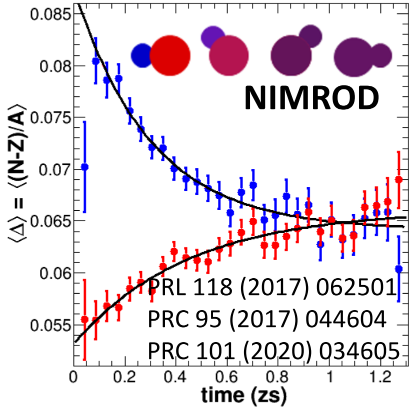
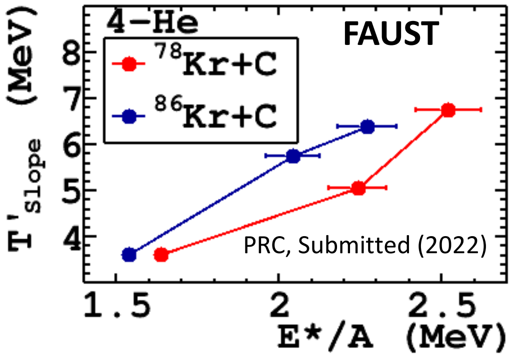
Nuclear Reactions for Nuclear Astro (and more)

Alan B. McIntosh – Town Hall, Nov 2022

Equation Of State



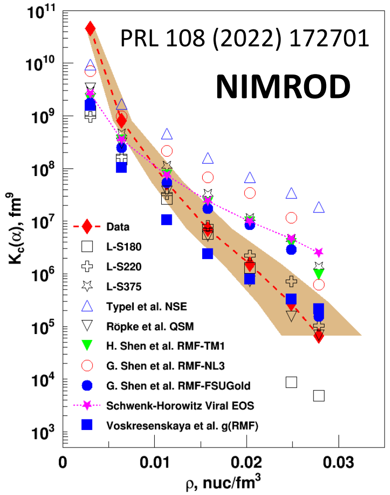
PRL 118 (2017) 062501
PRC 95 (2017) 044604
PRC 101 (2020) 034605



PRC, Submitted (2022)

Measure:

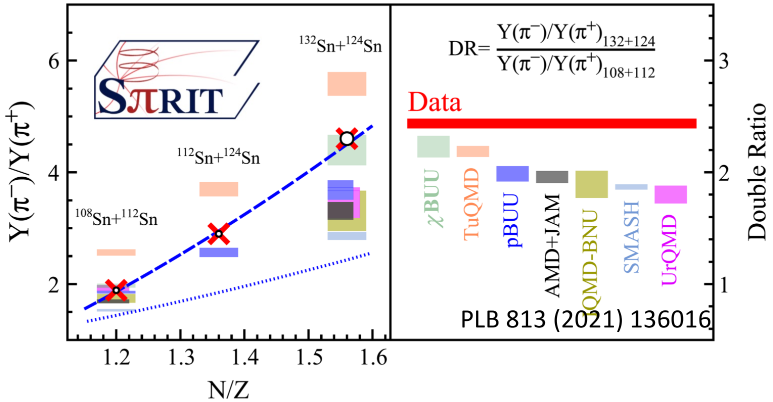
Neutron-Proton Equilibration Chronometry
Asymmetry Dependence of Caloric Curve
Equilibrium constants of alpha coalescence
Pion yield ratios



PRL 108 (2022) 172701

Impacts:

neutron star structure
n-star merger grav wave
r-process site physics



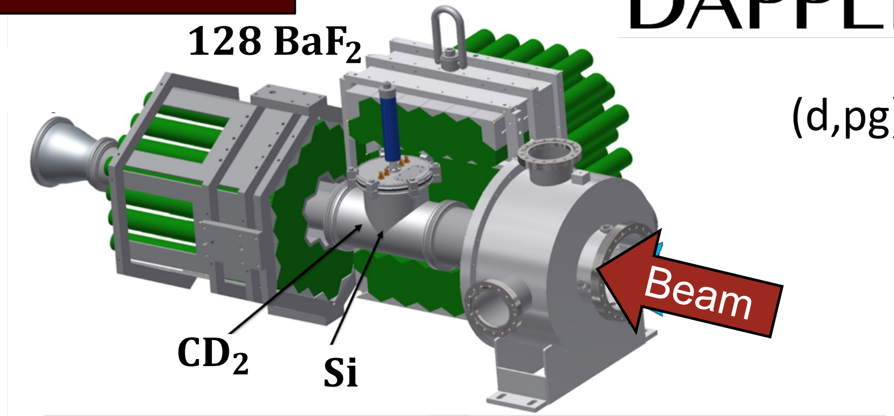
PLB 813 (2021) 136016

Future:

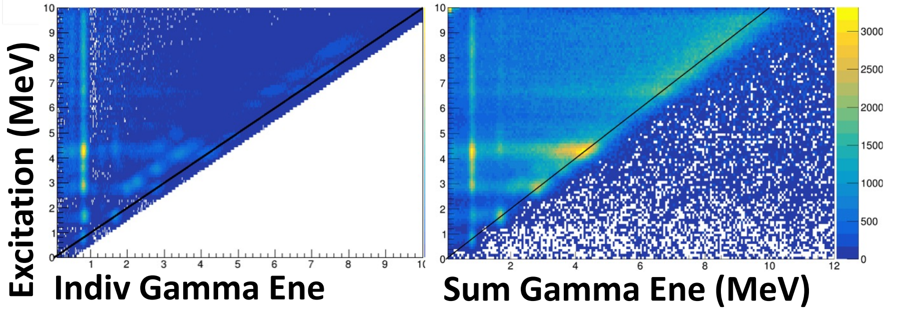
Low Density Correlations
Equilibration Chronometry
SpiRIT@RIKEN
FRIB EoS: nucleon flow
EoS TPC @ FRIB: pions

Direct Reactions

DAPPER



(d,pg)



Current & Future:

Photon strength function
Neutron Capture
Compare **proxy rxns** & direct methods
    DAPPER + DANCE + Hyperion
Key nucl & isotopic chains

Impacts: nucleosynth: capture & burning

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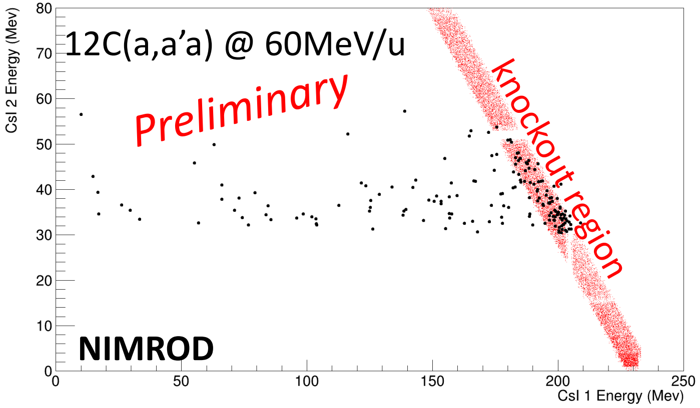
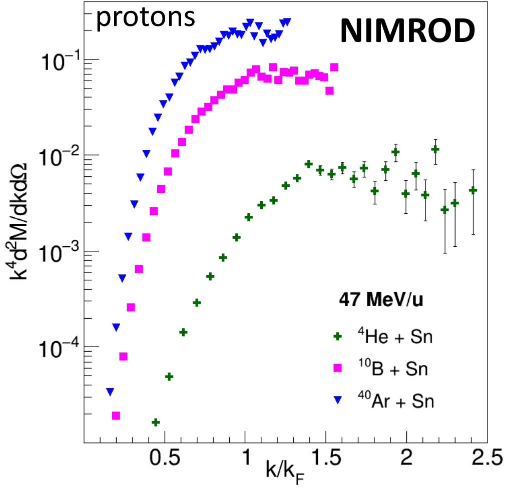
Clustering & Correlations

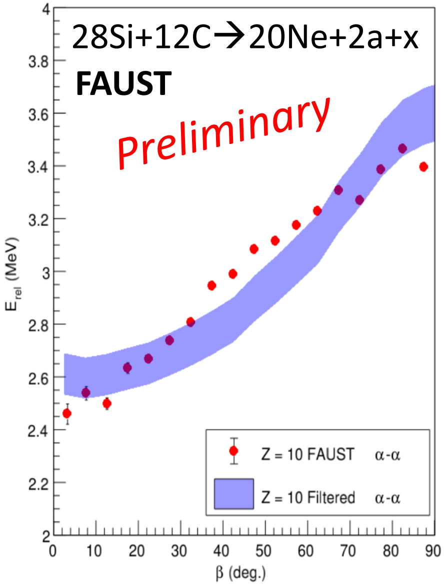
Alpha Knockout



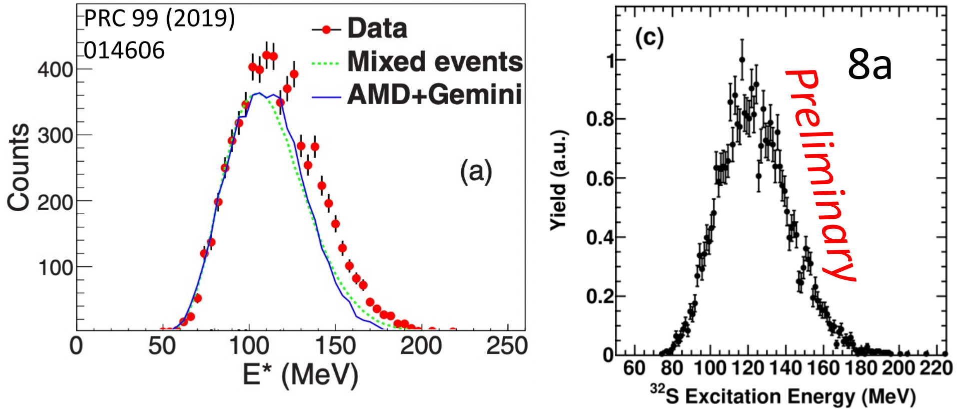
Short-Range Correlations



Proximity Decay



Exotic 8a cluster decay, Toroidal nuclei



<u>Impacts:</u>
Cluster Structure
 -> Low-mass nucl burning
Clustering -> Low Dens EoS
SRC -> High Dens EoS

Critical Tools

to constrain:
Equation of State
Direct Reactions
Clustering & Correlations

ARUNA labs

Rare Isotope Beams

FRIB 400, HRS

TPC Community

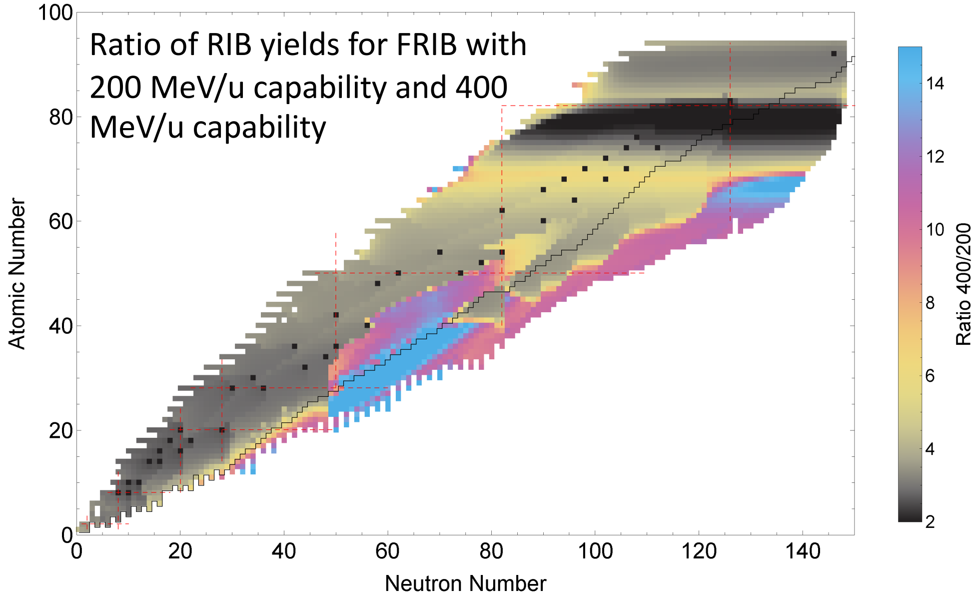
Targets

Neutron Targ & RIB Ring

Accurate Models
(transport, direct rxns)

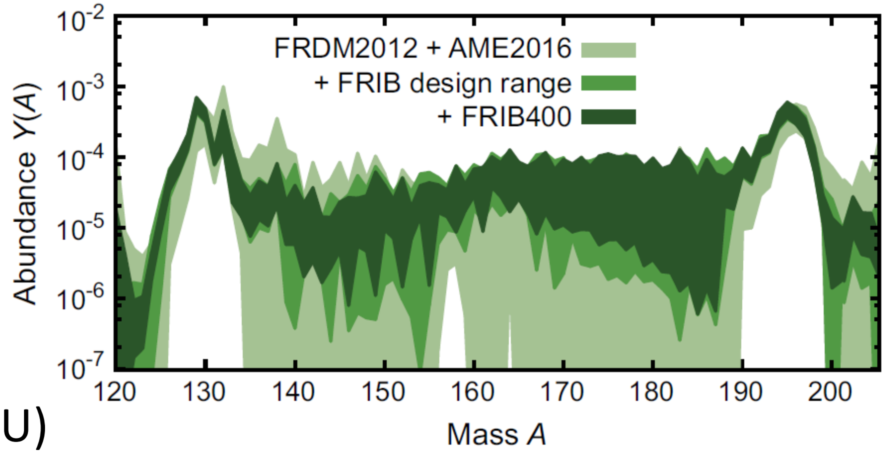
FRIB 400-MeV/u Energy Upgrade is Critical for Achieving Nuclear Astrophysics Goals

- FRIB400 will significantly extend the study of neutron-rich isotopes of importance for the r-process, substantially reducing nuclear-physics uncertainties in simulations
- FRIB400 will extend study of nuclei along the neutron dripline into a region important for modeling the crust of neutron stars
- FRIB400 will allow the study of very neutron-rich nuclear matter at twice normal nuclear density, strongly constraining the Equation of State
- All types of experiments benefit, but enhanced opportunities at higher energies, e.g. quasifree reactions, in-flight fission, Coulex, charge-exchange reactions


