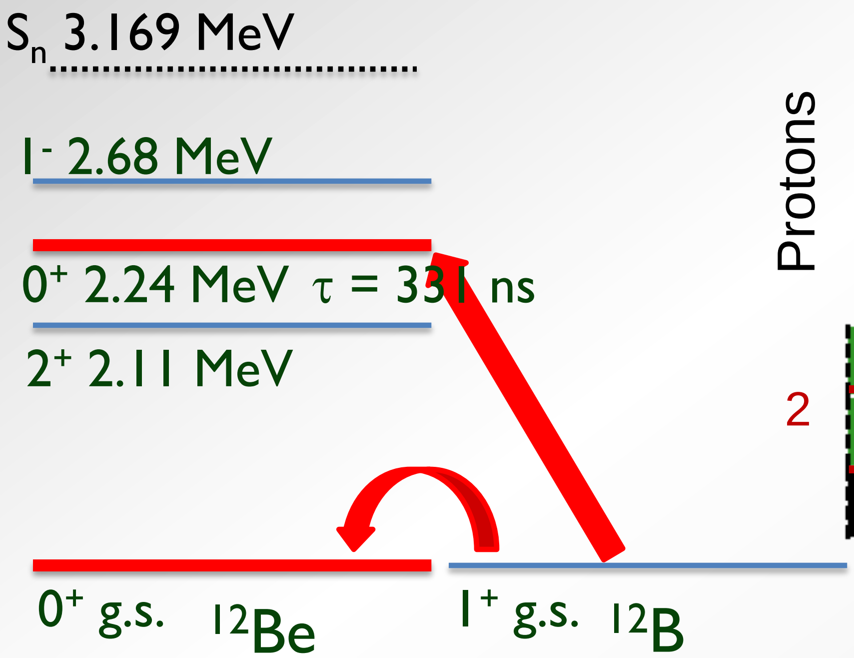
(n,p) – TRIUMF, RCNP
(d,^{2}He) – KVI
(t,^{3}He) - NSCL

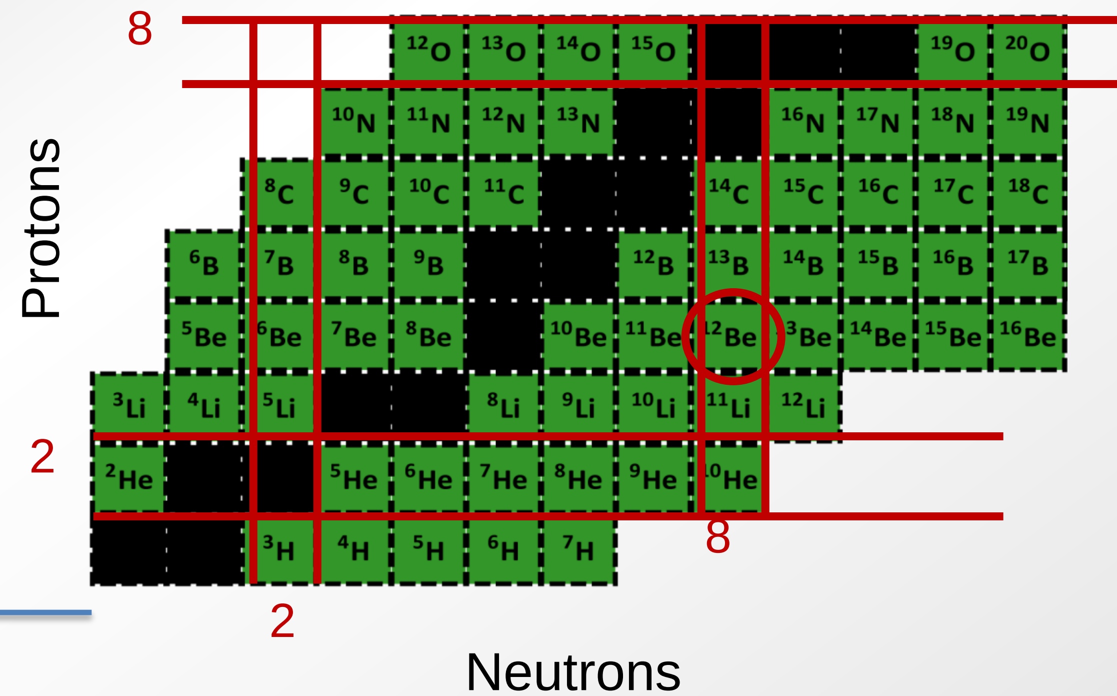
A. Cole et al.,
PRC 86, 034324 (2012)



$$\overline{|\Delta_{EC}|} = \frac{1}{N}\sum_{i=1}^{N}\frac{|\lambda_i^{th} - \lambda_i^{exp}|}{\lambda_i^{exp}}$$

