Fluorine production in AGB stars: the role of (p,α) reactions

...and (α,p) reactions

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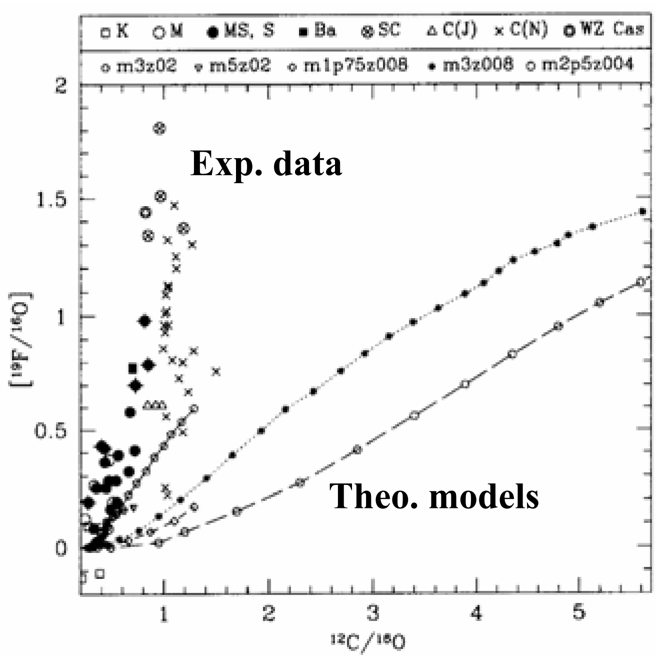
^{19}F Nucleosynthesis and Mixing

^{19}F is one of the few naturally occurring isotopes whose nucleosynthesis is still uncertain.

Possible sources: SNe, WF and AGB stars

Role: constraint in AGB models and s-process nucleosynthesis (TDU + TP)



from M. Lugaro et al. ApJ 615, 934 (2004)

Comparison of observed ^{19}F abundance and the predictions from AGB star models

High ^{19}F abundances → high C/O

NOT supported by observations!

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ [^{13}C-pocket?]
$^{13}C(\alpha,n)^{16}O$ [s-process]
$^{14}N(n,p)^{14}C$
$^{14}C(\alpha,\gamma)^{18}O$ or $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O$
$^{18}O(p,\alpha)^{15}N$ → $^{15}N(p,\alpha)^{12}C$
$^{18}O(\alpha,\gamma)^{22}Ne$
$^{15}N(\alpha,\gamma)^{19}F$ → $^{19}F(\alpha,p)^{22}Ne$

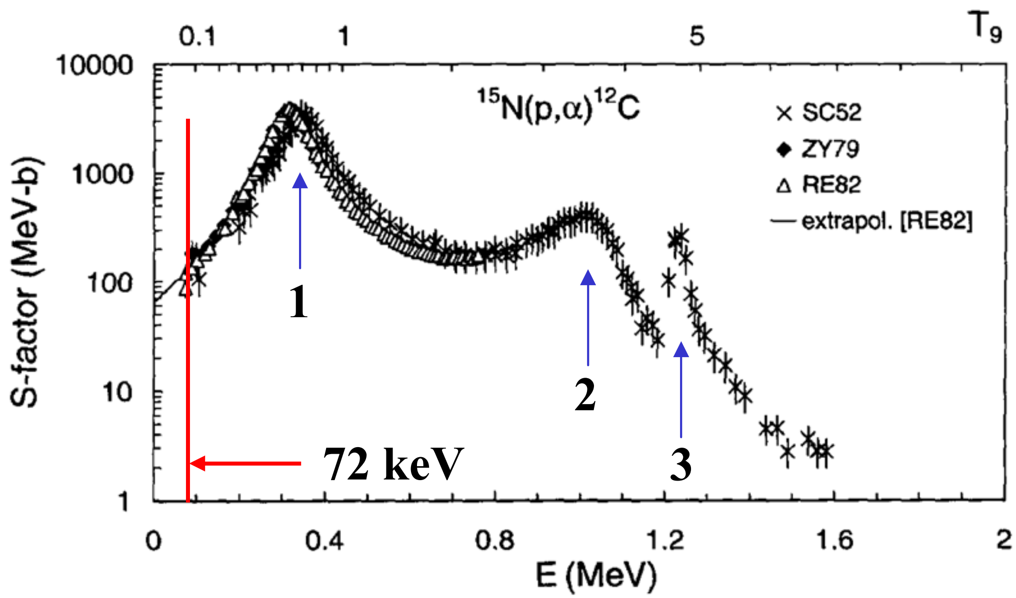
} ^{19}F depleting reactions

The $^{15}N(p,\alpha)^{12}C$ Reaction: Current Status

- **The $^{15}N(p,\alpha)^{12}C$ removes both protons and ^{15}N nuclei from ^{19}F production chain**
- **"Branch point" CNO (CN-NO) cycle**

