Particle-Gamma Coincidence Studies of $^{93}Sr(d,p)^{94}Sr$ via the Surrogate Reaction Method

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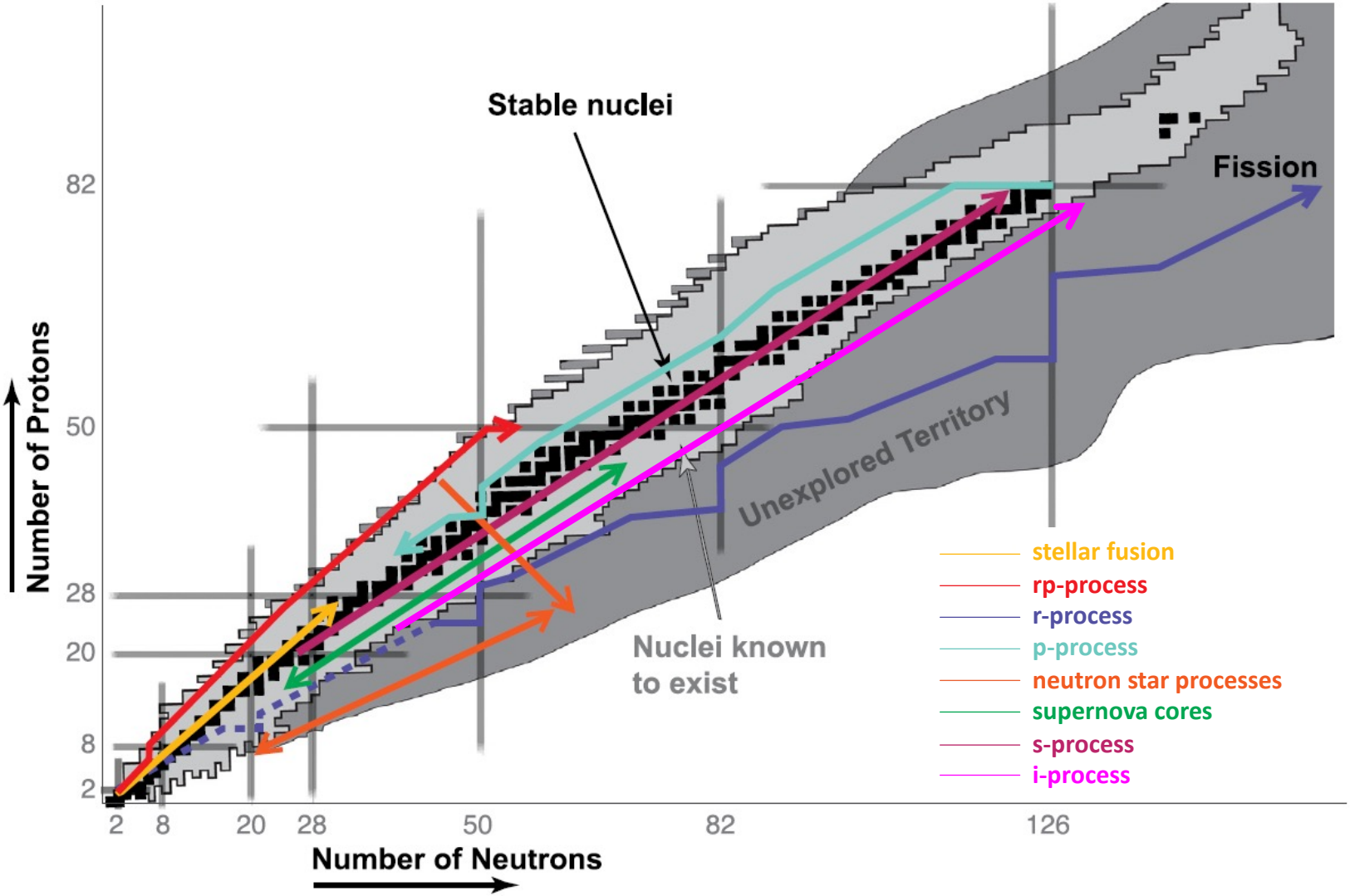
Nucleosynthesis across the Nuclear Landscape



A. Arcones *et al.*, PPNP **94**, 67 (2017) and adapted from Frank Timmes

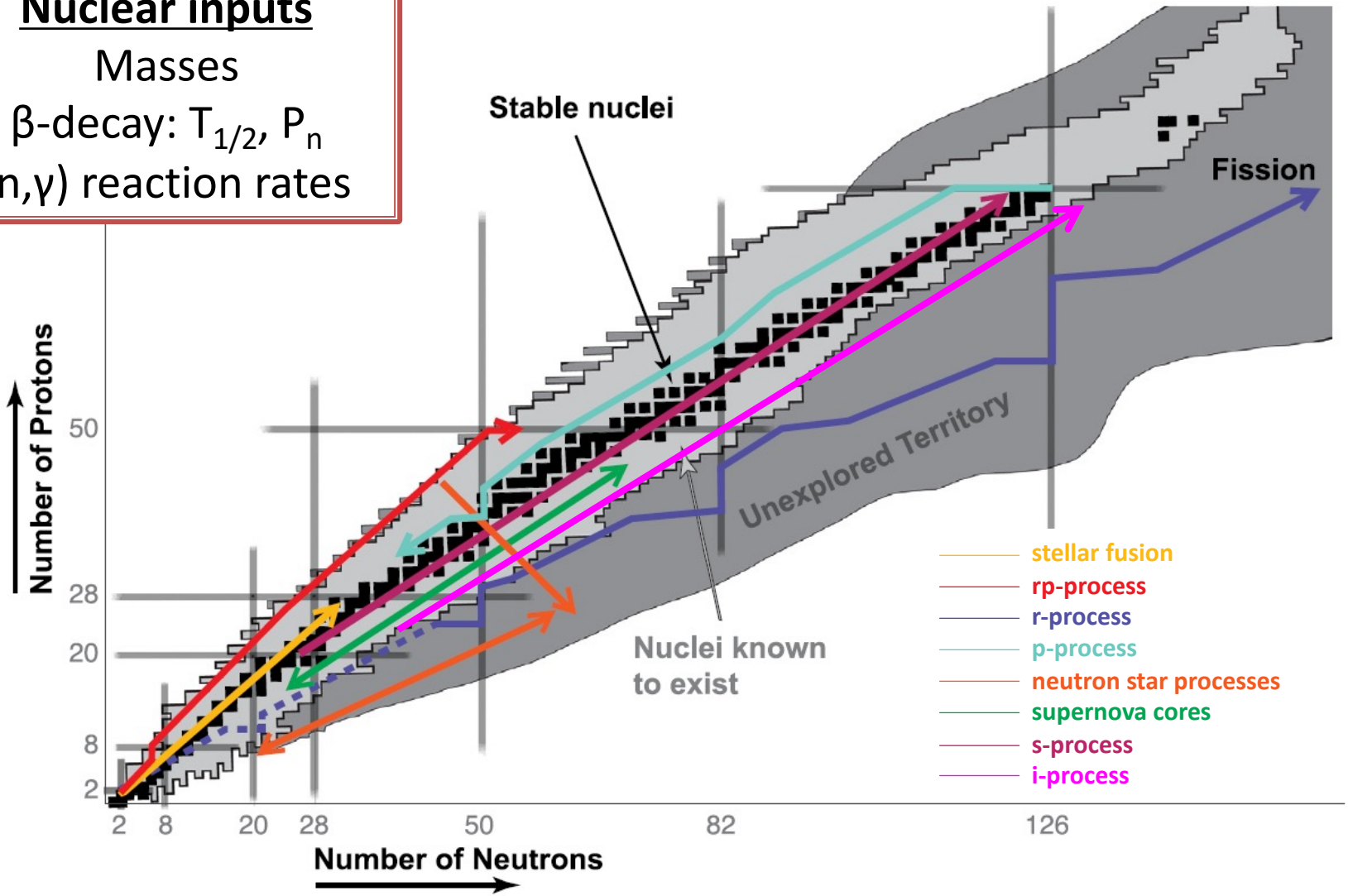
Nucleosynthesis across the Nuclear Landscape