$^{12}B(^7Li,^7Be)$ in inverse kinematics: configuration mixing around N=8 shell closure

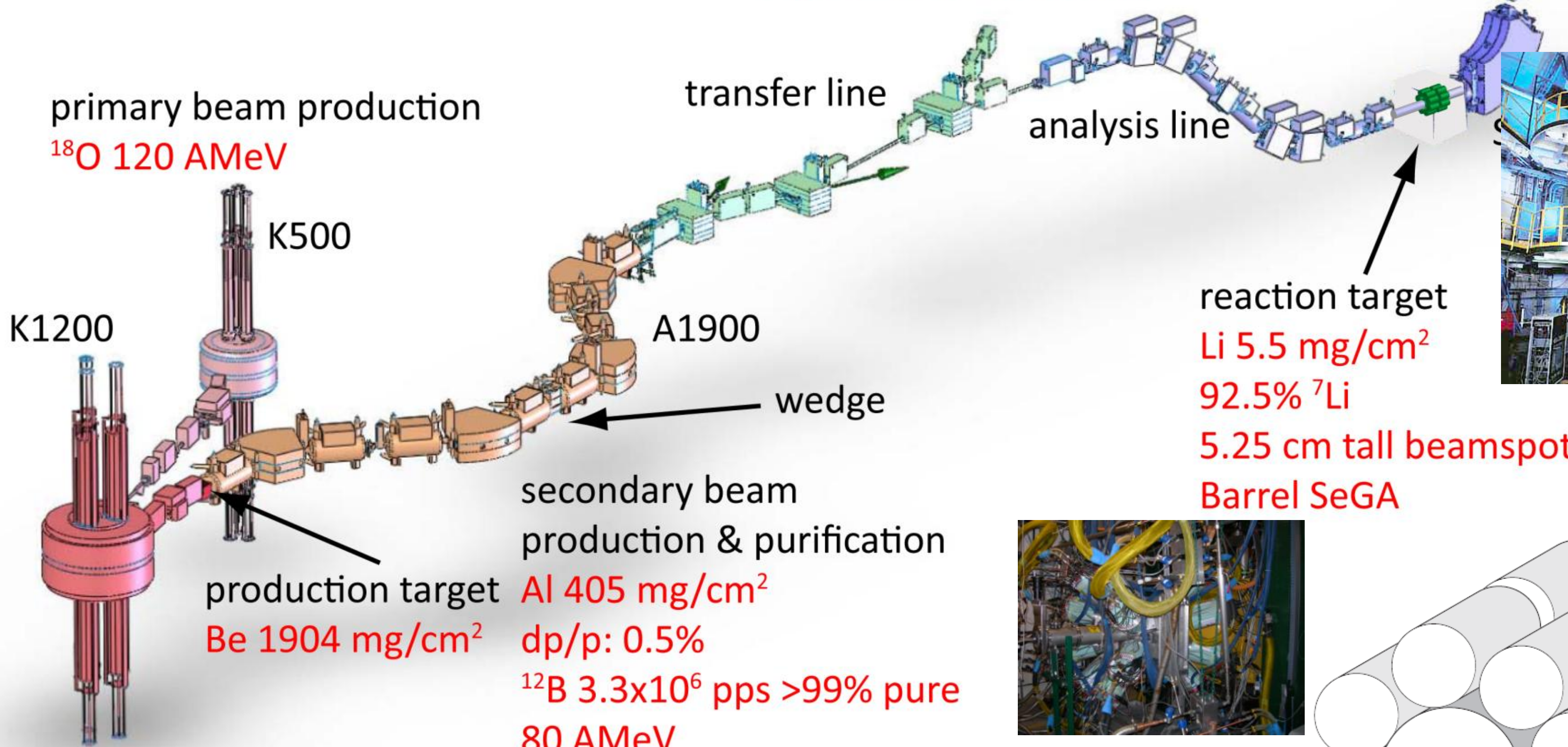


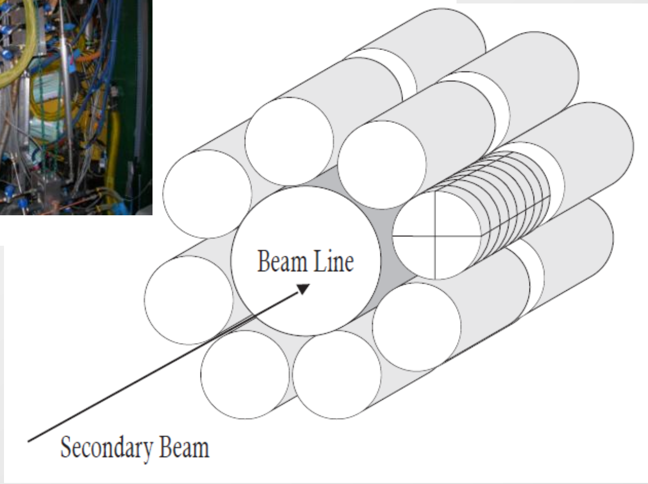


- Knockout, transfer studies probe the *sd*-component of the ^{12}Be 0^+ state wavefunctions
- Gamow-Teller transitions: ΔL=0, ΔS=1, 0ħw
  - Ground-state of ^{12}B(1^+) is predominantly 1*p*-shell in nature
  - GT transitions to 0^+ states in ^{12}Be probe 1*p*-component of wavefunction