Direct Measurements

from NACRE



The S(E)-factor is dominated by three resonances:

1. **J^{π} = 1-, l = 0, $E_{c.m.}$ = 314 keV**
2. **J^{π} = 1-, l = 0, $E_{c.m.}$ = 963 keV**
3. **J^{π} = 2-, l = 2, $E_{c.m.}$ = 1.13 MeV**

1+2 → constructive interference

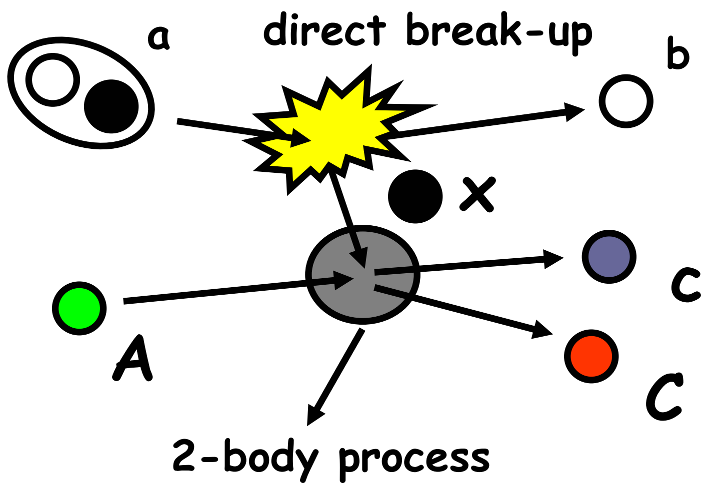
- **Extrapolation to the 0 – 72 keV region through a Breit-Wigner fit (+ interference)**
- **"Electron screening": enhancement ≥ 10% @ 80 keV**
- **Good test for the application of THM to reactions involving heavy nuclei (many resonances – different l's and interference effects)**

Indirect Techniques: the THM

Coulomb barrier → exponential damping of the cross section at astrophysical energies
+ electron screening

→ → low-energy, bare-nucleus cross section is experimentally available only through
<u>extrapolation OR indirect measurements</u>

THM reaction



From

A+a(x⊕b) → c+C+b @ 10-60 MeV

A + x → c + C @ 5-20 keV

By selecting the QF contribution

<u>Additional advantages:</u>

- **reduced systematic errors due to straggling, background…**
- **magnifying glass effect**

<u>But...</u>

- **off-shell cross section deduced (x → virtual particle)**
- **no absolute units**

Though $E_A >> V_{Coul}$ it is possible to measure at the Gamow peak since:

$$E_{c.m.}=E_{A\text{-}x}-Q_{x\text{-}b}$$

THM: Basic Features

Plane Wave Impulse Approximation:

- beam energy >> a = x ⊕ b breakup Q-value
- projectile k^{-1} wavelength << x – b intercluster distance

  \+ plane waves in the entrance and exit channel

See e.g.
C. Spitaleri et al.
PRC 60, 055802 (1999)

➔ **the 3-body cross section factorizes:**

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} \propto \mathrm{KF}\, |\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\mathrm{off}}$$

From the experiment

Evaluated through a MC code

Off-shell 2-body cross section

- **KF kinematic factor**
- **$\phi(p_b)^2$ spectator momentum distribution**
- **$d\sigma^{off}/d\Omega$ off-shell cross section or "nuclear" (N) cross section**

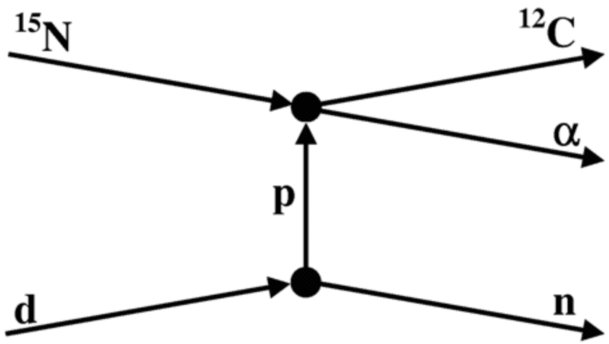
$d\sigma^{off}/d\Omega$ → $d\sigma/d\Omega$ (on shell)

