Direct reactions as indirect technique

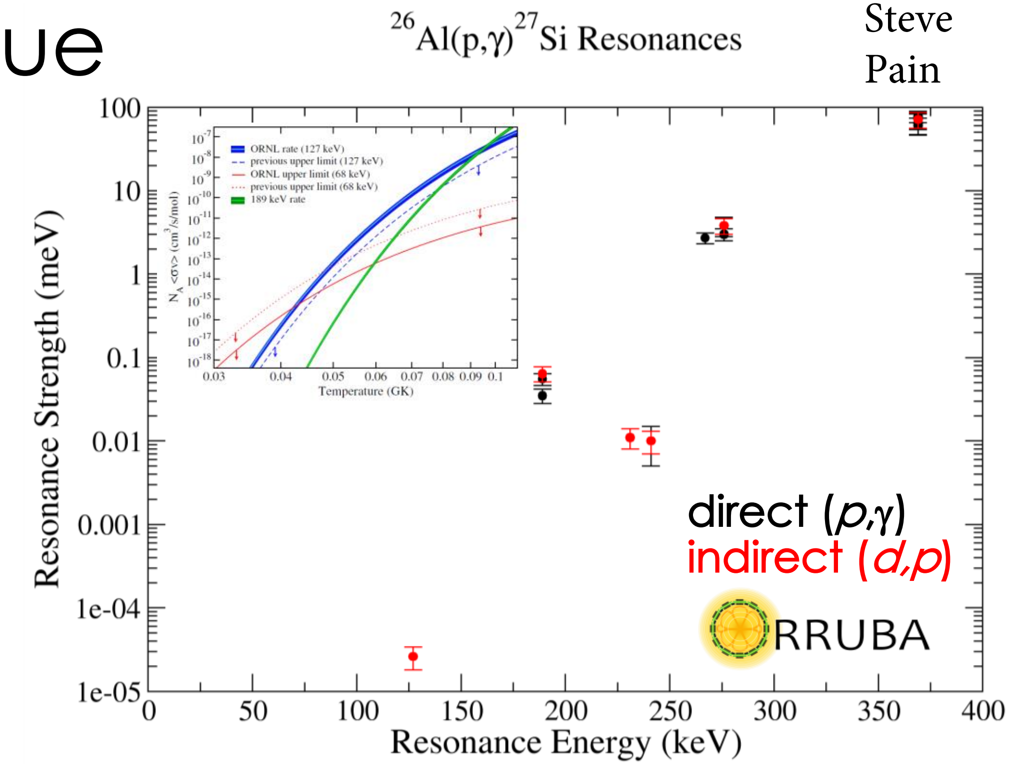
Transfer reactions can be used to determine energies and strengths of CP resonances (E, ℓ_p, J$^\pi$, C^{2}S)

- **Guidance to the SECAR program** – which resonances most important to target (including GS:isomer cases)
- *Some resonances are out of reach of direct measurements*

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \eta^2 \boxed{\omega\gamma} \exp\left(-\frac{\boxed{E}}{kT} \right)$$

$$\boxed{\omega = \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12}) \qquad \gamma = \frac{\Gamma_a \Gamma_b}{\Gamma}}$$

