Experimental Nuclear Astrophysics FRIB Day 1 workshop

2017 Low Energy Community Meeting

Melina Avila, ANL, 2 August 2017

Nuclear Astrophysics Experiments

- Exciting and broad program for FRIB day 1 in Astrophysics
- However, difficult planning for Day1 due to complex reaccelerated beam production

- **Topics:**
  - Novae
  - Supernovae
  - XRBs
  - Pop III stars
  - rp-, r-, αp-, np-processes
  - hot CNO
  - pp processes

- **Types of measurements:**
  - Direct capture
  - Transfer reactions
  - Direct (α,p) measurements
  - Decay
  - Masses
  - TAS
  - Fusion
  - Lifetimes

Nuclear Astrophysics Experiments

Equipment:

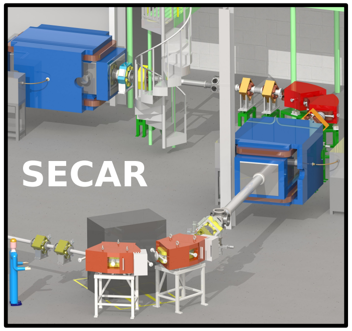
- SECAR, JENSA, AT TPC, ANASEN, MUSIC, SUN, DECAY STATION, HRS , ISLA, HELIOS, GRETINA/GRETA, HR AT TPC S800

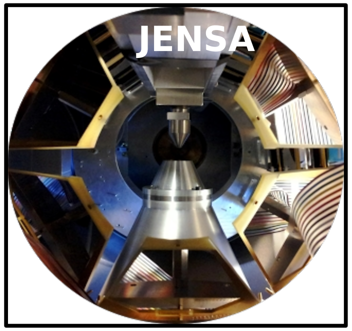
Beams:

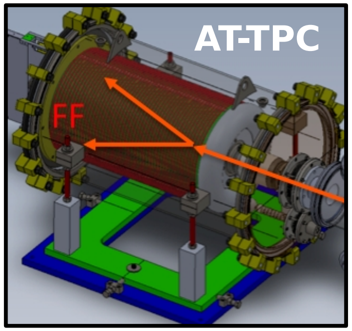
- ReA3 beams – ^{30}P, ^{18}F, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{56}Ni, ^{59}Cu, ^{45}V, ^{38}K, ^{8}B, ^{9}C, ^{13}O, ^{14}O , ^{18}Ne
- ReA6 – ReA12 beams – ^{18}F, ^{30}P, ^{38}K, ^{45}V, ^{59}Cu
- Fast beams – ^{15}O
- Stopped beams – near N=82 and N=126, Uranium

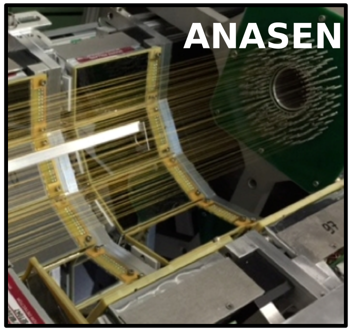
Intensities:

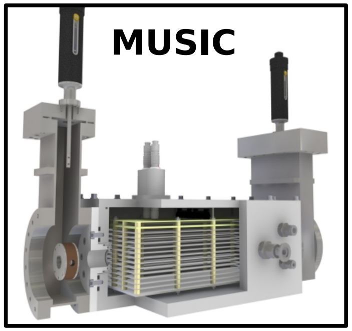
- Wide range of beam intensities needed depending on the experimental device

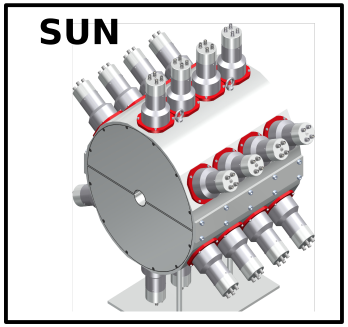


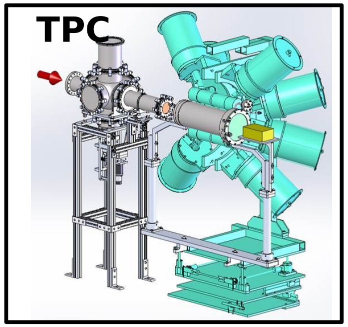


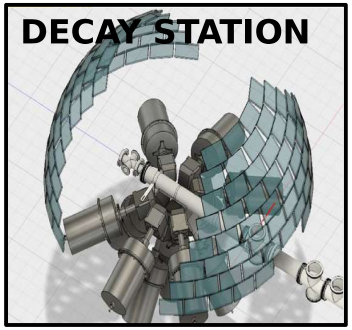






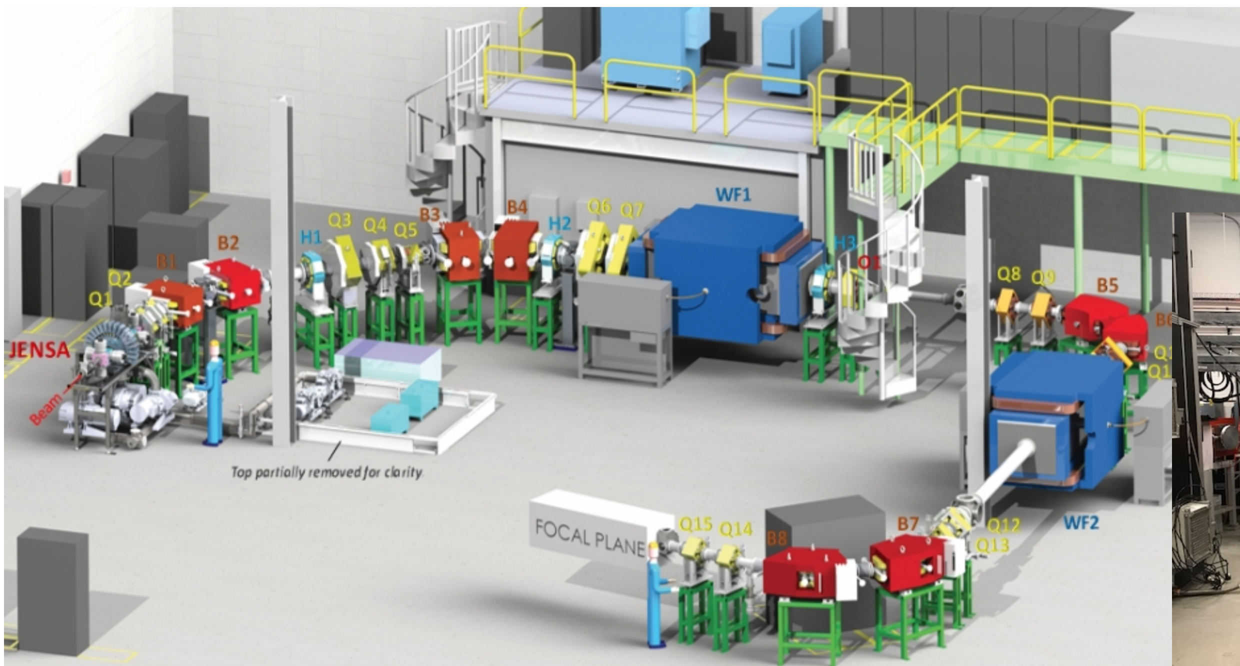






SECAR Enables Direct Reaction Rate Measurements at FRIB

- Under construction at MSU with support from DOE-SC and NSF
- Measures p- and a-capture reactions with RIBs in inverse kinematics for X-ray bursts, novae, np-process, p-process, explosive burning, Thorne-Zytkov objects, supermassive stars
- Works in conjunction with JENSA gas jet target and ReA3 re-accelerator