  - B(GT) is a direct reflection of *p*-shell component of 0^+ states

Experimental setup

"Low" beam energy is better!
Excitation energy and scattering determined from S800





Segmented Germanium Array:
Doppler reconstruction (in flight γ-rays from ^{12}Be)
Stopped γ-rays (from ^{7}Be)

Probing configuration mixing with Gamow-Teller strengths

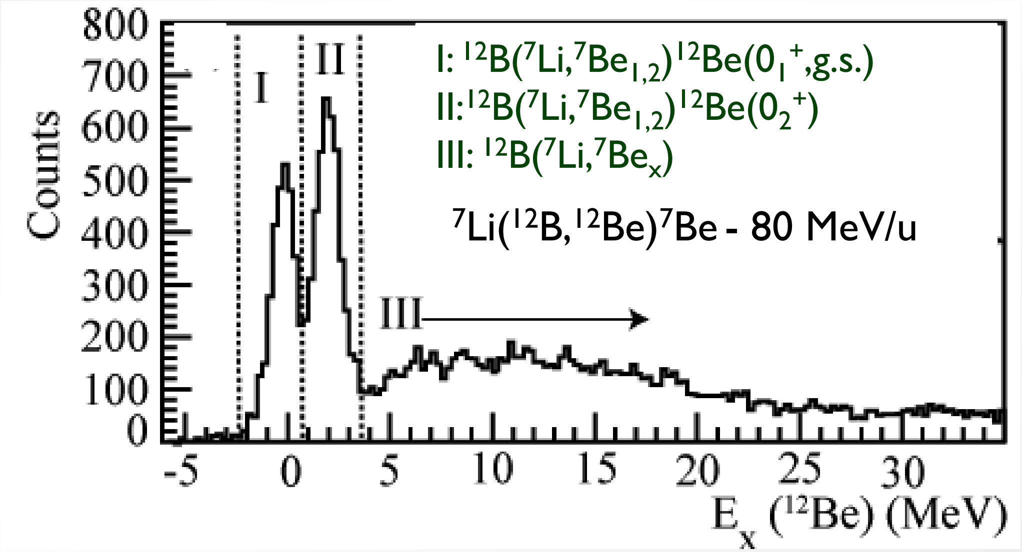
*R. Meharchand et al., PRL **108**, 122501 (2012)*