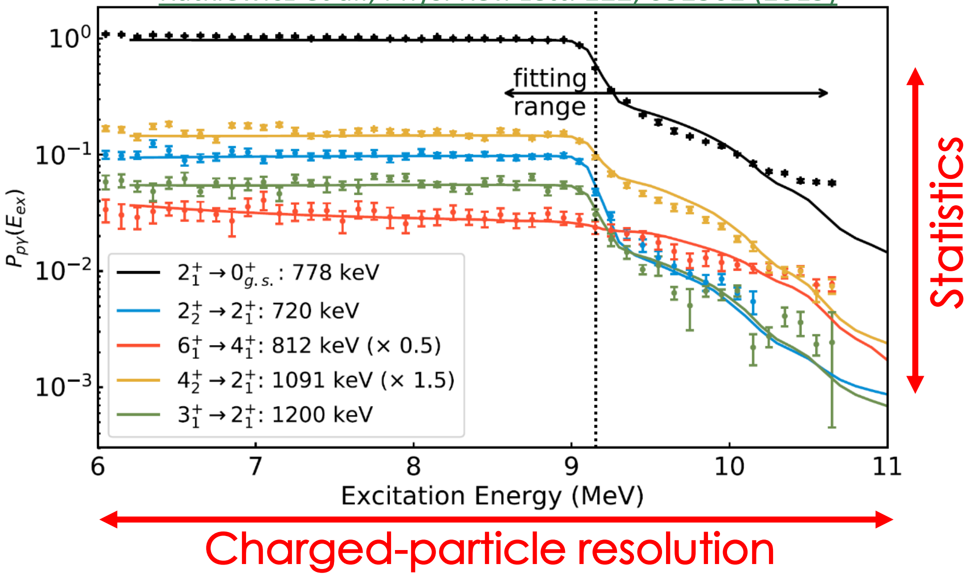
Steve Pain



Direct reactions can be used to determine (n,γ) cross sections

- DSD cross sections to bound states (E, ℓ_p, J$^\pi$, C^{2}S) eg (*d,p*)
- Decay of γ emission probabilities for unbound states (ie constraint of decay of CN)
  - eg via (*d,p* γ) (*p,d* γ) (*p,p*'γ) etc
- Crucial requirements
  - Beam energy (to reach states above S$_n$) > 10 MeV/A
  - Charged-particle resolution

