Particle-Induced Reactions: *Indirect Measurements*

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When and Why?

- This discussion: Nuclear Astrophysics

Guiding principle

We want to gain genuinely new insight to the most important issues as rapidly as possible

- But, we have to do this in the face of
  - low energies; Coulomb barrier, low cross sections
  - unstable nuclei; low intensities, poor beam/target quality

→ INDIRECT TECHNIQUES

Some Examples...

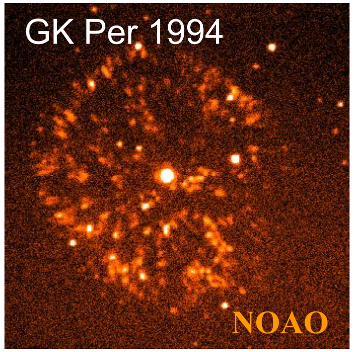
Example 1

Scattering Reactions

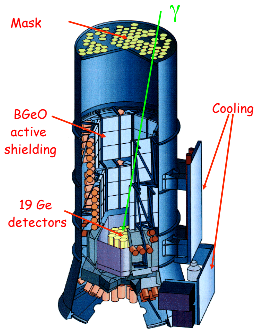
- (p,p) or (α,α)
- Especially good for *s*-wave resonances, Γ_p > few keV, A<30
- Frequently performed in inverse kinematics
  - H (polyethylene) or He (gas) targets
  - High detection efficiency
  - 'Low' intensities required
  - High segmentation, good angle knowledge required
- Can obtain 'direct' data simultaneously
  - And if you can, it's very useful!