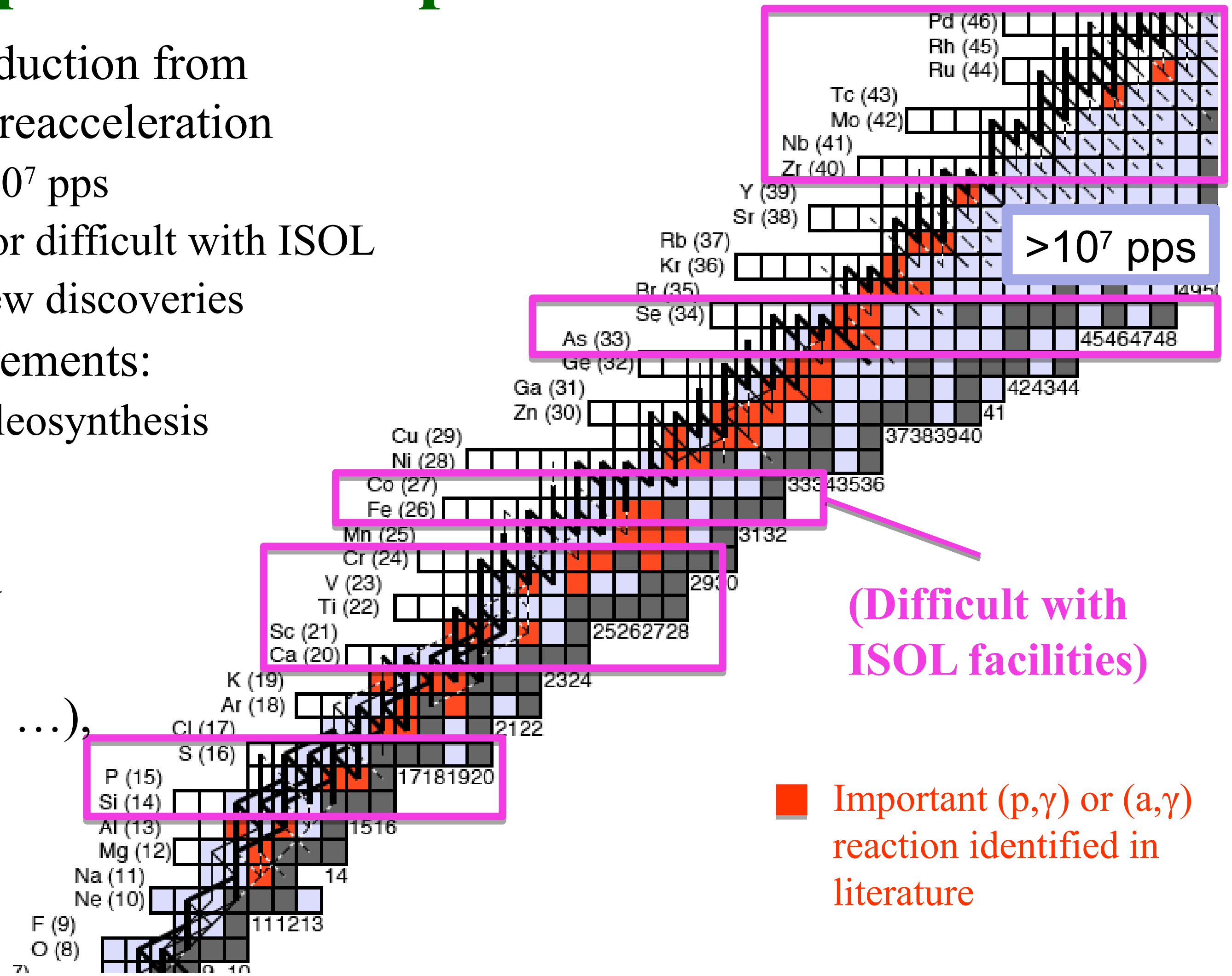
SECAR

Separator for Capture Reactions

Courtesy of H. Schatz, MSU

SECAR Takes Advantage of Unique FRIB Capabilities

- Unique radioactive beam production from fragmentation, stopping, and reacceleration
  - » Broad range of beams with >10^7 pps
  - » Includes beams not available or difficult with ISOL
  - » Offers flexibility to react to new discoveries
- Possible first reaction measurements:
  - » ^{30}P(p,γ), ^{38}K(p,γ) for nova nucleosynthesis
  - » ^{59}Cu(p,γ) for x-ray bursts
  - » ^{45}V(p,γ) for supernovae
- Science priorities can quickly change with new discoveries, new X-ray missions (NICER, …), new model work



(Difficult with ISOL facilities)

Important (p,γ) or (a,γ) reaction identified in literature

SECAR

Separator for Capture Reactions

Courtesy of H. Schatz, MSU

SECAR is an Open Collaboration

Argonne NATIONAL LABORATORY

CMU CENTRAL MICHIGAN UNIVERSITY

OHIO UNIVERSITY

LSU LOUISIANA STATE UNIVERSITY

MICHIGAN STATE UNIVERSITY

JINA-CEE

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

OAK RIDGE National Laboratory

UNIVERSITY OF NOTRE DAME

Pacific Northwest NATIONAL LABORATORY

INDIANA UNIVERSITY

COLORADO SCHOOL OF MINES 1874

McMaster University

http://fribastro.org/SECAR/SECAR.html

Interested in joining? Contact Hendrik Schatz

SECAR Separator for Capture Reactions

Courtesy of H. Schatz, MSU

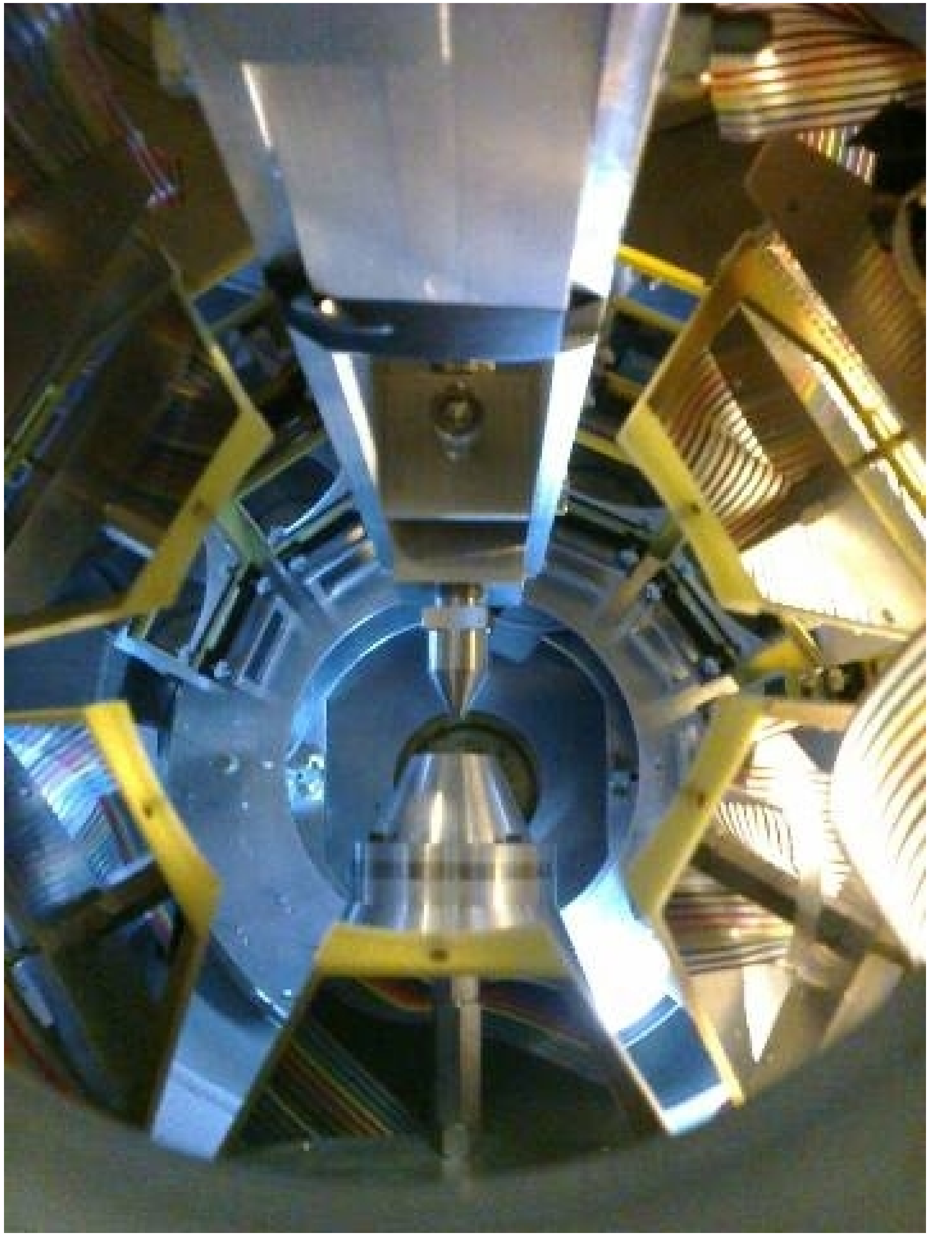
The Jet Experiments in Nuclear Structure and Astrophysics (JENSA)

