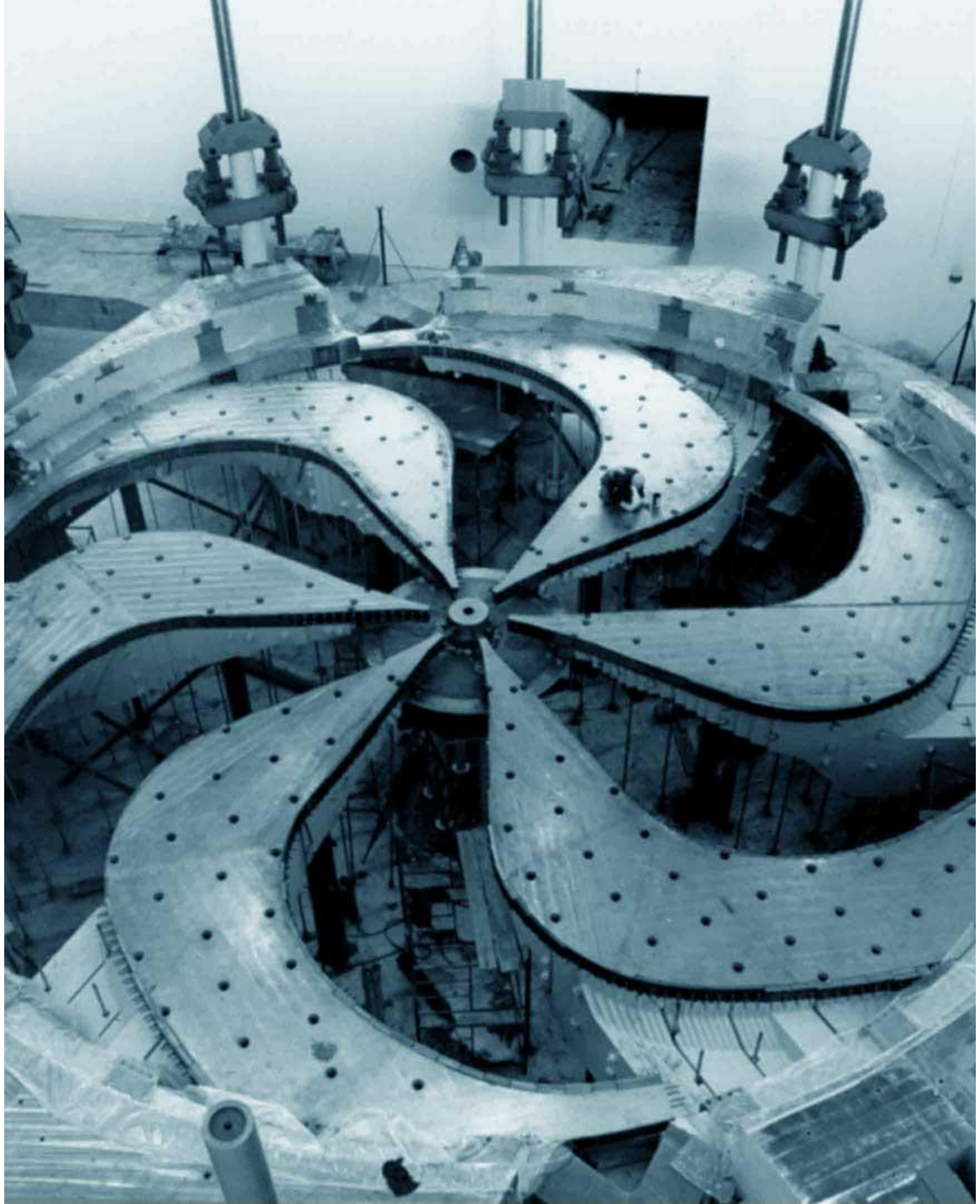
TRIUMF

Studies of (α,n) reactions with EMMA for the astrophysical weak r-process

Cameron Angus

EMIS XX, Whistler 2025

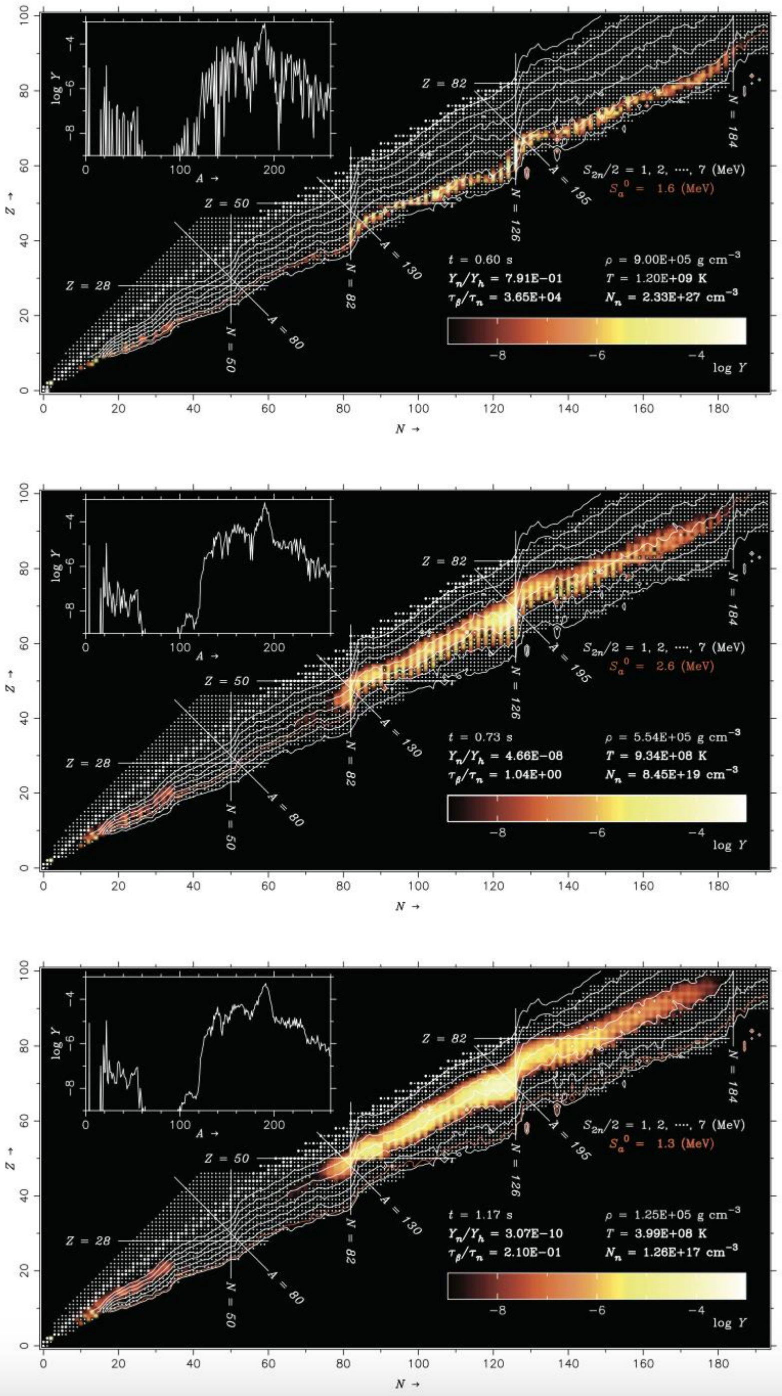
2025-10-23



Discovery, accelerated

‘Main’ r-process

- ‘rapid’ neutron-capture process
- Responsible for producing ~50% of heavier-than-iron elements
- Currently thought to take place in neutron star mergers (GW170817)



