OPPORTUNITIES WITH DIRECT REACTIONS

D. Bazin
National Superconducting Cyclotron Laboratory
Michigan State University

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- *Probes to study nuclear structure*

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- *Provide selectivity of the final states populated*

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- *But…*
- *In almost all cases rely on reaction models*
- *Progress in direct reaction theory is crucial!*

Direct reactions with radioactive beams

- *Light target probes* ⇉ ***inverse kinematics***

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- *Low intensities* ⇶ ***high luminosities***

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Direct reactions with radioactive beams

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Knockout reactions

- *High luminosity for inverse kinematics*
  - *Inclusive measurement: thick targets*
  - *Fast beams: focusing of projectile residues in small solid angle*
  - *Momentum distributions (l) and high efficiency γ-ray array (final state)*
  - *Measurements possible down to ~ 1 projectile/second*
  - ***Very well suited to rare isotope beams produced via projectile fragmentation***

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- *High physics output*
  - *Single-particle components of projectile wave function*
  - *Spectroscopy of residual nucleus (hole states)*

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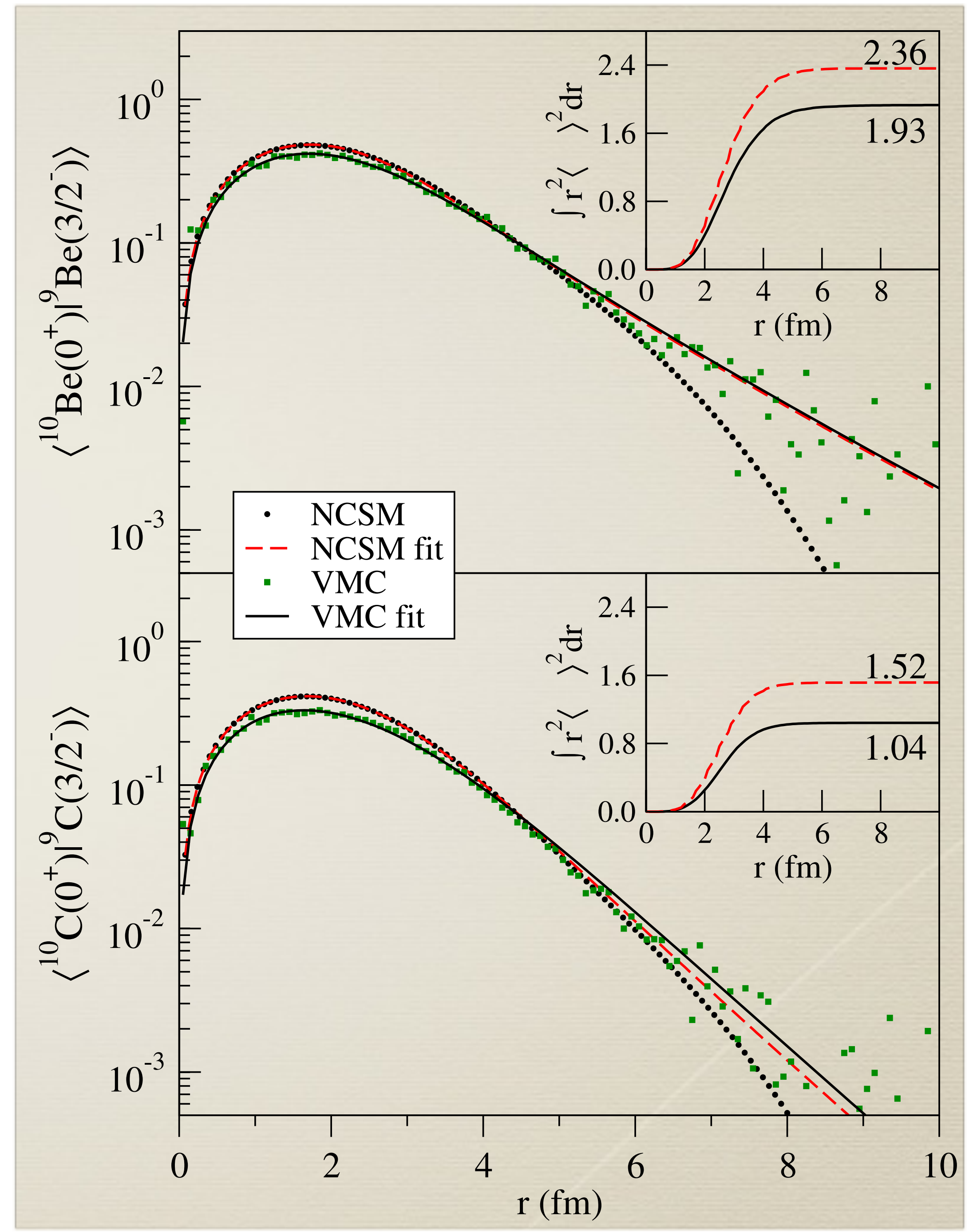
Test of ab initio structure models

- *One neutron knockout on ^{10}Be and ^{10}C (6.8 MeV and 21.3 MeV binding)*
- *Consistent calculation of eikonal cross sections*
- *First comparison of neutron single particle strength*
- *Complement to (e,e'p) on ^{7}Li and ^{12}C*

$\langle ^{10}\mathrm{Be} \vert ^{9}\mathrm{Be} + n \rangle$	S_F	σ_{th} (mb)	σ_{exp} (mb)
SM	2.62	96.6	
NCSM	2.36	86.9(16)	73(4)
VMC	1.93	72.8(13)	
$\langle ^{10}\mathrm{C} \vert ^{9}\mathrm{C} + n \rangle$			
SM	1.93	48.0	
NCSM	1.52	43.4(9)	23.2(10)
VMC	1.04	30.8(6)	



G. F. Grinyer *et al.*, Phys. Rev. Lett. **106**, 162502 (2011)

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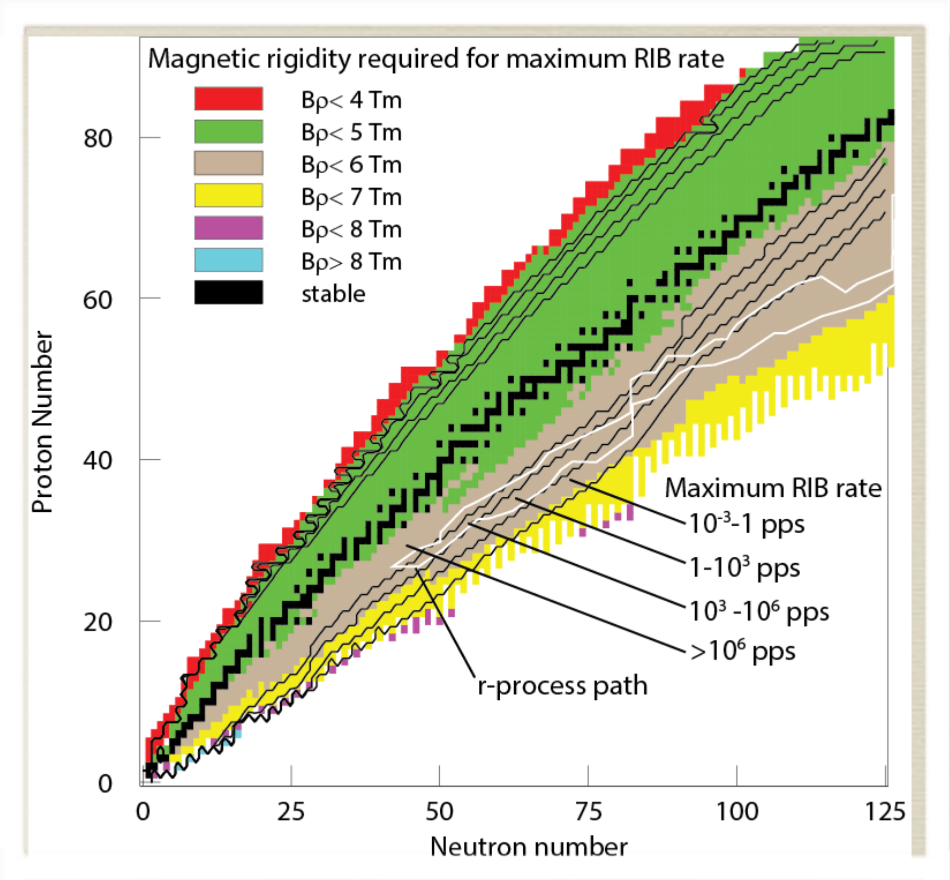
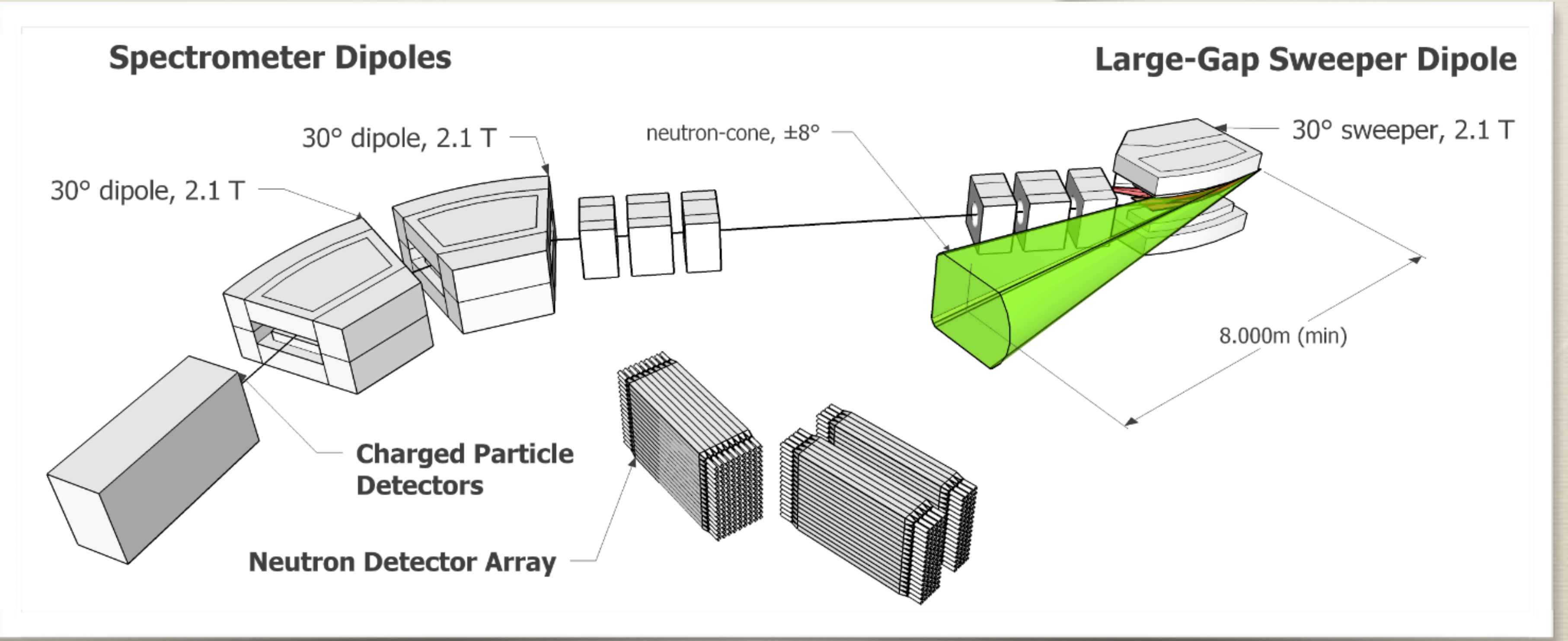
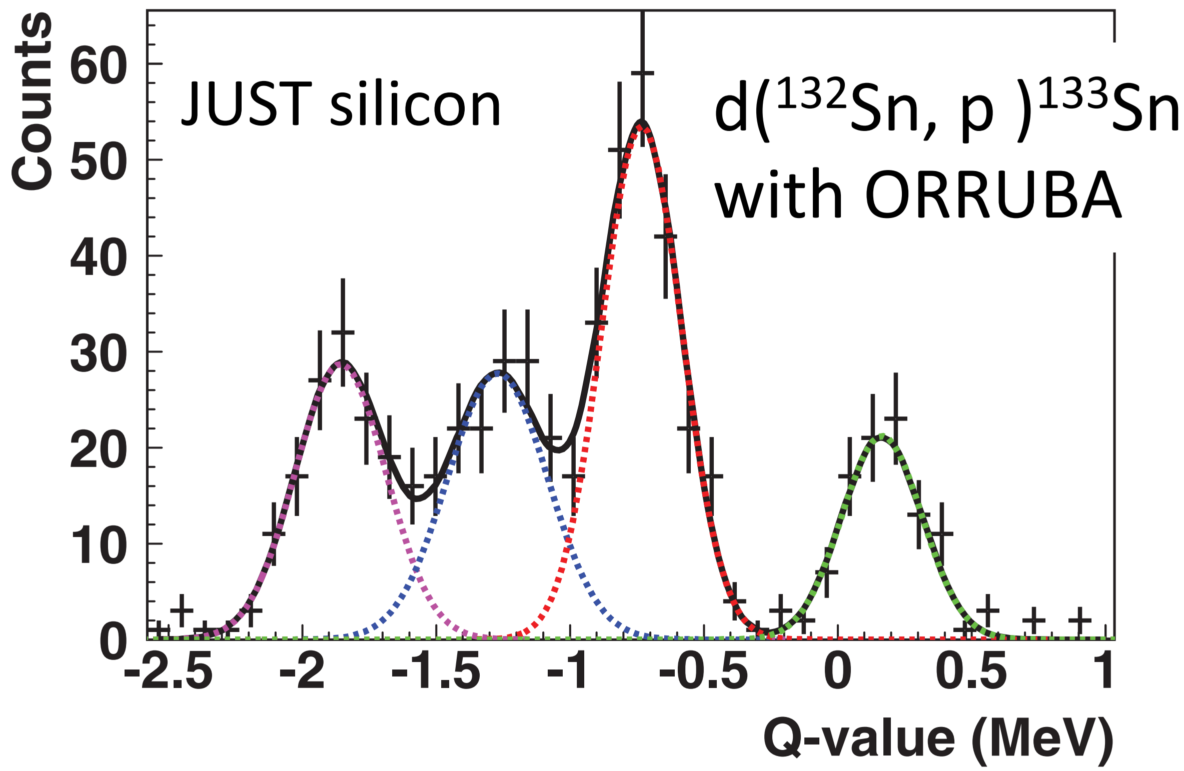
Knockout reactions at FRIB

- *S800 and Sweeper limited to 4 Tm*
- *FRIB will push reach of very neutron-rich nuclei to and beyond A=100*
- *Need high rigidity spectrometer with dispersion matching (HRS)*
- *Need high resolution / efficiency γ-ray array (GRETA)*



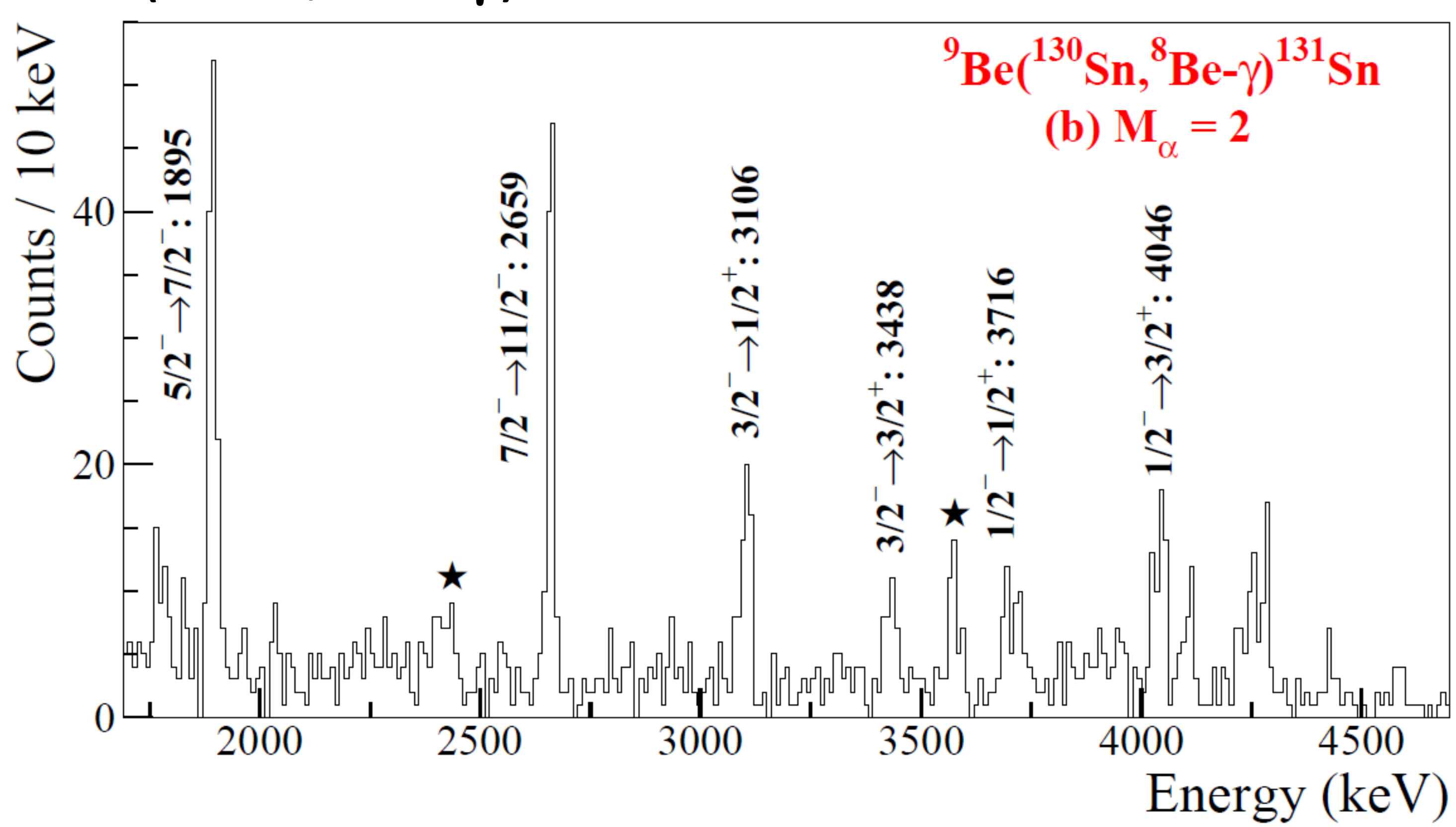


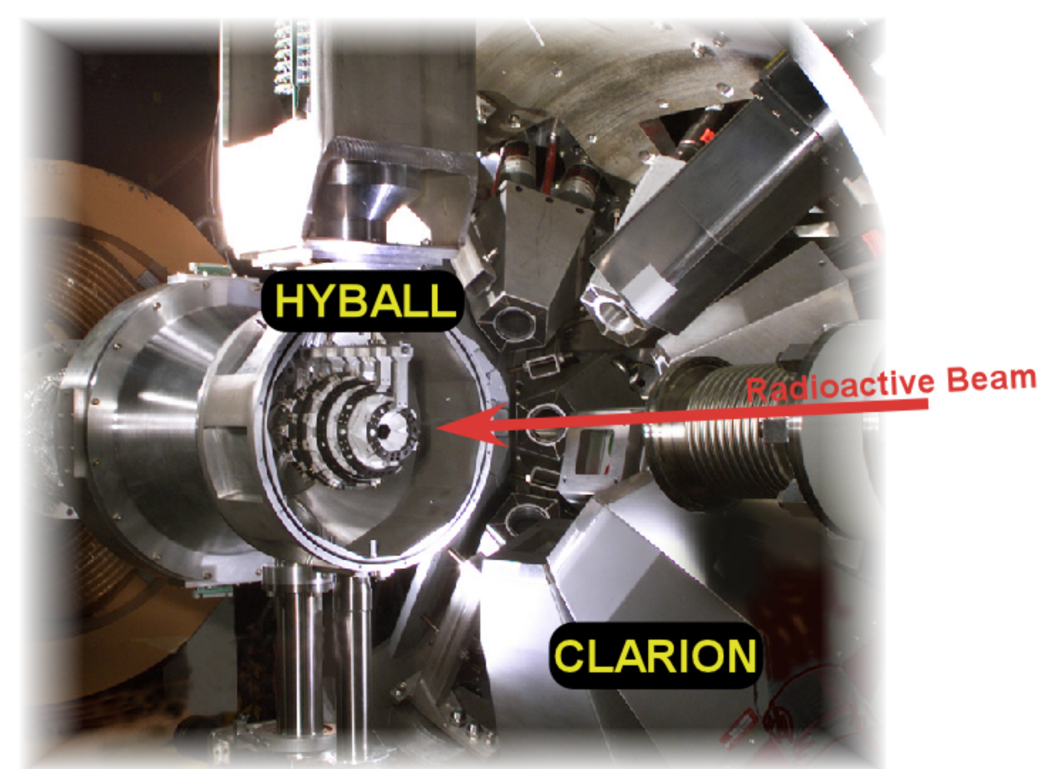
Transfer reactions with γ measurements give the best of both worlds



Not only improved resolution.
See cascades, including states not populated directly.
Possibility to measure lifetimes.
All the tricks available to γ spectroscopists, but different population to fusion-evaporation, deep-inelastic etc.

^{9}Be(^{130}Sn, ^{8}Be γ)^{131}Sn with HYBALL and CLARION





From K. Jones

GODDESS: Coupling ORRUBA and Gammasphere

Charged particles give:

Q-value (excitation energy) of state directly populated in reaction.

ℓ values from shape of angular distribution

intensities, linked to spectroscopic factors

γ rays give:

precise energies,

lifetimes,

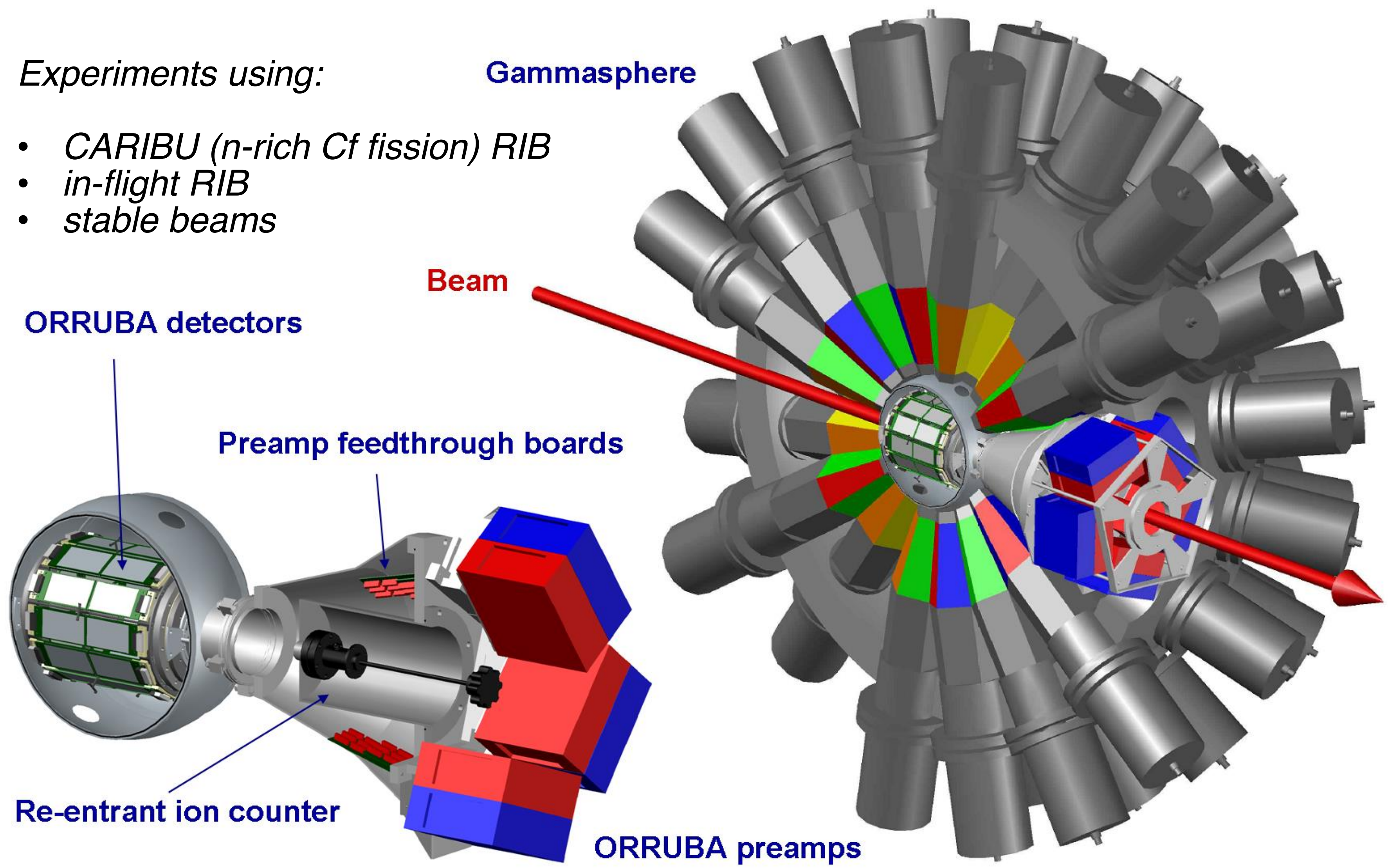
cascades,

branching ratios

etc., etc.

Experiments using:

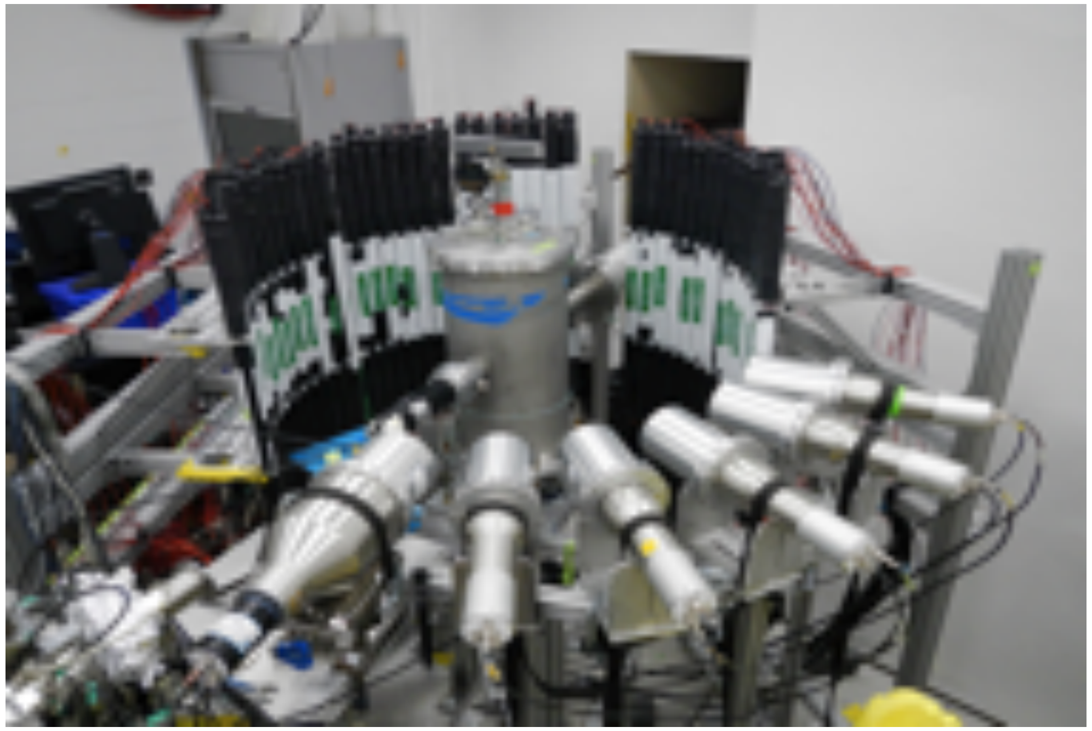
- *CARIBU (n-rich Cf fission) RIB*
- *in-flight RIB*
- *stable beams*



From K. Jones

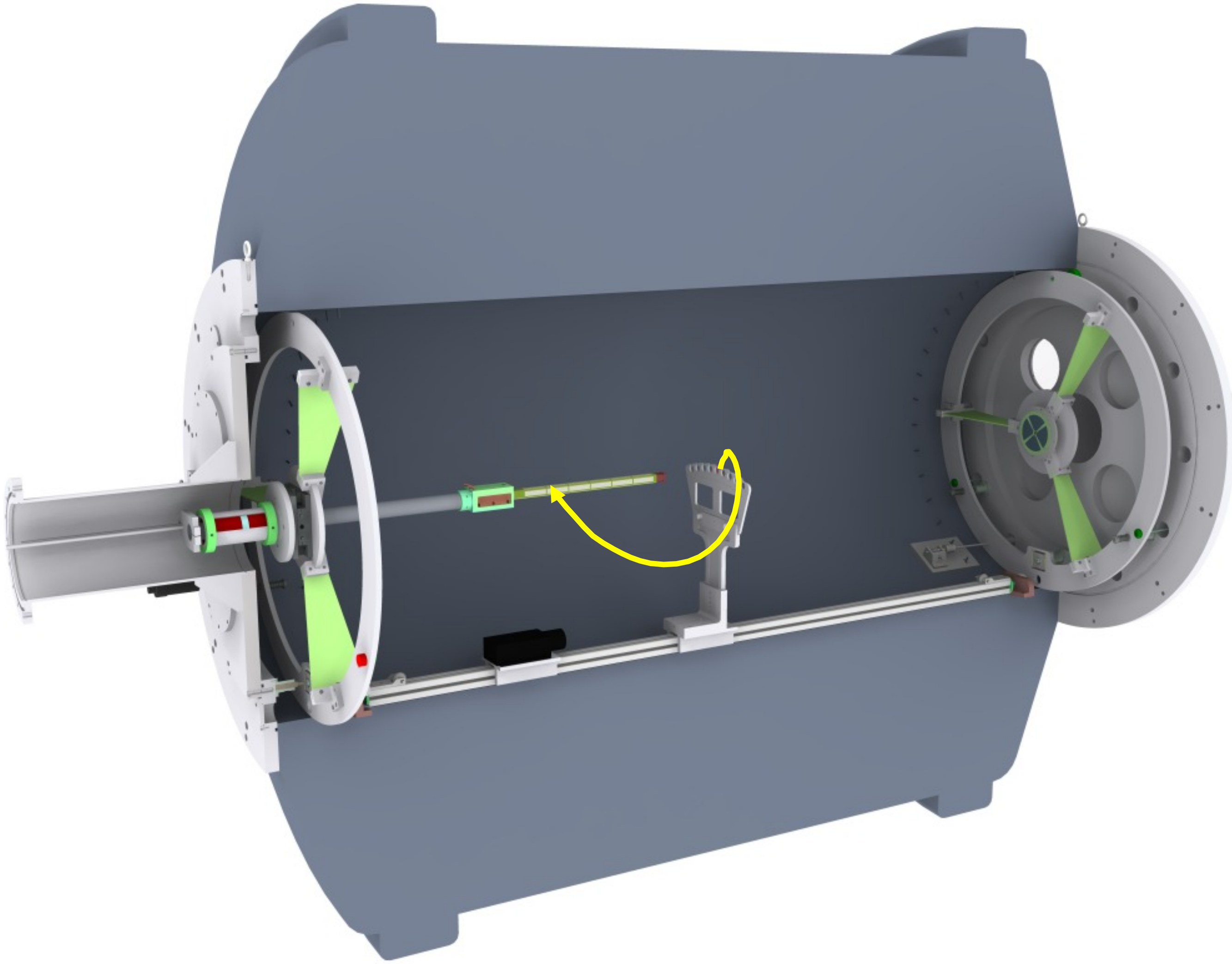
Looking at proton single-particle states with (d,n)

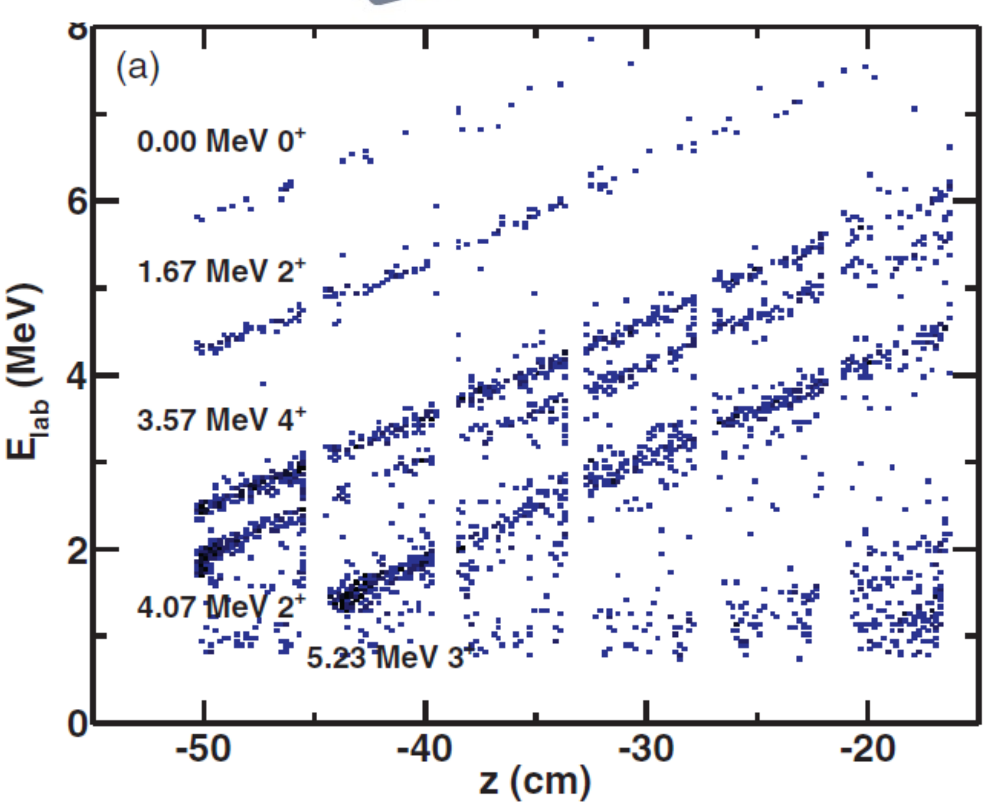
Can study proton s.p. states with (d,n) in same way that we study neutron s.p. states with (d,p).
ReA12 will give optimal beam energies.
Example of setup at Notre Dame using TWINSOL beams with VANDLE and UofM arrays.
More information from Karl Smith (UTK) later.



From K. Jones

HELIOS capabilities: reaction studies in inverse kinematics





C. R. Hoffman et al, PRC **85**, 054318 (2012)

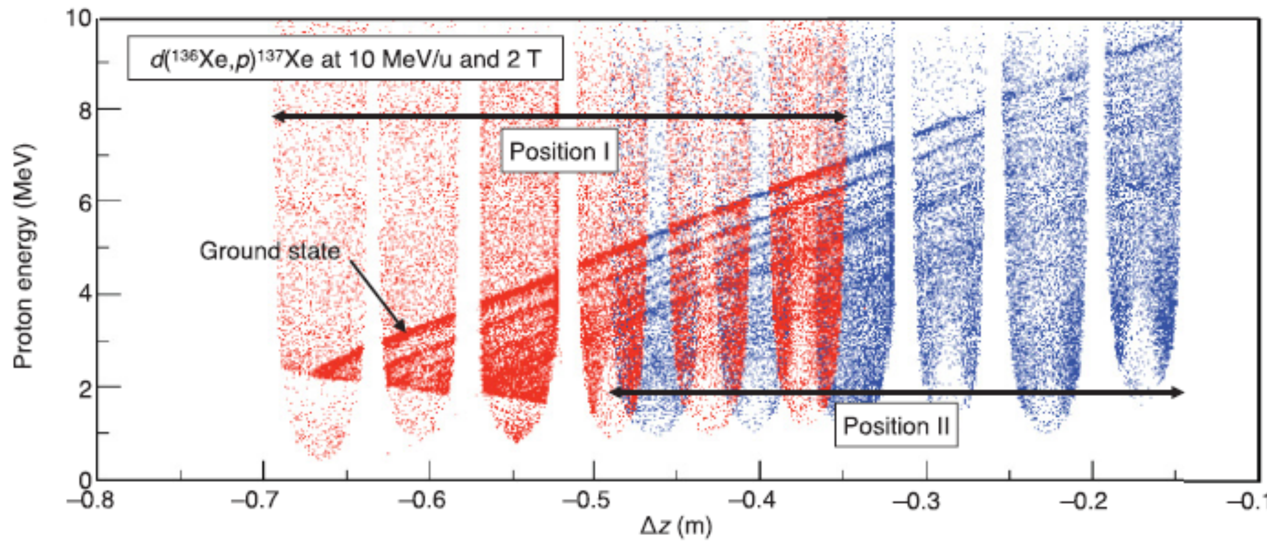
Particle energy versus position for d(^{19}O,p)^{20}O

- Reactions in inverse kinematics measured so far:
  - (*d*,*p*), (*d*,^{3,4}He): CD_2
  - (^{3}He,*d*): gas target
  - (^{6}Li,*d*): ^{6}LiF target
  - (*t*,*p*): ^{3}H/Ti implanted