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

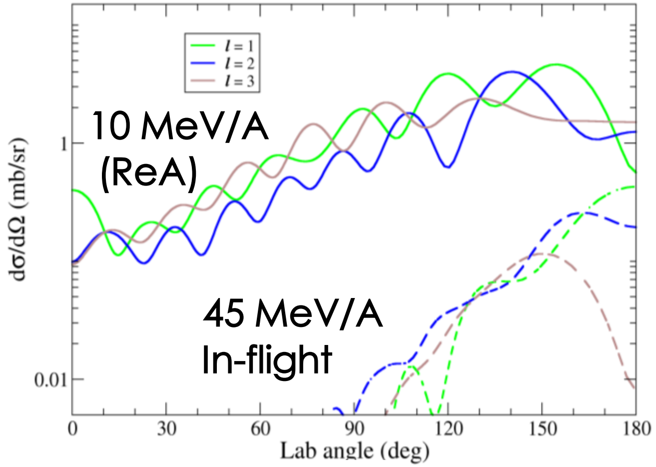


ReA is the place to do it…

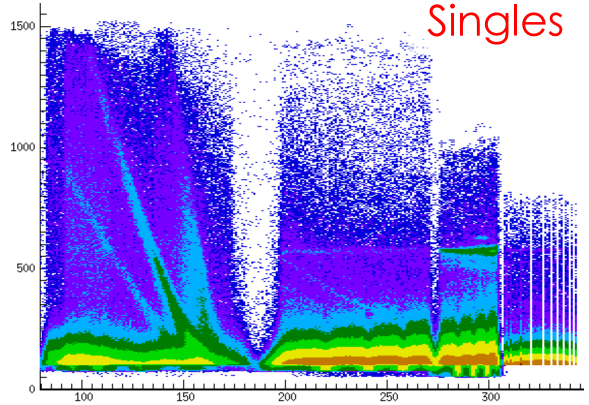
- Energy
- Emittance

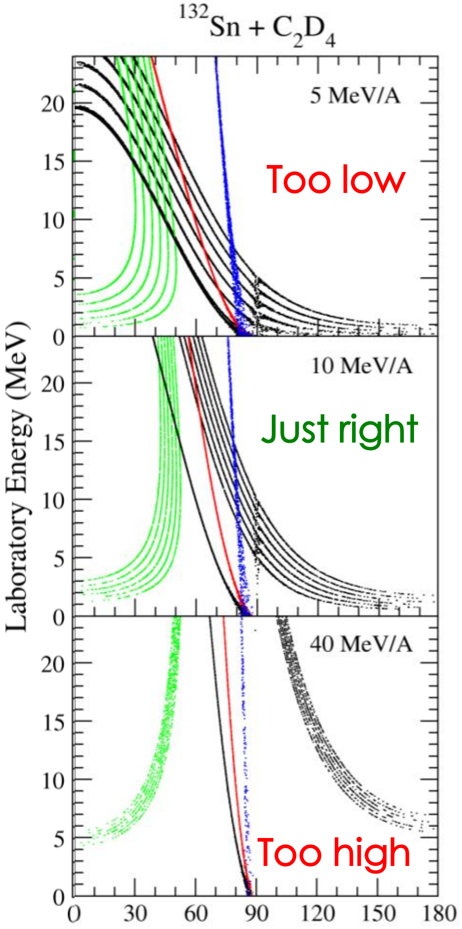
VASTLY improved CP resolution vs in-flight

(ReA ~100-200 keV vs In-flight 0.5-1 MeV)



^{38}K,^{38}Ar(*d*,*p*) @ ~5 MeV/u



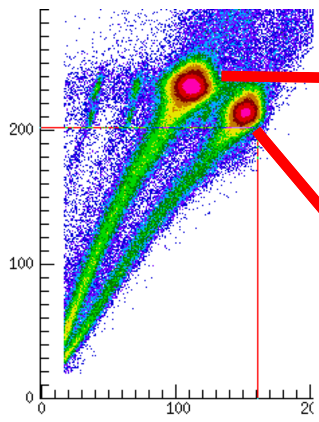
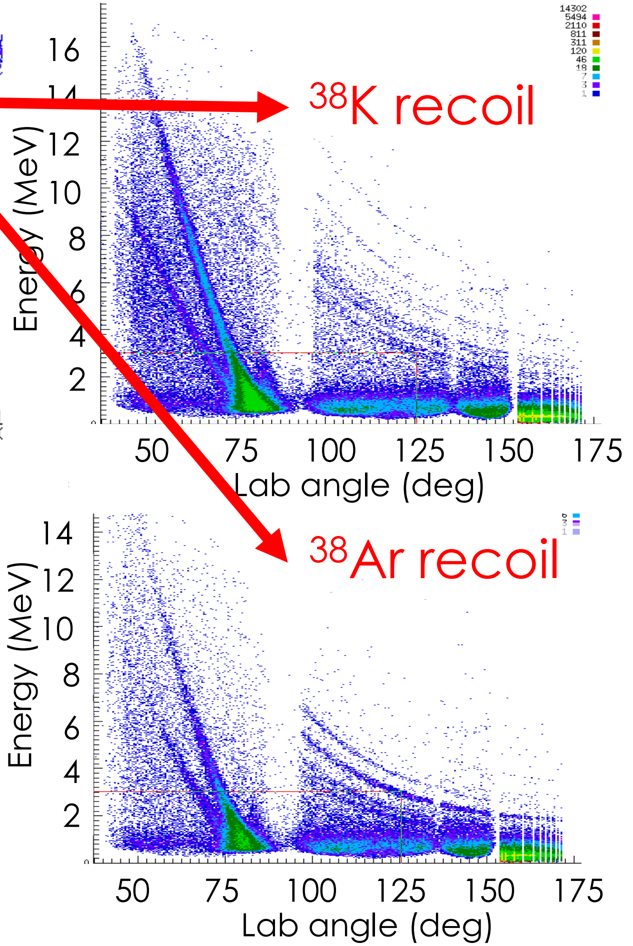


Priority Requests

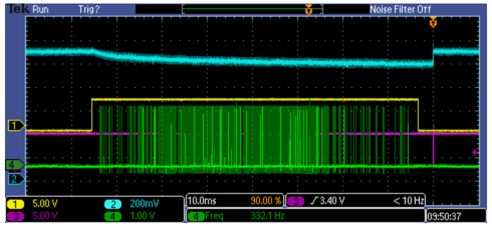
- **ReA12 upgrade** to populate above S_n, S_p

(comparatively minor investment away from world-leading facility)

- **High-acceptance recoil separator (ISLA)**, critical for recoil detection at FRIB intensities

instantaneous beam rates = 10 – 100 x av.