Nuclear inputs

Masses

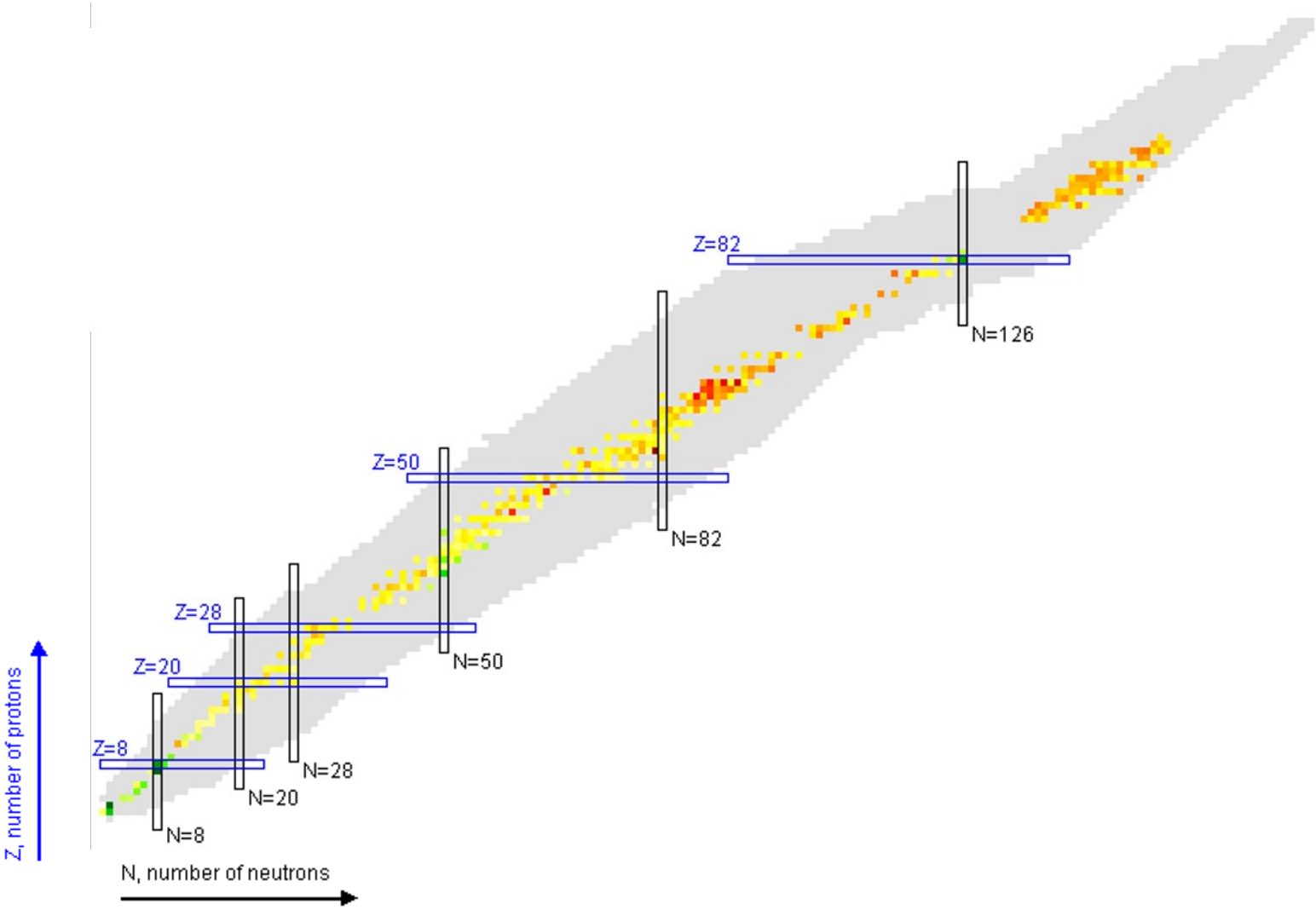
β-decay: $T_{1/2}$, P_n

(n,γ) reaction rates



A. Arcones *et al.*, PPNP **94**, 67 (2017) and adapted from Frank Timmes

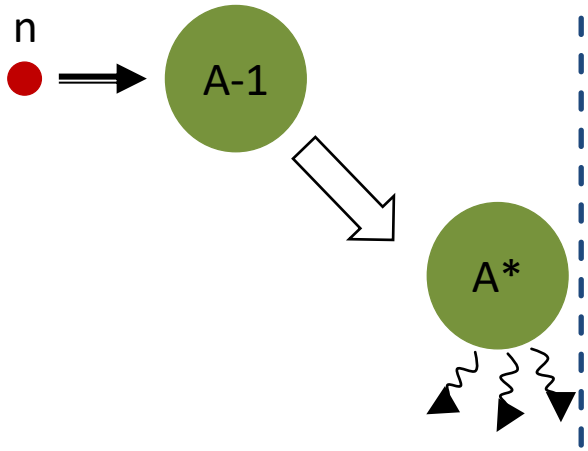
Current (n,γ) measurements are limited



Neutron-capture constraints for radioactive nuclei

Direct Measurement

- Desired targets are too short-lived
- No feasible neutron target
- Not possible for rare isotopes



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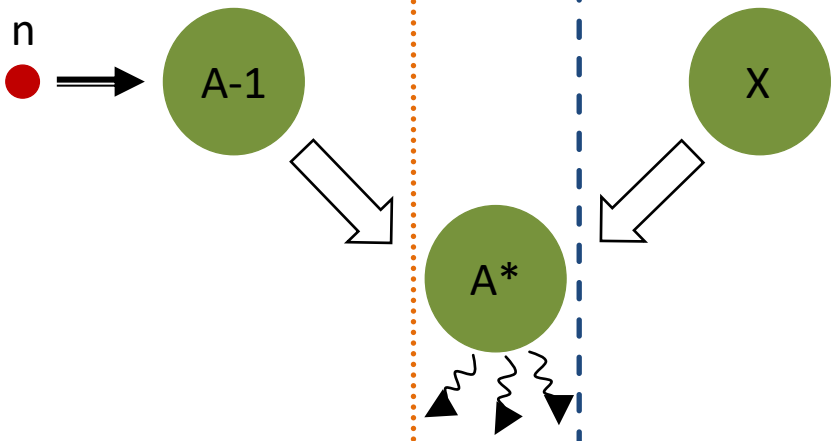
Indirect Measurement

- Access same nucleus through different pathway
- Can utilize short half-lives and reaction mechanisms



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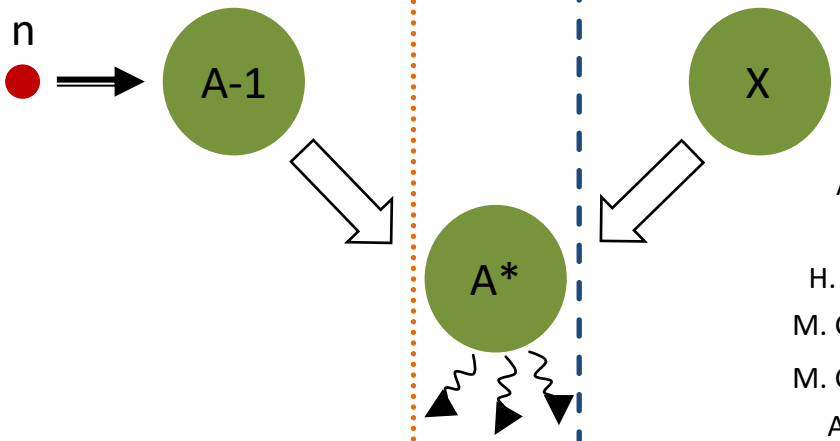


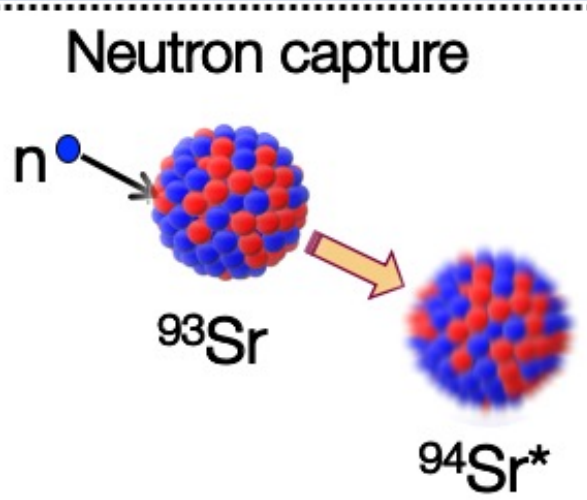
Indirect Measurement

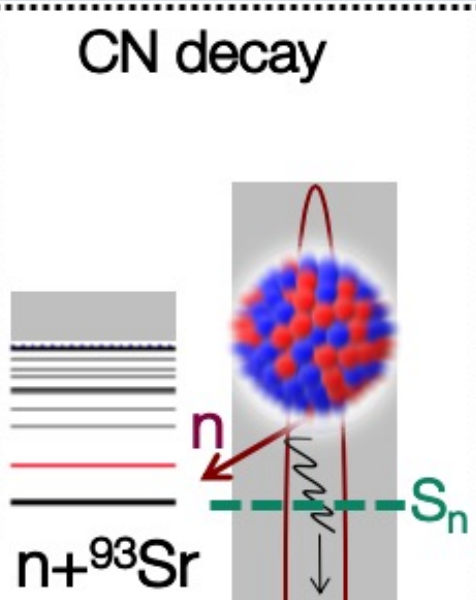
- Access same nucleus through different pathway
- Can utilize short half-lives and reaction mechanisms

Examples:
Oslo Method
β-Oslo Method
Surrogate Method
γ-ray strength method

A. Spyrou *et al.*, PRL **113**, 232502 (2014)
J. Escher *et al.*, PRL **121**, 052501 (2018)
H. Utsunomiya *et al.*, PRC **82**, 064610 (2010)
M. Guttormsen *et al.*, NIMA **255**, 518 (1987)
M. Guttormsen *et al.*, NIMA **374**, 371 (1996)
A. Schiller *et al.*, NIMA **447**, 498 (2000)
A.C. Larsen *et al.*, PRC **83**, 034315 (2011)