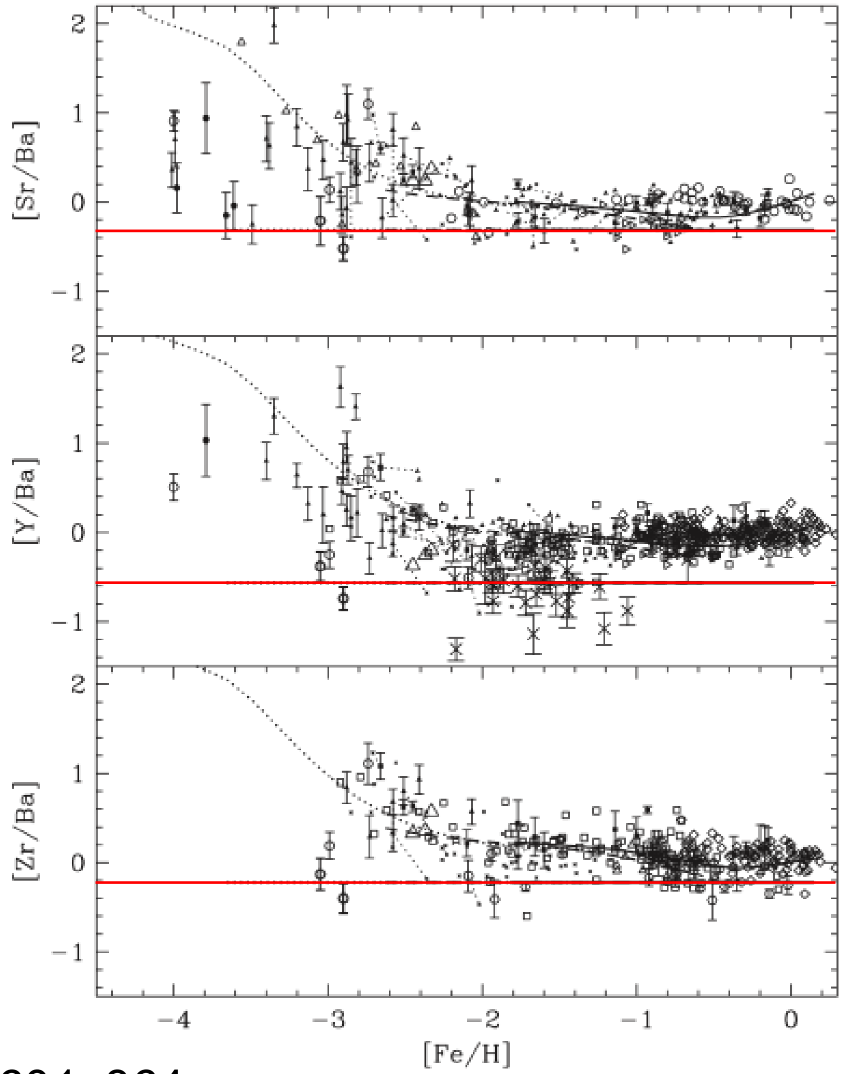
Wanajo *et al.* (2004) ApJ 606: 1057.

Comparisons of Models to Observations

- Predictions for heavy element abundances agree with observations of Ultra metal-poor (UMP) stars

- Intermediate-mass elements are more abundant than expected (26<Z<45)

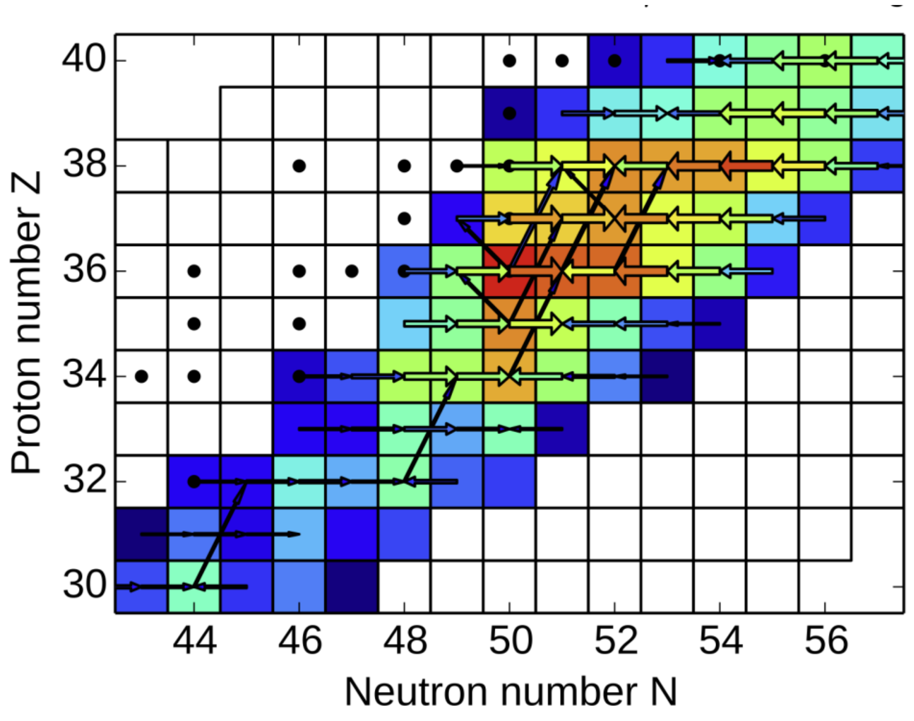
- Additional source of nucleosynthesis operating at early times?



Travaglio *et al.* (2004) ApJ 601: 864.

