Indirect studies of astrophysical reaction rates

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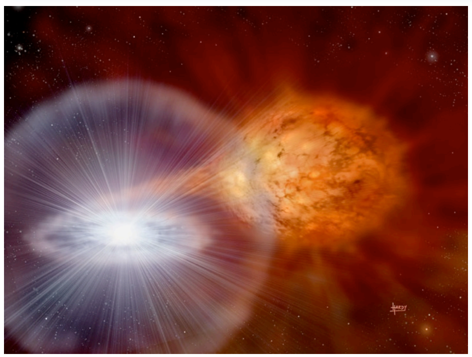
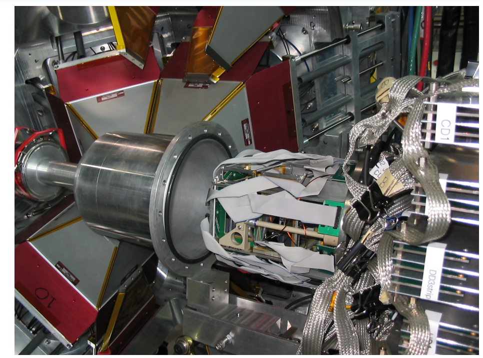
Indirect $^{18}Ne(\alpha,p)^{21}Na$ Hot-CNO breakout studies and the utilisation of cluster-transfer reactions with TIGRESS-SHARC



- Stellar explosions and reaction rates
- Experiment: reactions, instrumentation, and data
- Prospects for RIB cluster-transfers for astrophysics



Christian Aa. Digget and Phillip Adsley,

DREB, 26th March 2012

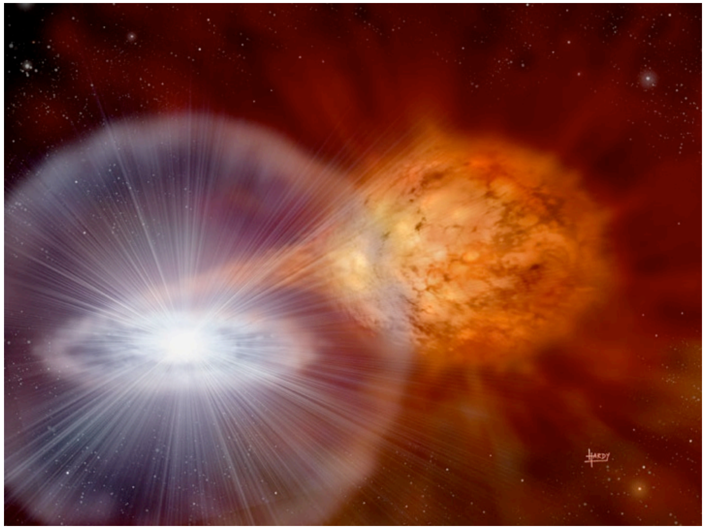
In collaboration with:

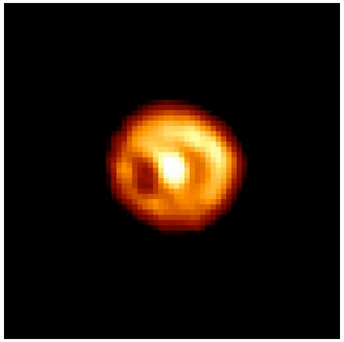
L. Achouri, G.C. Ball, J.C. Blackmon, J.R. Brown, W.N. Catford, R.M. Churchman, D. Cross, S.P. Fox, B.R. Fulton, A. Garnsworthy, G. Hackman, U. Hager, L. Linhardt, M. Matos, N.A. Orr, C.J. Pearson, M. Pearson, F. Sarazin, D. Smalley, C.E. Svensson, E. Tardiff, S. Williams, and G.L. Wilson.

Nova / X-ray burst illustration: David Hardy/PPARC

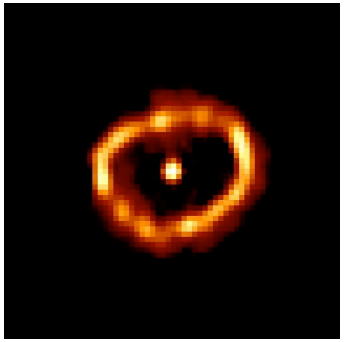
Novae and X-ray bursts

- Novae and X-ray bursts
  - Thermo-nuclear run-away on surface of white dwarf / neutron star in binary system
  - Fuelled by material from red-giant companion
  - Recurrent in time scales of hours-days (X-ray bursts) up to 10^4–10^5 years (classical novae)





15 months



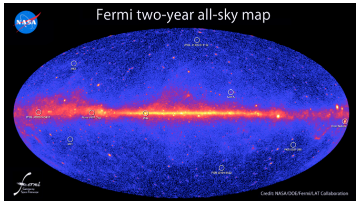
22 months

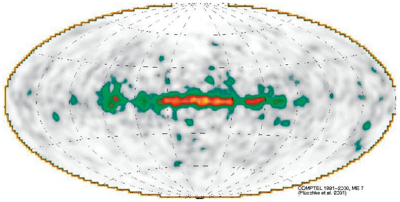
- Nova-ejecta (Cygni-1992) observed by Hubble 1993,1994 (d = 10^3 a.u.)

GAMMA-RAY LINES FROM NOVAE

DONALD D. CLAYTON AND FRED HOYLE*
Department of Space Physics and Astronomy, Rice University
Received 1973 November 12

- Gamma-ray telescopes: COMPTEL/INTEGRAL, FERMI/GLAST

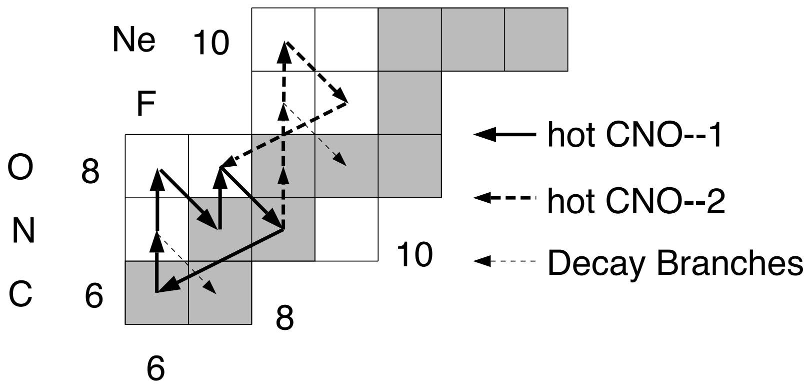




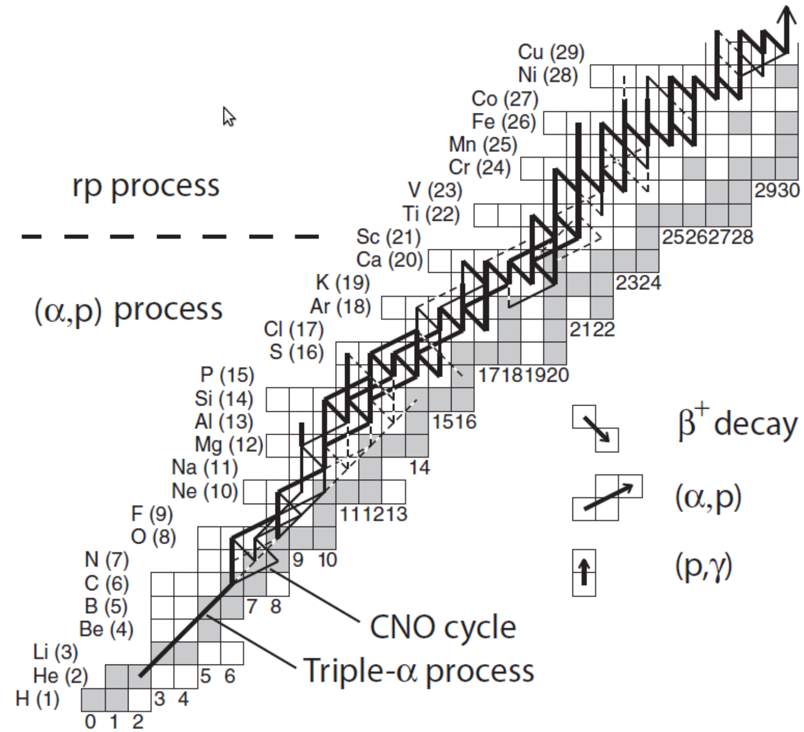
Nova / X-ray burst illustration: David Hardy/PPARC; F. Paresce, R. Jedrzejewski (STScI-1994-06), NASA/ESA; Clayton & Hoyle., APJ, 187:L101 (1974); S. Plüschke, et al., in Exploring the

Nuclear measurements of Hot-CNO breakout

- The CNO and Hot-CNO cycles



- Build-up of waiting-point nuclei in novae and X-ray bursts: ^{14}O, ^{15}O, and ^{18}Ne
- Breakout from Hot-CNO cycles:
  - ^{15}O$(\alpha,\gamma)^{19}$Ne
  - ^{18}Ne$(\alpha,p)^{21}$Na
  - ^{14}O$(\alpha,p)^{17}$F
- Followed by rp- and (α,p) processes:
  - ^{23}Mg$(p,\gamma)^{24}$Al



- Resonant reaction rates:

$$\sigma(E) \propto (2J+1)\,\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\,\exp(-\frac{E_r}{k_B T})$$

- Gamow-window: 0.7–2.0 MeV resonance energy for α-induced (Γ_α-limited) reactions at temperatures of 0.5–1.5 GK.