Scattering Reactions: Example

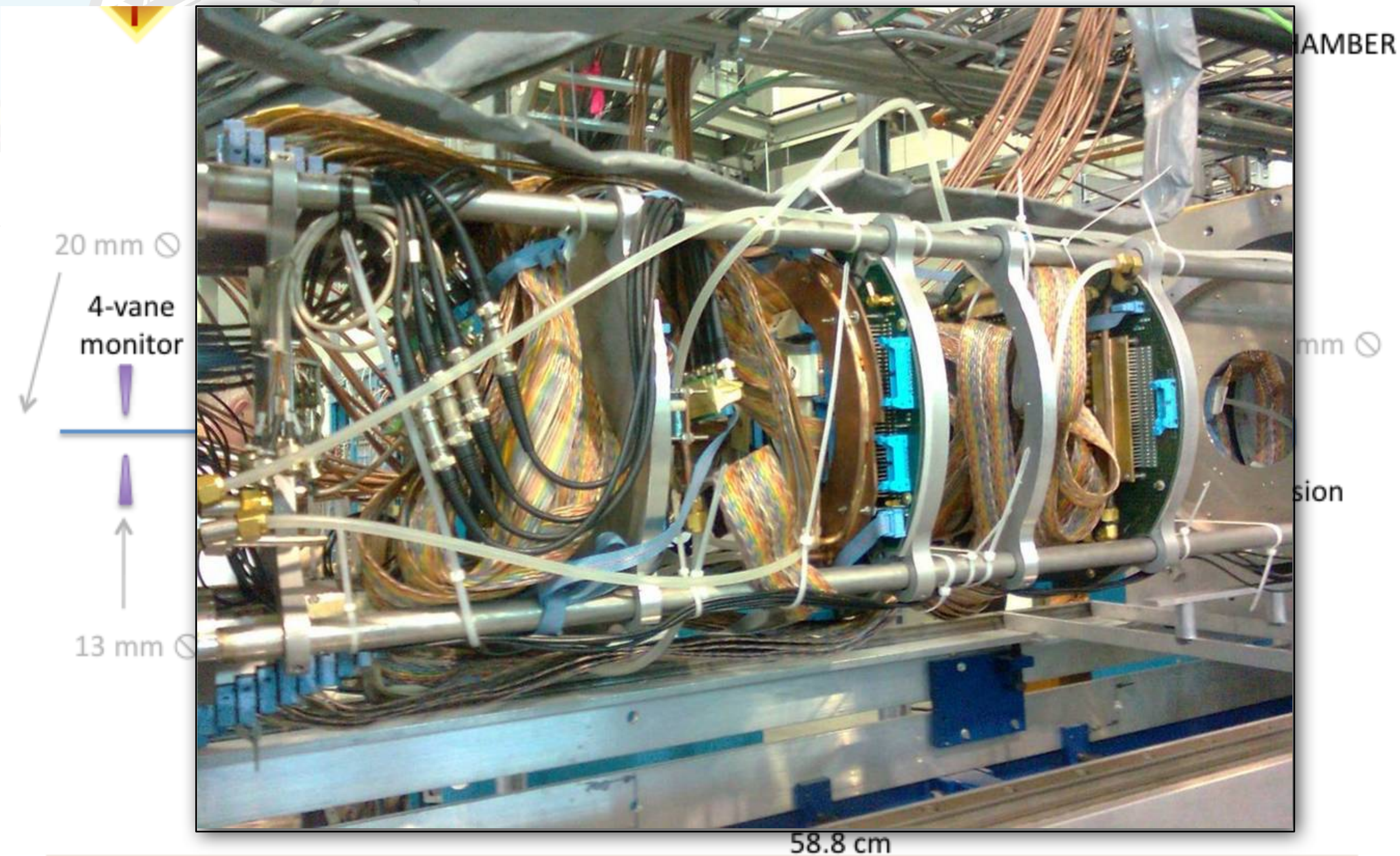
$^{18}F(p,\alpha)^{15}O$ in novae



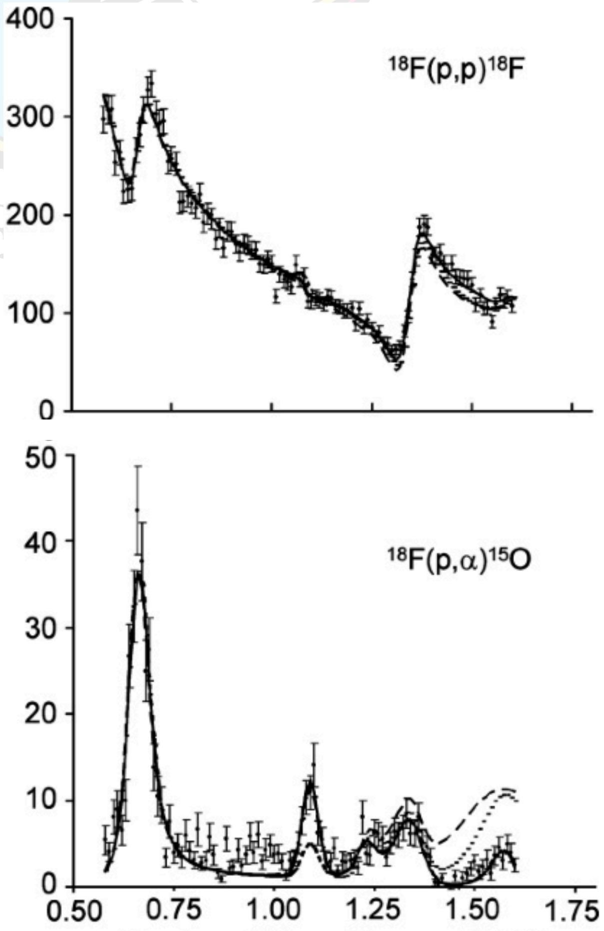
- Motivation: ^{18}F is leading candidate for satellite gamma-ray observation
- This reaction is the main nuclear physics uncertainty in ^{18}F production
- Direct measurements in the Gamow window 'challenging'
- Issues concerning ℓ=0 resonances, missing and broad resonances
- Recent data from TRIUMF and GANIL



(Typical) TRIUMF set-up



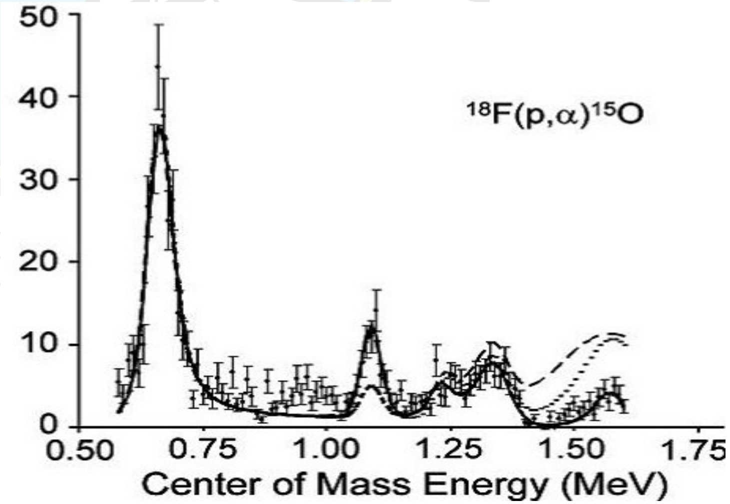
Data



ASM et al. PRC 79 (2009)

- R-matrix analysis
- Analysis based on (p,p) only would have been VERY different to that based on simultaneous (p,p) and (p,α)
- Deduce $E, \Gamma_p, \Gamma_\alpha, \ell,$ interference

Broad ℓ = 0 state at ~1.5 MeV?