Measurements done with stable and unstable beams with A=11 to 136

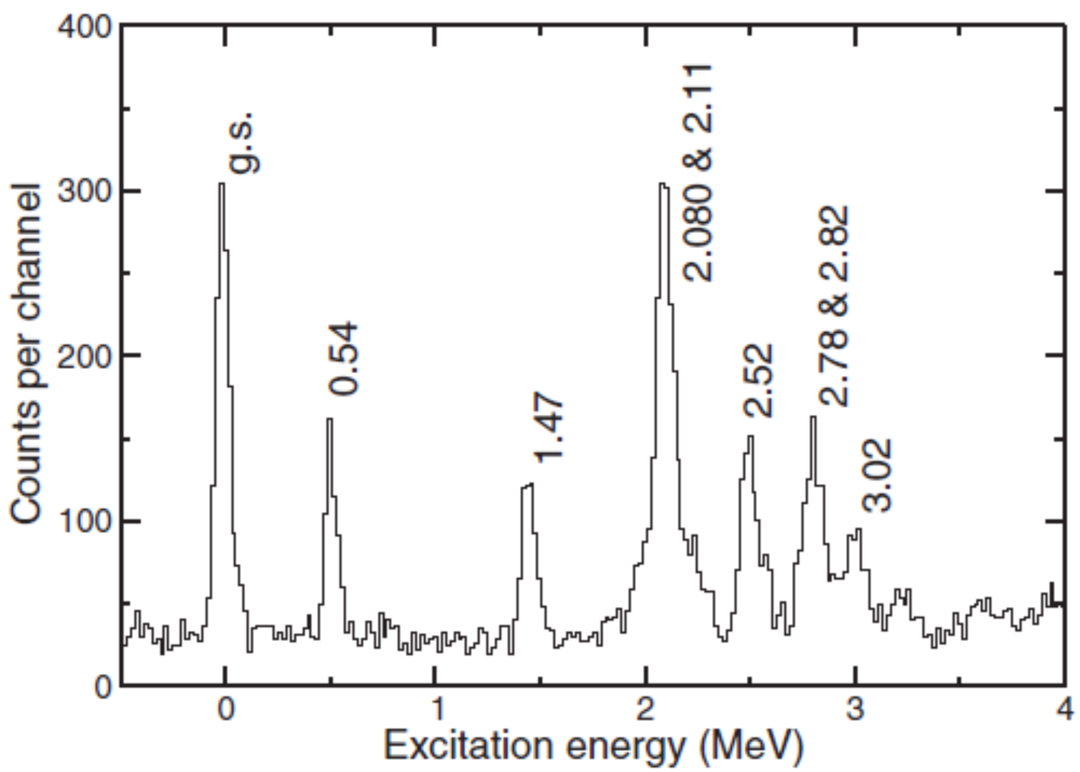
From A. Wuosmaa

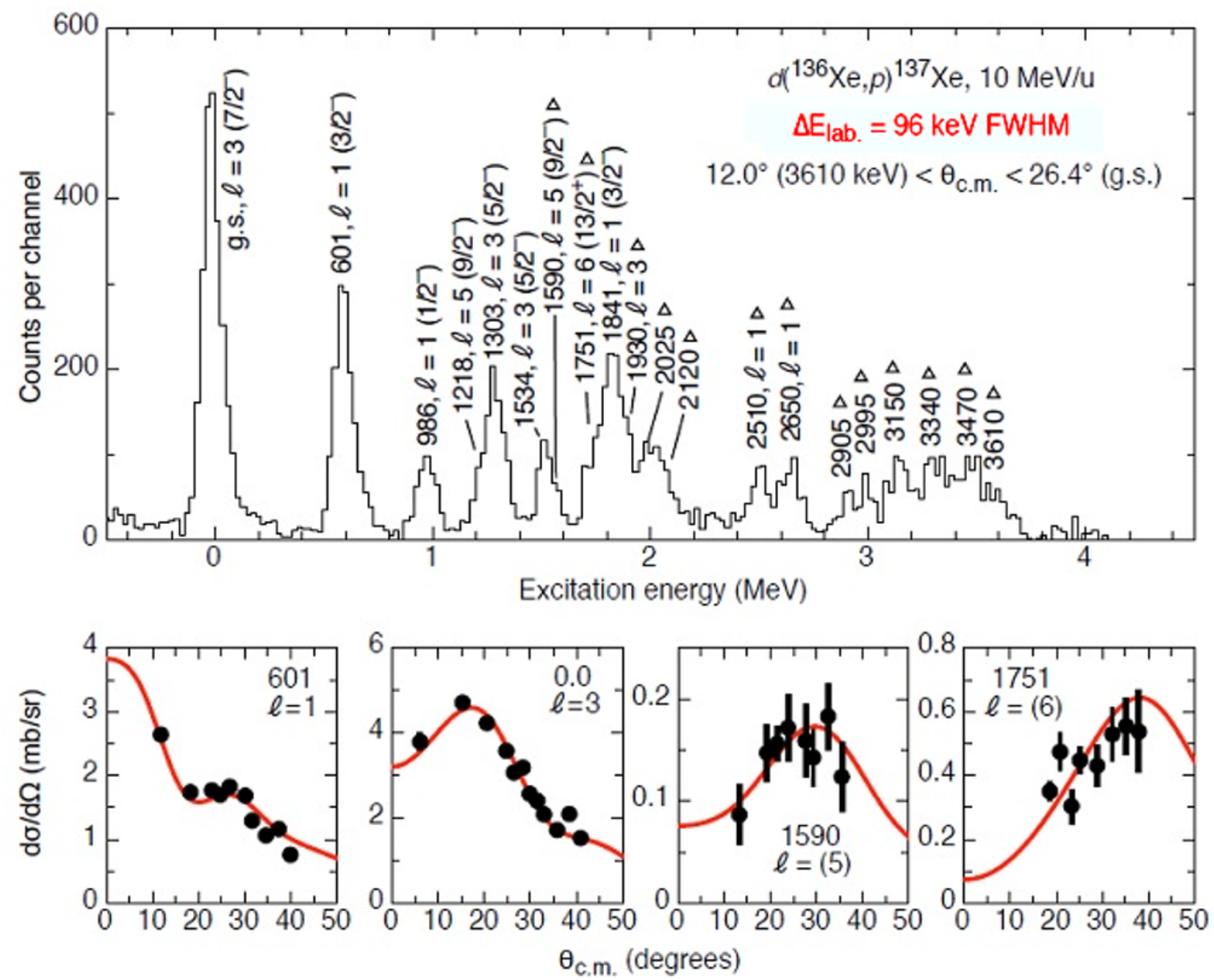
Heavy beams: ^{86}Kr and ^{136}Xe



Particle energy versus position for d(^{136}Xe,p)^{137}Xe

d(^{86}Kr,*p*)^{87}Kr





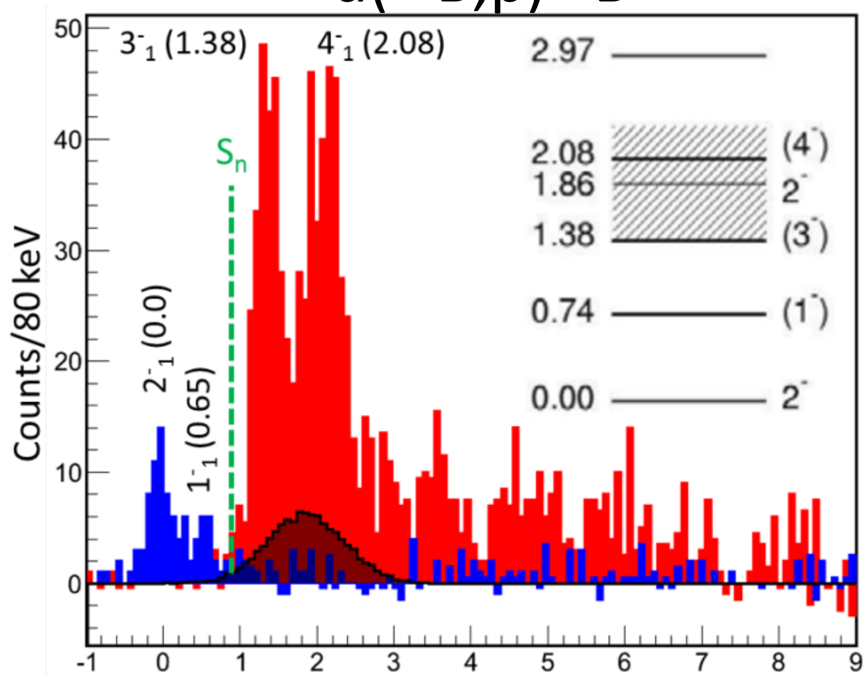
D. K. Sharp et al, PRC **87**, 014312 (2013)

B. P. Kay et al, PRC **84**, 024325 (2011)

From A. Wuosmaa

Light unstable beams

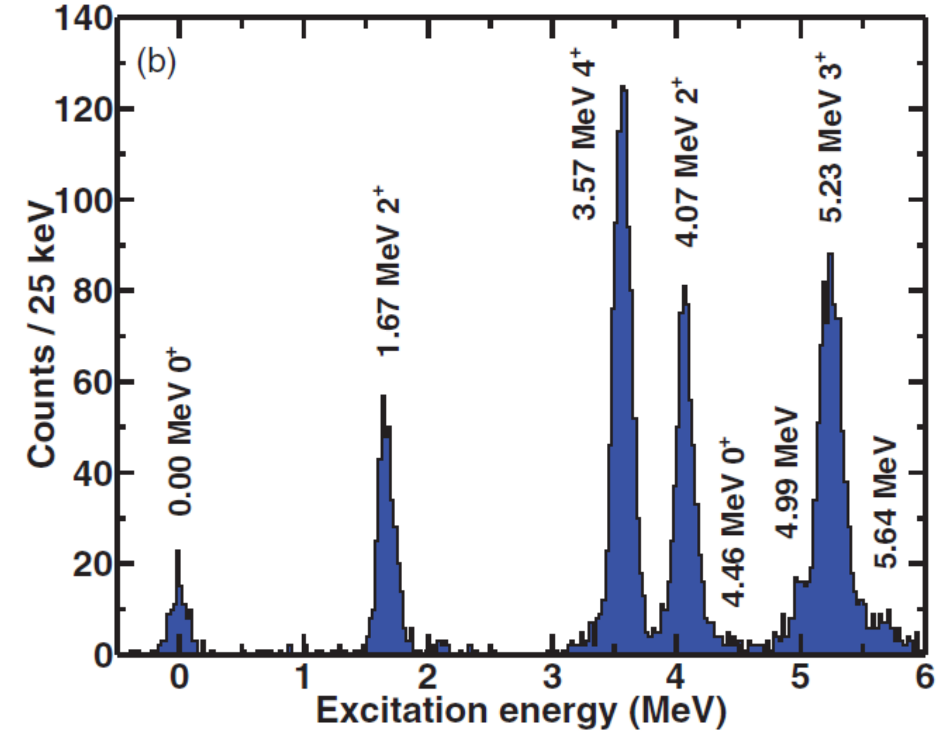
$d(^{13}B,p)^{14}B$



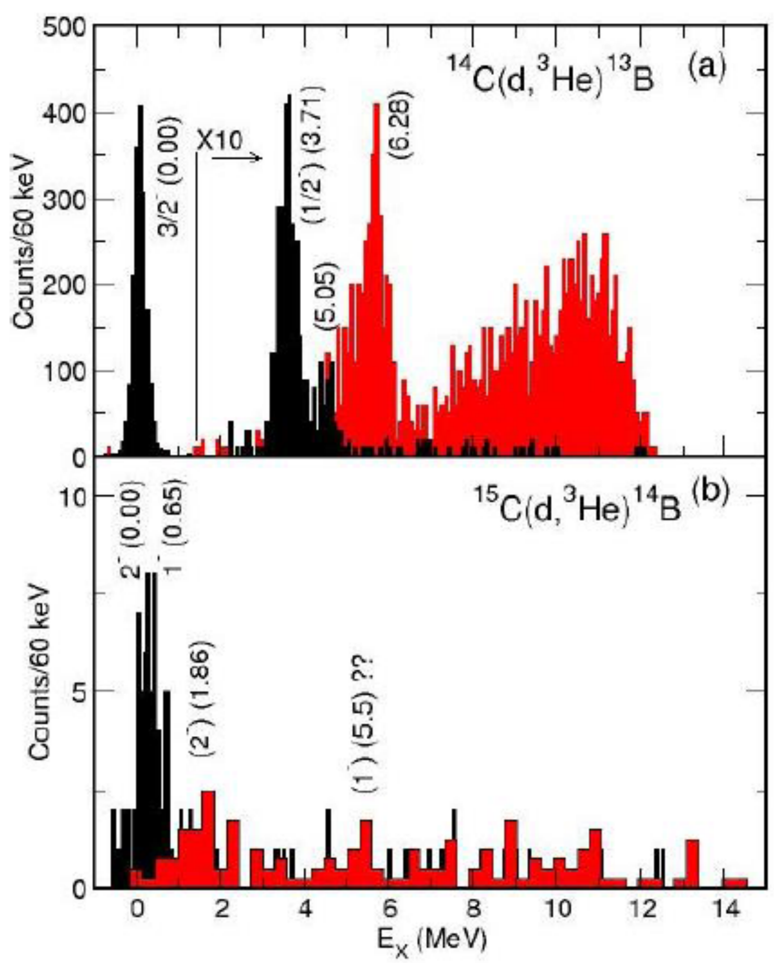
S. Bedoor et al, PRC **88**, 011304R (2013)

(d,p)

$d(^{19}O,p)^{20}O$



C. R. Hoffman et al, PRC **85**, 054318 (2012)

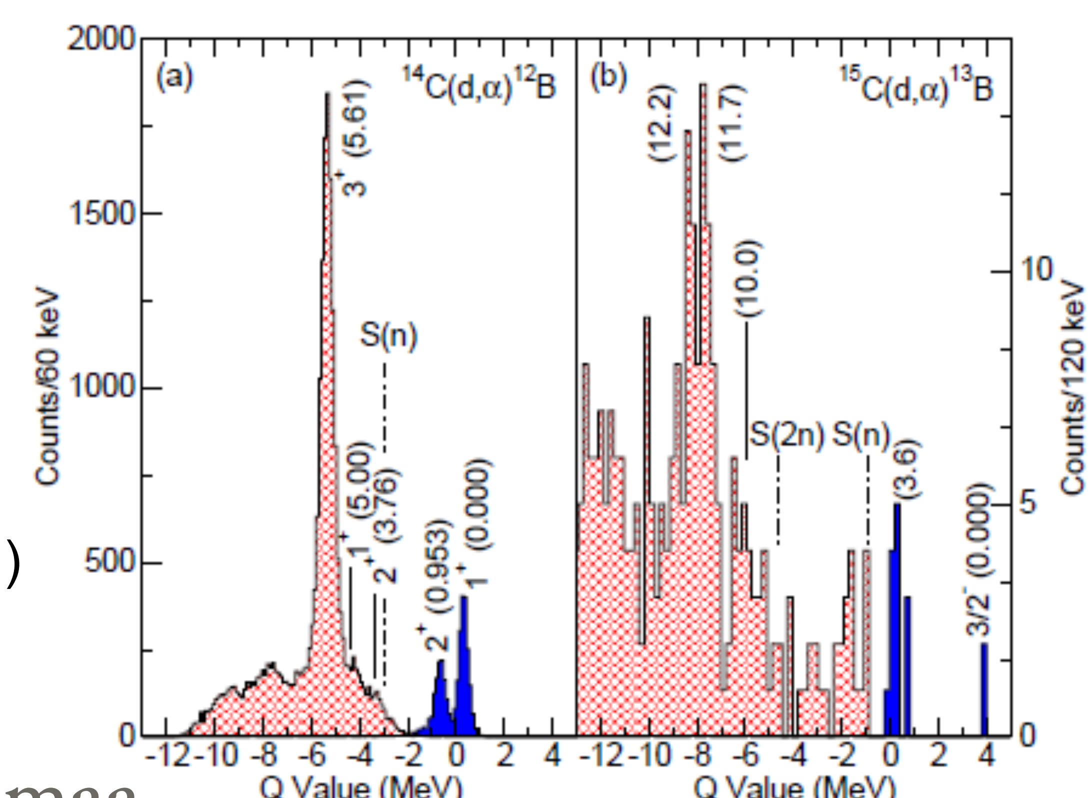


$(d,^3He)$

(S. Bedoor et al.)

(d,α)

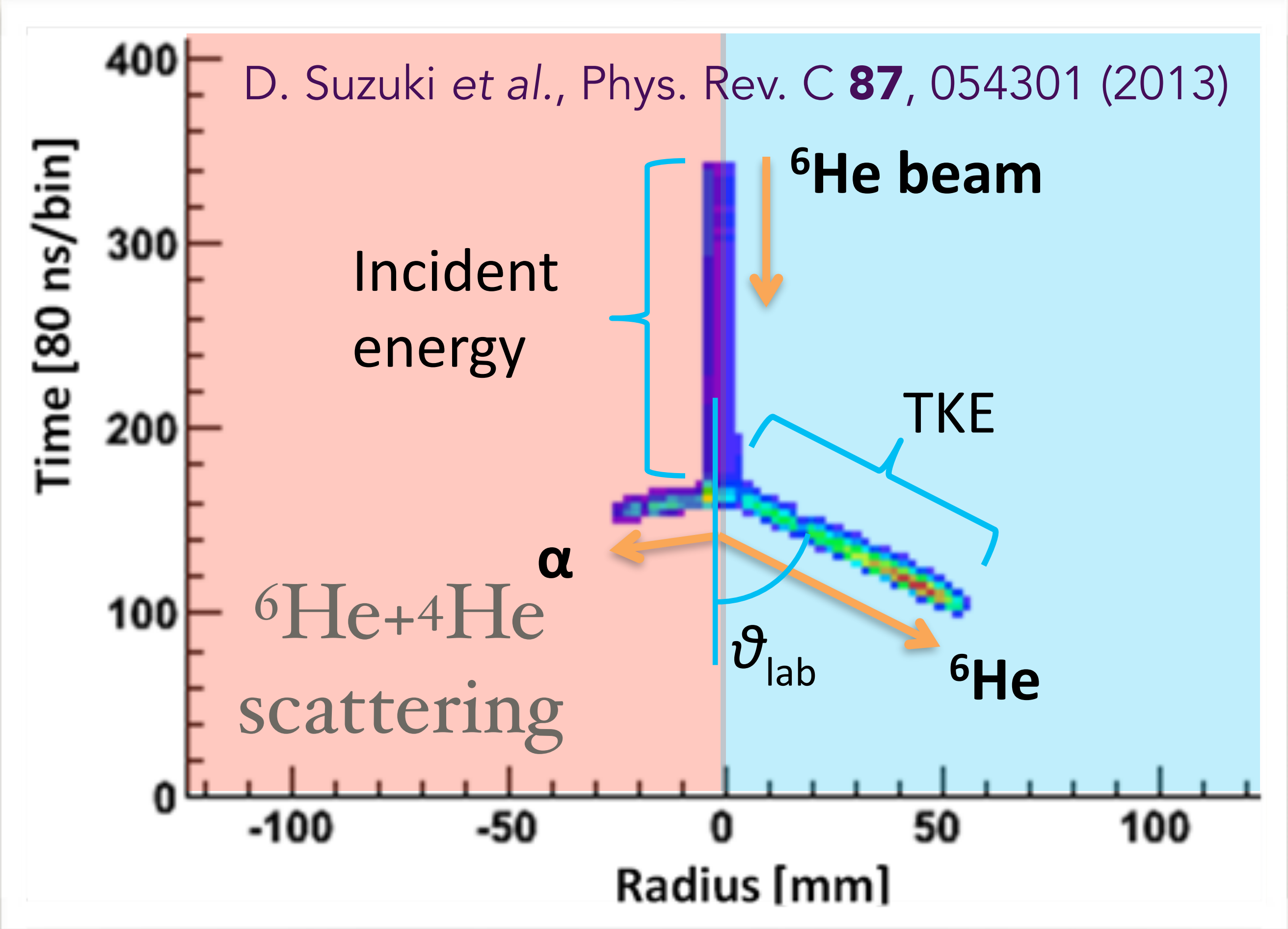
(A. H. Wuosmaa,
J. P. Schiffer et al.)

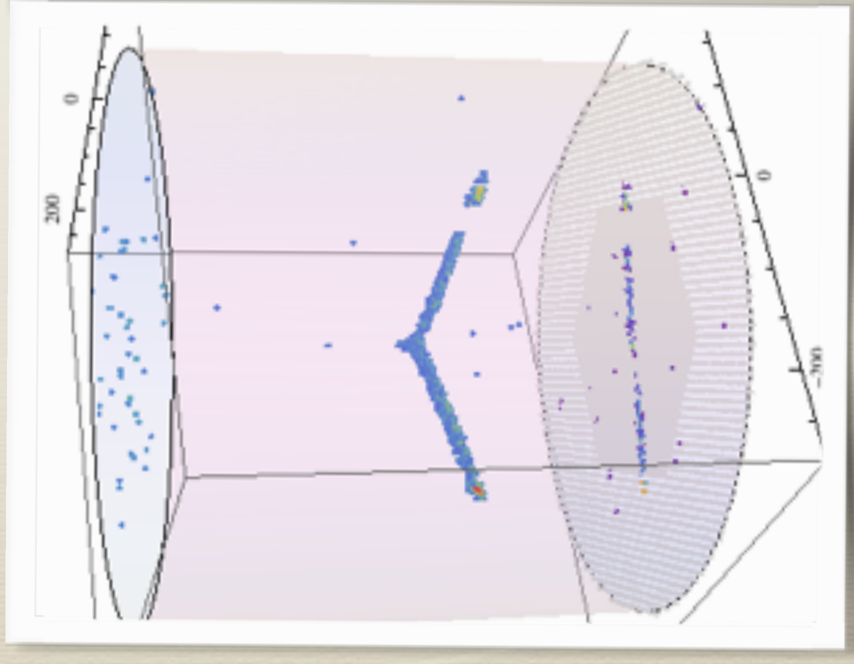


From A. Wuosmaa

Direct reactions with the AT-TPC

- *High luminosity for low energy reactions*
  - *Resonant scattering*
  - *Transfer reactions*
  - *Elastic p scattering to IAS*
- *Reach to most exotic beams (low intensity)*
  - *Thick gas target*
  - *4π angular coverage*
  - *Excitation functions*





AT-TPC α+α elastic scattering

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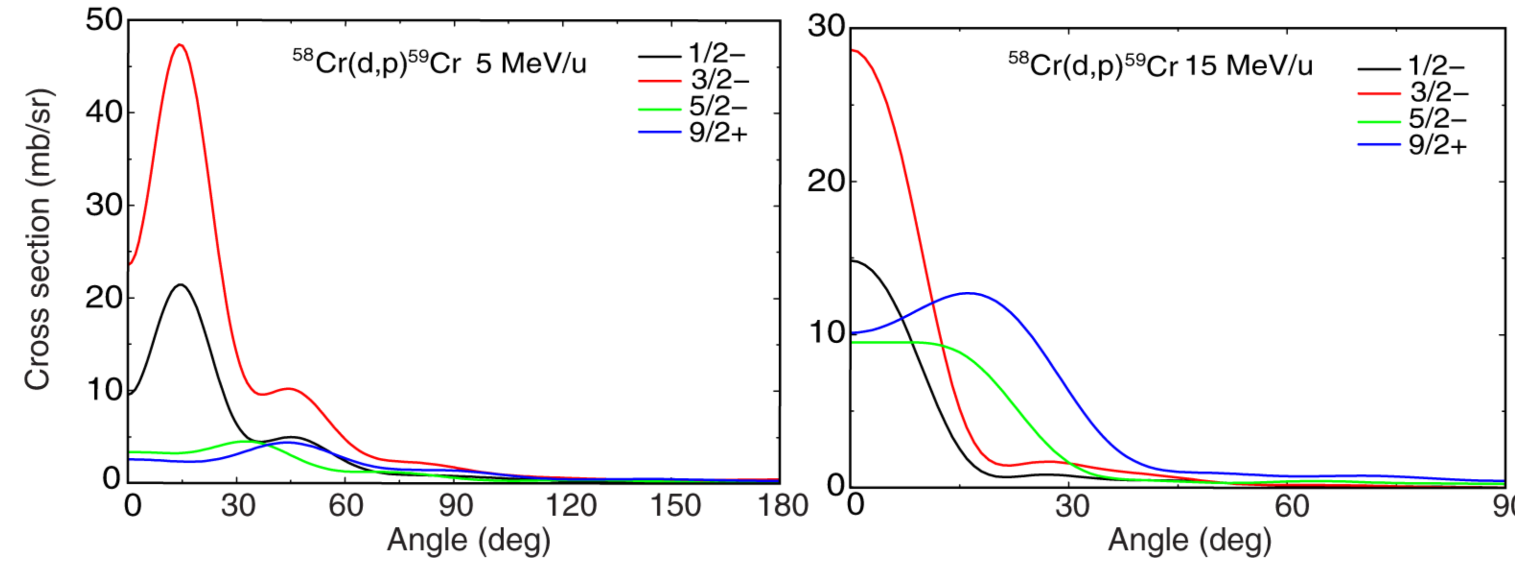
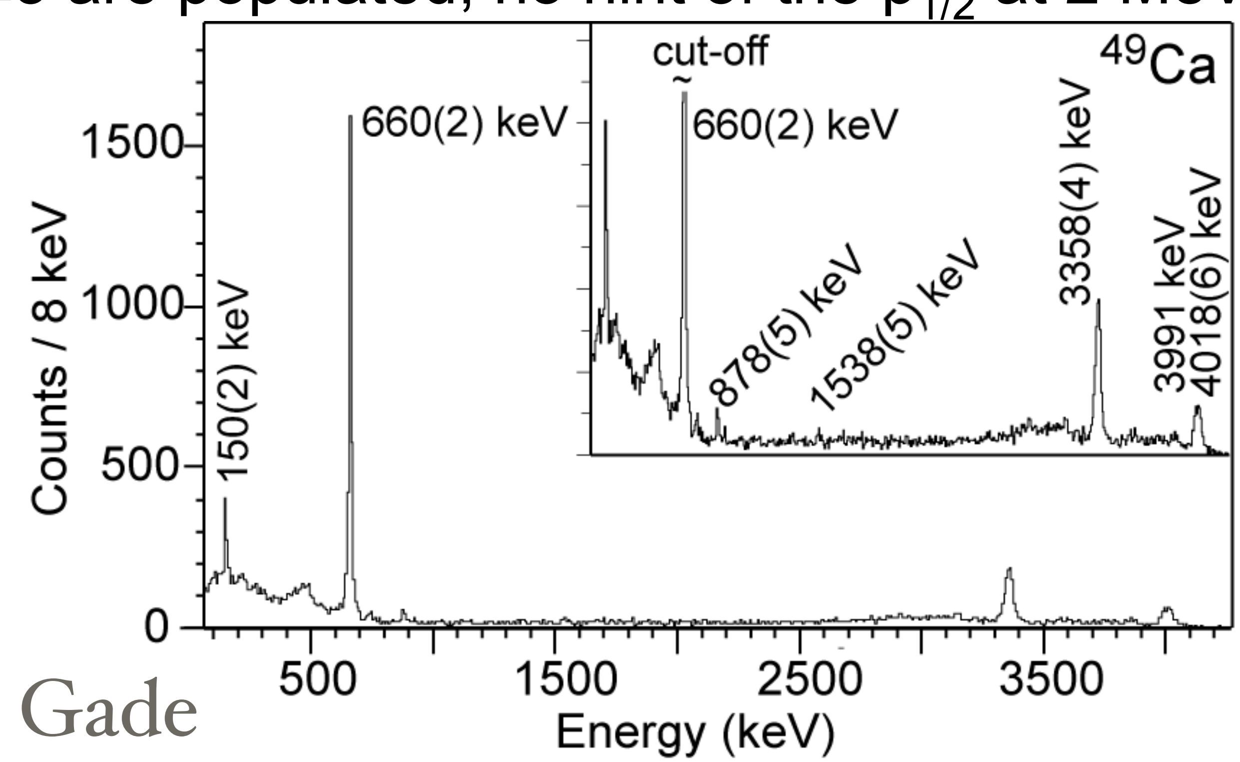
Exploiting momentum matching in transfer reactions

- High-l states are often the unambiguous indicator for shell evolution (intruder states)
- Nucleon-adding transfer reactions at various beam energies can be used to selectively populate the high l states
- Opportunity at NSCL now and at FRIB in the future with
  - C-induced one-nucleon pickup at ~60 MeV/u with GRETA at S800@NSCL/FRIB (high luminosity)
  - Classic light-ion induced transfer reactions at ReA6 and ReA12 [γ-ray tagged with GRETA at a recoil separator, or with GRETA + light-ion detection (Si) at recoil separator



^{12}C(^{48}Ca,^{49}Ca+γ) at 65 MeV/u with GRETINA at S800

only l≥3 are populated, no hint of the $p_{1/2}$ at 2 MeV



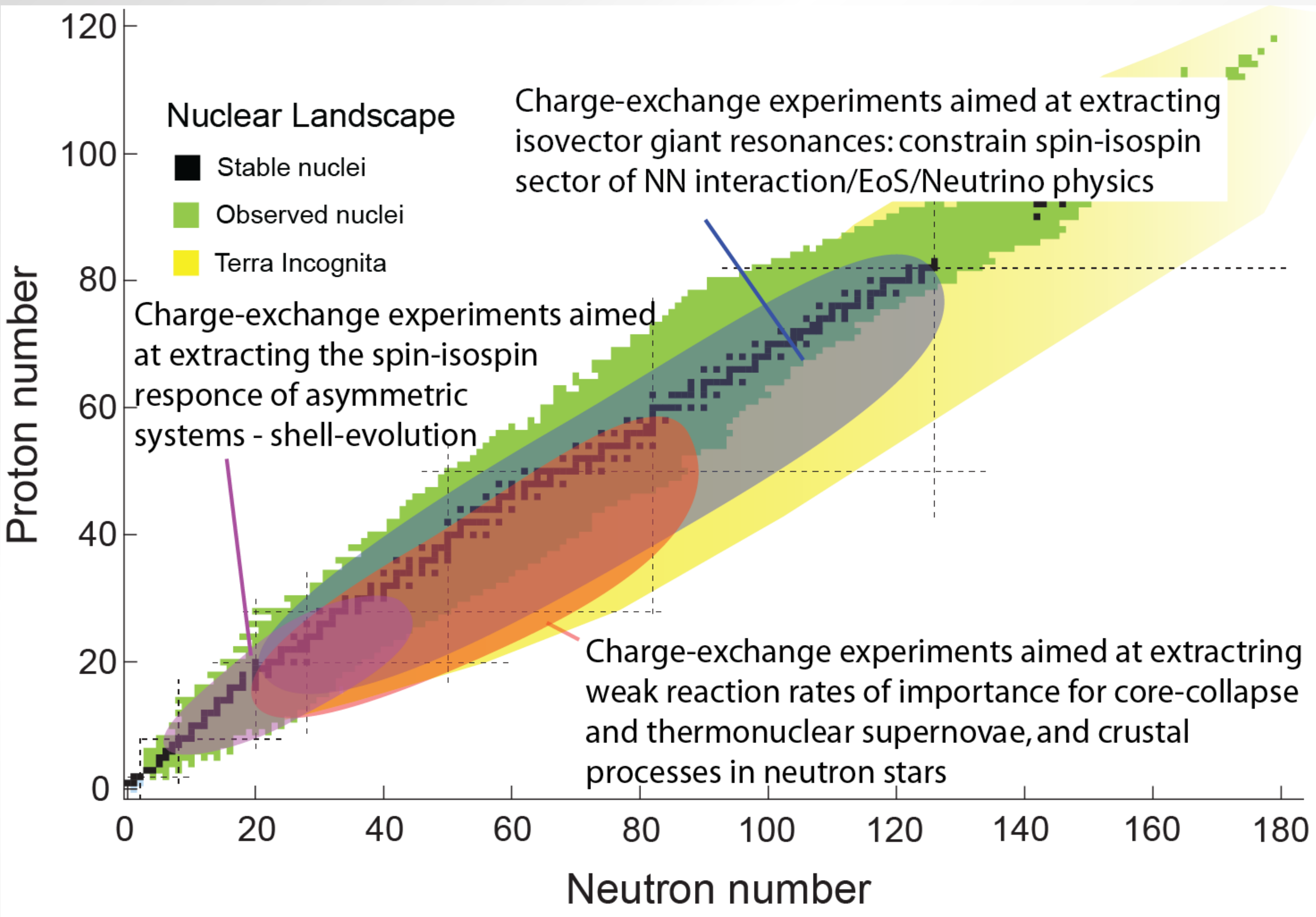
From A. Gade

NSCL

Nucleon-adding transfer at beam energies from 5-70 MeV/u offer unique opportunity to identify high-l states and track them in uncharted territory opened up by FRIB

Charge-exchange reactions at intermediate energies

- Model-independent extraction of Gamow-Teller strength distributions up to high excitation energies to constrain models aimed at describing the spin-isospin response and shell evolution, with important application for weak reaction rates in nuclear astrophysics
- Constrain the spin-isospin component of the nucleon-nucleon interaction and probe properties of nuclear matter (neutron-skins, equation of state) through the study of isovector giant resonances



From R. Zegers

Charge-exchange reactions with unstable beams

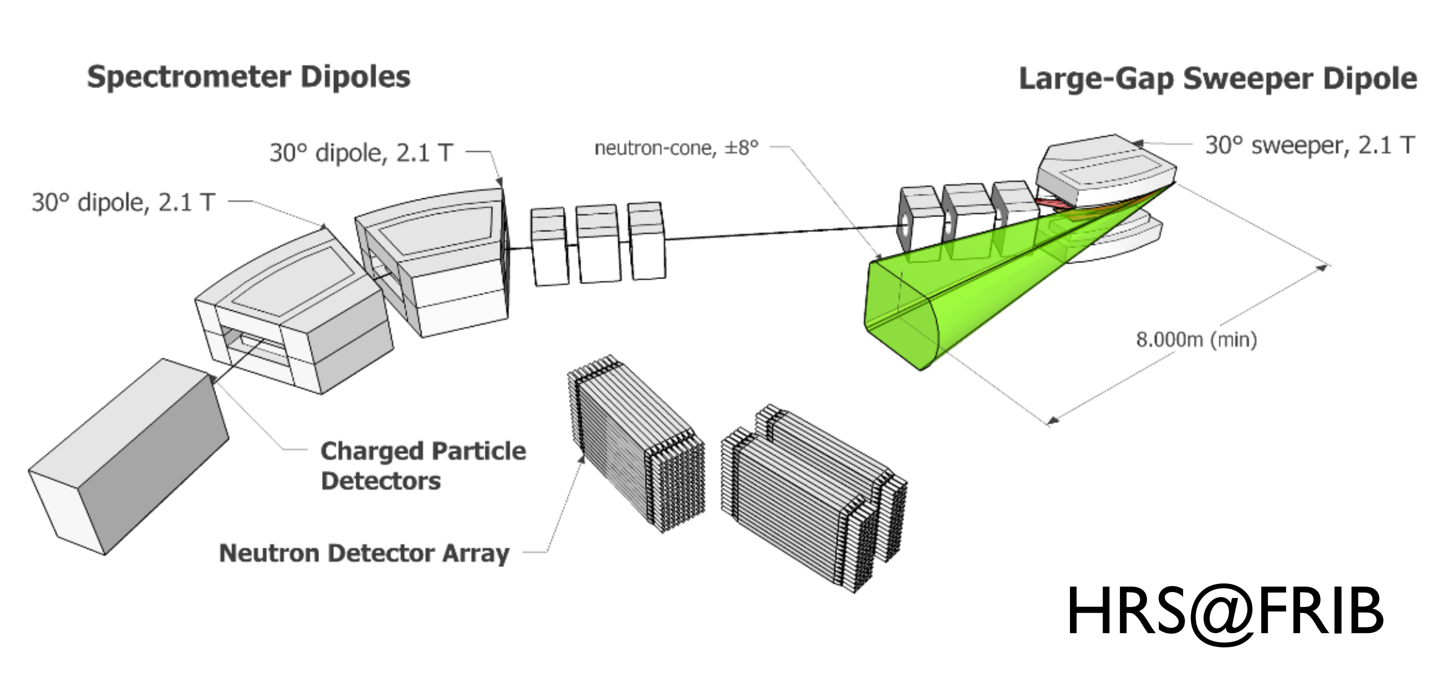
CE reactions on rare isotopes in inverse kinematics:

- β^+ direction: (^{7}Li,^{7}Be+γ) – S800 (HRS)+SeGA (GRET(IN)A)
  Planned: (d,^{2}He) – HRS+Active Target TPC
- β^- direction: (p,n) – S800 (HRS)+LENDA/VANDLE+Ursinus LH_2 target

Rare isotopes CE probes to isolate specific strength distributions

- β^+ direction: (t,^{3}He), (t,^{3}He+n), (t,^{3}He+γ) – S800 (HRS)+GRET(IN)A+LENDA/VANDLE
  (^{10}Be,^{10}B+γ), (^{12}B,^{12}C+γ)…. –S800(HRS)+GRET(IN)A
- β^- direction: (^{10}C,^{10}B+γ), (^{12}B,^{12}C+ γ)…. –S800(HRS)+GRET(IN)A

The construction of the High Rigidity Spectrometer (HRS) is critically important to fully exploit the scientific opportunities with charge-exchange reactions at FRIB



From R. Zegers

Neutron-Proton Pairing and Direct Reactions at FRIB

N=Z nuclei, unique systems to study *np* correlations

- As you move out of N=Z *nn* and *pp* pairs are favored
- Large spatial overlap of *n* and *p*

Role of isoscalar (T=0) and isovector (T=1) pairing

- Does isoscalar pairing give rise to collective modes?

T=1,
S=0

Direct reactions are unique tools in our studies of exotic nuclei

- Two particle transfer reactions provide specific probes of the amplitude of pairing collective modes

T=0,
S=1

T_z=0

From A. Macchiavelli

(p,^{3}He) and (^{3}He,p) are the *"classical"* probes we can use to firmly elucidate this question, particularly in the region from ^{56}Ni to ^{100}Sn. Also (α,d) ΔT=0

- Inverse kinematics
- Gas and solid targets
- Light particle and recoil detection
- Proof of principle with stable beams and first experiment with a ^{44}Ti beam carried out at ATLAS ✔

***np*- Knockout reactions may offer a complementary tool.**
Contributions to the form factor from S- and P- waves

- Higher luminosity
- Exclusive measurement with HRS and GRETA
- Cross section and momentum distributions

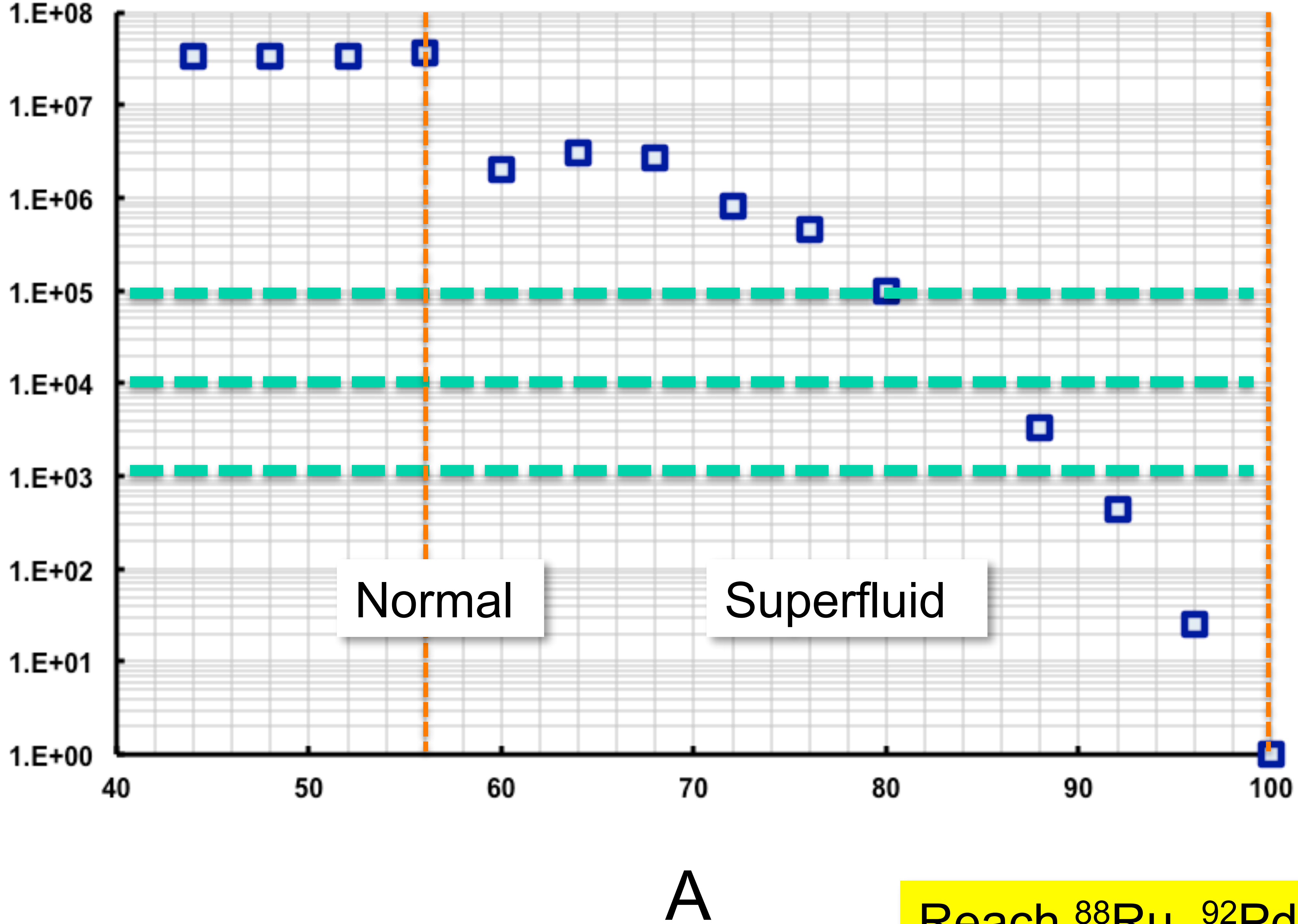
We need:

- **Intense N=Z beams (A>40, fast and reaccelerated)**
- **Efficient, high-resolution particle detectors**
- **Spectrometer**
- **Gamma-ray detectors**

From A. Macchiavelli

YIELDS (pps)

FRIB Estimated Rates Version 1.06
02/07/2011



Simple Setup

HELIOS

AT-TPC

Reach ^{88}Ru, ^{92}Pd

From A. Macchiavelli

Summary: needs for direct reactions at FRIB

- *Low and high energy spectrometers*
  - *S800 and HRS for high energy, including open forward cone for neutron-unbound resonance experiments*
  - *ISLA for low energy re-accelerated radioactive beams, beam rejection, high acceptance and high resolution residue tagging*
- *Devices for inverse kinematics and high luminosity*
  - *Charged particles: ORRUBA-type, Helios, AT-TPC, ANASEN …*
  - *Neutrons: MoNA-LISA, VANDLE, LENDA, …*
  - *γ-rays: GRETA, CAESAR, …*
- *Progress in nuclear reaction models*

Thanks to …

- *Augusto Macchiavelli*
- *Alan Wuosmaa*
- *Kate Jones*
- *Alexandra Gade*
- *Remco Zegers*

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- *Remco Zegers*

and thank you for your attention!