The penetration factor P_l has to be introduced:

since → → →

$$\frac{d\sigma}{d\Omega} = \sum_l P_l \frac{d\sigma_l^N}{d\Omega}$$

$^{15}N(p,\alpha)^{12}C$: Indirect Study



THM: the cross section of the reaction

$^{15}N(p,\alpha)^{12}C$

is deduced from the one of the three-body process:

$^{2}H(^{15}N,\alpha^{12}C)n$

@ E_{beam} = 60 MeV

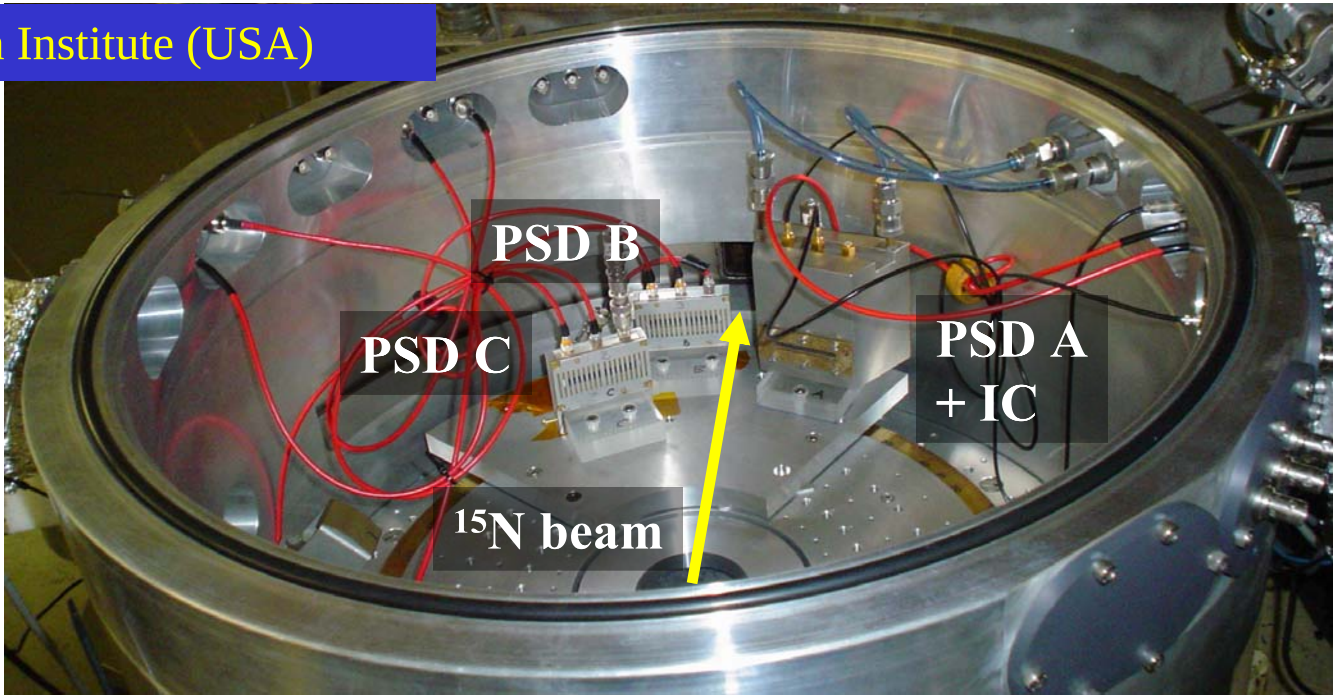
A single beam energy → a full excitation function (covering the astrophysically relevant energy interval)

Lab.: Texas A&M Cyclotron Institute (USA)

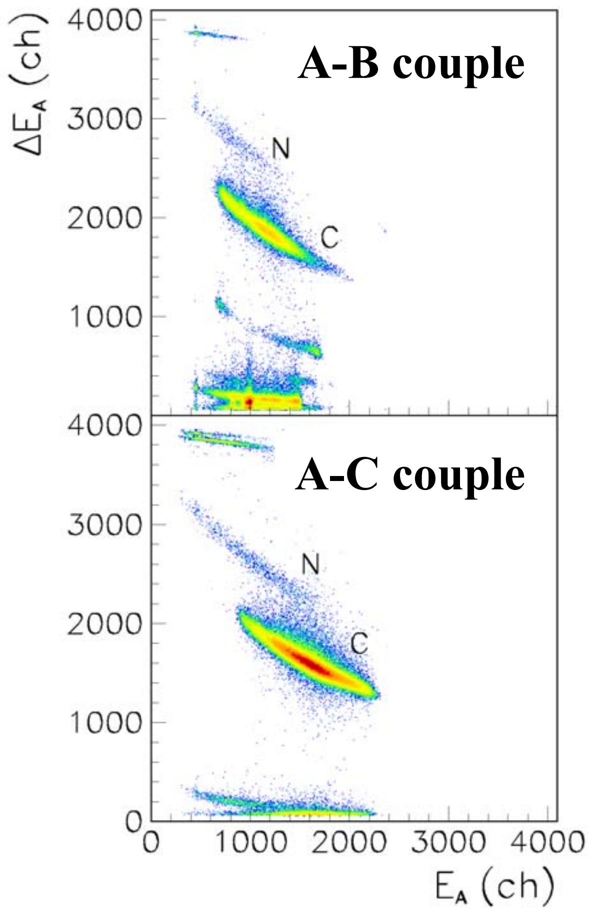
PSD A + IC for carbon discrimination (ΔE- E)