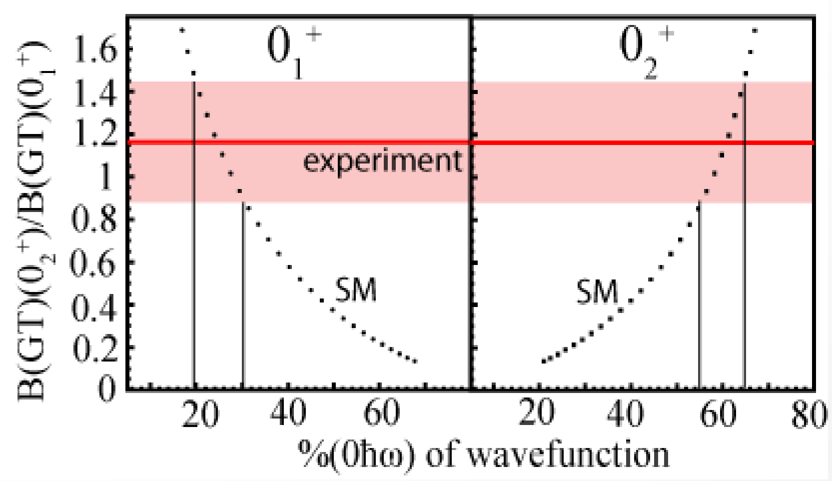
$^{7}Li(^{12}B,^{12}Be^{*})^{7}Be^{*}$reaction

S800 (dispersion matched)

Segmented Germanium Array

(sensitively tag the reaction channel)





Ratio $B(GT)[0_2^+]/B(GT)[0_1^+]$ is used to extract the 0ħω (p-shell) component of the $^{12}Be(0^+)$ states.

Result: 0_1^+: 25±5% (0ħω) 0_2^+: 60±5% (0ħω) ; helps resolve long standing debate

Sensitive probe for shell configuration mixing in rare isotopes

*R. Meharchand et. al., PRL **108**, 122501 (2012)*

beam energies

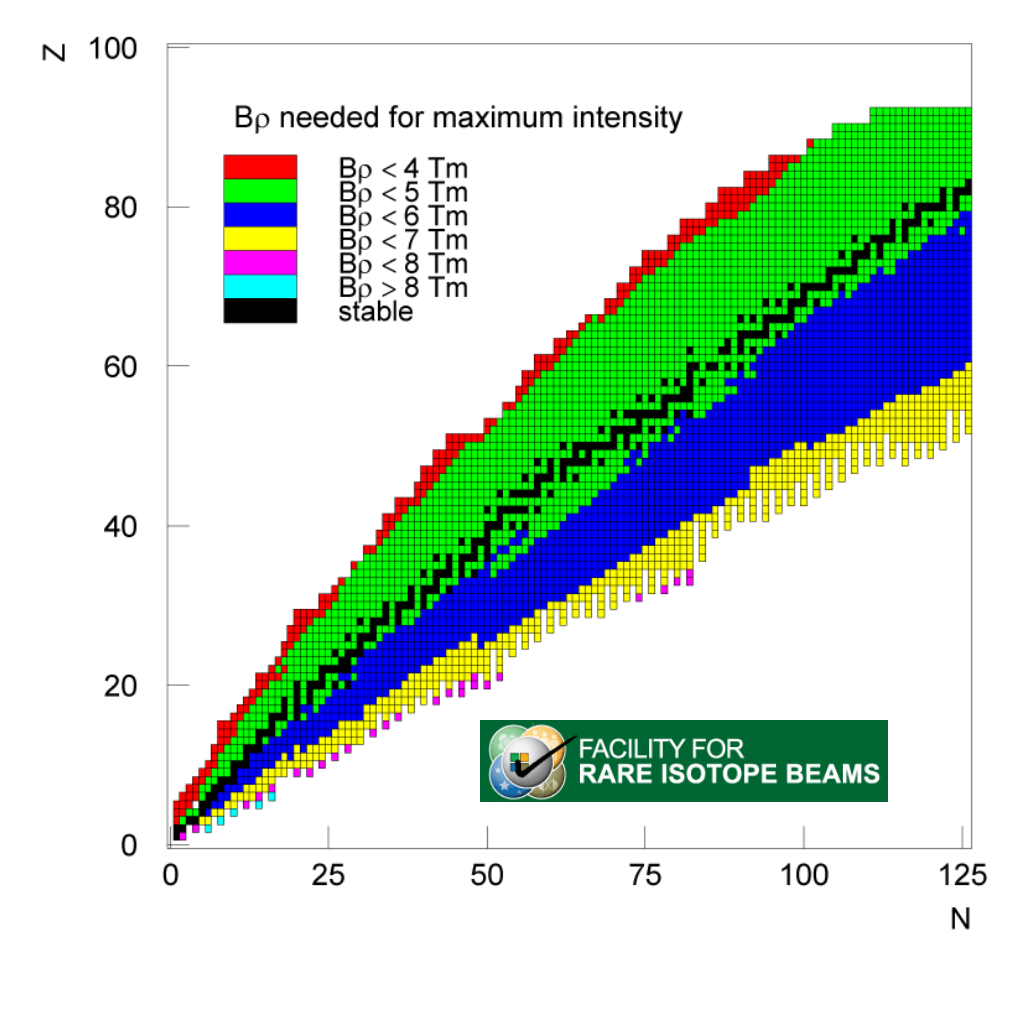
- some physics objectives are best achieved at certain beam energies
- to understand model dependences certain experiments are best performed at several beam energies
- experience with stable beams has often been restricted to a limited set of energies
- kinematical and resolution conditions can constrain the choice of beam energy