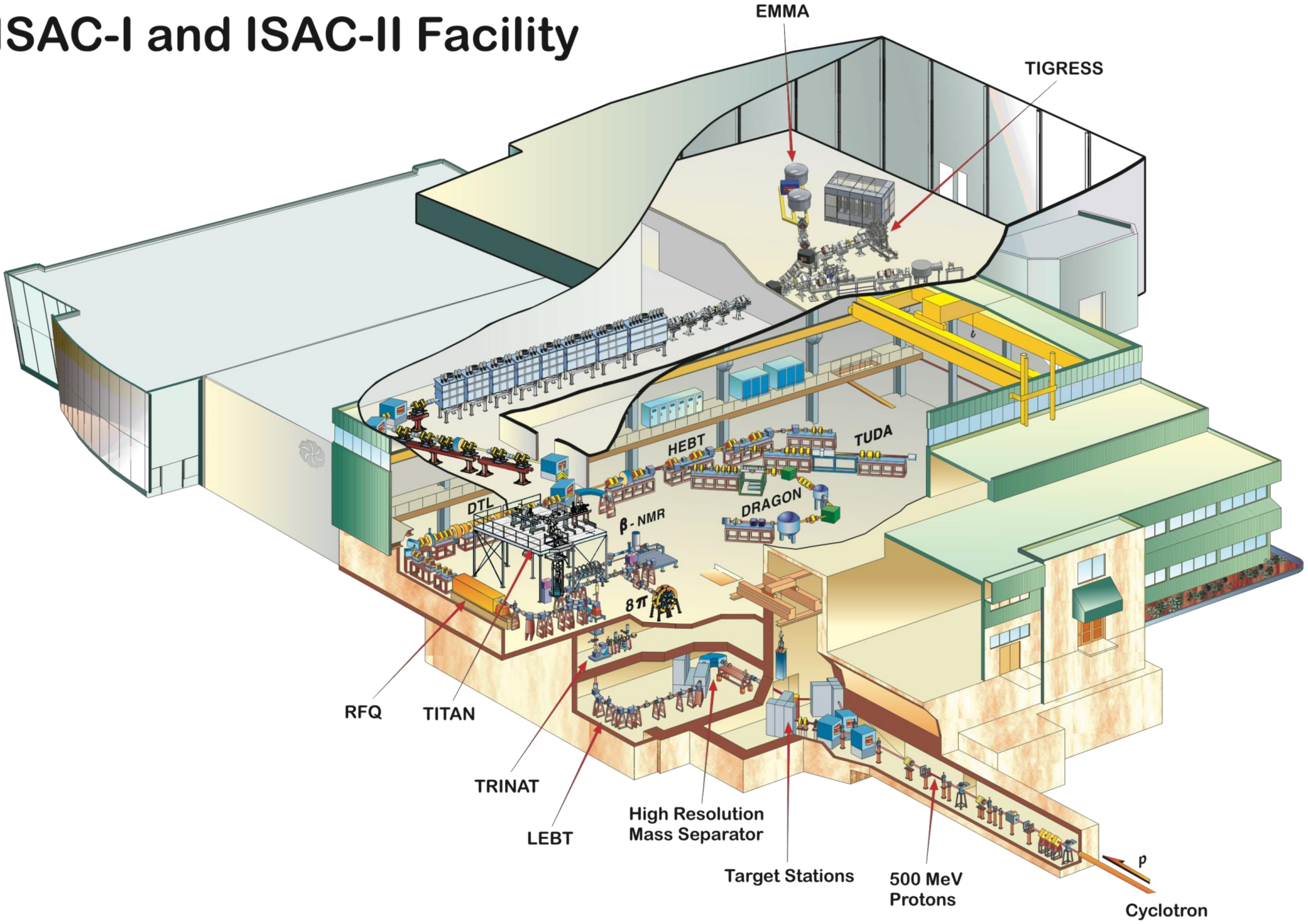
(α,n) reactions in core-collapse Supernovae

- Neutrino-driven winds drive the shock
  - Neutrinos released from cooling proto-neutron star
- Simulations suggest nucleosynthesis viable for $A < 130$ at T $= 2 \; - 5$GK
- Pathway close to stability, in contrast to the 'main' r-process
- Most (α,n) reactions on the intermediate-mass elements do not have measured cross sections…



Bliss *et al.* (2017) J. Phys. G. 44: 054003

ISAC-I and ISAC-II Facility



Experiments

- Reactions
  - $^{86}Kr(\alpha,n)^{89}Sr$
  - **$^{94}Sr(\alpha,n)^{97}Zr$**
  - **$^{93}Sr(\alpha,n)^{96}Zr$**

"affecting many astrophysical abundances under many astrophysical conditions" – Bliss *et al.* (2020) PRC 101: 055807.

- EMMA+TIGRESS at the TRIUMF-ISAC facility
  - Using inverse kinematics with novel He-containing targets

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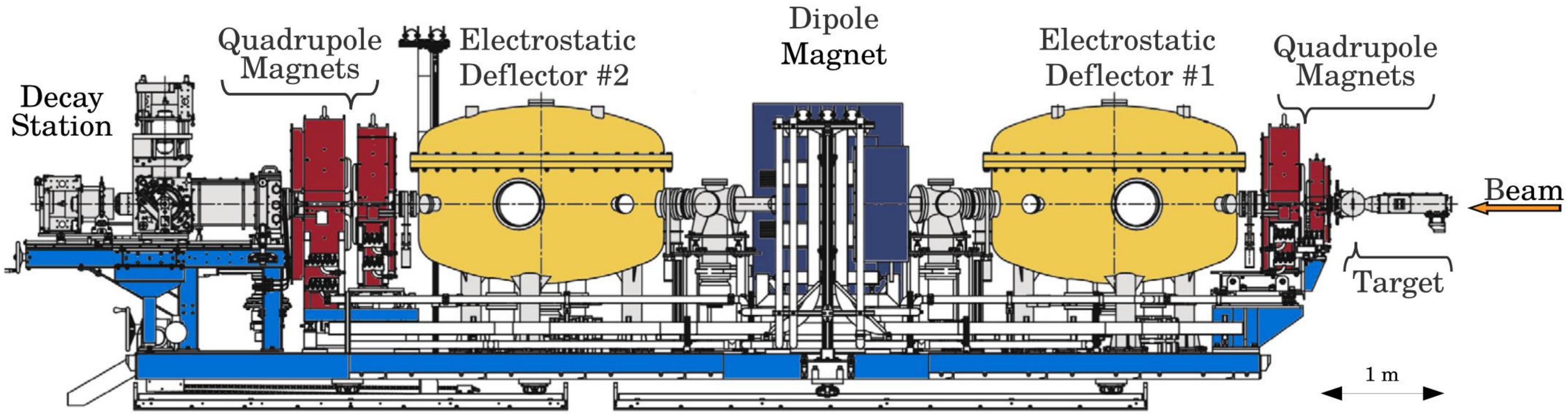
  - Using inverse kinematics with novel He-containing targets

226 MeV	265 MeV	213 MeV 247 MeV	259 MeV	279 MeV
^{86}Kr	^{86}Kr	^{86}Kr	^{94}Sr	^{93}Sr
Dec 2021	Aug 2022	Aug 2023	Dec 2023	Jun 2025

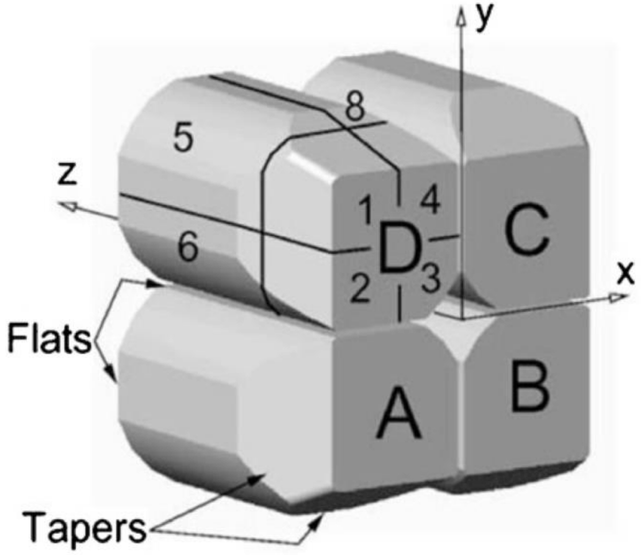
ElectroMagnetic Mass Analyser

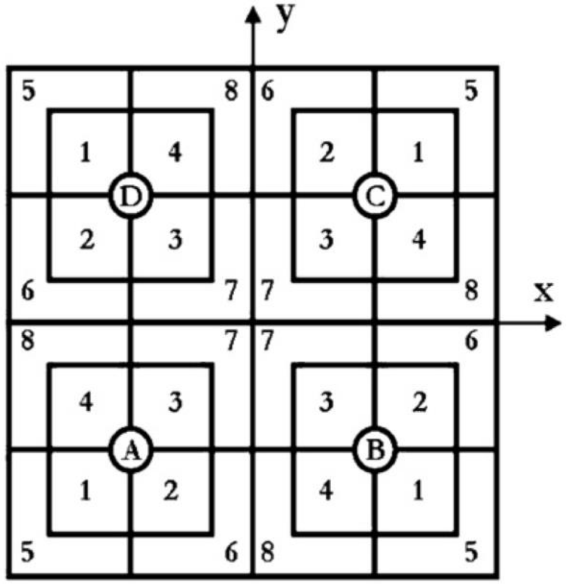


- Recoil mass spectrometer, separates ions by M/q ratio
- 3 detectors at focal plane
  - PGAC
  - Ionization Chamber
  - Si detector