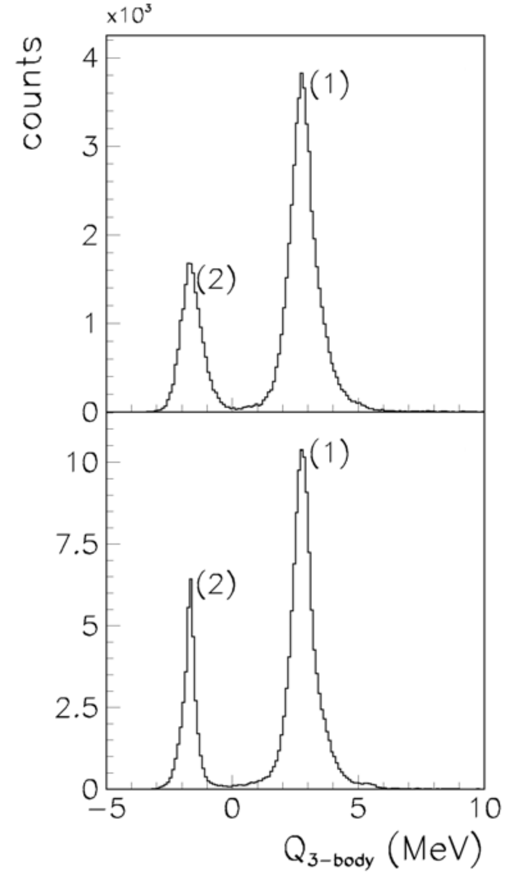
PSD B e C to detect α's from the $^{2}H(^{15}N,\alpha^{12}C)n$ reaction

Detectors placed at the QF angles



Channel Selection





ΔE-E 2D spectra to select the locus of carbon nuclei
After calibration Q-value is evaluated event by event...

Q-value spectra:

1- $^{2}H(^{15}N,\alpha_0{}^{12}C)n$ @ 2.74 MeV

2- $^{2}H(^{15}N,\alpha_1{}^{12}C)n$ @ -1.7 MeV

only (1) is selected for further analysis

+ Cross check on calibrations!

Study of the Reaction Mechanisms

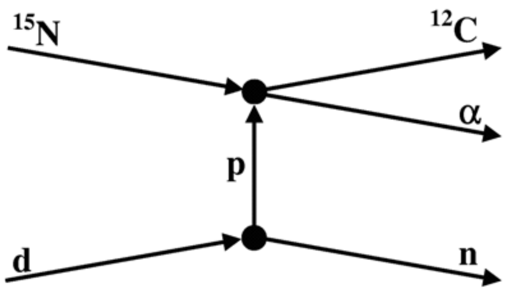
$\alpha+{}^{12}C+n$ exit channel can be fed through a number of reaction mechanisms

QF → direct

SD (sequential decay) → two step

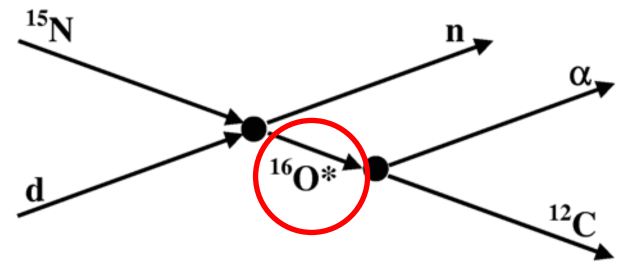
(*n* does not behave as spectator)

