Approaching the stellar burning energies indirectly

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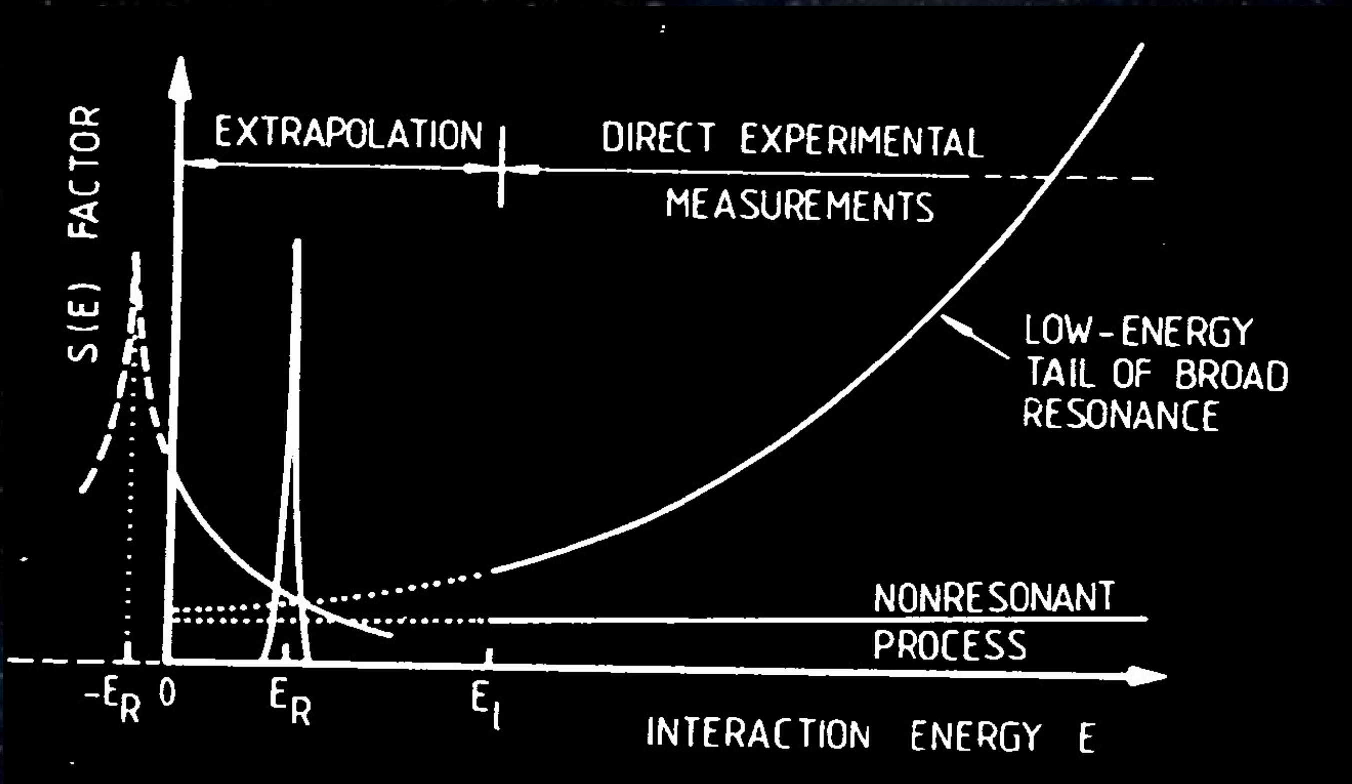
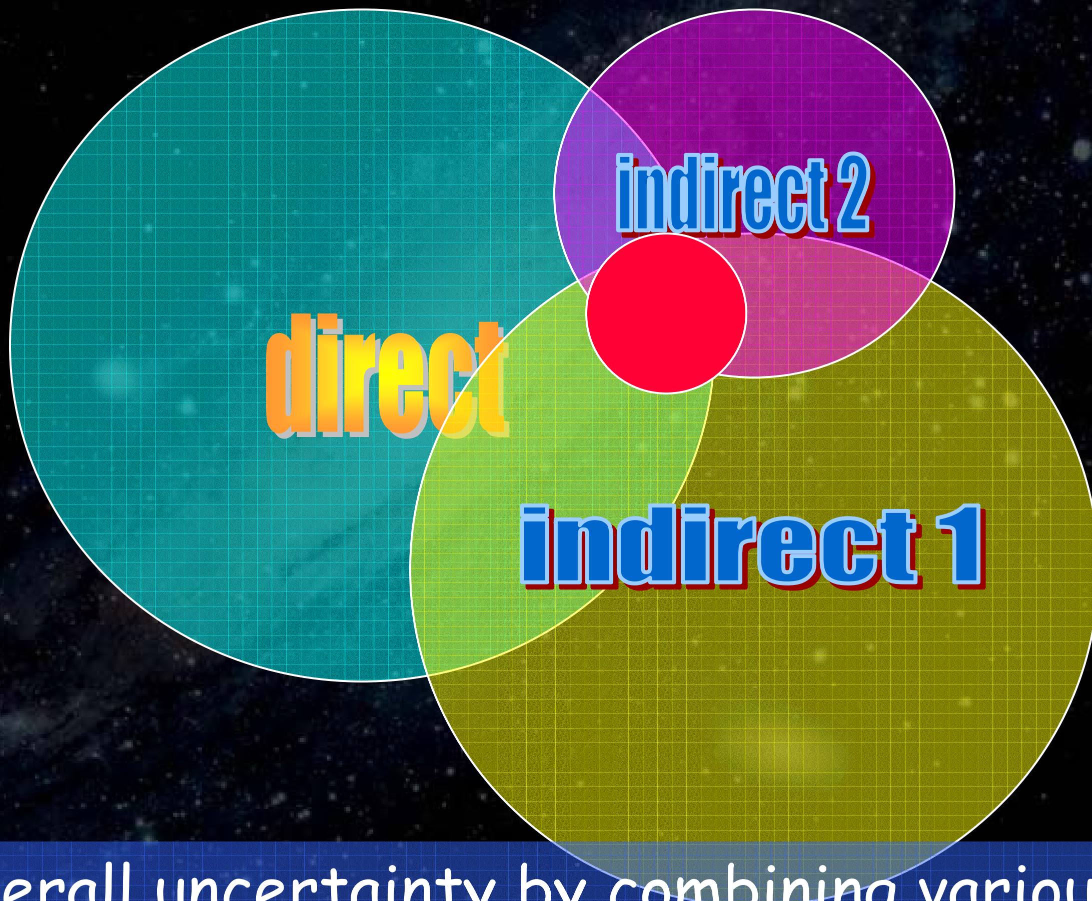
Approaching the stellar energies