E_x=1573+6411=7984 keV

Γ_p =8^{+8}_{-4} keV

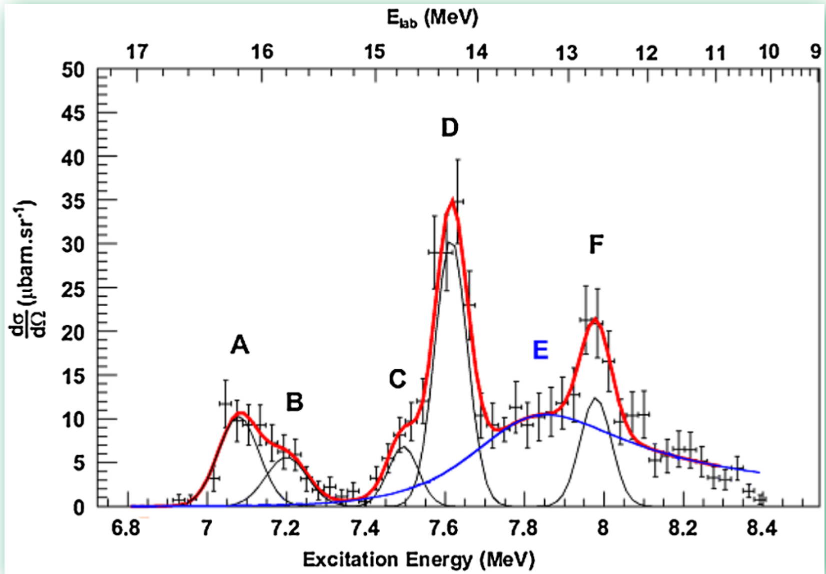
Γ_α = 34± 13 keV

Dalouzy *et al.* PRL 102 (2009) 162503

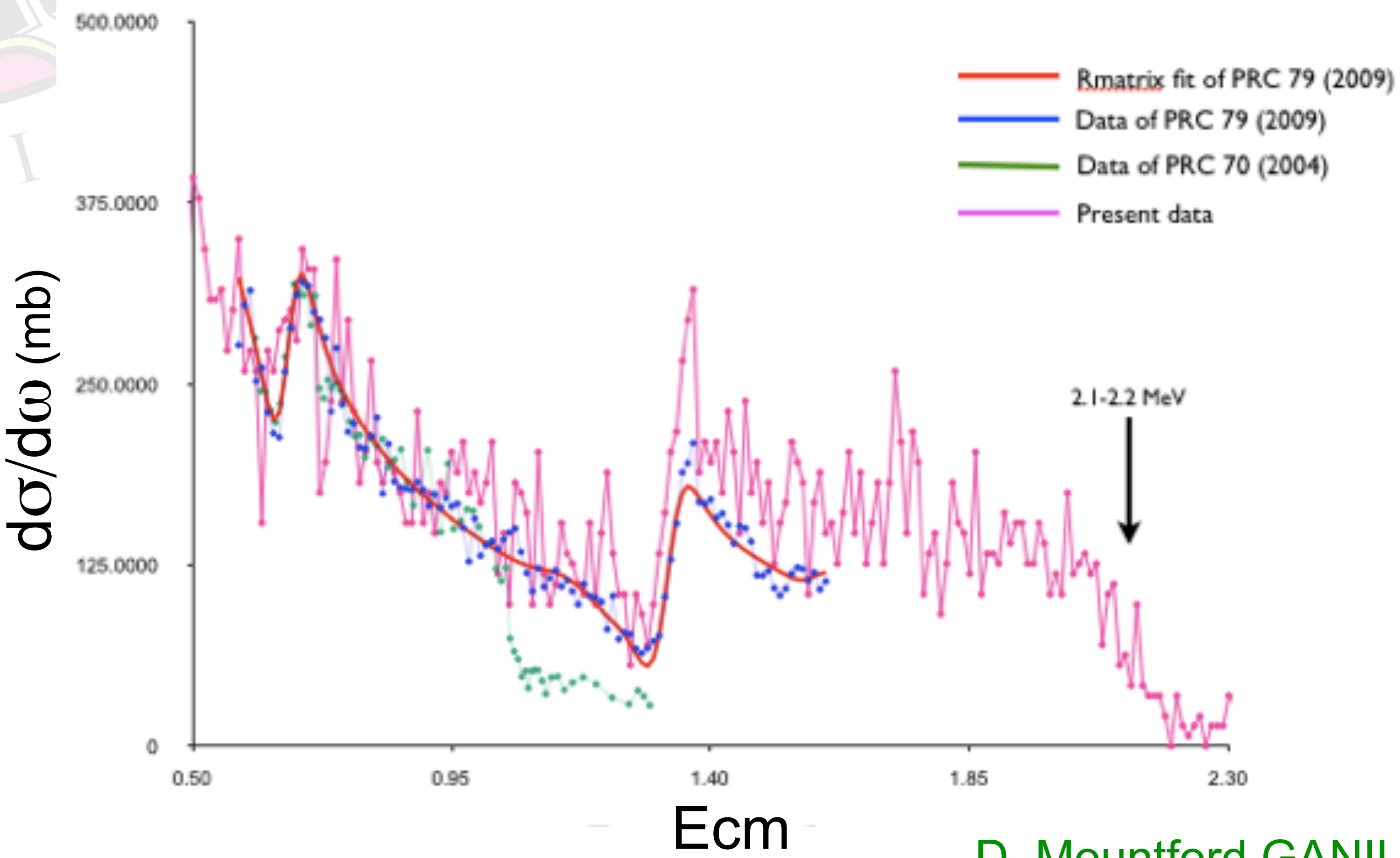
Use inelastic scattering
$^{1}H(^{19}Ne,p)^{19}Ne^{*}(p)^{18}F$

E_x=7863±39 keV

Γ_{tot} =292± 107 keV



New data



D. Mountford GANIL 2010

Notable recent references

- R. Azuma, AZURE: Phys.Rev. C 81, 045805 (2010)
  - A new public access R-Matrix code
- J.J. He *et al.* Phys.Rev. C 80, 042801 (2009)
  - $^{14}O(\alpha, p)^{17}F$ via $^{17}F(p, p')$
- ASM *et al.* Phys.Rev. C 79, 058801 (2009)
  - $^{18}F(p, p)^{18}F$ and $^{18}F(p, \alpha)^{15}O$ 0.6 < Ecm < 1.5 MeV
- J.C. Dalouzy *et al.* Phys.Rev.Lett. 102, 162503 (2009)
  - Observation of the 1.49 MeV state in 19Ne relevant to $^{18}F(p, \alpha)$
- J. Chen et al., RIKEN Accelerator report
  - ^{26}Si via the $p(^{25}Al, p)^{25}Al$
- J. J. He et al. Phys.Rev. C 80, 015801 (2009)
  - $^{21}Na+p$ for $^{22}Mg^*$