Wiescher, et al. JPG, 25:R133 (1999)
H. Schatz, NSCL-MSU
Rauscher, Phys. Rev. C, 81:045807 (2010)

Direct and indirect reaction rate studies

Direct measurement:

- Resonant reaction measurement with **intense** RIB:
  - Separator or silicon array depending on the reaction

$$\sigma(E) \propto (2J+1)\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\exp(-\frac{E_r}{k_B T})$$

Indirect, determining E_r, J_π, Γ_x:

- E_r, J_π from direct reaction studies (angular distributions)
- Widths (the smaller partial width):
  - Measuring both B_x and τ for states down to $\tau \sim 10$ fs
  - Deduced from time-reversed reaction, e.g. (p,α) instead of (α,p)
  - Using measured α-spectroscopic factors in mirror α-transfer to infer Γ_α from mirror symmetry
  - Measuring α-spectroscopic factors with RIB α-transfer to deduce Γ_α

- Breakout from Hot-CNO cycles:
  - $^{15}O(\alpha,\gamma)^{19}Ne$
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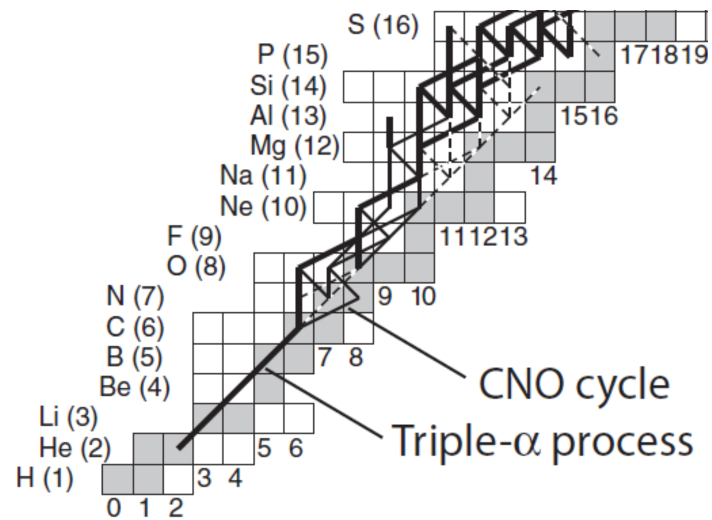


Jenkins, DREB-2012
Tan et al., Phys. Rev. C, 79:055805 (2009)
Kanungo et al., Phys. Rev. C, 74:045803 (2006)

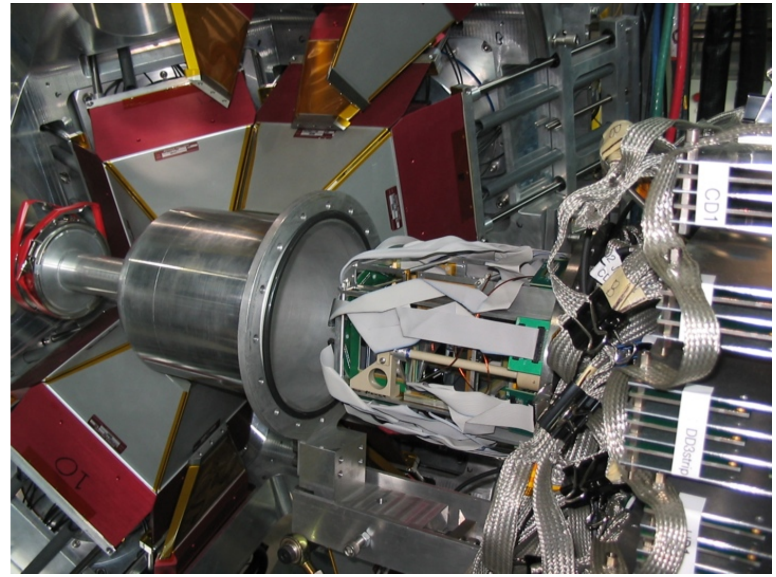
Utilising RIB transfer reactions in inverse kinematics

Inverse kinematics transfer reactions to populate states of interest in ^{22}Mg and ^{24}Al with detection of subsequent decay channels:

- For the ^{18}Ne(α,p)^{21}Na reaction:
  - ^{6}Li(^{20}Na,α)^{22}Mg(,pγ)^{21}Na

- For the ^{23}Mg(p,γ)^{24}Al reaction:
  - ^{6}Li(^{20}Na,d)^{24}Al(,γ)^{24}Al
  - ^{6}Li(^{20}Na,d)^{24}Al(,pγ)^{23}Mg

- Measuring angular distributions for the light ejectile
- Potentially angular correlations between the ejectile and the secondary particle (p or γ)

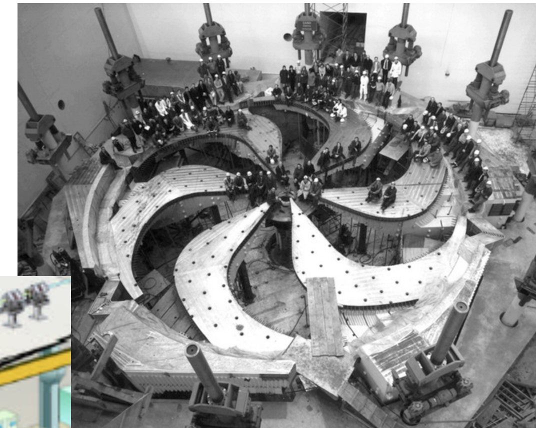


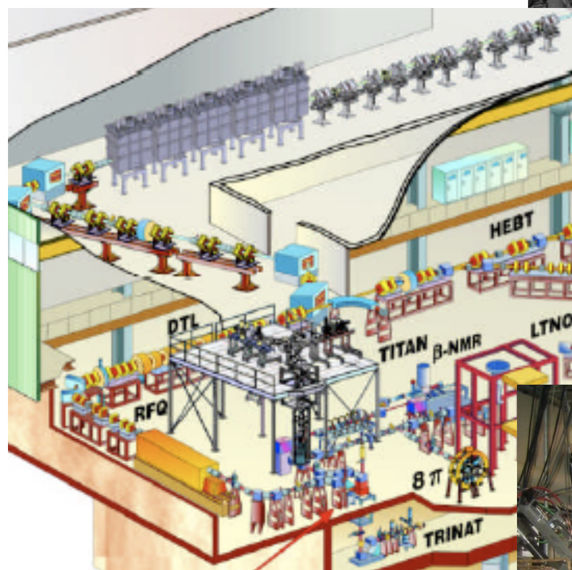
- Compact particle detector array around interaction point
  - Particle spectroscopy
  - Ejectile PID from dE-E

- HPGe γ-ray spectrometer
  - high-resolution spectroscopy from γ-ray detection

RIB production at TRIUMF

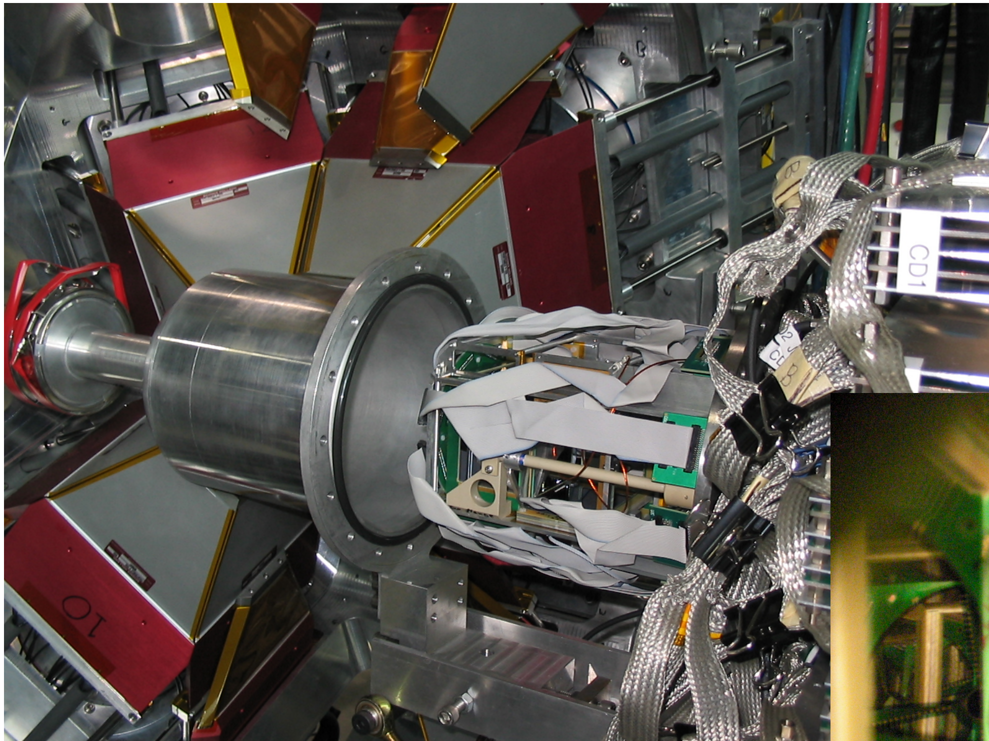
- TRIUMF facility, Vancouver (Cyclotron primary beam):
  - 500-MeV 100-μA continuous proton beam
- ISAC (Isotope Separator and Accelerator):
  - RIB production targets: Ta, Ni, ZiC, SiC, UCx, UO
  - Chemical selectivity from ion sources: Surface, laser, electron plasma
  - Magnetic separation of beams (A/q)
  - Super-conducting Linac (10.0 MeV/u)
- Intense RIBs for direct reactions