- Better experimental technologies, lower energies.
- Hard to reach stellar energy regions, especially for RNB.
- Extrapolation is inevitable for most cases.

Direct + Indirect



Reduce the overall uncertainty by combining various approaches, with assurance that systematic uncertainties are independent.

Indirect Measurements

Trojan Horse Method	ANC Method
• Study 3-body reaction A+a→C+c+b With Trojan horse a=b+x(d(p+n), ^{6}Li(a+d)) (^{7}Li+d→^{4}He+^{4}He+n) • Extract energy dependence of the cross section of 2-body reaction A+x→C+c (^{7}Li+p→^{4}He+^{4}He)	• Extract Asymptotic Normalization Coefficient of bound and unbound state wave function of a(b+c) (^{15}O(^{14}N+p)) from peripheral reactions. (^{14}N(^{3}He, d)^{15}O) • Calculate the matrix elements for radiative capture b(c,γ)a. ^{14}N(p,γ)^{15}O

- Trojan Horse Method

Main application:

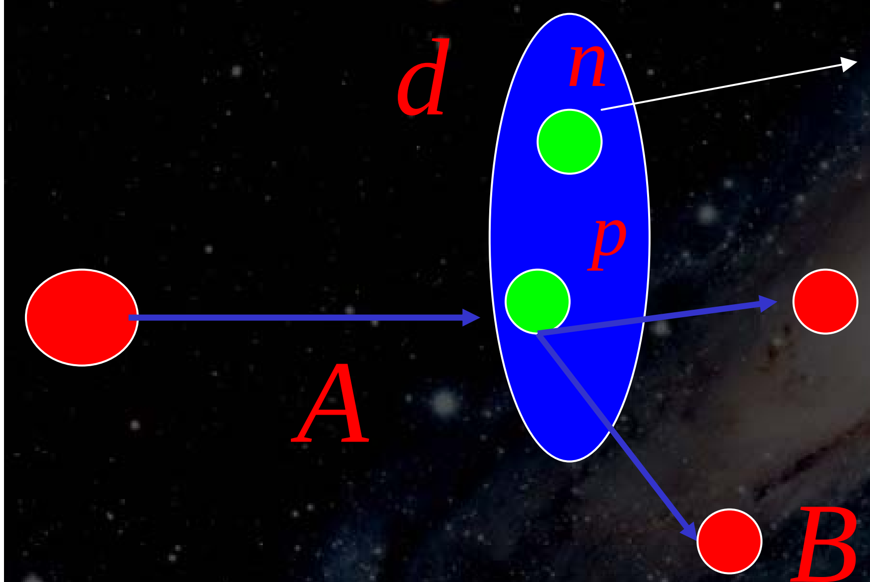
to extract bare nucleus cross sections for two-body charged particle reactions

(no capture cross sections)

using the

quasi-free mechanism…

Trojan Horse Method (Quasi-Free Kinematics)



$$p + {}^{7}Li \rightarrow \alpha + \alpha$$

$$d + {}^{7}Li \rightarrow n + \alpha + \alpha$$

$$E_{p^{7}Li} = \frac{1}{8} E_{A}^{(L)} - 2.224\ (\mathrm{MeV})$$

$$E_{^{7}Li}^{(L)} = 20\,\mathrm{MeV}$$

$$E_{p^{7}Li} = 0.276\,\mathrm{MeV}$$

$$E_{p^{7}Li} = 0.0 \qquad E_{^{7}Li}^{(L)} = 8 * 2.224\,\mathrm{MeV}$$

$$E_{pA} = \frac{m_p}{m_p + m_A} E_{A}^{(L)} - e_{pn}^{d}$$

$$(p_{pn}^{2} = 0)$$

Quasi-Free

No electron screening!

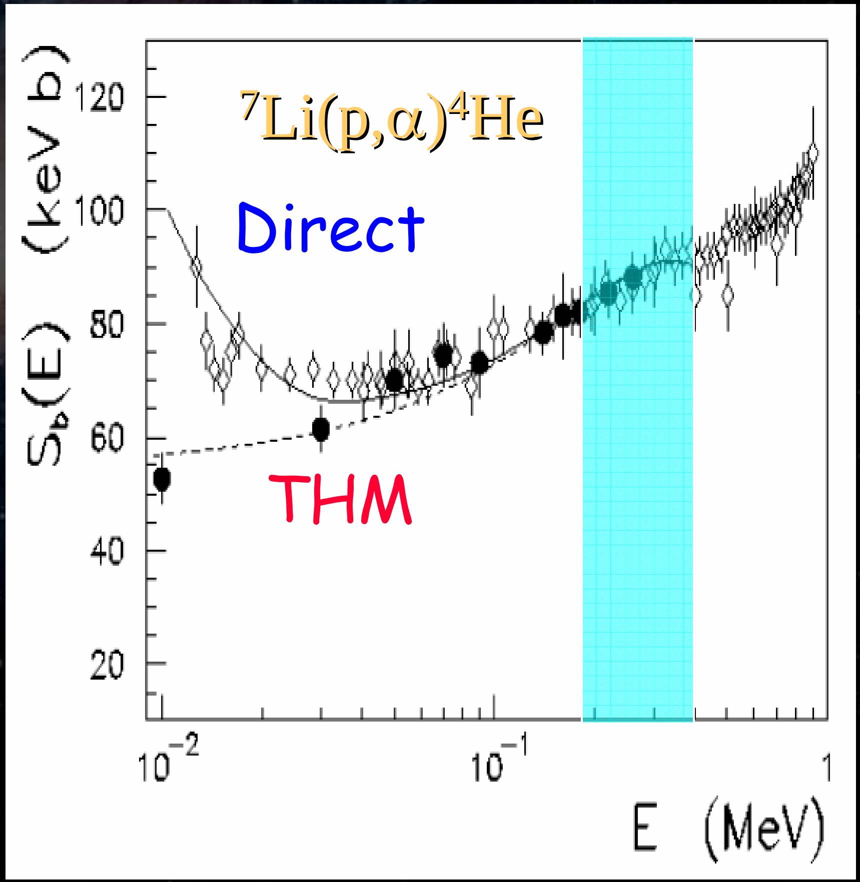
No Coulomb penetration effect!