- JENSA will form the main target for the proposed SEparator for CApture Reactions (SECAR)

- JENSA can be used for transfer reactions such as (d,p), (d,n) and (^{3}He,d)

- Direct measurements such as (α,p)

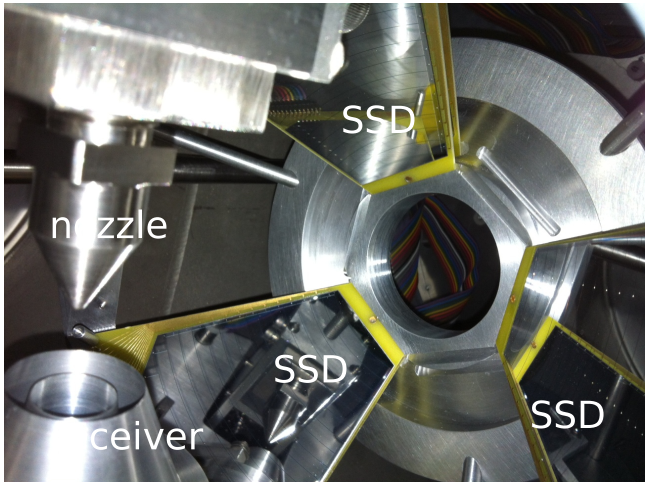
Example: ^{30}P(d,p), ^{56}Ni(a,p)

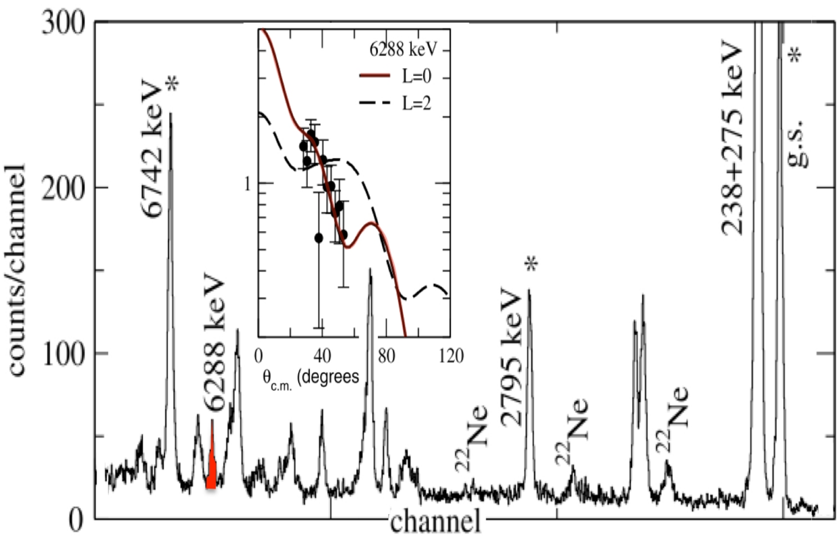


Source: jensajet.org

First Science Result from JENSA gas jet target

- ^{18}F decay in space can help diagnose the mechanism of nova explosions which create this radionuclide
- A possible ^{19}Ne resonance below the threshold of the ^{18}F(p,α)^{15}O reaction has contributed a large uncertainty in the net ^{18}F synthesis in novae
- The new Jet Experiments in Nuclear Structure and Astrophysics (JENSA) enabled an unambiguous confirmation of the subthreshold resonance and determined its spin via a ^{20}Ne(p,d)^{19}Ne measurement
- The high density (equivalent to some solid targets), few mm target width, and no impurities enabled this measurement to succeed where solid targets failed
- Result reduces the ^{18}F(p,α)^{15}O reaction rate uncertainty by factor of approximately 3 at nova temperatures, giving a corresponding factor of 2 reduction in uncertainty of nova ^{18}F production and a factor of 2.8 decrease in the uncertainty of nova ^{18}F detection probability by satellite observatories