Ratio of RIB yields for FRIB with 200 MeV/u capability and 400 MeV/u capability

FRIB400 – Whitepaper – June 2019

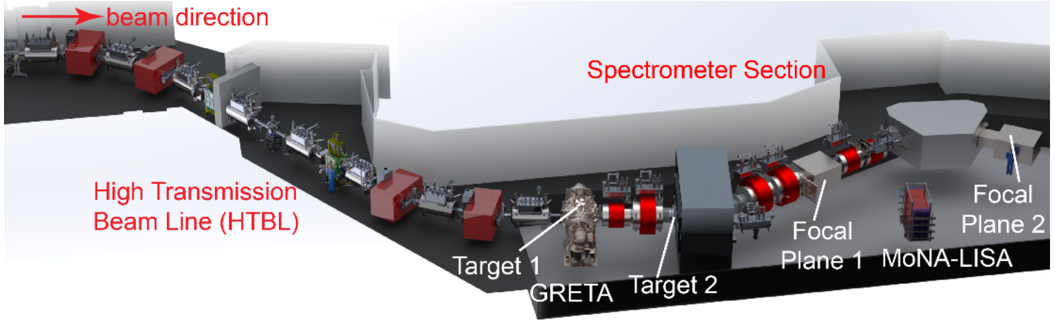
https://frib.msu.edu/_files/pdfs/frib400_final.pdf



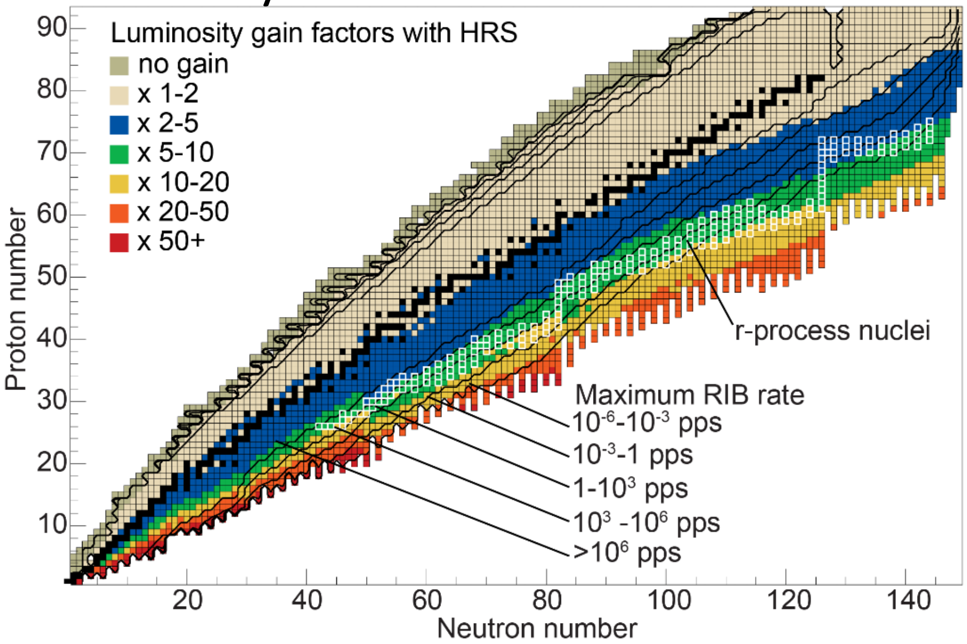
R. Zegers (FRIB/MSU)

The High Rigidity Spectrometer Enhances the Luminosity for Fast-Beam Experiments with Factors of up to ~100 for the Most Neutron-Rich Systems

- Ability to perform experiments at rigidities for which isotope production is maximized (FRIB200 AND FRIB400)
- HRS Project underway – Goal: CD2/3A Summer 2023



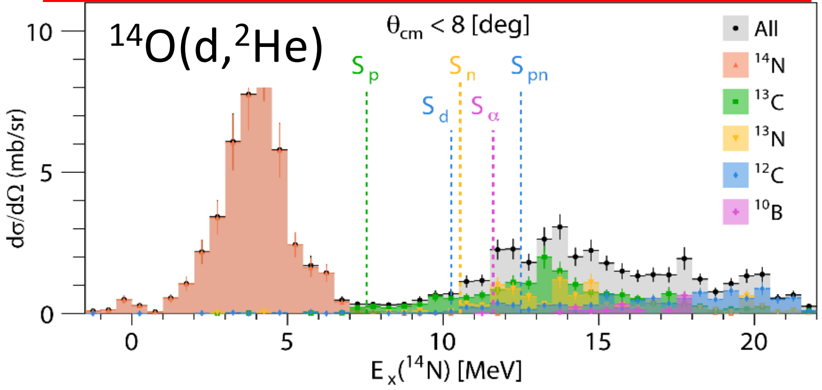
- Nuclear Astrophysics Experiments are key drivers for HRS' capabilities – next 5 years provide ample opportunity for community to define new opportunities and contribute
- The extraction of weak transition rates on unstable nuclei through charge-exchange reactions is now feasible in both the β^+/EC and β^- directions through (d,^{2}He) and (p,n) reactions in inverse kinematics



HRS Working group: https://hrs.lbl.gov/

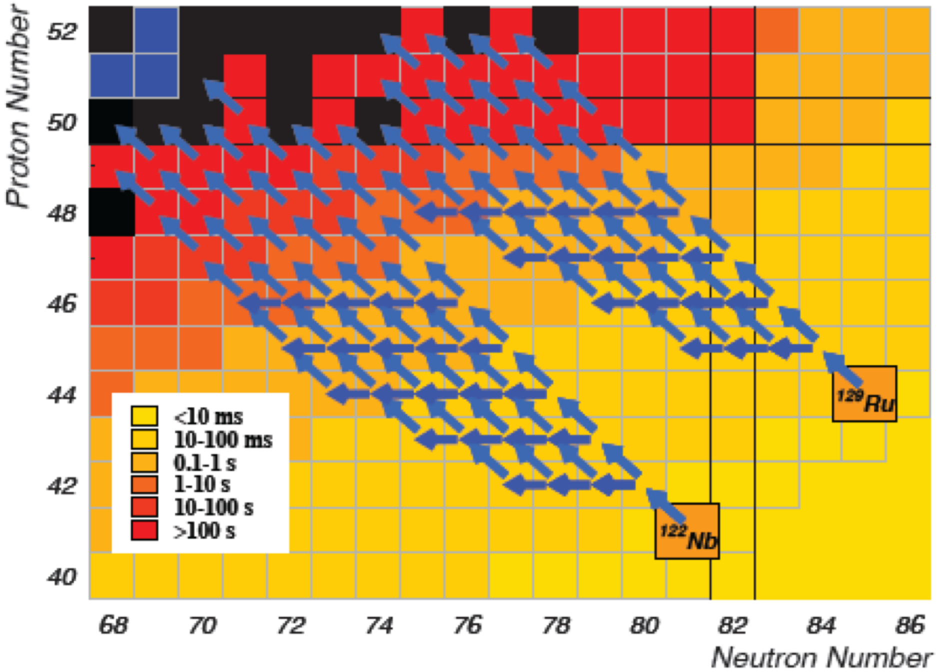
[HRS Preliminary Design Report]()

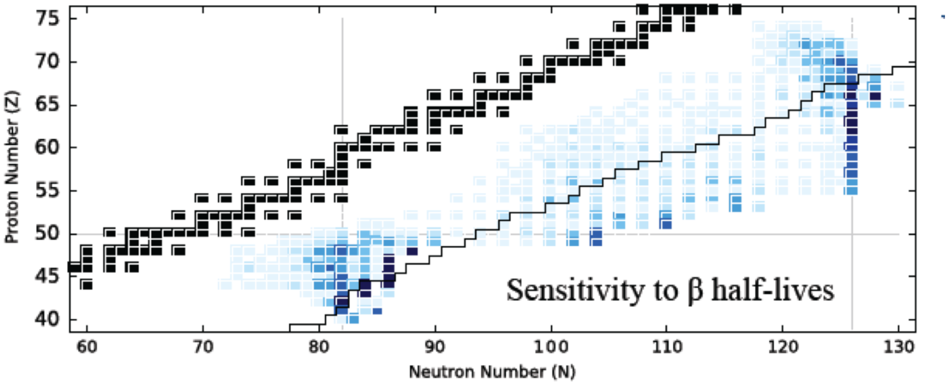
New: (d,^{2}He) in inverse kinematics

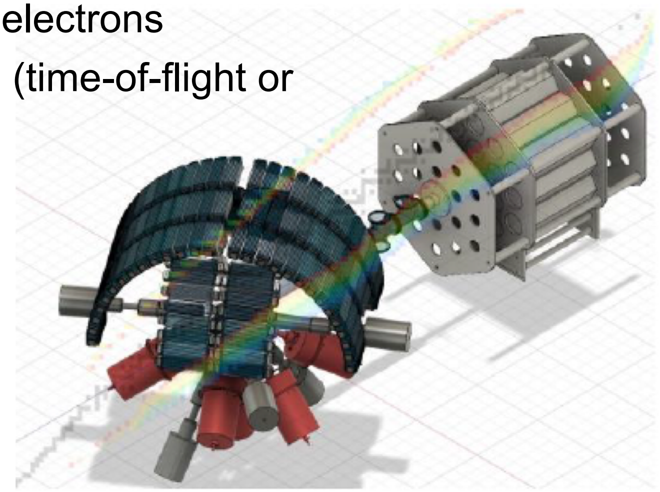


Science: Understanding the Origin of the Elements with the FDS

- Critical inputs for astrophysical modeling
  - Half-lives
  - Delayed neutron branches
  - Strength determination (above and below S_n)
  - n,γ reaction cross sections
- Required FDS detector configurations
  - Charged particle detection for ions and electrons
  - Neutrons (time-of-flight or thermal)
  - Photons
  - TAS







https://fds.ornl.gov/wp-content/uploads/2020/09/FDS-WP.pdf

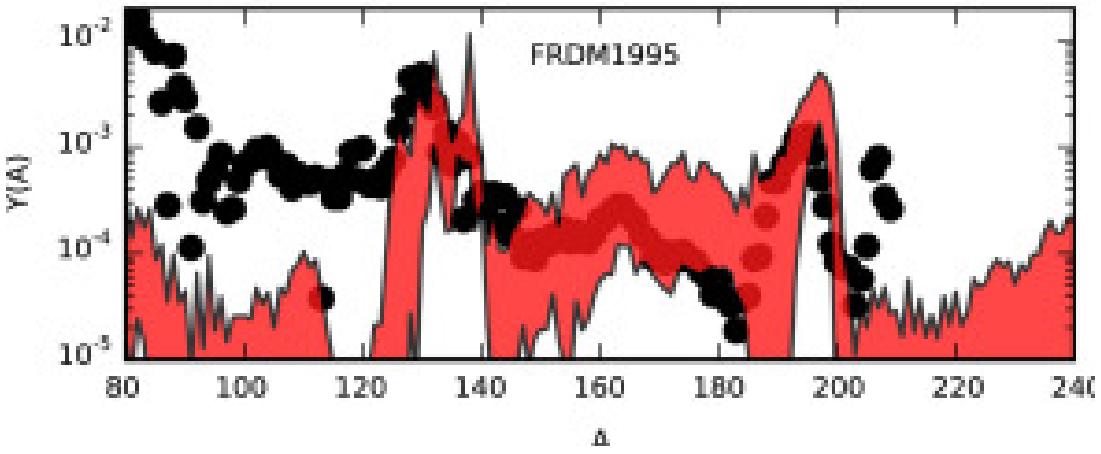
M. Mumpower *et al.*, et al., Prog. Part. and Nucl. Phys. 86, 86 (2016)

Improving β-decay properties using total absorption spectroscopy

Total Absorption Spectroscopy: What and Why

High efficiency γ-ray calorimeters (MTAS, SuN, HECTOR, etc.)

- Sensitive to small-feeding branches
- More accurate determination of I_β
- Variations in set-ups based on expected $T_{1/2}$ (tape-stations, implantation detectors, etc.)



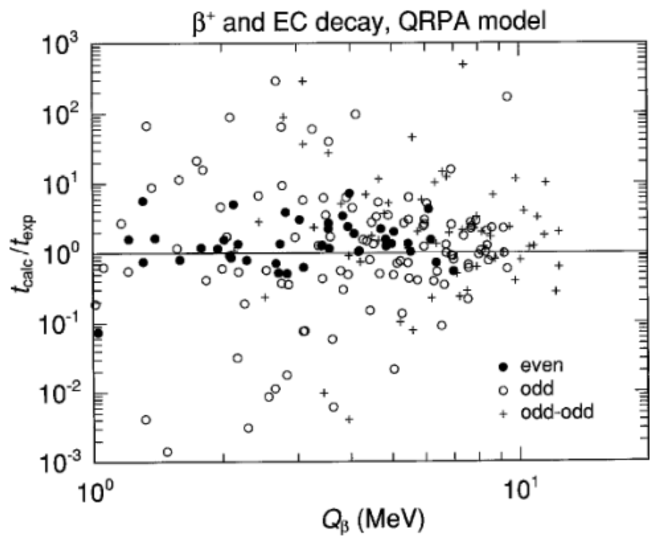
Nucleosynthesis sensitivity studies demonstrate orders of magnitude variation based on varying the β-decay rates and half-lives for short-lived nuclei.