Nuclear Astrophysics at TUNL

Comparative Review: Top two among 32 university and national laboratory groups

7 students received Ph.D.since last LRP

Monte Carlo reaction rates
Bayesian S factors
Starlib reaction rate library
Monte Carlo nucleosynthesis
Bayesian DWBA

Starlib

HIγS

Robert Janssens, Akaa Ayangaekaa

World's highest-flux Compton γ-ray source
1 - 120 MeV with ~ 10^9 s^{-1}
Linearly or circularly polarized
New NRF clover+CeBr3 detector array

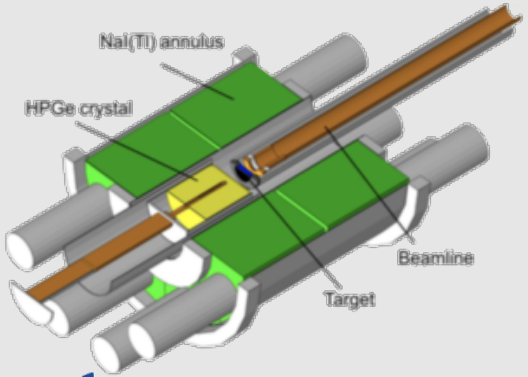
$^{22}\mathrm{Ne}(\alpha,n)^{26}\mathrm{Mg}$ (Longland 2010)
$\alpha + \alpha + n \rightarrow {}^{9}\mathrm{Be}$ (Arnold 2012)
$^{39}\mathrm{K}(p,\gamma)^{40}\mathrm{Ca}$ (Gribble 2022)

LENA-II

Christian Iliadis, Art Champagne

Recent LENA-II Upgrade ($3M):
- 230-kV ECR (20 mA, 10% duty cycle)
- 2 MV Singletron (up to 2 mA, 4 MHz, 2 ns pulsing)
- γ-ray coincidence spectrometer

Recent Highlights:
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ (Buckner 2015) DOE Highlight
$^{29}\mathrm{Si}(p,\gamma)^{30}\mathrm{P}$ (Downen 2021)



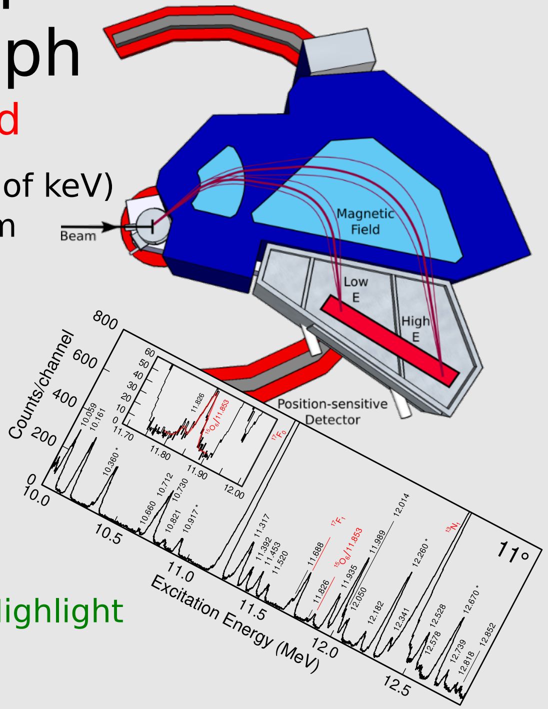
Enge Split-pole Spectrograph

Richard Longland

High energy resolution (10s of keV)
Detector resolution ~0.3 mm

Ion source upgrades ($1.5M):
- 10x beam intensity
- Greater stability for long-term measurements

Highlights:
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$ (Setoodehnia 2018)
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$ (Marshall 2021) DOE Highlight
$^{17}\mathrm{O}(\alpha,n)^{20}\mathrm{Ne}$ (Frost-Schenk 2022)