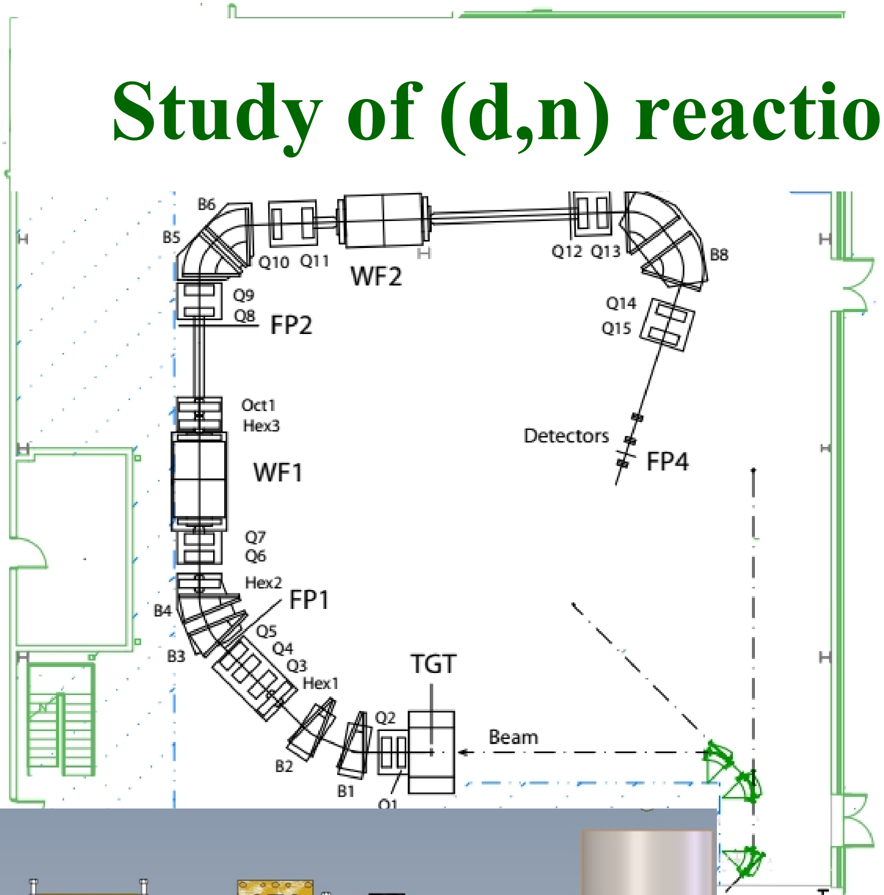


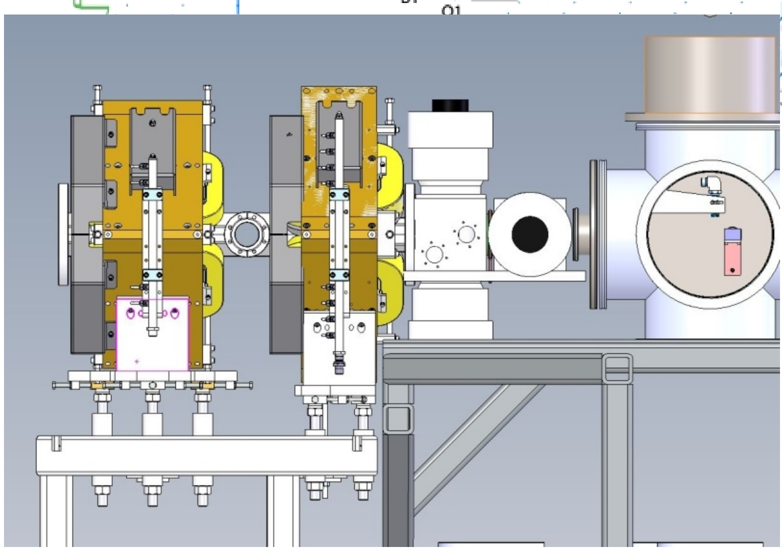
Top: photographs of the JENSA gas jet target system showing where the gas flows from the nozzle to the receiver, and the surrounding Silicon strip detectors (SSD) for detecting charged particles. Bottom: spectra of deuterons from the ^{20}Ne(p,d)^{19}Ne reaction showing the subthreshold level at 6288 keV (in red) and its angular distribution (inset) consistent with a zero angular momentum transfer. Reference: D.W. Bardayan et al., Phys. Lett. B751 (2015) 311.

Contact:
Kelly Chipps (ORNL), chippska@ornl.gov

Funding sources:
DOE Office of Science
Resources: ORNL

Study of (d,n) reactions with JENSA + SECAR



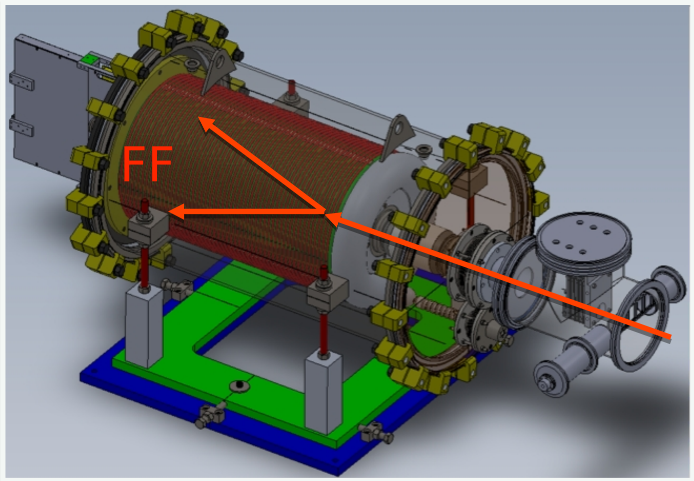


- Day 1 beams may not be intense enough for (p,γ) but (d,n) would be useful and necessary to plan (p,γ) experiments.
- JENSA could provide pure d target. Forward recoils could be separated by SECAR.
- Neutron detectors (VANDLE+U. Mich. Liquid Scintillators+NEXT) at backward lab angles.
- Proton decaying states detected by JENSA Si detectors. Gamma decaying states tagged by recoil in SECAR.
- SECAR energy, magnetic rigidity, electric rigidity acceptance are sufficient. Angular acceptance is marginal.
- Need to perform optics calculations, geant neutron scattering calculations, etc… to optimize.
- Possibility to use CD_2 instead of JENSA to increase SECAR acceptance and reduce n scattering from pumps.

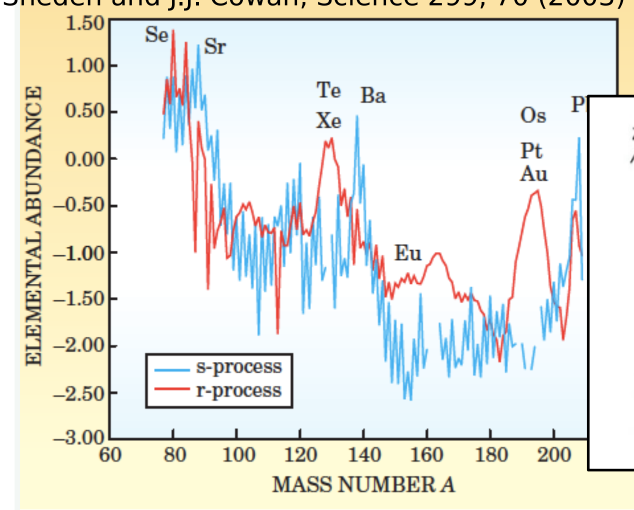
UNIVERSITY OF NOTRE DAME

Courtesy of D. W. Bardayan, UND

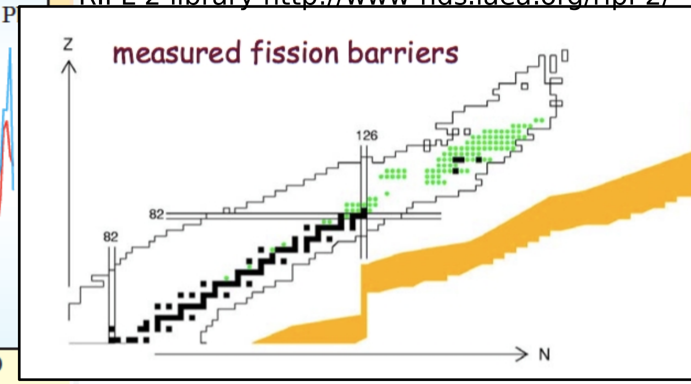
First Day Experiments: AT-TPC



C. Sneden and J.J. Cowan, Science 299, 70 (2003)



RIPL-2 library http://www-nds.iaea.org/ripl-2/

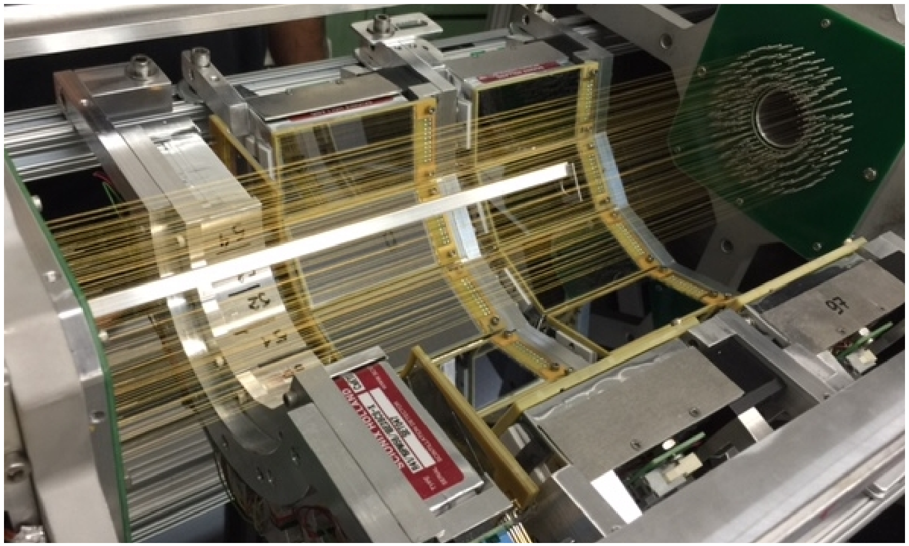


- Measurement of fission barriers of neutron-rich nuclei
  - High precision measurement of fission barriers of neutron-rich nuclei relevant for the r-process and elemental abundance. Fission cycling.
  - Mass and charge division in fission.
  - Nuclear viscosity.