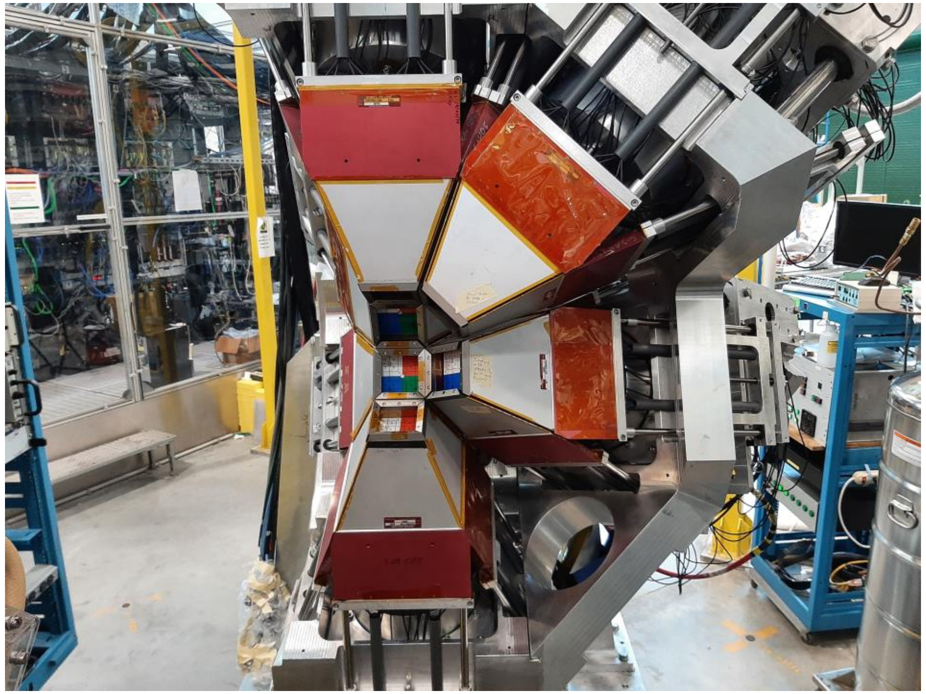
Davids *et al.* (2019), NIM.A. 930: 191-195.

Triumf-Isac Gamma-Ray Escape Suppressed Spectrometer





- Gamma-ray detector currently coupled to EMMA
- 12 HPGe clovers surrounded by BGO scintillators for Compton suppression
- Segmented readouts give high angular resolution



Svensson *et al.* (2005) *J. Phys. G.* 540: 348-360.

EMMA Acceptance

- Maximum electric field limits the possible E_K/q
  - Use a 'degrader' to slow the recoils
  - Select a charge state that maximizes count rate

- Spectrometer entrance limited by a 3^o aperture

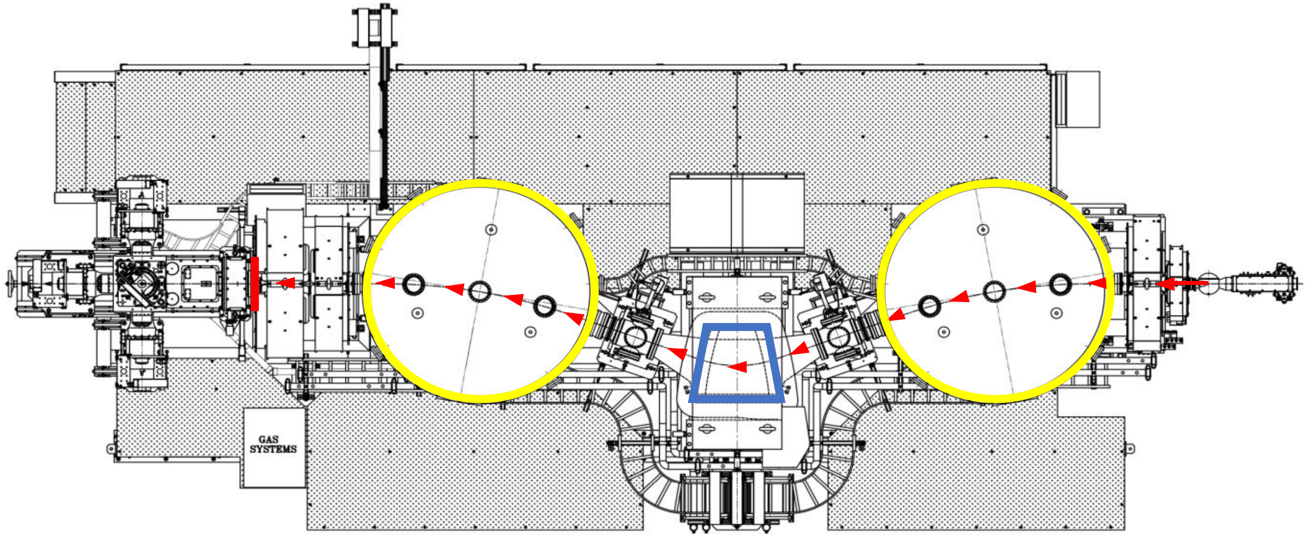
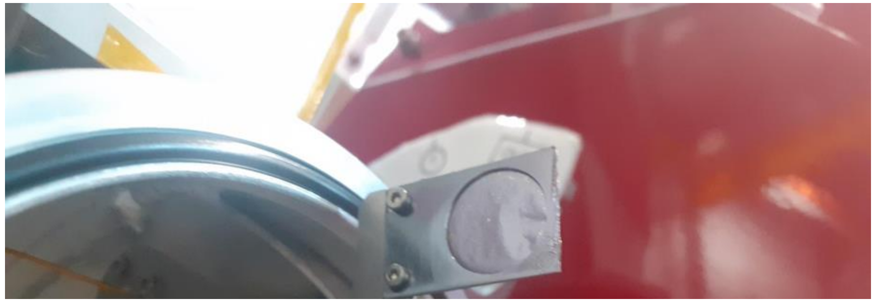


Image credit: Dr. M. Williams (2022)