M.R. Mumpower, et al., Prog. in Part. and Nuc. Phys., Vol. 86, Jan 2016, (86-126)

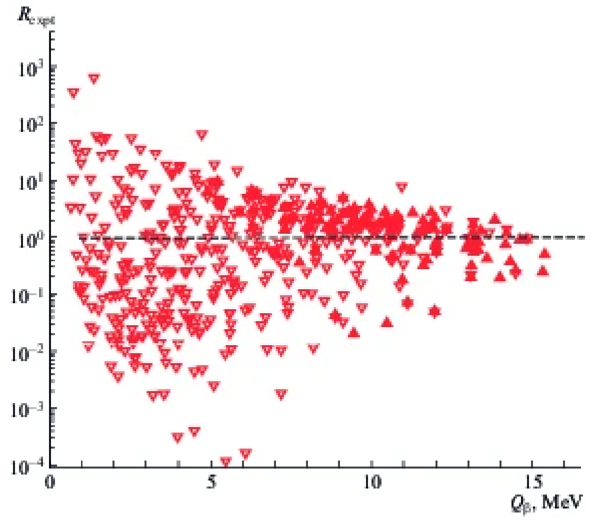
Measurement of I_β offers a more stringent test of global theoretical calculations.

$$\frac{1}{T_{1/2}} \propto \sum_{0\le E_x\le Q_\beta} f\left(Z, Q_\beta - E_x\right) B(\mathrm{GT}, E_x)$$

Measured vs. predicted β-decay half-lives



Moller and Randrup
Nuclear Physics A ***514***, 1-48 (**1990**)

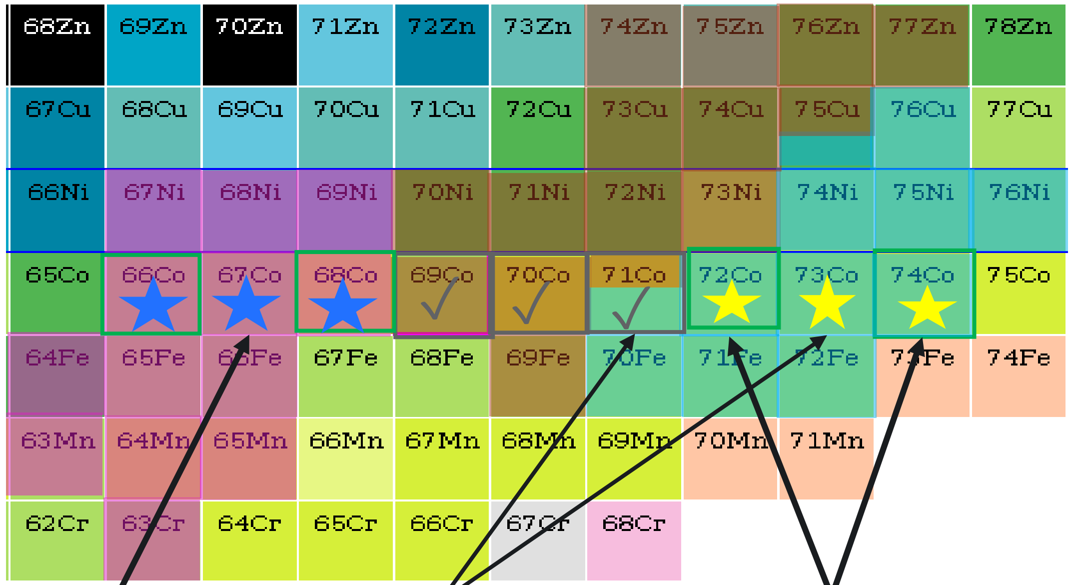


Panov & Lutostansky
Physics of Atomic Nuclei **83**, 613-620 (**2020**)

The fan-TAS-tic future

Current and future facilities will enable the refinement of theoretical calculations

- Use of cocktail beams enables multiple nuclei to be measured in a single experiment
- Direct r-process path nuclei will be able to be measured with TAS
- Measurement campaigns can provide systematics for regions of interest



68Zn	69Zn	70Zn	71Zn	72Zn	73Zn	74Zn	75Zn	76Zn	77Zn	78Zn
67Cu	68Cu	69Cu	70Cu	71Cu	72Cu	73Cu	74Cu	75Cu	76Cu	77Cu
66Ni	67Ni	68Ni	69Ni	70Ni	71Ni	72Ni	73Ni	74Ni	75Ni	76Ni
65Co	66Co ★	67Co ★	68Co ★	69Co ✓	70Co ✓	71Co ✓	72Co ★	73Co ★	74Co ★	75Co
64Fe	65Fe	66Fe	67Fe	68Fe	69Fe	70Fe	71Fe	72Fe	73Fe	74Fe
63Mn	64Mn	65Mn	66Mn	67Mn	68Mn	69Mn	70Mn	71Mn		
62Cr	63Cr	64Cr	65Cr	66Cr	67Cr	68Cr				

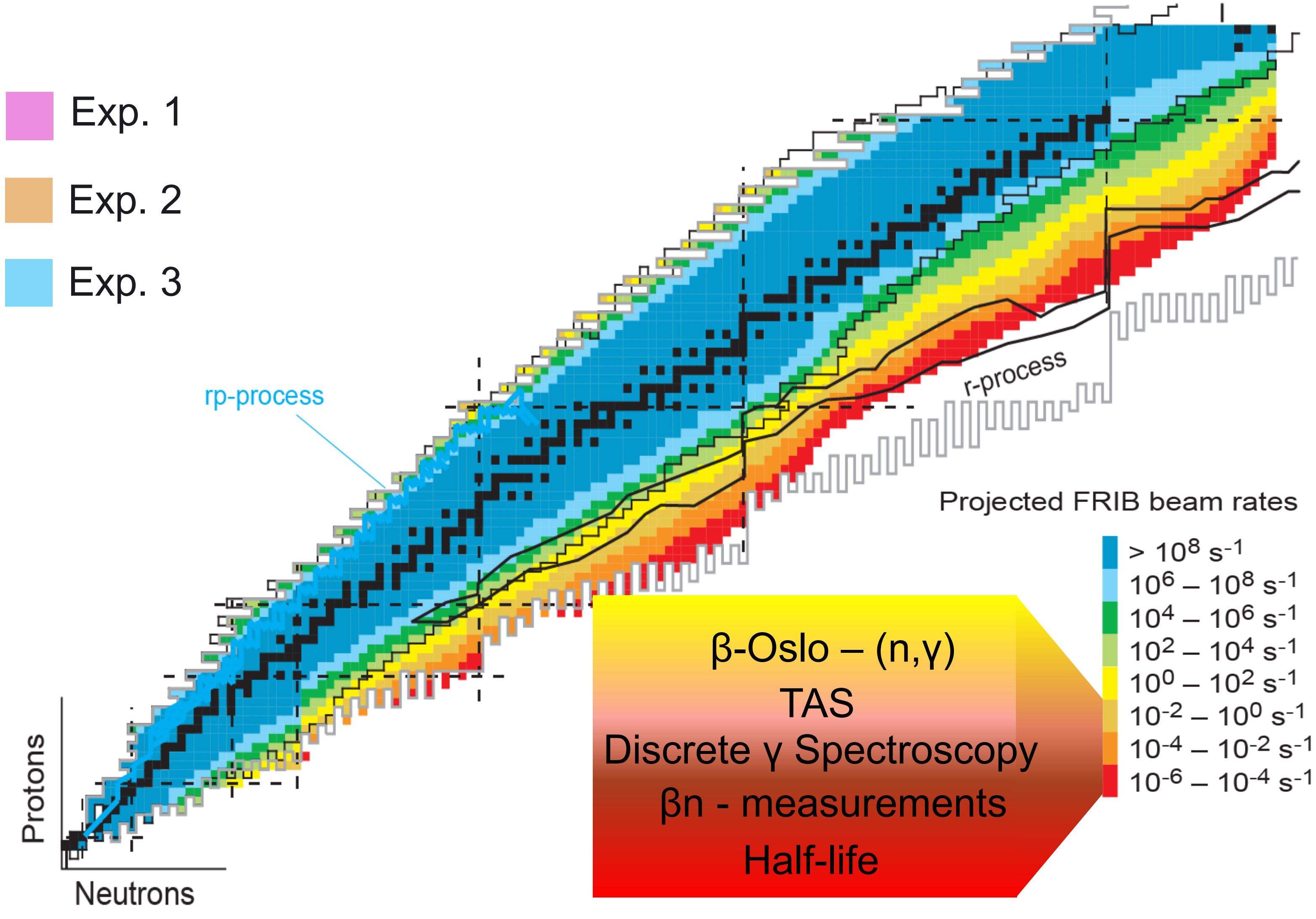
- 🟪 Exp. 1
- 🟧 Exp. 2
- 🟦 Exp. 3

Jacob Davis

Mejdi Mogannam

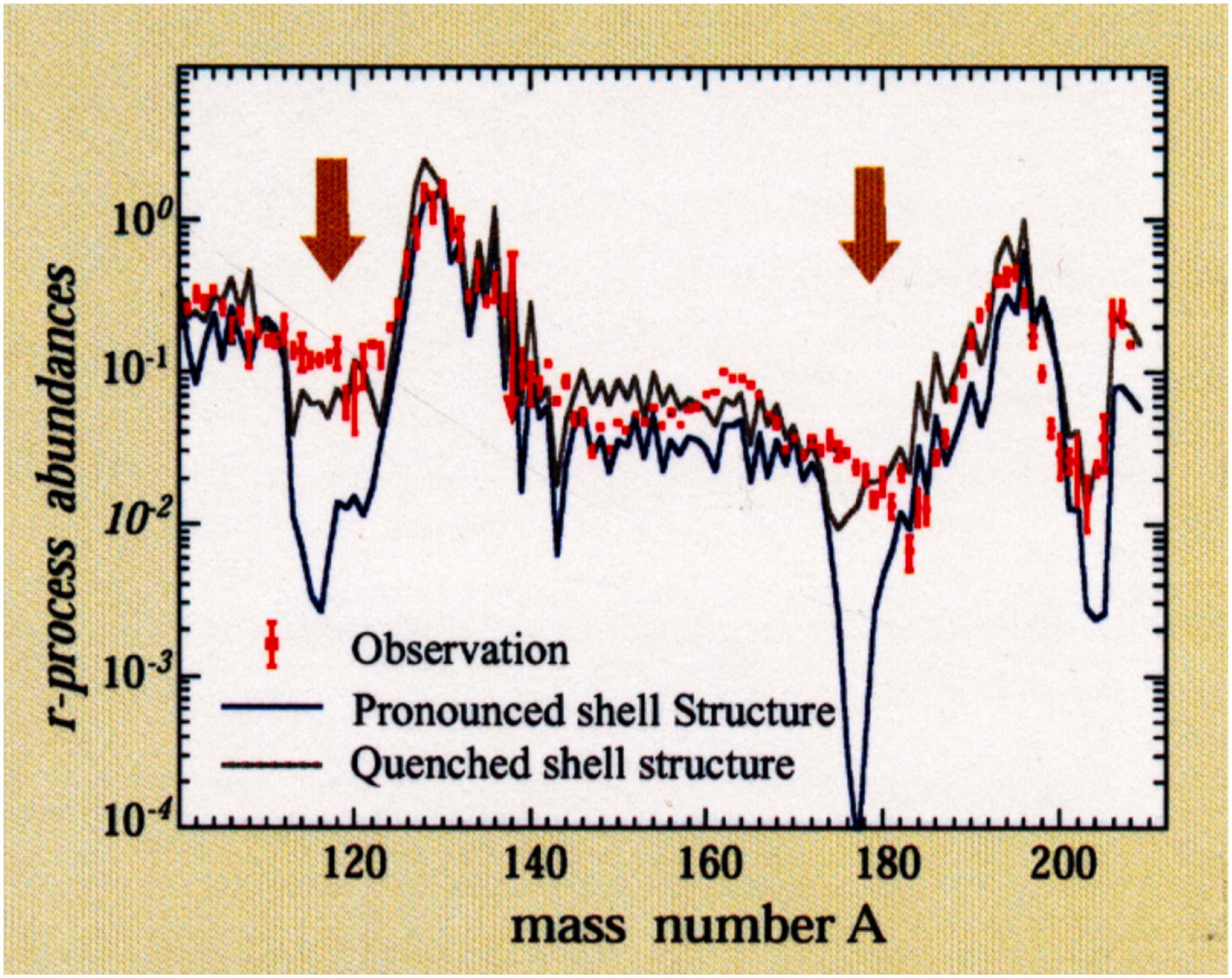
Hannah Berg

✓ S. Lyons et al. *PRC* 100, 025806 (2019)
✓ A. Spyrou et al. *PRL* 117, 142701 (2016)



β-Oslo – (n,γ)
TAS
Discrete γ Spectroscopy
βn - measurements
Half-life

Bill Walters



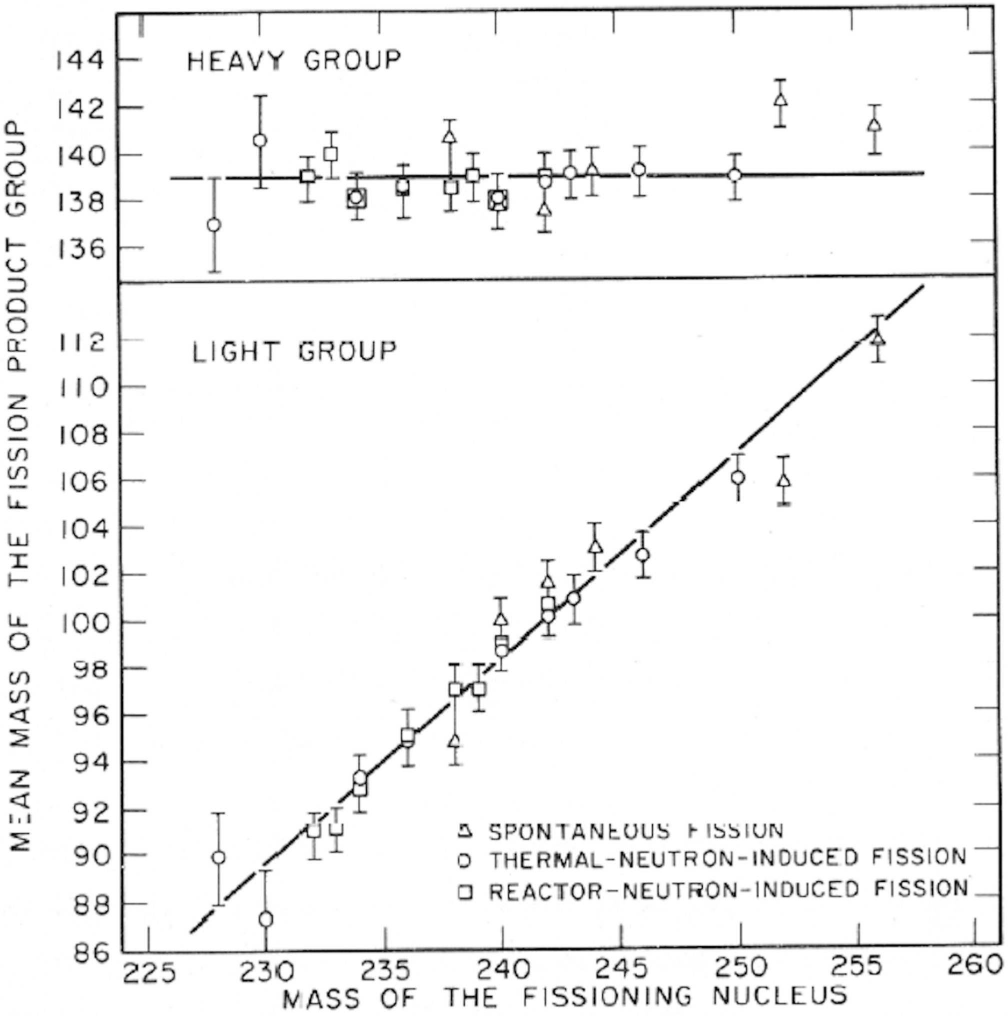


Fig. XI-8B. Average masses of the light and heavy fission product groups as functions of the masses of the fissioning nucleus. [After Flynn *et al.* (1972b).]