"quasi-free" reaction

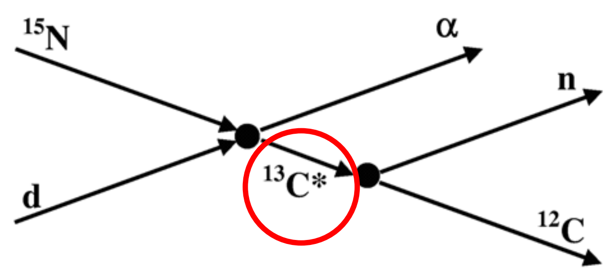


Possible SD processes

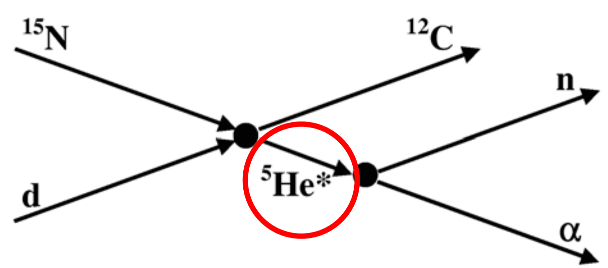
${}^{16}O^* \rightarrow {}^{4}He+{}^{12}C$



${}^{13}C^* \rightarrow {}^{12}C+n$



${}^{5}He^* \rightarrow {}^{4}He+n$



Factorization of $d^3\sigma$ is valid only for QF breakup

→ Reaction mechanism selection

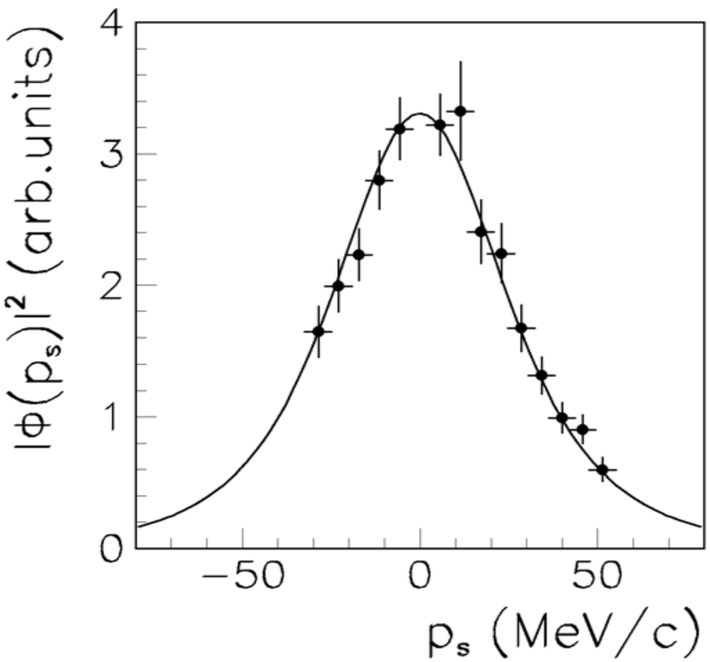
How? Study of $d^3\sigma$ as a function of p_b

- **angular correlation analysis**
- **coincidence yield for different Δp_b**
- **shape of the momentum distribution**

Selection of the QF Contribution

If the reaction is taking place through the QF mechanism → direct process

n **experimental momentum distribution should be the same as the one inside *d* → the deduced *n* momentum distribution is sensitive to the reaction mechanism**



From

$$|\Phi(\vec{p}_s)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\text{off}}_{E_0} \propto \left[\frac{d^3\sigma}{d\Omega_\alpha d\Omega_{^{12}C} dE_{c.m.}}\right] \cdot [\text{KF}]^{-1}$$

if $d\sigma^{off}/d\Omega \sim$ constant →

$$|\Phi(\vec{p}_s)|^2 \propto \left[\frac{d^3\sigma}{d\Omega_\alpha d\Omega_{^{12}C} dE_{c.m.}}\right] \cdot [\text{KF}]^{-1}$$