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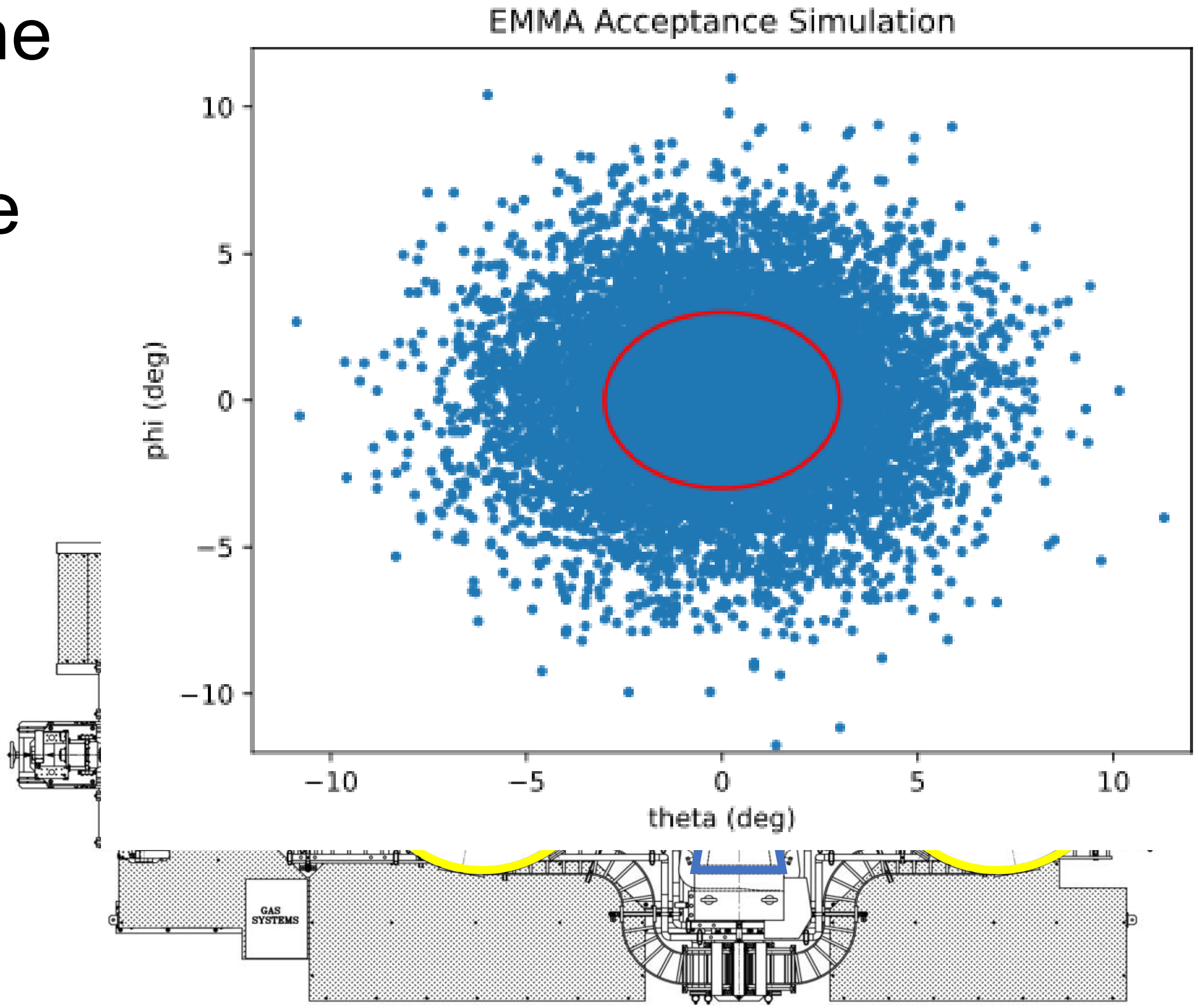
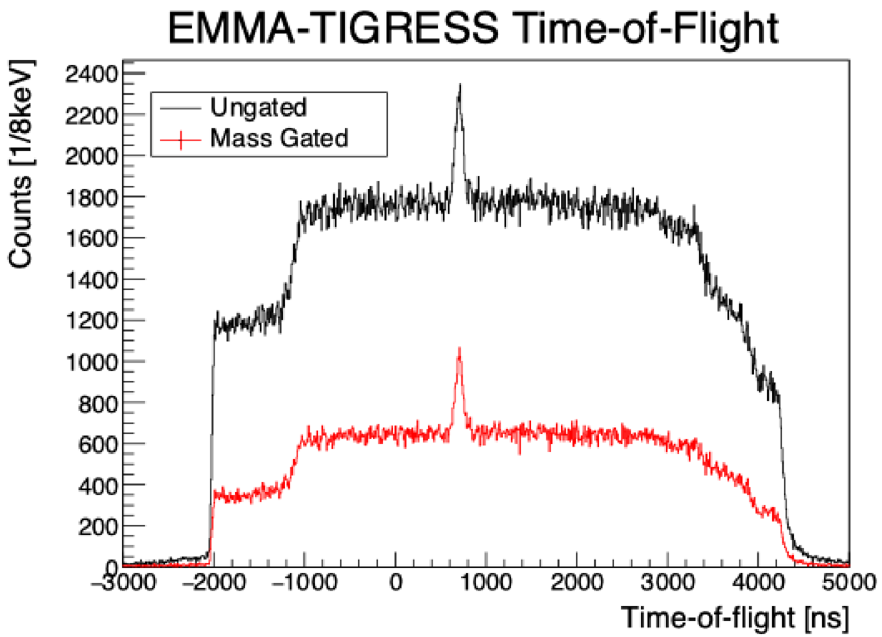
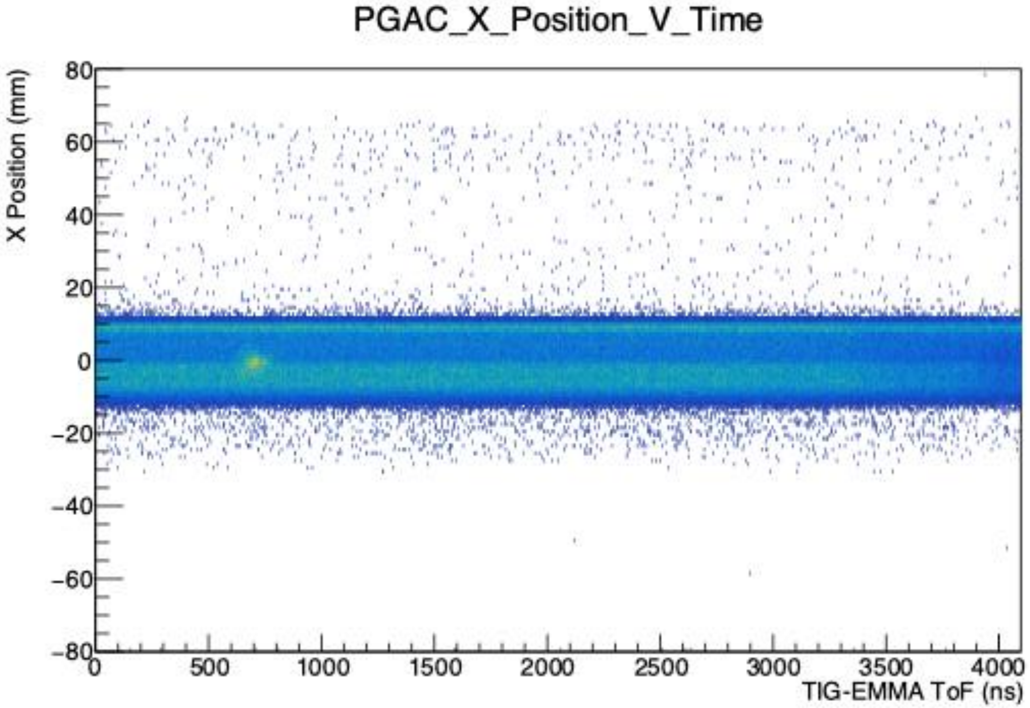


Image credit: Dr. M. Williams (2022)

EMMA + TIGRESS

- EMMA measures recoiling ^{89}Sr (and $^{96/97}Zr$)
- TIGRESS detects gamma rays emitted from recoiling nuclei
- Coupling allow allow coincidence measurements