Surrogate Reaction Method

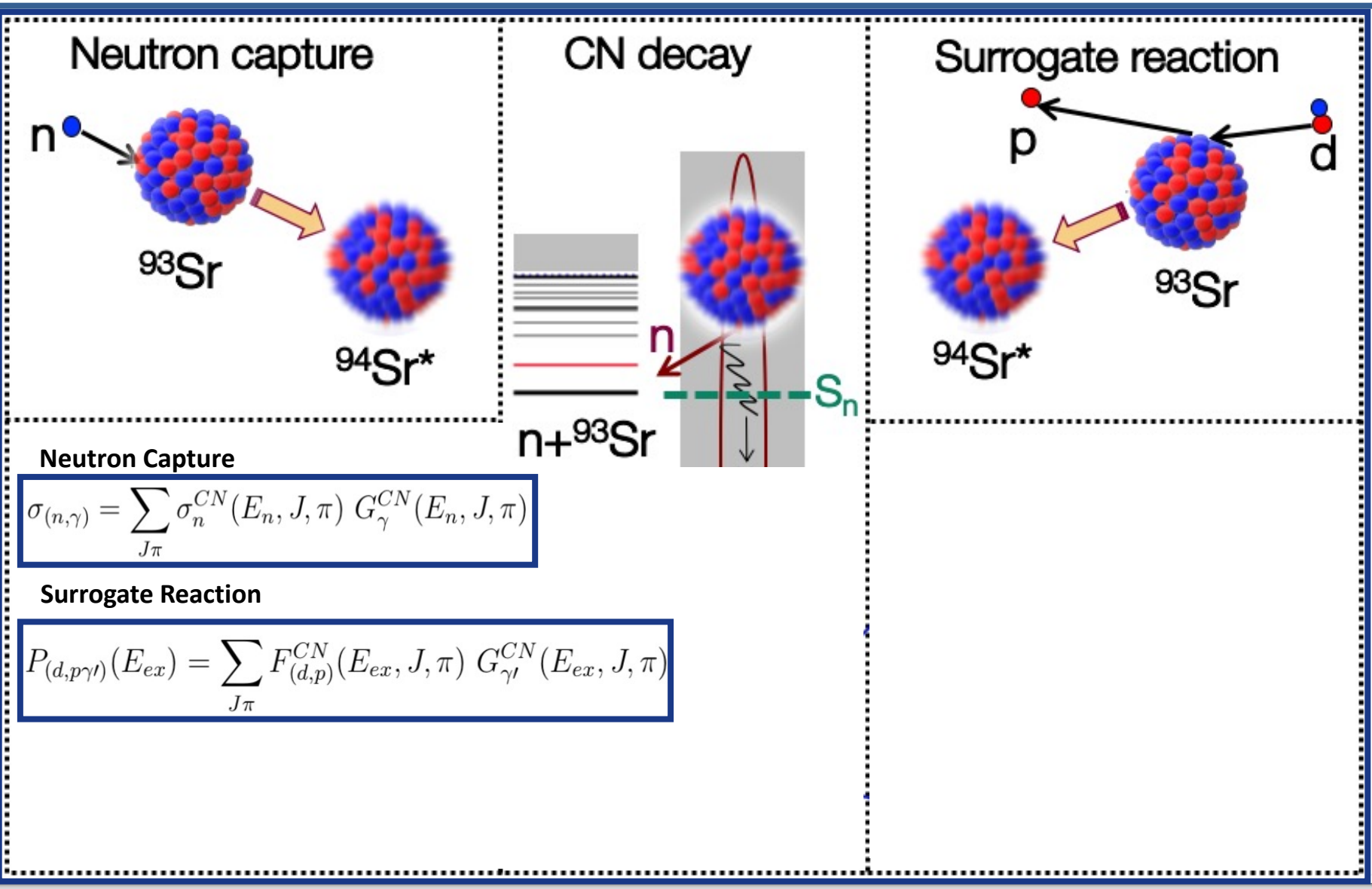




Neutron Capture

$$\sigma_{(n,\gamma)} = \sum_{J\pi} \sigma_n^{CN}(E_n, J, \pi)\; G_\gamma^{CN}(E_n, J, \pi)$$

Surrogate Reaction Method



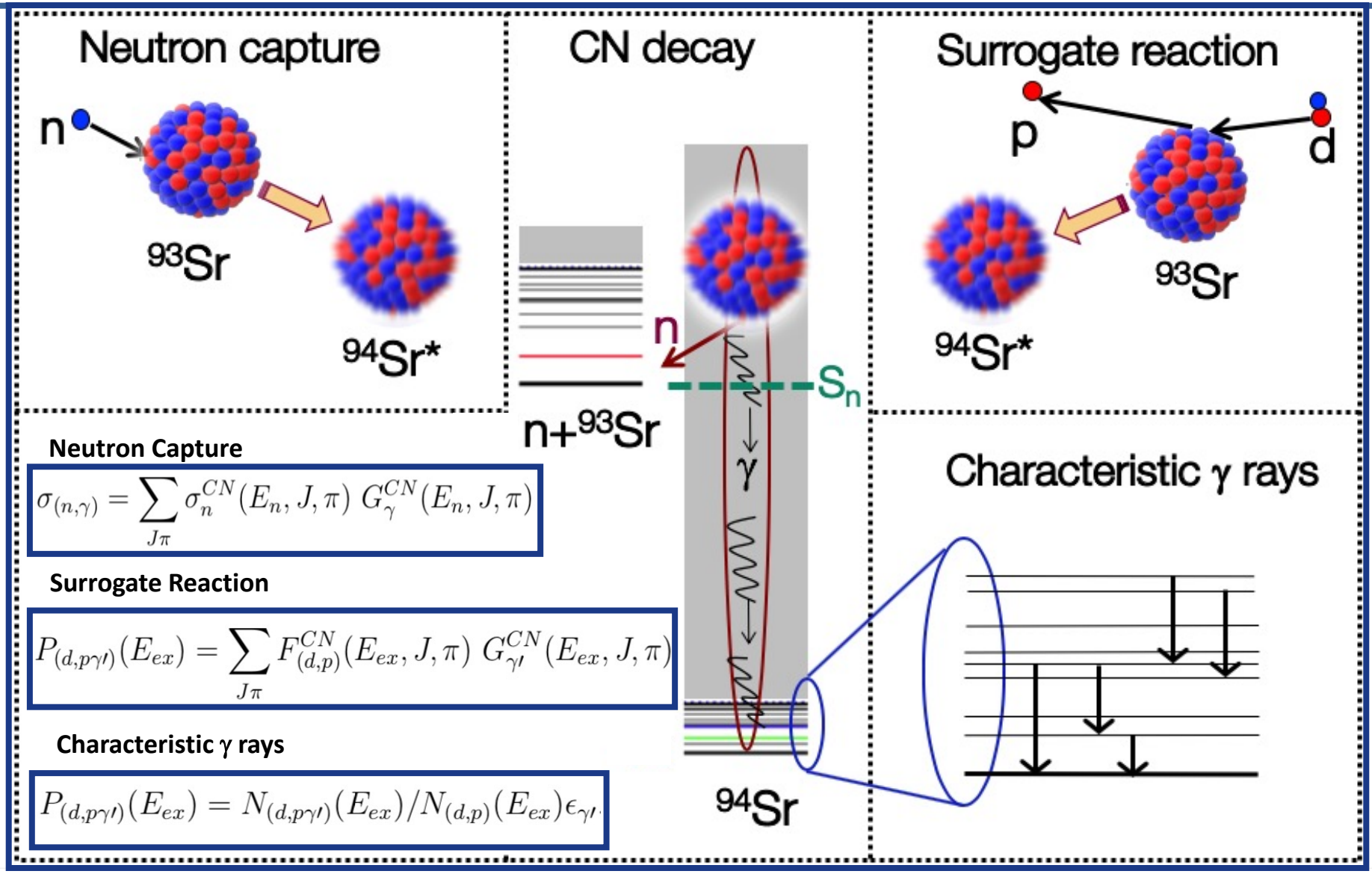
Neutron Capture

$$\sigma_{(n,\gamma)} = \sum_{J\pi} \sigma_n^{CN}(E_n, J, \pi)\; G_\gamma^{CN}(E_n, J, \pi)$$

Surrogate Reaction

$$P_{(d,p\gamma\prime)}(E_{ex}) = \sum_{J\pi} F_{(d,p)}^{CN}(E_{ex}, J, \pi)\; G_{\gamma\prime}^{CN}(E_{ex}, J, \pi)$$

Surrogate Reaction Method



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$$P_{(d,p\gamma\prime)}(E_{ex}) = \sum_{J\pi} F_{(d,p)}^{CN}(E_{ex}, J, \pi)\ G_{\gamma\prime}^{CN}(E_{ex}, J, \pi)$$