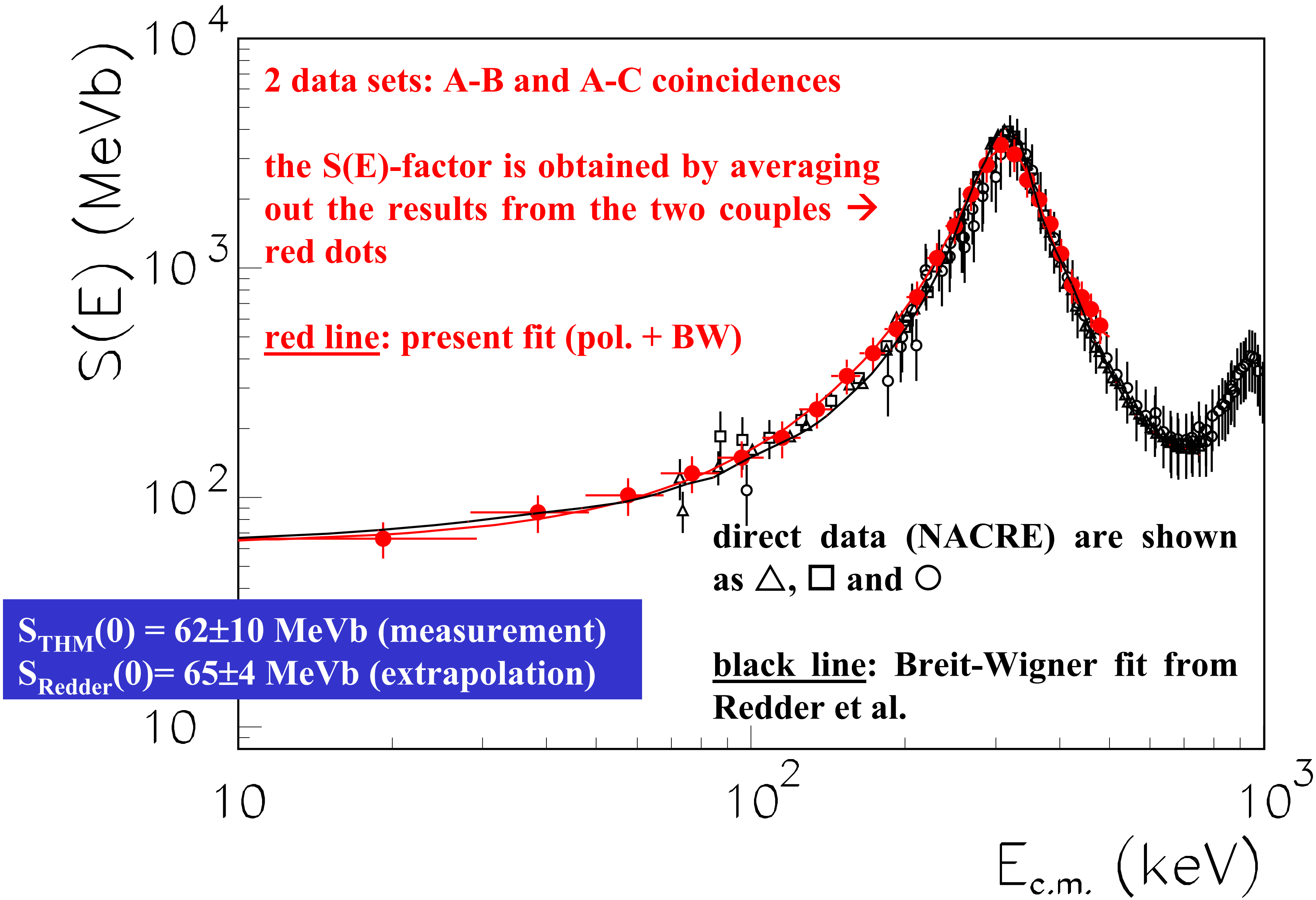
$$\Phi(\vec{p}_s) = \frac{1}{\pi}\sqrt{\frac{ab(a+b)}{(a-b)^2}}\left[\frac{1}{a^2+p_s^2} - \frac{1}{b^2+p_s^2}\right]$$

Thus p_b → p_s
(Neutron → spectator to $^{15}N(p,\alpha)^{12}C$)
QF mechanism is dominant in the p_s<40 MeV/c momentum interval