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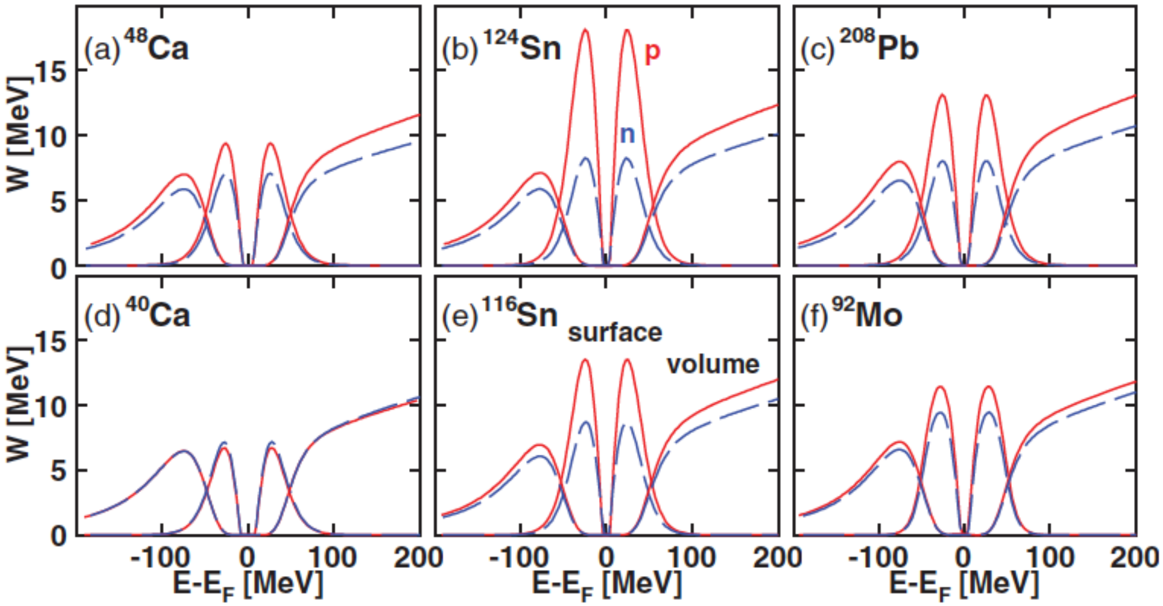
Experiments to probe correlations in exotic nuclei

All know that OM's are needed for reaction theories.
But unlike NMR, Optical, ultrasound… spectroscopists many nuclear structure experimentalists have missed the DIRECT link between scattering (+|E|) and structure (-|E|) energy observables.

FOR EXAMPLE

- If you think SF have **no** asymmetry dependence ….
- If you think that SF have **a strong** asymmetry dependence…
- If you think that the reduction of spectroscopic strength is a **new** insight…
- If you think that the reduction is **only due to SRC** …

The WU groups, both theoretical and experimental, think you are wrong.



DOM

← data **REQUIRE** increase in W_{sur} as n content increases

This suppresses SF's

This is a weak trend but a trend it is.

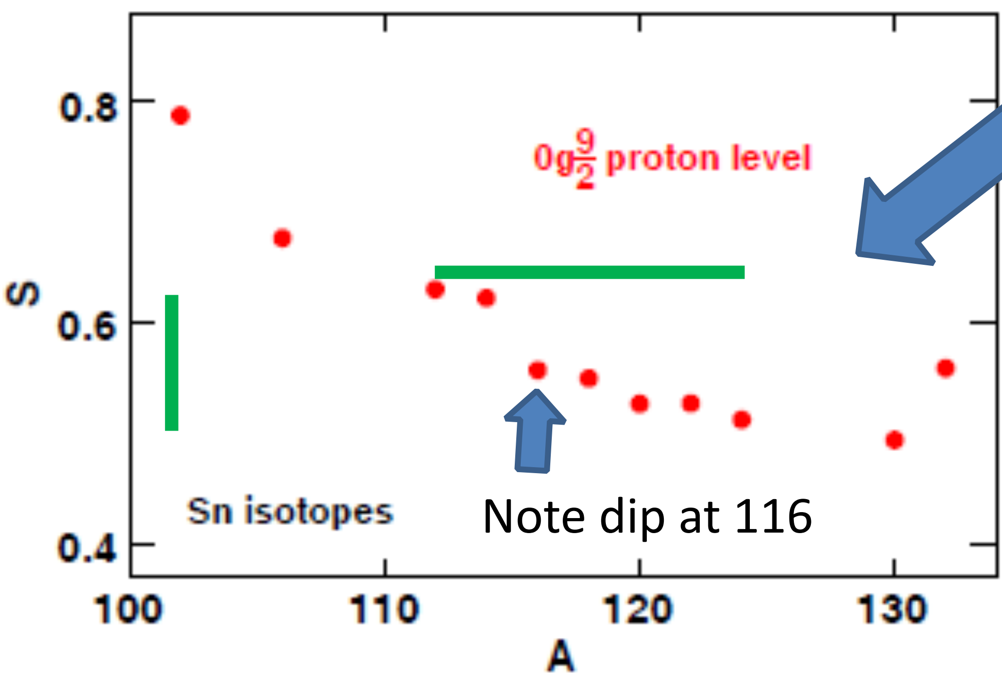


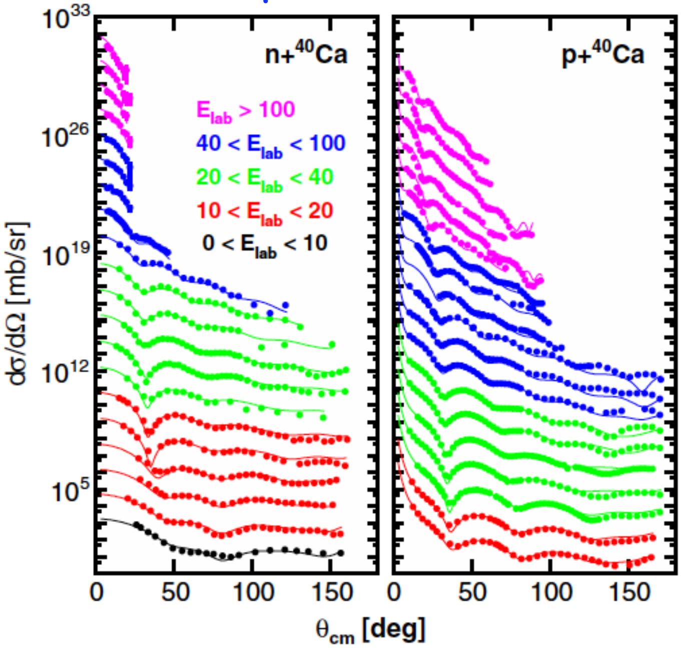
TABLE III. ectroscopic factors S (relative to the IPM predictions) and occ on numbers n for the $0g_{9/2}$ proton orbit in Sn isotopes using th nonlocal (nl) and local (l) versions of the DOM.

Isotope	S_{nl}	n^c_{nl}	n_{nl}	n_l	S_l
102	0.80	0.11	0.91	0.86	0.79
106	0.68	0.17	0.85	0.81	0.68
112	0.63	0.20	0.83	0.74	0.63
124	0.50	0.28	0.78	0.62	0.51
130	0.48	0.30	0.78	0.60	0.49
132	0.56	0.25	0.81	0.65	0.56

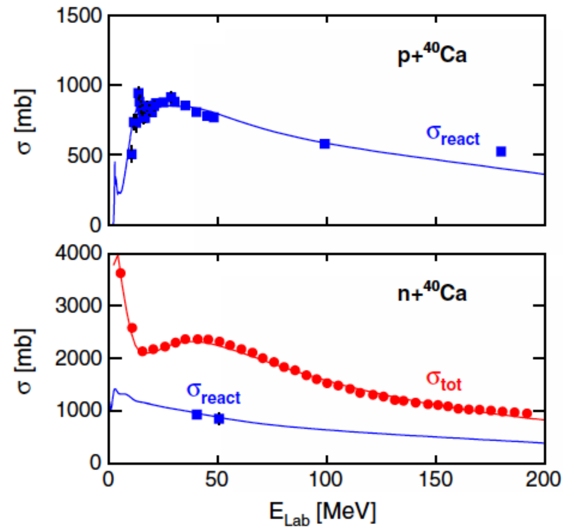
Linking nuclear reactions and nuclear structure

DOM links positive and negative energy physics

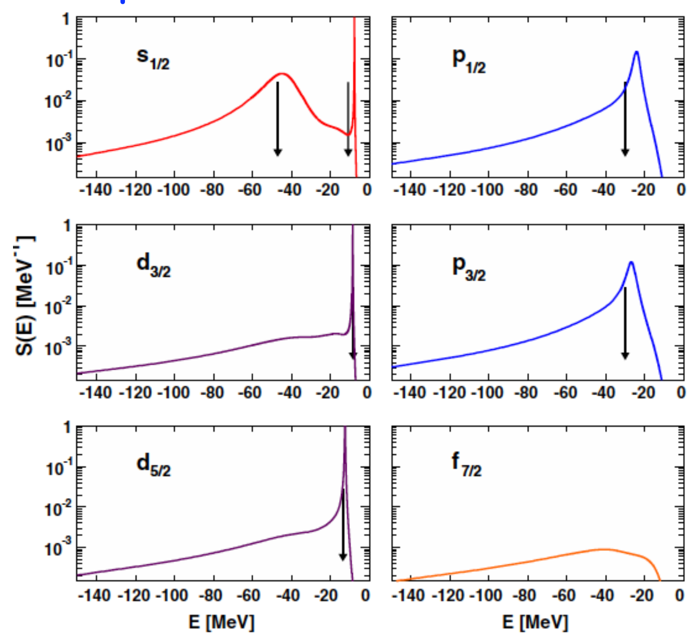
Elastic p&n cross section



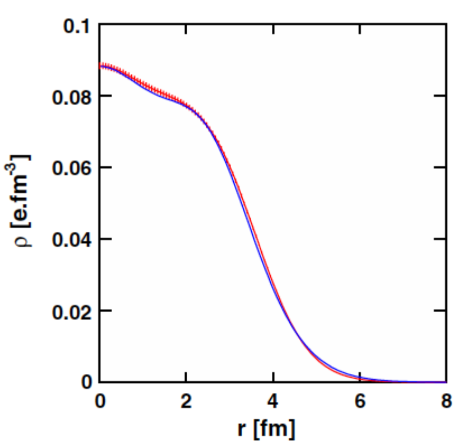
Total & Reaction



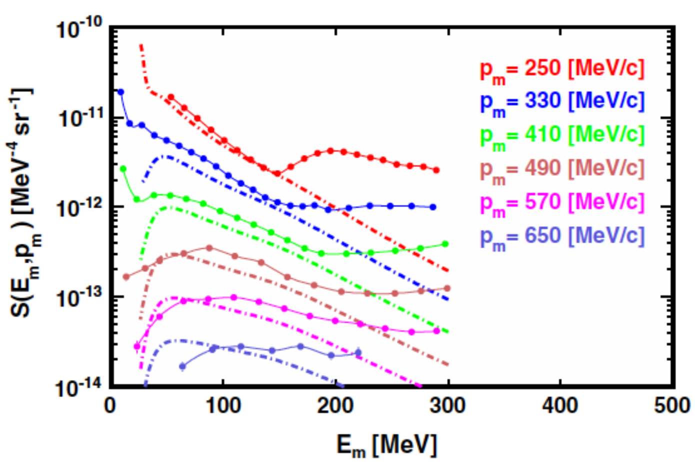
Spectral function E < 0



Charge density



High-momentum nucleons JLab



PRL 112, 162503 (2014)

DOM++

Non-locality essential

Linking nuclear reactions and nuclear structure

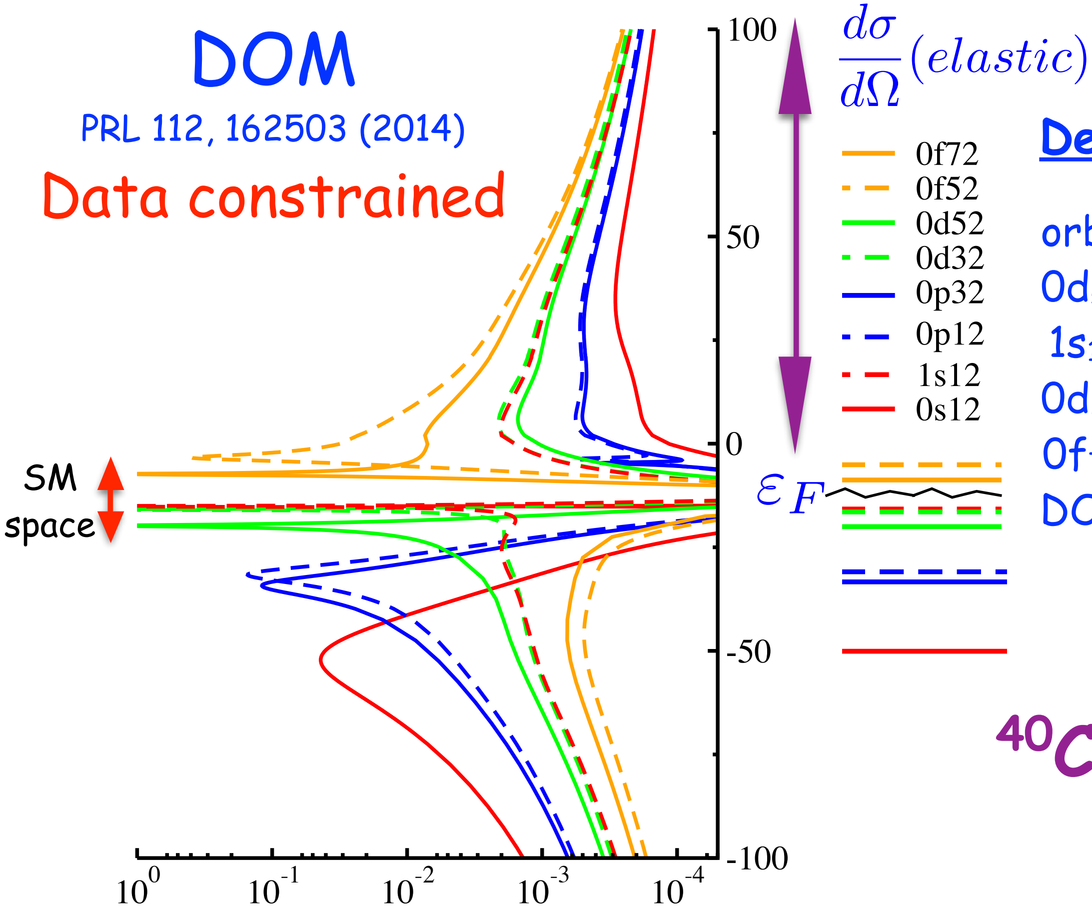
- Dispersive optical model (DOM) —> real nucleus

Spectral function for bound orbits

DOM

PRL 112, 162503 (2014)

Data constrained



Depletion [0,200]

orbit	0.08	
$0d_{5/2}$	0.09	0.04
$1s_{1/2}$	0.09	0.04
$0d_{3/2}$	0.17	0.04
$0f_{7/2}$	CDBonn	
DOM	0.04	

CDBonn
SRC only

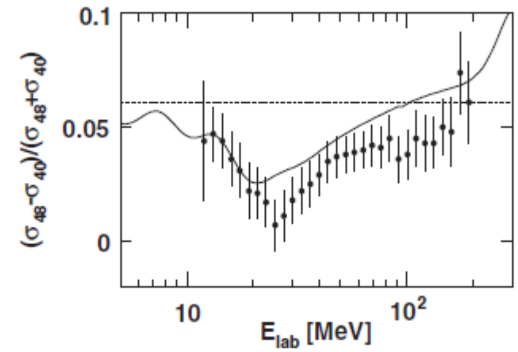
^{40}Ca

Main physics:

- surface (LRC)
- continuum
- non-locality
- energy scale
- SRC
  - "high" k
  - moderate depletion
- ^{40}Ca: some aspects not too different from exotic nuclei

Future: Consider the complete picture and analyze nuclear reactions with causal non-local potentials

Reaction Studies to Buttress DOM^{++} analysis
WU wish list



Using the most important radioactive beam

1. σ_{tot}(n) $^{112-124}$Sn → <u>Believe it or not, these have not been measured !</u>
2. $(d\sigma/d\Omega)_{el}$ n $^{112-124}$Sn ….. 124 yes but 112 No.

Using protons

3. $\sigma_{reaction}$(p) on separated stable isotopes <u>This is very hard!</u>

Using secondary HI beams

4. $(d\sigma/d\Omega)_{el}$ p … long list e.g. ^{14,20}O (triples isospin range) & ^{36,52}Ca

   ➔ need secondary beams in the 15 – 30 MeV/A range. ⬅ FRIB ?? Marginal at best

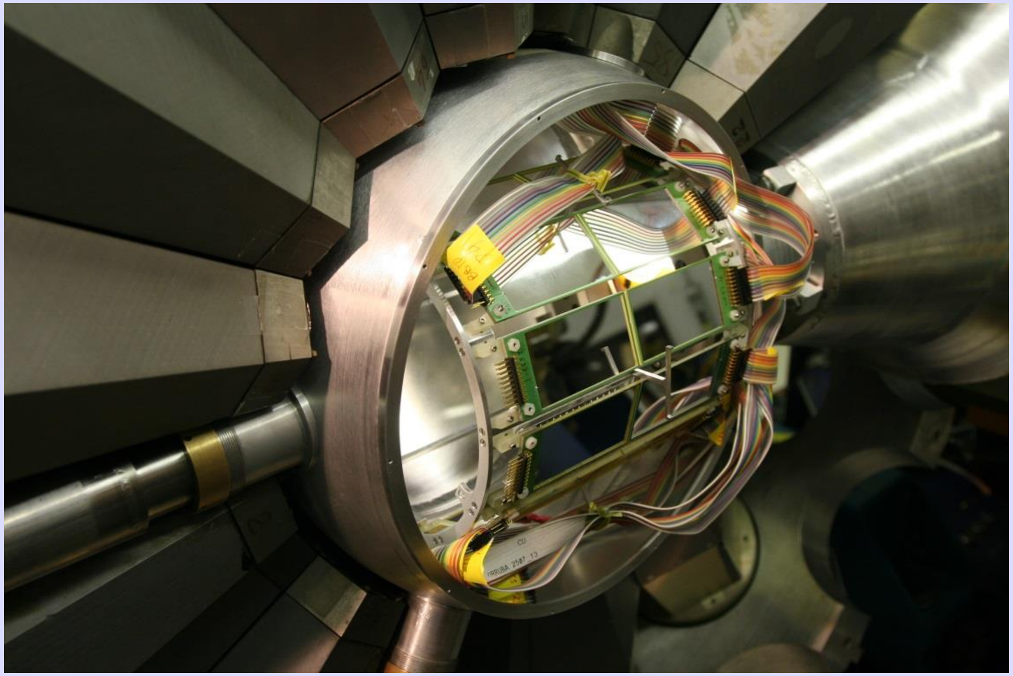
5. $^{108,112…124,130}$Sn (d,^{3}He) and (d,^{6}Li)

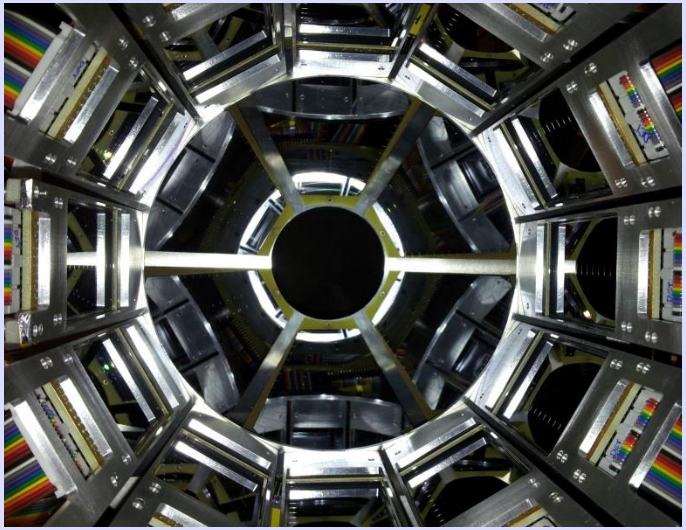
Particle-gamma reactions with GODDESS

Steven D. Pain

Oak Ridge National Laboratory

- Gammasphere ORRUBA Dual Detectors for Experimetal Structure Studies at ATLAS
- GODDESS with GRETINA/GRETA at FRIB





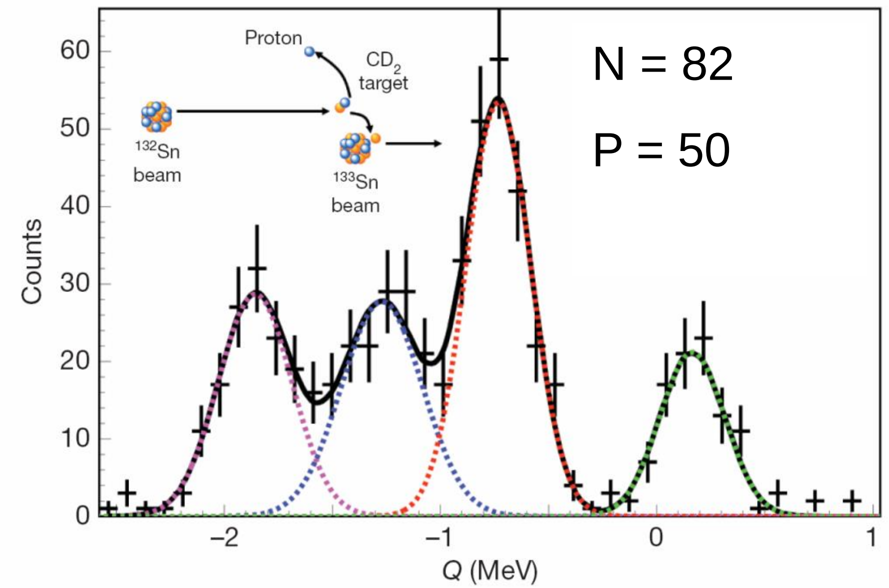
Low E Community Meeting, TAMU, August 2014

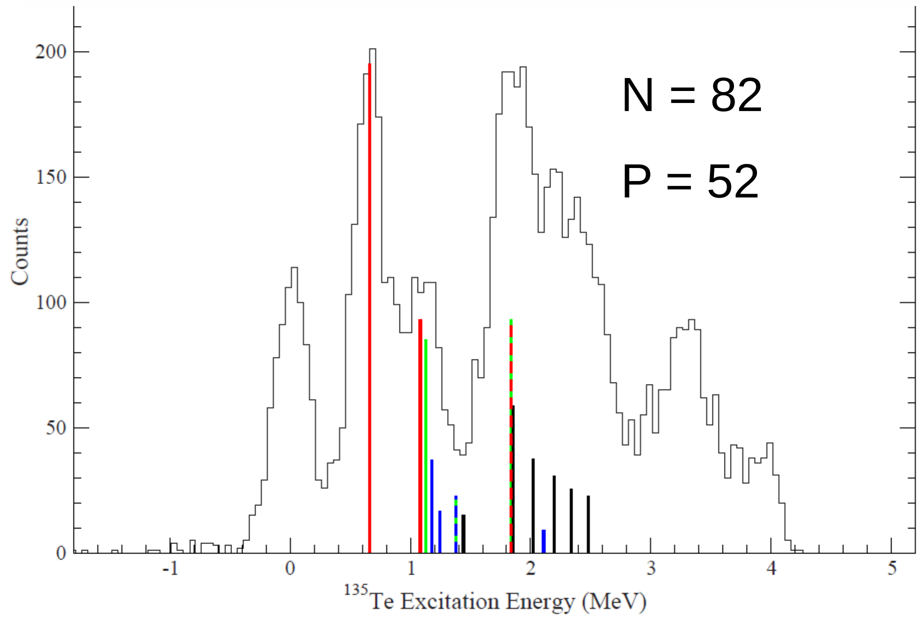
Particle gamma experiments

Particle gamma measurements
(light/heavy, p/n-rich)

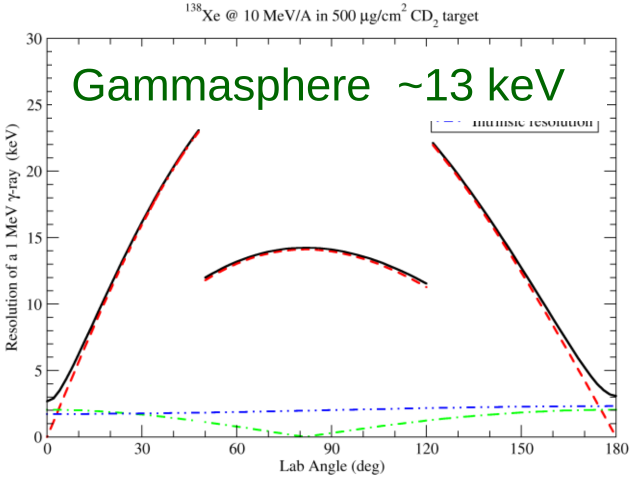
- Light ion transfer reactions (d,p) (d,t) (d,^{3}He) (p,t) etc
- Heavy-ion transfer reactions (^{9}Be,^{8}Be) (^{13}C,^{12}C) (^{7}Li,^{6}He) (^{19}F,^{18}O)
- Inelastic scattering
- Coulex

- Search for single-particle/hole states (both measured at the same time)
- Measurement of SF/tracking fragmentation of SP states (structure, DSD n-capture)
- ANC measurements
- Surrogate for stat. n capture
- Lifetime measurements (DSAM)

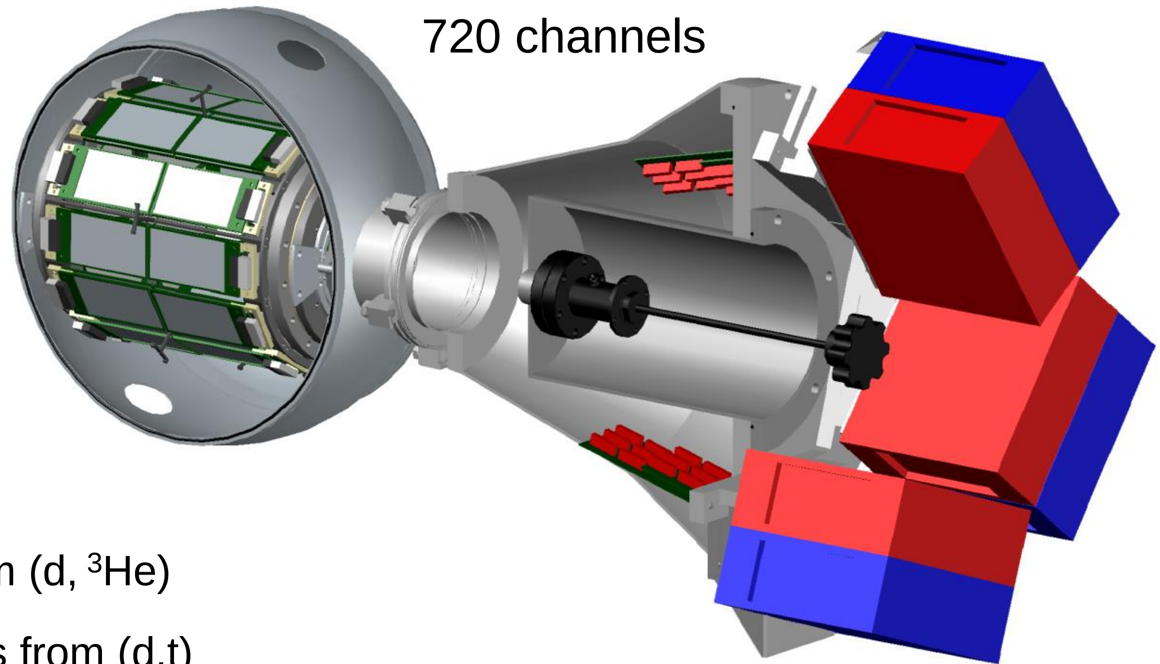


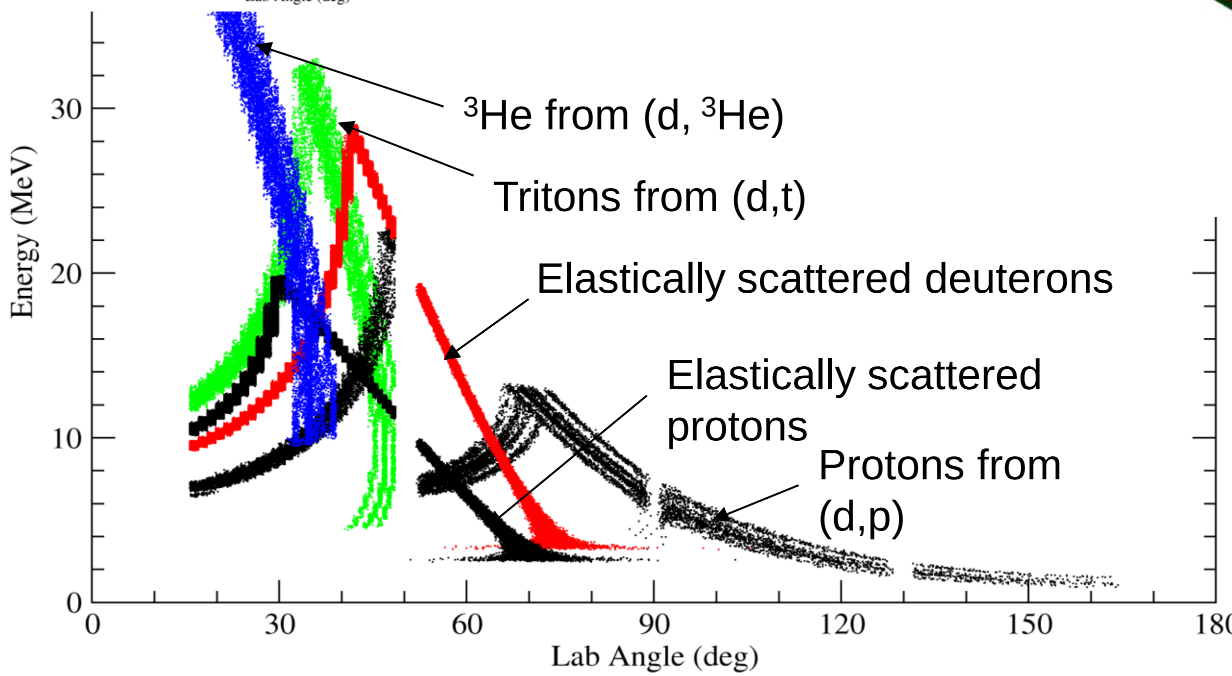


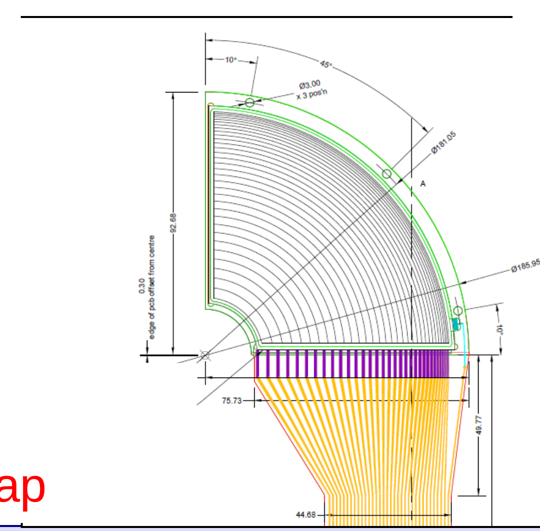
GODDESS – Measurements at ATLAS



720 channels

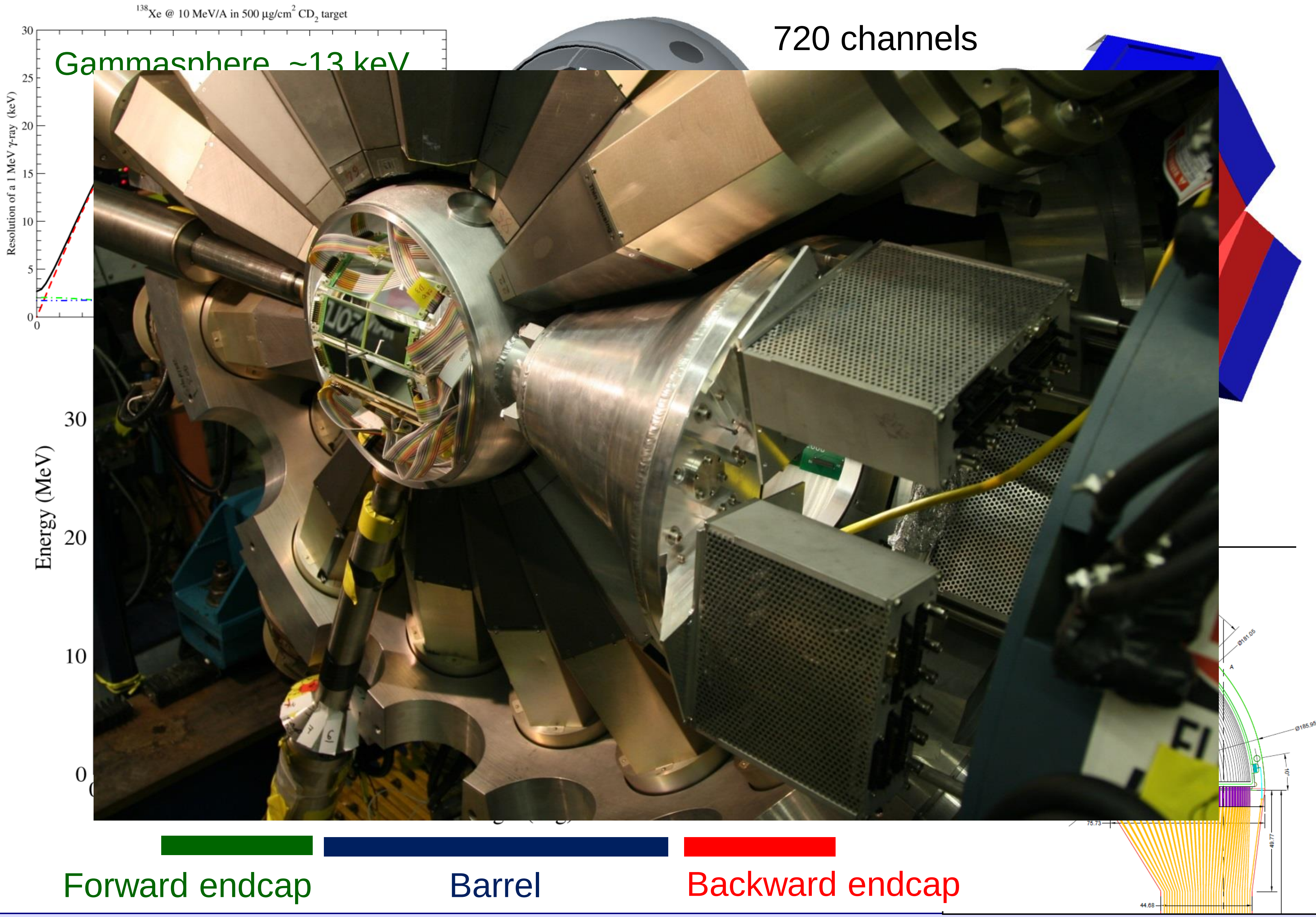






Forward endcap Barrel Backward endcap

GODDESS – Measurements at ATLAS

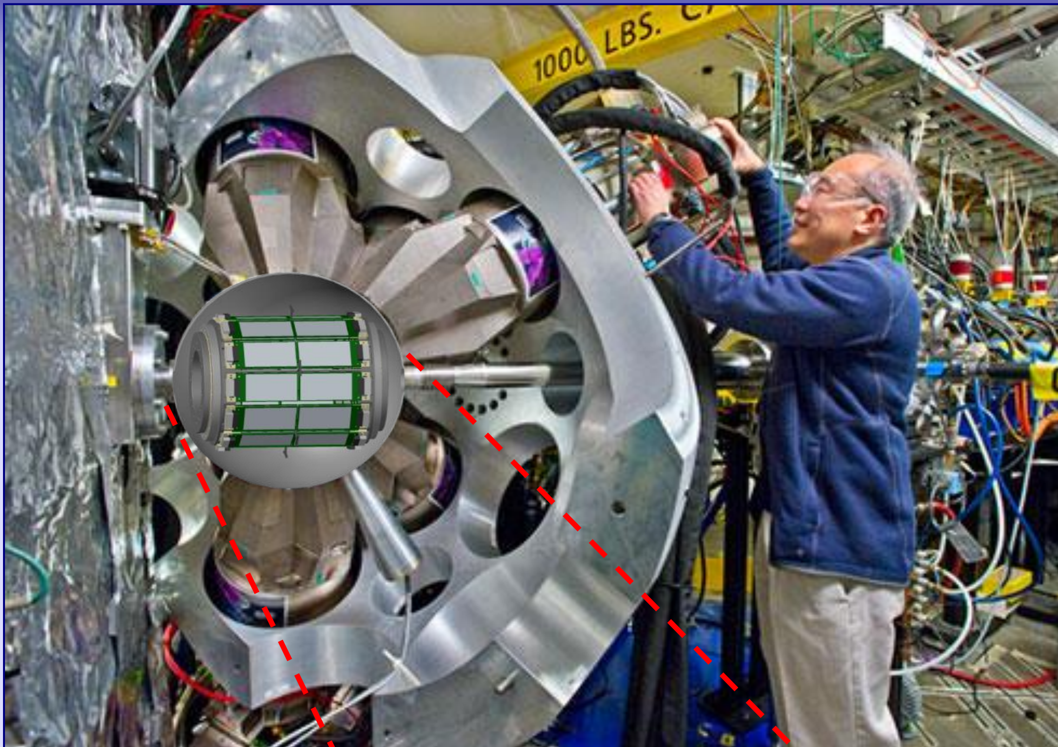


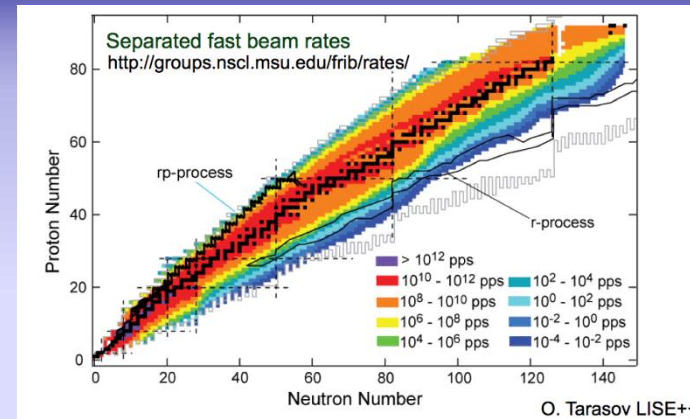
Forward endcap

Barrel

Backward endcap

G(RETINA)ODDESS at FRIB

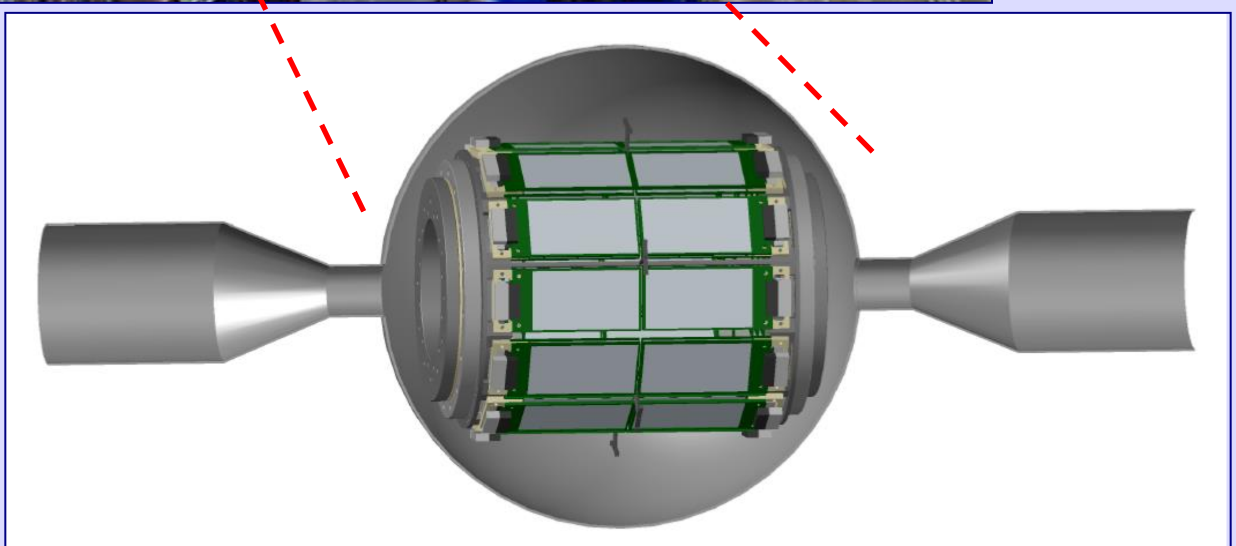


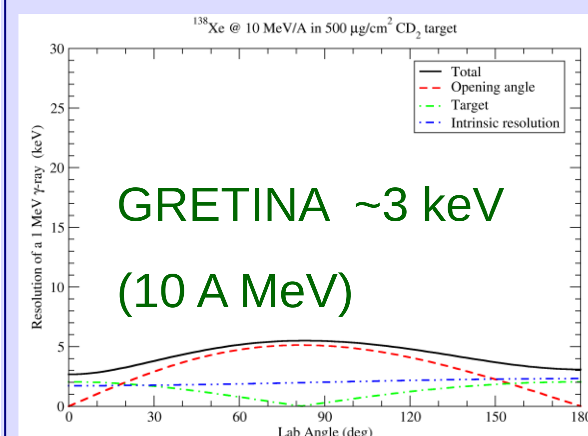


Intrinsic Ge resolution for 10 A-MeV

Critical for measurements with fast beams

Fits in standard GRETINA chamber



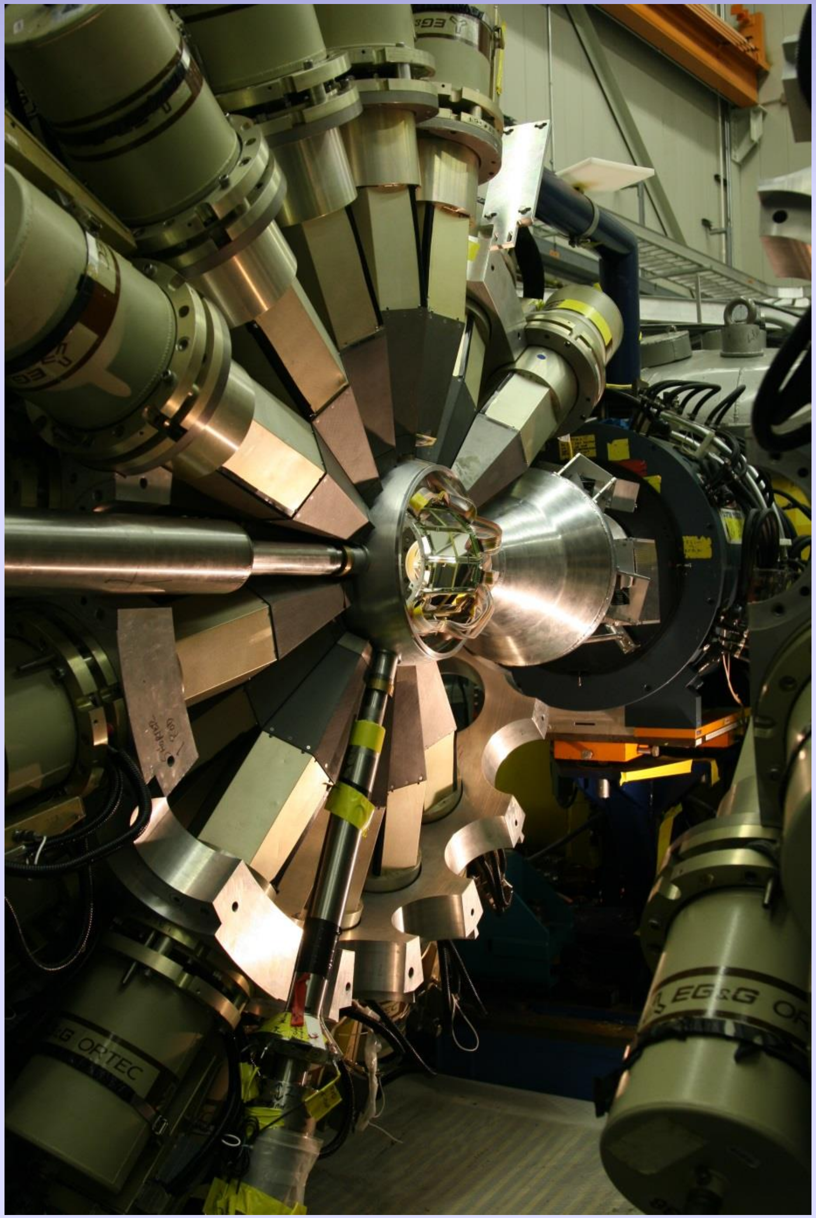


Overview to FRIB

- GODDESS at ATLAS
- Clarion at ReA3
- GODDESS with GRETINA/GRETA

FRIB Infrastructure

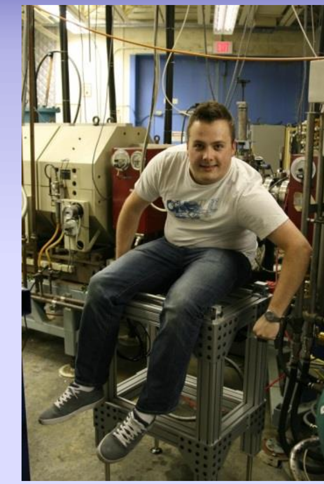
- Instrumentation – standard suite of digitizers for silicon arrays in general
  - Algorithms under development
  - 100 MHz minimum sampling
  - ~ 1000 ch system
  - GRETINA-style digitizers
  - Online merging of data critical capability
- Coupling to separator in medium/high energy halls



GODDESS Acknowledgements

Steven Hardy - cable crusher

Callum Shand testing his test stand



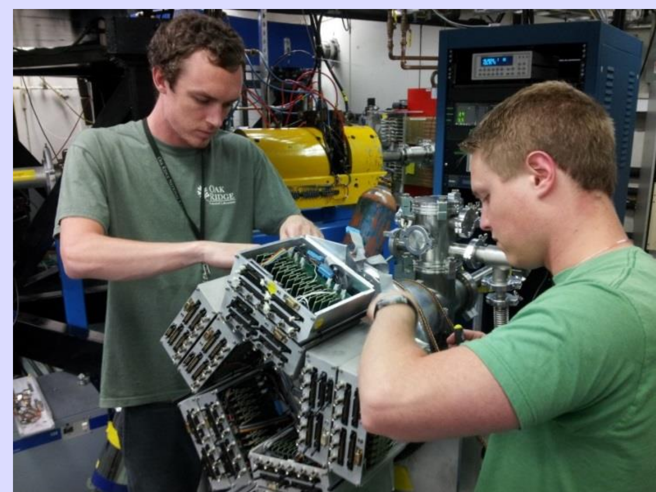
Travis Baugher – Simulating GODDESS

Andrew Ratkiewicz – not entirely convinced by the pineapple-eating dinosaurs at the creation museum

Student

Postdoc

Thanks also to the help from Argonne – Darek Seweryniak, Mike Carpenter, Shaofei Zhu and Kim Lister….