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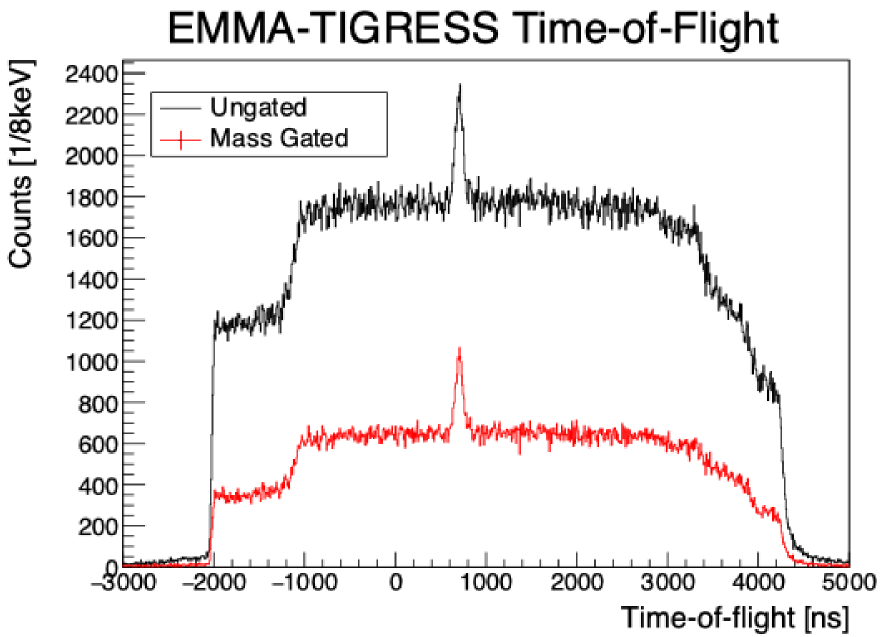
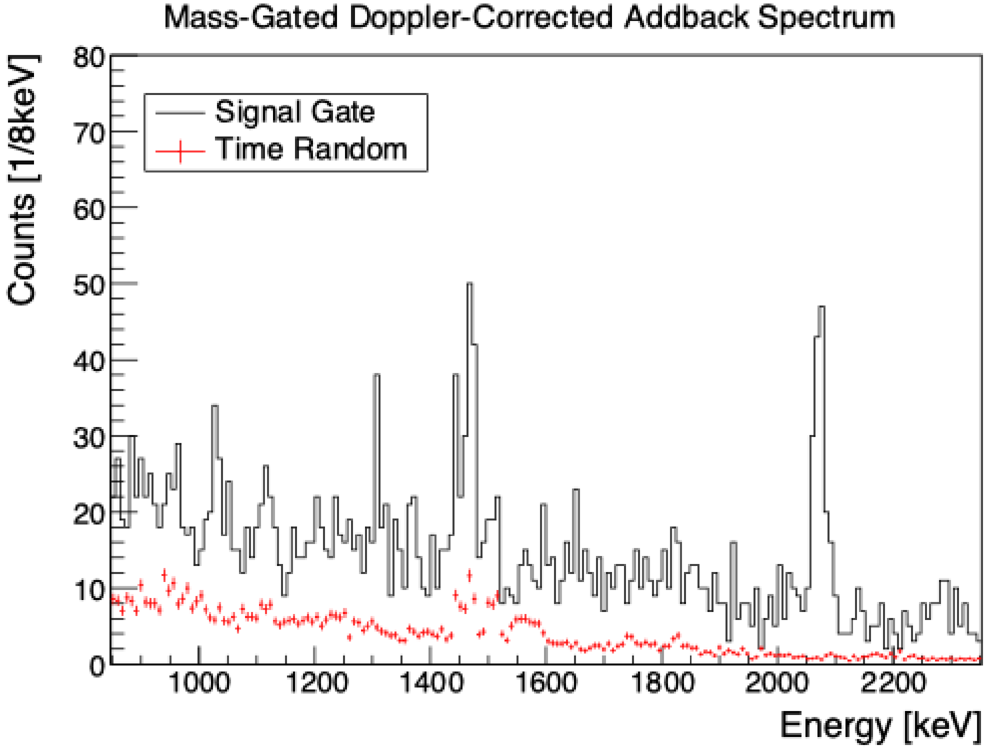
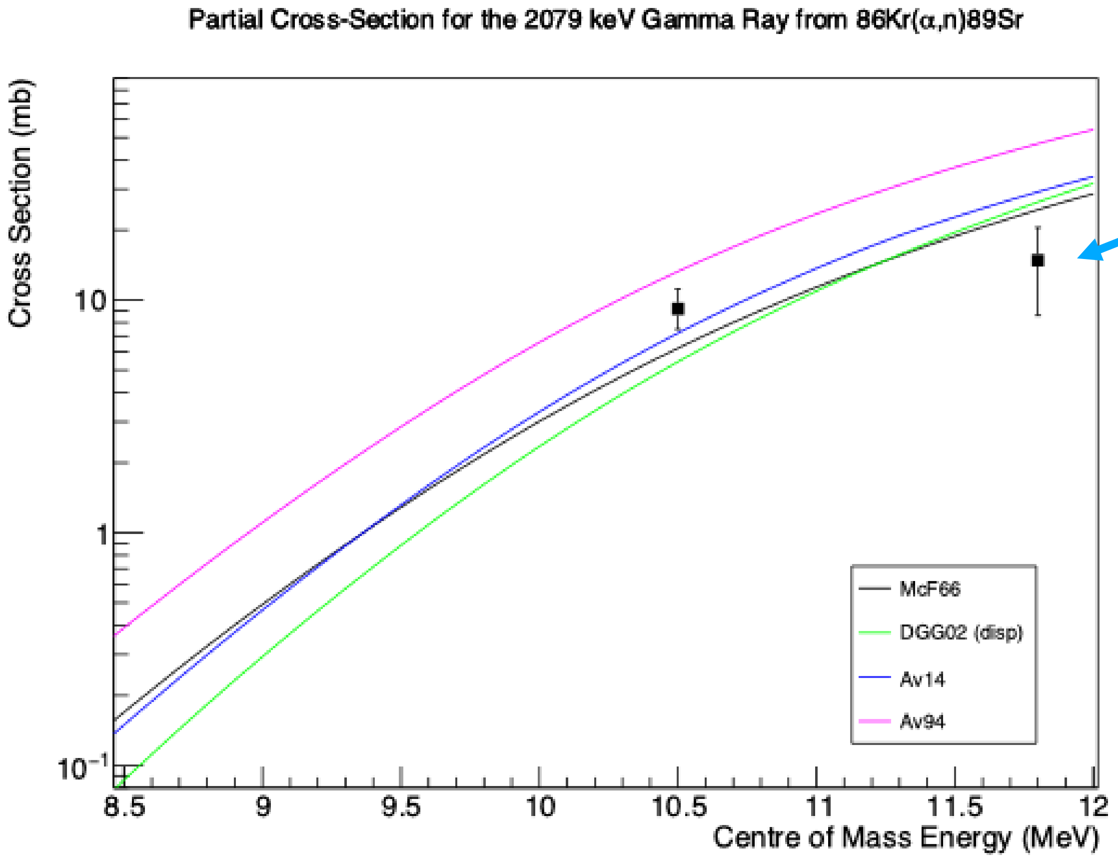