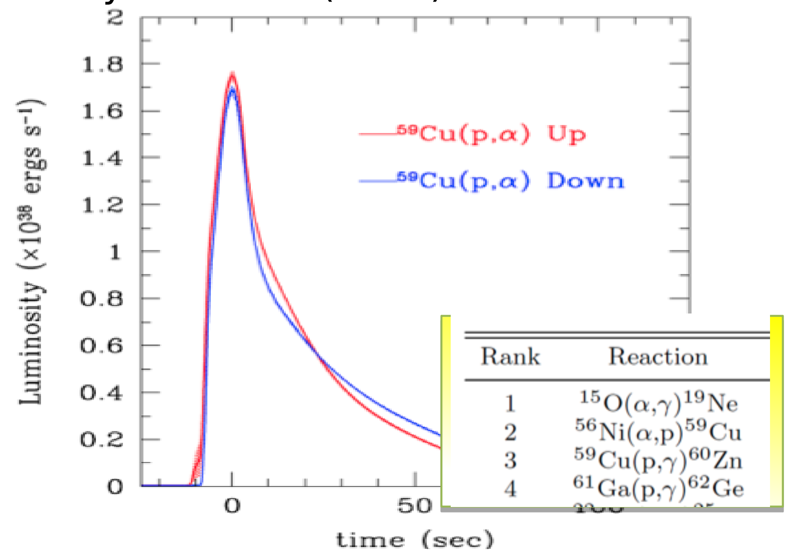
- (α,p) reactions (waiting point nuclei):
  - ^{22}Mg(α,p)^{25}Al
  - ^{26}Si(α,p)^{29}P
  - ^{30}S(α,p)^{33}Cl
  - ^{34}Ar(α,p)^{37}K

Courtesy of Y. Ayyad, MSU

ANASEN : Array for Nuclear Astrophysics and Structure with Exotic Nuclei



Cyburt *et al.* (2016)

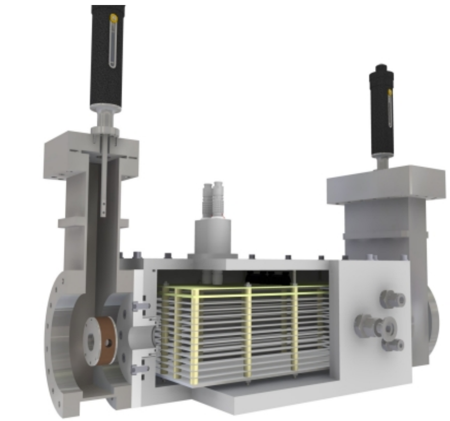


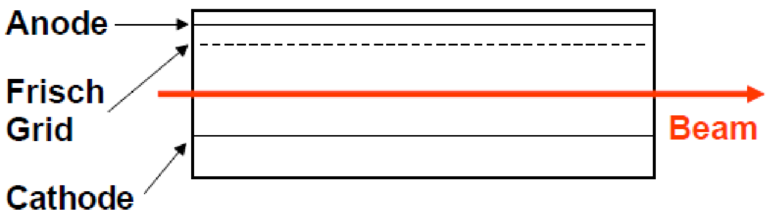
ANASEN - active target detector designed for reaction studies with RIBs. Commissioning runs with ReA3 at NSCL were performed in 2016.

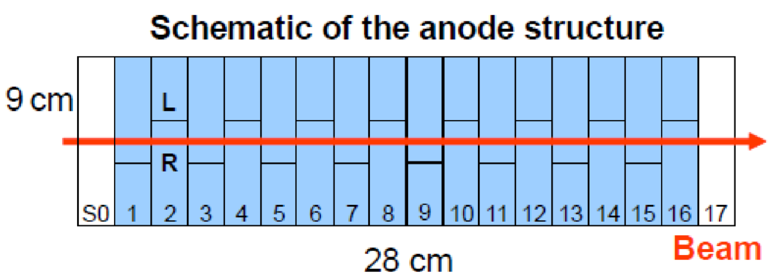
- Experiment: ^{56}Ni(α,p)^{59}Cu, ^{18}Ne(α,p)^{21}Na,^{36}Ar(α,p)^{37}K
- Physics Goals:
  - Directly measure cross section for one of the most important reactions in X-ray Bursts
- To be measured: ^{56}Ni(α,p)^{59}Cu, ^{18}Ne(α,p)^{21}Na, and ^{36}Ar(α,p)^{37}K cross section vs. E_{cm}
- Specific development needs: Technique for addressing ^{56}Co contamination
- Specific facility requirements: $>10^6$ ions/s with good purity

Courtesy of J. Blackmon, LSU

MUSIC: Multi-Sampling Ionization Chamber







- Measure a large range of excitation functions of angle and energy integrated cross sections using single beam energies
- Self normalizing: No additional monitors for absolute normalization
- Counting gases: He, CH_4, Ne, Ar
- Clean separation between primary and secondary beam

Physics Cases:

$^{8}B(\alpha,p)^{11}C$
$^{9}C(\alpha,p)^{12}N$
$^{13}O(\alpha,p)^{16}F$
Breakout from hot pp chains in population III stars

$^{14}O(\alpha,p)^{17}F$
$^{18}Ne(\alpha,p)^{21}Na$
Breakout from hot CNO

$^{22}Mg(\alpha,p)^{25}Al$
$^{26}Si(\alpha,p)^{29}P$
$^{30}S(\alpha,p)^{33}Cl$
$^{34}Ar(\alpha,p)^{37}K$
(α,p) reactions (waiting point nuclei)

$^{12}C+{\ldots}^{19}{\ldots}C$
$^{20}Ne+{\ldots}^{28}{\ldots}Ne$
Fusion reactions for superbursts

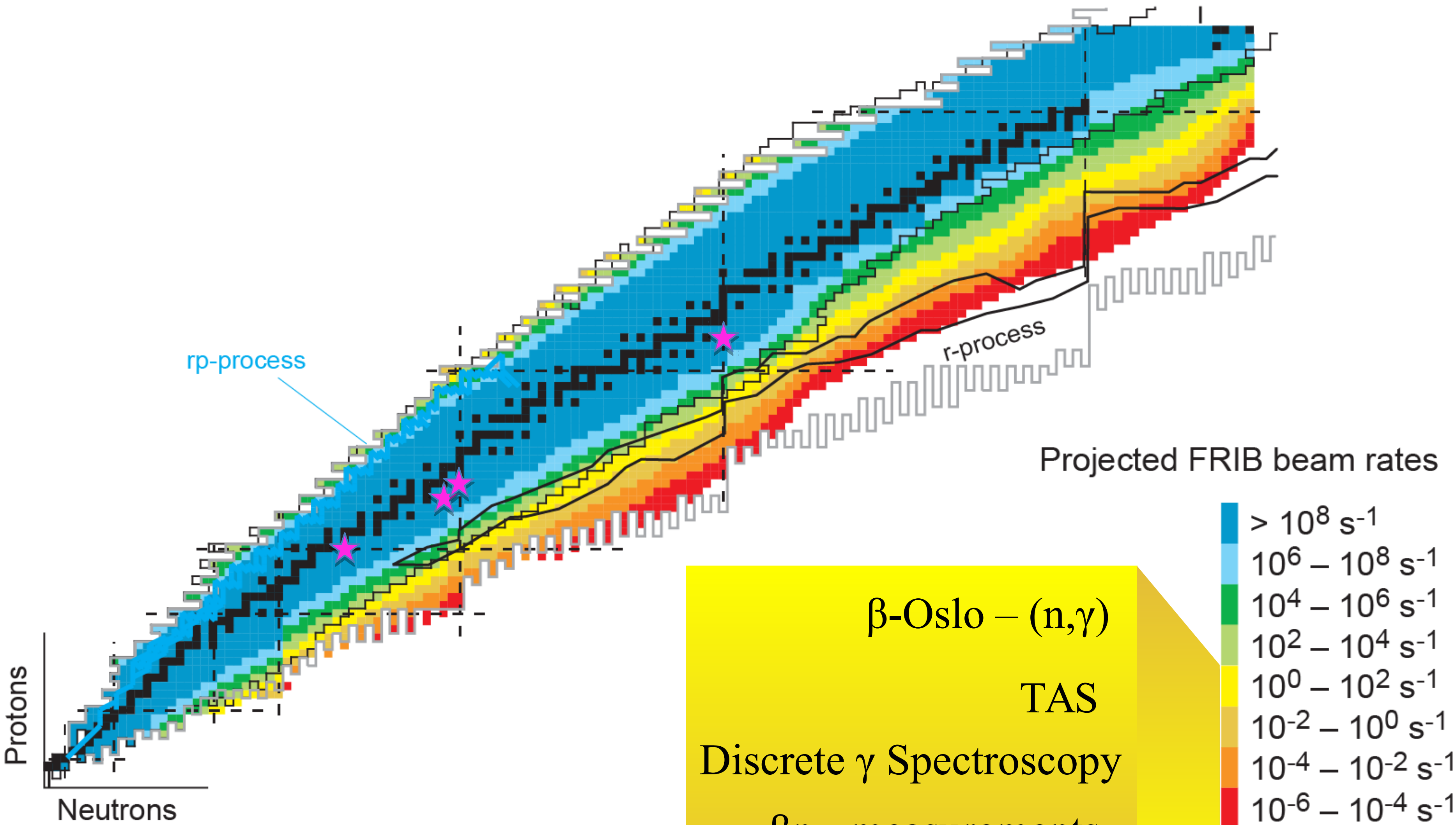
Beam Requirement:

> 500 counts/sec
< 2MeV/nucleon

Argonne NATIONAL LABORATORY

Courtesy of R. Talwar, ANL

FRIB Rates – Full power



β-Oslo – (n,γ)

TAS

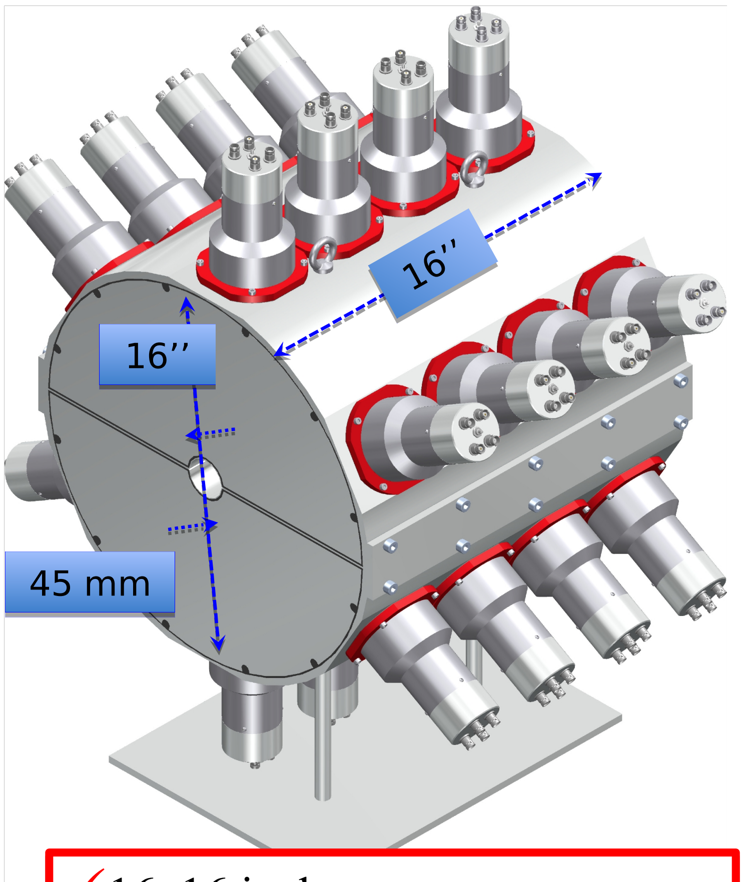
Discrete γ Spectroscopy

βn - measurements

Half-life

Courtesy of A. Spyrou, MSU

Summing NaI (SuN)



- ✓ 16x16 inch
- ✓ 45 mm borehole
- ✓ 2 pieces
- ✓ 8 segments
- ✓ 24 PMTs
- ✓ Efficiency > 85% for 1 MeV

β-decays – Total Absorption Spectroscopy

- ✓ Motivation: r-process constrains, nuclear structure
- ✓ Extract β-decay intensity
- ✓ Beam Intensities: > 0.5 pps
- ✓ Fast beams – Ion-β correlation for $T_{1/2} < 2$ s
- ✓ Thermalized beams – Moving tape for $T_{1/2} > 2$ s

Neutron captures – β-Oslo

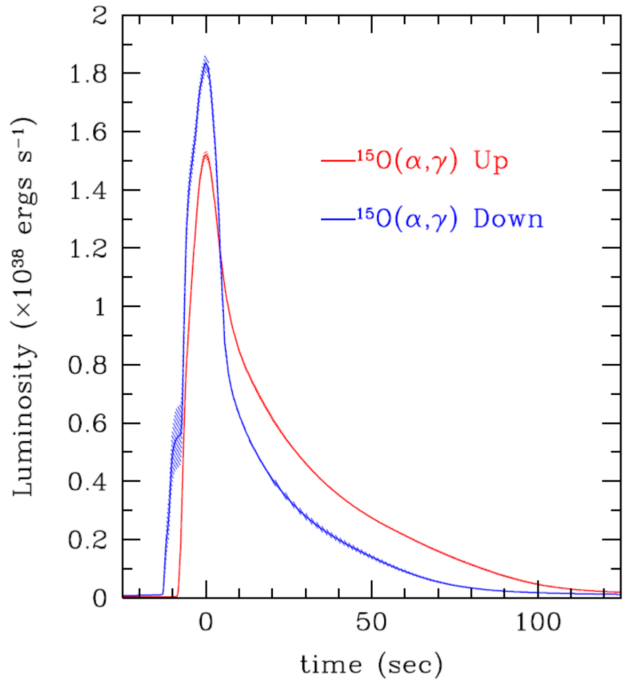
- ✓ Motivation: s,i,r processes
- ✓ Extract nuclear level density, γ-ray strength
- ✓ Constrain (n,γ) reaction rates
- ✓ Beam Intensity: > 5 pps
- ✓ Fast or thermalized beams

Proton captures – p-process

- ✓ Motivation: nucleosynthesis of p-nuclei
- ✓ Direct measurement of (p,γ) reaction cross section
- ✓ Use of RIB - inverse kinematics
- ✓ Beam energy: 2-4 MeV/u – **ReA3**
- ✓ Beam Intensity: $>5\times10^4$ pps