Duke UNIVERSITY
NC Central UNIVERSITY
NC STATE UNIVERSITY
UNC
ARUNA

Nuclear Astrophysics at (mostly) Ohio University

Carl Brune, Tom Massey, Alexander Voinov

Nuclear Astrophysics Working Group, Town Hall, November 15, 2022

- $^{3}\mathrm{He} + {}^{4}\mathrm{He}$ and $^{7}\mathrm{Be} + p$ elastic scattering at TRIUMF
  - Better understanding of $^{3}\mathrm{He}(^{4}\mathrm{He},\gamma)$ and $^{7}\mathrm{Be}(p,\gamma)$ and solar neutrinos
- p- and α- induced reactions on $^{10}\mathrm{Be}$
  - nucleosynthesis of Be and B in core-collapse supernovae
- Neutron scattering on $^{16}\mathrm{O}$
  - constraining the s-process neutron source $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$
- Level densities in $^{28}\mathrm{Si}$ for $^{24}\mathrm{Mg}(\alpha,\gamma)$
  - nucleosynthesis in massive stars
- Branchings in $^{60}\mathrm{Zn}$ via $^{58}\mathrm{Ni}(^{3}\mathrm{He},n) + p/\alpha$ coincidences
  - $^{59}\mathrm{Cu}(p,\gamma)$ in x-ray bursts

OHIO UNIVERSITY

ARUNA

Association for Research
at University Nuclear Accelerators

EAL

Nuclear Astrophysics at the High Intensity Frontiers With AT-TPCs

Improved eTPC with good Timing

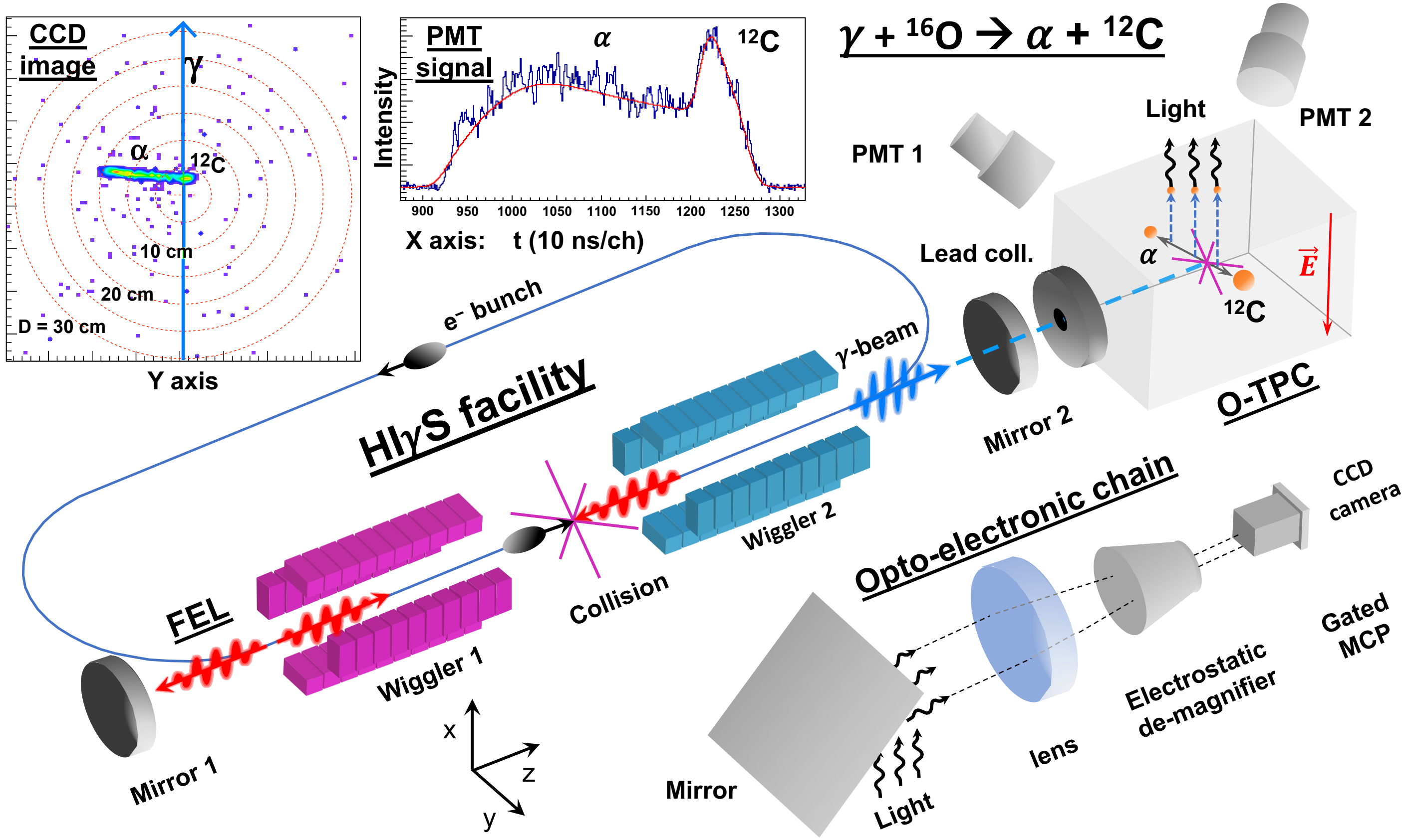
(R&D Developments for Readout of Prompt Light)