Hulthén function: standard parameters
a=0.2317 fm^{-1}
b=1.202 fm^{-1}

A single fitting parameter, the normalization constant

Extraction of the indirect S(E)-factor



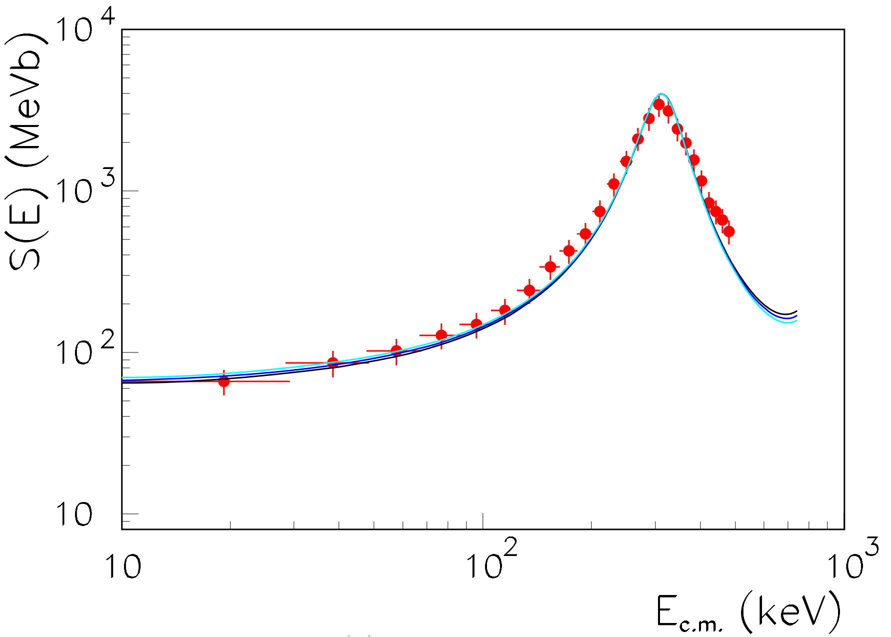
Modified R-matrix Approach

Particle x in the entry channel → off-the-energy-shell

No standard R-matrix theory applicable

→ Modified R-matrix approach: resonance widths in the entry channel are replaced by form factors

present case: 2 interfering resonances



$$S^{HOES(norm)}(E_{xA}) = \pi \lambda_N^2 \frac{1}{2} \frac{(2J+1)}{(2J_x+1)(2J_A+1)} \frac{m_x + m_A}{m_x m_A} m c^2 e^{2\pi\eta_{xA}} 10^{-2} \Gamma_{xA(1)}(E_{xA})$$
$$\times \left| \frac{\sqrt{\Gamma_{cC(1)}(E_{cC})}}{E_{xA} - E_{xA(R1)} + i\frac{\Gamma_{(1)}}{2}} + \frac{\sqrt{\Gamma_{cC(2)}(E_{cC})}\, W_{xA(R2R1)}(p_{xA})}{E_{xA} - E_{xA(R2)} + i\frac{\Gamma_{(2)}}{2}} \right|^2.$$

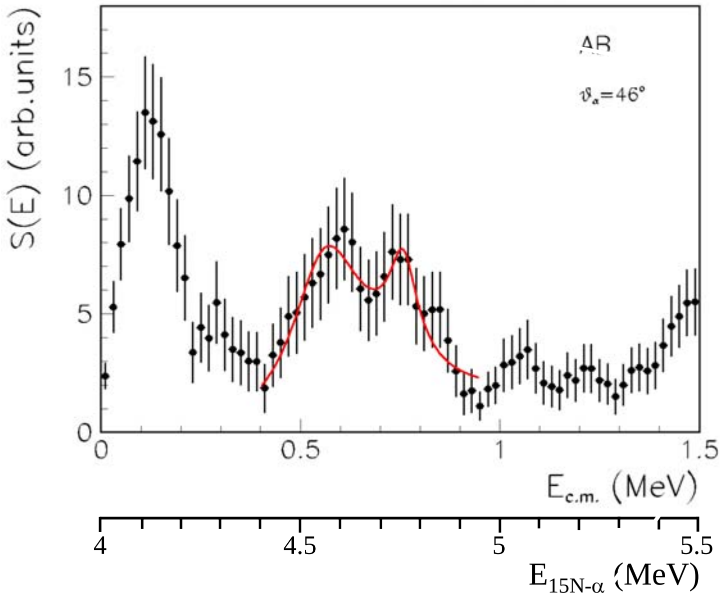
Where $W_{xA(R2R1)}(p_{xA}) = \frac{W_{xA(R2)}(p_{xA})}{W_{xA(R1)}(p_{xA})}$ **~** $\gamma_{xA(21)} = \sqrt{\frac{\Gamma_{xA(2)}(E_{xA})}{\Gamma_{xA(1)}(E_{xA})}} = \frac{\gamma_{xA(2)}}{\gamma_{xA(1)}}$

$W_{xA}(Ri)(p_{xA})$ [i=1,2] → resonance form factors: $W_{xA(i)}(p_{xA}) = < j_{l_i}(p_{xA})| < V_{xA} > |I_{xA}^{F_{(i)}} >$