Characteristic γ rays

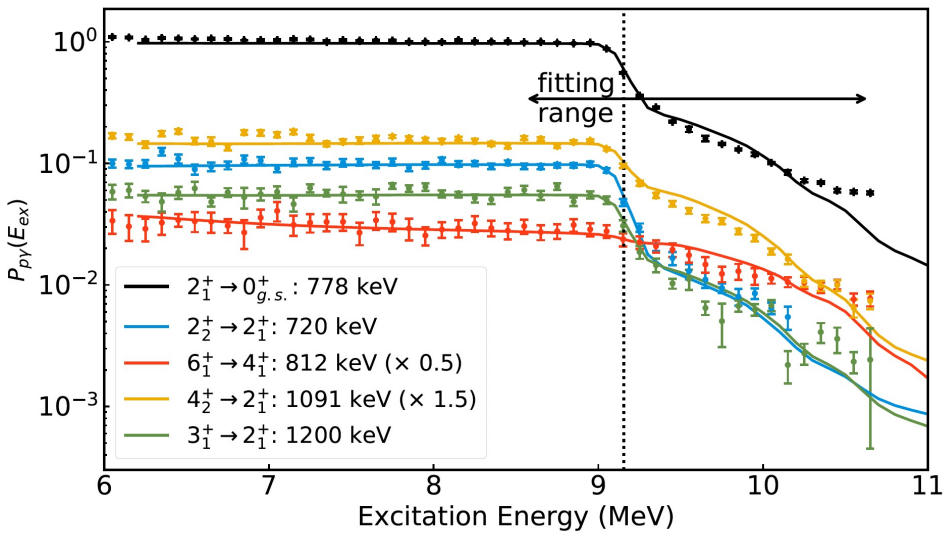
$$P_{(d,p\gamma\prime)}(E_{ex}) = N_{(d,p\gamma\prime)}(E_{ex})/N_{(d,p)}(E_{ex})\epsilon_{\gamma\prime}$$

G. Potel *et al.*, PRC **92**, 034611 (2015).
J. Escher *et al.*, PRL **121**, 052501 (2018)

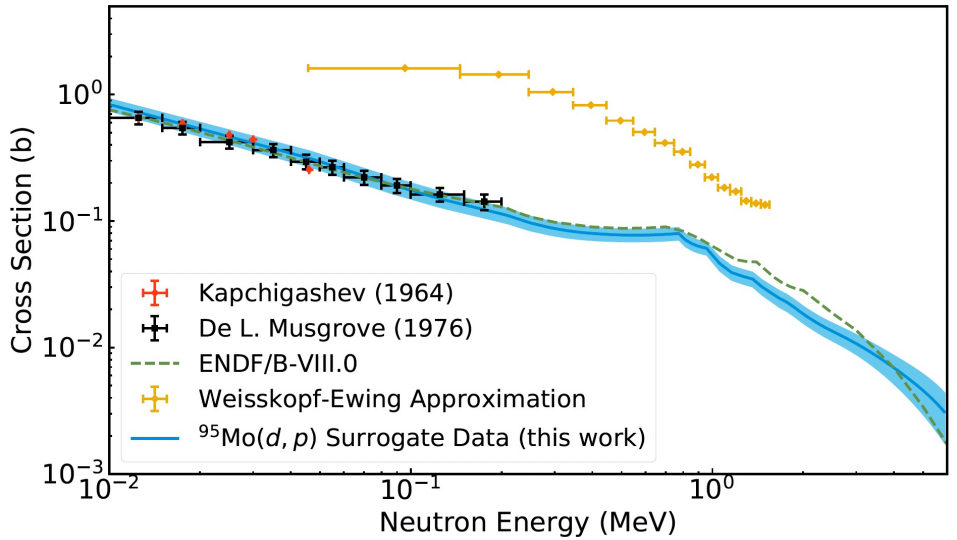
Surrogate Reaction Method validated (d,p) reactions as surrogate for (n,γ)

- (d,p) validated as a surrogate for (n,γ) using ^{95}Mo(d,pγ) in normal kinematics

γ-ray coincidence probabilities for characteristic γ rays in ^{95}Mo(d,pγ)



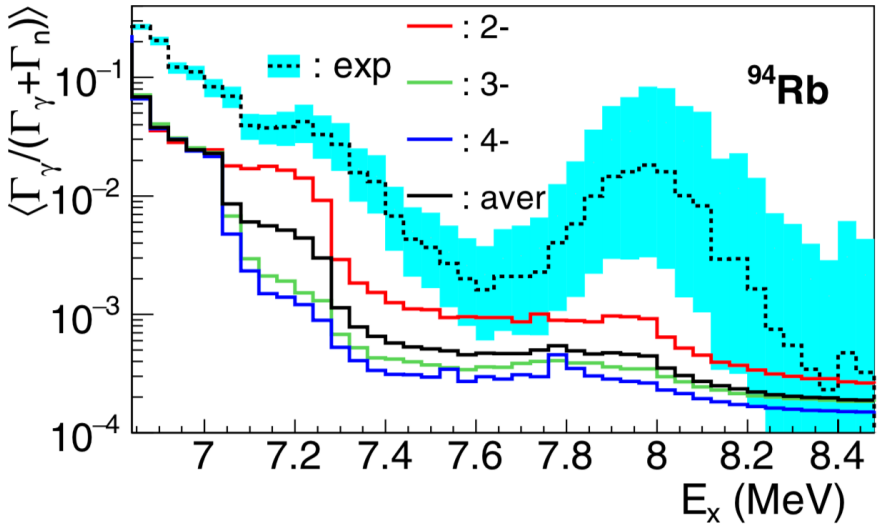
Constrained ^{95}Mo(n,γ) cross section



A. Ratkiewicz *et al.* PRL **122**, 052502 (2019)

Decay studies suggest enhanced capture rate for ^{93}Sr(n,γ)

- β-decay studies following ^{94}Rb decay to ^{94}Sr show unusually high γ-decay branch above S_n
  - Enhancement in neutron-capture of ^{93}Sr?
- Constraining (n,γ) for ^{93}Sr imperative, but $t_{1/2}$ = 7.4 min
- Surrogate reaction measurement at TRIUMF to probe ^{93}Sr(d,pγ)!



J. L. Tain *et al.* PRL **115**, 062502 (2015)

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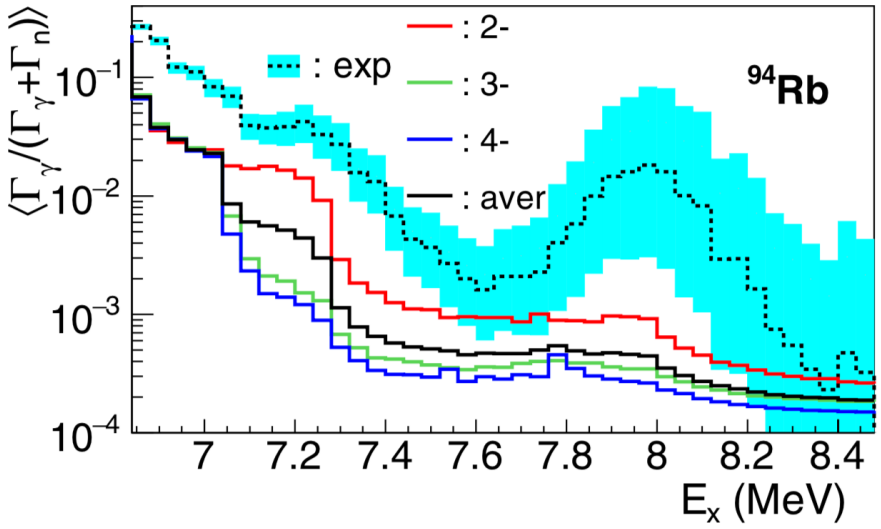
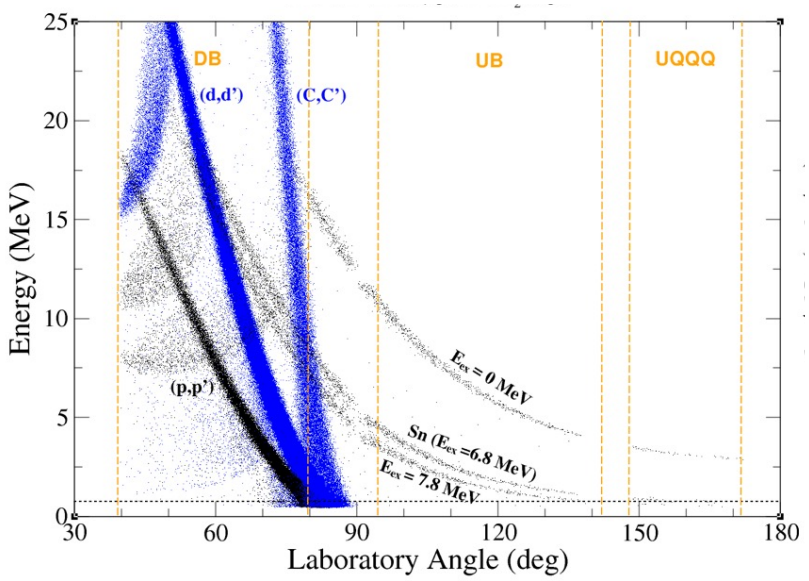