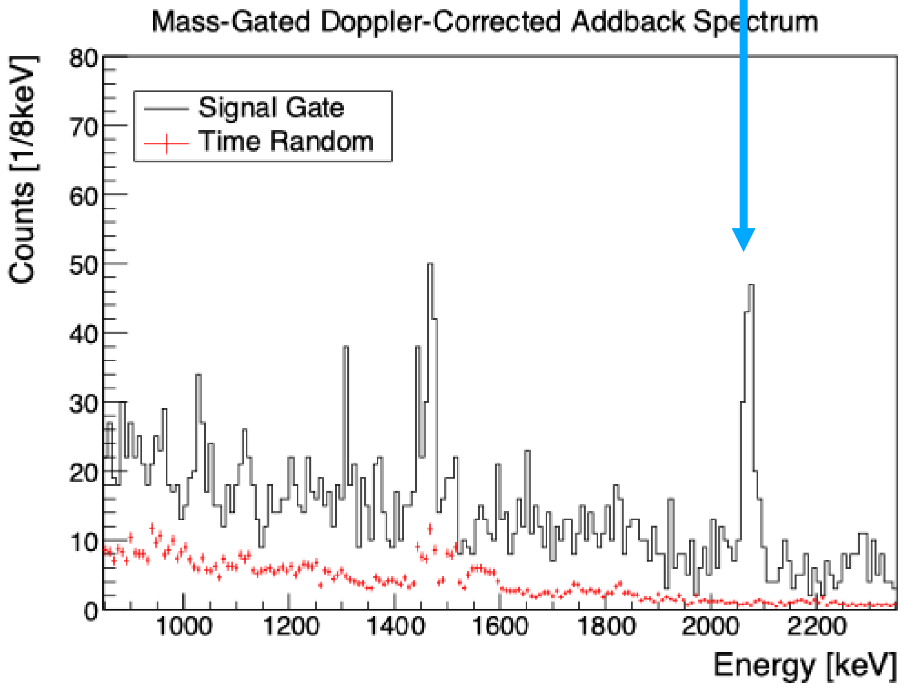


Preliminary results from ^{86}Kr(α,n)^{89}Sr: August 2022



$\sigma_{2079} = 14.8^{+5.7}_{-6.2}$ mb

2,079-keV

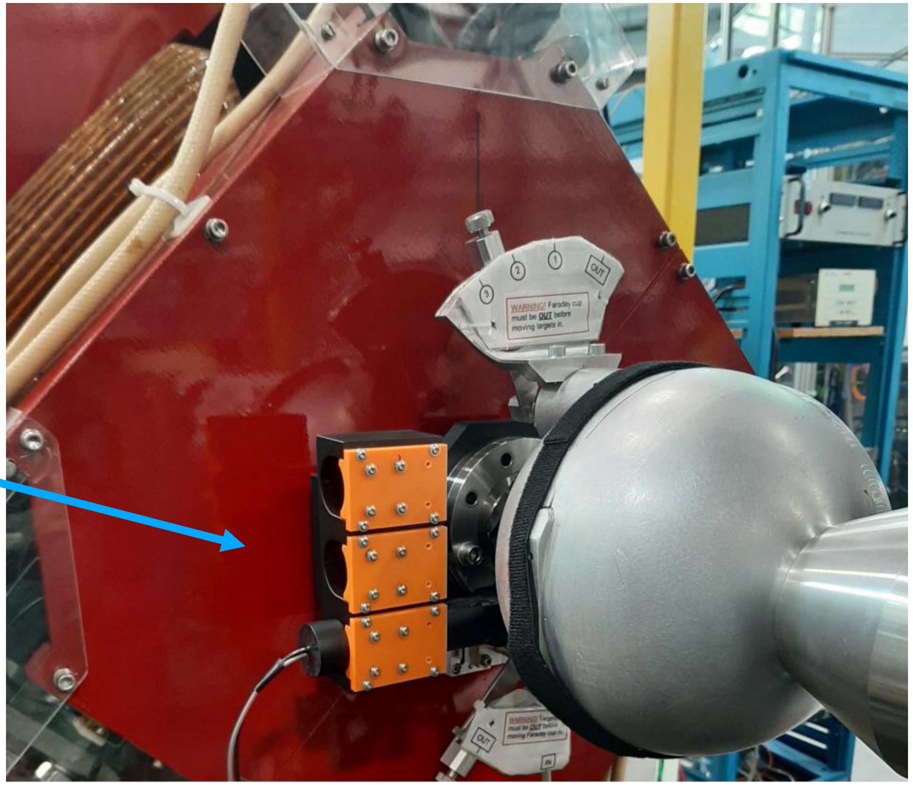


Williams *et al.* (2025) P.R.L. 134: 112701

Continuation and Future Work

- ^{93}Sr(α,n)^{96}Zr was measured earlier this year
  - Analysis being conducted by Claire Jameson from the University of Surrey

- Neutron detectors at EMMA!
  - The DEMAND array borrowed from the University of Surrey/ Saint Mary's University



Summary

- The weak r-process is a potential source of intermediate-mass elements at early times in the universe
  - (a,n) reactions a source of significant uncertainty, reaction studies are ongoing

- Partial cross sections measured at with EMMA and TIGRESS at TRIUMF for ^{86}Kr(α,n)^{89}Sr, ^{94}Sr(α,n)^{97}Zr and ^{93}Sr(α,n)^{96}Zr

M. Williams[1], A.M. Laird[2], B. Davids[1,5], A. Andreyev[2], A. Arcones[11], S. S. Bhattacharjee[3], S. Buck[4], S. Chakraborty[1,2], C. Aa. Diget[2], D. Galaviz[12], S. Gillespie[1], C. Griffin[1], A. Fernandez[6], G. Hackman[1], K. Hudson[1,5], V. Karayonchev[1], Y. H. Kim[7], \A. Lennarz[1], G. Lotay[13], K. Mashtakov[4], P. Machule[1], F. Montes[14,15], C. Natzke[8], K. Pak[7], J. Pereira[14], T. Psaltis[9], A. Radich[4], D. Rhodes[1], C. Ruiz[1], A. Simon[16], S. Upadhyayula[1], R. Wadsworth[2], J. Wiliams[1], D. Yates[1,10] & T. Zidar[4].

[1]TRIUMF, [2]University of York, [3]Czech Technical University Prague, [4]University of Guelph, [5]Simon Fraser University, [6]Universidad de Sevilla, [7]Hanyang University, [8]Colorado School of Mines, [9]Technische Universität Darmstadt, [10]University of British Columbia, [11]GSI, [12]Fisica Nuclear Liboa, [13]University of Surrey, [14]NSCL, [15]Michigan State University, [16]University of Notre Dame.

And thank you to the University of Seville for the targets!

TRIUMF

Thank you
Merci

www.triumf.ca

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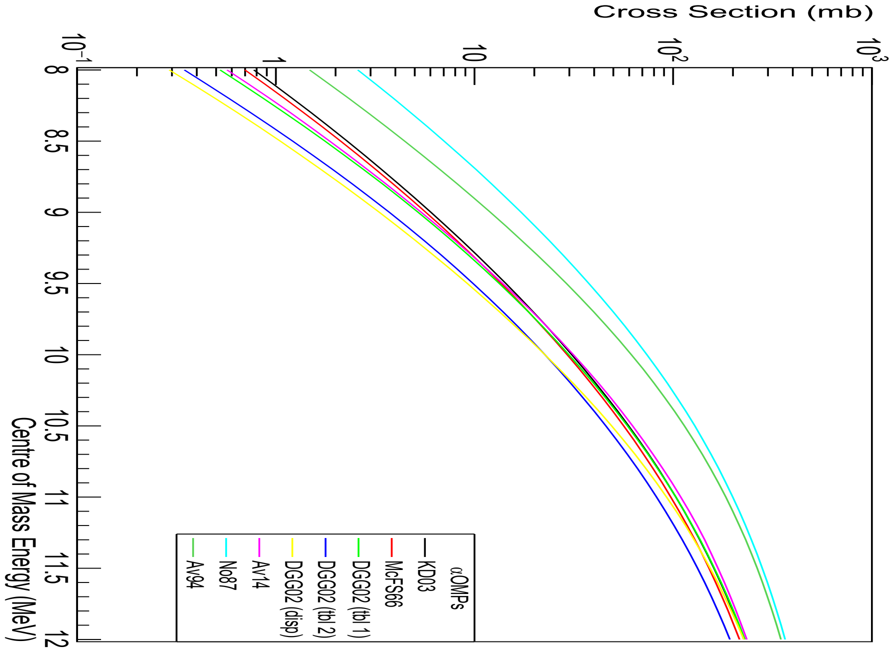
Discovery, accelerated