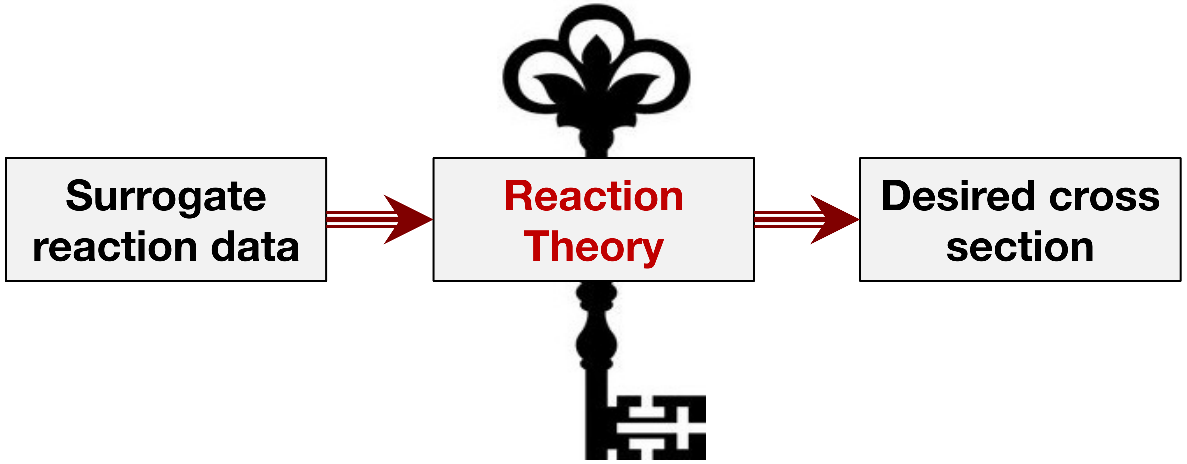
Theory for indirect reaction measurements

Determining capture rates for unstable nuclei directly is hard

- Short-lived target make measurements difficult to impossible
- Statistical Hauser-Feshbach (HF) calculations lack predictive power away from stability

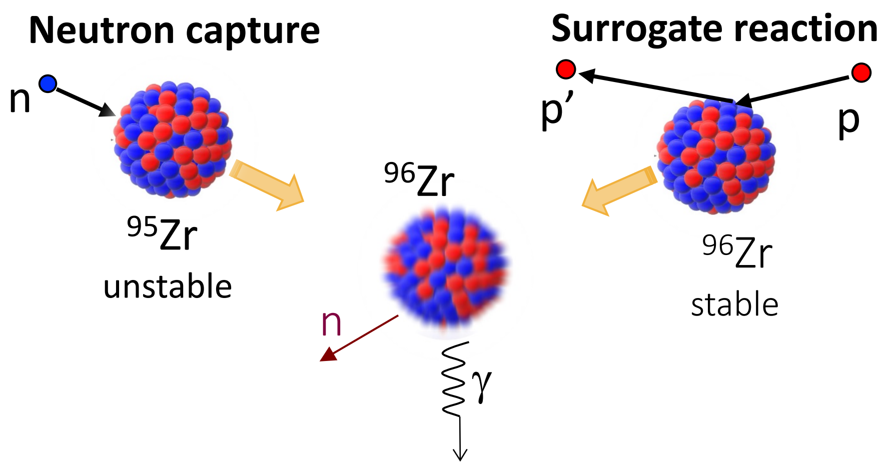
Surrogate reactions provide a solution

- A transfer or inelastic scattering experiment produces the compound nucleus and the decay is measured
- Advanced reaction theory turns this data into constraints for calculations of the desired neutron capture rate



Surrogate reaction data → **Reaction Theory** → **Desired cross section**

Neutron capture on s-process branch point ^{95}Zr from inelastic scattering



Status:

- Capture cross sections have been obtained from surrogate reactions using (p,d) and (d,p) transfers and inelastic scattering.
- Cross sections for capture involving isomers have been obtained.

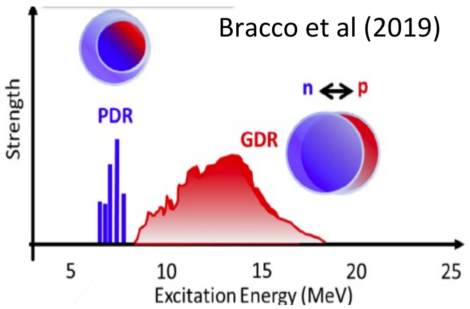
Jutta Escher, escher1@llnl.gov

Theory for indirect reaction measurements: Opportunities

Opportunity: inverse-kinematics experiments - leverage surrogate reaction applications and structure studies

- Inelastic scattering can serve as surrogate mechanism and provide information on collective motion in exotic nuclei
- The (d,p) reaction can serve as surrogate mechanism and provide information on single-particle structure

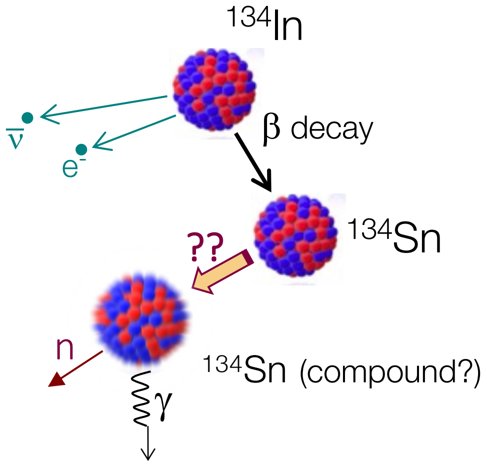
Collective dipole excitations



Bracco et al (2019)

Opportunity: β-delayed n/γ emission

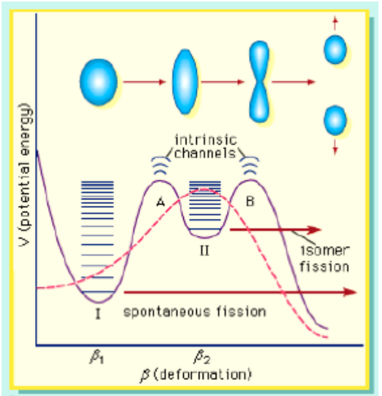
- β-decay to states above/below particle thresholds allows us to study subsequent decays
- Improved understanding of β-delayed processes will tell us when the process is statistical
- Statistical decay can provide constraints for HF calculations



Opportunity: Surrogate reactions for fission applications

- Observe fission properties in coincidence with surrogate ejectile
- Control over energy of fissioning nucleus, including sub-threshold
- Multiple surrogate reactions in one experiment

Schematic view of fission



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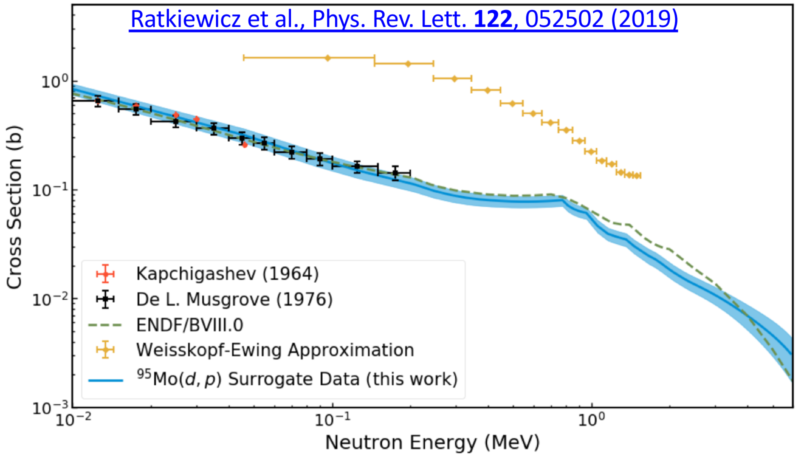
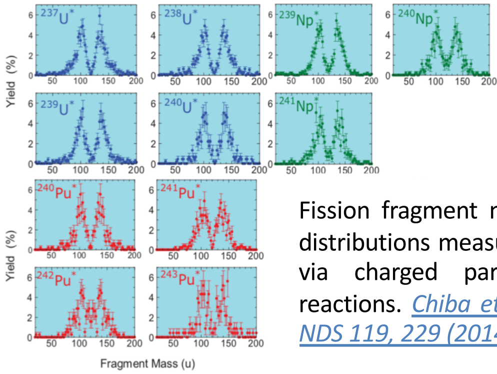
Needs:

- Extend our theoretical tools to be applicable to broader range of nuclei (exotic, deformed) and reactions ((α,γ), (n,p),…)
- Revisit past assumptions of simplified (Weisskopf-Ewing) treatment of surrogate applications to fission
- Study conditions for statistical n/γ emission
- Close collaboration with experiment: plan, interpret, validate
- Contemplate new applications: can we modify the method to deal with reactions proceeding through isolated or weakly-overlapping resonances?

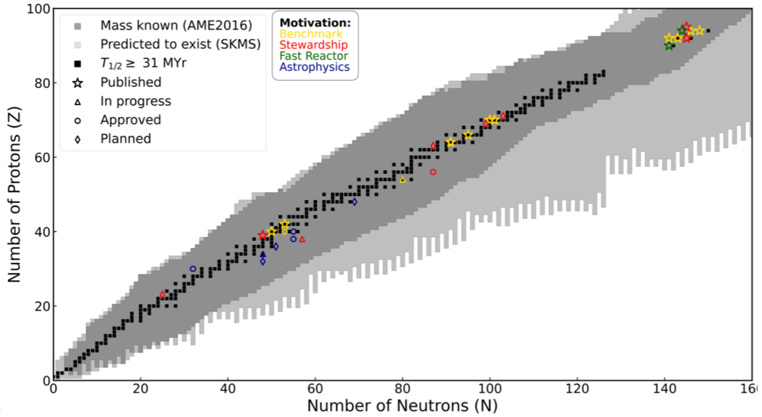
Jutta Escher, escher1@llnl.gov

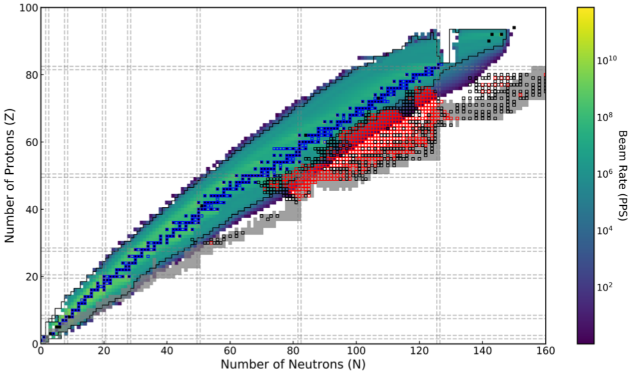
The Surrogate Reactions Method provides essential constraints on neutron-induced reactions we can’t measure directly.


Ratkiewicz et al., Phys. Rev. Lett. **122**, 052502 (2019)



Fission fragment mass distributions measured via charged particle reactions. *Chiba et al., NDS 119, 229 (2014).*





- SRM: a surrogate reaction is chosen that forms the “same” compound nucleus as the desired reaction. Measuring the decay of the CN as a function of excitation energy provides constraints on Hauser-Feshbach parameters which are used to calculate the desired reaction.
  - This means that the SRM can provide constraints on quantities calculated by or input into Hauser-Feshbach codes (cross sections, gSF, NLD, etc).
- Indirect techniques like the SRM provide essential constraints on neutron-induced important for nuclear astrophysics.

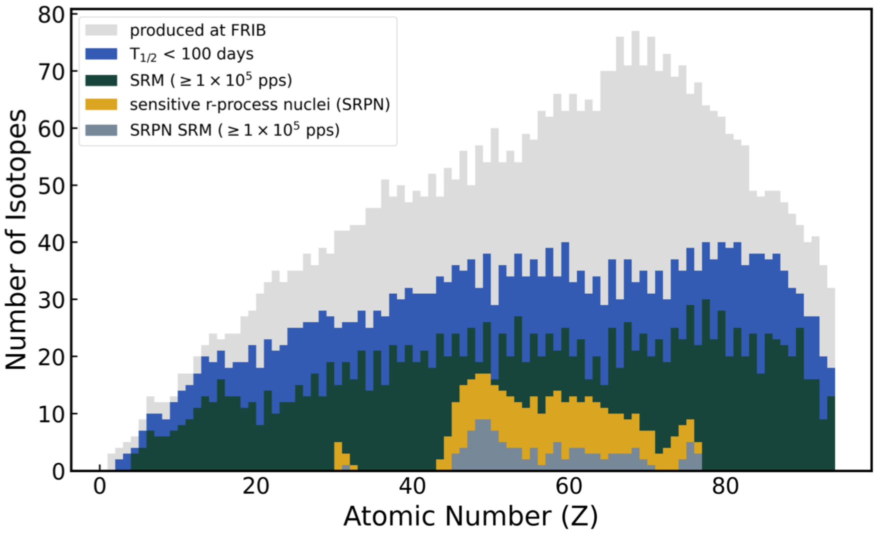
Exploiting the opportunities offered by FRIB requires timely construction of a high-acceptance spectrograph on ReA12.