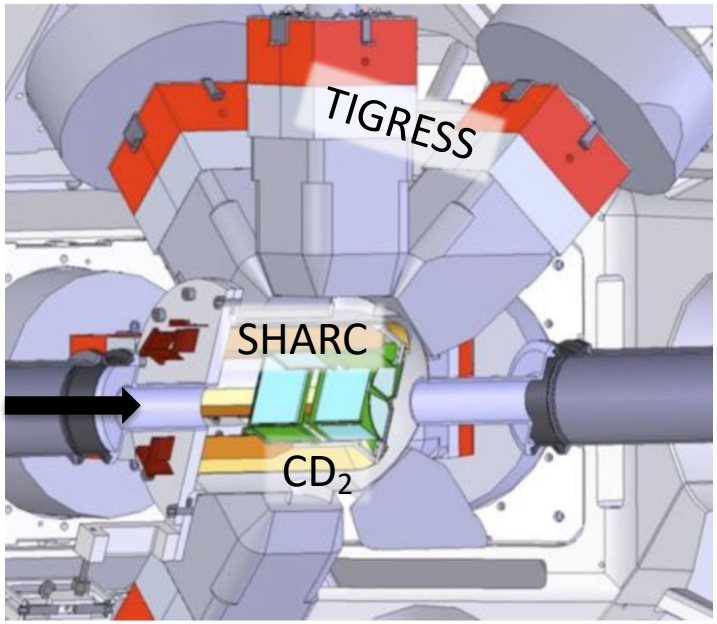


J. L. Tain *et al.* PRL **115**, 062502 (2015)

Surrogate reaction measurement of ^{93}Sr(d,p) at TRIUMF

- 8 MeV/u ^{93}Sr beam impinged on CD_2 target (369 $\mu g/cm^2$, 446 $\mu g/cm^2$)
- Proton detection: SHARC
  - Segmented Si array
  - 80% of 4π coverage
  - ~80% efficiency
- Gamma detection: TIGRESS
  - 12 HPGe clovers
  - Efficiency (1 MeV) ~ 10%
  - ~2π coverage
- SHARC + TIGRESS enable particle-gamma coincidences

^{93}Sr



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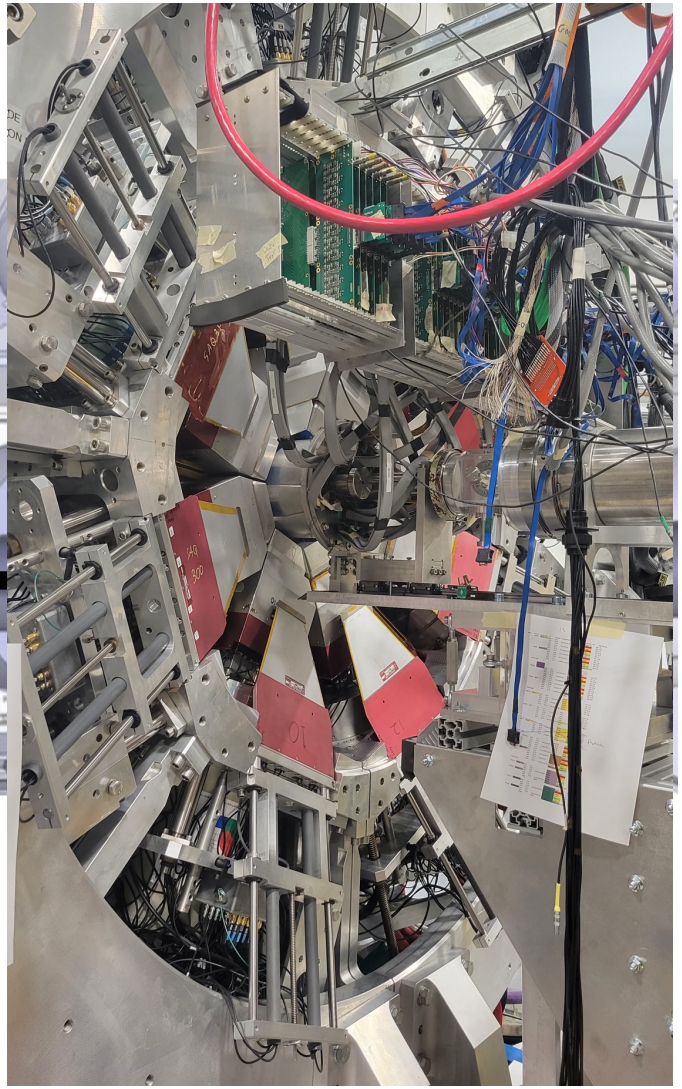
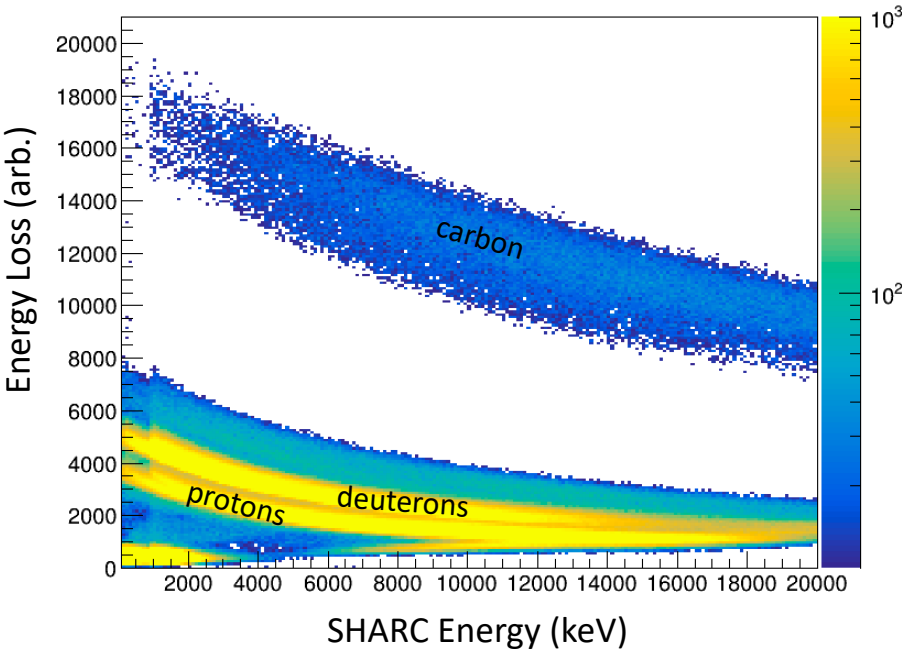
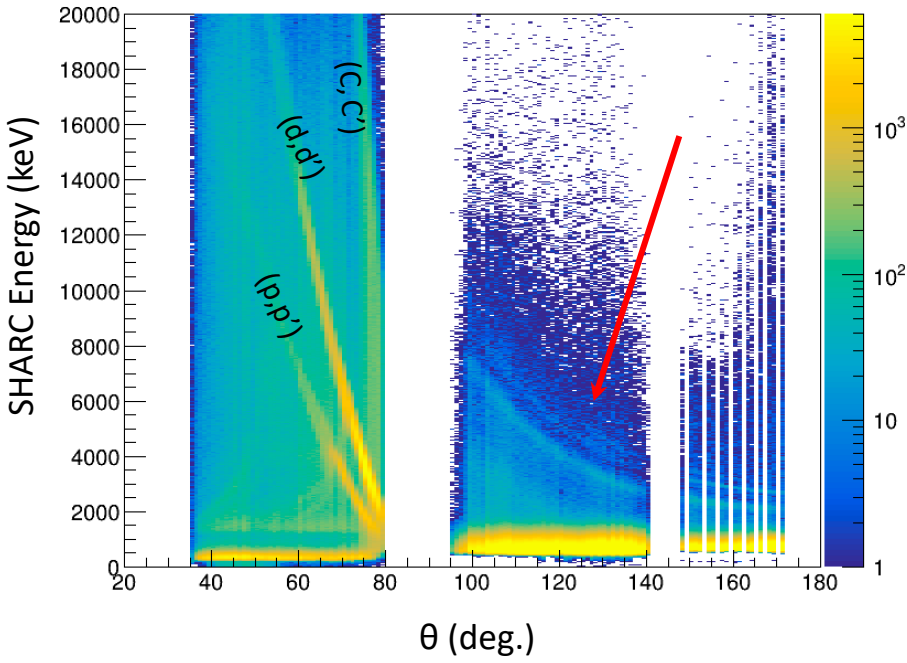