Sean Burcher and **Ian Marsh** assembling GODDESS for the first time

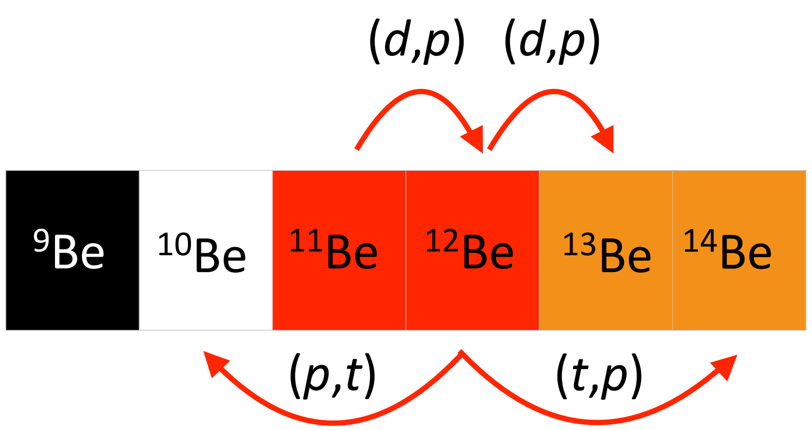
Argonne NATIONAL LABORATORY

(Some) Future Opportunities and Needs for Transfer-Reaction Studies

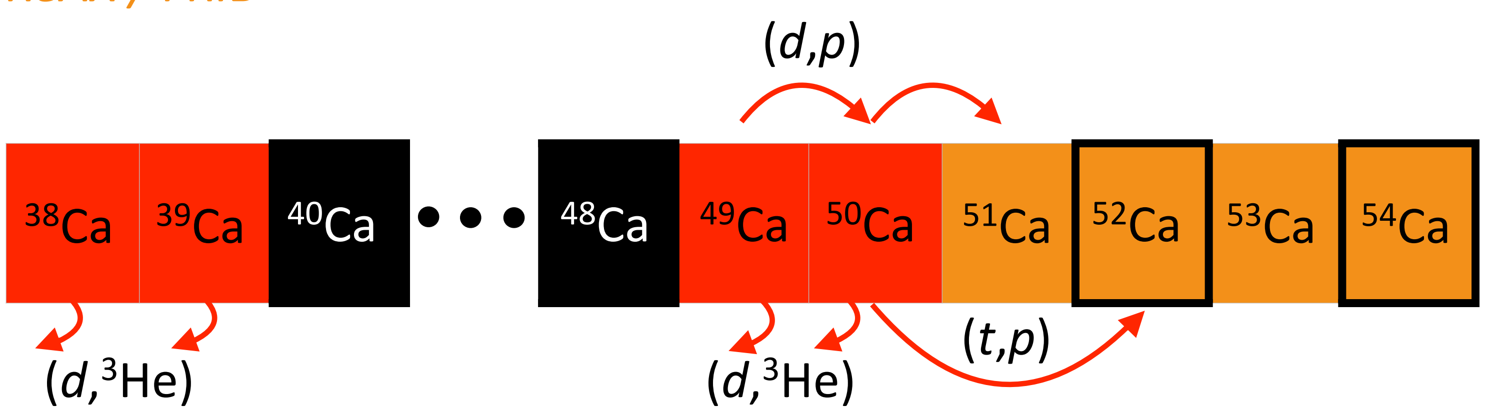
Ben Kay, ANL

U.S. DEPARTMENT OF ENERGY

Studies with light (A < 60) RIB beams

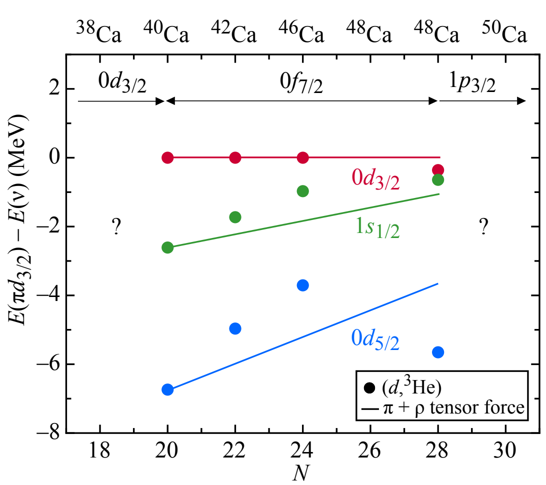


AIRIS
ReAX / FRIB

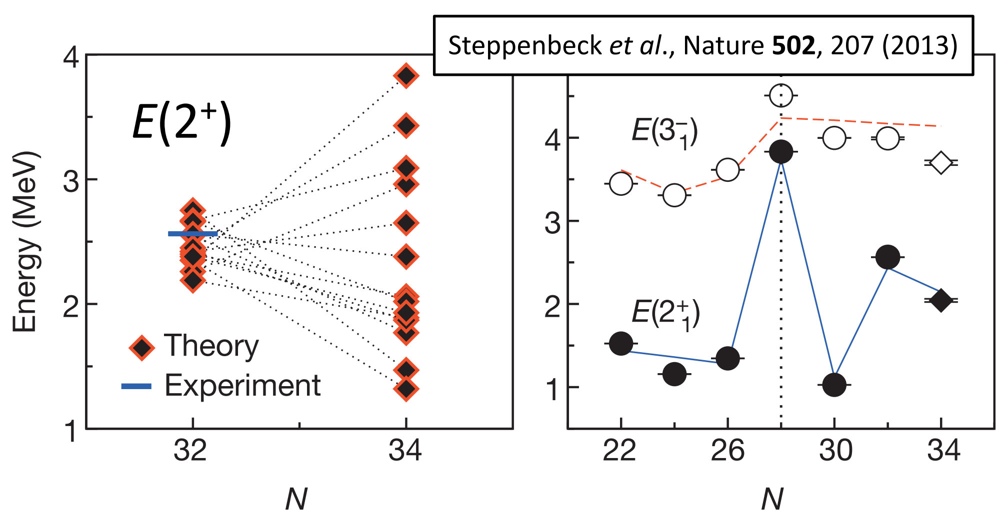


Opportunities

In the next 5-10 years, use ***single- and two-nucleon transfer reactions*** to probe aspects on nuclear structure ***complementary*** to those accessible by ***e.g. knockout***. Reactions on chains of related isotopes ***at energies of 5-20 MeV/u***



SPEs below Ca



Magic numbers at N = 32,34 for Z = 20

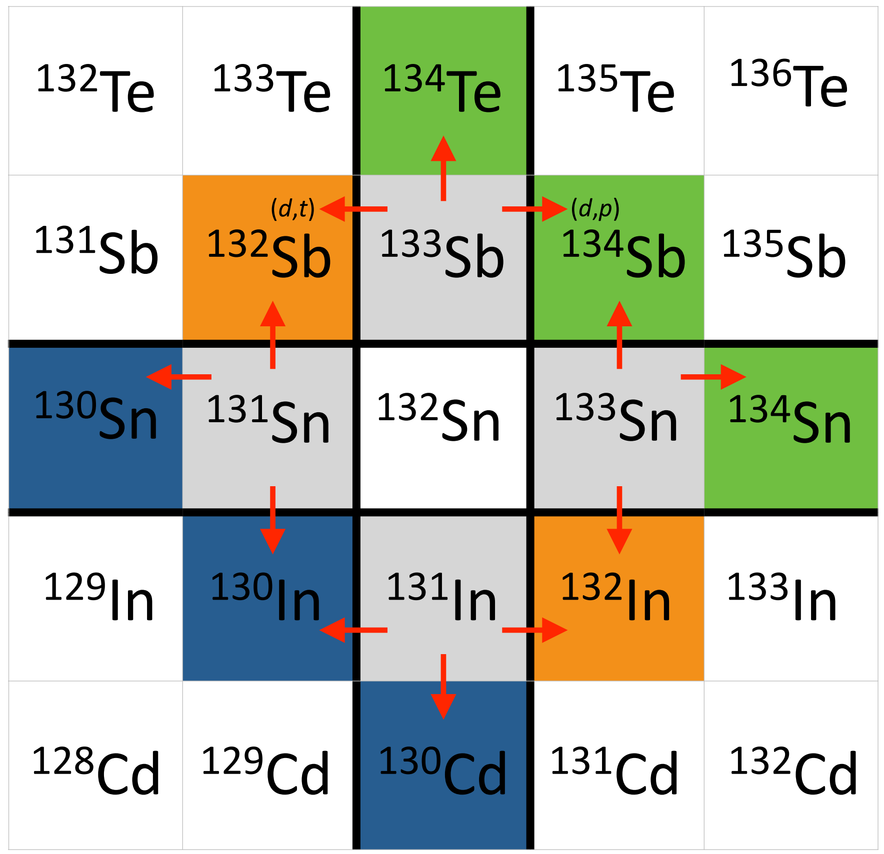
Needs

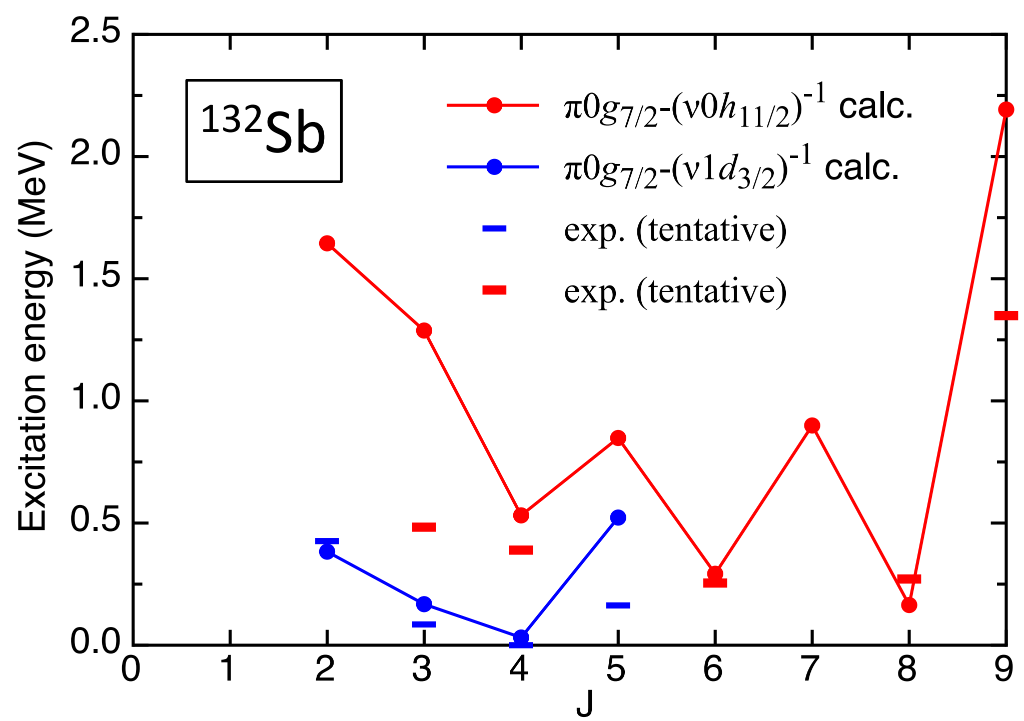
- In-flight beams, implementation of ***AIRIS***
- Continued evolution of ***HELIOS spectrometer*** at Argonne
- Development of ***solenoidal spectrometer (4 T)*** for ***ReAX***, ***FRIB***
- Explore ***solenoidal-spectrometer*** concept for ***fast beams*** with ***beam tracking to target***
- …

Detailed spectroscopy around A = 130-134

Opportunities
Mapping out the effective interaction by determining ***particle-hole***, ***particle-particle***, and ***hole-hole*** multiplets quantitatively with single-nucleon transfer

(N.B. Many long-lived isomers in the region (μs to mins), so particle-γ coincidences nontrivial, but may provide new insights)





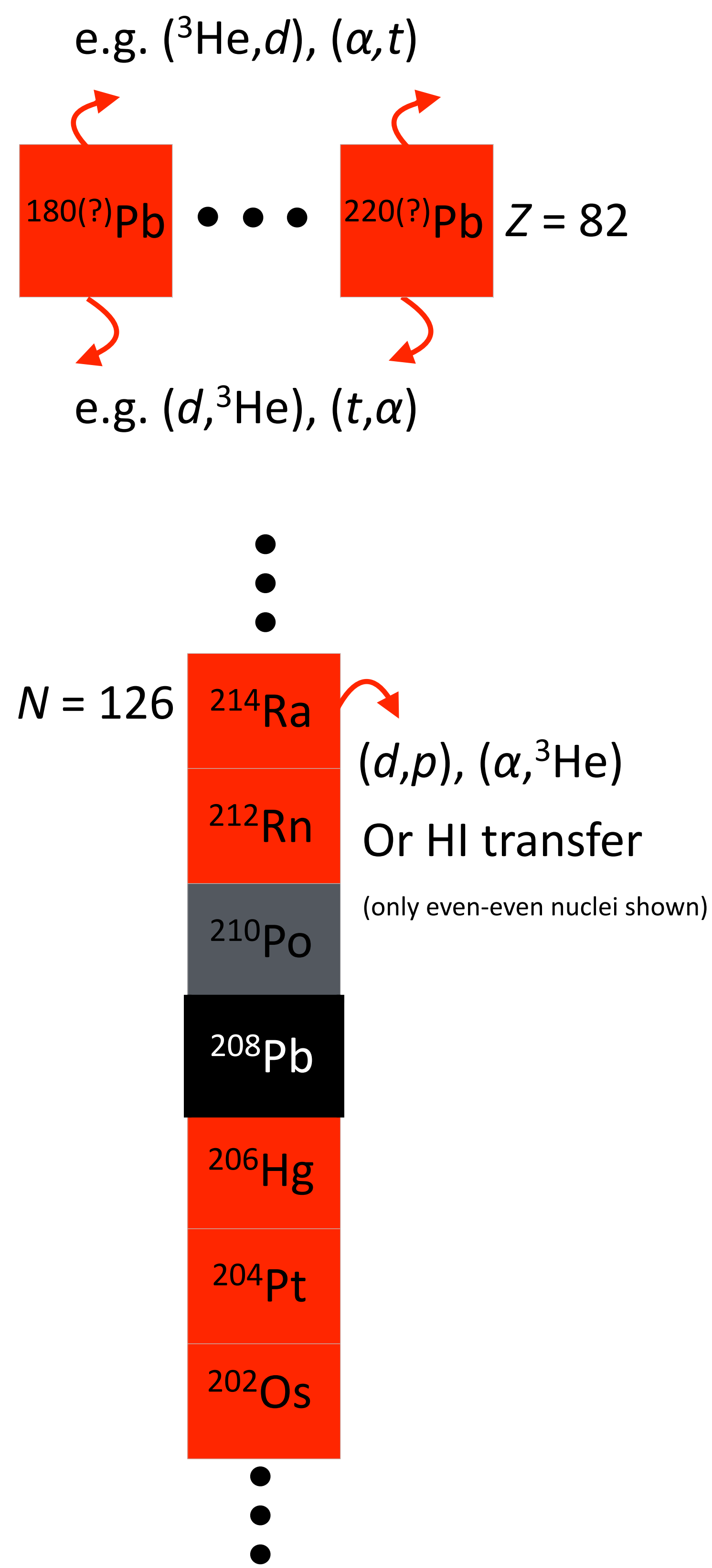
Tentative spins from γ-ray spectroscopy

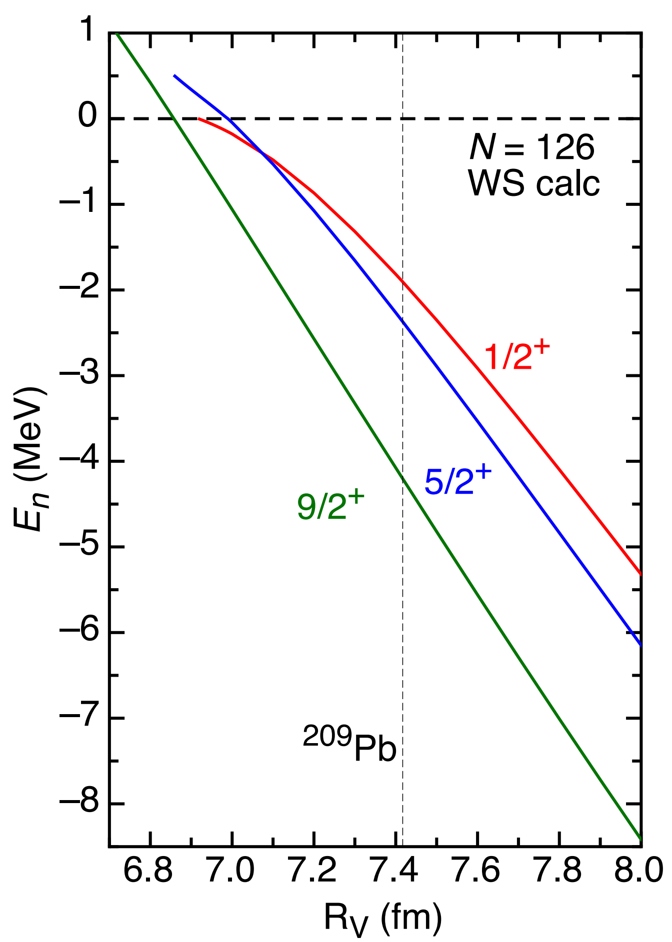
Needs
- In-flight beams, implementation of ***AIRIS***
- Continued evolution of ***HELIOS spectrometer*** at Argonne
- Development of ***solenoidal spectrometer (4 T)*** for ***ReAX***, ***FRIB***
- Explore ***solenoidal-spectrometer*** concept for ***fast beams*** with ***beam tracking to target***
- Continued development of charged-particle spectroscopy techniques
- Continued development of ***CARIBU*** beams, first steps e.g., ^{133}Sb
- ***Solutions for recoil detection / separation*** (high rate, high res.)
- ***Pure beams*** if e.g., active target ***resonant inelastic scattering*** used
- Complementary (simultaneous?) ***gamma-ray spectroscopy*** e.g. GODDESS
- …

Transfer around Z = 82, N = 126

Opportunities

Probing ***high-j states*** above the Pb isotopes, potentially from ~$^{180\text{-}220}$Pb, and hole states below. The ***first transfer-reaction measurements below ^{208}Pb*** at *N* = 126, and above ^{210}Po, and well beyond (FRIB era).





Needs

- In-flight beams, implementation of ***AIRIS***
- Continued evolution of ***HELIOS spectrometer*** at Argonne
- Development of ***solenoidal spectrometer (4 T)*** for ***ReAX***, ***FRIB***
- Explore ***solenoidal-spectrometer*** concept for ***fast beams*** with ***beam tracking to target***
- Continued development of charged-particle spectroscopy techniques
- Continued development of ***CARIBU*** beams, first steps e.g., ^{133}Sb
- ***Solutions for recoil detection / separation*** (high rate, high res.)
- ***Pure beams*** if e.g., active target ***resonant inelastic scattering*** used
- Complementary (simultaneous?) ***gamma-ray spectroscopy*** e.g. GODDESS
- ***Variety of probes***, such as heavy-ion transfer, reactions well matched to high-ℓ transfer
- Production method for N = 126 isotopes below ^{208}Pb?

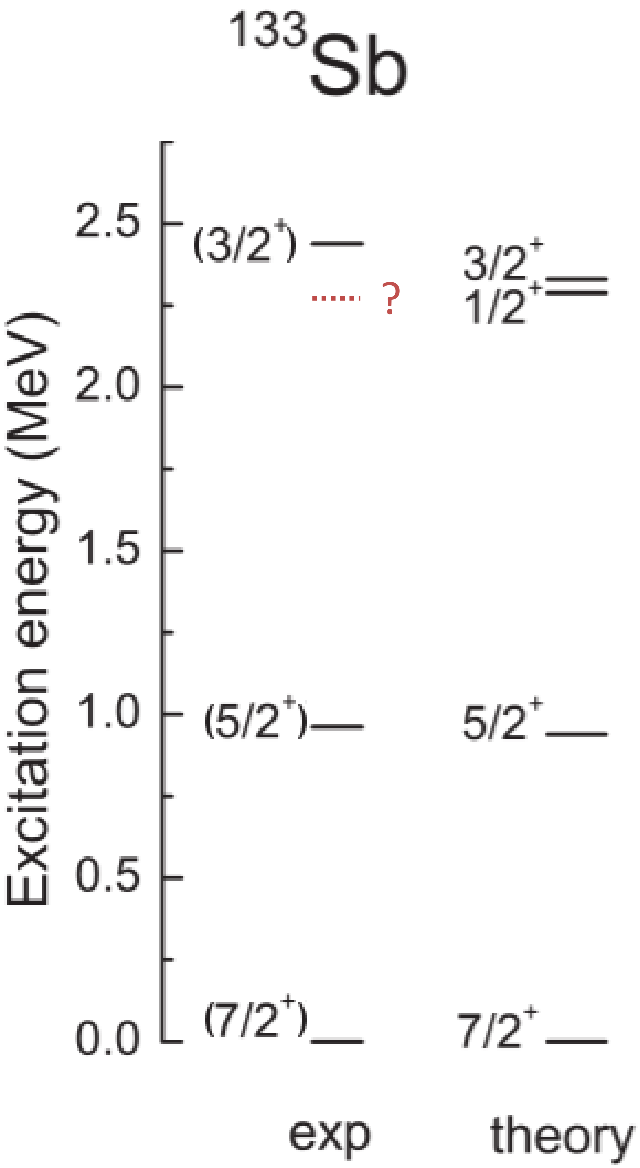
Proton-Transfer Reactions around 5 MeV/u with VANDLE

Karl Smith
Univ. of Tennessee - Knoxville

Showcase Experiment
^{132}Sn(d,n)

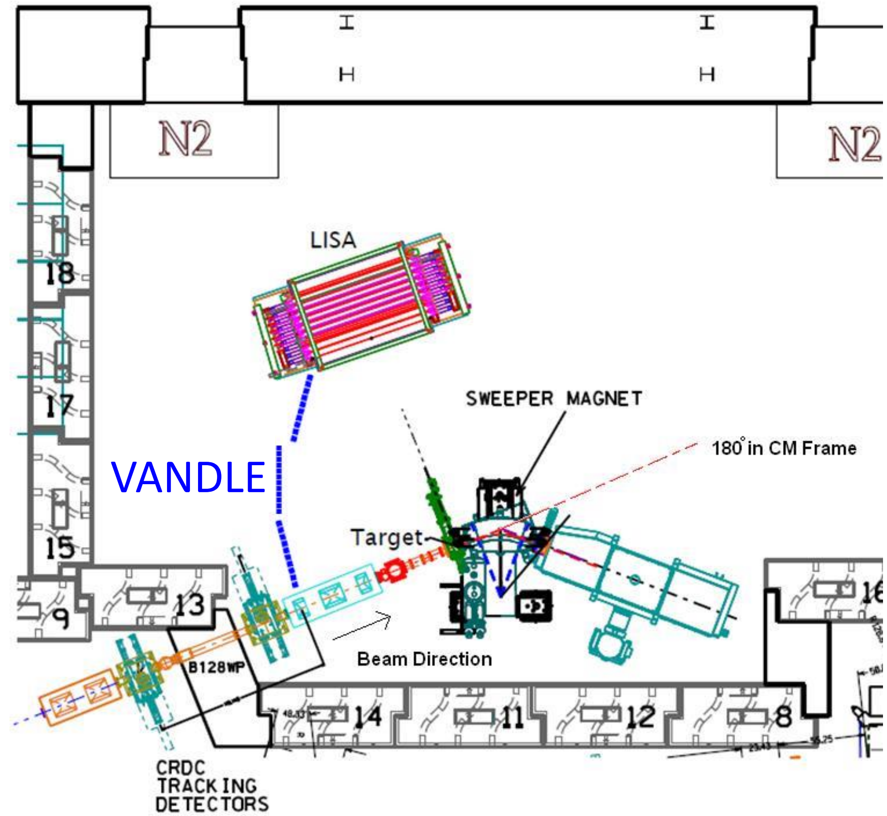
- Study single particle states in ^{133}Sb.
- Lowest spin state, $1/2^+$, is unidentified.
    - Expected around 2 MeV.
- Spin assignments are tentative.

- Good candidate experiment for (d,n) at ReA12.
    - Pre-FRIB estimated rate of 20 pps of ^{132}Sn.
    - FRIB estimated rate of 8x10^5 pps.



^{56}Ni(d,n)

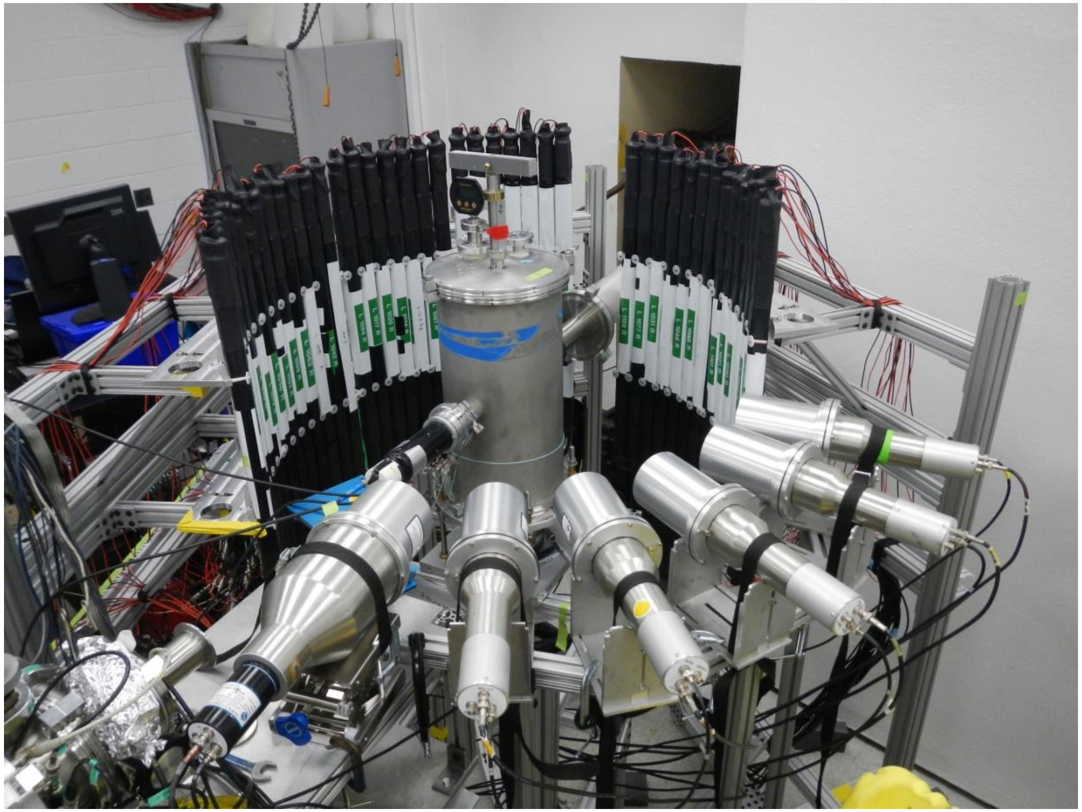
- Study spectroscopic factors of the single-proton states in ^{57}Cu.
    - Experiment E11027B at the NSCL performed June 2013.
- Versatile Array of Neutron Detectors at Low Energy (VANDLE) coupled with the Modular Neutron Array and Large multi-Institutional Scintillator Array (MoNA-LISA)
- VANDLE extended coverage to backward angles.
- Currently under analysis.



Courtesy of Bill Peters

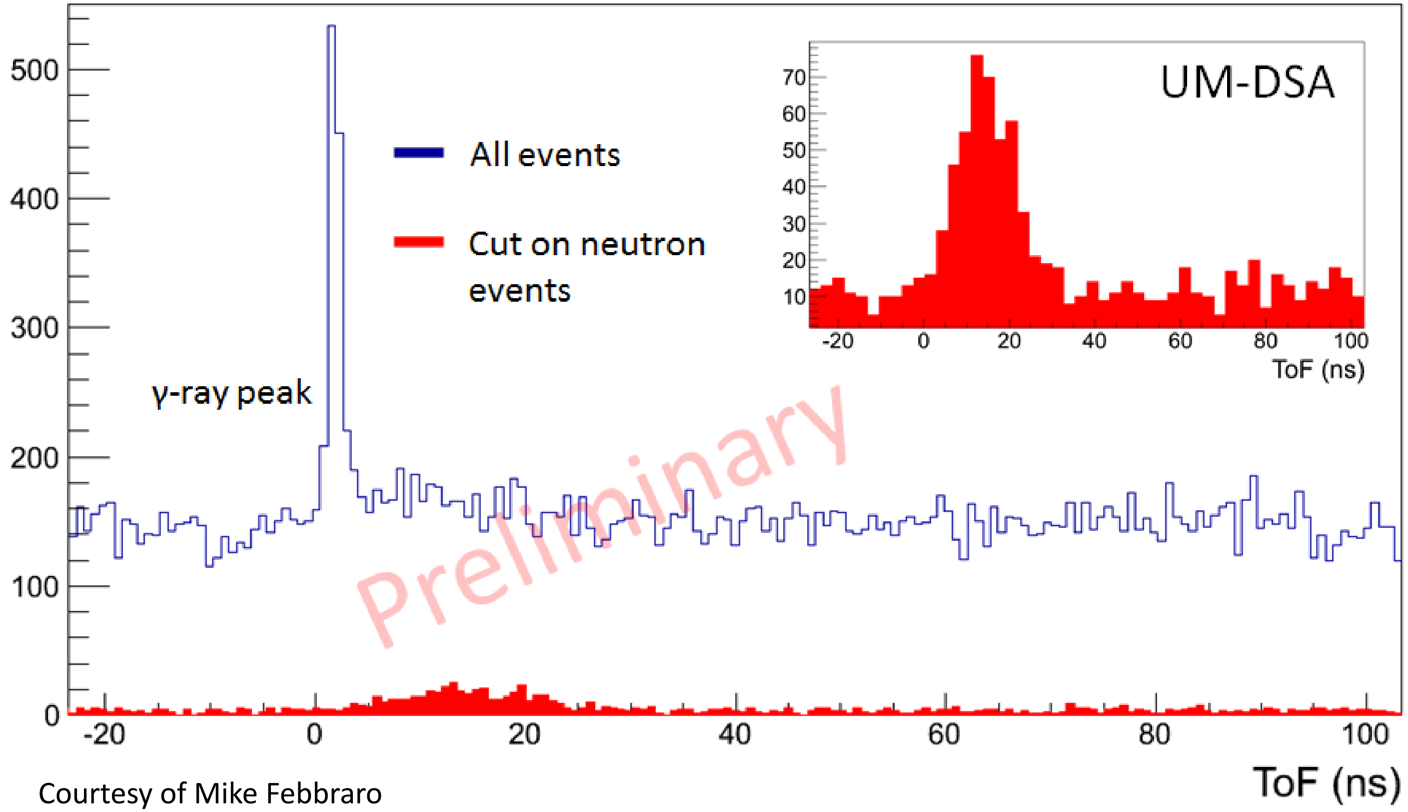
^{7}Be(d,n) and ^{17}F(d,n)

- Performed at the Nuclear Structure Laboratory in May 2014
- Utilized TwinSol and ^{6}Li(^{3}He,d) to produce secondary beam of ^{7}Be beam at 31 MeV
- Used VANDLE at backward angles and the Univ. of Michigan Deuterated Scintillator Array (UM-DSA) at forward angles.
- Under analysis by Cory Thornsberry and Patrick O'Malley



^{7}Be(d,n)
Preliminary Result

Separate neutron and gamma events using pulse shape discrimination.



Courtesy of Mike Febbraro

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

Validating a surrogate for neutron capture with radioactive ion beams

Jolie A. Cizewski
Rutgers University

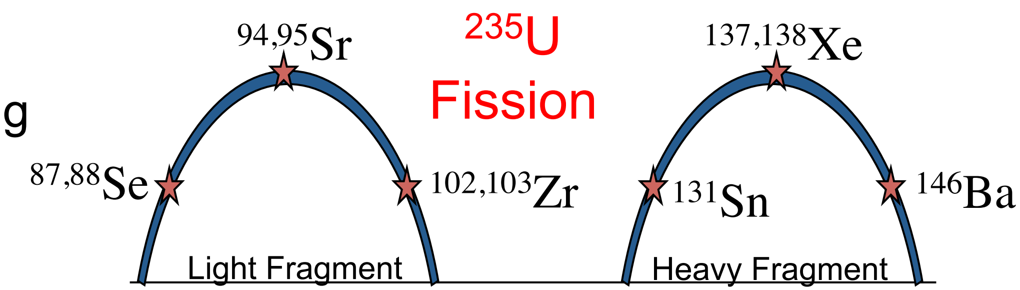
Low Energy Nuclear Physics Town Meeting

TAMU, Aug 21-23, 2014

Neutron Capture is important

Important for basic and applied nuclear science

- Nucleosynthesis processes
  - s and r process
- Nuclear reactors
  - Cross sections on fission fragments
- Nuclear forensics & weapons modeling
  - Fission fragments, actinides, etc.