- FRIB will make a large number of radioactive beams available for study, at rates sufficient for SRM measurements.

- The SRM gives the best results with ~10 MeV/A beams and small beam spot (~1 mm) sizes.
  - We can run in front of the S800 with degraded beams (~40 MeV/A), but this would impose rate limitations and require beam tracking.

- ReA12 will provide the beams we need for SRM measurements. However, we need high-acceptance spectrograph on ReA12 to enable event-by-event recoil detection.

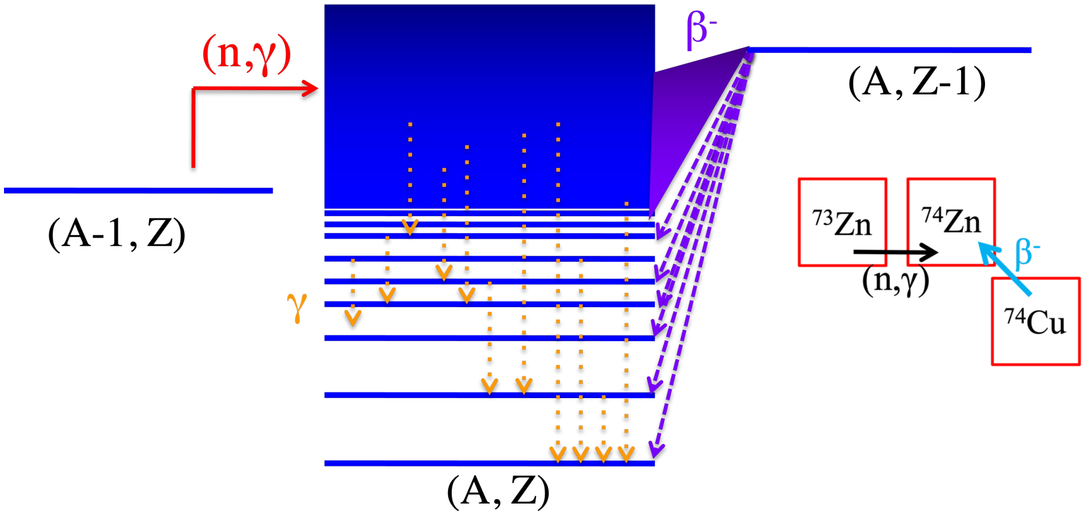
- ISLA is ideally suited for these measurements; we should build it.



Indirect (n,γ) constraints using the β-Oslo method

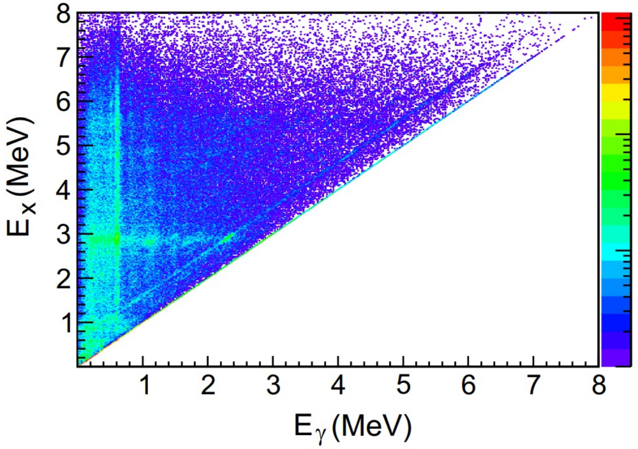
Overview of Method:

- Populate the compound nucleus via β-decay
  - Extract NLD, γSF, (n,γ) rates
- Study nuclei far from stability
- Feasible with low beam intensities



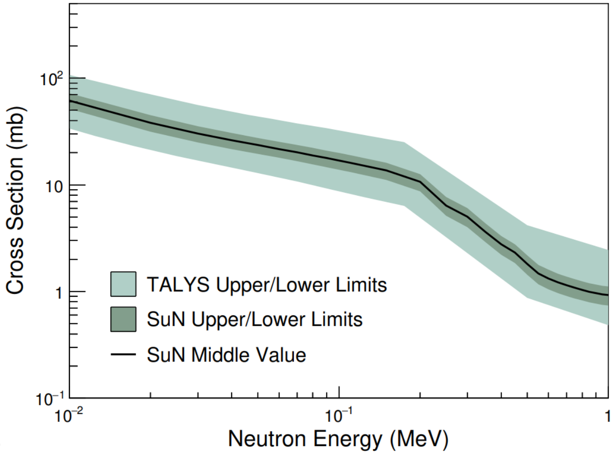
What do we need?

- ✓ Radioactive Beam
- ✓ Segmented γ-ray calorimeter (SuN, FDS, …)
- ✓ Normalization techniques*



Extract Nuclear Level Density and γ-ray Strength Function

Apply Normalizations

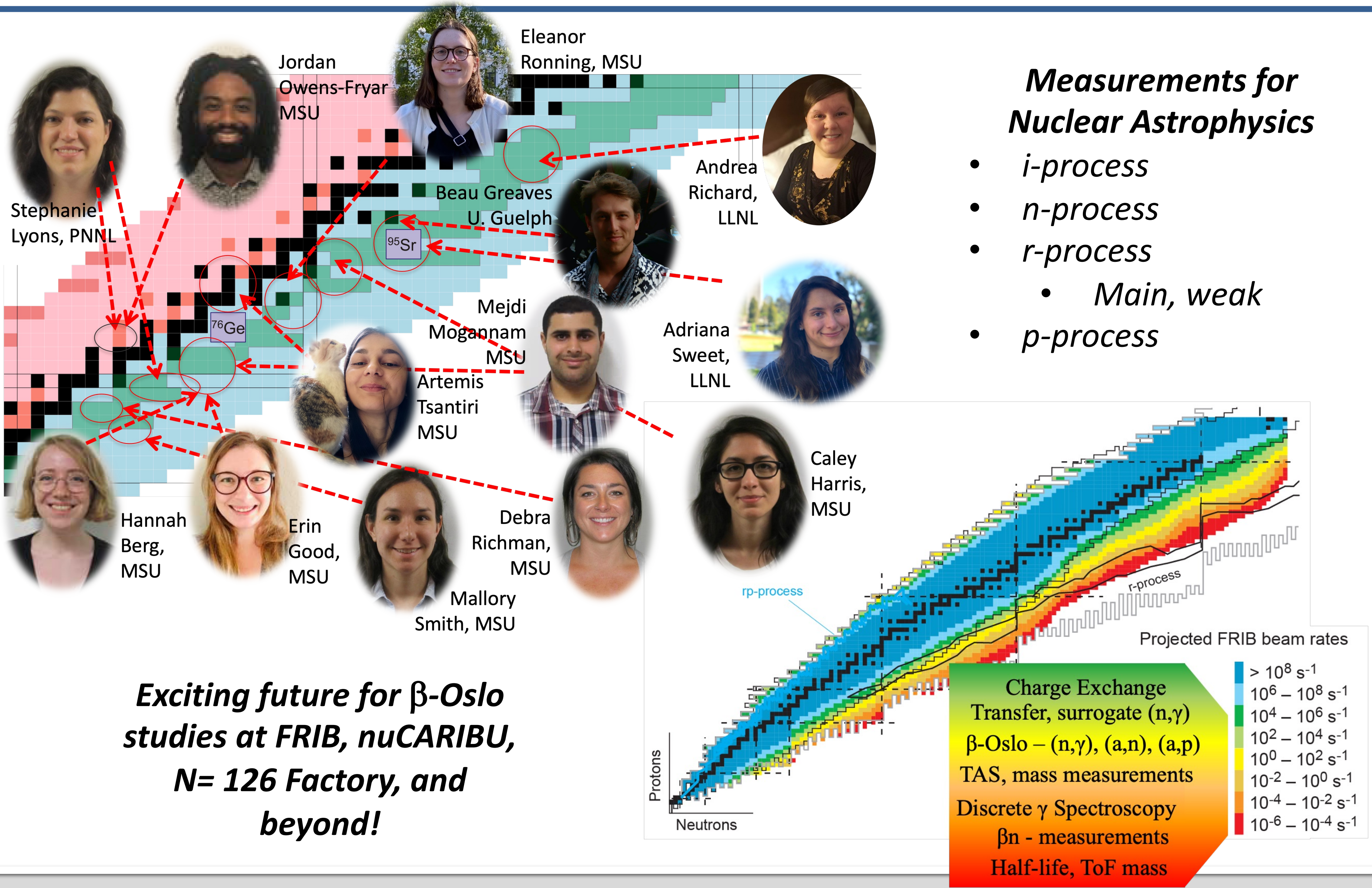


*M. Wiedeking *et al.*, PRC **104**, 014311 (2021)
R. Lewis *et al.*, PRC **99**, 034601 (2019)

β-Oslo Measurements: Current and Future

Measurements for Nuclear Astrophysics

- *i-process*
- *n-process*
- *r-process*
  - *Main, weak*
- *p-process*



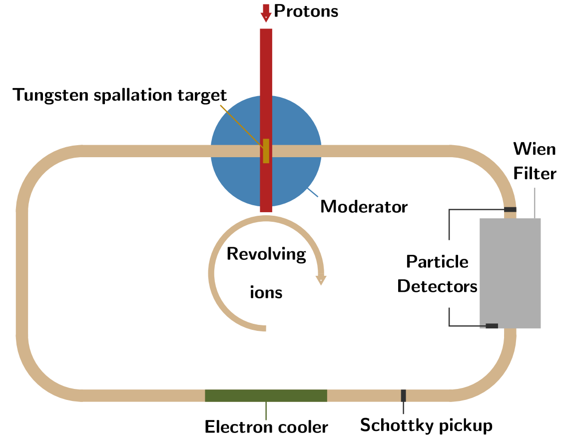
Charge Exchange
Transfer, surrogate (n,γ)
β-Oslo – (n,γ), (a,n), (a,p)
TAS, mass measurements
Discrete γ Spectroscopy
βn - measurements
Half-life, ToF mass

Exciting future for β-Oslo studies at FRIB, nuCARIBU, N= 126 Factory, and beyond!

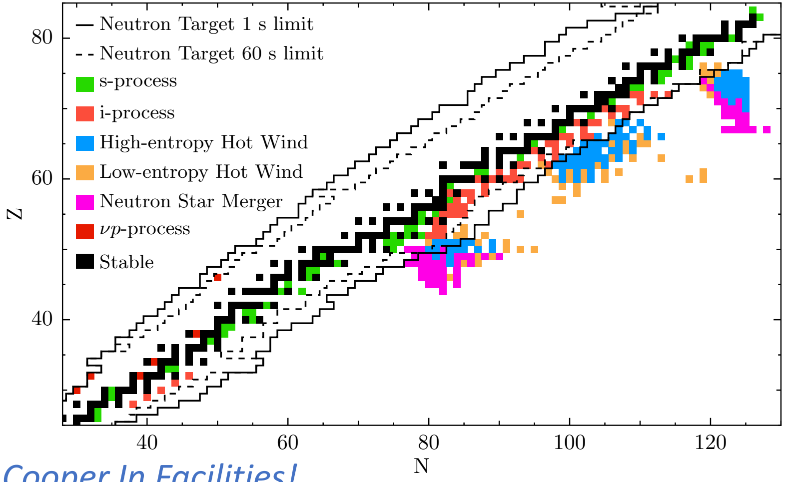
A neutron target facility would revolutionize our understanding of neutron reactions on short-lived nuclei

Shea Mosby, LANL

- Neutron-induced reaction rates are critical for nucleosynthesis as well as a range of other applications, yet remain stubbornly resistant to reliable prediction.
- We’ve developed a LANSCE-based concept to **directly measure** these reactions by interacting a radioactive ion beam with a standing neutron field or ”neutron target”.
- Such a facility would dramatically expand our reach for astrophysically-relevant cases.
- Direct reaction rates off stability provide stringent constraints testing theoretical models to enable predictive capability.
- We should begin the necessary technical maturation to make the concept a reality.
  - NNSA anticipated buy-in: $38M
  - NP ISOL development: $30M



Neutron target conceptual rendering (left) and predicted reach based on S. Mosby et al. LA-UR-21-30261 (below)