1. At the **HIGS** for $^{12}C(\alpha,\gamma)$
   C/O Ratio at low energies
   (n - γ discrimination)

2. At the **FRIB** an (α,p) Factory
   for X- Ray Bursts
   (Fast Beam Trigger)

3. At the **SARAF** the p(n,γ)
   for BBN
   (Neutron TOF)

The HIgS O-TPC Measurement of the $^{12}C(\alpha,\gamma)$ Reaction

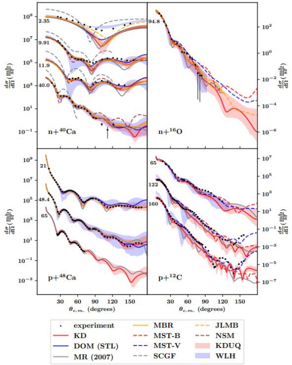


R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed,
Nature Communications, 12, 5920 (2021).
https://www.nature.com/articles/s41467-021-26179-x

Motivation for elastic, inelastic and total cross sections with ILSA

Elastic scattering

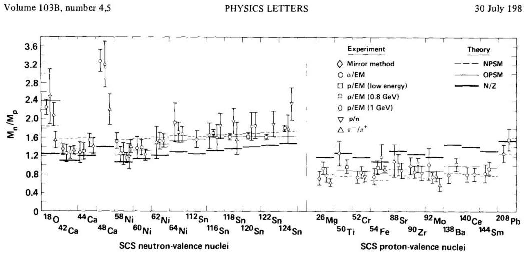
-optical-model potentials
-vital for capture rates for astrophysics and applications
-probe of nuclear structure
-needed for interpretation of other reactions such as transfer
-relatively quick to measure (I think) but requires some thought as to placement of detectors



Hebborn++ arXiv:2210.07293

Inelastic scattering

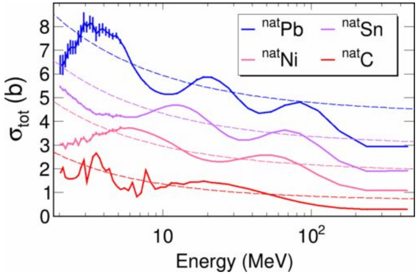
-Transition strengths give information about underlying structure
-e.g. recent use of (p,p') for deformation lengths and (d,d') for octupole deformation
-Scattering of different probes gives access to different information, unpick neutron and proton contributions to collectivity