Preliminary particle-γ coincidence results

Particle Identification



Kinematics of measured particles



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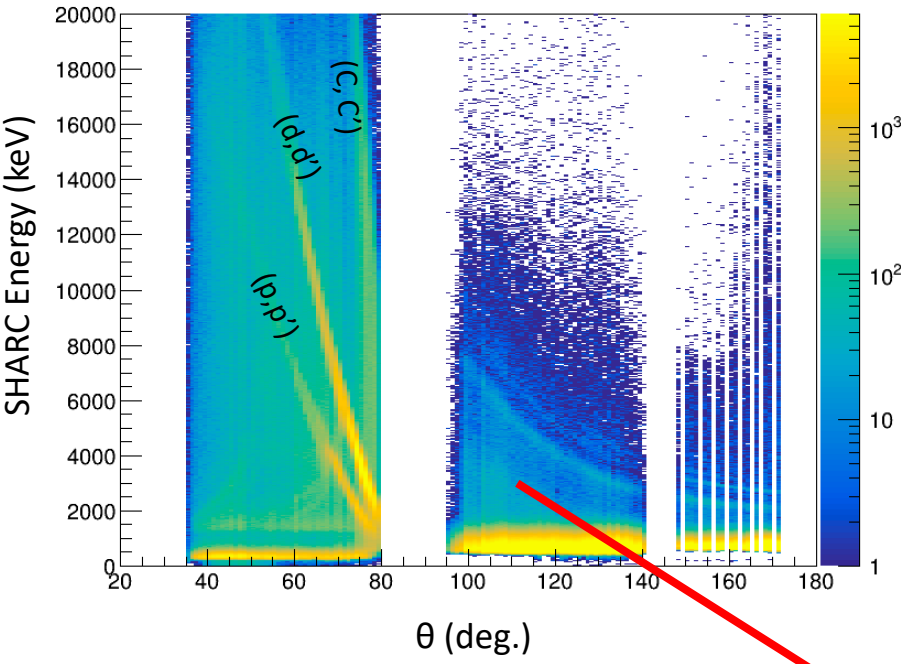

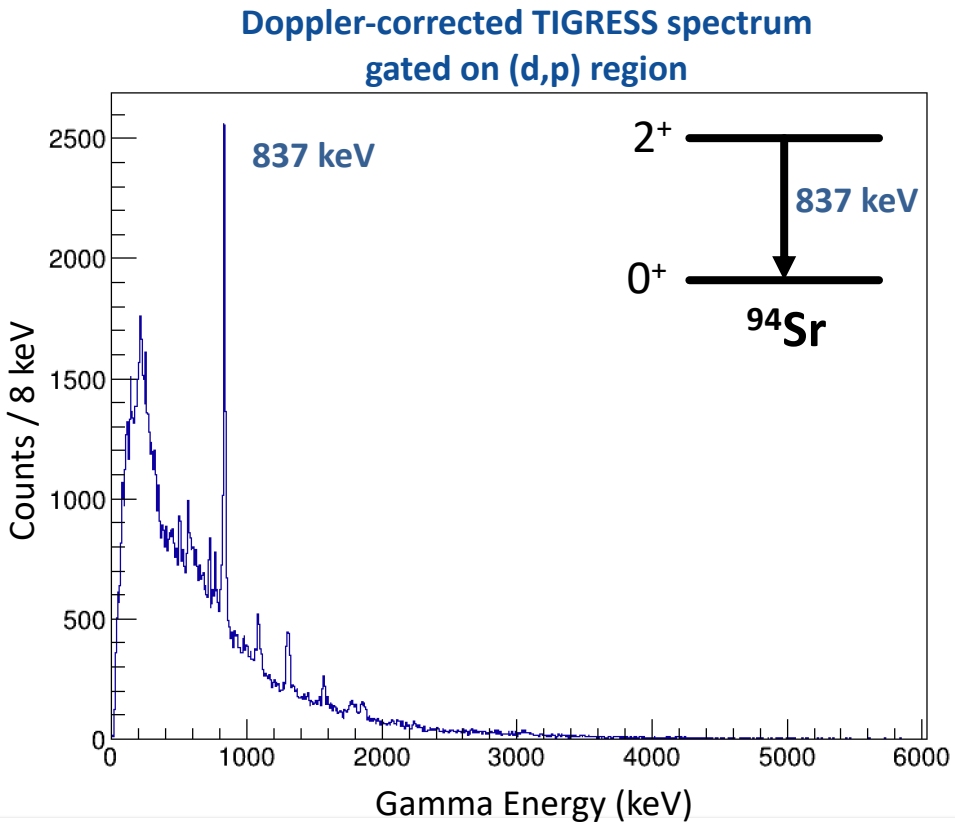

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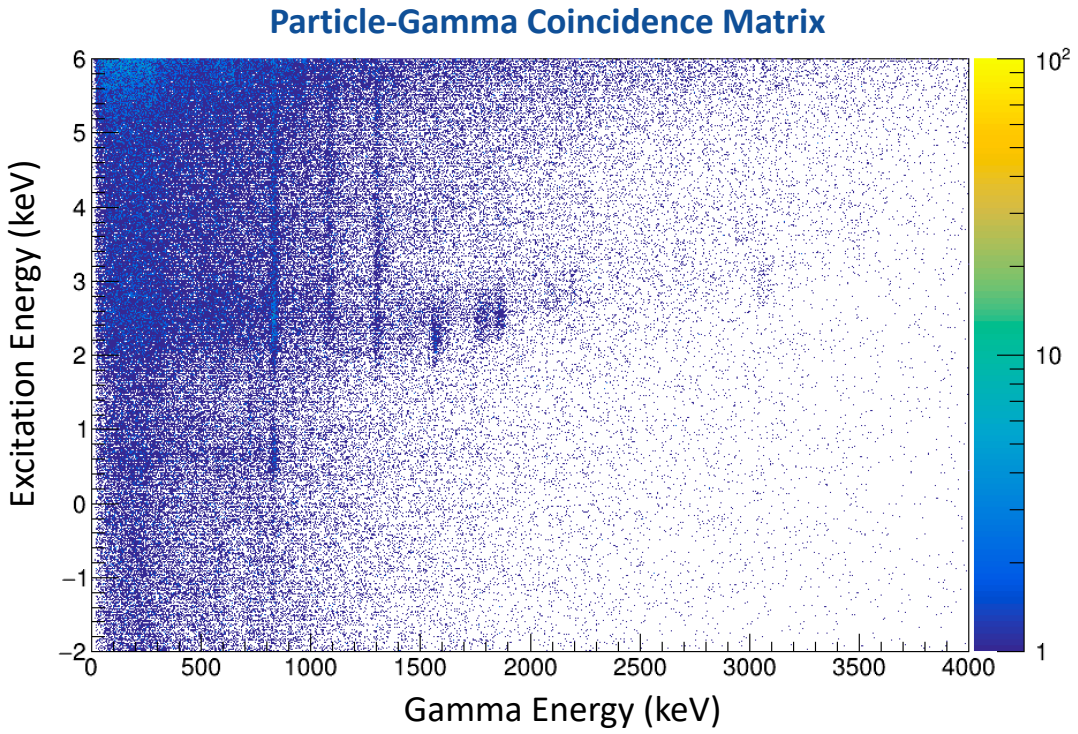

- Excitation energy vs. gamma-ray energy spectra will be used to create $P_{(d,p\gamma)}$ for Surrogate Analysis

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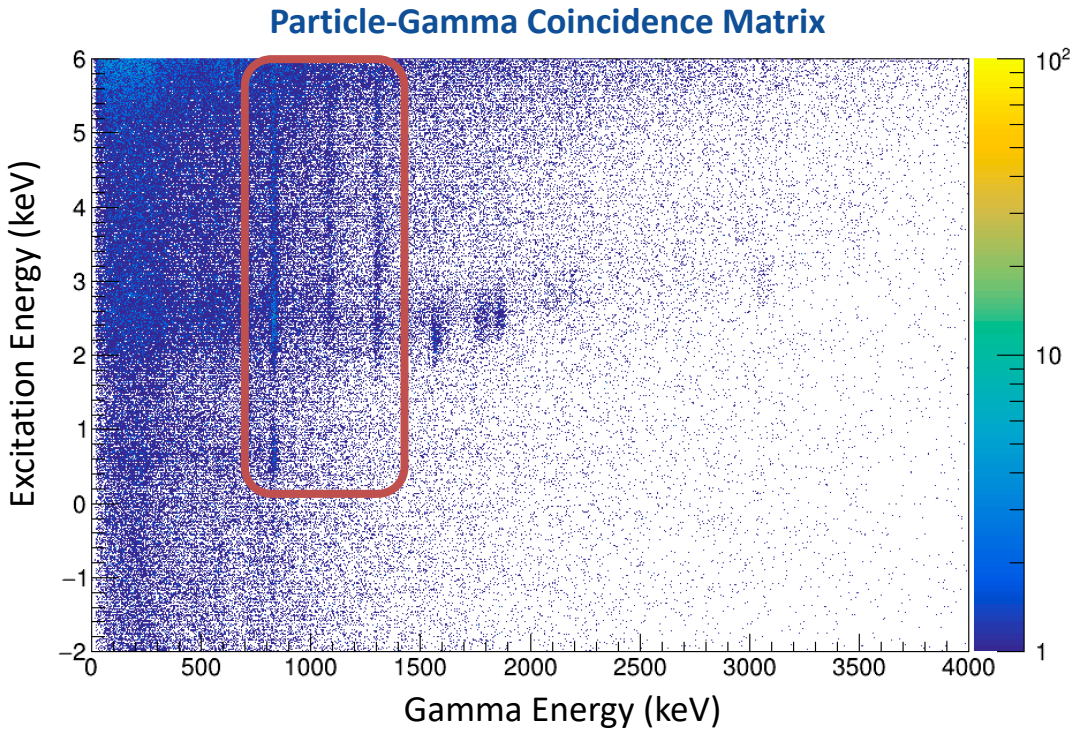
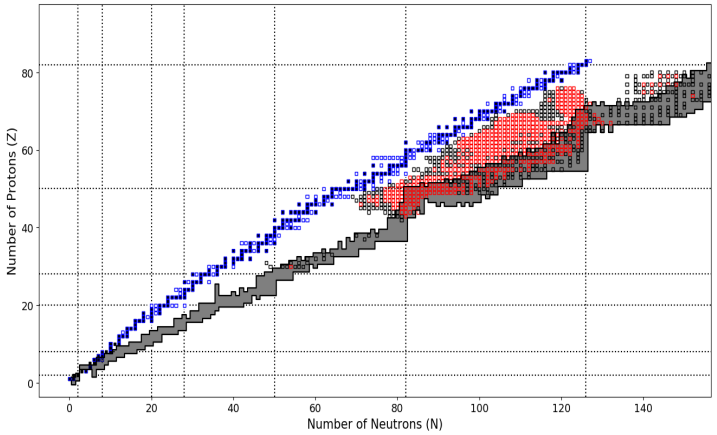