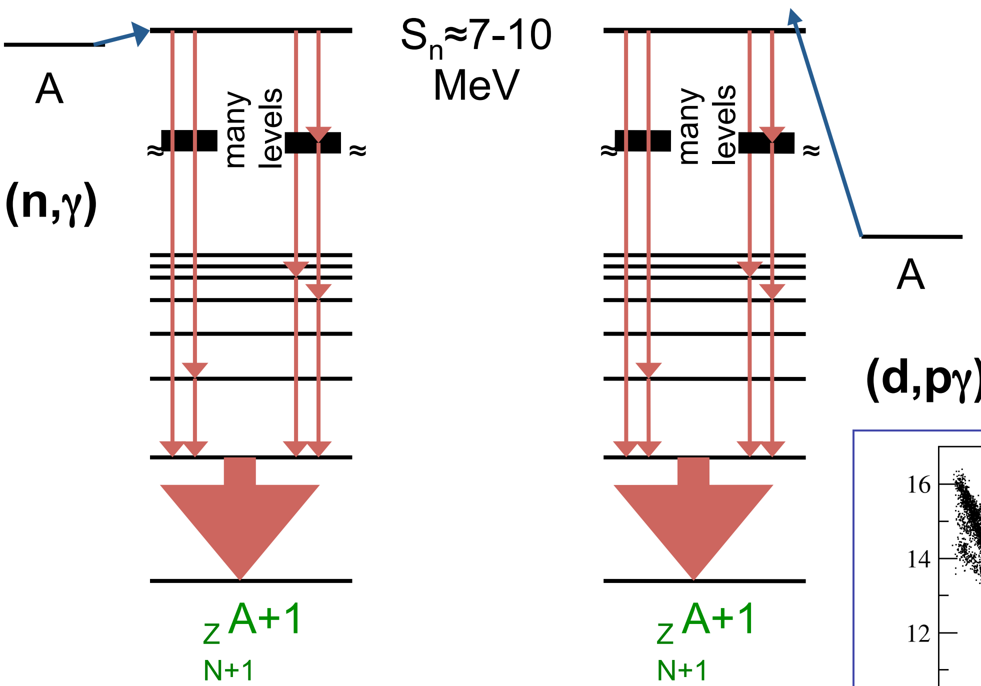
- On stable isotopes: well studied
- On rare isotopes:
  - Direct measurements when $t_{1/2}$ > 100 days
- **Need a validated surrogate for (n,γ)**

Z										
52	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te
51	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb
50	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn
49	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In	^{133}In	^{134}In	^{135}In	^{136}In
48	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd	^{132}Cd	^{133}Cd	^{134}Cd	^{135}Cd
	78	79	80	81	82	83	84	85	86	87

References
(top): D.G. Foster and E.D. Arthur, LA-9168, February 1982 (unpublished)

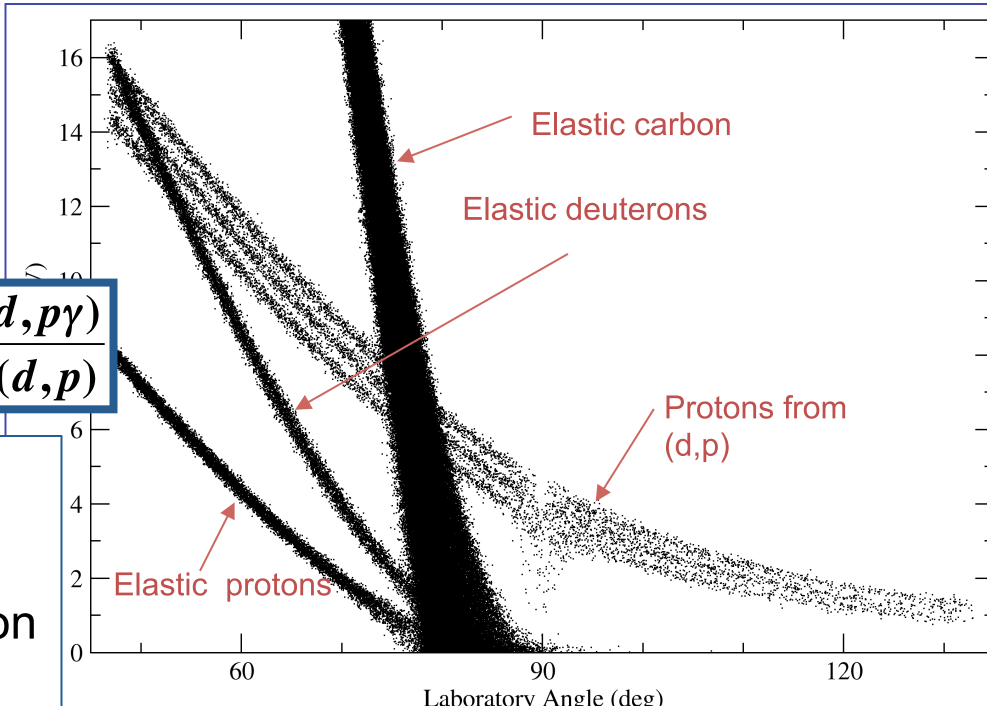
(bottom): R. Surman, J. Beun, G.C. Mclaughlin, W.R. Hix, Phys. Rev. C **79**, 045809 (2009)

(d,pγ): Good candidate for (n,γ) surrogate with beams



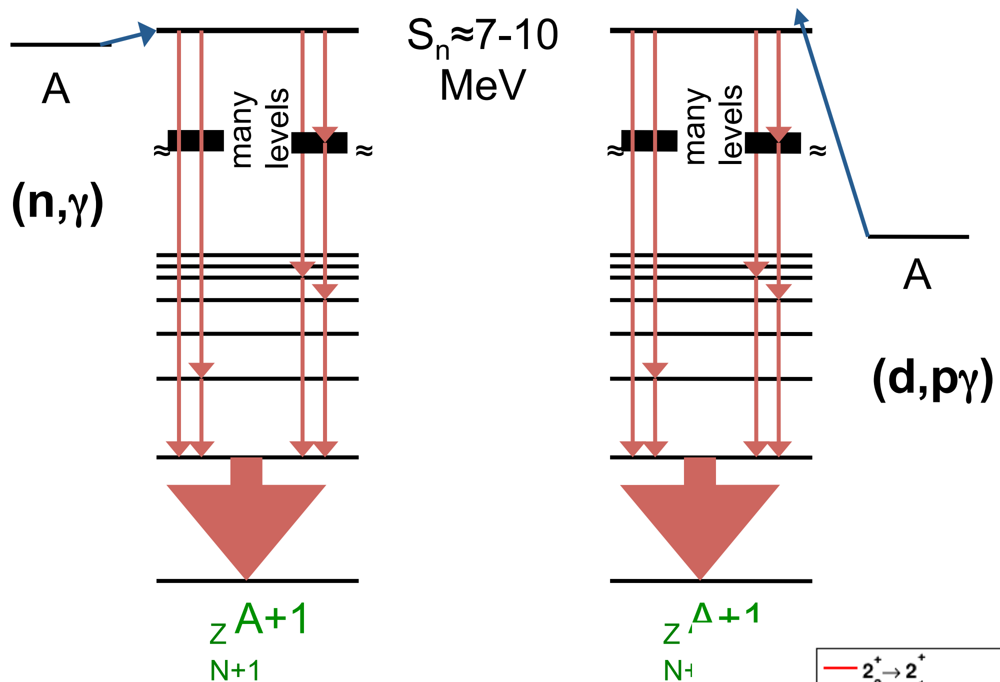
- Relatively good match with spin distribution in (n,γ) which is dominated by ℓ=0
- Reaction predominantly one-step transfer of j=ℓ±1/2 neutron

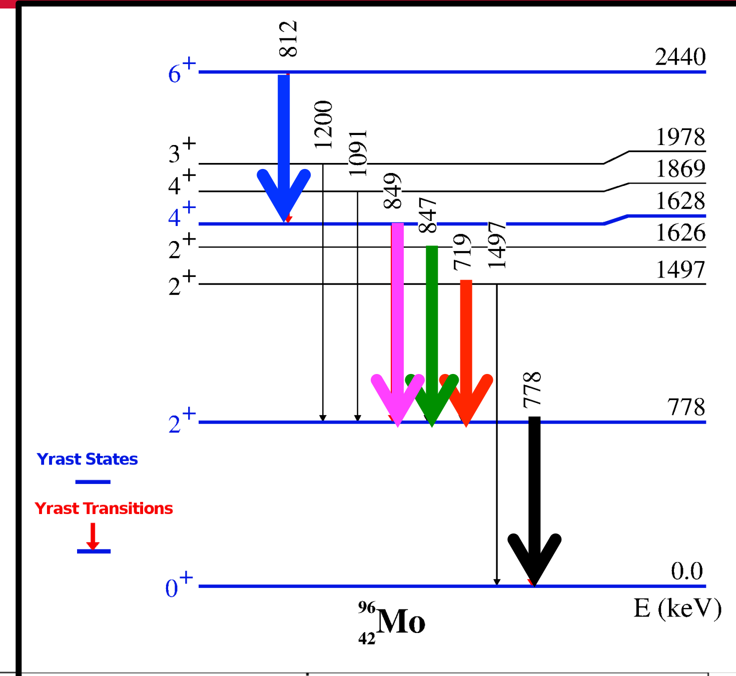
$$\sigma_{n\gamma}^{WE}(E_n) = \sigma_n^{CN}(E_n)G_\gamma^{CN}(E_n) = \sigma_n^{CN}(E_n)\frac{N(d,p\gamma)}{\varepsilon N(d,p)}$$



- “Easy” to produce CD_2 targets
- “Lower” beam energies (than heavier targets) to get above neutron separation energy
- Kinematics favors cleaner reaction

(d,pγ): Good candidate for (n,γ) surrogate with beams

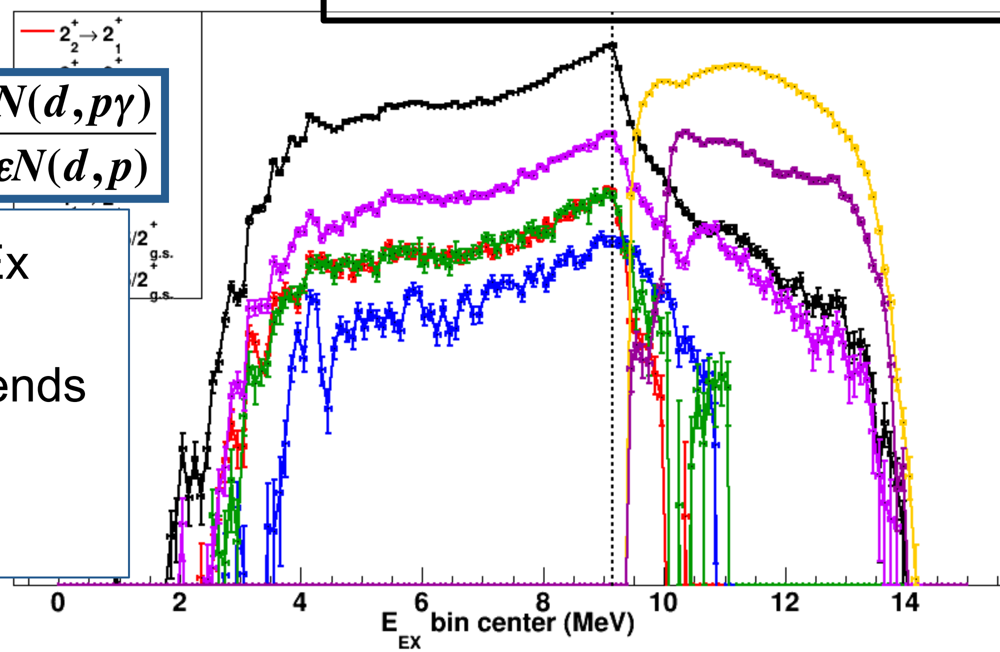




$$\sigma_{n\gamma}^{WE}(E_n) = \sigma_n^{CN}(E_n) G_\gamma^{CN}(E_n) = \sigma_n^{CN}(E_n)\frac{N(d,p\gamma)}{\varepsilon N(d,p)}$$

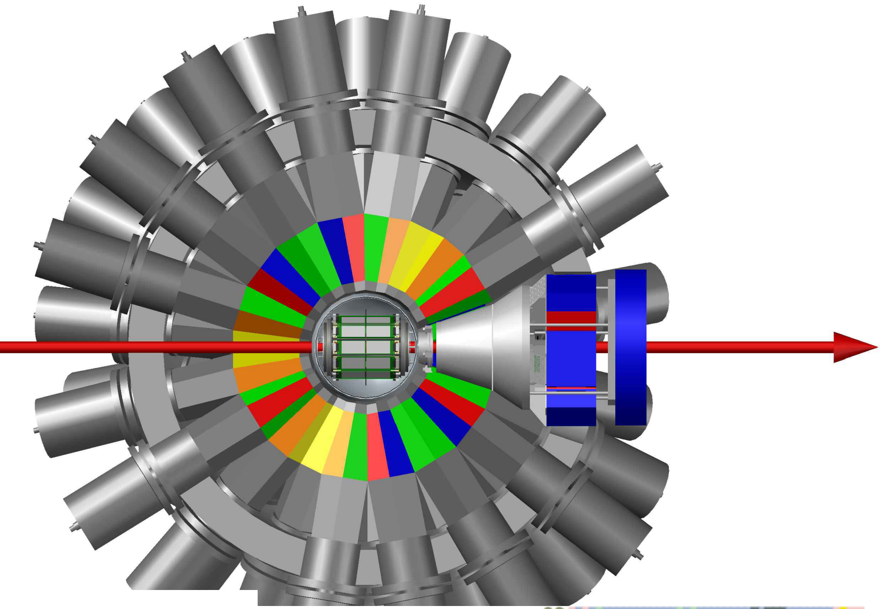
Preliminary ^{95}Mo(d,pγ) results vs Ex
A. Ratkiewicz (priv.com.)

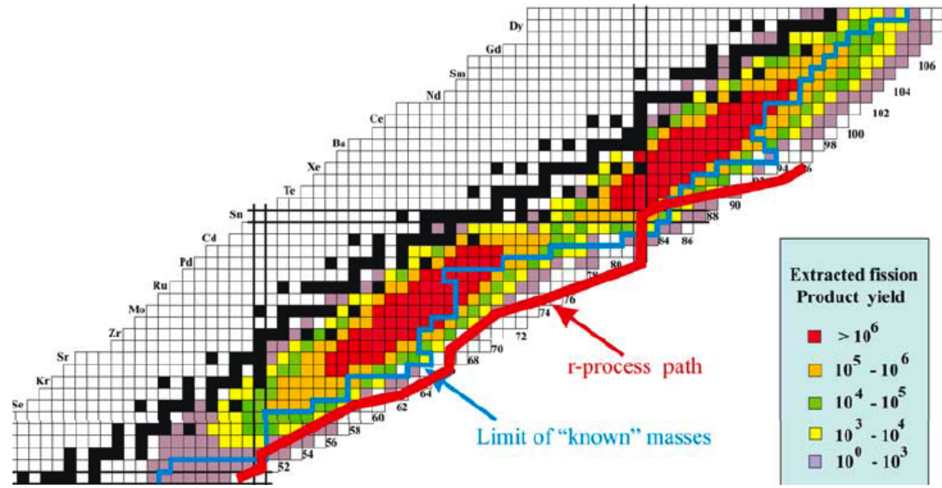
- Transition intensities = expected trends
  - Excited 2+ states decease rapidly
  - 6+ state more important higher energies
  - No population of 8+ state

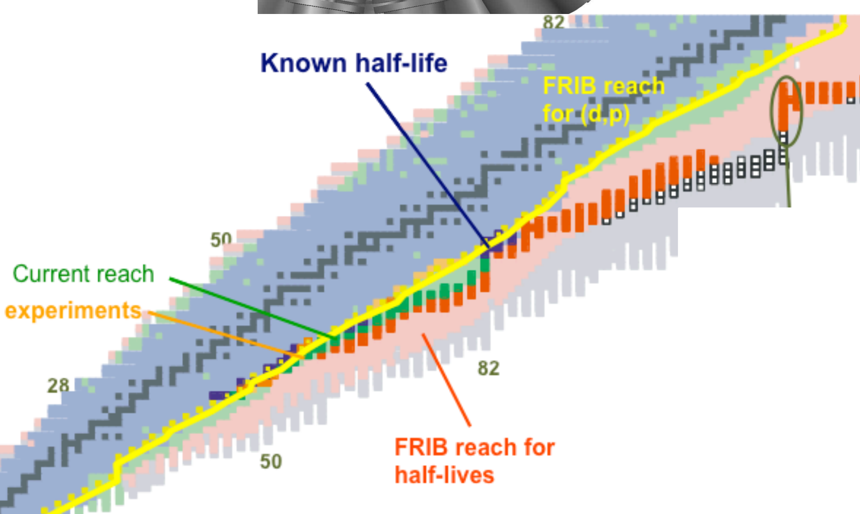


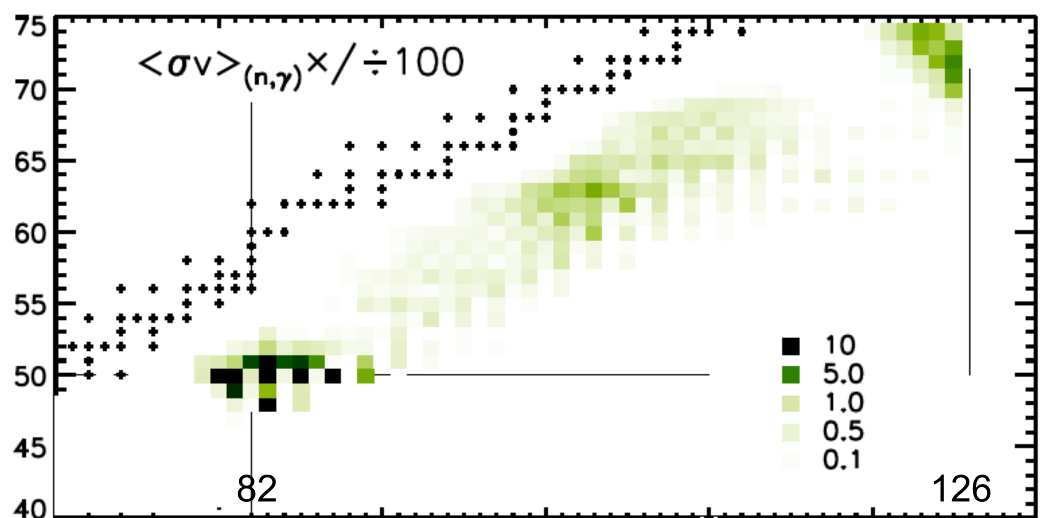
(d,pγ) as (n,γ) surrogate for radioactive beams

Measurements with GODDESS:
Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies
(or GRETINA or other Gamma-array)









(n,γ) sensitivities in hot r-process
R. Surman et al., EPJ Web **66**, 07024 (2014)

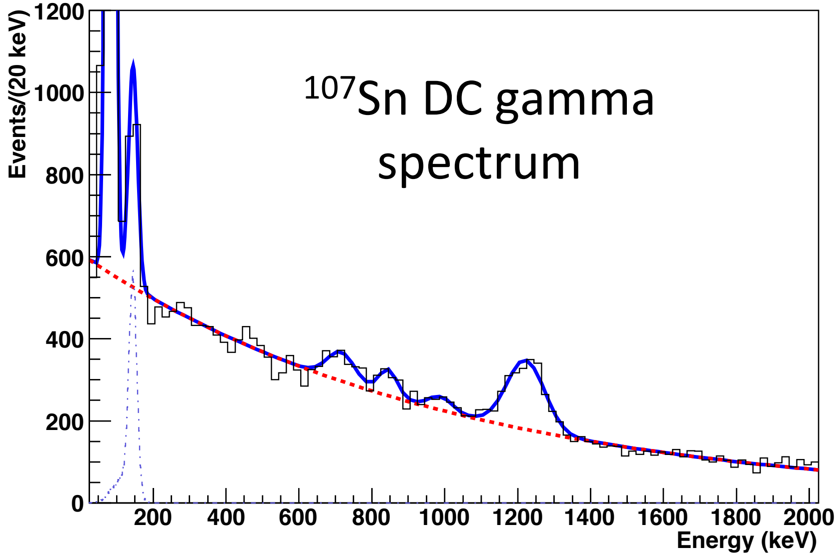
Knockout reactions in the ^{100}Sn region

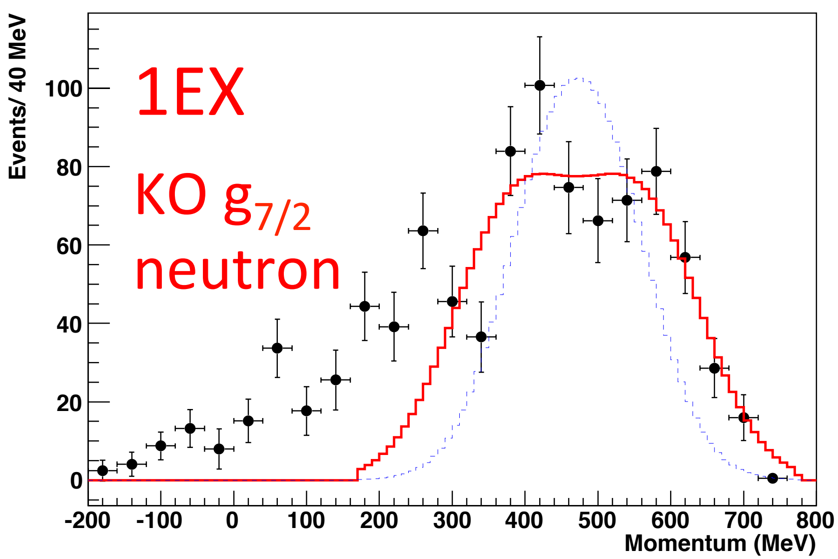
Giordano Cerizza
Univ. of Tennessee

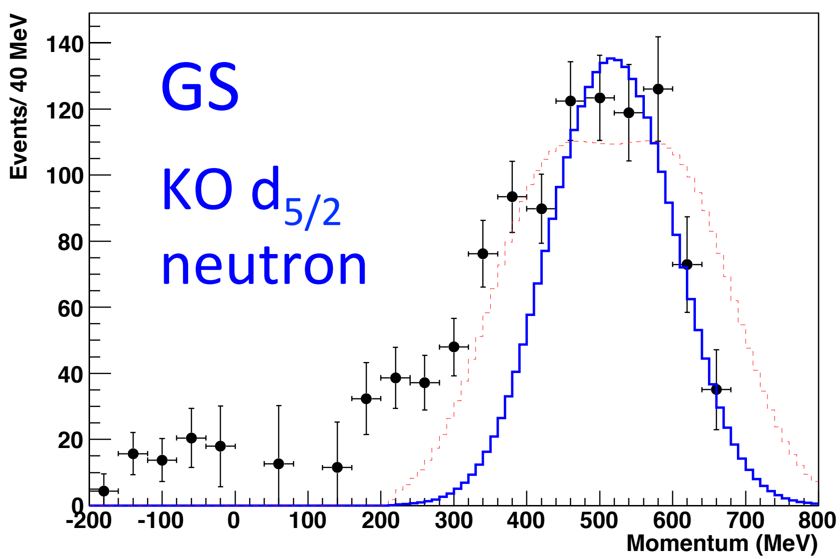
Town Meeting 2014

Present: NSCL

- S800 + CAESAR
- Observed ^{107,105}Sn KO reactions
- Measured momentum distribution
- Calculated inclusive and exclusive cross section for GS, 1EX, higher ex.
- Paper in preparation





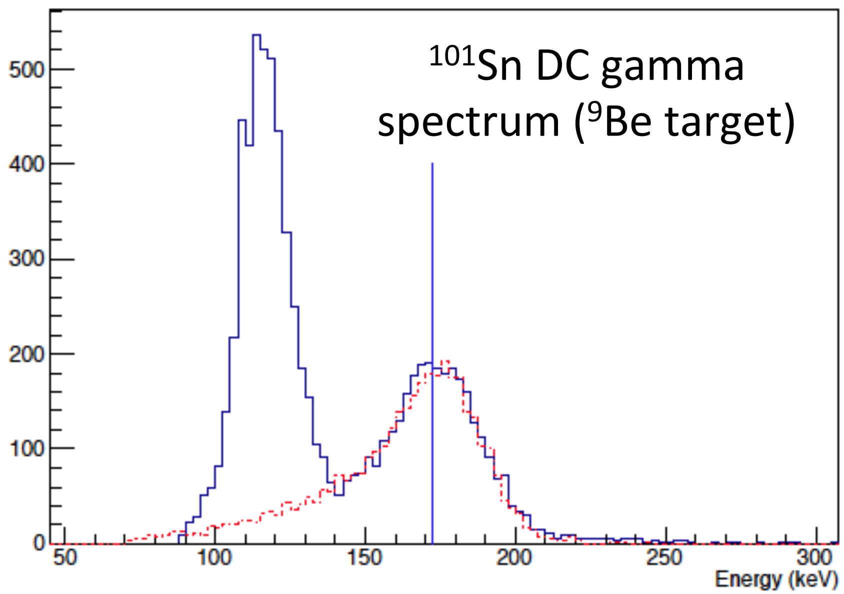


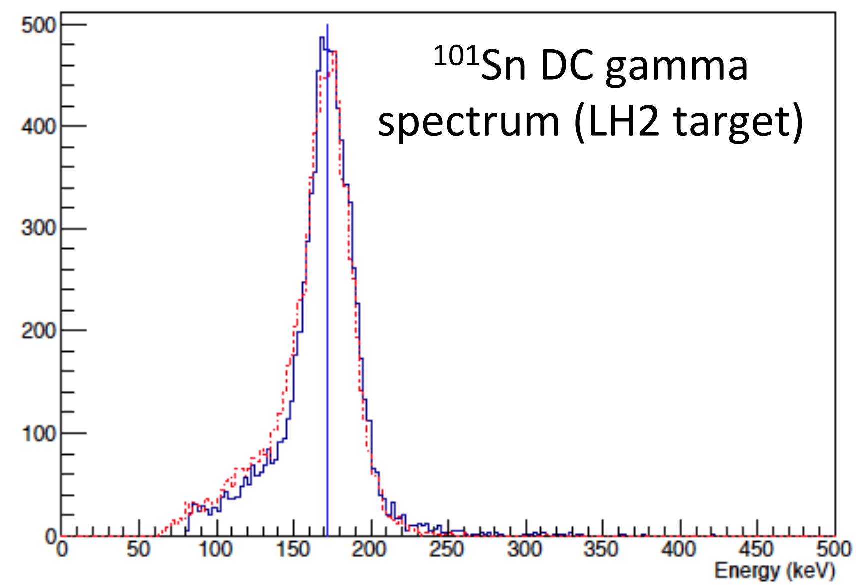
Near future: RIKEN

Experiment proposal with ZDS + DALI2+ with ^{9}Be target

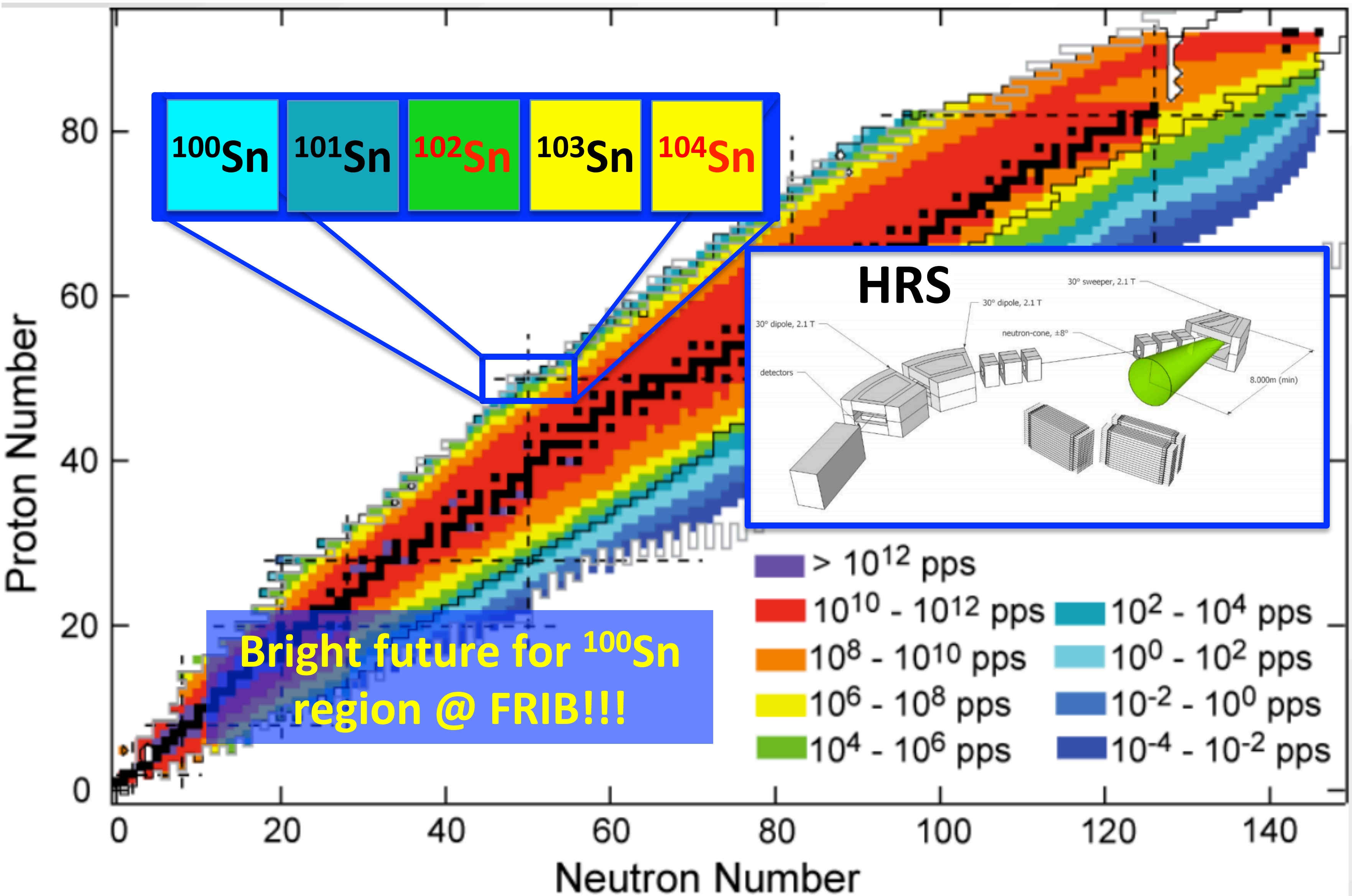
In	Rate (pps/pnA)	Energy (MeV/u)	Out	Rate (pph)	Gamma/hour
^{104}Sn	280 (150)	124 (157)	^{103}Sn	608 (1187)	72 (140)
^{102}Sn	0.51 (0.22)	122 (153)	^{101}Sn	4.1 (6.4)	0.7 (1.0)

* In parenthesis rates with LH2 target

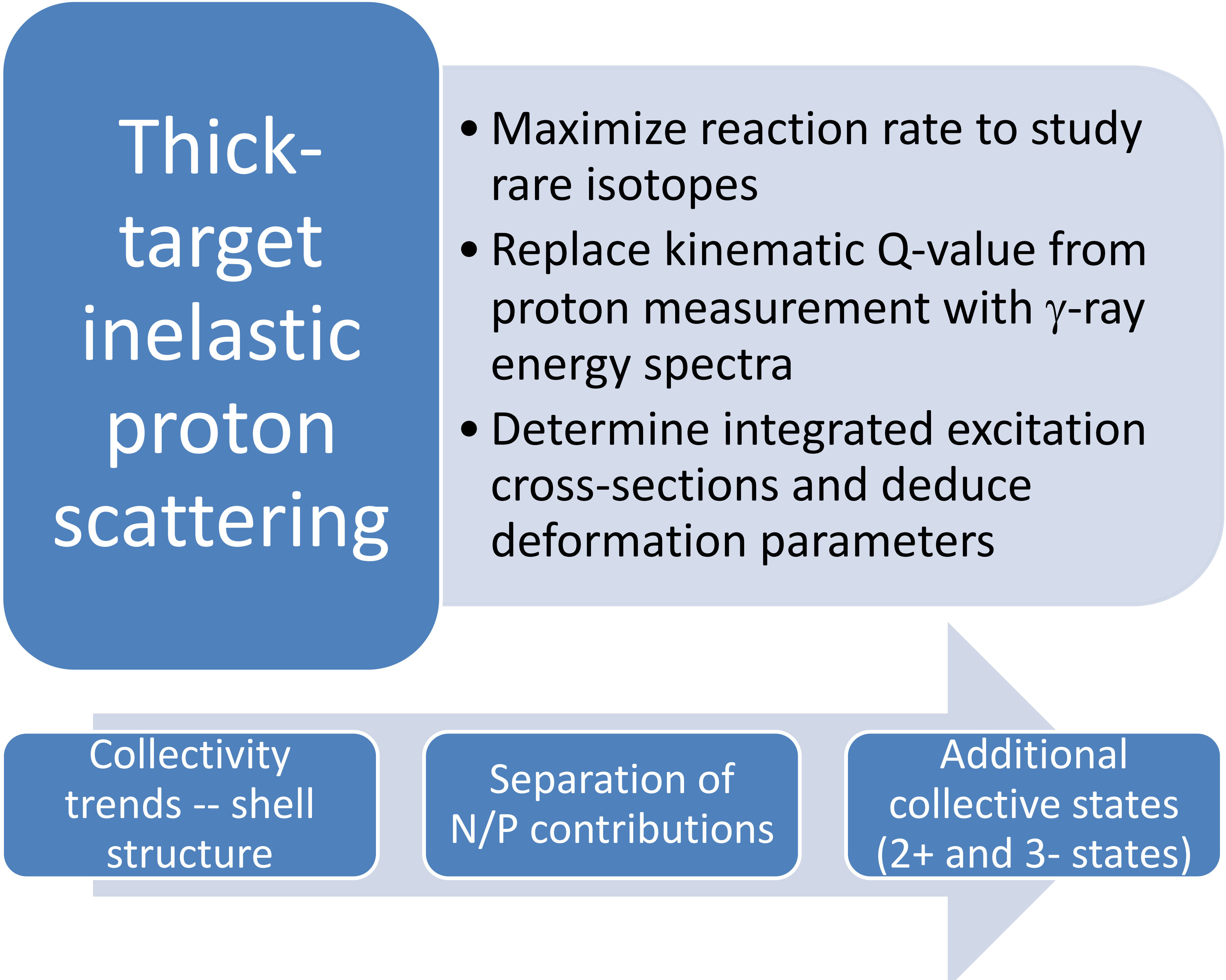




Future: FRIB



Slide taken from R. Zegers HRS workshop


Thick-target inelastic proton scattering
Maximize reaction rate to study rare isotopes
Replace kinematic Q-value from proton measurement with γ-ray energy spectra
Determine integrated excitation cross-sections and deduce deformation parameters
Collectivity trends -- shell structure
Separation of N/P contributions
Additional collective states (2+ and 3- states)

Future opportunities

Mapping quadrupole and octupole collectivity

- Trace shell closure/breakdown
- Examine evolution of collectivity at large neutron excess

Isoscalar probes

such as (d,d') or (α,α')

- Study N/P contributions to states difficult to study by Coulomb excitation or lifetime methods

Consider simultaneous experiments

- Study inelastic scattering and transfer reactions with a single beam/target combination, look at more of the total reaction cross-section

Explore possibilities of detecting also the scattered protons in some thick-target experiments

- Angular distributions & correlation information
- Useful in determining the J^{π} of the excited state

Needs for future RIB inelastic scattering

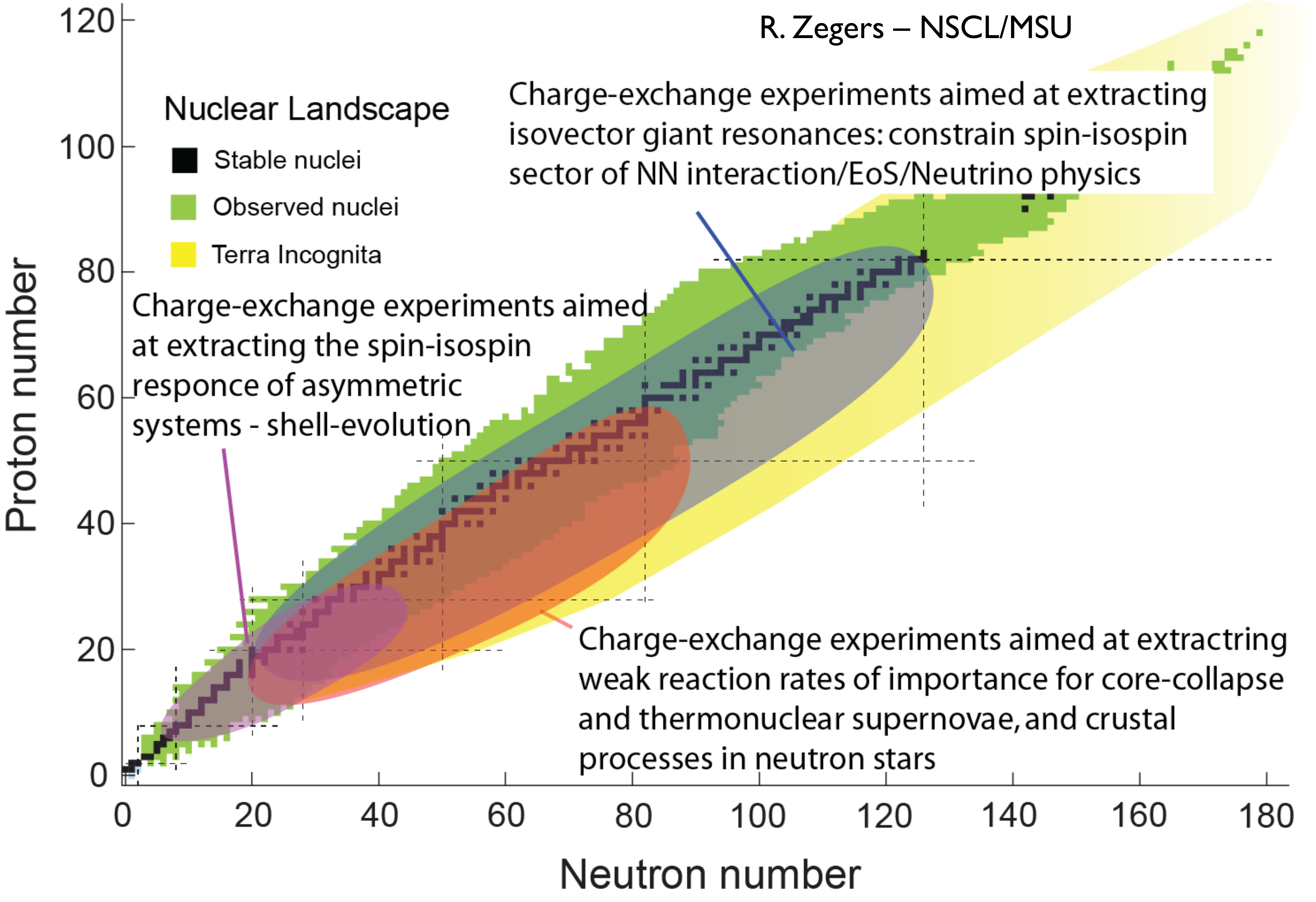
GRETA

- Resolution down to ~10 keV to resolve states
- Doppler correction
- High efficiency

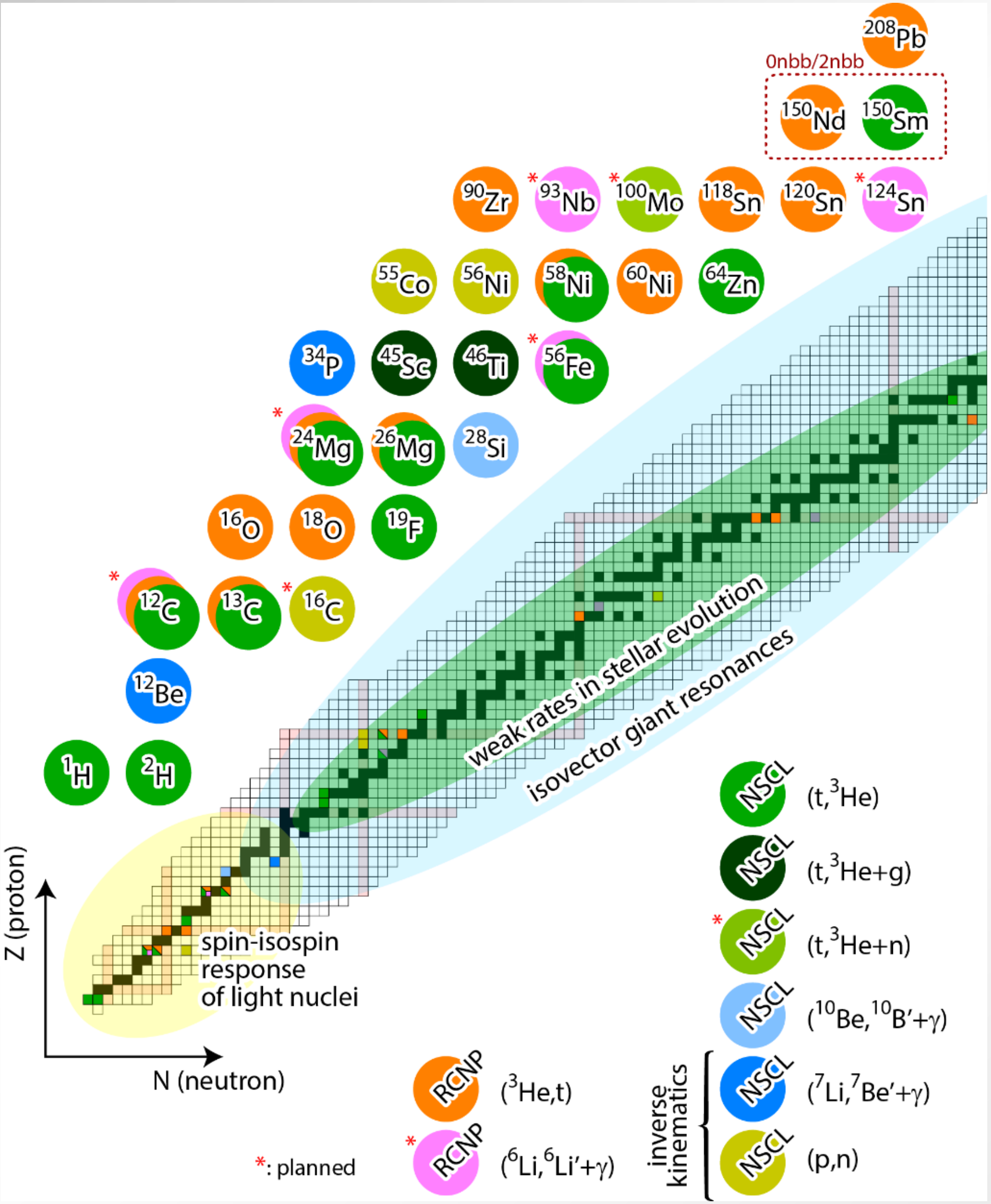
High-Rigidity Spectrometer

- Reduce charge state problem
    - Higher Bρ => more species fully-stripped
- Larger momentum acceptance focal plane to collect multiple charge states and reaction channels
- Identification and tracking of incoming and outgoing rare ion beams