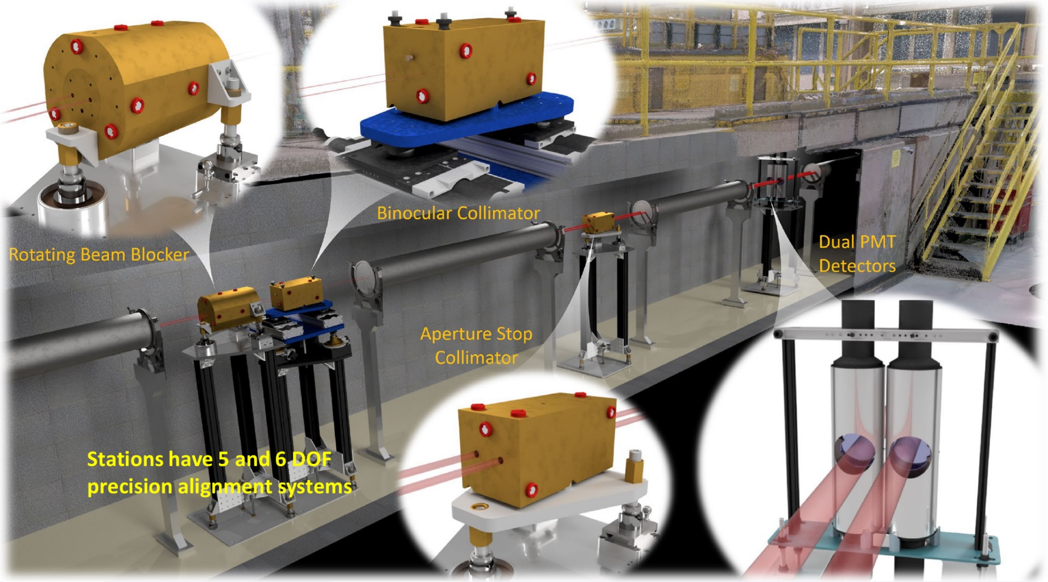


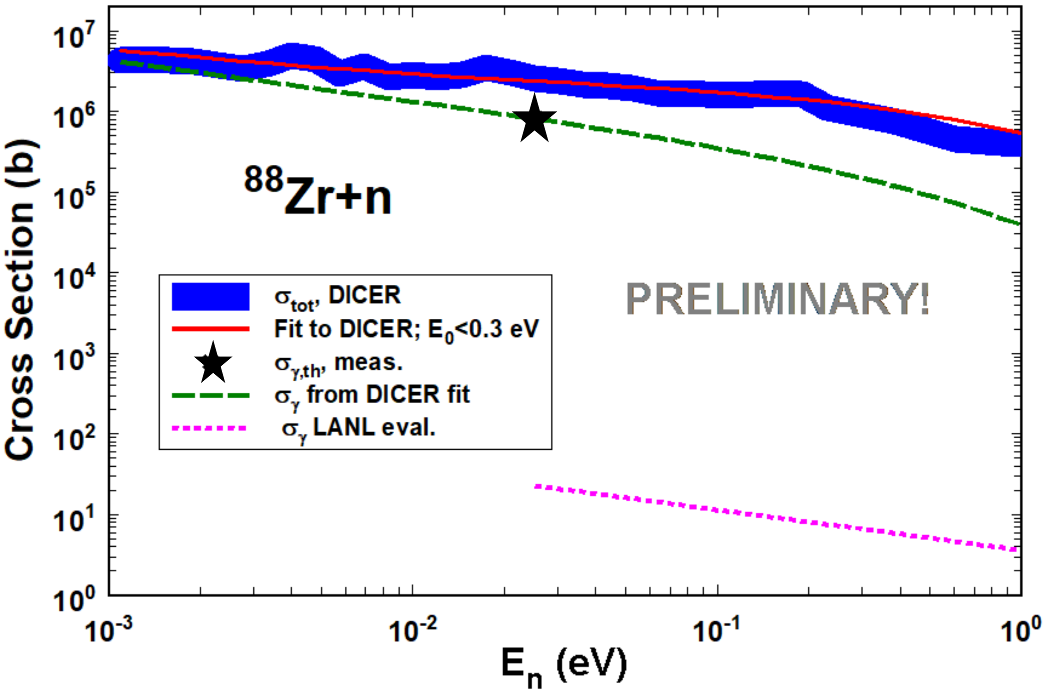
See Discussion of First Experiments by A. Cooper In Facilities!

DICER: a new device to constrain (n,γ) rates on tiny radioactive samples through innovative transmission experiments

Thanos Stamatopoulos, LANL
athanasios.stamatopoulos@lanl.gov

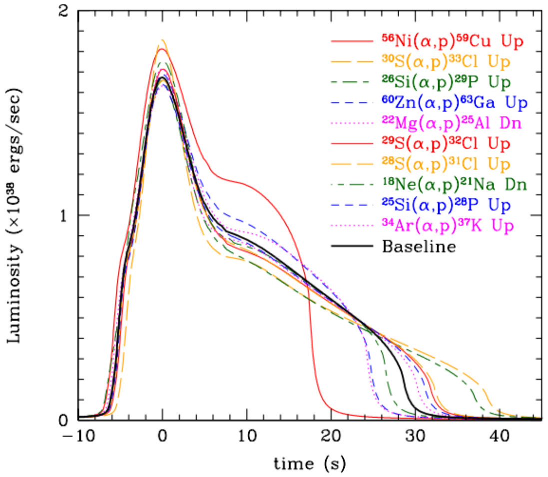
- (n,γ) rates on radionuclides are important for nucleosynthesis but very few have been measured.
- DICER performs transmission studies on tiny radioactive samples.
- Transmission data can be used to tightly constrain (n,γ) rates.
- DICER measurements on a 66 ng ^{88}Zr sample are revealing the reason for the extremely large thermal cross section.
- 50 radionuclides are within DICER's reach ($t_{1/2}$ ~ 10's days, D_0 ~ 10's eV).

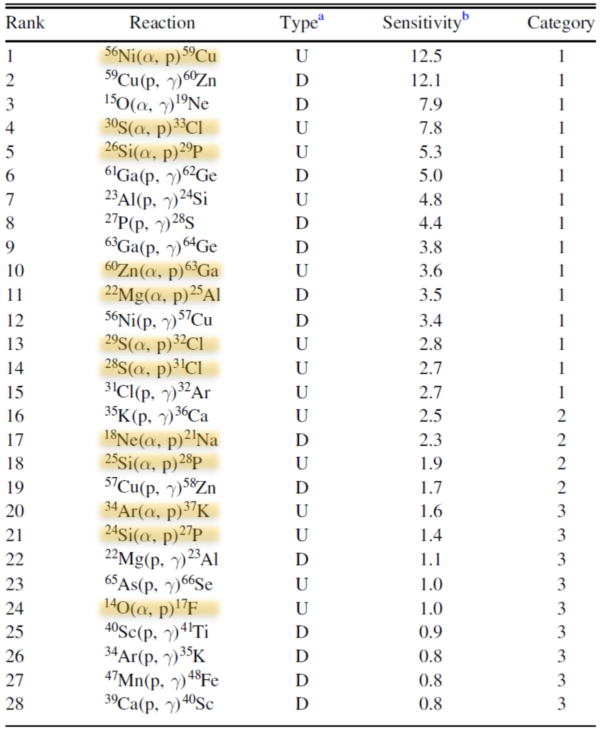




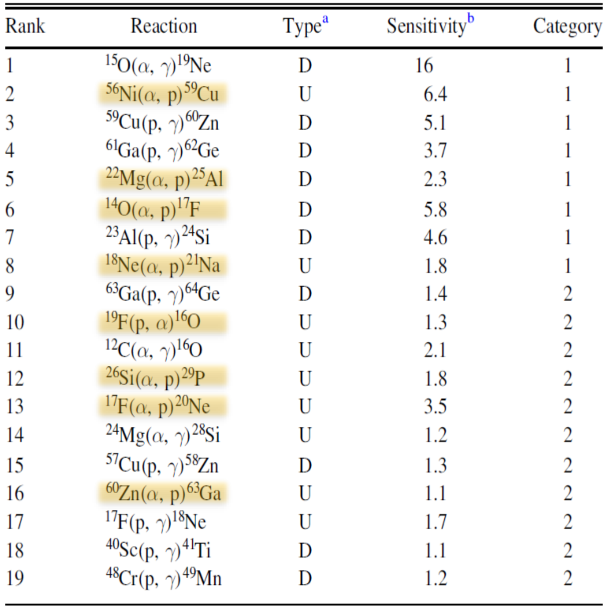
(α,p) cross section measurements with active target TPC devices

- **The sensitivity study by R.H. Cyburt *et al.* showed there are important astrophysical reaction rates affecting a large variation of energy generation and final ash in X-ray burst model.**
- **Limited experimental measurements of (p,ɣ), (α,ɣ) and (α,p) performed to reduce the uncertainties of reaction rates.**





Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{56}\mathrm{Ni}(\alpha, p)^{59}\mathrm{Cu}$	U	12.5	1
2	$^{59}\mathrm{Cu}(p, \gamma)^{60}\mathrm{Zn}$	D	12.1	1
3	$^{15}\mathrm{O}(\alpha, \gamma)^{19}\mathrm{Ne}$	D	7.9	1
4	$^{30}\mathrm{S}(\alpha, p)^{33}\mathrm{Cl}$	U	7.8	1
5	$^{26}\mathrm{Si}(\alpha, p)^{29}\mathrm{P}$	U	5.3	1
6	$^{61}\mathrm{Ga}(p, \gamma)^{62}\mathrm{Ge}$	D	5.0	1
7	$^{23}\mathrm{Al}(p, \gamma)^{24}\mathrm{Si}$	U	4.8	1
8	$^{27}\mathrm{P}(p, \gamma)^{28}\mathrm{S}$	D	4.4	1
9	$^{63}\mathrm{Ga}(p, \gamma)^{64}\mathrm{Ge}$	D	3.8	1
10	$^{60}\mathrm{Zn}(\alpha, p)^{63}\mathrm{Ga}$	U	3.6	1
11	$^{22}\mathrm{Mg}(\alpha, p)^{25}\mathrm{Al}$	D	3.5	1
12	$^{56}\mathrm{Ni}(p, \gamma)^{57}\mathrm{Cu}$	D	3.4	1
13	$^{29}\mathrm{S}(\alpha, p)^{32}\mathrm{Cl}$	U	2.8	1
14	$^{28}\mathrm{S}(\alpha, p)^{31}\mathrm{Cl}$	U	2.7	1
15	$^{31}\mathrm{Cl}(p, \gamma)^{32}\mathrm{Ar}$	U	2.7	1
16	$^{35}\mathrm{K}(p, \gamma)^{36}\mathrm{Ca}$	U	2.5	2
17	$^{18}\mathrm{Ne}(\alpha, p)^{21}\mathrm{Na}$	D	2.3	2
18	$^{25}\mathrm{Si}(\alpha, p)^{28}\mathrm{P}$	U	1.9	2
19	$^{57}\mathrm{Cu}(p, \gamma)^{58}\mathrm{Zn}$	D	1.7	2
20	$^{34}\mathrm{Ar}(\alpha, p)^{37}\mathrm{K}$	U	1.6	3
21	$^{24}\mathrm{Si}(\alpha, p)^{27}\mathrm{P}$	U	1.4	3
22	$^{22}\mathrm{Mg}(p, \gamma)^{23}\mathrm{Al}$	D	1.1	3
23	$^{65}\mathrm{As}(p, \gamma)^{66}\mathrm{Se}$	U	1.0	3
24	$^{14}\mathrm{O}(\alpha, p)^{17}\mathrm{F}$	U	1.0	3
25	$^{40}\mathrm{Sc}(p, \gamma)^{41}\mathrm{Ti}$	D	0.9	3
26	$^{34}\mathrm{Ar}(p, \gamma)^{35}\mathrm{K}$	D	0.8	3
27	$^{47}\mathrm{Mn}(p, \gamma)^{48}\mathrm{Fe}$	D	0.8	3
28	$^{39}\mathrm{Ca}(p, \gamma)^{40}\mathrm{Sc}$	D	0.8	3



Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}\mathrm{O}(\alpha, \gamma)^{19}\mathrm{Ne}$	D	16	1
2	$^{56}\mathrm{Ni}(\alpha, p)^{59}\mathrm{Cu}$	U	6.4	1
3	$^{59}\mathrm{Cu}(p, \gamma)^{60}\mathrm{Zn}$	D	5.1	1
4	$^{61}\mathrm{Ga}(p, \gamma)^{62}\mathrm{Ge}$	D	3.7	1
5	$^{22}\mathrm{Mg}(\alpha, p)^{25}\mathrm{Al}$	D	2.3	1
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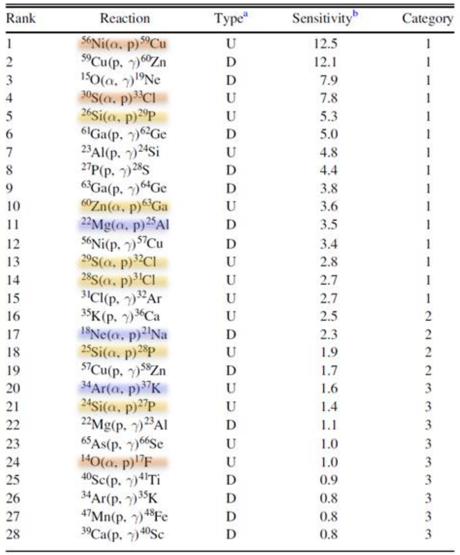
9	$^{63}\mathrm{Ga}(p, \gamma)^{64}\mathrm{Ge}$	D	1.4	2
10	$^{19}\mathrm{F}(p, \alpha)^{16}\mathrm{O}$	U	1.3	2
11	$^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$	U	2.1	2
12	$^{26}\mathrm{Si}(\alpha, p)^{29}\mathrm{P}$	U	1.8	2
13	$^{17}\mathrm{F}(\alpha, p)^{20}\mathrm{Ne}$	U	3.5	2
14	$^{24}\mathrm{Mg}(\alpha, \gamma)^{28}\mathrm{Si}$	U	1.2	2
15	$^{57}\mathrm{Cu}(p, \gamma)^{58}\mathrm{Zn}$	D	1.3	2
16	$^{60}\mathrm{Zn}(\alpha, p)^{63}\mathrm{Ga}$	U	1.1	2
17	$^{17}\mathrm{F}(p, \gamma)^{18}\mathrm{Ne}$	U	1.7	2
18	$^{40}\mathrm{Sc}(p, \gamma)^{41}\mathrm{Ti}$	D	1.1	2
19	$^{48}\mathrm{Cr}(p, \gamma)^{49}\mathrm{Mn}$	D	1.2	2

(Left) Calculated light curves of X-ray burst
(Middle) Reactions that impact the burst light curve in the single-zone X-ray burst model
(Right) Reactions that impact the burst light curve in the multi-zone X-ray burst model
R. H. Cyburt *et al.* ApJ 830:55 (2016)

(α,p) cross section measurements with active target TPC devices

- What we need to do is:
  1. Updates of the sensitivity studies with measured reaction rates
  2. Experimental efforts to reduce the uncertainties of key reaction rates.