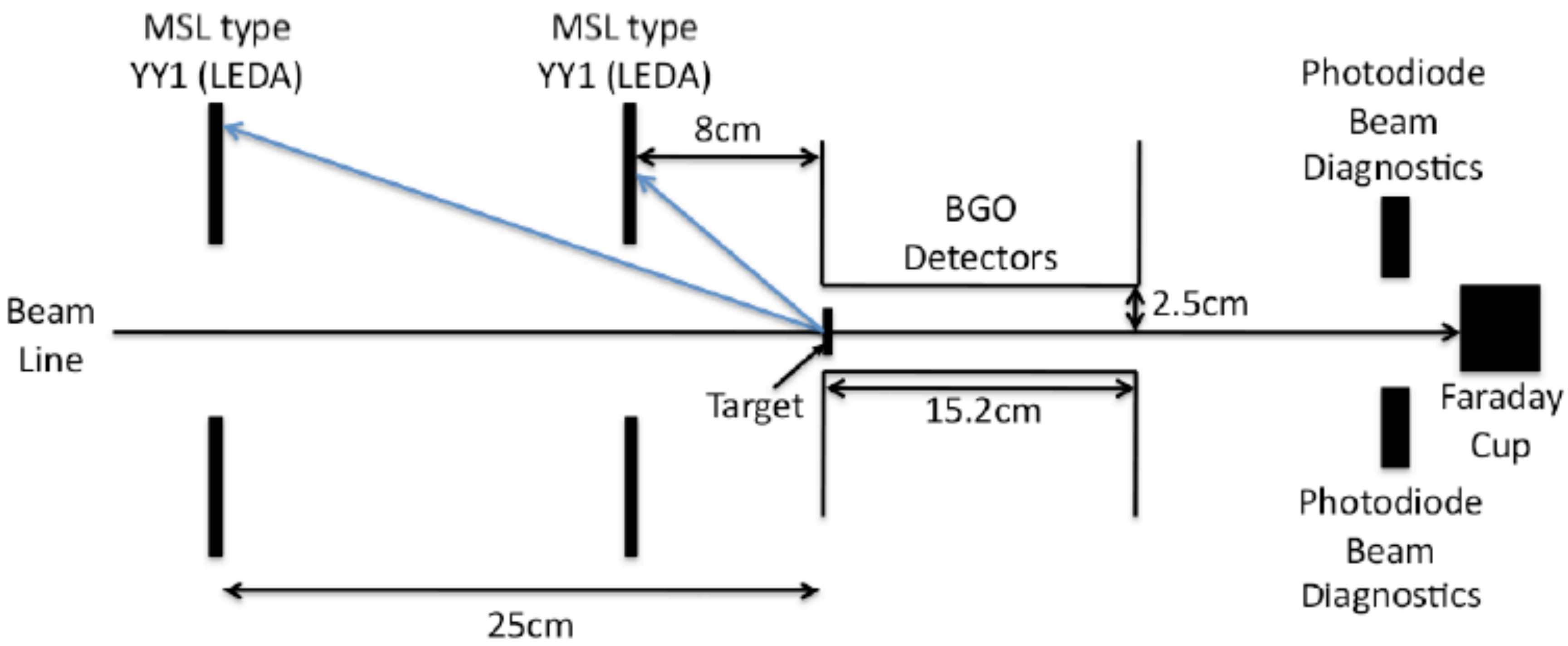
Example 2

Transfer Reactions

- $^{26}Al(p,\gamma)^{27}Si$; destruction of γ-observable ^{26}Al
- Too weak for direct methods