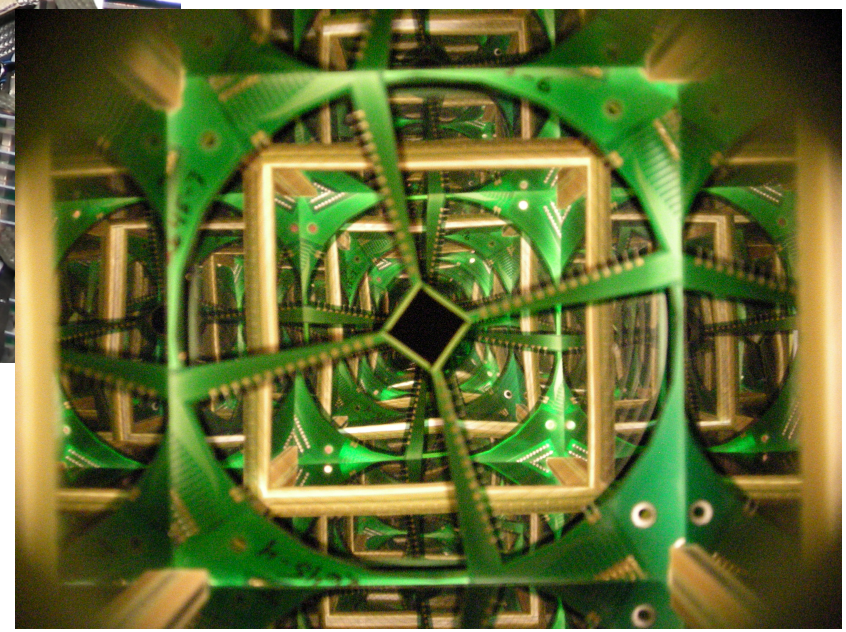




Bricault et al. NIMB, 126:231 (1997)
Laxdal, et al., proc. of LINAC08, p. 97 (2008)

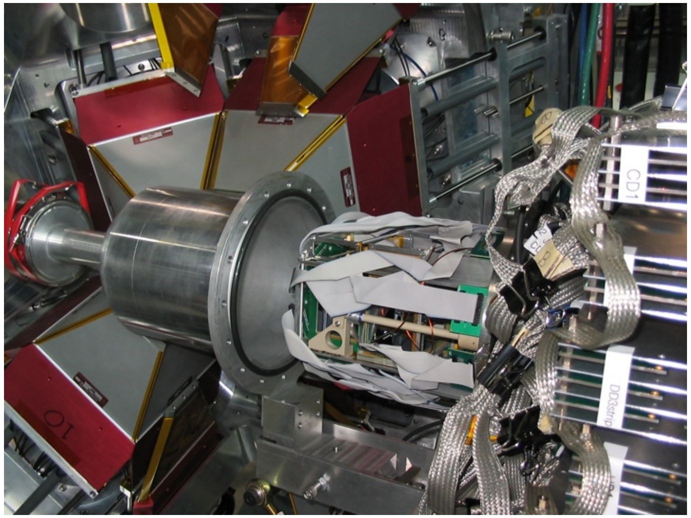
Compact setup for reaction studies: TIGRESS/SHARC

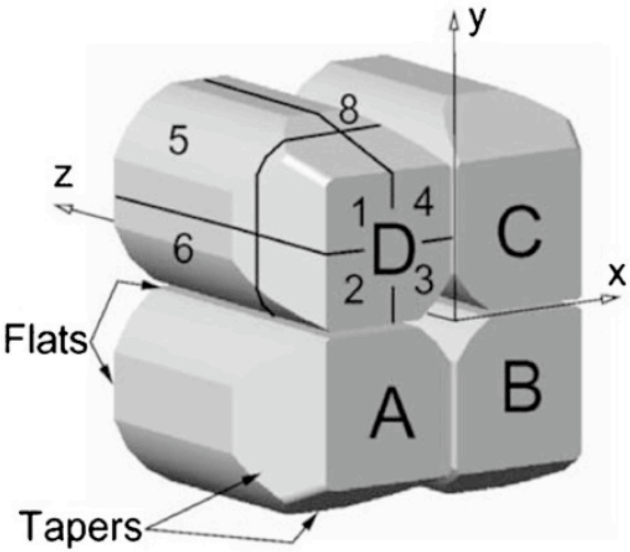




The TIGRESS gamma-ray detector system

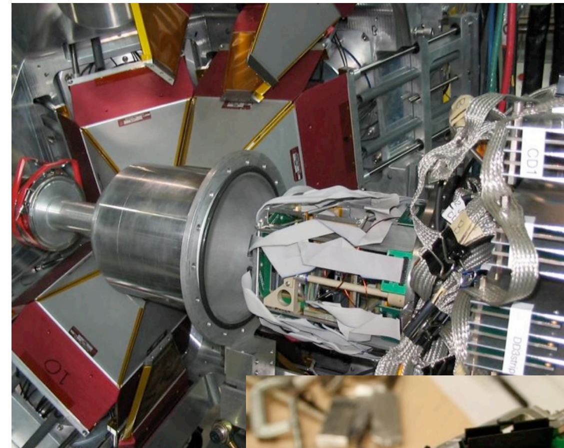
- TIGRESS: TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer:
  - Array of 10-12 HPGe gamma detectors.
  - 4 crystals with segmented contacts.
  - Doppler corrected energies from position measurement.
  - Efficiency: 5% at 4 MeV.
  - Doppler corrected gamma resolution: with pulse-shape analysis we have FWHM < 1% for 10 MeV/u RIB.

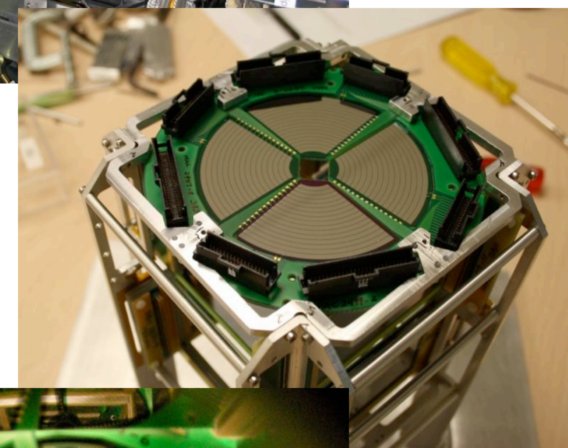


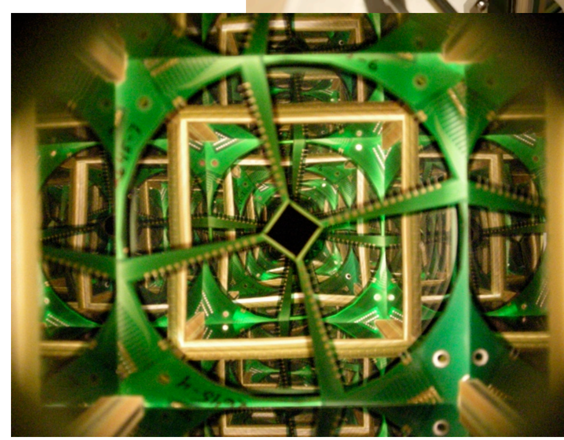


Sharc: Silicon Highly-segmented Array for Reactions and Coulex

- SHARC: Silicon Highly-segmented Array for Reactions and Coulex:
  - Upstream and downstream boxes (45-80 and 95-135 deg).
  - Upstream and downstream CDs (10-40 and 140-170).
  - dE-E for all angles 0-135 deg lab
  - Ranges: 14 MeV, 35 MeV, 180 MeV, 600 MeV
  - Energy resolution (Digital, Moving Window Deconvolution): 25 keV FWHM.

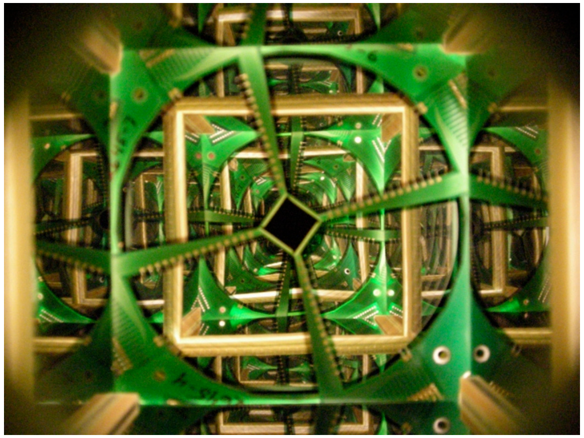




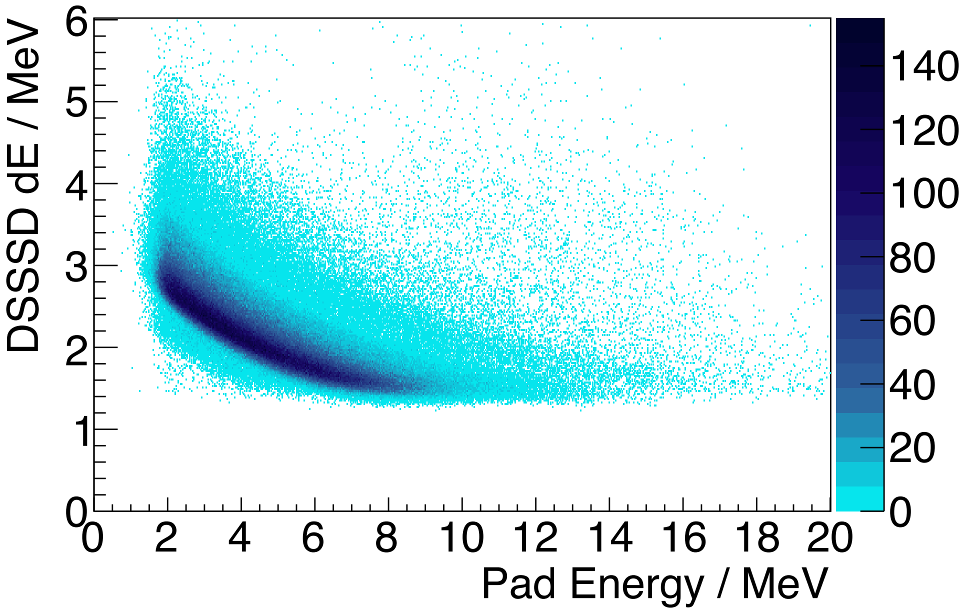


$^{6}Li(^{20}Na,\alpha)^{22}Mg(,p\gamma)^{21}Na$ and $^{6}Li(^{20}Na,d)^{24}Al(,p\gamma)^{23}Mg$