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5	^{26}Si(α, p)^{29}P	U	5.3	1
6	^{61}Ga(p, γ)^{62}Ge	D	5.0	1
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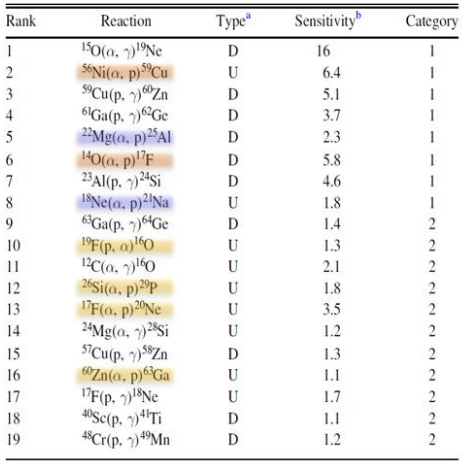
10	^{60}Zn(α, p)^{63}Ga	U	3.6	1
11	^{22}Mg(α, p)^{25}Al	D	3.5	1
12	^{56}Ni(p, γ)^{57}Cu	D	3.4	1
13	^{29}S(α, p)^{32}Cl	U	2.8	1
14	^{28}S(α, p)^{31}Cl	U	2.7	1
15	^{31}Cl(p, γ)^{32}Ar	U	2.7	1
16	^{35}K(p, γ)^{36}Ca	U	2.5	2
17	^{18}Ne(α, p)^{21}Na	D	2.3	2
18	^{25}Si(α, p)^{28}P	U	1.9	2
19	^{57}Cu(p, γ)^{58}Zn	D	1.7	2
20	^{34}Ar(α, p)^{37}K	U	1.6	3
21	^{24}Si(α, p)^{27}P	U	1.4	3
22	^{22}Mg(p, γ)^{23}Al	D	1.1	3
23	^{65}As(p, γ)^{66}Se	U	1.0	3
24	^{14}O(α, p)^{17}F	U	1.0	3
25	^{40}Sc(p, γ)^{41}Ti	D	0.9	3
26	^{34}Ar(p, γ)^{35}K	D	0.8	3
27	^{47}Mn(p, γ)^{48}Fe	D	0.8	3
28	^{39}Ca(p, γ)^{40}Sc	D	0.8	3



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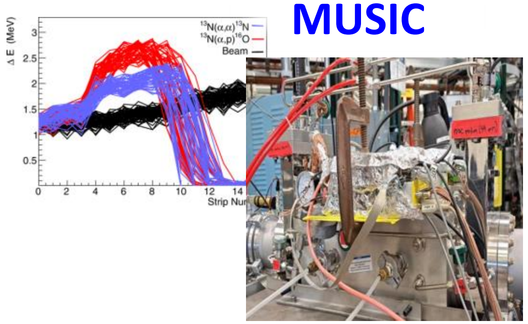
9	^{63}Ga(p, γ)^{64}Ge	D	1.4	2
10	^{19}F(p, α)^{16}O	U	1.3	2
11	^{12}C(α, γ)^{16}O	U	2.1	2
12	^{26}Si(α, p)^{29}P	U	1.8	2
13	^{17}F(α, p)^{20}Ne	U	3.5	2
14	^{24}Mg(α, γ)^{28}Si	U	1.2	2
15	^{57}Cu(p, γ)^{58}Zn	D	1.3	2
16	^{60}Zn(α, p)^{63}Ga	U	1.1	2
17	^{17}F(p, γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p, γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p, γ)^{49}Mn	D	1.2	2

R. H. Cyburt *et al.* ApJ 830:55 (2016)

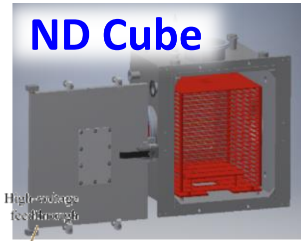
RI Beams

FRIB/USA **ATLAS/USA** **TRIUMF/CANADA**

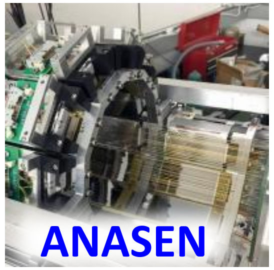
TAMU/USA **FSU/USA** **ND/USA**



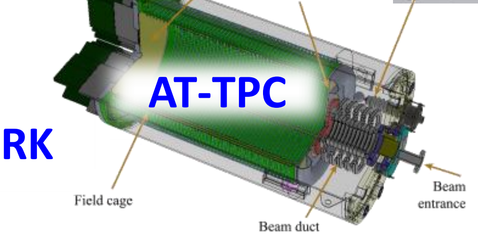
MUSIC



ND Cube

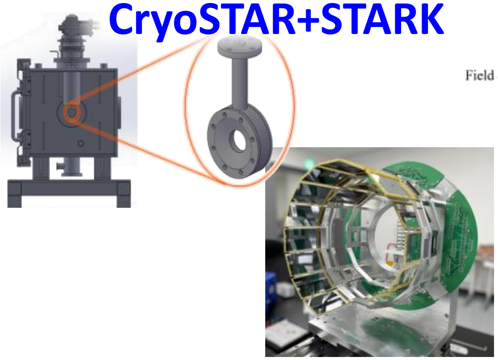


ANASEN

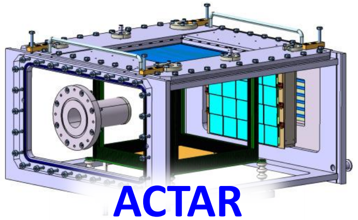


AT-TPC

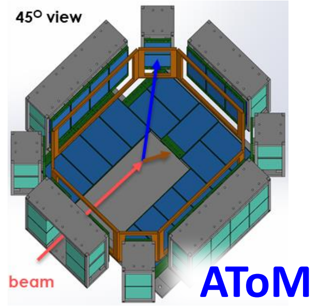
JENSA+sORRUBA +SECAR



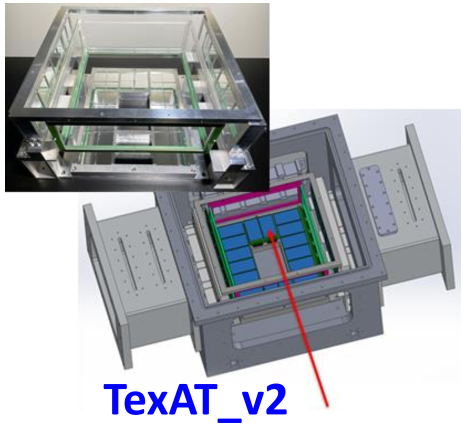
CryoSTAR+STARK



ACTAR



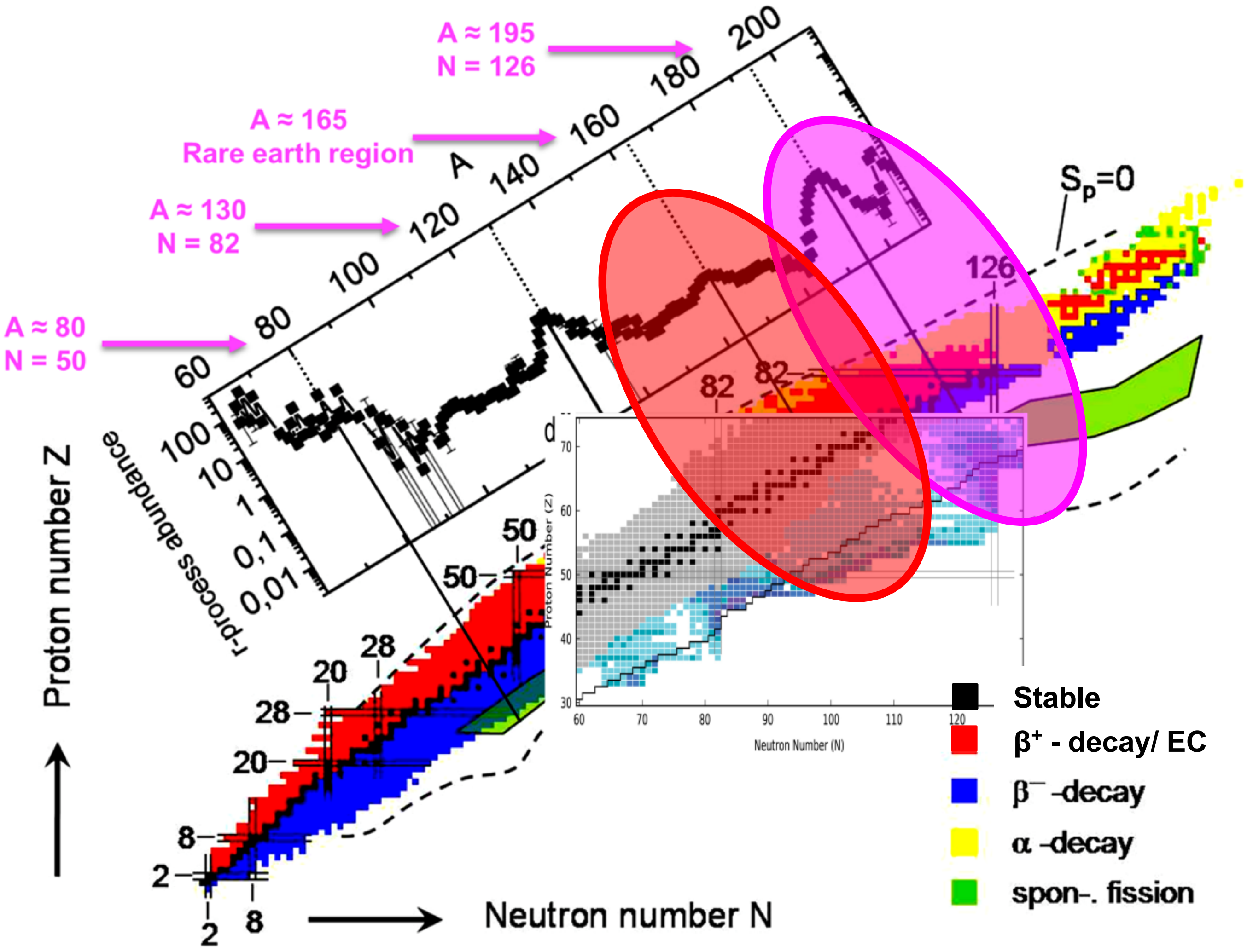
AToM-X



TexAT_v2

R-PROCESS STUDIES WITH THE CPT AT ANL

- Need access to masses, etc. for neutron rich isotopes of interest to understand the r-process abundance pattern
- Multi-nucleon transfer reactions in the N=126 Factory will provide access to new masses for the rare earth peak and the heaviest, N=126, r-process peak that are difficult to reach with fragmentation.

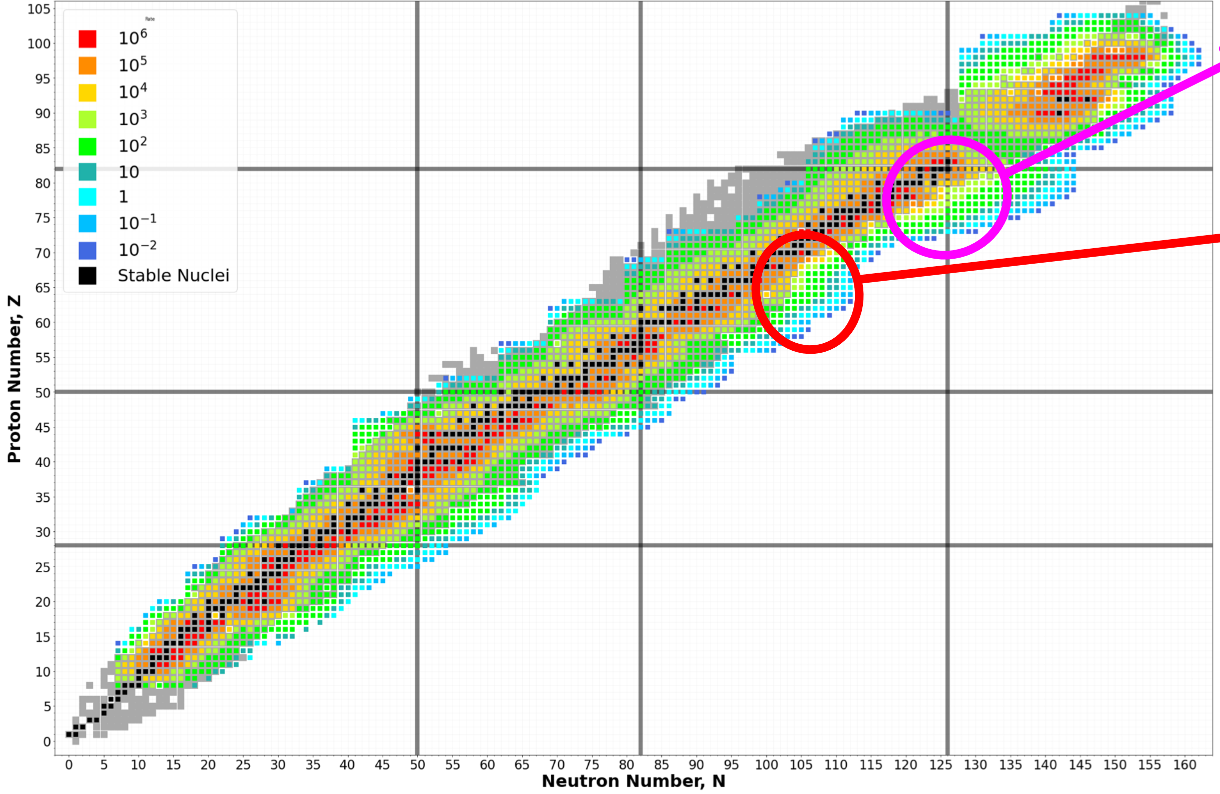


R. Kruecken, arXiv:1006.2520 (2010),

M.R. Mumpower et al., PPNP, 86 (2016)

R-PROCESS STUDIES WITH THE CPT AT ANL

Many neutron- rich nuclei can be produced at the N=126 Factory through the use of different targets

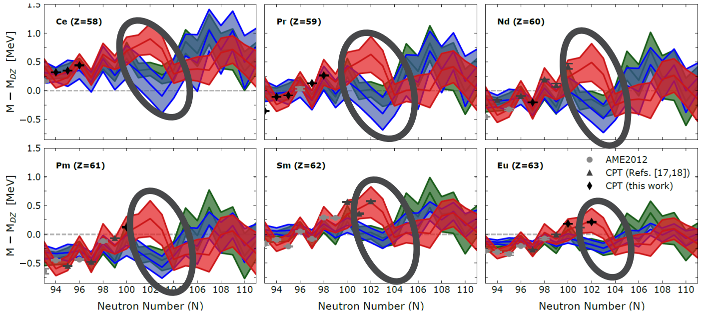


N=126 Region

Many previously-unmeasured masses near N=126 shell closure

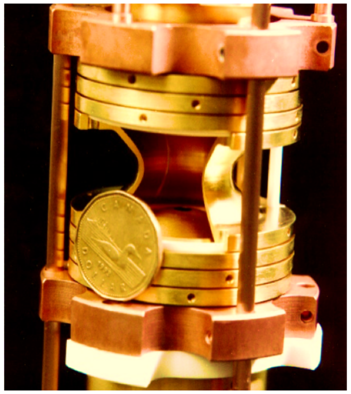
Rare Earth Region

Exploring feature around N~104



Orford, Vassh, *et al.*, PRC **105**, L052802 (2022)

Phase Imaging Ion Cyclotron Resonances at the Canadian Penning Trap provide precise and accurate mass measurements.