Courtesy of A. Spyrou, MSU

$^{15}O(\alpha,\gamma)^{19}Ne$: the most important reaction for XRBs

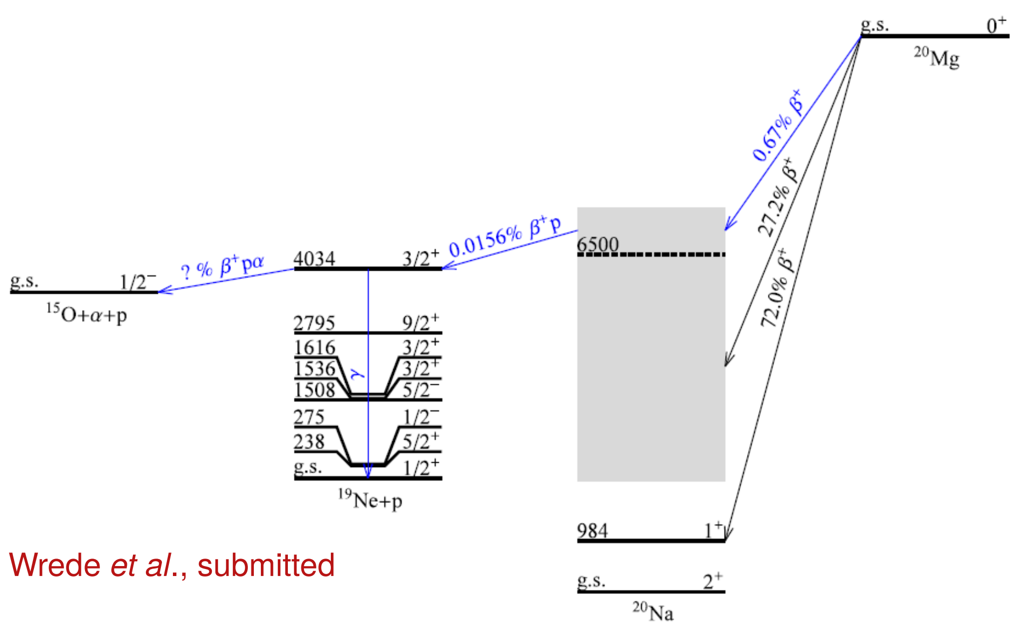


- The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate has the greatest effect on the modeling of type I X-ray burst light curves.
- The rate is dominated by a single ^{19}Ne resonance at an excitation energy of 4.03 MeV.
- In order to determine the rate experimentally, one only needs to know the branching ratio Γ_α/Γ of this resonance.

R. Cyburt *et al.*, Astrophys. J. 830, 55 (2016)
B. Davids *et al.*, Astrophys. J. 735, 40 (2011)

New portal to key $^{15}O(\alpha,\gamma)^{19}Ne$ resonance

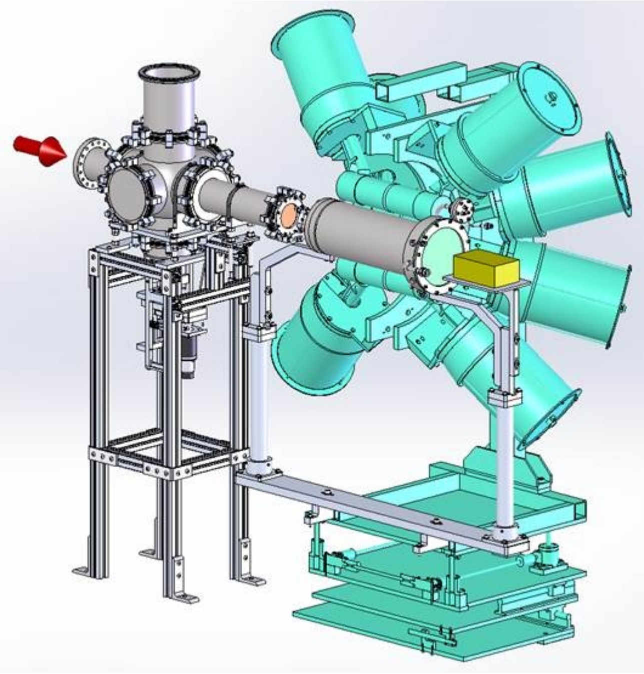
- Recent ^{20}Mg β delayed γ decay work using SeGA at NSCL has shown that the 4.03 MeV state of ^{19}Ne is populated.
- New opportunity to measure Γ_α/Γ and determine the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate.



C. Wrede *et al.*, submitted

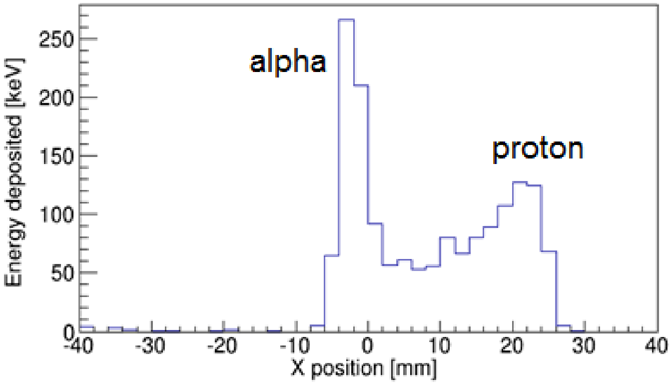
Courtesy of C.Wrede, MSU

New "Proton Detector" TPC for NSCL/FRIB: design, simulations, and assembly

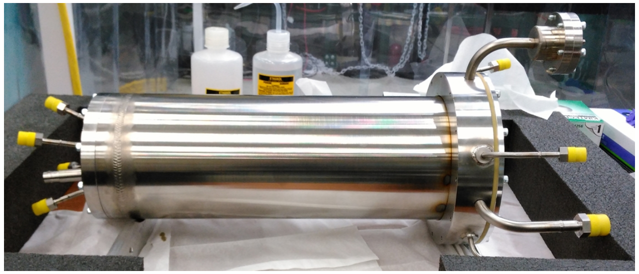


TPC will be used to measure ^{20}Mg(β p α)^{15}O through the E_x = 4033-keV ^{15}O(α,γ)^{19}Ne resonance to determine Γ_α/Γ.

Monte Carlo simulations show a unique signature that can be used to select the events of interest.



TPC stops fragmented ^{20}Mg RIB and detects β delayed charged particles. Surrounded by SeGA HPGe array to detect γ rays.



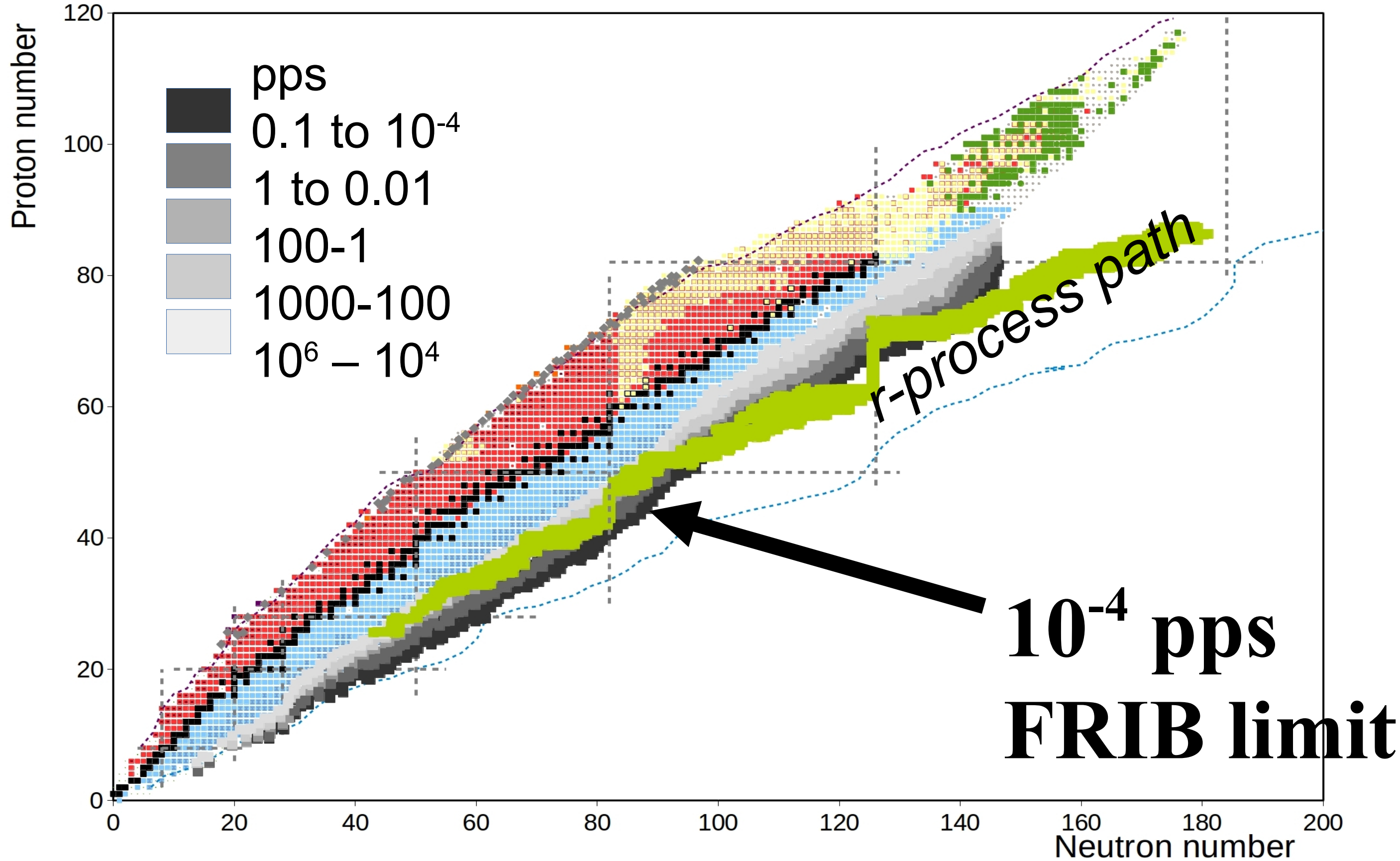
During the 1st year of operation, FRIB will offer a fast ^{20}Mg beam of 4.8 x 10^5 pps, corresponding to 2000 events per day (compared to 16/day at NSCL).