- SHARC+TIGRESS
- 200μm 6LiF target
- ^{20}Na at 6MeV/u
  - dE-E (140μm + 1000μm silicon)
  - Ranges: 14 MeV, 35 MeV, 180 MeV, 600 MeV



Unadjusted particle-identification



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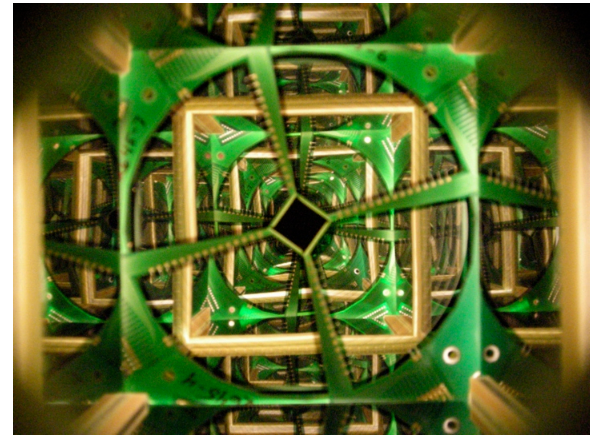

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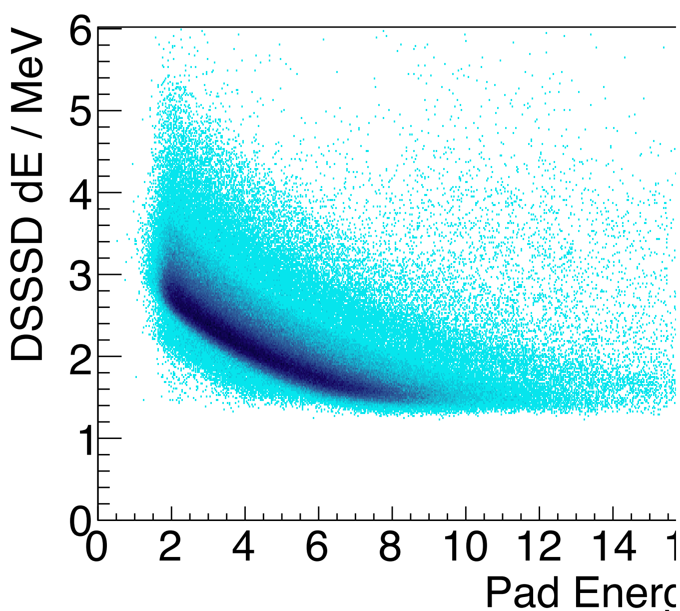
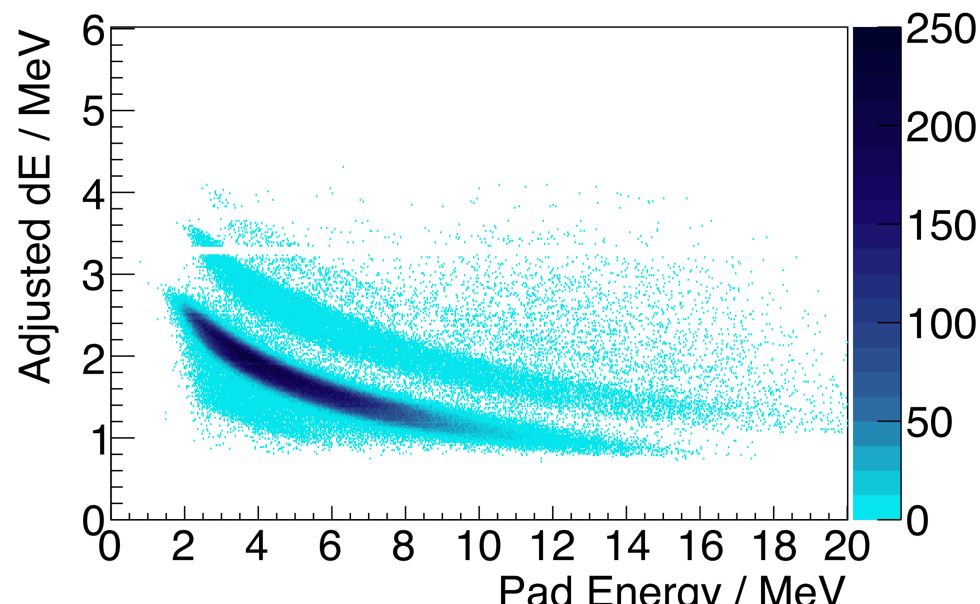
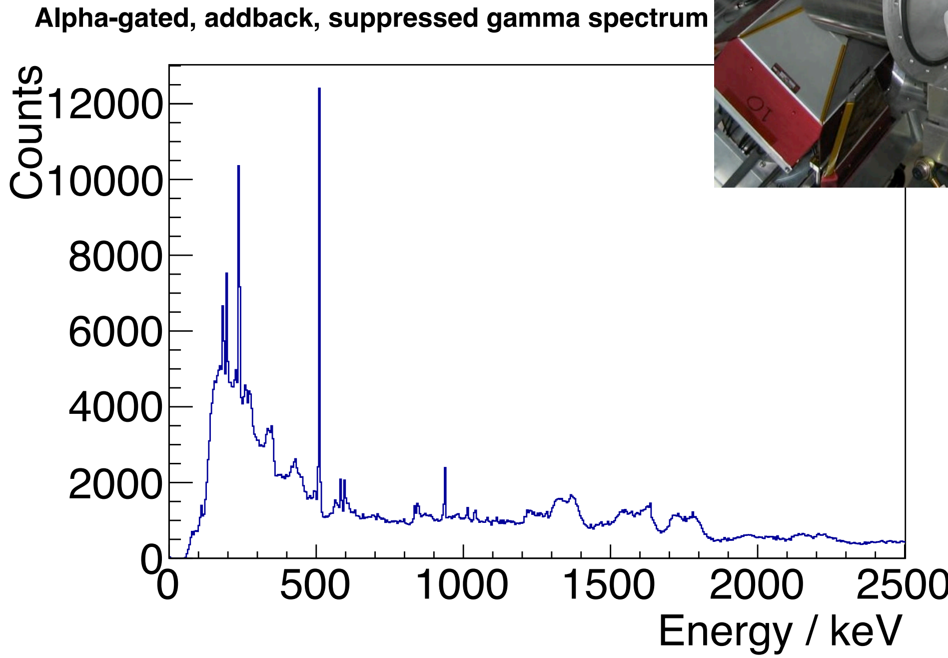


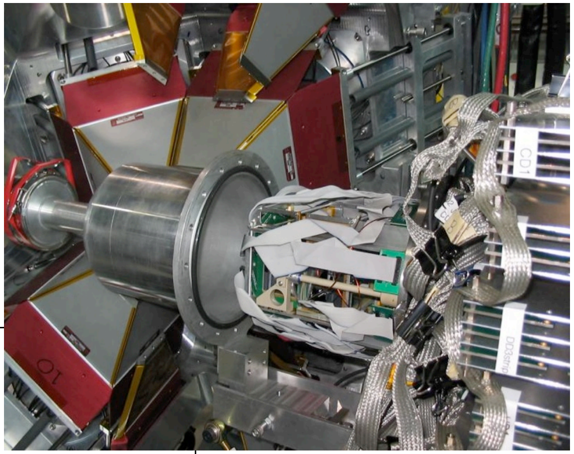
Impact-angle-adjusted particle-identification



TIGRESS γ-ray spectrometer, $^{6}Li(^{20}Na,\alpha)^{22}Mg$:

- Alpha-gated γ-ray spectrum
  - 200μm 6LiF target
  - ^{20}Na at 6MeV/u
- BGO-suppressed
- Crystal-crystal addback