$I_{xA}^{F(i)}$ the overlap function and $<V_{xA}>$ the interaction potential

The $^{18}O(p,\alpha)^{15}N$ Reaction: Preliminary Results

TAMU Experiment



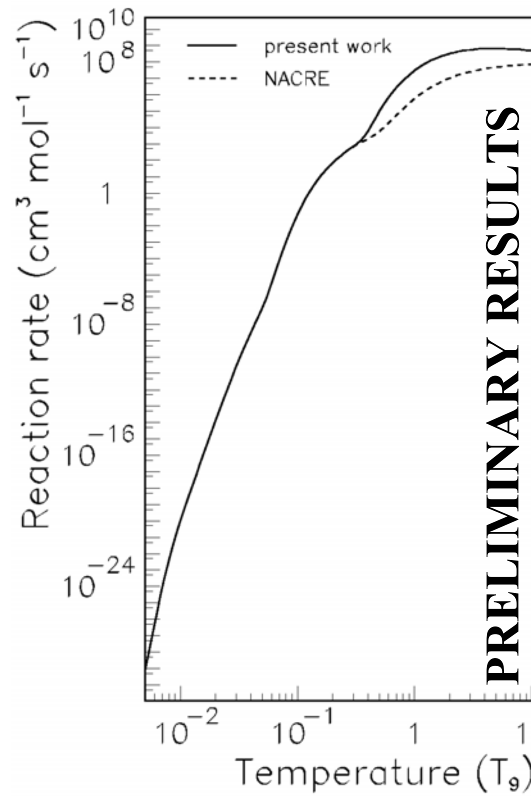
The strength of the 656 keV resonance is deduced from the ratio to the one of the 799 keV level, by fitting the S(E) for fixed $\theta_{c.m.}$ (and correcting for angular distributions)

$$(\omega\gamma)_1/(\omega\gamma)_2 = 14.8 \pm 2.5$$

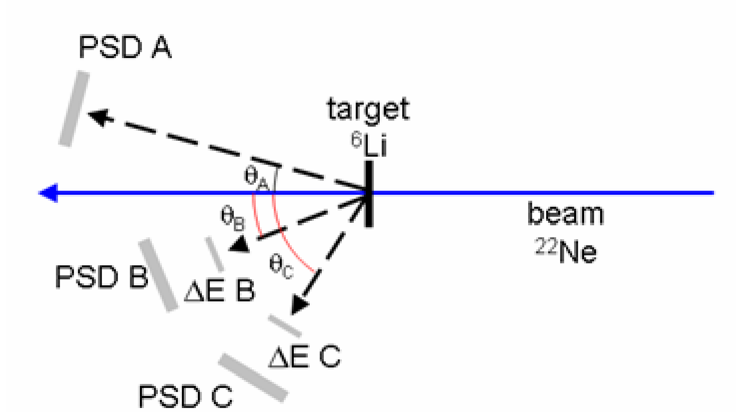
NACRE → 0.5 LW79 → 3 Yagi et al. (1962) → 0.4

E_{res} (fit) = 0.59 ± 0.02 MeV ≠ E_{res} (literature)

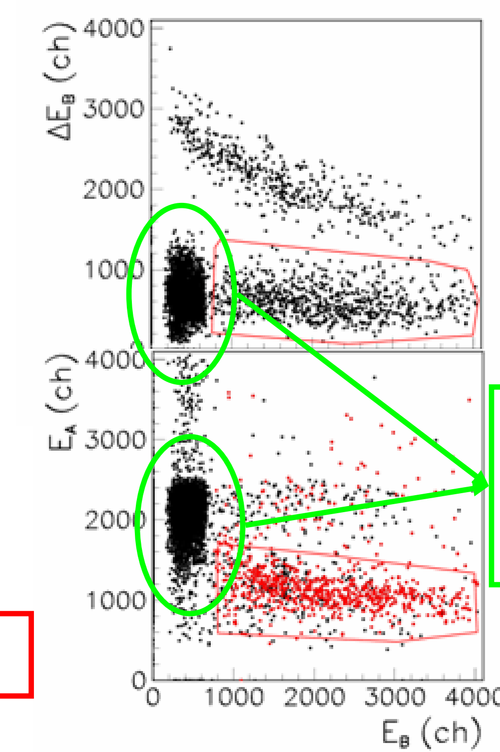
Huge variation (up to a factor 50) but for the highest temperatures only (above 4×10⁸ K)
→ No significant change in model predictions for AGB stars
Mod. R-Mat. Analysis needed!



Next Step: the $^{19}F(\alpha,p)^{22}Ne$ Reaction



experimental setup for the indirect study of the $^{19}F(\alpha,p)^{22}Ne$ reaction via the 3-body one $^{6}Li(^{19}F,\alpha^{22}Ne)^{2}H$



ΔE-E 2D spectrum from PSD B. The red line marks the proton locus

protons (impurities in the target) from scattering

PSD A

telescopes B and C (ΔE + PSD)

FSU Experiment

Kinematical locus for the A-B coincidences

Black dots → full coincidence yield

Proton events are marked by red dots

kinematical locus for the THM $^{6}Li(^{19}F, p^{22}Ne)^{2}H$ → red line

The collaboration

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