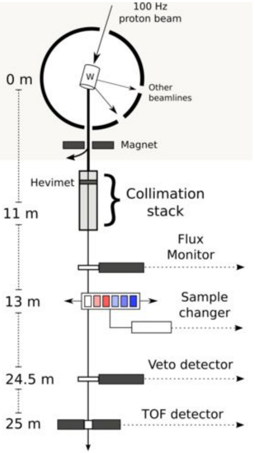


Bernstein, Brown and Madsen
PLB 103 255 (1981)

Total interaction cross sections

-can use these to constrain optical-model potentials
-see Pruitt++ work on DOM using neutron data from LANL
-total reaction cross sections for reactions on protons and αs are also needed (and probably easier to get for unstable systems than neutron transmission measurements)





Pruit++ PRC 102 034601 (2020)

Nuclear Astrophysics

large scale simulations/computation
are ***at the heart*** of the creation
of a *"cosmic laboratory"* that
**facilitates integration across theory,
experiment, observation, and
new computing technologies**

experimental
facilities

FRIB
JLAB
DUNE
RHIC
LHC
$0\nu\beta\beta$
Stage-4 CMB
SNS
ultra-cold neutrons
Dark Matter
(e.g., direct detection)

– nucleosynthesis (light,intermediate,heavy)
– gravitational collapse
– compact object mergers
– neutron stars/ultra-dense matter
– nuclear structure/reactions
– explosive nuclear burning (X-ray bursts, SNIa)
– neutrino physics
– many body theory/quantum dynamics
– quantum technologies

multi-messenger astro,
cosmology capabilities

Gravitational Waves
(LIGO, VIRGO, KAGRA,
LISA, BBO/DECIGO, etc.)
see *3G Science Book*

Electromagnetic
JWST; Rubin (LSST); 30m/ELT, etc.
X-ray (XRSM/ATHENA); gamma-ray

Neutrino Detectors
(DUNE, hyperK, ICECUBE, etc.)

CMB
(Stage-4, Simons Observatory)

augment the discovery potential at the frontiers
of each of the experimental & observational facilities

Optimizing the Nucleosynthesis “tool”

- Nuclear masses/properties/EOS; weak interaction properties; e.g., FRIB
- High temperature/high excitation energy nuclear structure/response
- Neutrino-nucleus interactions (DUNE energies; astrophysical energies)
- Neutrino Physics: Standard Model Nonlinear Flavor Transformation
- Modeling/computation

Beyond Standard Model Physics

- Neutrinos: NSIs; lepton number violation; sterile νs (range of masses/mixing)
- axion-like particles (ALPs), etc.
- dark sectors (e.g., dark photons, etc.)

Dark Matter/Dark Sectors

see the INT program (August 2022):
“*Dark Matter in Compact Objects, Stars, and Low Energy Experiments*”

- direct detection: light dark matter (detector physics)
- gravitational wave probes/other gravitational signatures
- nucleosynthesis constraints
- dark matter-induced neutron star implosion (nuclear EOS; heat transport)

Future directions of indirect methods

building on current tools & successes

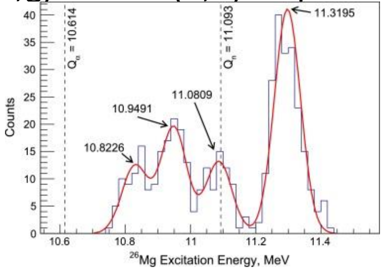
Sub-Coulomb α-transfer

(α,n), (α,g), (α,p) …

Powerful tool, lower theory uncertainties

RIBs and spectrometers

H. Jayatissa et al. PLB 802, 135267: ^{22}Ne(α,g) vs ^{22}Ne(α,n) –s-process source



Current work: E. Harris, ^{12}C(^{20}Ne,^{16}O)^{16}O – ^{16}O g.s α-ANCs

Trojan Horse Method

Under-utilized in US?