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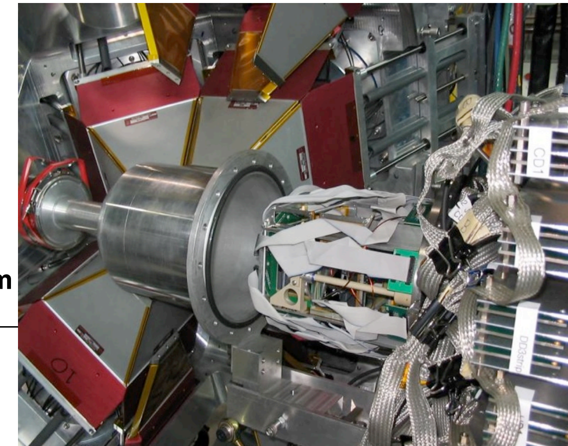
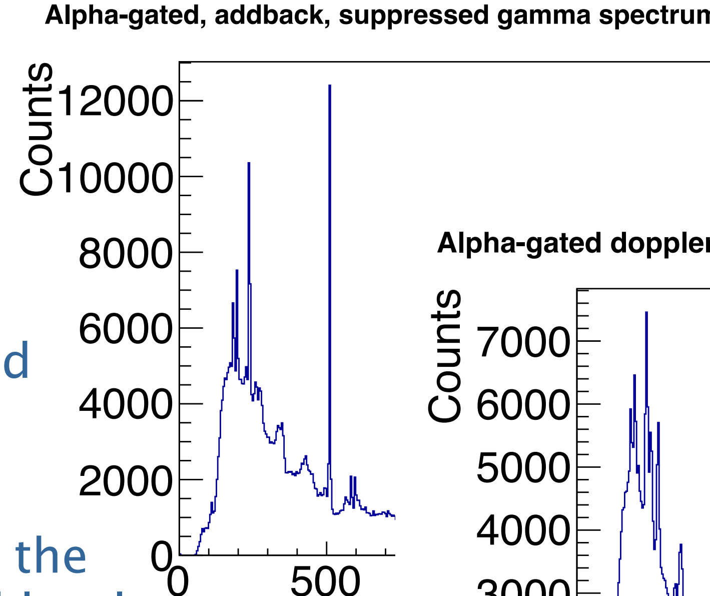
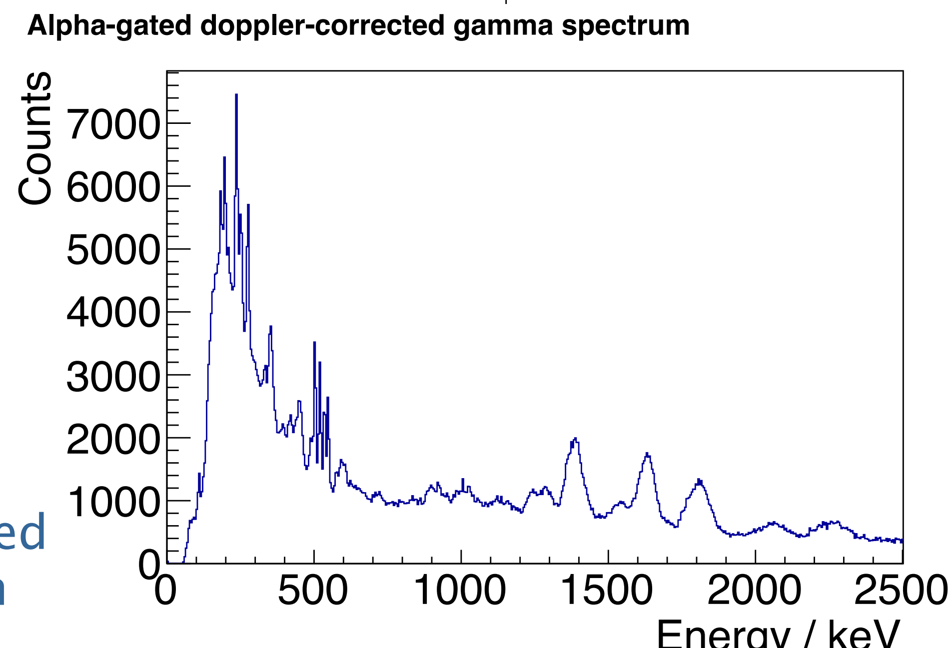




- Doppler-corrected assuming direct reaction on ^{6}Li
- Only corrected at the individual-crystal level



- Strong fusion-evaporation and random coincidences with β-delayed γ rays and 511-keV β⁺ annihilation
- Work on timing gates ongoing

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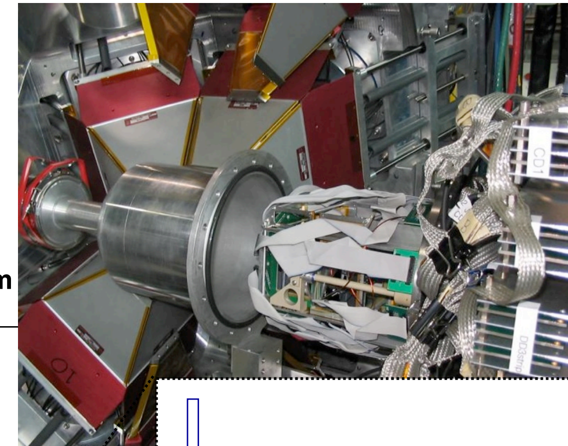
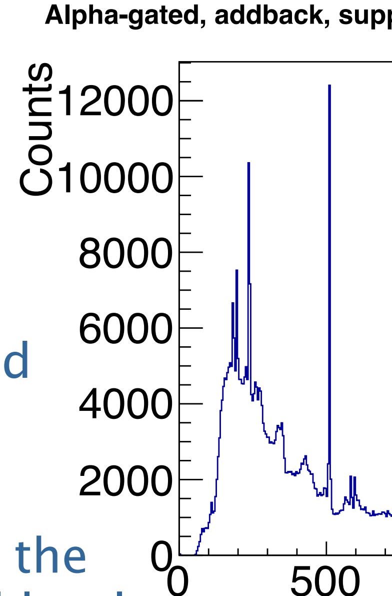
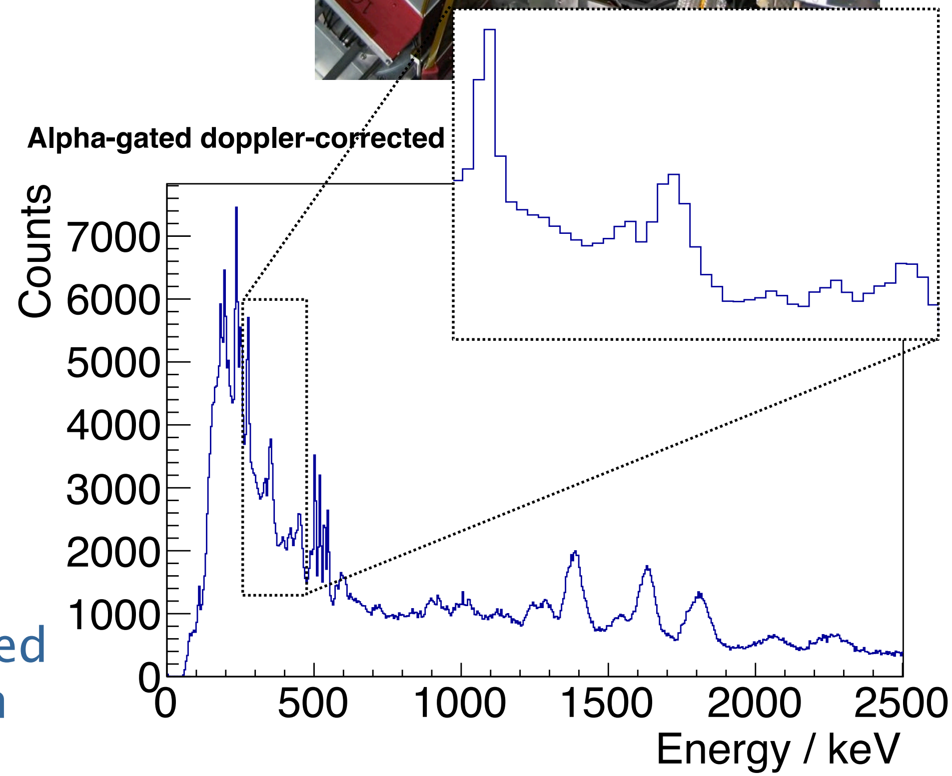
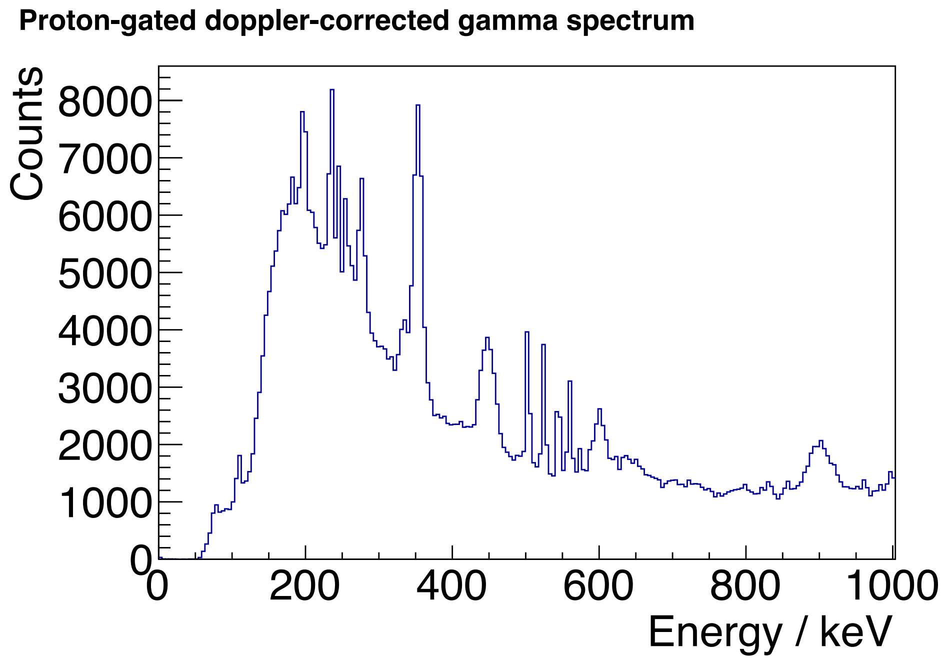