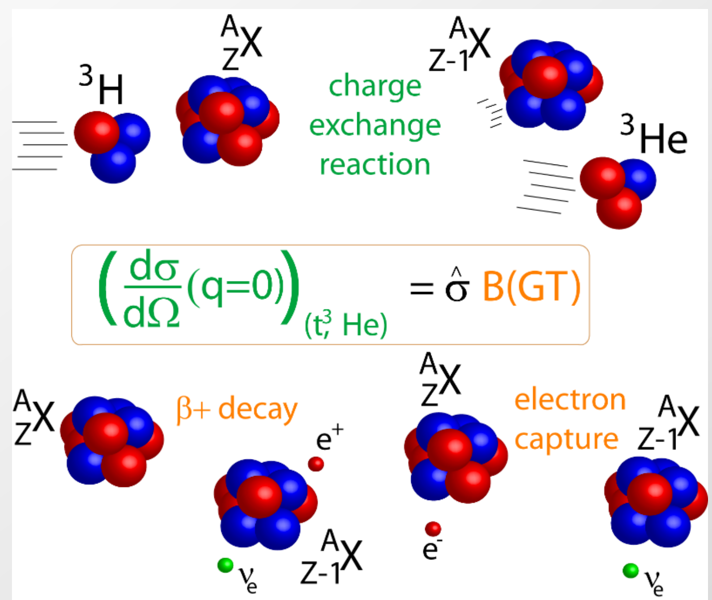
Probing the spin-isospin response via charge-exchange reactions



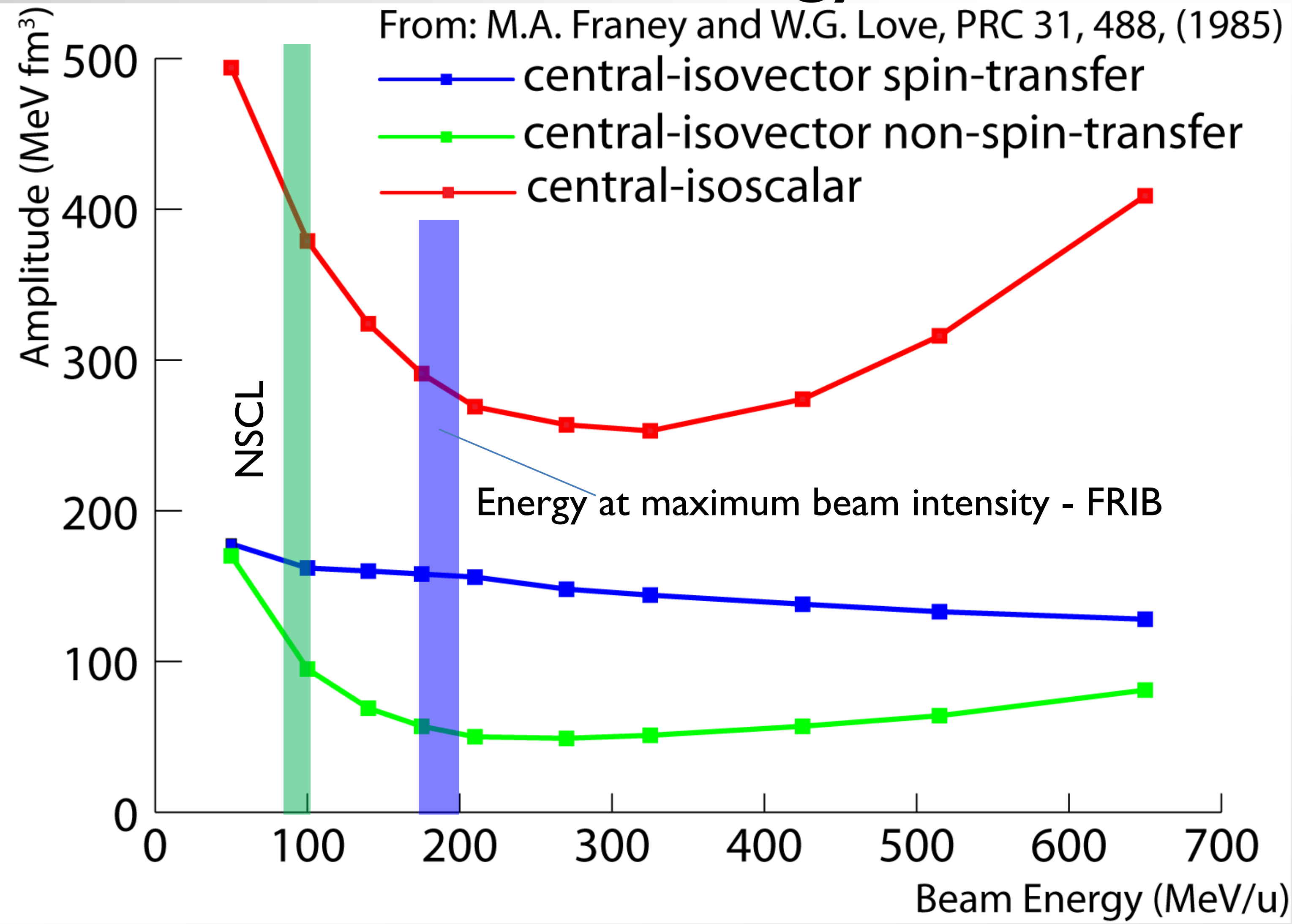
Spin-isospin probes



- Astrophysics – weak reaction rates
- (Neutrinoless) Double beta decay
- Shell evolution in light systems
- Giant resonances and the macroscopic properties of nuclear matter
- Novel probes for isolating particular multipole responses
- Studies of the charge-exchange reaction mechanism

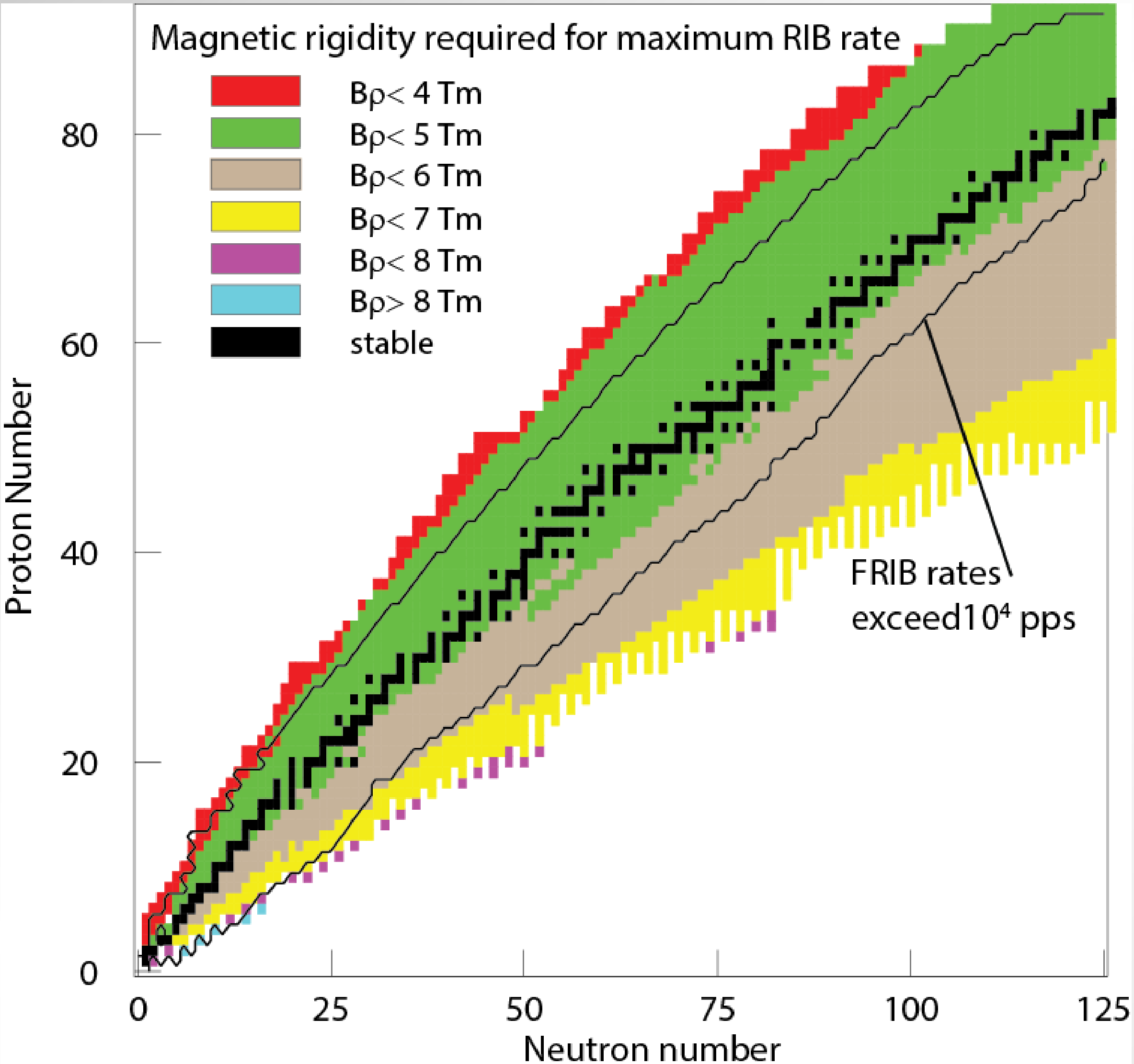


Beam energy



There is a clear advantage from the reaction point-of-view to perform CE experiments at the high RI beam energies available at FRIB

Beam intensities & energies



Charge-exchange experiments require at least 10^4pps

Maximum beam intensities for neutron rich nuclei are achieved at magnetic rigidities of 5-7 Tm

The construction of the High Rigidity Spectrometer is critical to maximize the scientific output of the CE experiments at FRIB

Charge-exchange experiments at the HRS

Inverse kinematics experiments – heavy fragments detected in HRS

(p,n): LENDA/VANDLE around target (Ursinus LH_2) target

Additional physics: GRETA

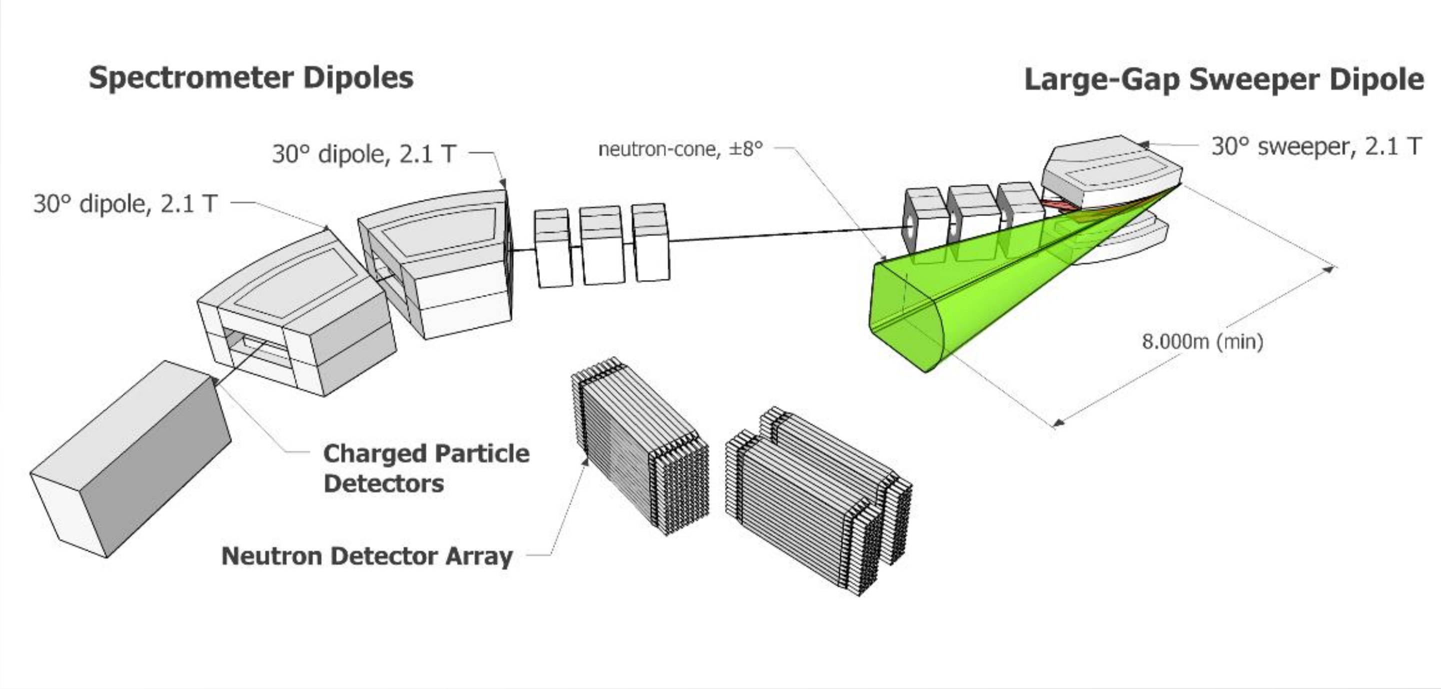
(d,^{2}He): Active Target TPC

(^{7}Li,^{7}Be+γ): GRETA+MoNA-LISA(+charge particle array)

Forward kinematics experiments – scattered ejectile in HRS

(t,^{3}He), (t,^{3}He+n), (t,^{3}He+γ) – LENDA/VANDLE, GRETA – dispersion matching

(^{10}Be,^{10}B+γ), (^{10}C,^{10}B+γ) etc – GRETA – dispersion matching



Nuclear structure with stable and Rear Isotope Beams at TAMU

Grigory Rogachev

TEXAS A&M UNIVERSITY®
Cyclotron Institute

2014 Town Meeting, College Station, August 2014

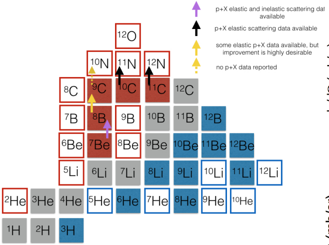
Main thrusts

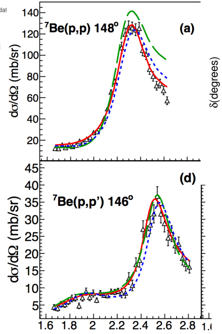
- Exploring nuclear structure at and beyond the drip line:
  - Level structure of exotic nuclei to assess the validity of the ab initio theoretical approaches (GFMC, NCSM, Couple Clusters, Lattice EFT, etc.)
  - Exotic nuclei plus nucleon and α scattering phase shifts to facilitate integration of nuclear structure and nuclear reactions into unified theoretical framework.
  - Evolution of nuclear shell structure with increasing isospin.
- Clustering phenomena with stable and rare isotope beams.
- Major upgrade of TAMU facilities (T-REX) opens wide range of opportunities in pre-FRIB era and beyond

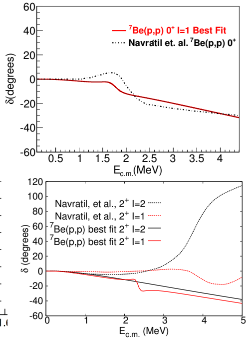
Structure of the light neutron-deficient nuclei

Nuclear structure with stable and Rear Isotope Beams at TAMU

Grigory Rogachev







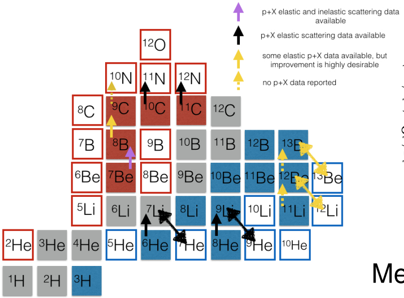
J.P. Mitchell, GR, et al., PRC **87**, 054617 (2013)

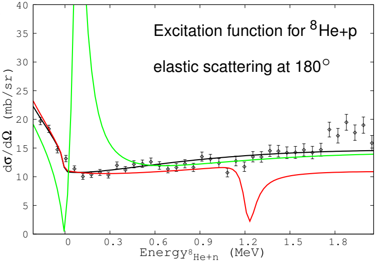
- Resonance scattering with rare isotope beams - powerful tool to study structure of weakly bound and abound nuclei
- Structure of ^{9}C and ^{10}N will be studied using ^{8}B+p and ^{9}C+p reactions

Structure of the light neutron-rich nuclei (IAR)

Nuclear structure with stable and Rear Isotope Beams at TAMU

Grigory Rogachev

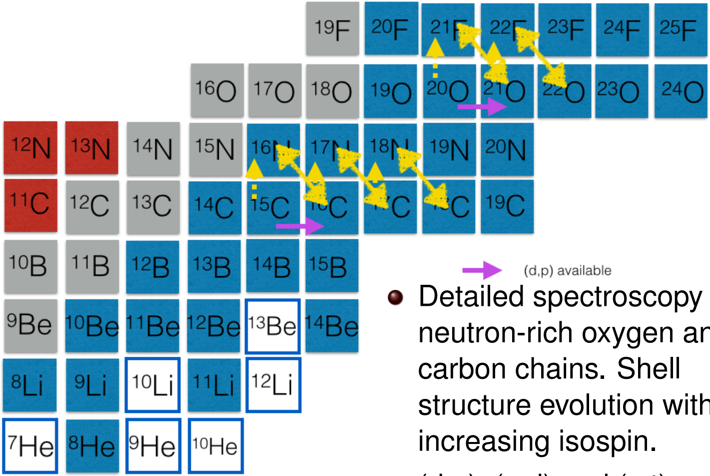




Measured at TRIUMF 5 weeks ago. PRELIMINARY

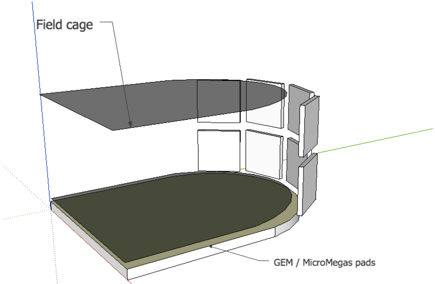
- Isobaric Analog Resonances (IAR) populated via proton scattering for spectroscopy of neutron rich nuclei. Most recent example ^{8}He+p (^{9}He). Long standing questions on low lying states in ^{9}He are resolved.
- Search for IAR in ^{12}Be (^{12}Li) and ^{13}B (^{13}Be)

IAR of heavier neutron-rich nuclei, Carbon and Oxygen chains. Transfer reactions



- Detailed spectroscopy of neutron-rich oxygen and carbon chains. Shell structure evolution with increasing isospin.
- (d,p), (p,d) and (p,t) reactions with active target

Active targets at TAMU

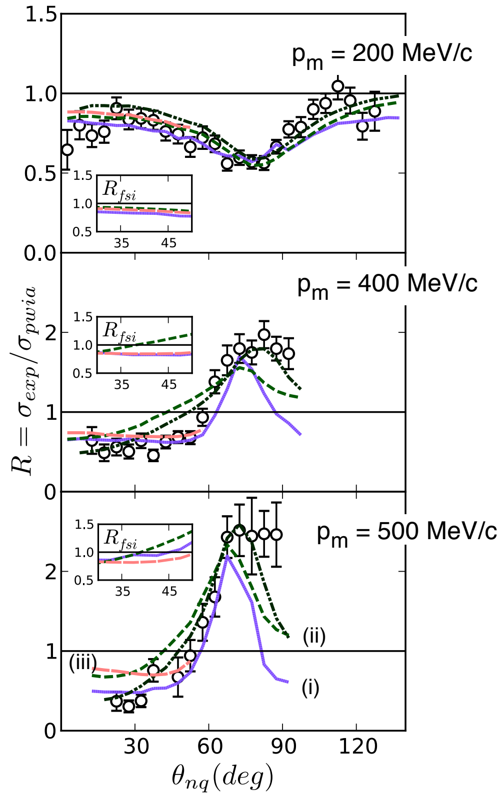


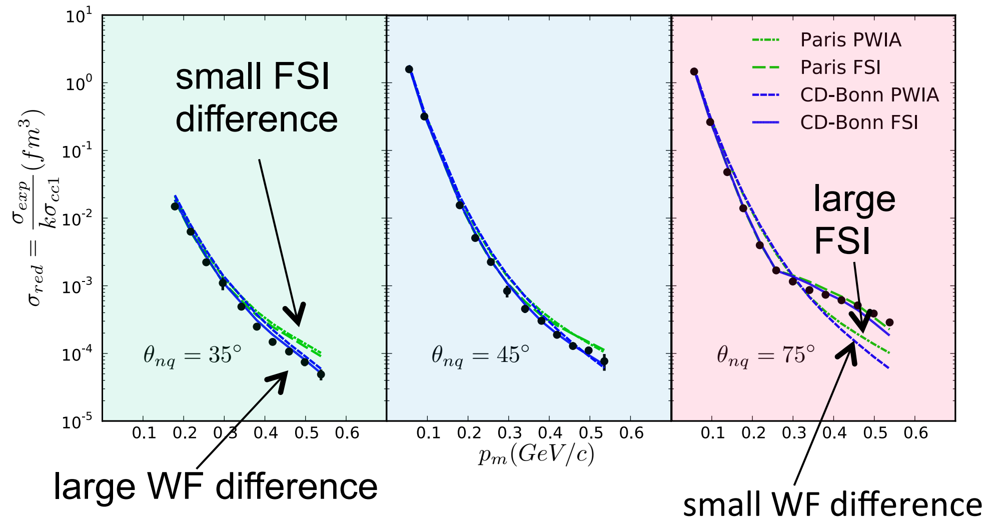
- Active target detector in several configurations. Resistive wire readout (already implemented, TexAT-P1) and MicroMegas TPCs TexAT-P2. Trigger - Si array.
- Next generation - TexAT - time projection chamber embedded into the dipole magnet. Simulation and initial design are under way. Targeted energy resolution - 1 keV. MRI planned

D(e,e'p) Angular distributions and p_m up to 1 GeV/c at large Q^2 (E12-10-003)

Define reduced cross section:

$$R = \frac{\sigma}{\sigma_{PWIA}}$$

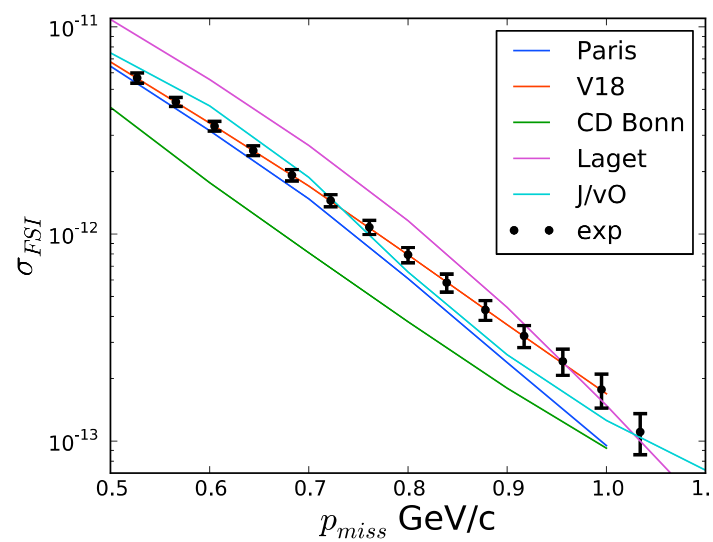




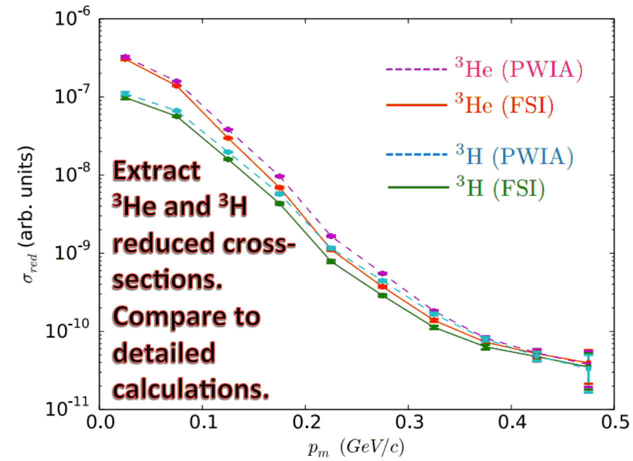
Potential sensitivity

Strong theoretical support

JLAB uniquely suited for high p_m studies

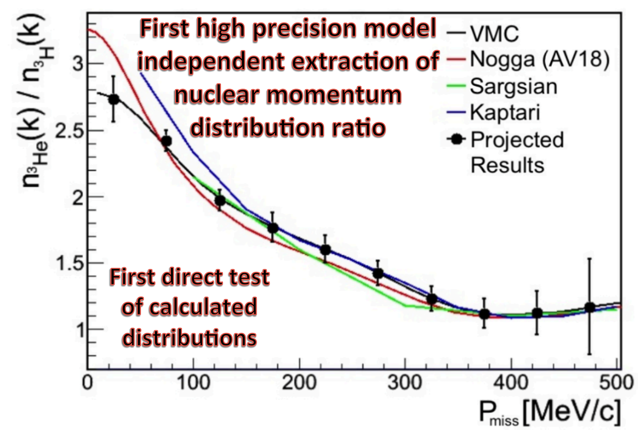


^{3}He/^{3}H(e,e'p): Proton and Neutron Momentum Distributions in *A*=3 Asymmetric Nuclei (E12-14-011)

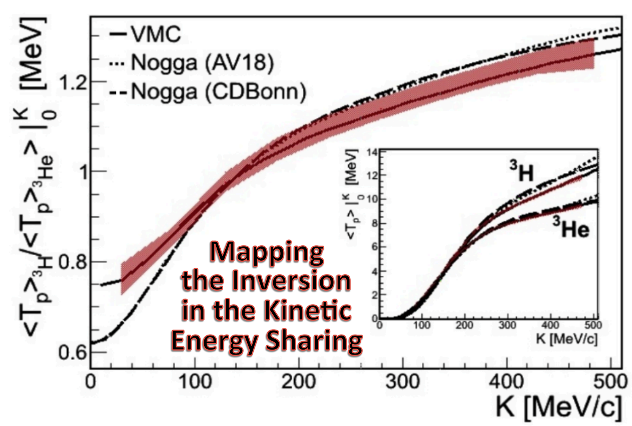


Determine:

- Ratio of reduced cross sections



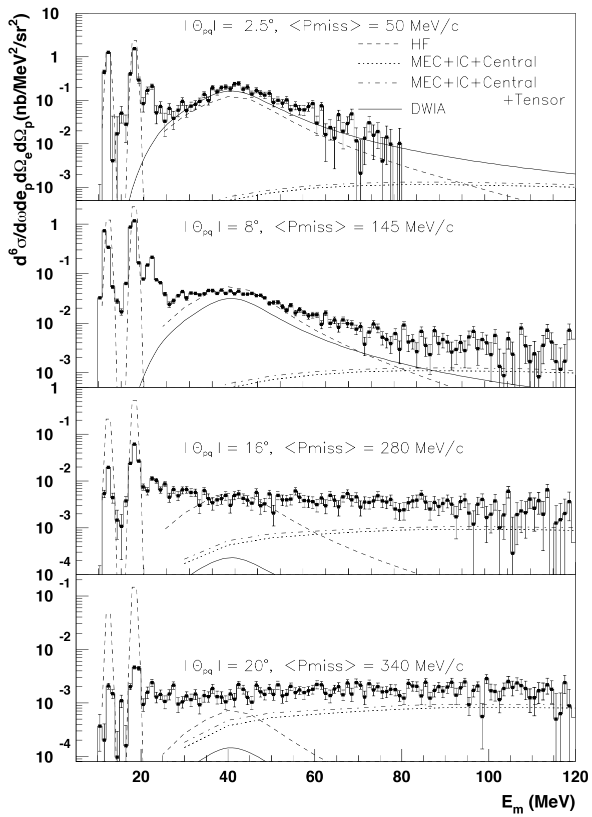
- Proton-to-Neutron momentum distribution



- Energy sharing in asymmetric systems

$^{40}Ar(e,e'p)$ Measurement of the Spectral Function: Synergy between Electron and Neutrino Physics (E12-14-012)

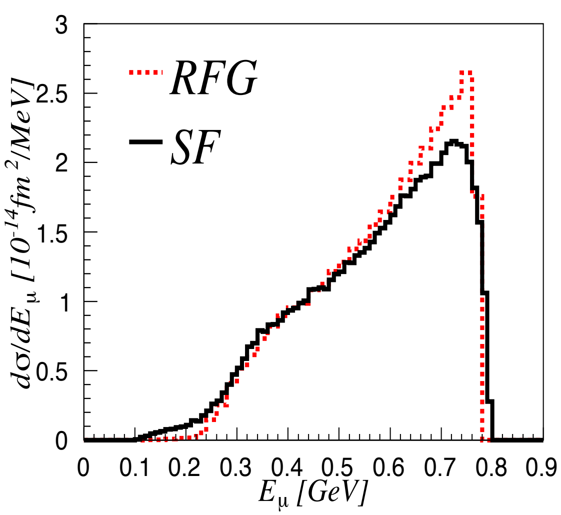
$^{16}O(e, e'p)X$, E_e = 2.4 GeV

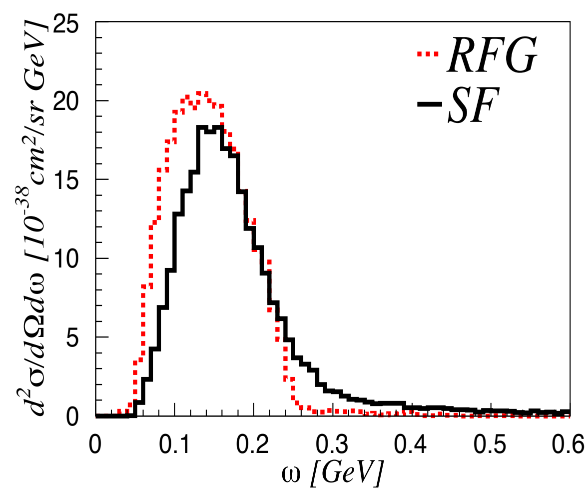


Electron scattering determined spectral functions for ^{12}C and ^{16}O, used in neutrino event generator GENIE

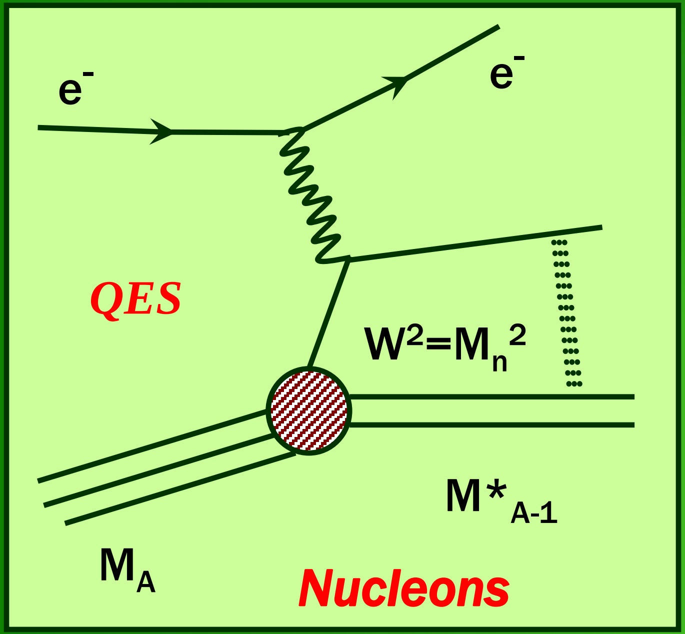
Next generations of neutrino experiments will use ^{40}Ar target, for which Spectral function is not previously measured:

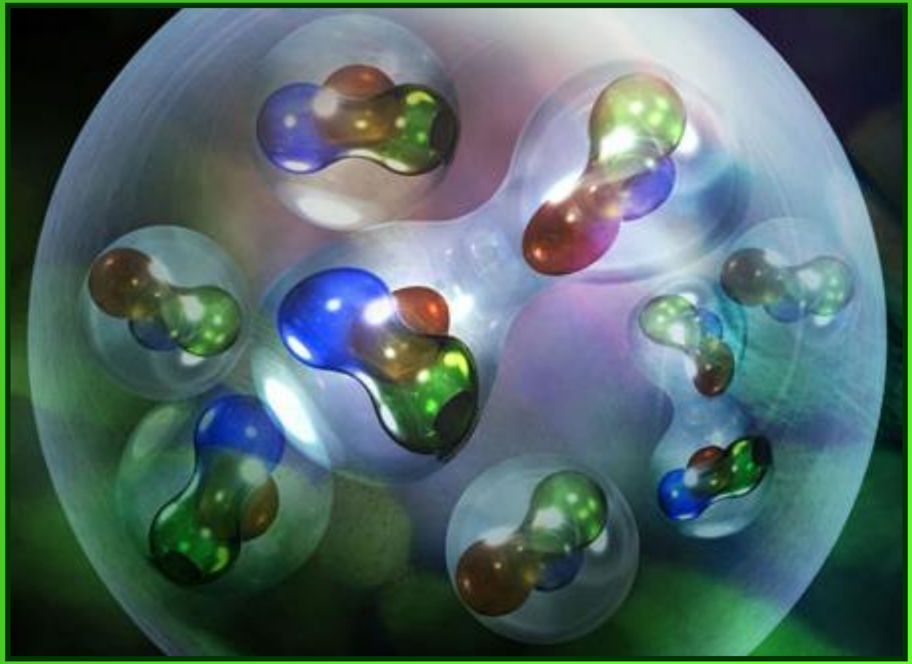
Impacts ArgoNeuT, CAPTAIN, LarIAT, LBNE, MicroBooNE (and FNAL)





"Clusters and correlations: future (e,e') measurements"

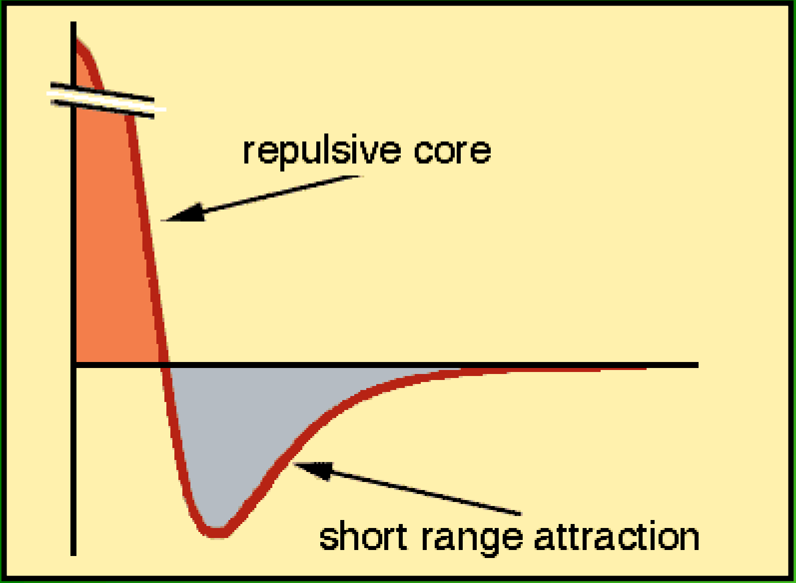


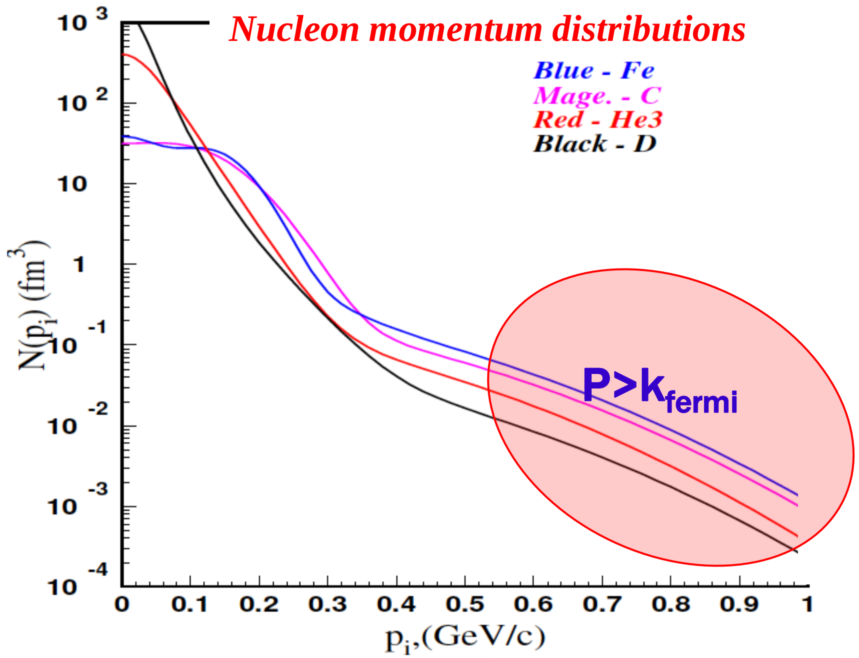


Nadia Fomin - University of Tennessee

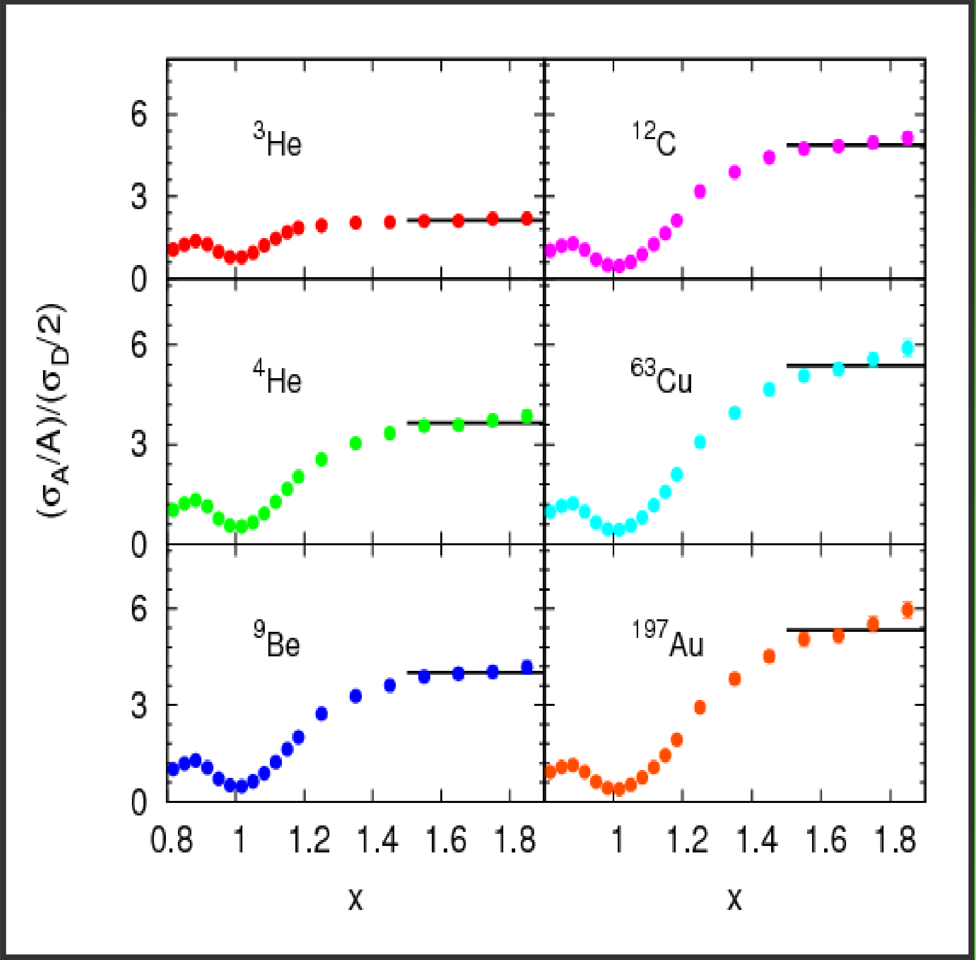
High momentum nucleons

- Short Range Correlations



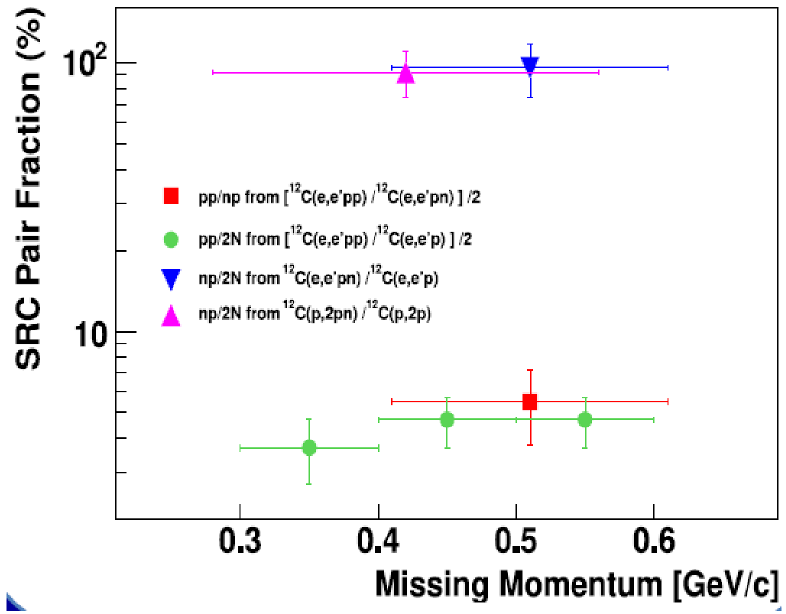


C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53** (1996).