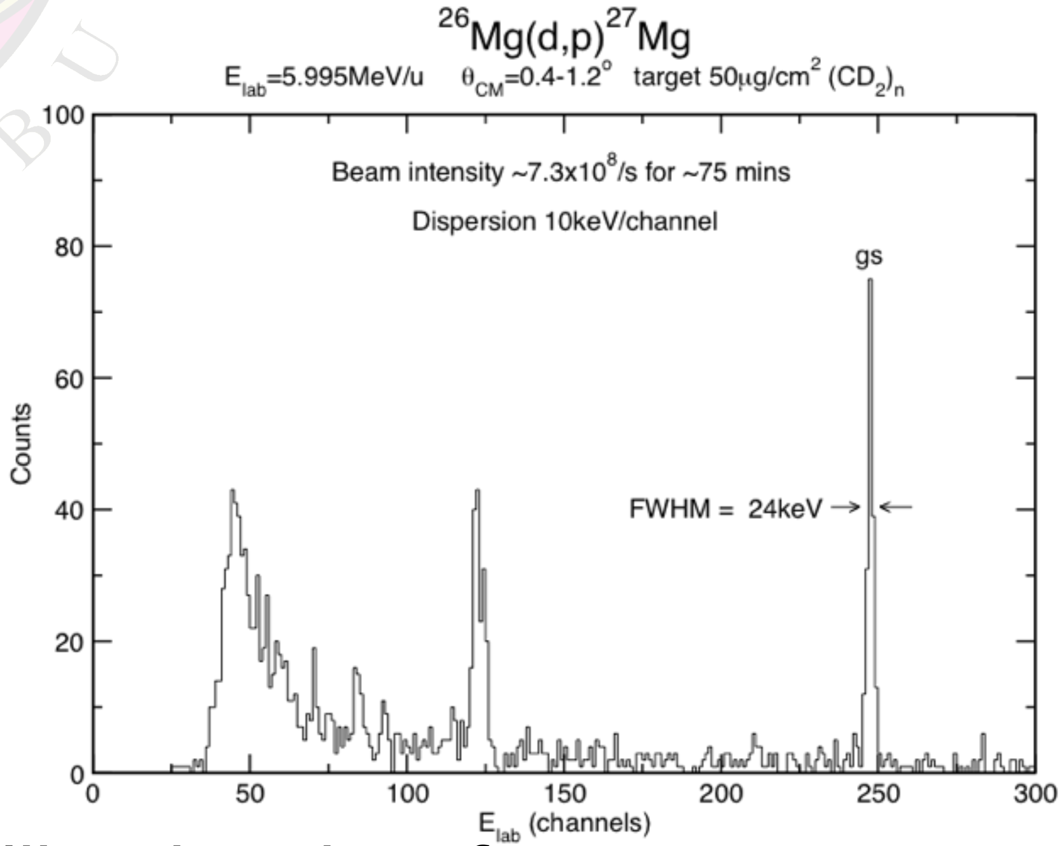
  ➔Infer from $^{26}Al(d,p)^{27}Al$
- Mirrors proton transfer onto ^{26}Al
- Need to determine the s.f. of key states in ^{27}Al (assume s.f. identical to those in ^{27}Si)
- Compare yield to expectation from DWBA
- Could use ANCs (as this actually probing peripheral wavefunction only)
- Precursor to $^{3}He(^{26g}Al,d)^{27}Si$ study

$^{26}Al(d,p)^{27}Al$



MSL type
YY1 (LEDA)
MSL type
YY1 (LEDA)
8cm
Photodiode
Beam
Diagnostics
BGO
Detectors
2.5cm
Beam
Line
Target
15.2cm
Faraday
Cup
Photodiode
Beam
Diagnostics
25cm

Recent data: G. Lotay *et al.*



- Only calibration data from recent run

...but promising!

Notable references

- A,. Deltuva Phys. Rev. C 79, 054603 (2009)
  - Three-body (d,p) and (p,d) calculations
- A.Parikh et al. Phys. Rev. C 80, 015802 (2009)
  - $^{34}S(^{3}He, t)$ for $^{33}S(p, \gamma)^{34}Cl$ rate in ONe novae
- C.M.Deibel et al. Phys. Rev. C 80, 035806 (2009)
  - $^{27}Al(^{3}He,t)^{27}Si^{*}(p)^{26}Al^{m}$ and $^{28}Si(^{3}He,\alpha)^{27}Si^{*}(p)^{26}Al^{m}$
- A. Matic Phys. Rev. C 80, 055804 (2009)
  - (p, t) for $^{18}Ne(\alpha, p)^{21}Na$
- K.Y. Chae et al. Phys. Rev. C 79, 055804 (2009)
  - $^{18}Ne(\alpha, p)^{21}Na$ reaction rate via $^{24}Mg(p, t)^{22}Mg$
- D. Bardayan et al. Phys. Rev. C 78, 052801 (2008)
  - $^{15}N(d,p)^{16}N$ to access $^{16}N^{*}$; $^{15}N(n,\gamma)^{16}N$ in AGBs
- D. Bardayan et al. Phys. Rev. C 76, 045803 (2007)
  - ^{30}S studied with $^{32}S(p, t)^{30}S$; for $^{29}P(p, \gamma)^{30}S$