experiments with fast beams at spectrometers

- Elastic (proton) scattering
- decay spectroscopy near the dripline – unbound states
- Total absorption measurements
- Knockout/pickup reactions
- Quasifree scattering reactions such as (p,2p), (p,pn) and (p,pd)
- Charge-exchange and inelastic reactions
- Projectile fragmentation and fission reactions
- Invariant mass spectroscopy
- Heavy-ion induced electromagnetic excitations
- …

Not all are best performed at FRIB energies…
(until energy is upgraded)

Rigidity



Optimum Rigidities for neutron-rich rare isotopes are beyond the capabilities of the S800 and Sweeper magnets.

Slowing down the beams reduces the intensity and increases contaminant and charge-state distributions, and requires reducing the reaction target thickness

FRIB energy upgrade
200 MeV->400 MeV

Fast-beams at FRIB

HRS
Replaces sweeper

- High-Rigidity
- Medium resolution
- Large acceptance
- Variety of auxiliary detectors-maximize beam opportunities

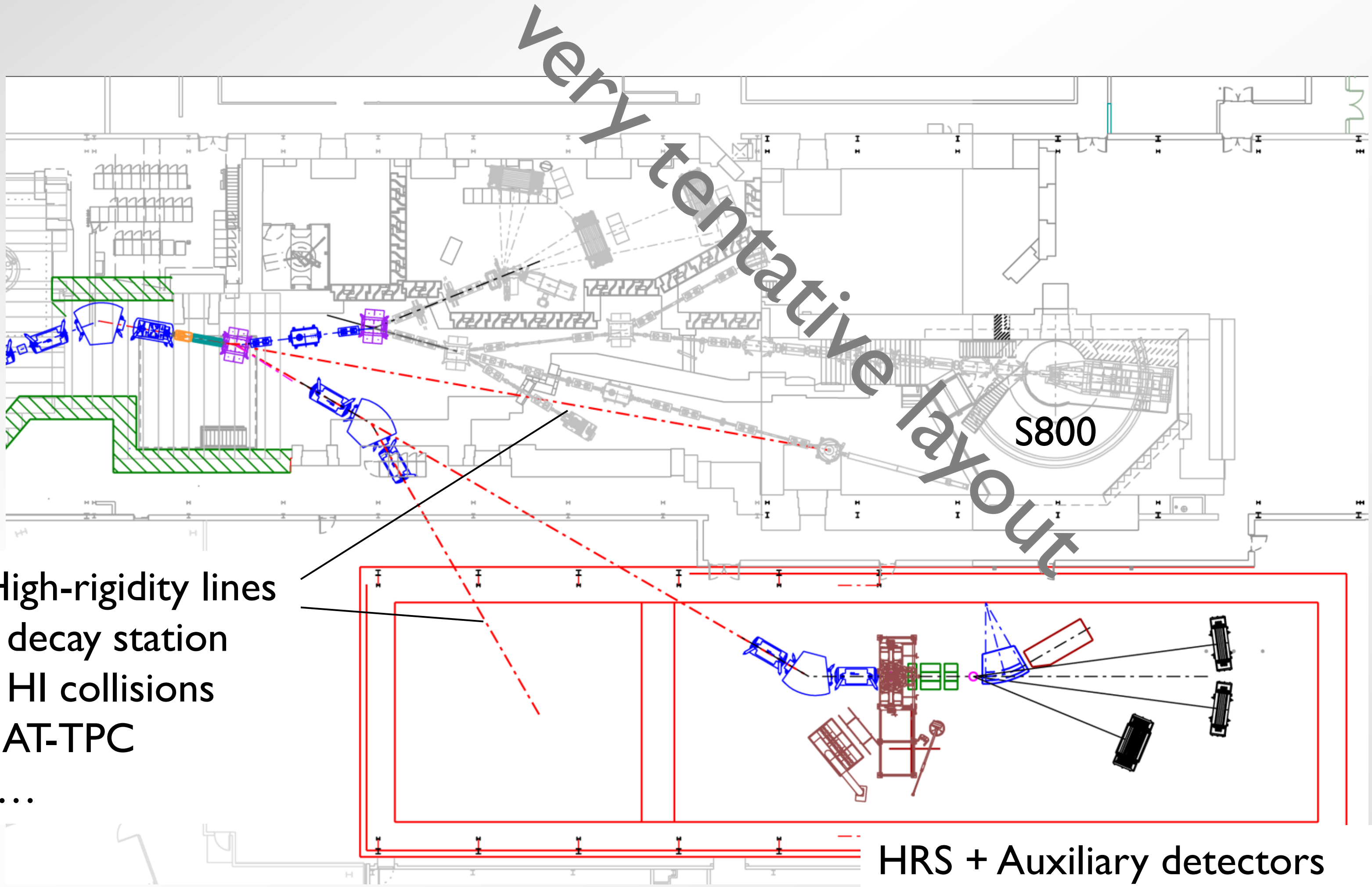
S800

- Medium rigidity (experiments at 50-100 MeV/u)
- Large Acceptance
- High resolution
- Auxiliary detectors

Multi-purpose station(s)

- Decay Station
- Heavy-ions collisions
- AT-TPC
- …

Possible layout of additional fast-beam experimental areas



High-rigidity lines
- decay station
- HI collisions
- AT-TPC
- …

HRS + Auxiliary detectors
(MoNA-LISA, GRET(IN)A, AT-TPCetc.)

A possible HRS@FRIB

	Dipole	Quadrupole Triplet		