Nadia Fomin - University of Tennessee

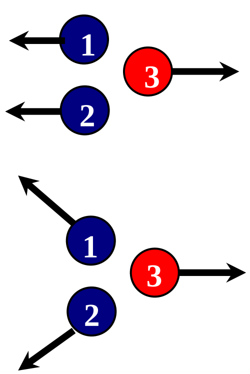
[Jlab E12-11-112]



R. Shneor et al., PRL 99, 072501 (2007)

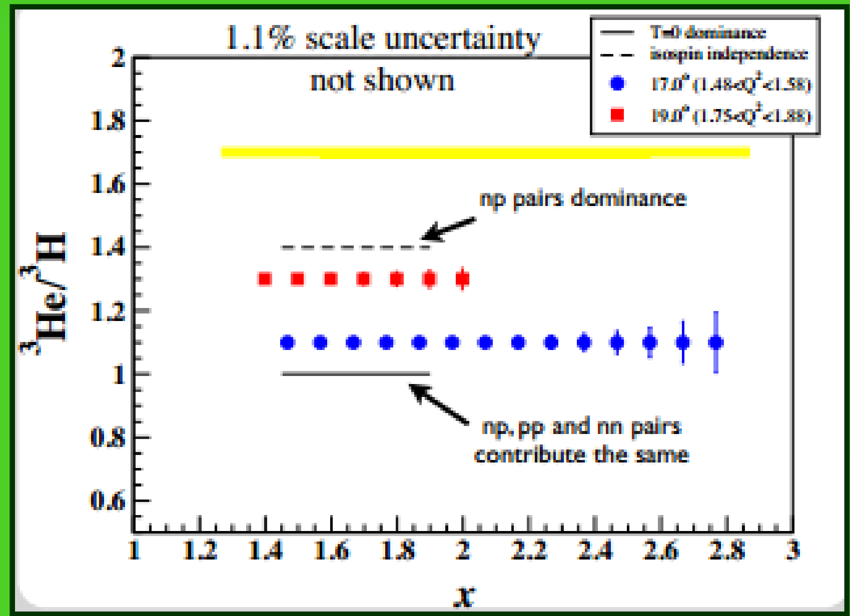
R. Subedi et al., Science 320, 1476 (2008)

- Quasielastic electron scattering with 3H and 3He
- Study isospin dependence of 2N and 3N correlations
- Test calculations of FSI for well-understood nuclei

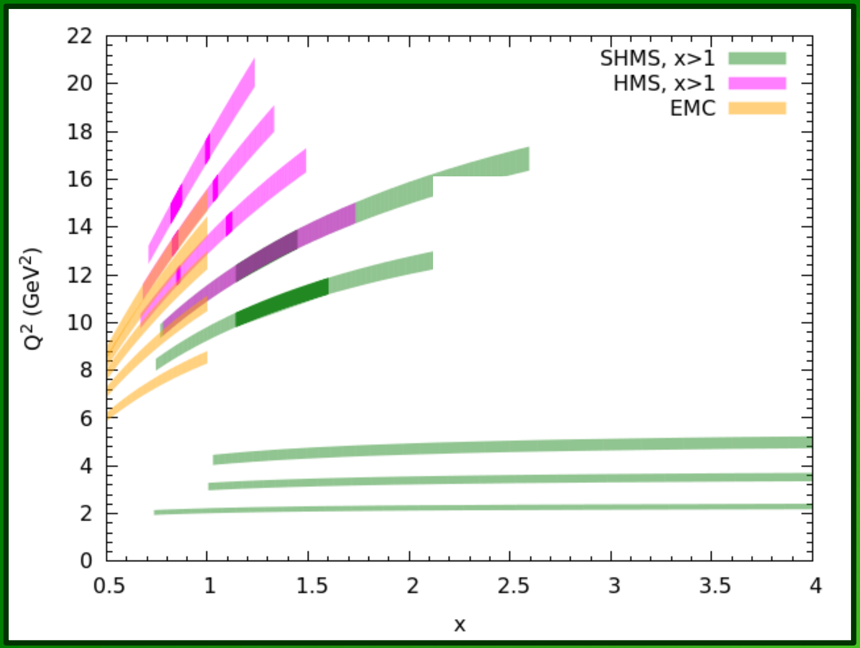


$p_3 = p_1 + p_2$

$p_3 = p_1 = p_2$

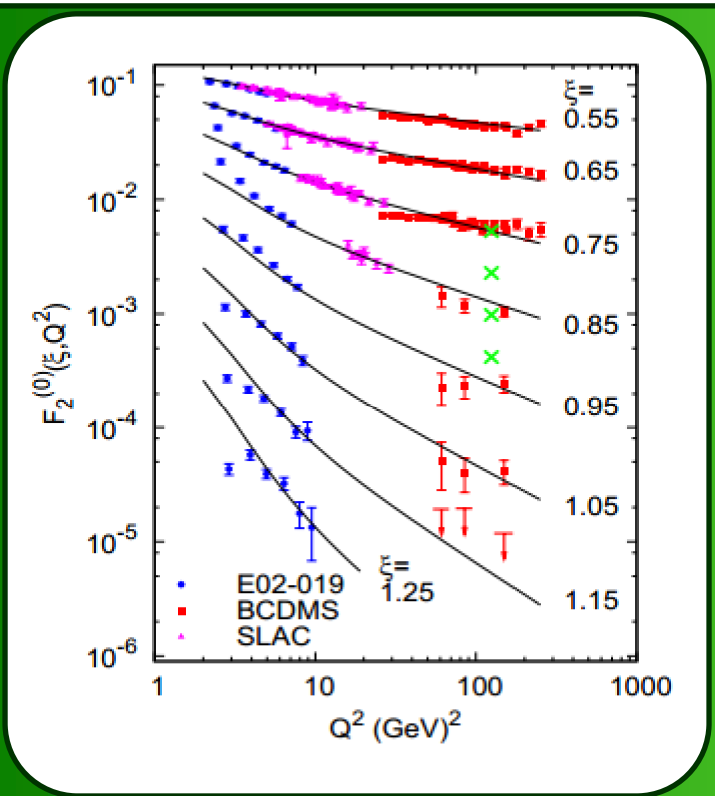


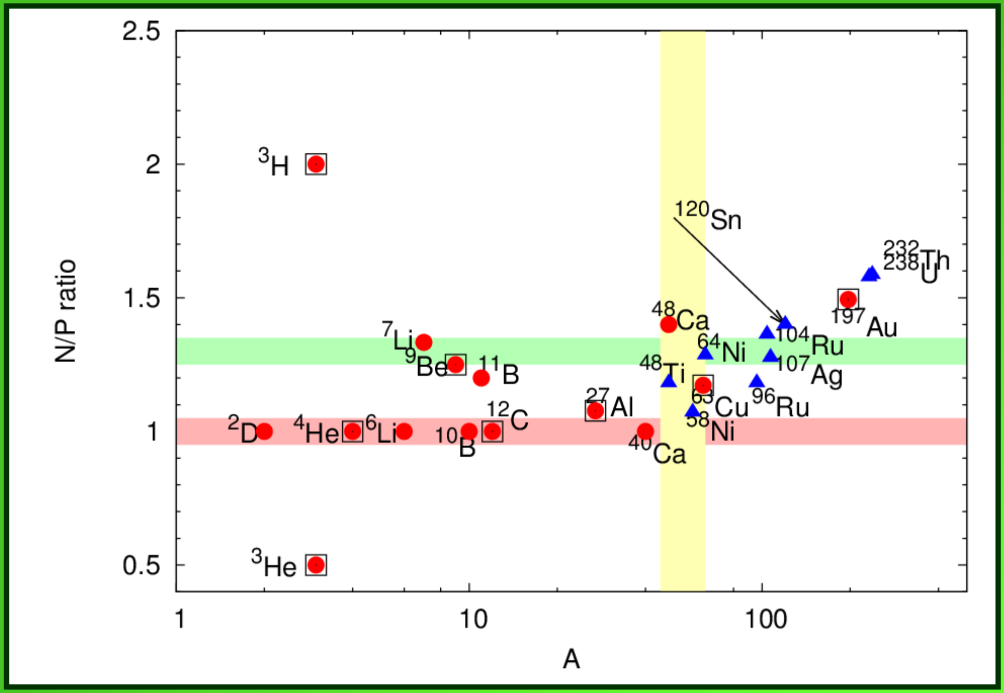
Nadia Fomin - University of Tennessee



Jlab E12-06-105

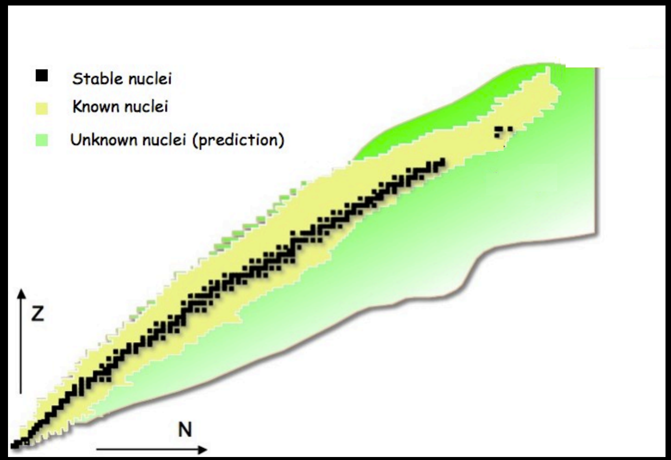
- short-range nuclear structure
  - Isospin dependence
  - A-dependence
- Super-fast quarks



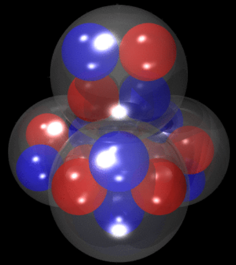


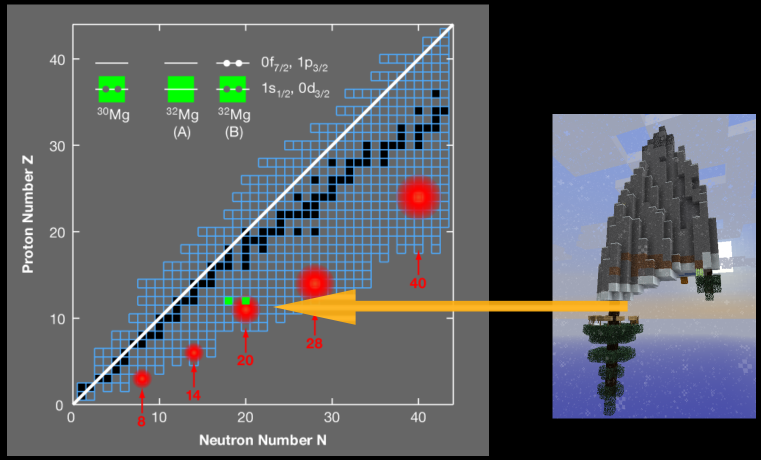
Nadia Fomin - University of Tennessee

CURRENT AND FUTURE OPPORTUNITIES WITH THE PROTOTYPE AT-TPC

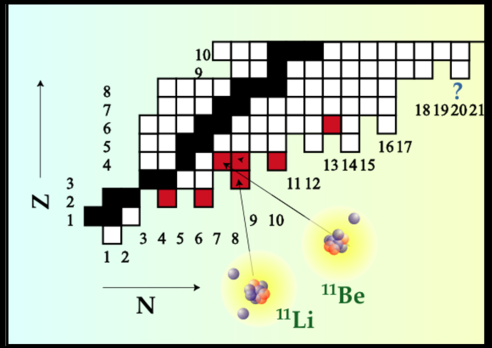


- Exploration of the terra incognita (*detailed spectroscopy*)
    - Reactions with radioactive beams
- Science Opportunties



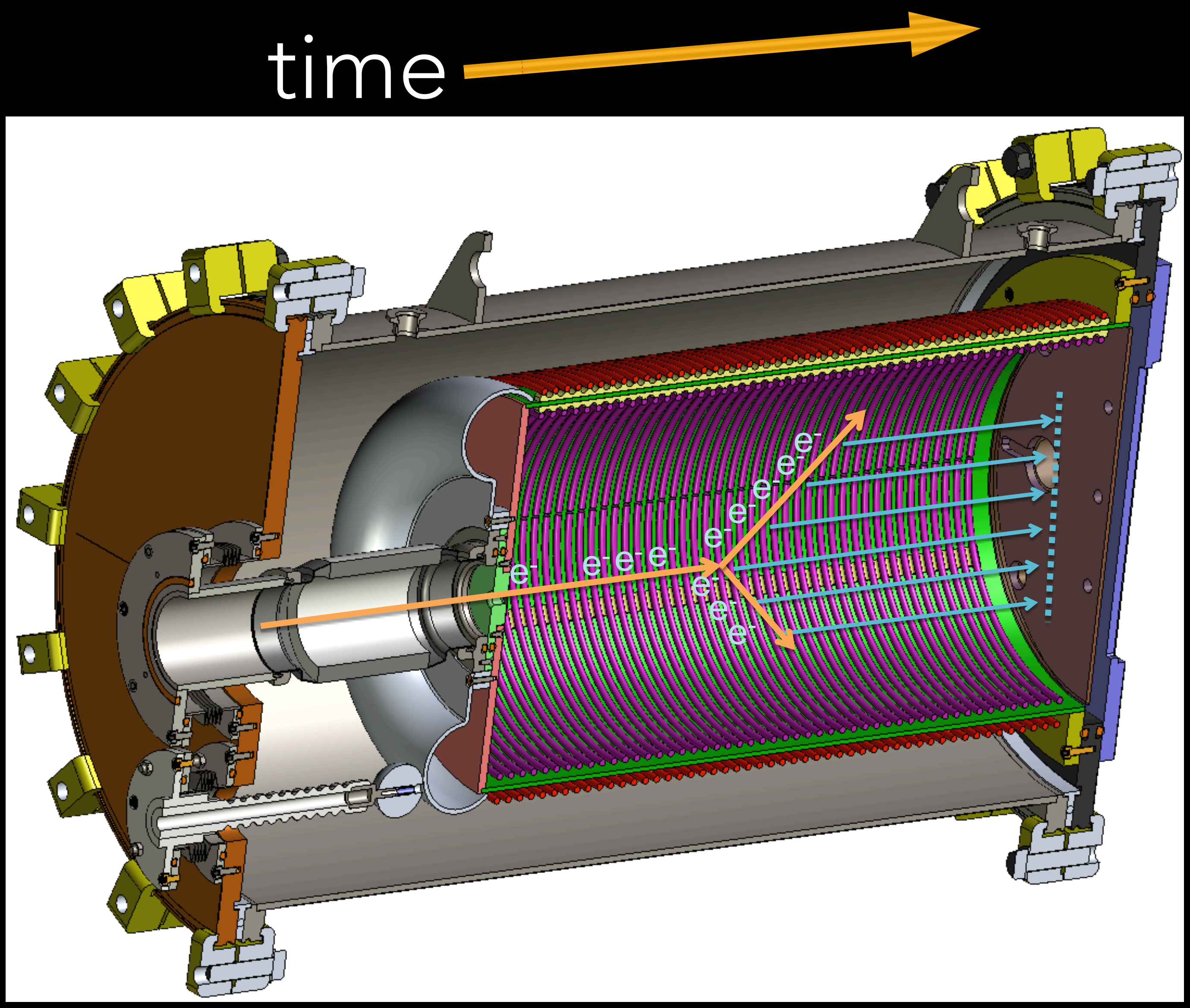


    - clustering in nuclei (stable and unstable)
    - evolution of single-particle structure of exotic nuclei
    - many-body effects: correlations, pairing, halos
    - ab-initio nuclear models
    - astrophysics



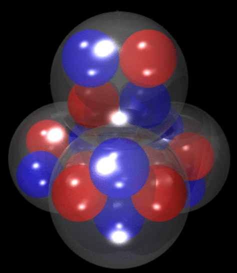
PROTOTYPE ACTIVE-TARGET TIME-PROJECTION-CHAMBER

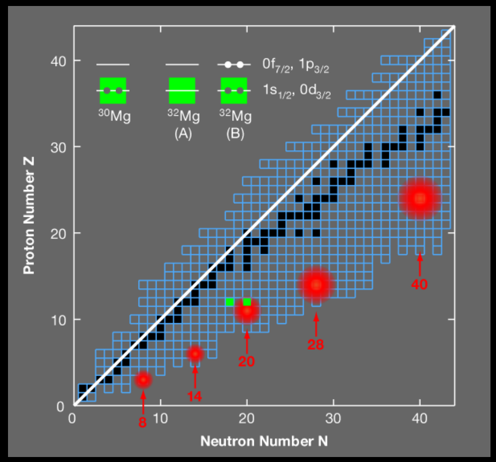
- imaging of charged particle tracks
- active-target (target and tracking medium the same)
- increase in luminosity
  - low-intensity RIB's
  - scan energy range
  - good energy and angle resolution



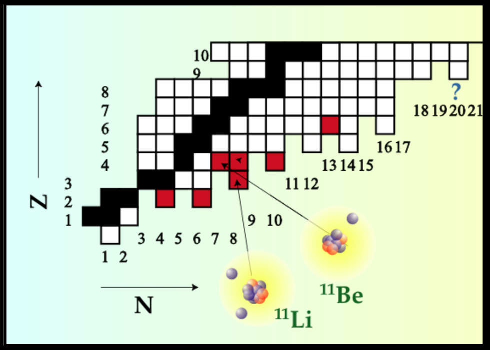
POSSIBLE REACTIONS

- (α,α), (d,d), (p,p) - cluster structure, single-particle
- (d,p), (d,t), (^{3}He,d) - single-particle





- (p,t) - 2-nucleon transfer, pairing correlations
- (α,p), (^{6}Li,d) - astrophysics



- charged-particles in exit channel
  - decay studies: Hoyle state, β decay, fission

WHAT WE NEED

- Measurements of reactions at the nuclear frontier
- Radioactive-beam facilities
    - at *sufficient energies* (both above and below Coulomb barrier) (>10 MeV/u)
- Active-target detectors that can take **full advantage** of RIB's
    - Support for continuous development
    - Smaller university-based laboratories, (basic research & development)
        - Mobility of detector (Prototype AT-TPC, ANASEN)
    - Support for theory (theorists, experimentalists)

Isomeric beams at CARIBU

Low Energy Community Town Meeting 2014

Aug 22, 2014

Ching-Yen Wu

Lawrence Livermore National Laboratory

LLNL-PRES-654342

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Isomer; a unique environment to explore the nuclear structure

- It has a distinguishable characteristics from that of the ground state, such as the spin or the shape.
- A beam can be developed for isomer with half-life longer than 10 ms and then an opportunity exists to explore the nuclear structure of its unique configuration through reactions.

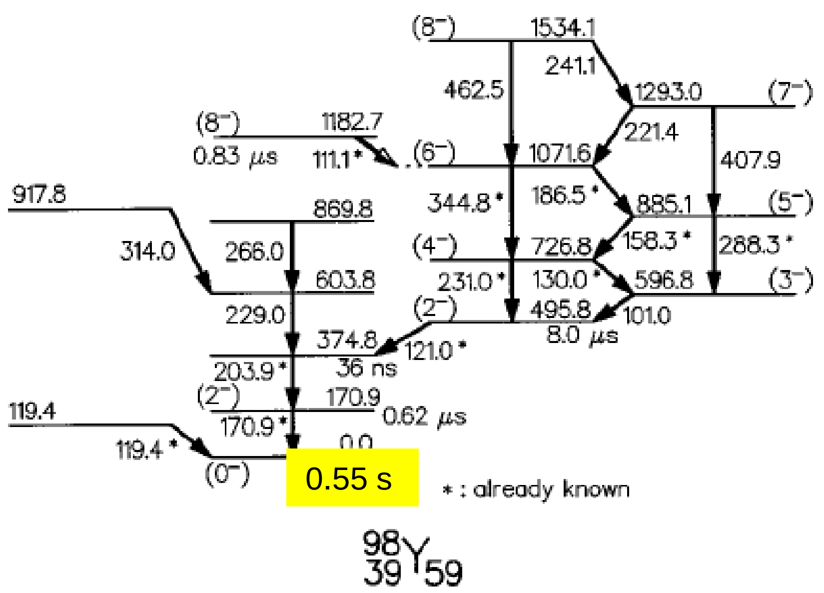
Example and technical approach

- Probe the quadrupole collectivity of the shape isomer by measuring its electromagnetic properties using the sub-barrier Coulomb excitation method
  - Extract the transition and static matrix elements from the γ-ray transitions measured using DGS or GRETINA /CHICO2
- Experience with CARIBU at ANL could be a precursor prior to that of FRIB at MSU

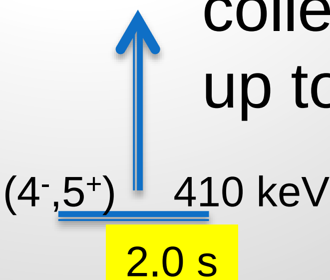
^{98m}Y ($T_{1/2}$ = 2 s); a case study with CARIBU at ANL

- Located in the neutron-rich nuclei with A ~ 100, where the nuclear structure sensitive to the occupancy level of the $h_{11/2}$ neutron and $g_{9/2}$ proton orbitals
- Ideal testing ground for various theoretical models, including the nuclear density functional theory

^{252}Cf(S.F.) PRC 58, 3252 (1998)



- CARIBU/GRETINA/CHICO2 allows the study of the E2 collectivity for excited states up to spin 10



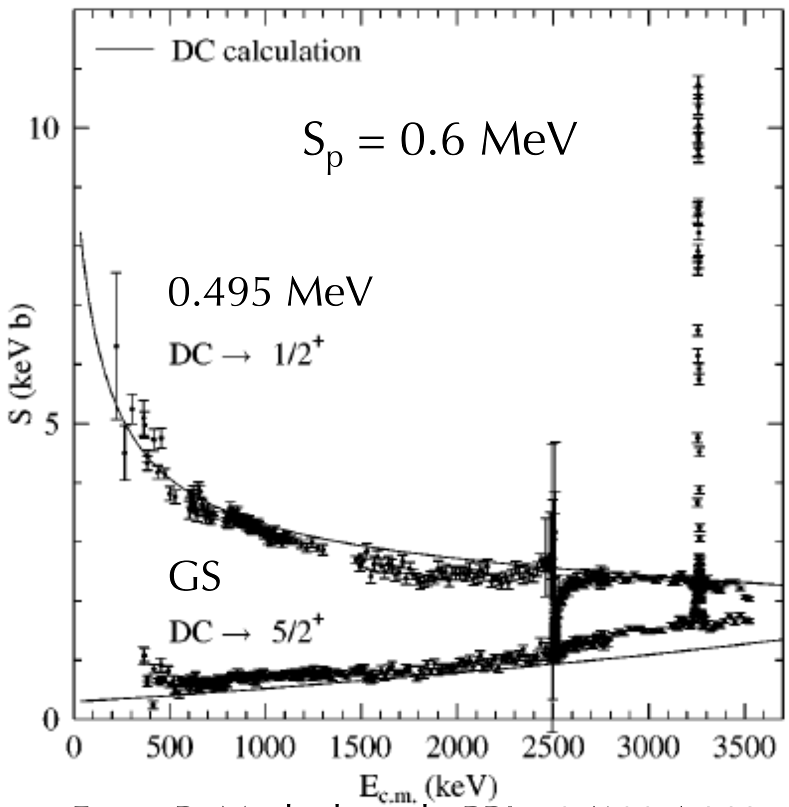
Intrinsic Q_0 = 3.12 b (Laser spectroscopy) PLB 645, 133 (2007)

Study of light (halo) nuclei with transfer reactions

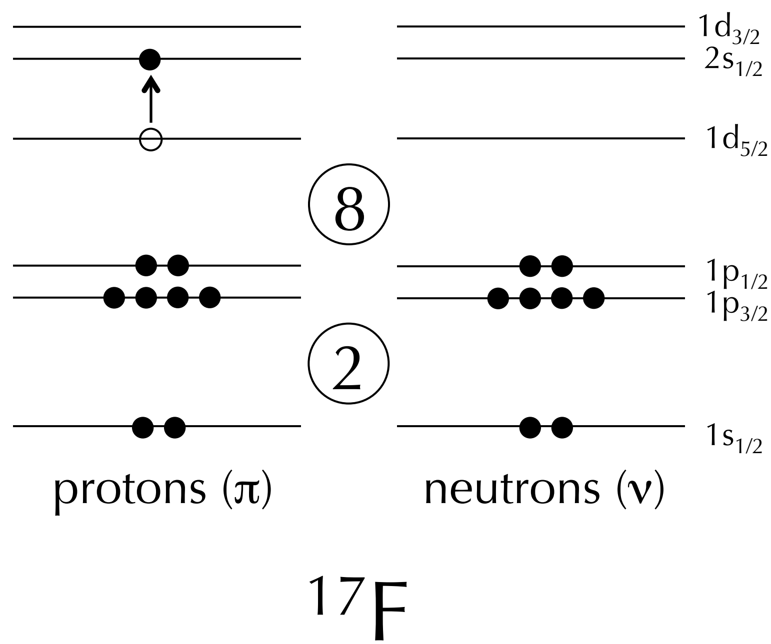
Fred SARAZIN
Colorado School of Mines

Halo nuclei and halo states

The halo phenomenon arises from nucleons in weakly-bound low angular momentum orbitals. The concept of halo does not only apply to the ground state of a nucleus. It can also be applied to excited states.



From: R. Morlock et al., PRL 79 (1997) 3837



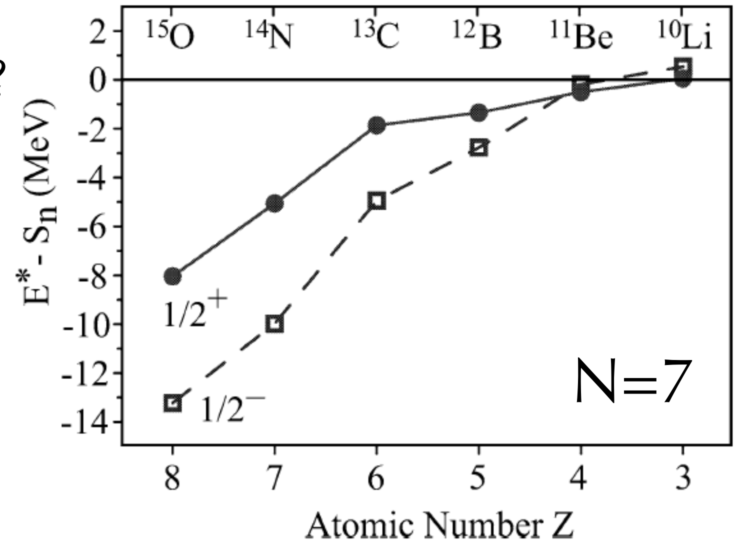
Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

Excited halo states

Why are excited halo states worth investigating?

- Track the $s_{1/2}$ and $p_{1/2}$ orbitals across shells.
- Migration of $s_{1/2}$ and $p_{1/2}$ orbitals does not only happen at N=8, but around other shell closures as well (e.g. N=20, 28). A consequence of shell quenching?

M.Chartier et al., PLB 510 (2001) 24



Neutron-rich nuclei – some cases:

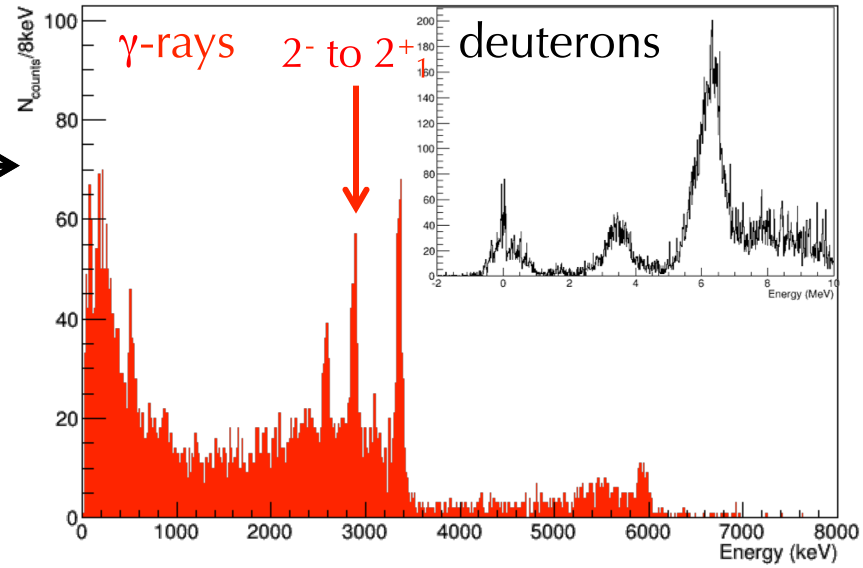
- 2^- state in ^{10}Be (^{9}Be($3/2^-$,gs) x ($\nu s_{1/2}$) – 549 keV below S_n)
- 1^- state in ^{12}Be (^{10}Be(0^+,gs) x ($\nu s_{1/2}$,$\nu p_{1/2}$) [tentative] – 467 keV below S_n)
- 1^- state in ^{14}B (^{13}B($3/2^-$,gs) x ($\nu s_{1/2}$) – 316 keV below S_n)

→ Populate, identify and study these states from angular distributions obtained in transfer reaction studies.

Transfer reactions of light nuclei using fragmented and reaccelerated beams at NSCL / FRIB

Experiments done at TRIUMF / ISAC-II with charged-particle + γ-ray arrays

- May 2013: $^{11}Be(p,d)$ @ 110 MeV →
- Aug 2014: $^{11}Be(^{9}Be,^{8}Be)$ @ 30 MeV



ISOL beams:

- Pros: beam quality, low contaminants*,…
- Cons: chemical selectivity, very low intensities for short-lived species…

Opportunities with NSCL / FRIB ReAX facilities:

- No chemical selectivity, ISOL-like beam quality*, fast(er) release time, the "right" energy for transfer studies, potential for high-quality studies (Boron, Carbon,…)
- Needs the cyclotron stopper

Opportunities with NSCL / FRIB fragmented beams:

- Studies of (near) drip line nuclei, where intensities are low. Detectors needed to track light beams at the target position (collaboration Mines / ORNL / Notre Dame).

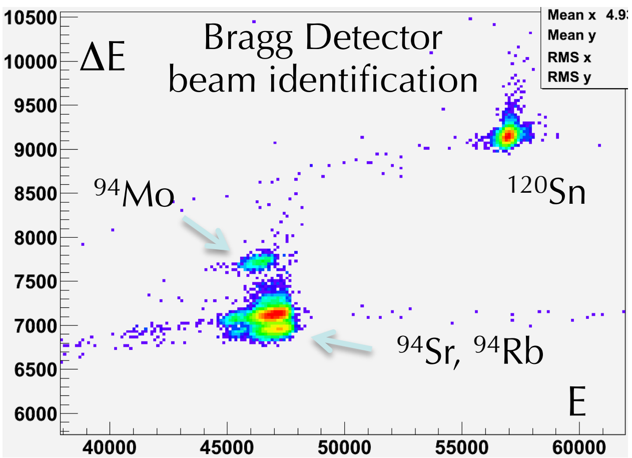
Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

Exploiting ISOL-like beams at ReAX facilities

ISOL (-like) beams:

- Pros: beam quality, low contaminants*,…

HEAVIER BEAMS



First charge-bred A>30 accelerated RIB with ISAC-II SC LINAC ➔ Evolution of shell structure in medium mass and heavy neutron-rich nuclei

d(^{94}Sr,p)^{95}Sr, ~10^5 pps
d(^{95}Sr,p)^{96}Sr, ~10^7 pps
d(^{96}Sr,p)^{97}Sr, ~10^5 pps
energy: 5.5 MeV/u

Reiner Kruecken (TRIUMF), private communication (2014)

To ensure success at ReAX:

- Accelerator chain:
  - Driver / cyclotron stopper or gas catcher / (charge breeding) / <u>beam diagnostics</u>
- Detectors:
  - Compact charged particle array (e.g. S-ORRUBA, SHARC, T-Rex…)
  - γ-ray arrays (e.g. HPGe: GRETINA, $LaBr_3$: HAGRID)
  - 0° detectors (recoil spectrometer, Bragg detector, ionization chamber, …)

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Opportunities for Isotope Discovery

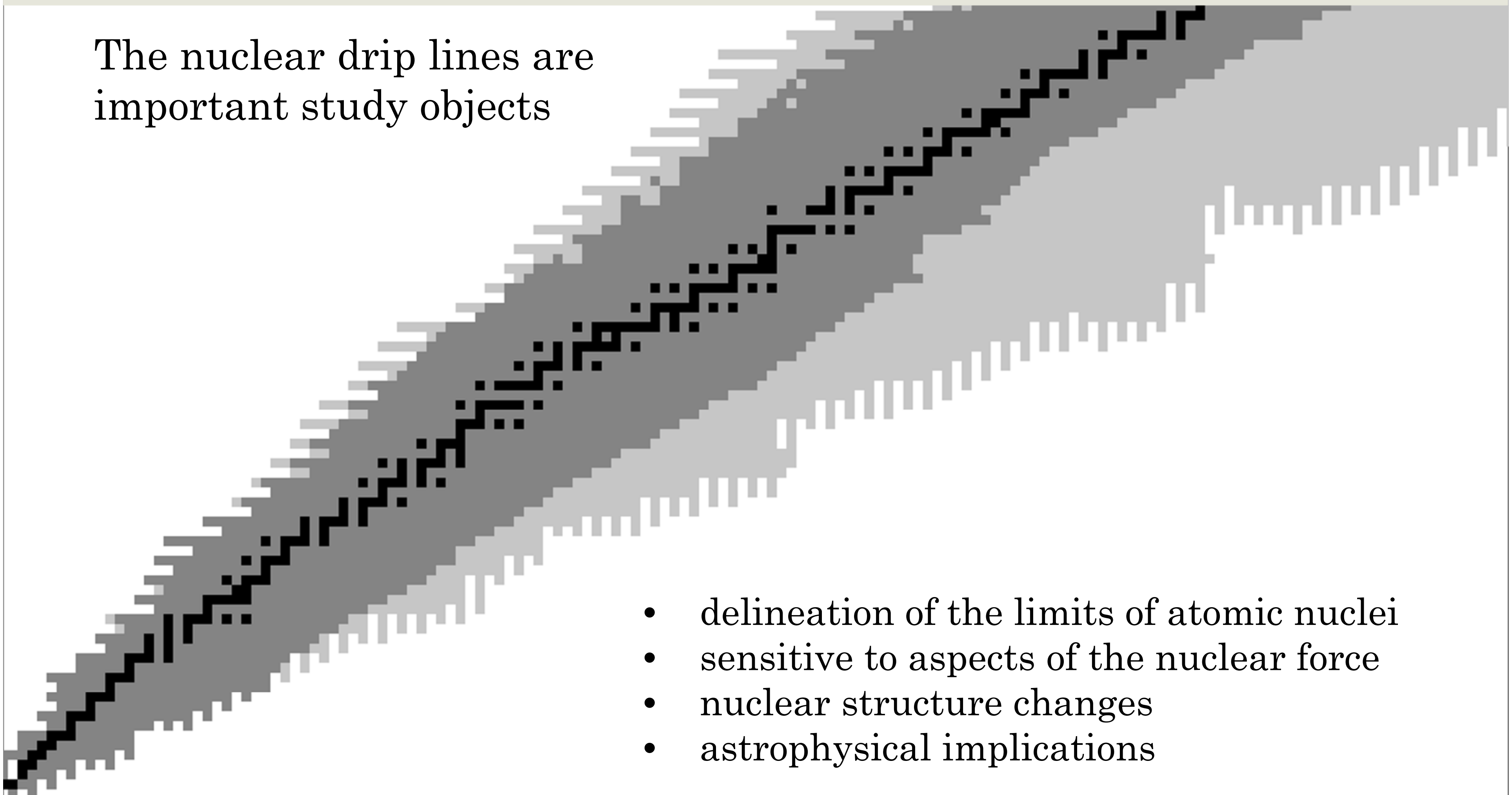
Outline:

- Introduction
- Recent discoveries with NSCL's Coupled Cyclotron Facility
- Projected production yields at the Facility for Rare Isotope Beams
- Potential for isotope discoveries and exploration of the neutron drip line

Thomas Baumann, NSCL

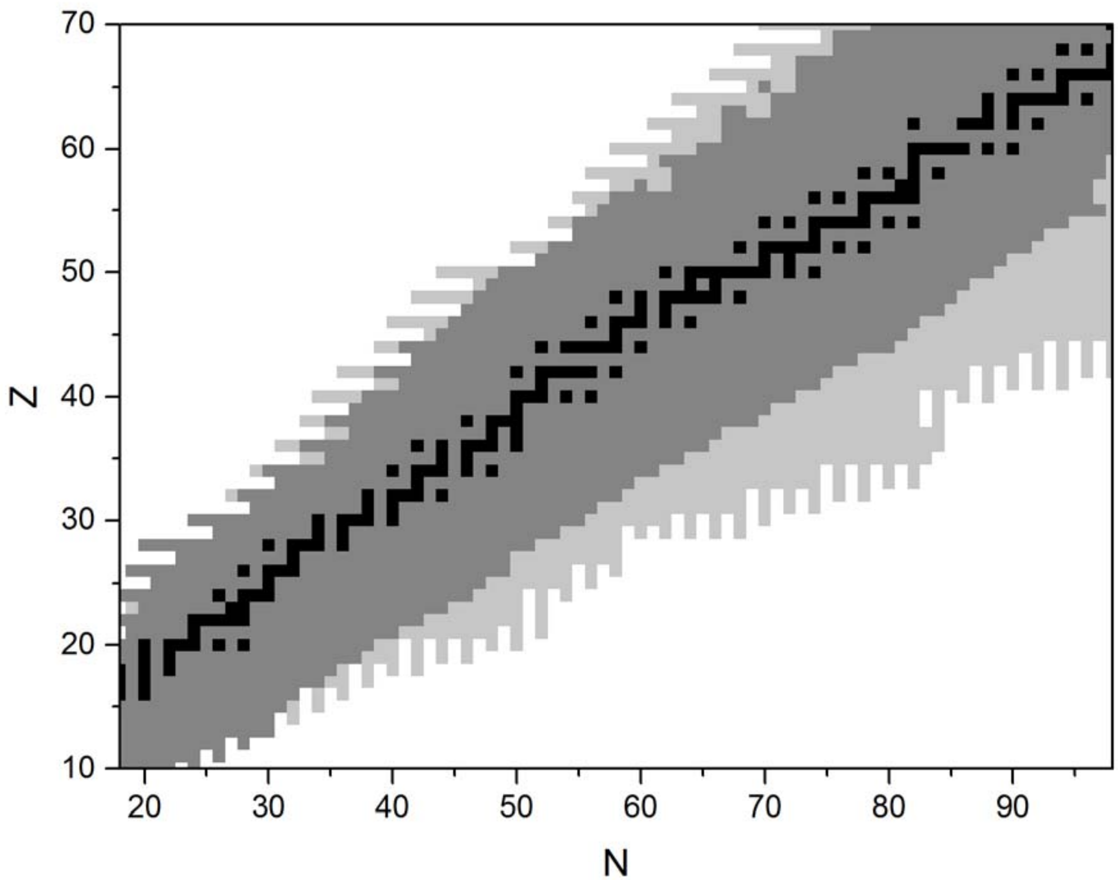
Exploration of the nuclear landscape

The nuclear drip lines are important study objects



- delineation of the limits of atomic nuclei
- sensitive to aspects of the nuclear force
- nuclear structure changes
- astrophysical implications

Discoveries of new isotopes at NSCL



Bound nuclei based on LISE++ 9.8.105 using KTUY mass model (Koura et al., Prog. Theor. Phys. 113, 2005)

Discoveries of new isotopes at NSCL

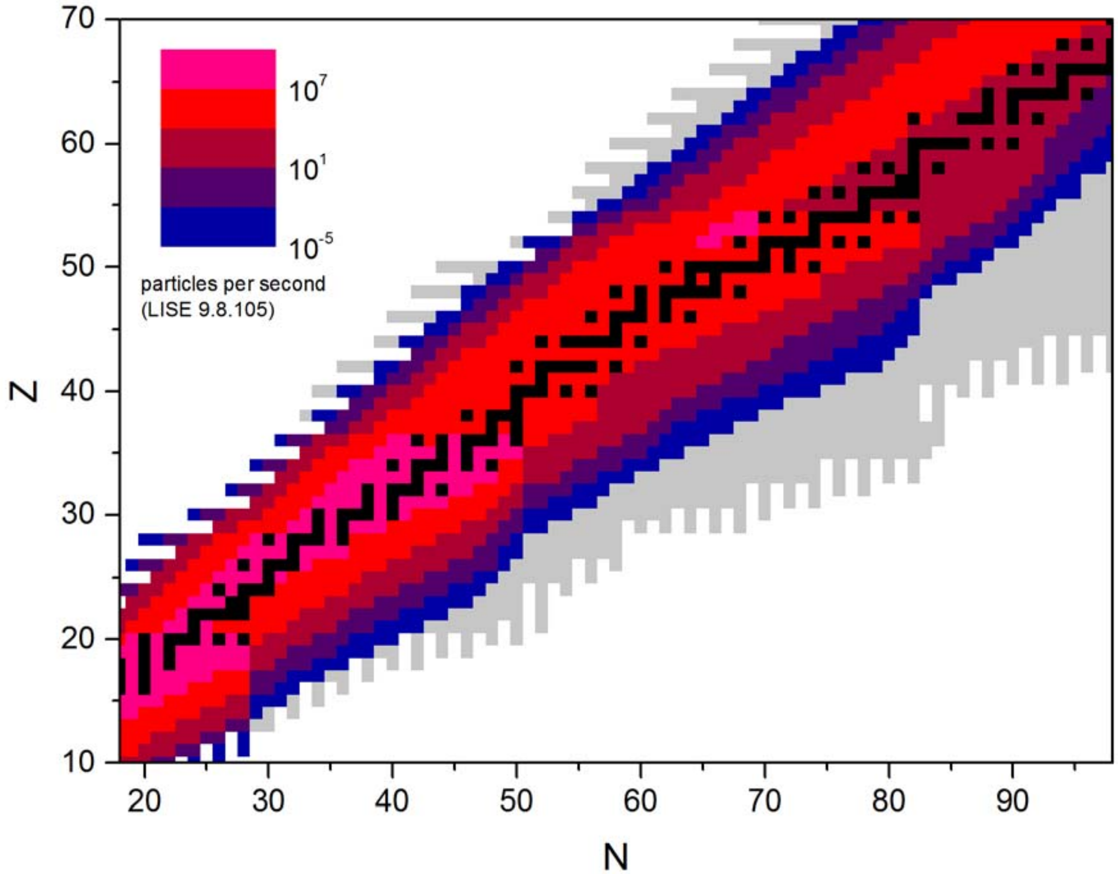


Chart shows production yields for current Coupled Cyclotron Facility.