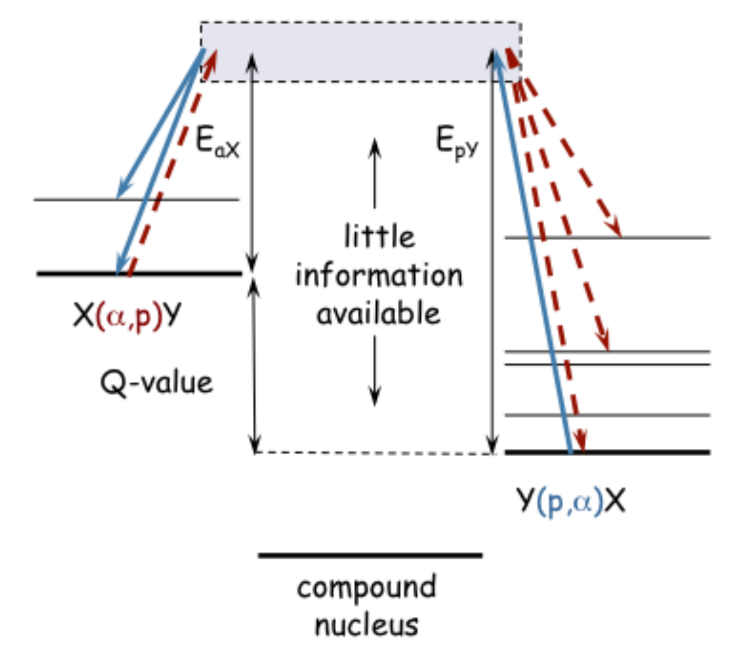
…(d,p) for r-process

Example 3

Detailed Balance

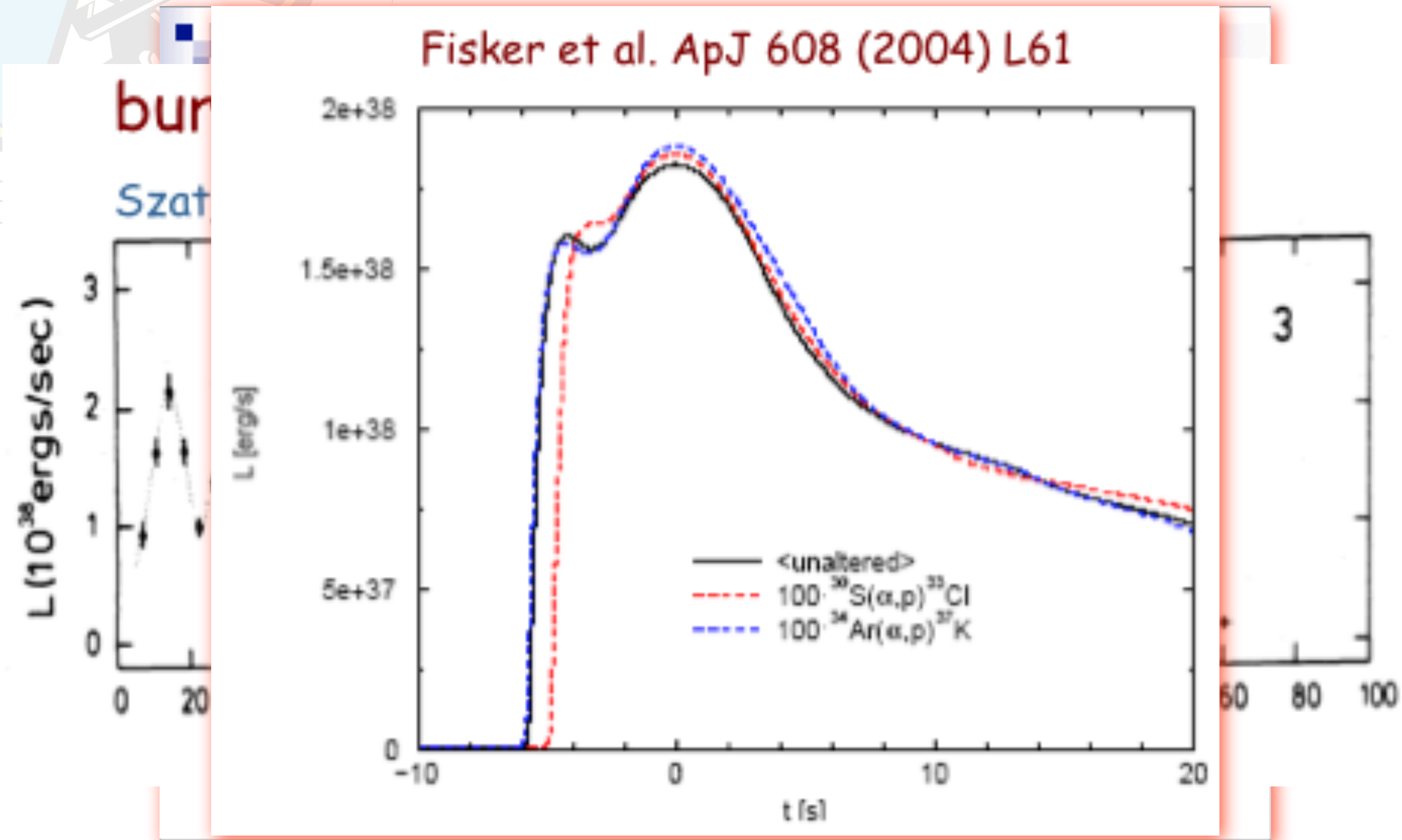
- Here, measure the (p,α) rather than the required (α,p).

$$\frac{\sigma_{\alpha X}}{\sigma_{pY}} = \frac{m_p m_Y}{m_\alpha m_X} \frac{E_{pY}}{E_{\alpha X}} \frac{(2J_p+1)(2J_Y+1)}{(2J_\alpha+1)(2J_X+1)}$$