No Electron Screening with THM

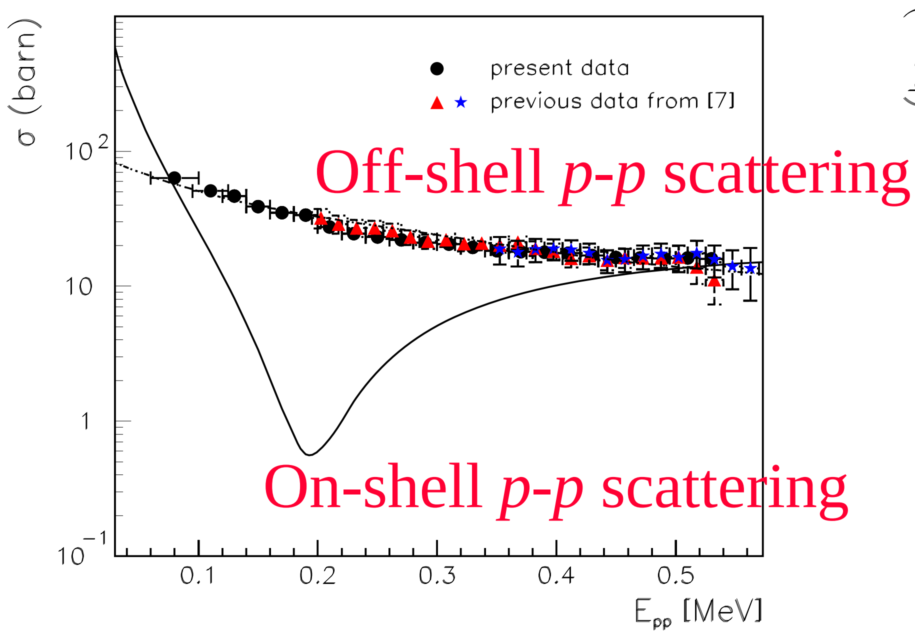
- THM: $^2H(^7Li,\alpha n)^4He$
- Exact the energy dependence of S factor. Normalize to the direct measurement at higher energy.
- No Coulomb suppression and no screening effect.

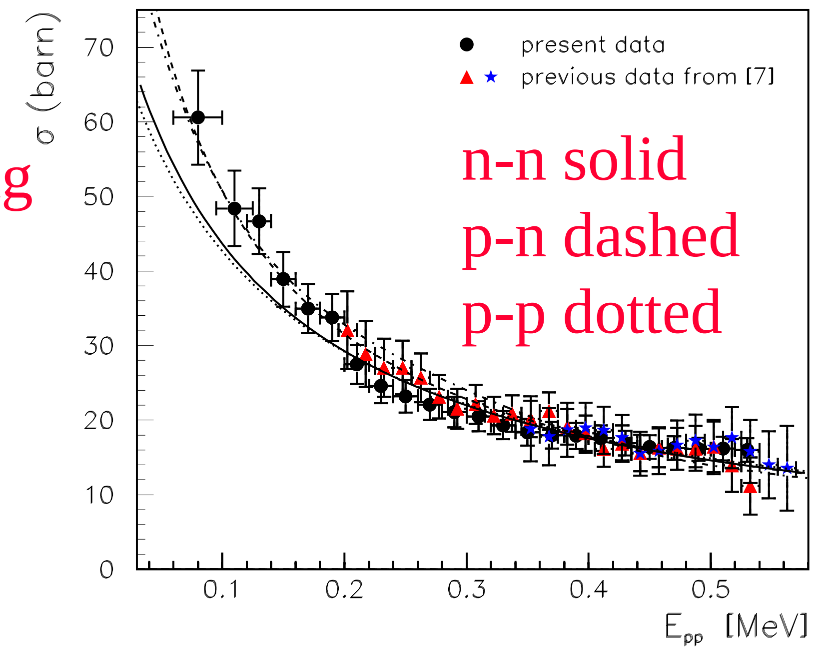
•Electron screening potential:
U_e(THM) = 330±40 eV
U_e(direct) = 340 eV
U_e(theory) = 186 eV