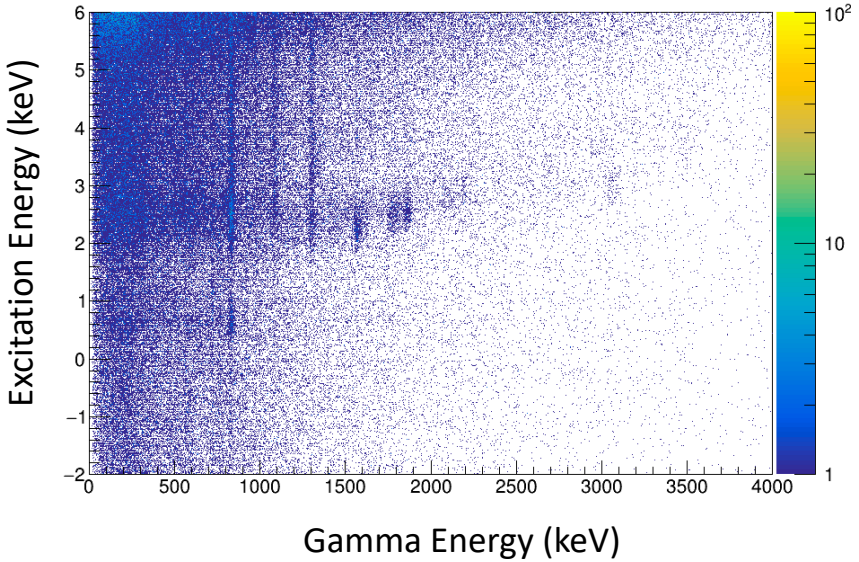
- Excitation energy vs. gamma-ray energy spectra will be used to create $P_{(d,p\gamma)}$ for Surrogate Analysis

Summary & Outlook

- (n,γ) reactions are vital for our understanding of nucleosynthesis
- Surrogate Reaction Method provides experimental constraints for (n,γ) reactions far from stability
- ^{93}Sr(n,γ) predicted to have enhanced (n,γ) rate from β-decay studies
- ^{93}Sr(d,pγ) preformed at TRIUMF using SHARC + TIGRESS
- More results to come for ^{93}Sr and ^{95}Sr
- Many opportunities at FRIB, nuCARIBU, TRIUMF



Ratkiewicz, DNP Presentation, 2018



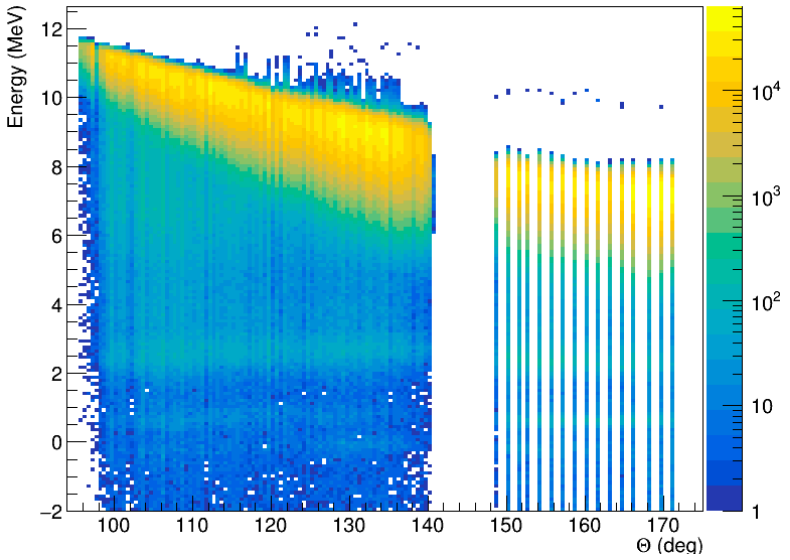
Acknowledgments

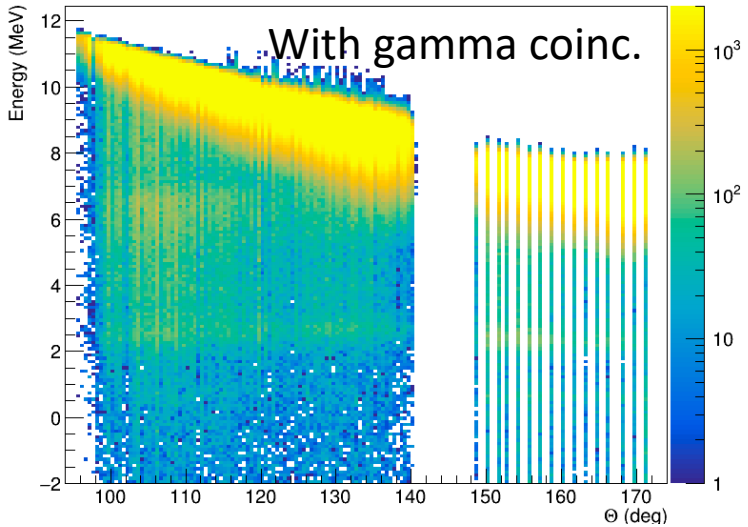
R. O. Hughes[1], G. Hackman[2], D. Yates[2], C. Angus[2], D. Bishop[2], R. Caballero-Folch[2], L. Canete[3], R. Coleman[4], B. Davids[2], S. Devinyak[2], I. Dillman[2], A. Garnsworthy[2], S. Georges[2], M. Gott[5], B. Greaves[4], C. Griffin[2], J. Henderson[3], K. Hudson[2], D. Hymers[4], V. Karayonchev[2], E. Kasanda[4], R. Kruecken[2], G. Leckenby[2], P. Machule[2], M. Martin[2], C. Natzke[2], K. Pak[2], A. Ratkiewicz[1], D. Rhodes[2], Y. Saito[2], T. Schilbach[2], N. Scielzo[1], B. Shaw[2], J. Smallcombe[6], C. Svensson[4], D. Torres[2], R. Umashankar[2], S. Upadhyayula[2], P. Virally[2], J. Williams[2], M. Williams[2]

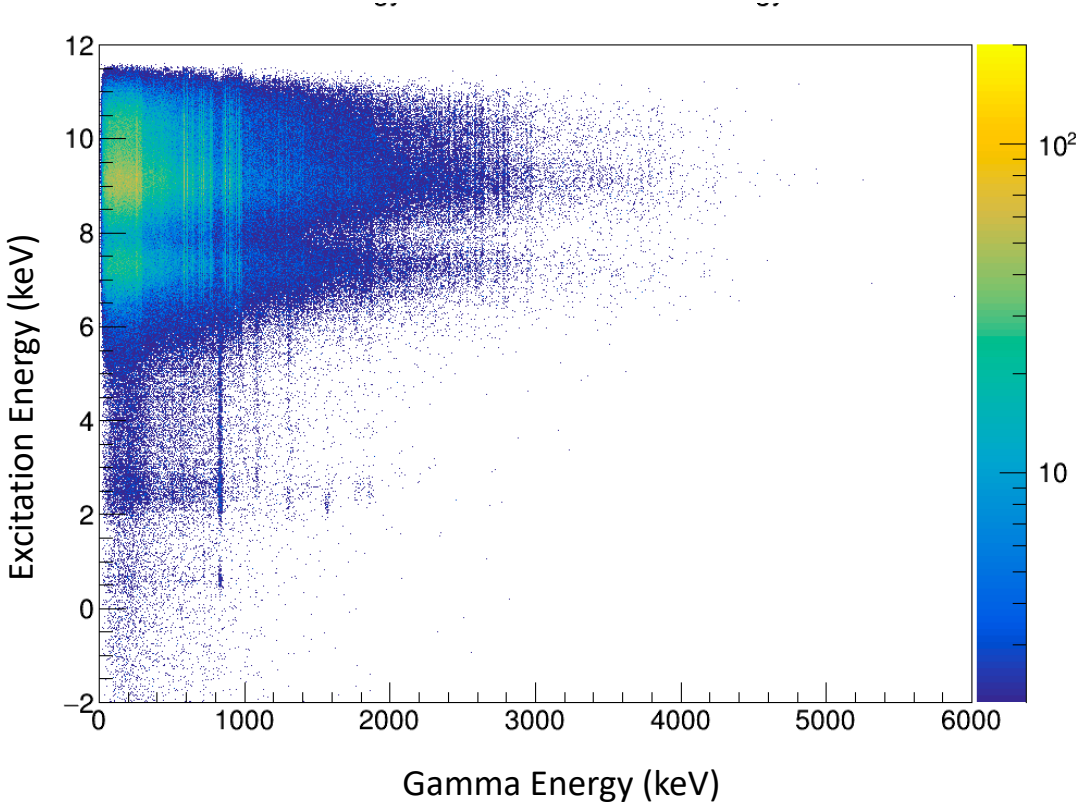
*This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344