	Dipole	Quadrupole 1	Quadrupole 2	Quadrupole 3
Bending angle	30^0			
Bending Radius	4.5 m			
Vertical gap	30 cm			
Half Hor. gap	25 cm (C-type)			
Length	2.35 m	50 cm	120 cm	80 cm
Max. B-field	1.6 T	2.5 T (pole tip)	-2.3 T (pole tip)	2.1 T (pole tip)
Type	Iron Saturated	Superconducting	Superconducting	Superconducting
Warm bore radius		20 cm	25 cm	25 cm
Pole tip radius		23 cm	28 cm	28 cm

Parameter	S800@FRIB	HRS
Energy resolution	1/2000 (1/10000 with tracking/primary beam)	1/1400 with tracking
Bending Capability	4 Tm (beam line 5 Tm)	7 Tm
Momentum Acceptance	5%	10%
Angular acceptance	20 msr (120 mrad x 170 mrad)	20 msr (120 mrad x 170 mrad)
Bending angle/radius	150^{o}/2.8 m	30^{o}/4.5 m
Layout	QQDD	QQQD
Focal plane detectors	Ion Chamber/CRDCs/plastic scintillators/ Segmented CsI Hodoscope	Ion Chamber/CRDCs/plastic scintillators/ Segmented CsI Hodoscope
Tracking Detectors	Tracking PPACs/Channel Plates/ Segmented Diamond Detectors	Segmented Diamond Detectors
Other devices	SeGA/CAESAR/LENDA/ HiRA/Gretina/Greta	SeGA/CAESAR/LENDA/ Gretina/Greta/MoNA-LISA

summary

- Development of next generation spectrometers for experiments with fast and reaccelerated beams at NSCL and FRIB in progress
- Concepts for a new high-rigidity spectrometer for FRIB are being studied
- Experimental approaches at a variety of beam energies and with a variety of techniques are complementary and all are needed to accomplish a wide range a physics objectives with modern facilities