TIGRESS γ-ray spectrometer, $p(^{20}Na,p')^{20}Na(,\gamma)$

- Proton-gated γ-ray spectrum:
  $^{20}Na(p,p')^{20}Na^{*}(,\gamma)$
- Adsorbed water
- Limited kinematic acceptance



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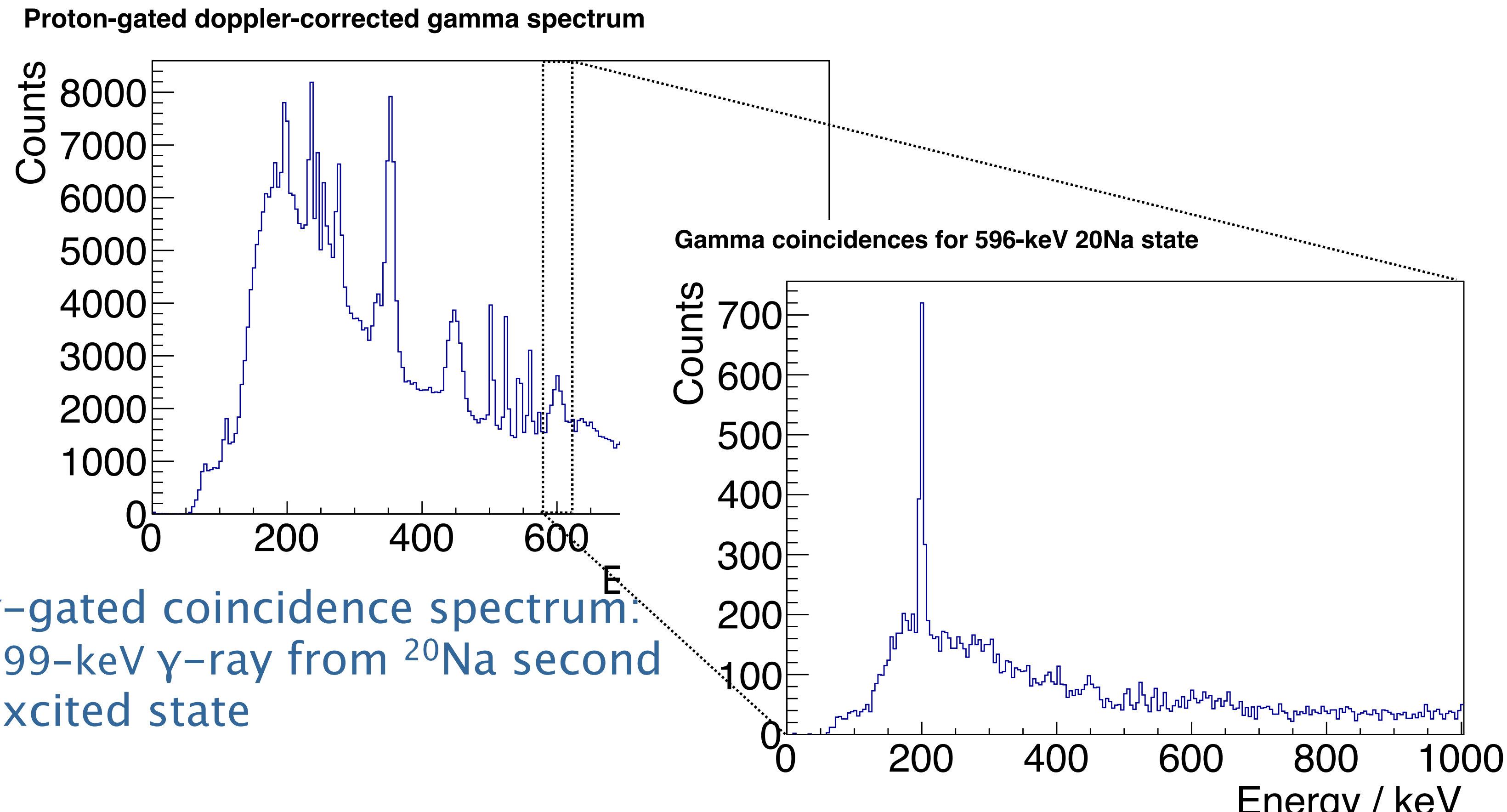

- γ-gated coincidence spectrum: 199-keV γ-ray from ^{20}Na second excited state

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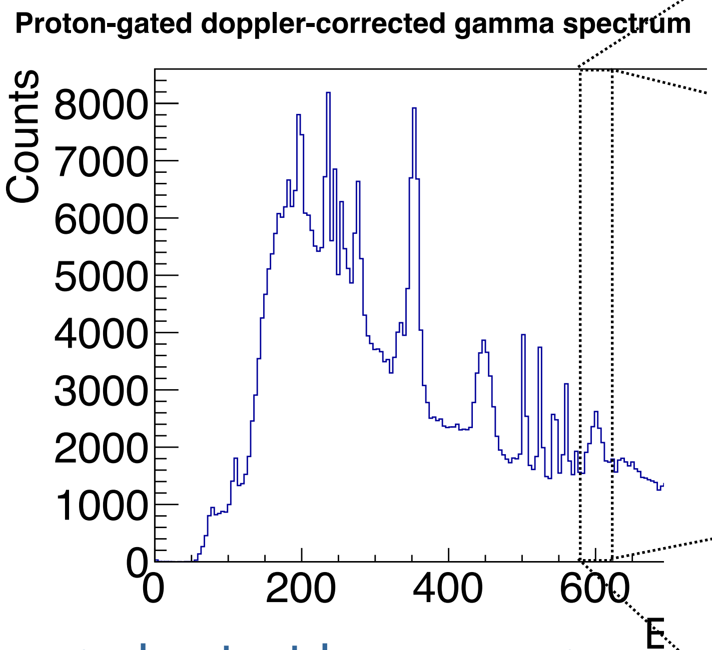
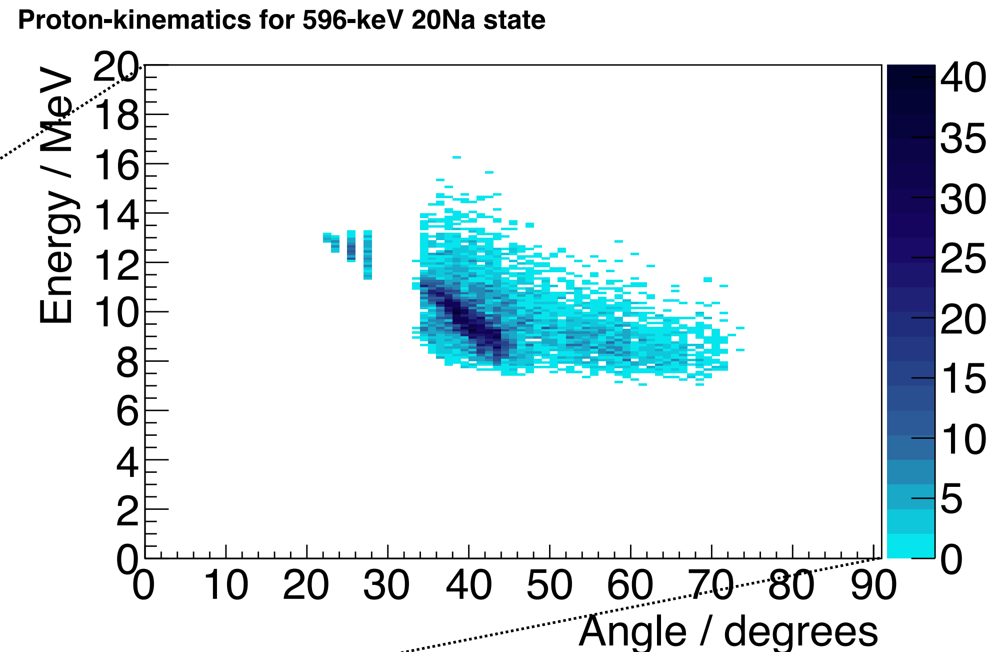
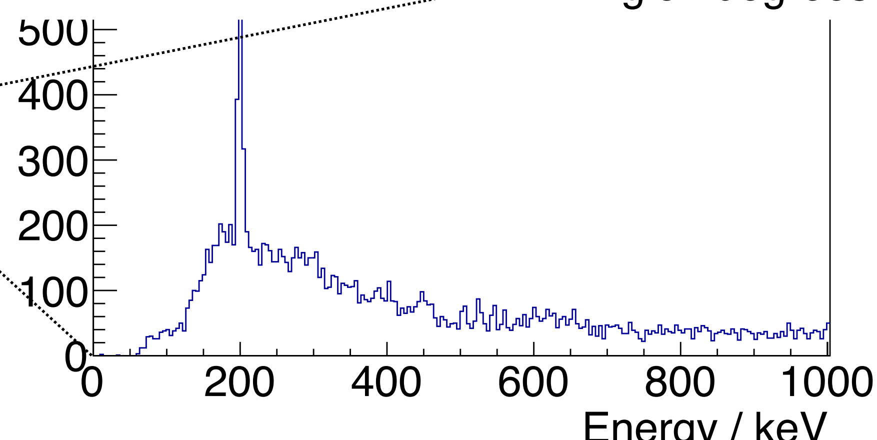