Thank you!
Questions?

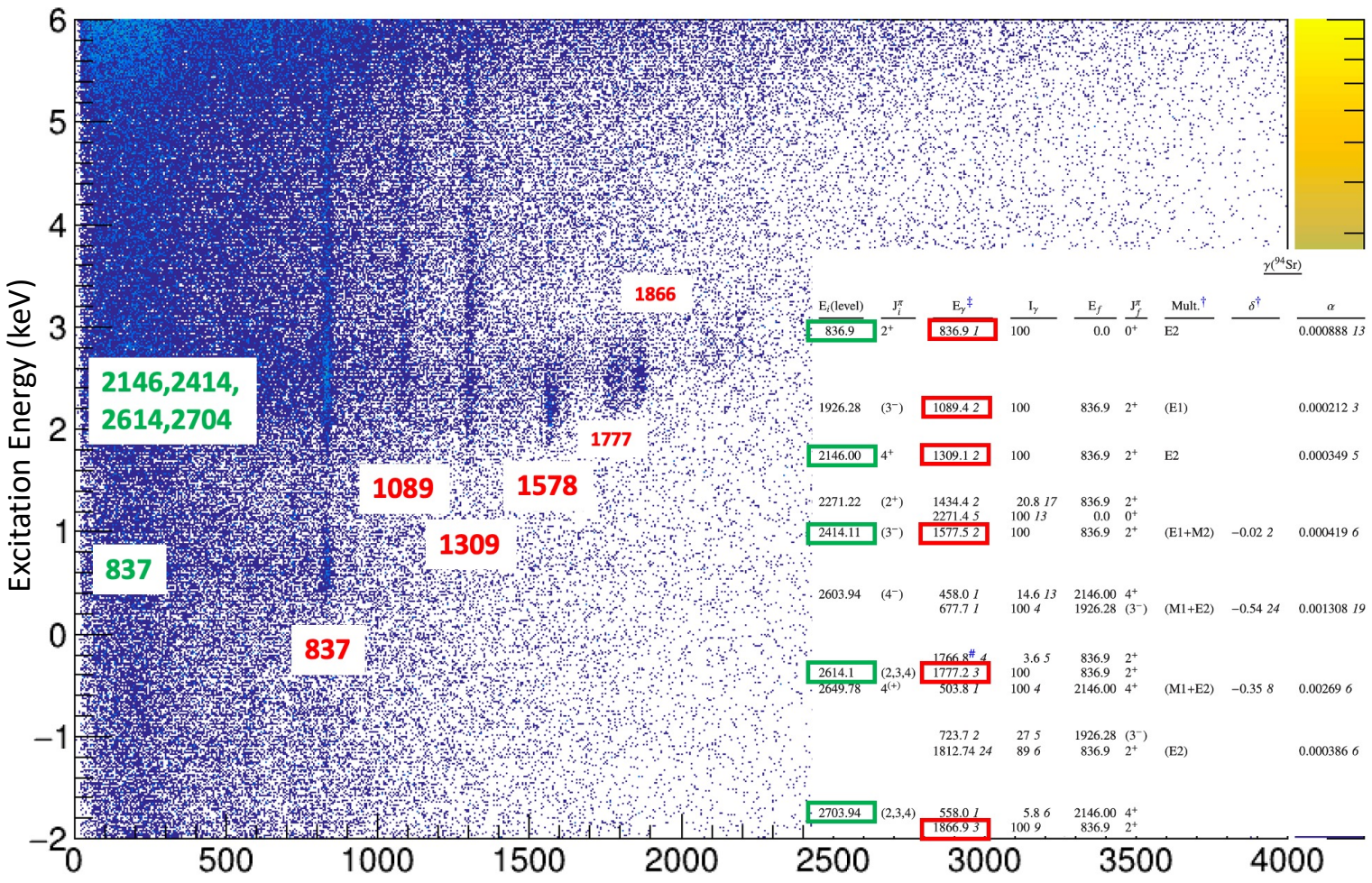
Excitation Energy Plots







Excitation energy with identified levels and gammas



E_i(level)	J_i^π	E_γ‡	I_γ	E_f	J_f^π	Mult.†	δ†	α	Comments
836.9	2^+	836.9 *1*	100	0.0	0^+	E2		0.000888 *13*	α=0.000888 *13*; α(K)=0.000785 *11*; α(L)=8.63×10^{-5} *12*; α(M)=1.448×10^{-5} *21* α(O)=1.160×10^{-7} *17*; α(N+..)=1.93×10^{-6} B(E2)(W.u.)=8 *4* Mult.: From γγ(θ) and B(E2) =8.4.
1926.28	(3^-)	1089.4 *2*	100	836.9	2^+	(E1)		0.000212 *3*	α=0.000212 *3*; α(K)=0.000188 *3*; α(L)=2.01×10^{-5} *3*; α(M)=3.36×10^{-6} *5*; α(N)=4.23×10^{-7} *6* α(O)=2.77×10^{-8} *4*; α(N+..)=4.50×10^{-7} *7*
2146.00	4^+	1309.1 *2*	100	836.9	2^+	E2		0.000349 *5*	α=0.000349 *5*; α(K)=0.000283 *4*; α(L)=3.06×10^{-5} *5*; α(M)=5.13×10^{-6} *8*; α(N)=6.44×10^{-7} *9* α(O)=4.20×10^{-8} *6*; α(N+..)=3.01×10^{-5} *5*
2271.22	(2^+)	1434.4 *2*	20.8 *17*	836.9	2^+				
		2271.4 *5*	100 *13*	0.0	0^+				
2414.11	(3^-)	1577.5 *2*	100	836.9	2^+	(E1+M2)	−0.02 *2*	0.000419 *6*	α=0.000419 *6*; α(K)=9.89×10^{-5} *15*; α(L)=1.050×10^{-5} *16*; α(M)=1.76×10^{-6} *3*; α(N)=2.21×10^{-7} *4* α(O)=1.459×10^{-8} *22*; α(N+..)=0.000308 *5* B(E1)(W.u.)=(2.0×10^{-5} *7*); B(M2)(W.u.)=(0.015 *+30−15*)
2603.94	(4^-)	458.0 *1*	14.6 *13*	2146.00	4^+				
		677.7 *1*	100 *4*	1926.28	(3^-)	(M1+E2)	−0.54 *24*	0.001308 *19*	α=0.001308 *19*; α(K)=0.001158 *17*; α(L)=0.0001256 *18*; α(M)=2.11×10^{-5} *3* α(O)=1.742×10^{-7} *25*; α(N+..)=2.83×10^{-6}
		1766.8# *4*	3.6 *5*	836.9	2^+				
2614.1	(2,3,4)	1777.2 *3*	100	836.9	2^+				
2649.78	$4^{(+)}$	503.8 *1*	100 *4*	2146.00	4^+	(M1+E2)	−0.35 *8*	0.00269 *6*	α(K)=0.00238 *6*; α(L)=0.000261 *7*; α(M)=4.39×10^{-5} *11*; α(N)=5.50×10^{-6} *13*; α(O)=3.57×10^{-7} *8* α(N+..)=5.86×10^{-6} *14*
		723.7 *2*	27 *5*	1926.28	(3^-)				
		1812.74 *24*	89 *6*	836.9	2^+	(E2)		0.000386 *6*	α=0.000386 *6*; α(K)=0.0001485 *21*; α(L)=1.588×10^{-5} *23*; α(M)=2.66×10^{-6} *4* α(O)=2.20×10^{-8} *3*; α(N+..)=0.000219 Mult.: measured to be Q in ^{248}Cm SF decay.
2703.94	(2,3,4)	558.0 *1*	5.8 *6*	2146.00	4^+				
		1866.9 *3*	100 *9*	836.9	2^+				