Probing the Equation of State of Neutron Stars with Heavy Ion Collisions at FRIB

EOS at FRIB:

More precision symmetry energy data at 1.5-2.5 ρ_0

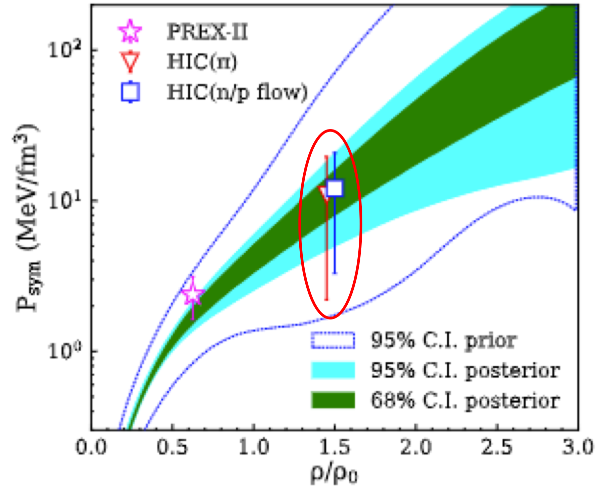
Primary observables:

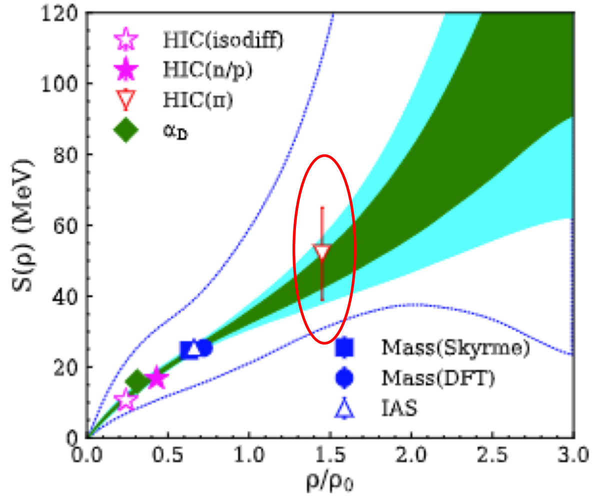
- pion and n/p differential flow→ Symmetry energy
- proton flow→ symmetric matter constraints

What we need:

Investment in detector development to measure pions, charged particles and neutron with high granularity

Zbigniew Chajecki, WMU





Opportunities and challenges

Goals:

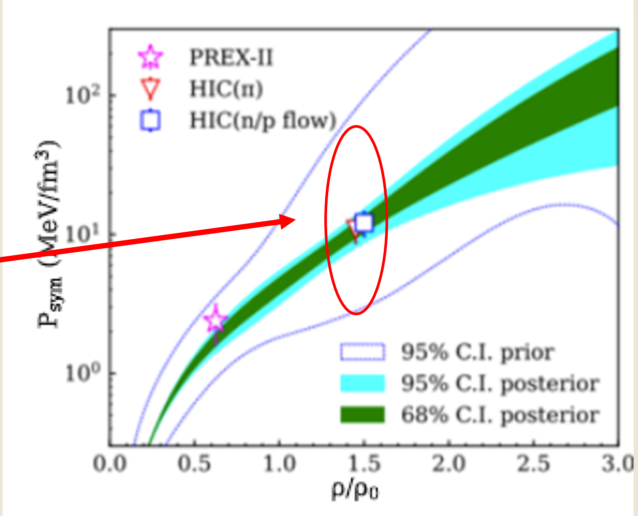
Comprehensive nuclear matter EOS from crust to outer core is in sight

Effect of reducing the error bars to 20%

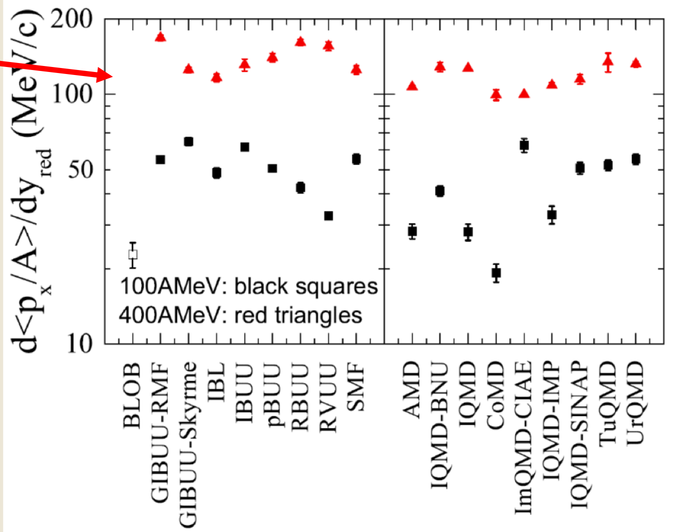
Needs:

- Need more data from NS observations in NICER and GW observatories
- Flow Experiments at highest energy/density achievable where Transport models agree better.
- Continued improved in transport theory
- More data from HIC and structure
- **Detector development**

To reach high density: We need FRIB400!



Transport model evaluation project (TMEP)



Need for Centers in Nuclear Astrophysics

Nuclear Astrophysics has a special need for exchange and communication across field boundaries

- Everything we do on the nuclear side depends on the astrophysics connection
- New results in astrophysics can change major activities and science priorities in nuclear physics
- New results in nuclear physics are essential for addressing some astrophysical science questions
- Nuclear astrophysics defines its own science questions at the intersection of the fields
- **There is now a special opportunity to take advantage of the unique combination of novel capabilities in the multi-messenger era in nuclear physics, gravitational wave physics, computational modeling, astronomy (JWST, COSI, NICER, astero-seismolog…), cosmo-chemistry**

Centers like JINA and JINA-CEE play an important role in facilitating these exchanges, building research bridges, and forming the necessary communities and collaborations to generate new ideas and directions

Center for Nuclear Astrophysics Across Messengers

CeNAM addresses this need in the multi-messenger era

- Community building
  - Connect nuclear astrophysics **experiments** with theory, observations, and other fields
  - Connect university labs, national labs, small and large universities, MSI
  - Connects to new areas needed for new science
- Open interdisciplinary collaborations on (1) Novel dynamic nucleosynthesis in stars (2) Origin of the heavy elements in the multi-messenger era

- Build community through targeted workshops and annual Frontiers meeting all open to the community
- Dissemination of data, tools, codes, results to the community across field boundaries
- Foster an interdisciplinary community of students and postdocs and provide professional development opportunities
- Connect US community to international nuclear astrophysics communities and partner networks through International Research Network for Nuclear Astrophysics (IReNA) (NSF supported)
- Contribute to a diverse nuclear astrophysics community (10 MSI partners)

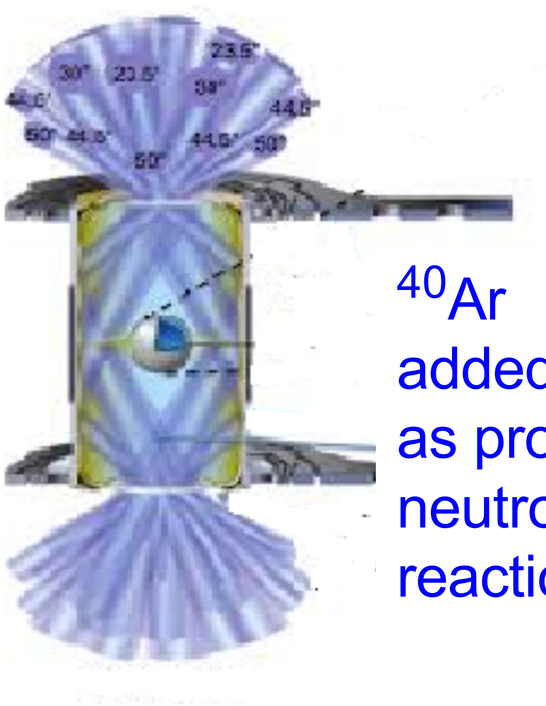
CeNAM status:

- This year DOE NP support for 3 community building CeNAM workshops/conferences
  - A CeNAM Frontiers meeting May 21-26 at MSU, including a workshop on new observational opportunities for nuclear astrophysics
  - A stellar nuclear astrophysics workshop (TBA)
- New (smaller) proposal for a CeNAM center submitted to DOE

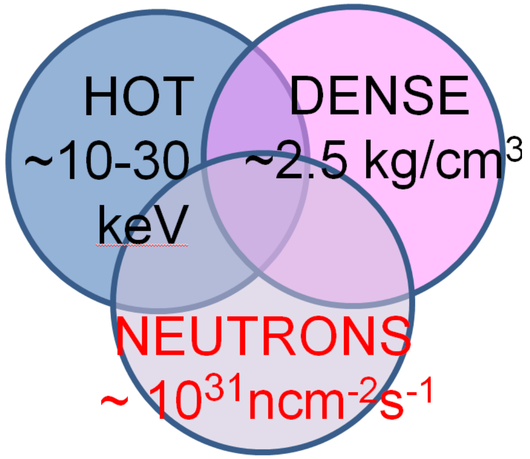
Neutron-induced reactions in the high-density plasma at the National Ignition Facility

M. Paul, A. Zylstra et al.

Laser energy/power:
1.8 MJ/400 TW



^{40}Ar
added to DT
as probe for
neutron-induced
reactions



HOT
~10-30
keV

DENSE
~2.5 kg/cm^3

NEUTRONS
~ 10^{31}ncm^{-2}s^{-1}

~ 10^{22} ncm^{-3}

**Closest laboratory analog
to explosive stellar conditions**

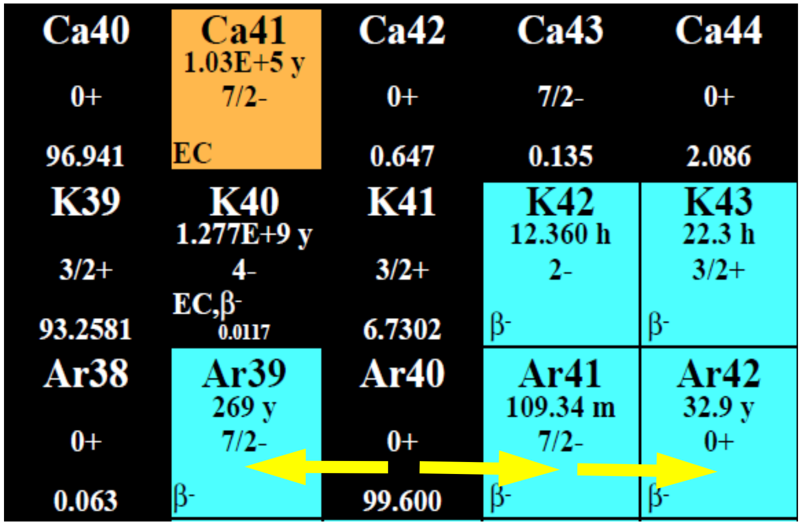
Zylstra et al., Nature (2022)
Abu-Shawareb et al., PRL (2022)

Soreq Nuclear Research Center
Lawrence Livermore National Laboratory
Argonne NATIONAL LABORATORY
UNIVERSITY OF NOTRE DAME
INSTITUT LAUE-LANGEVIN
TECHNISCHE UNIVERSITÄT DRESDEN
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

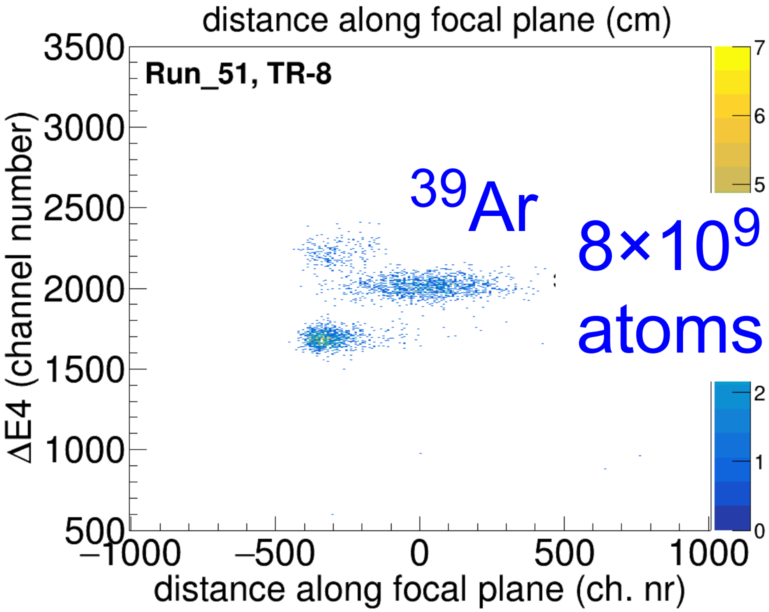
DT+Ar shot at NIF

^{39,41}Ar collected and detected

- **^{40}Ar(n,2n)^{39}Ar ($t_{1/2}$ = 268 y):** fast-neutron monitor
- **^{40}Ar(n,γ)^{41}Ar ($t_{1/2}$ = 110 min):** sensitive to **neutron downscattered fluence**
- **Search for ^{40}Ar(2n,γ)^{42}Ar ($t_{1/2}$ = 33 y):** *rapid two neutron-capture ("mini r-process")* **sensitive to neutron density**



Ca40 0+ 96.941	**Ca41** 1.03E+5 y 7/2- EC	**Ca42** 0+ 0.647	**Ca43** 7/2- 0.135	**Ca44** 0+ 2.086
K39 3/2+ 93.2581	**K40** 1.277E+9 y 4- EC,β- 0.0117	**K41** 3/2+ 6.7302	**K42** 12.360 h 2- β-	**K43** 22.3 h 3/2+ β-
Ar38 0+ 0.063	**Ar39** 269 y 7/2- β-	**Ar40** 0+ 99.600	**Ar41** 109.34 m 7/2- β-	**Ar42** 32.9 y 0+ β-



8×10^9 atoms

^{40}Ar(n,2n)^{39}Ar