Necessary compliment to strong direct approaches

RIBs and spectrometers

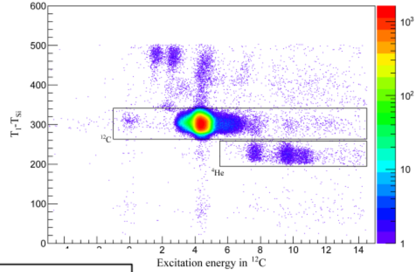
Branching ratios

Si + spectrometer (+ RIB)

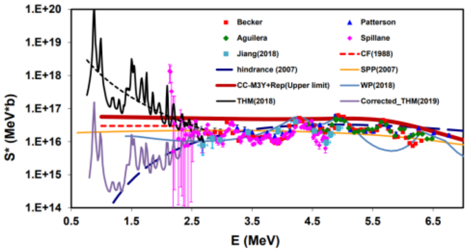
e.g. Γ_α vs Γ_p for (α,p) reactions or $\Gamma_{\alpha/n}$ vs Γ_γ for capture reactions

Current work: Z. Luo

Measure Hoyle radiative decay BR with ^{12}C(α, $α_2$) + MDM + PPACs



^{12}C+^{12}C: – complimentary ^{13}C+^{12}C study to ^{14}N+^{12}C study, lower dependence on outgoing Coulomb barrier



3 orders of magnitude theory interpretation difference – water needs unmuddying…

Measurements with TPCs

TexAT, AT-TPC, ND-cube, ACTAR, GADGET etc. (+MUSIC-type detectors) … have had many results after coming online in the past 7(+) years

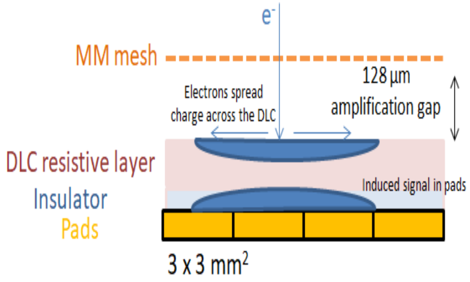
Next generation…

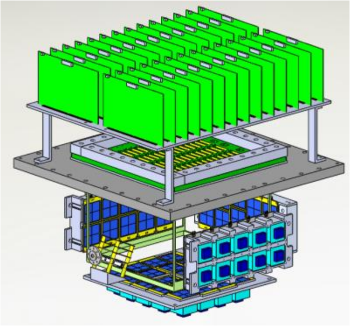
Building on 7+ years of experience with TexAT

Collaborating with Univ. Birmingham, UK

1k MM channels → 8k MM channels

Resistive DLC (GADGET2 too!)





Pos. resolution improves from ~1.5 mm to ~300 µm

Gamma/neutrons beams

UConn @ HIGS (Gai/Smith) $^{12}C(\gamma,\alpha)$ ('13) → $^{16}O(\gamma,\alpha)$ ('21)

TAMU/OU/WashU with TexAT $^{12}C(n,n_2)3\alpha$ ('22)

^3He target and recycling system

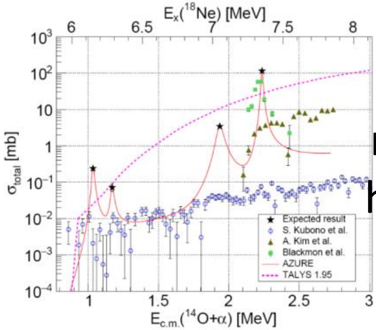
^3He recycling and purification system for ^3He:CO2 as an active-target gas - (^{3}He,d) and (^{3}He,n) experiments with RIBs as indirect probe of (p,g) for astrophysical scenarios

Coupling neutron detectors - TexNeut

Highly-segmented, PSD-capable neutron detector – *p*-terphenyl crystals – D. Scriven NIMA 1010, 165492 ('21)

Commissioned with TexAT + TexNeut (Dec' 21) $^9Li(p,n)$

$^{14}O(\alpha,p)$



Led by Tony Ahn @ CENS, Korea using TexAT

Astrophysically-important $^{14}O(\alpha,p)$ measured with TexAT – high rates (few 10^5 pps) at TAMU (2022) and RIKEN (2023)

Direct measurements down to low E_{CM}