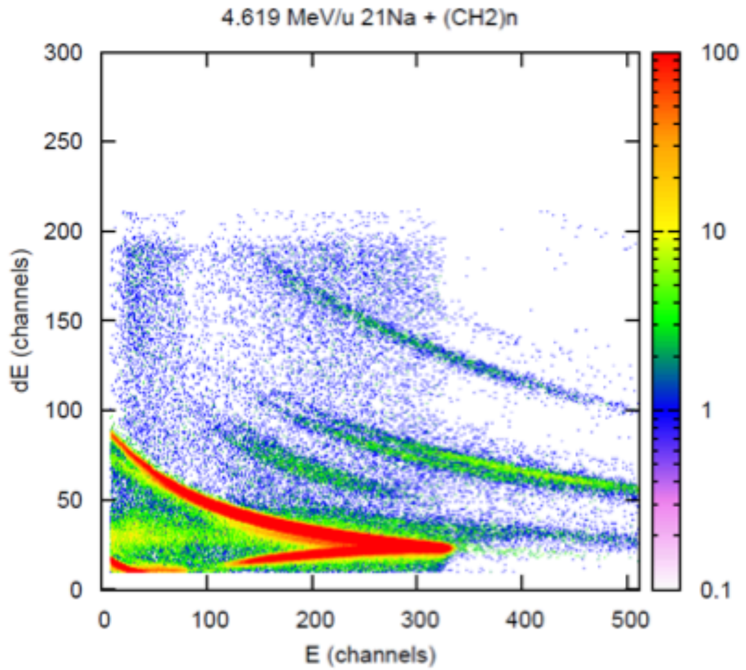
- Limitation: *contributions to the reaction rate from excited states in the final nucleus must be determined separately*
- Example: ^{17}F(p,α) for ^{14}O(α,p)
- Example: ^{21}Na(p,α) for ^{18}Ne(α,p)

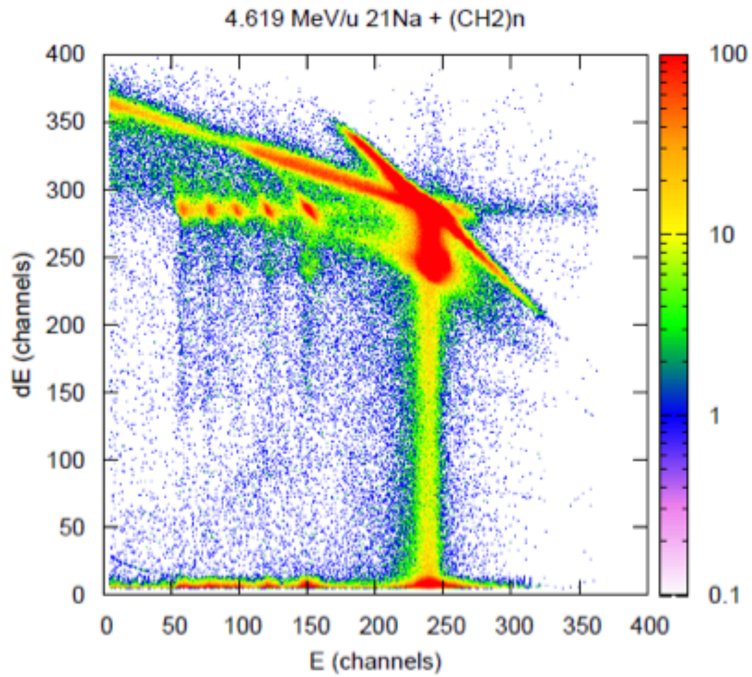
(α,p) reactions in XRBs



alpha particles in
S2 detector

heavy ions in
CD-PAD detector

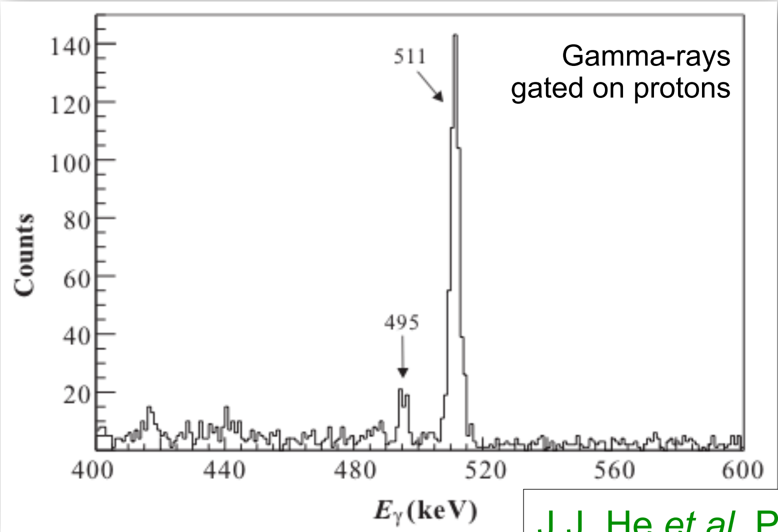


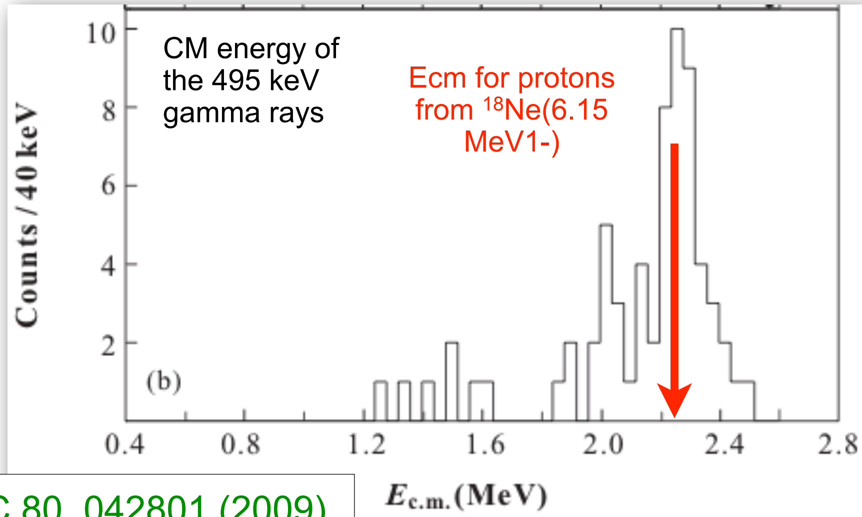


- ^{21}Na(p, α)^{18}Ne Nov 2009 Analysis in progress
- ^{37}K(p,α)^{34}Ar Accepted at TRIUMF
- ^{29}P(p,α)^{26}Si and ^{33}Cl(p,α)^{30}S LOI at GANIL