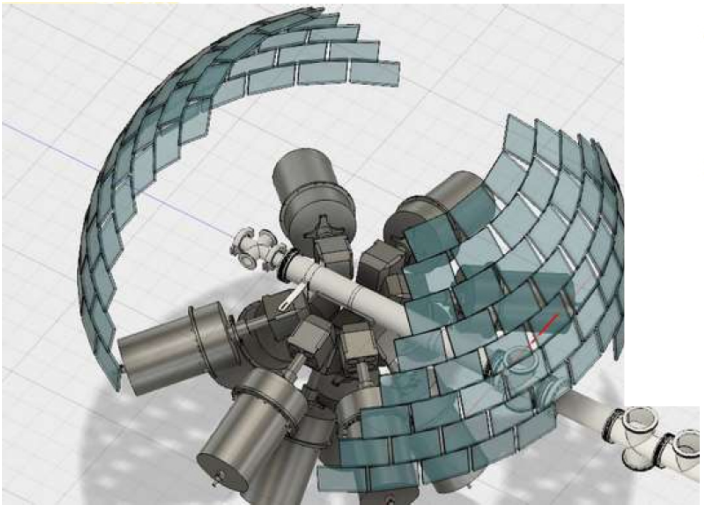
Courtesy of C.Wrede, MSU

FRIB: r-process laboratory

Decay Station will measure new data (lifetimes, branching ratios) for most exotic isotopes

- Essential for astrophysical r-process simulations
- Critical to develop nuclear structure models relevant for astrophysics





Courtesy of R. Grzywacz, UTK

Decay of FRIB r-process nucleus ^{124}Nb: from N=82 to Z=50

Q_β ~ 21 MeV

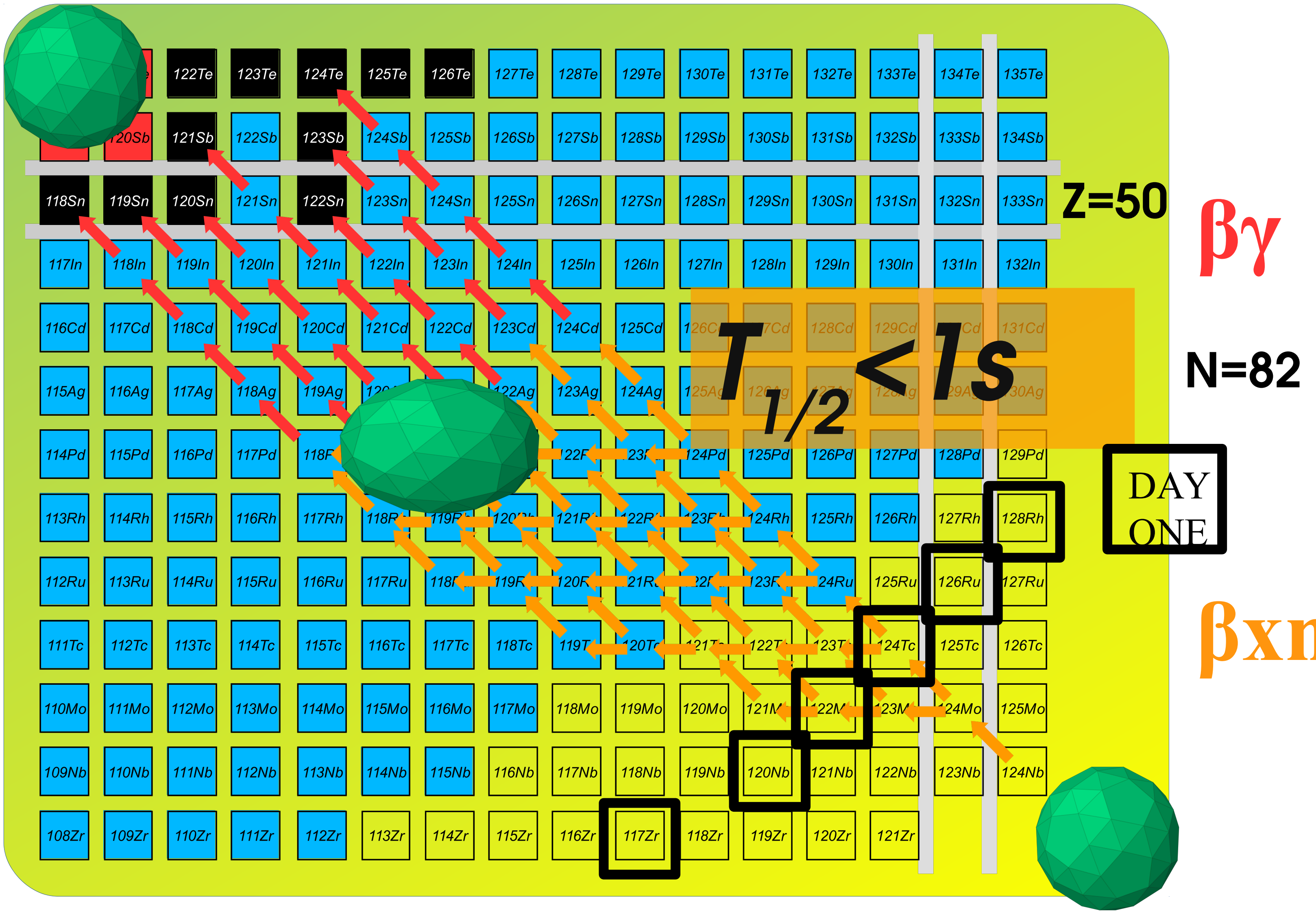
$T_{1/2}$ ~2 ms

Decay modes:

βγ, βn, β2n, β3n…

30 isotopes in 1s

~100 MeV released



Courtesy of R. Grzywacz, UTK

Community concerns

- Unknown intensity and purity of reaccelerated beams
- Difficult to plan for Day 1 without knowing available beam intensities
- Not enough general purpose beamlines planned
- In current design some end-stations are limited to specific energy. Example: ReA3 end-stations will never have access to ReA12 beams

Summary

- Exciting program for day 1 in Astrophysics
  Topics: nova nucleosynthesis, supernovae, XRBs, Pop III stars, rp– , r– , αp–, np–, hot CNO, hot pp processes

- Measurements:
  capture, transfer, (α,p), decay, total cross sections, TAS, fusion, fission, β-Oslo …

- Experimental devices: SECAR, JENSA, AT -TPC, ANASEN, MUSIC, SUN, DECAY STATION...

- Wide range of beam intensities needed depending on the experimental device