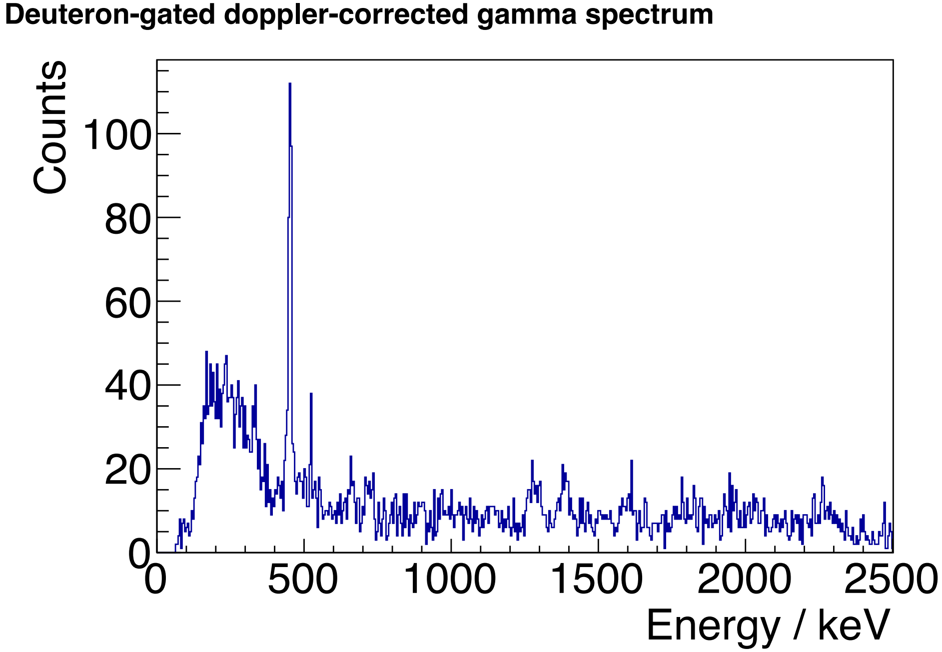




- γ-gated coincidence spectrum: 199-keV γ-ray from ^{20}Na second excited state
- Expected (p,p') kinematics

$^{6}Li(^{20}Na,d)^{24}Al(,p\gamma)^{23}Mg$ for $^{23}Mg(p,\gamma)^{24}Al$ states

- Deuteron-gated γ-ray spectrum:
  $^{6}Li(^{20}Na,d)^{24}Al^{*}(,p)^{23}Mg^{*}(,\gamma)^{23}Mg$
- ^{23}Mg first-excited state (451 keV)



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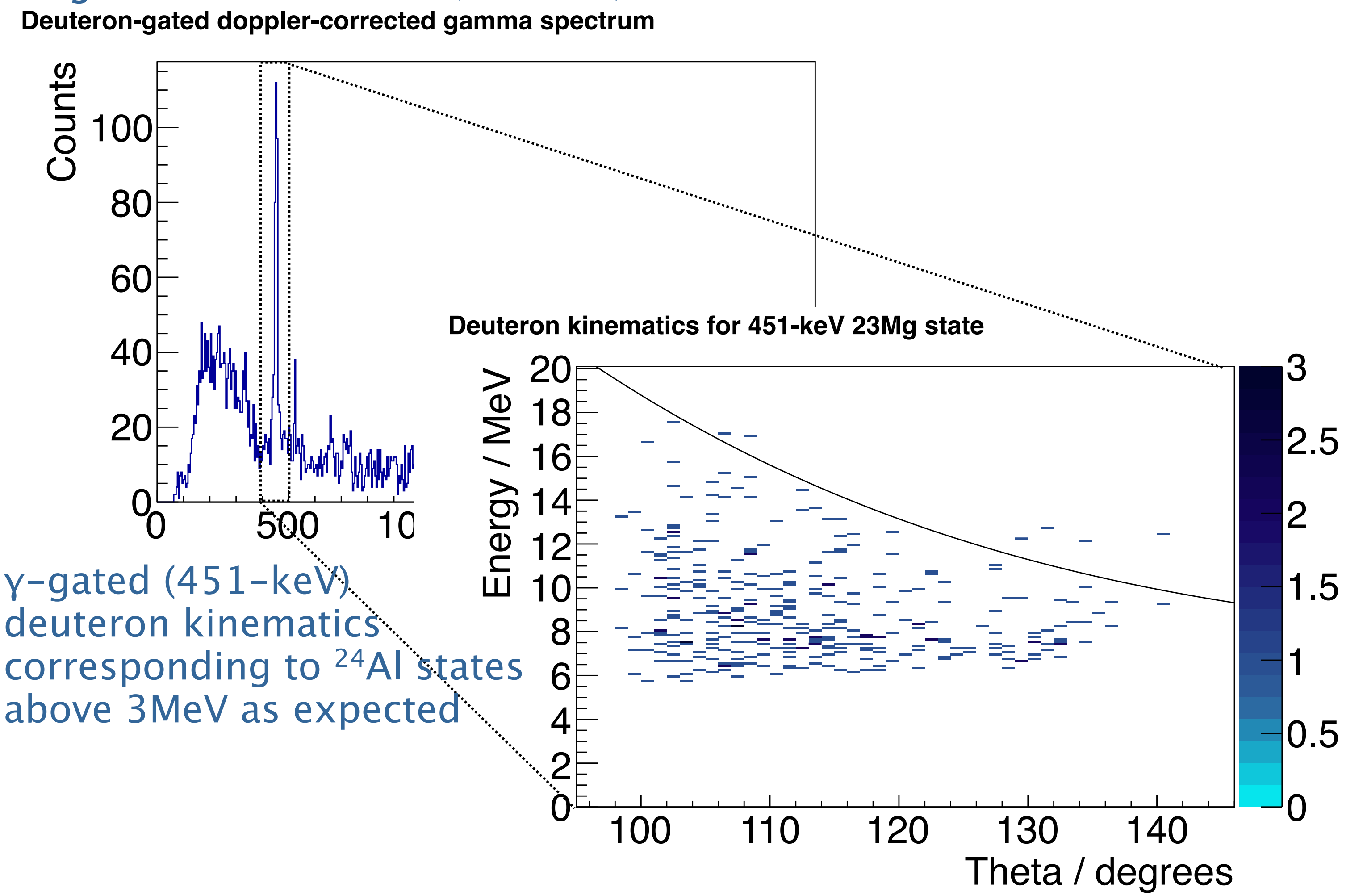

- γ-gated (451-keV) deuteron kinematics corresponding to ^{24}Al states above 3MeV as expected

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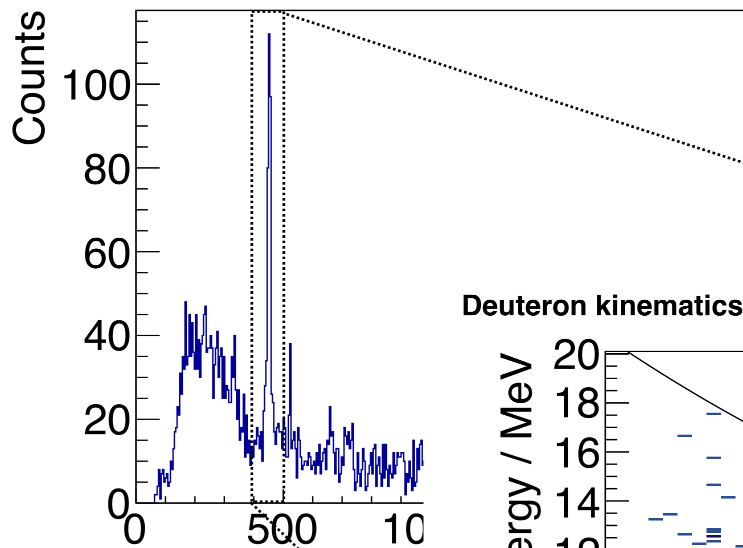
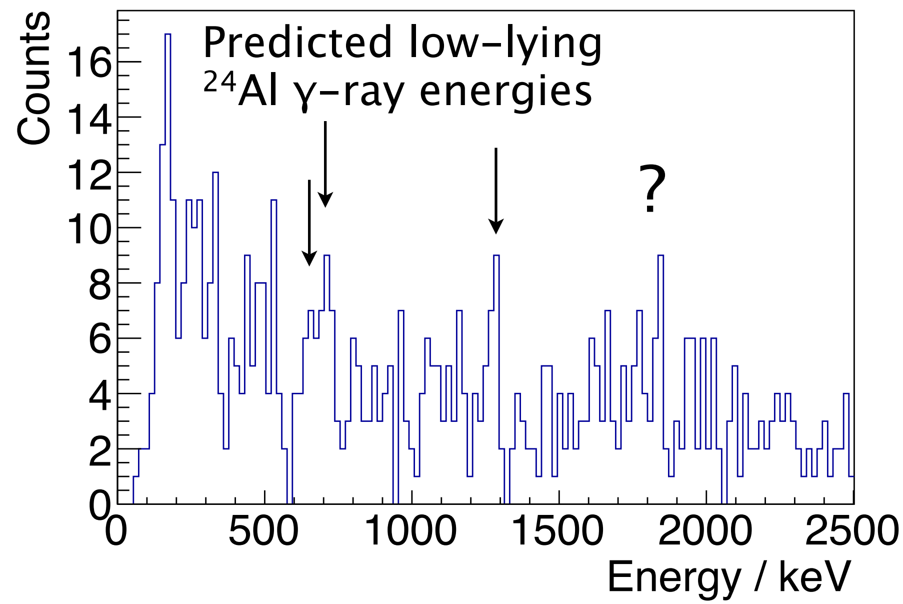
- Deuteron-gated γ-ray spectrum:
  ^{6}Li(^{20}Na,d)^{24}Al*(,p)^{23}Mg*(,γ)^{23}Mg
- ^{23}Mg first-excited state (451 keV)