Inelastic contribution?

- Can use inelastic proton scattering
- REX-ISOLDE, MINIBALL+CD
- ^{17}F on CH_2, stopped beam, detect protons and gamma-rays
- Yield seen from 495 keV $1/2^+$ state coincident with protons from $^{17}F^*$





J.J. He *et al.* PRC. C 80, 042801 (2009)

Inelastic component <u>is</u> comparable to g.s. contribution

Notable references

- B. Harss *et al*. PRL. 82, 3964–3967; PRC 65, 035803 (2002)
  - $^{17}F(p, \alpha)$ for $^{14}O(\alpha, p)^{17}F$
- J.J. He *et al.* PRC. C 80, 042801 (2009)
  - $^{14}O(\alpha, p)^{17}F$ inelastic component evaluated via $^{17}F(p, p')$
- D Bardayan et al, PRC 81, 065802 (2010)
  - $^{17}F(p,p')$
- H.Y. Lee PRC 80 025805 (2009)
  - $^{21}Ne(p,\alpha)$ for $^{18}F(\alpha,p)$ and a neutron source for r-processing

Example 4

Activation Methods

- In some astrophysical environments, detailed nuclear physics not needed
  - e.g. far from stability, (Q)NSR, r-process, p-process
- Need masses, lifetimes, level densities
- Use global approaches
- Benchmark where possible
- *Recent work on p+^{120}Te*

Activation

- p beam on ^{120}Te
- (p,γ) and (p,n) produce ^{121}I, $^{120}I^{g}$, $^{120}I^{m}$
- These have beta-delayed gamma emission ($t_{1/2}$=127, 82, 53 m respectively).
- Measure the γ-rays to infer original production
- Compare with HF (NON-SMOKER & TALYS)
- Explores the accuracy of the OMP and NLDs used
- Q: What further work is needed here? (α,γ) and (α,n)?

Notable References

G. G. Kiss, Phys. Rev. C 76, 055807 (2007).
Gy.Gyurky, Phys. Rev. C 68, 055803 (2003).
Gy. Gyurky, Phys. Rev. C 64, 065803 (2001).
S. Galanopoulos, Phys. Rev. C 67, 015801 (2003).
P. Tsagari, Phys. Rev. C 70, 015802 (2004).
C. E. Laird, Phys. Rev. C 35, 1265 (1987).
S. Harissopulos Phys. Rev. C 64, 055804 (2001).
T. Sauter Phys. Rev. C 55, 3127 (1997).
F. R. Chloupek, Nucl. Phys. A652, 391 (1999).
J. Bork, Phys. Rev. C58, 524 (1998).
N. Ozkan Nucl. Phys. A688, 459c (2001).
N. Ozkan, Nucl. Phys. A710, 469 (2002).
Gy. Gyurky, J. Phys. G: Nucl. Part. Phys. 34, 817 (2007).
M. A. Famiano, Nucl. Phys. A802, 26 (2008).
G.G. Kiss, Phys. Rev. Lett. 101, 191101 (2008).
A. Spyrou, Phys. Rev. C 77, 065801 (2008).

Notables not mentioned...

- ANCs
  - Artemov *et al.* Int.J.Mod.Phys. E19, 1102 (2010), $^{10}B(p,\gamma)$ and $^{24}Mg(p,\gamma)$
- Trojan Horse Method
  - M.L. Sergi *et al*. (Conf), $^{17}O(p,\alpha)^{14}N$ via THM
- Beta-decay population
  - Y. Itchikawa *et al*. PRC C 80, 044302 (2009) $^{24}Mg^*$, non Nuc. Ast, TES with analogues
  - X.D. Tang PRC 81, 045809 (2010), $^{16}N(\beta\alpha)$ for $^{12}C(\alpha,\gamma)$
- Gamma-ray spectroscopy
  - G. Lotay *et al.* PRC 77, 042802 (2008) ^{24}Al for $^{23}Mg(p,\gamma)^{24}Al$
  - G. Lotay *et al*. PRC 80, 055802 (2009) ^{27}Si for $^{26}Al(p,\gamma)^{27}Si$
- Depth profiling
  - R. Longland *et al.* PRC 81 (2010) 055804 $^{22}Ne(p,\gamma)$
- Resonance fluorescence
  - R. Longland PRC 80, 055803 (2009) Real γ-rays to excite $^{26}Mg^*$ for $^{22}Ne(\alpha,n)^{25}Mg$
- Storage rings, Coulex, Coulomb dissociation, Anthropic inferences...

DISCUSSION