Spare Slides

Hauser-Feshbach Predictions

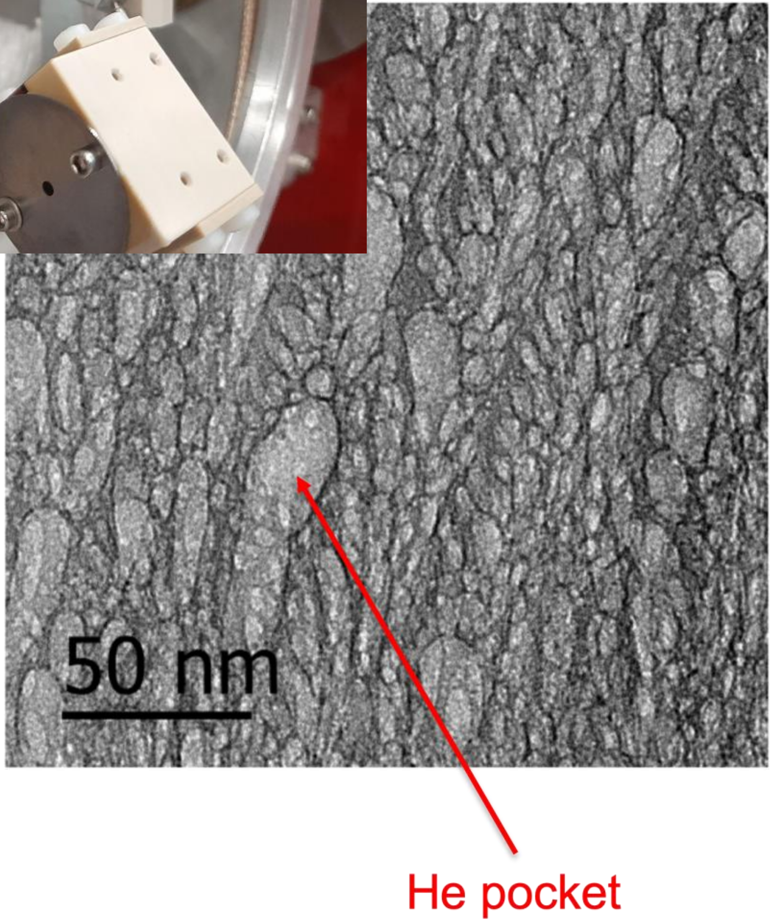
- Nucleosynthesis models rely on Hauser-Feshbach theory for (α,n) cross sections
  - Statistical averaging over many energy levels

- Significant uncertainties in abundance predictions arising from choice of α-Optical Model Potential (αOMP)



He:Si Targets

- Novel target design
- Magnetron-sputtered Si
- Traps pockets of He
- He density ~ $3.3 - 5.4 \times 10^{18}$ atoms cm^{-2}
  - Comparable to windowless gas-targets



Godinho *et al.* (2016) ACS Omega

Magnetron Sputtering

- He plasma forms a torus in the head
- Electric field accelerates He ions into Silicon surface
- Si atoms scattered into chamber
- Si deposits grow as a film on chosen substrate

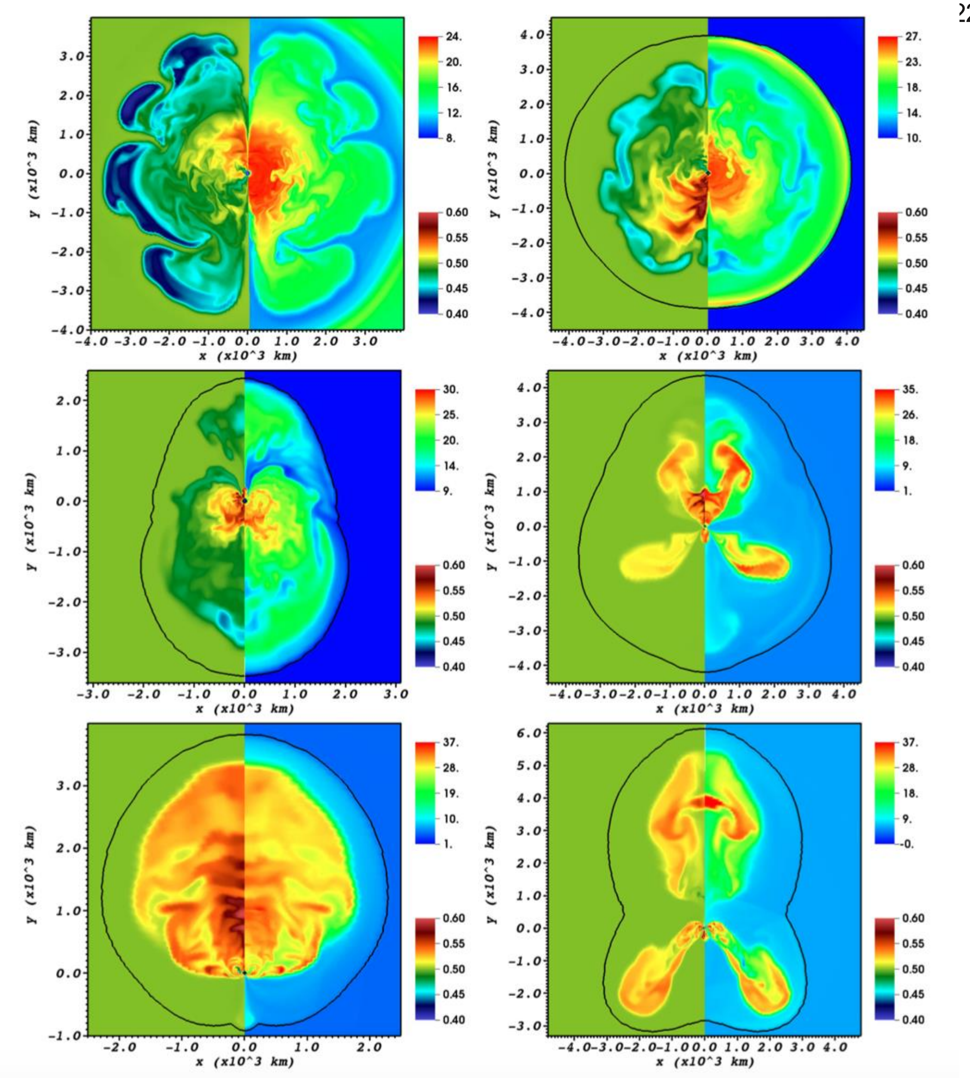
Neutrino-driven Winds

$$Y_e = \frac{N_p}{N_p + N_n}$$

- Expected to be proton-rich, but with significant slightly neutron-rich pockets

- $(\alpha$,n) reactions are most important for driving nucleosynthesis

- $T = 2\ - 5$GK and $Y_e = 0.40\ - 0.49$



Wanajo *et al*., (2018) ApJ.