Deuteron-gated doppler-corrected gamma spectrum

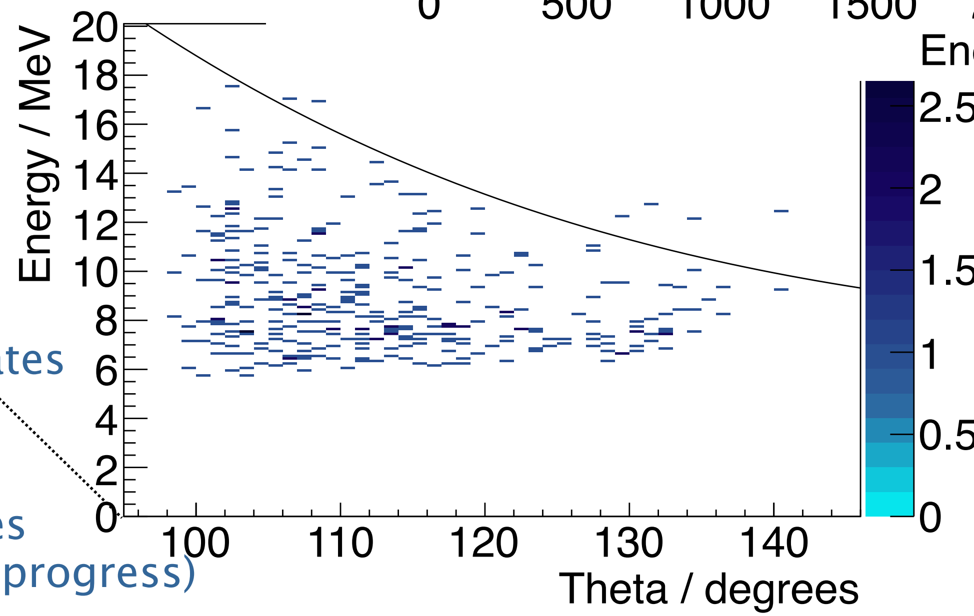


- γ-gated (451-keV) deuteron kinematics corresponding to ^{24}Al states above 3MeV as expected
- ^{24}Al γ-rays for E_x<3MeV
  Low statistics necessitates Doppler optimisation (in progress)

Deuteron-energy-gated doppler-corrected gamma spectrum



Deuteron kinematics



Direct-reaction studies to determine Γ_α

Indirect reaction-rate studies, determining Γ_α:

$$\sigma(E) \propto (2J+1)\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\exp(-\frac{E_r}{k_B T})$$

- Widths (Γ_α is the smallest width):
  - Using measured α-spectroscopic factors in mirror α-transfer to infer Γ_α from mirror symmetry
  - Measuring α-spectroscopic factors with RIB α-transfer to deduce Γ_α
- Hot-CNO breakout reactions:
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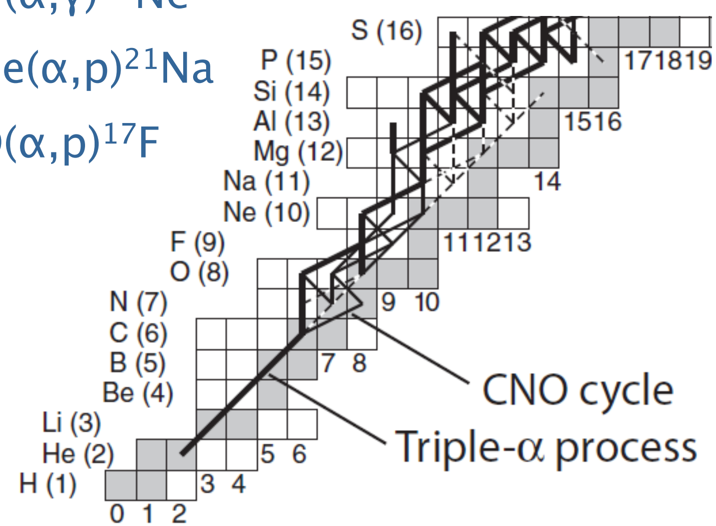

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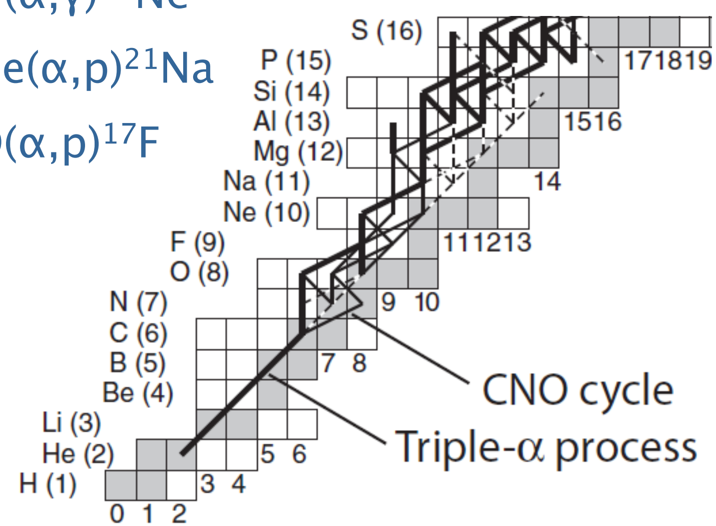
  - Using measured α-spectroscopic factors in mirror α-transfer to infer Γ_α from mirror symmetry
  - Measuring α-spectroscopic factors with RIB α-transfer to deduce Γ_α
- Hot-CNO breakout reactions:
  - $^{15}O(\alpha,\gamma)^{19}Ne$
  - $^{18}Ne(\alpha,p)^{21}Na$
  - $^{14}O(\alpha,p)^{17}F$



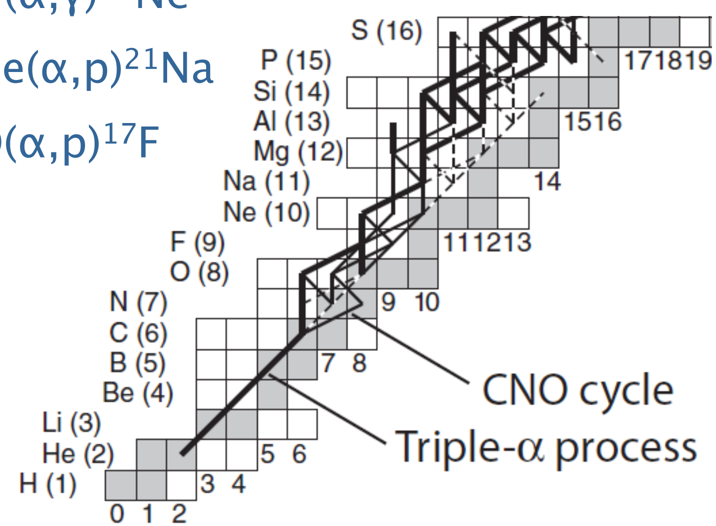
- Γ_α for Hot-CNO breakout reactions:
  - $^{7}Li(^{15}O,t\gamma)^{19}Ne$
  - $^{7}Li(^{18}Ne,tp)^{21}Na$
  - $^{7}Li(^{14}O,tp)^{17}F$
- Γ_α for (α,p) reactions up to ^{40}Ca
- Parallel studies on mirror nuclei
- Possibly including (^{6}Li,d)

Jenkins, DREB-2012
Tan et al., Phys. Rev. C, 79:055805 (2009)
Kanungo et al., Phys. Rev. C, 74:045803 (2006)

Direct-reaction studies to determine Γ_α

Indirect reaction-rate studies, determining Γ_α:

- Widths (Γ_α is the smallest width):
  - Using measured α-spectroscopic factors in mirror α-transfer to infer Γ_α from mirror symmetry
  - Measuring α-spectroscopic factors with RIB α-transfer to deduce Γ_α
- Hot-CNO breakout reactions:
  - $^{15}O(\alpha,\gamma)^{19}Ne$
  - $^{18}Ne(\alpha,p)^{21}Na$
  - $^{14}O(\alpha,p)^{17}F$



$$\sigma(E) \propto (2J+1)\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\exp\left(-\frac{E_r}{k_B T}\right)$$

- Γ_α for Hot-CNO breakout reactions:
  - $^{7}Li(^{15}O,t\gamma)^{19}Ne$
  - $^{7}Li(^{18}Ne,tp)^{21}Na$
  - $^{7}Li(^{14}O,tp)^{17}F$
- Γ_α for (α,p) reactions up to ^{40}Ca
- Parallel studies on mirror nuclei
- Possibly including (^{6}Li,d)

- Intense radioactive ion-beams necessary: 10^6–10^8 pps depending on reaction. Beams under development at:

  TRIUMF ISAC-II

  HIE-ISOLDE

  SPIRAL-2

Jenkins, DREB-2012
Tan et al., Phys. Rev. C, 79:055805 (2009)
Kanungo et al., Phys. Rev. C, 74:045803 (2006)

Investigating stellar explosions

- Hot CNO breakout reaction rates for X-ray bursts – and possibly Novae

- States for the $^{18}Ne(\alpha,p)^{21}Na$, and $^{23}Mg(p,\gamma)^{24}Al$ reactions searched for through the $^{6}Li(^{20}Na,x)$ reaction

- Prospects for RIB cluster-transfers for astrophysics, particularly α-transfer

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