- Rate of 10^{-5}/s corresponds to about 1 particle per day.

Bound nuclei based on LISE++ 9.8.105 using KTUY mass model (Koura et al., Prog. Theor. Phys. 113, 2005)

Discoveries of new isotopes at NSCL

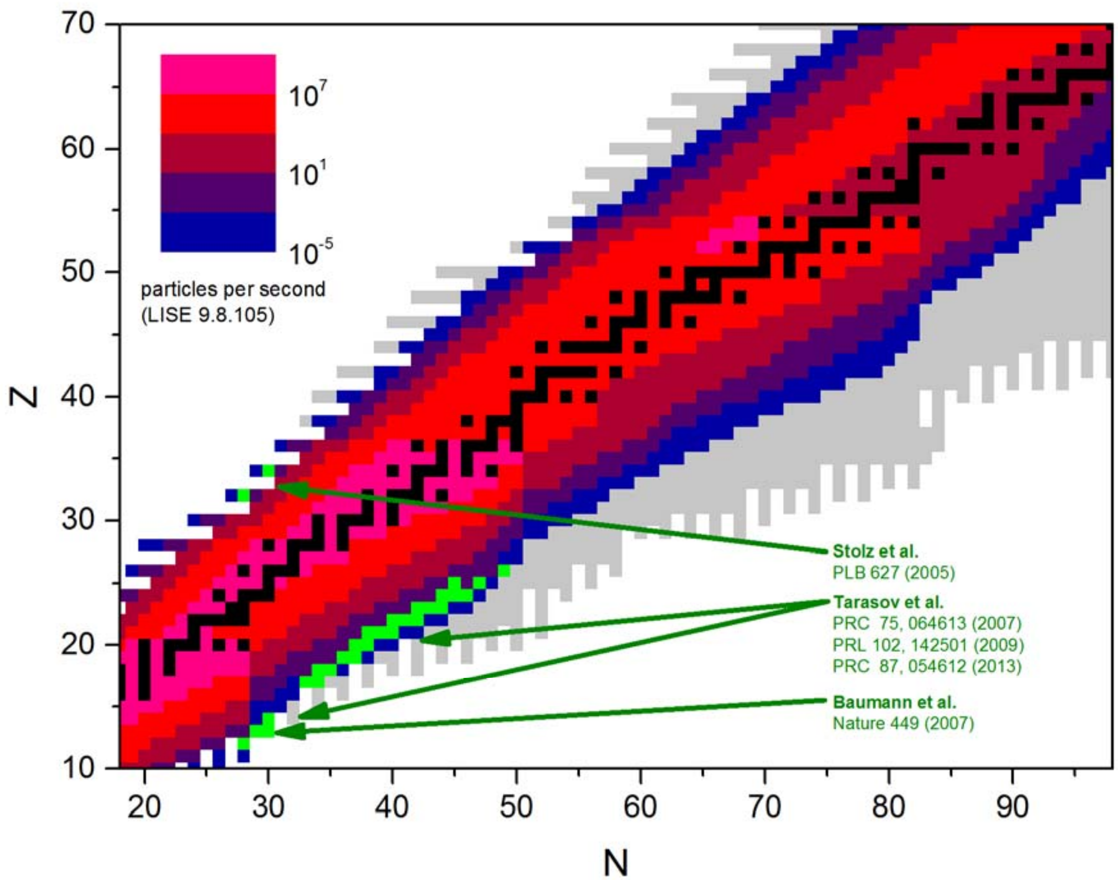


Chart shows production yields for current Coupled Cyclotron Facility.

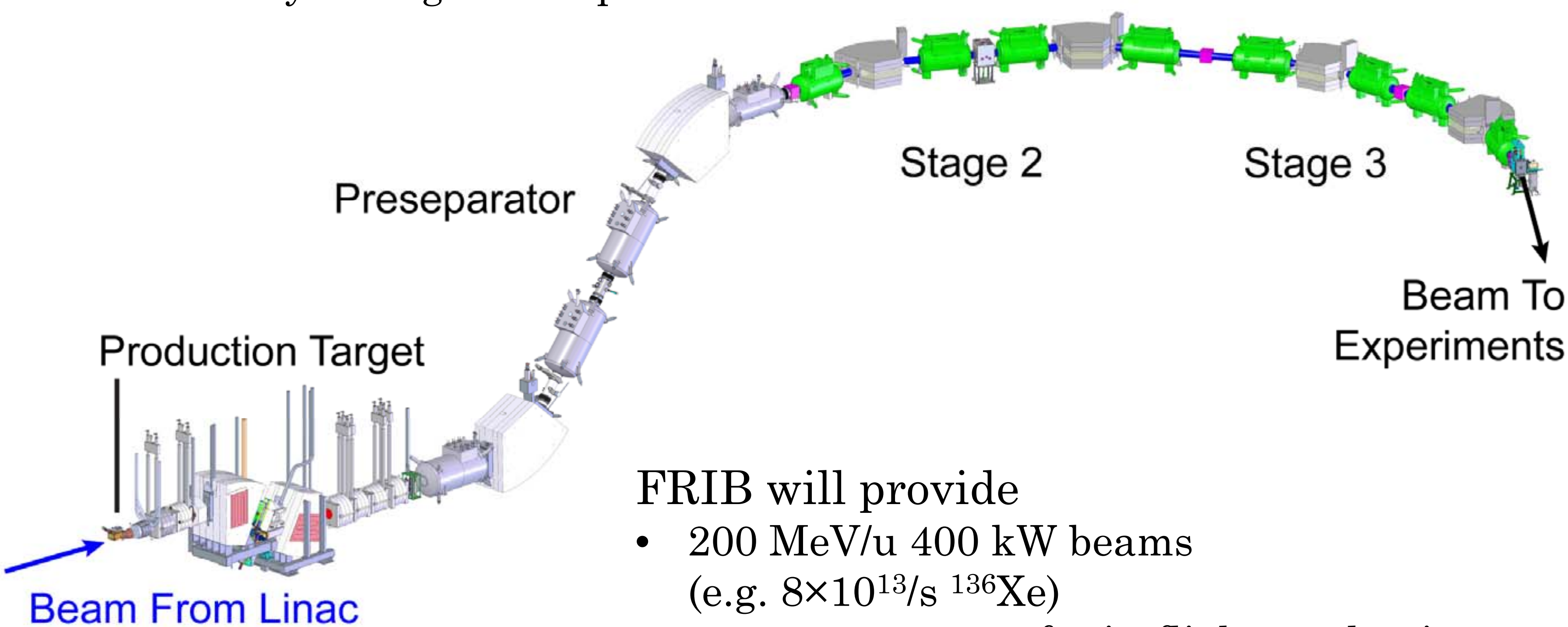
- Rate of 10^{-5}/s corresponds to about 1 particle per day.
- Highlighted are isotopes that were discovered at NSCL in the past decade.
- Production cross sections for these isotopes are in the range of 1 pb to 0.01 pb.

Bound nuclei based on LISE^{++} 9.8.105 using KTUY mass model (Koura et al., Prog. Theor. Phys. 113, 2005)

Potential for isotope discoveries at FRIB

Key requirements for new discoveries:

- particle yields
- selectivity of fragment separator



FRIB will provide

- 200 MeV/u 400 kW beams (e.g. 8×10^{13}/s ^{136}Xe)
- 3-stage separator for in-flight production and separation of rare isotopes

Projected particle yields

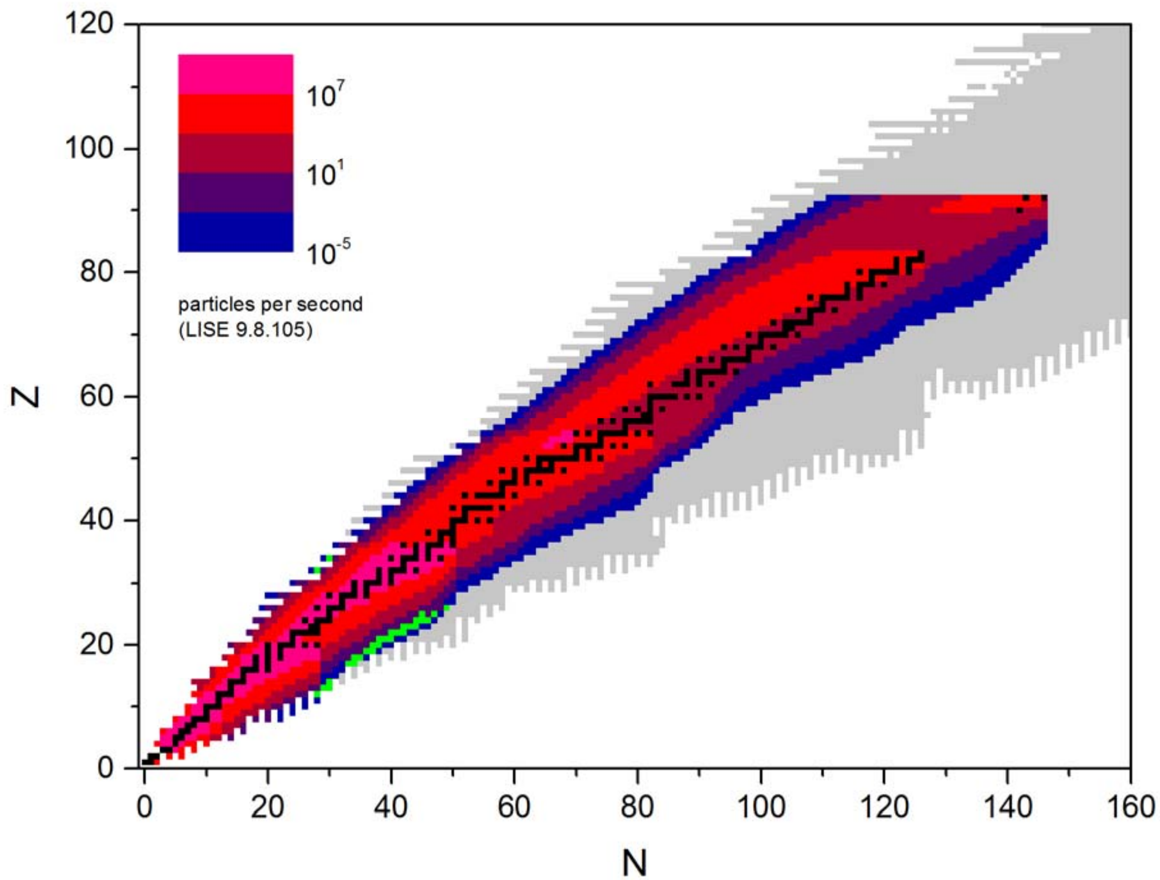


Chart shows production yields for current CCF.

- Rate of 10^{-5}/s corresponds to about 1 particle per day.

Projected particle yields

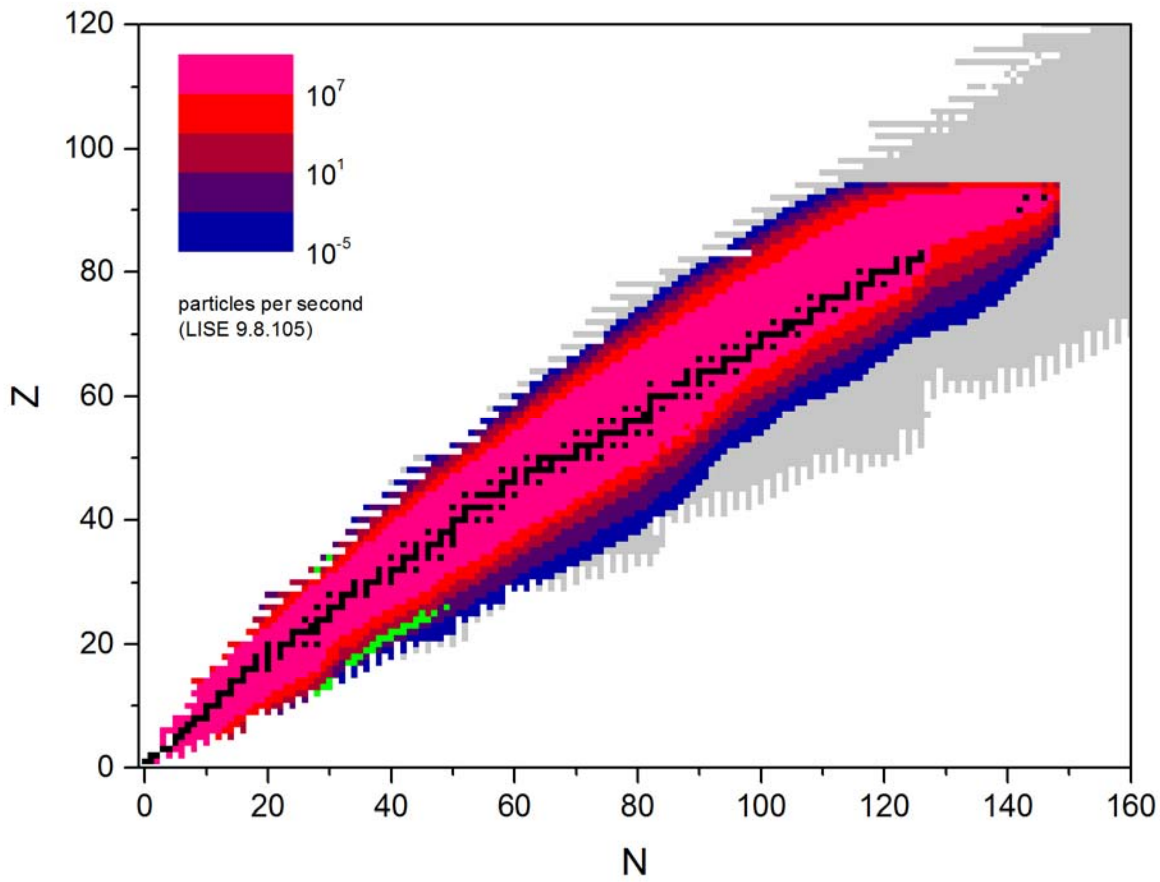


Chart shows projected production yields for FRIB.

- Rate of 10^{-5}/s corresponds to about 1 particle per day.

Projected particle yields

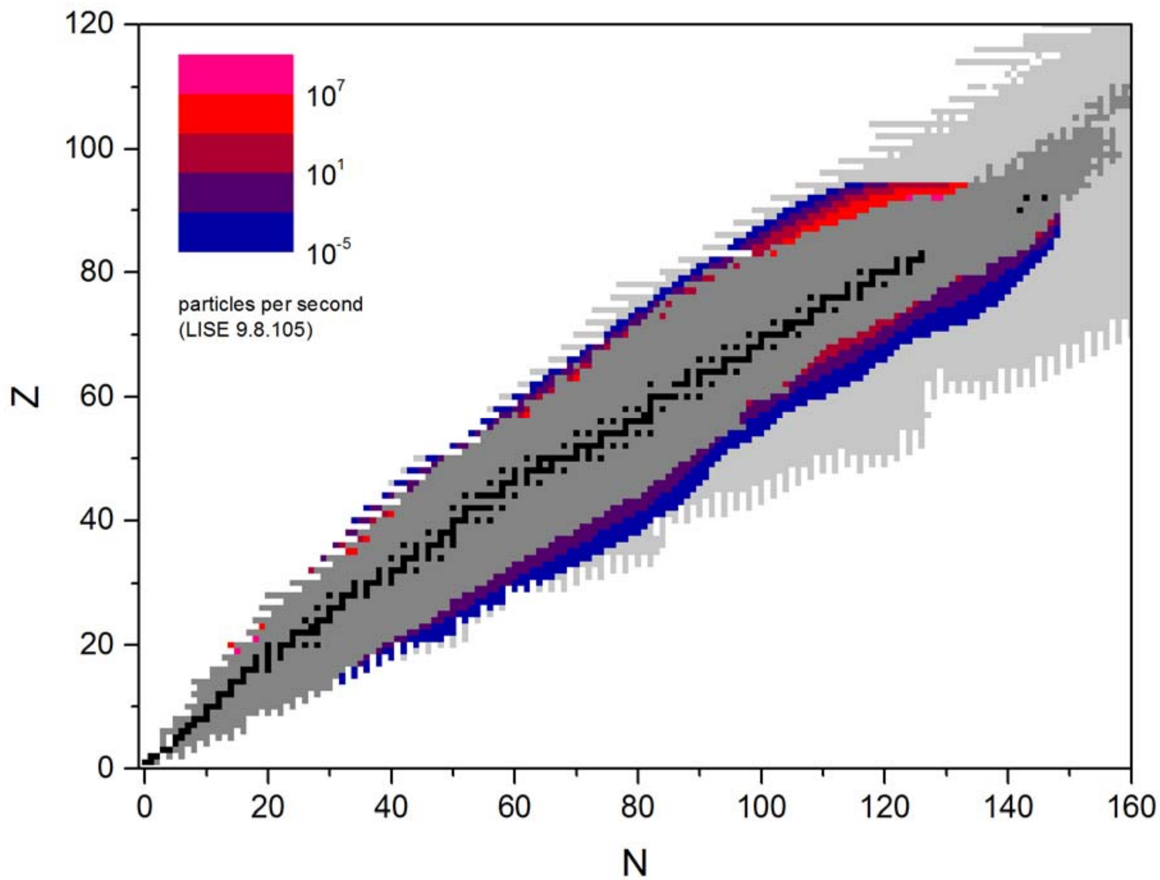


Chart shows projected production yields for FRIB.

- Rate of 10^{-5}/s corresponds to about 1 particle per day.
- Overlay with known isotopes indicates potential new discoveries.
- Production cross sections for these isotopes are of the order of 10^{-17} barn (10 attobarn).

Projected particle yields

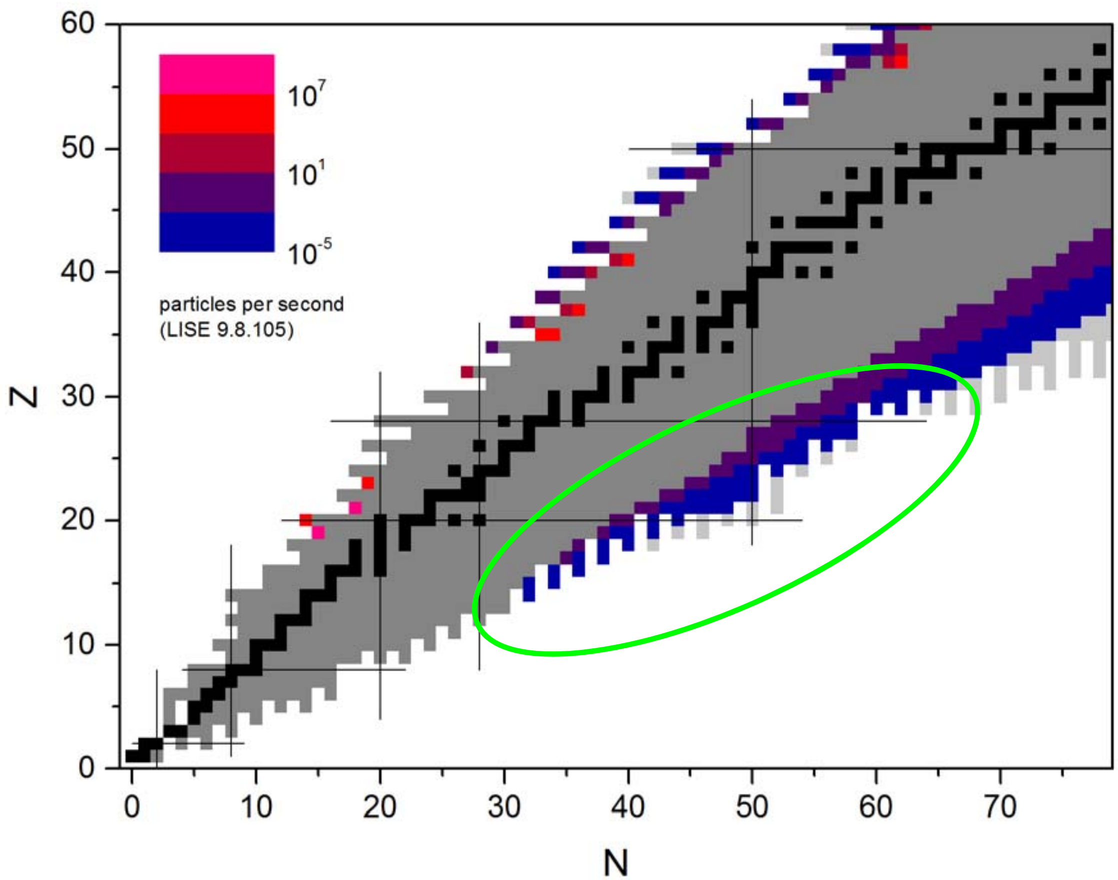
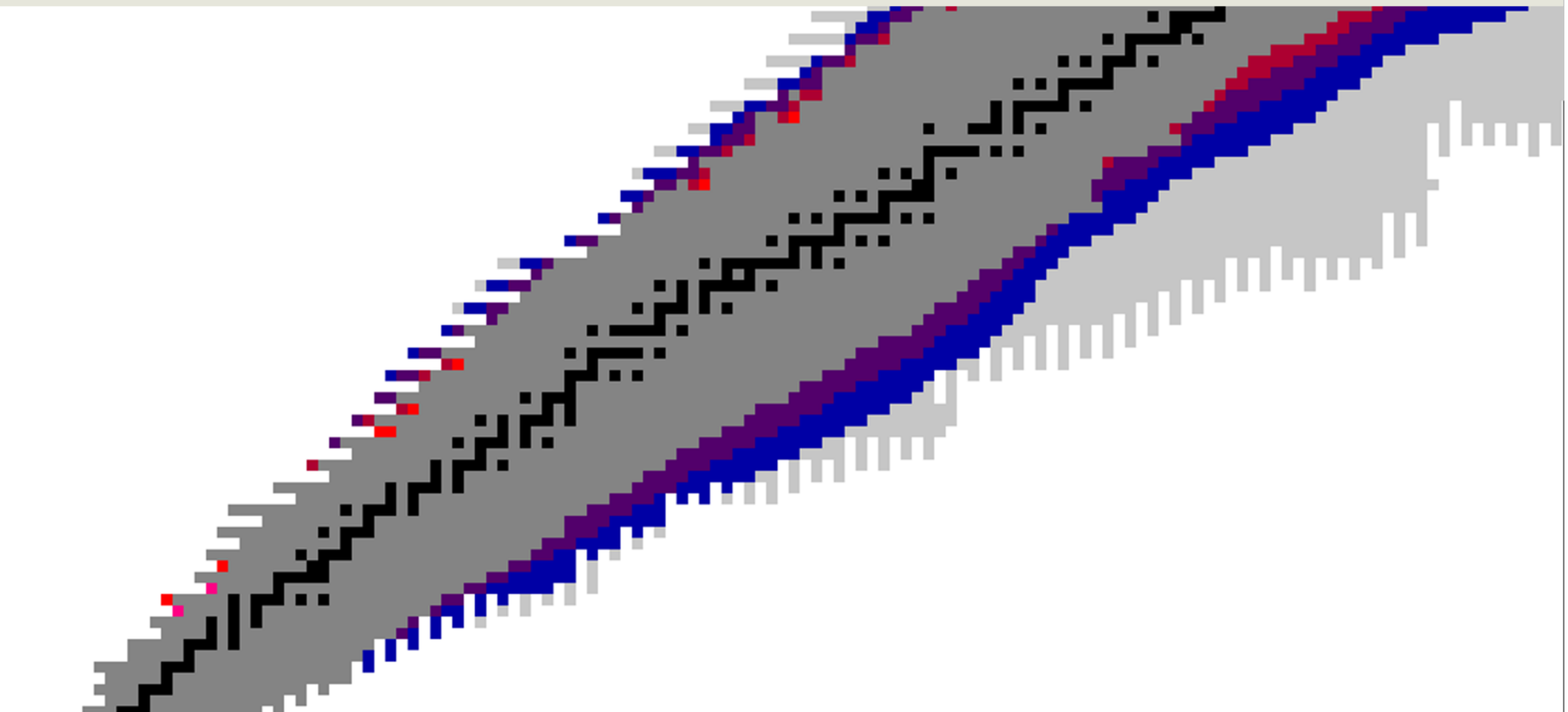


Chart shows projected production yields for FRIB.

- Rate of 10^{-5}/s corresponds to about 1 particle per day.
- Overlay with known isotopes indicates potential new discoveries.
- Production cross sections for these isotopes are of the order of 10^{-17} barn (10 attobarn).
- The neutron drip line will become accessible up to Fe, and possibly beyond.

Acknowledgments



Thanks for input and feedback from:
Marc Hausmann, Brad Sherrill, Oleg Tarasov.

The proliferation of Structural Symmetries in nuclei

Structural symmetries give unique insights into complex many-body systems, described in terms of system quantum numbers, selection rules, analytic formulas (often parameter free, except for scale)

Unfortunately, very few nuclei manifest an idealized structural symmetry exactly, limiting their direct role to that of benchmarks

However, this situation is radically changing with a profusion of new "partial" and "quasi" dynamical symmetries (PDS, QDS) - some empirically validated - in which important symmetry remnants (e.g., pure symmetry for some states, transition rates, degeneracies, etc) persist in systems with otherwise severely broken parent symmetries.

This offers the possibility of a considerably expanded role of symmetry descriptions for nuclei

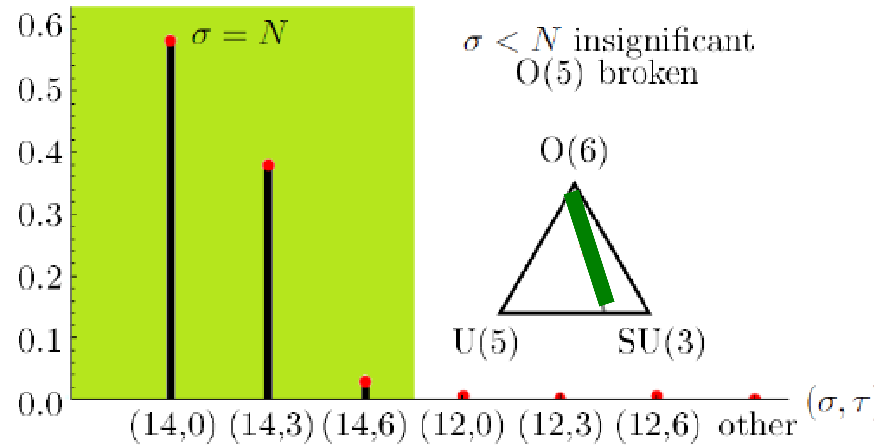
Three recent examples of PDS and QDS are illustrated in the next slide

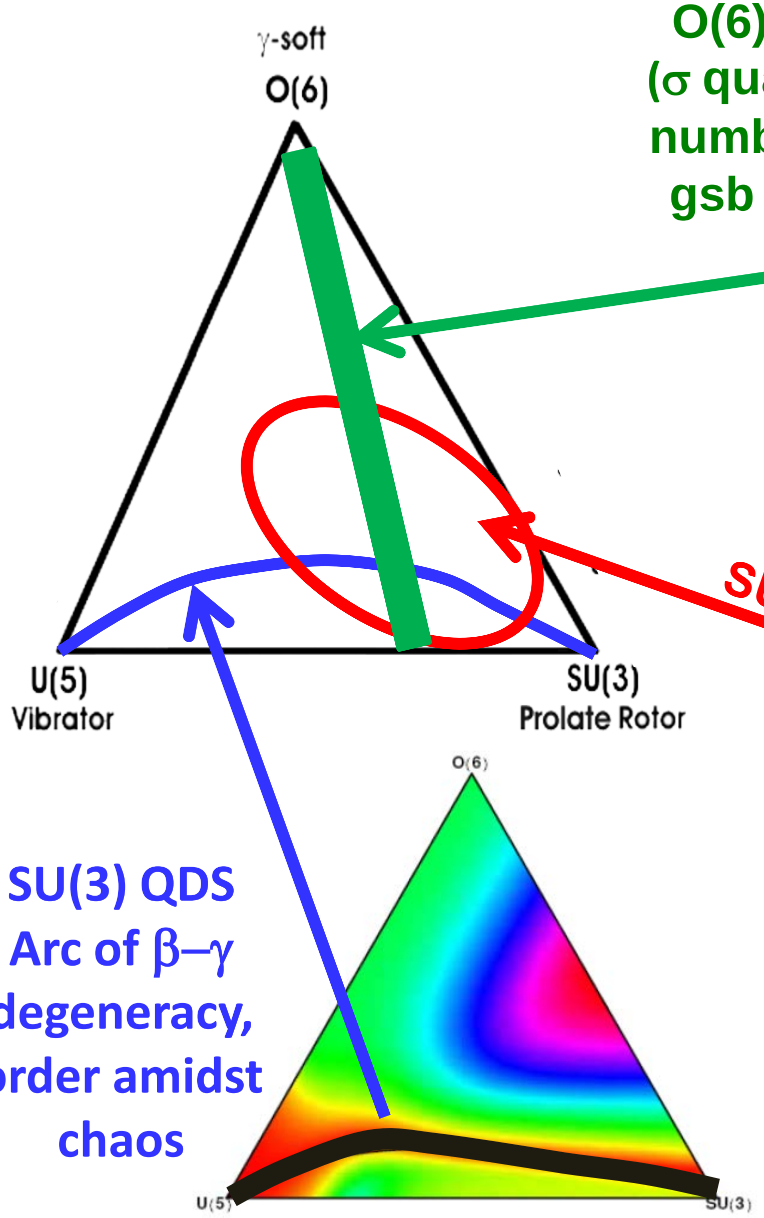
Partial, quasi dynamical symmetries in the symmetry triangle

(Color coded guide)

O(6) PDS
(σ quantum number for gsb only)

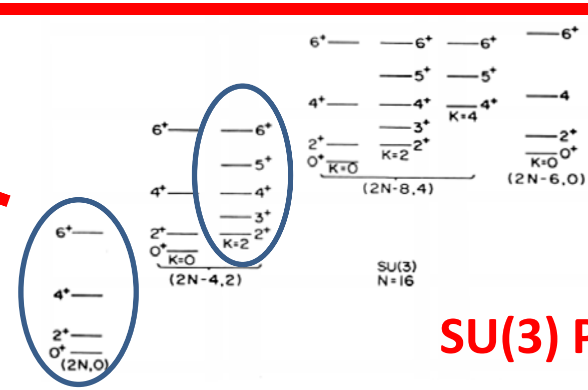
Expansion in O(6) basis (σ,τ)





SU(3)PDS

SU(3) QDS
Arc of β–γ degeneracy, order amidst chaos



SU(3) PDS

γ, ground states pure SU(3). Others highly mixed. Valid in *most* deformed nuclei! Relation to previous models.

Perspectives for the future

• Identifying the empirical signatures of partial symmetries.

• Uncovering which partial symmetries are relevant to actual nuclei and whether their manifestations are different in exotic nuclei

• Experimental techniques: will vary by case.

A) SU(3) – PDS: Rel. B(E2)s from γ band – beta decay;
B) Arc: Test degeneracy of vibrational modes + B(E2)s – β decay, Coul Ex
C) O(6) – PDS: signtures not yet established, yrast levels, possibly Coul Ex.
D) New PDS, QDS: ????

• Understanding the relation of these partial symmetries to numerical calculations – how such seemingly diverse descriptions can be simultaneously successful.

• Role of finite valence space (predictions of PDS and deviations from parent symmetries are valence nucleon-number dependent).

Nuclear structure physics with an Electron-Ion Collider

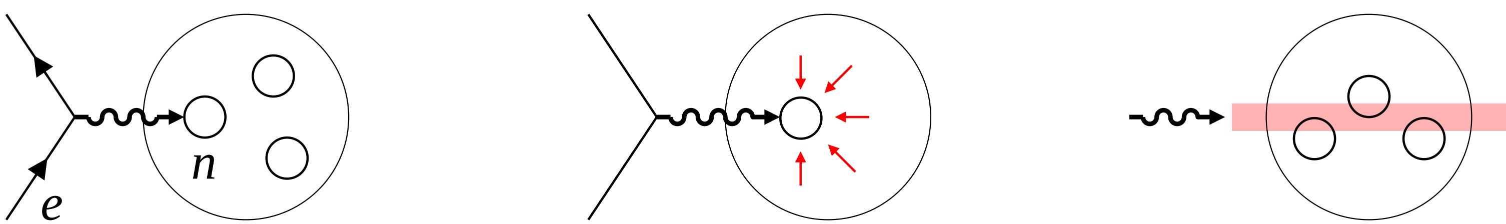
- High–luminosity polarized ep/eA collider (JLab, BNL)

  Next–generation facility for QCD and nuclear physics

  CM energy $\sqrt{s} \sim$ 10-40 GeV/nucleon, luminosity $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

  Polarized light ions: Deuterium D(pol), ^{3}He(pol), ^{4}He, Li, Be, . . .

- High–energy eA scattering with light ions



Neutron DIS for quark spin/flavor

Bound nucleon in QCD: $q\bar{q}$ sea, gluons

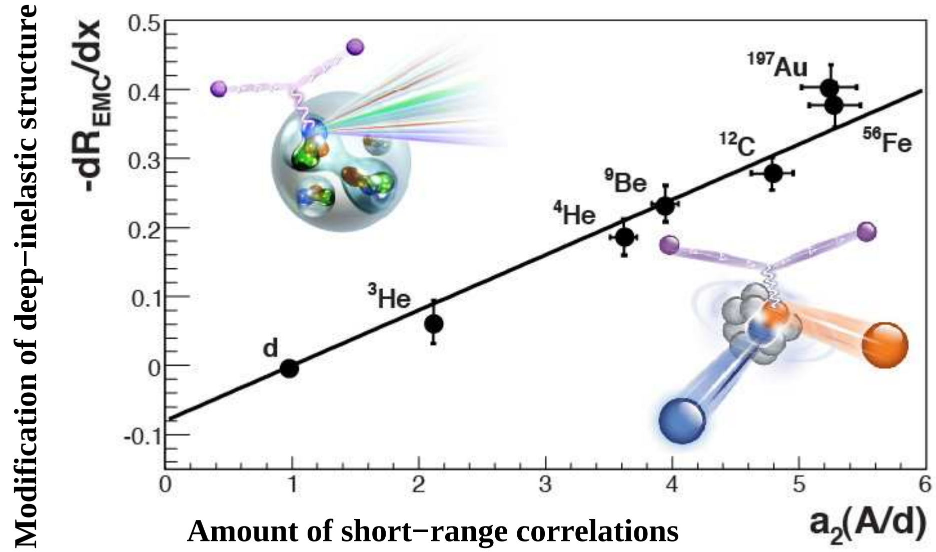
Coherent phenomena, collective fields

Probes **nuclear structure** as much as short-range QCD dynamics!
Opportunities for novel nuclear structure studies!

- Example: Deep-inelastic structure and short-range NN correlations

Modification of nuclear DIS structure at $x > 0.2$ proportional to amount of short-range NN correlations
"EMC effect," JLab 6/12 GeV

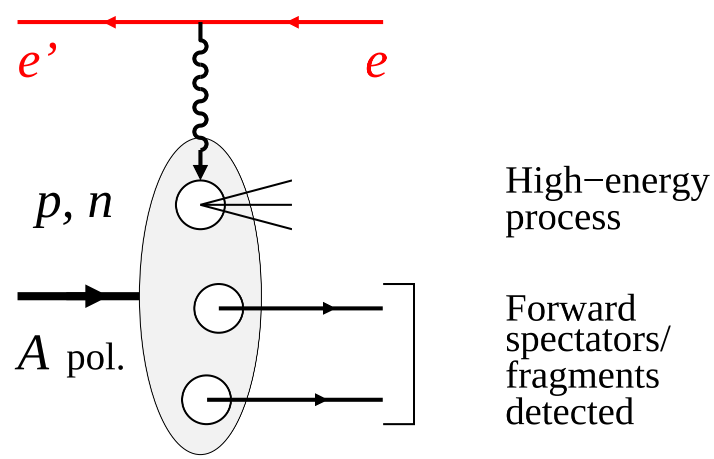
QCD origin of short-range NN interaction?



- Spectator nucleon tagging

Identify active nucleon, control its quantum state

Uniquely suited for collider: Dedicated forward detectors, full coverage for nucleons/fragments, momentum resolution $\delta p/p \sim 10^{-4}$
JLab MEIC interaction region & forward detector design



- Next-generation nuclear structure studies with EIC

  Nuclear modification of single–nucleon structure:
  QCD structure of bound nucleon ($q\bar{q}$ sea, gluons),
  non-nucleonic degrees of freedom, role of color
  Tagging with $p \sim p_{\rm Fermi}$

  QCD origin of short-range NN correlations:
  Effect on deep-inelastic structure, spin-isospin dependence, universality.
  $\rightarrow$ Superdense matter in astrophysical systems
  Tagging with $p \gg p_{\rm Fermi}$

  Low–energy nuclear breakup induced by high-energy processes:
  New operators, new probes of low-energy structure.
  Light–front wave functions, spectral functions.
  Tagging with $A > 2$, multiple spectators, cluster breakup

- R&D efforts and resources

  EIC accelerator and detector R&D at BNL and JLab.
  Physics simulations available. Great interest in user community.
  https://wiki.bnl.gov/eic/ (BNL), https://eic.jlab.org/wiki/ (JLab).

  Joint theoretical–experimental R&D for spectator nucleon tagging.
  JLab 2014 LDRD project "Physics potential of polarized light ions with EIC@JLab"