M. Lattuada et al., ApJ 562 (2001) 1076

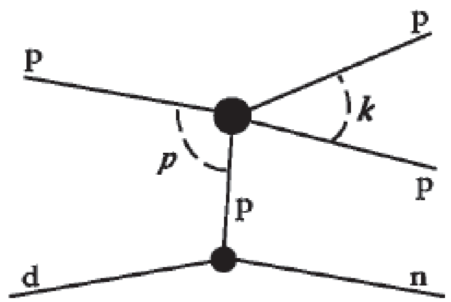


Suppress Coulomb Interaction (p+p elastic scattering)

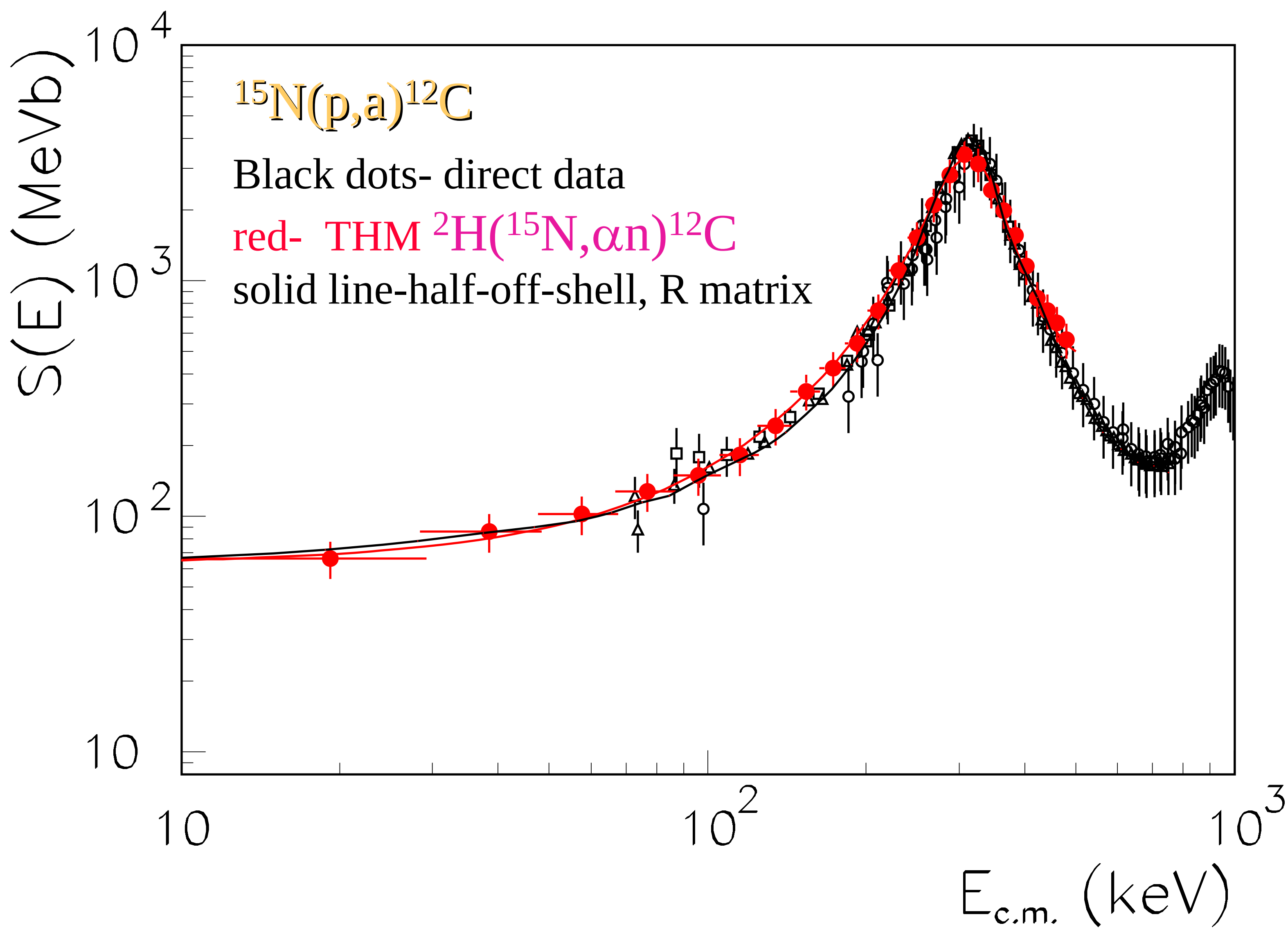




A. Tumino et al., Phys. Rev. Lett. 98, 252502 (2007)

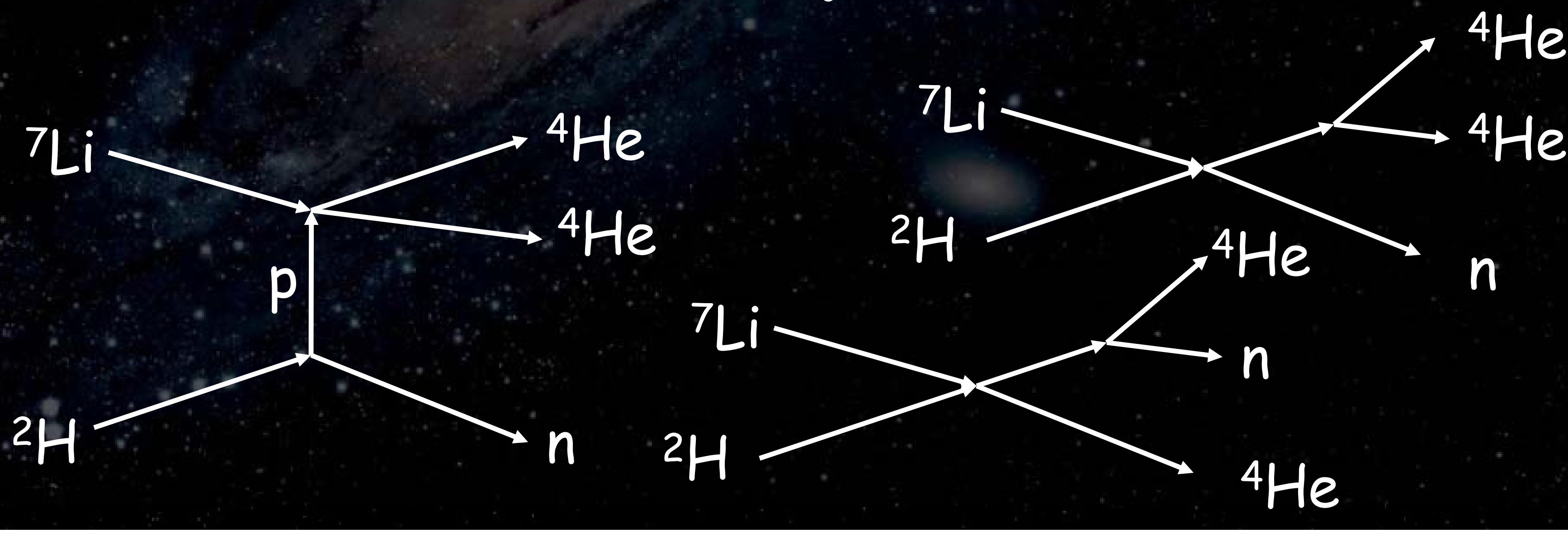


Study (p,α) reactions



Comments on THM

• Work for A+x→C+c; No Coulomb barrier; No screening effect; Provide interference information;
• Need high energy data to normalize;
• IPWBA analysis; Off-shell effect; Multi-step contribution (eg. Compound nuclei process, can be estimated with different Trojan Horse);



Indirectly Studied Charged-Particle Radiative Capture

(Incomplete list)

Reaction	Method
$^{7}Be(p,\gamma)^{8}B$	Non-Res(Direct/CD/ANC)
$^{8}B(p,\gamma)^{9}C$	Non-Res(CD/ANC)
$^{11}C(p,\gamma)^{12}N$	$\Gamma\gamma$(CD); Non-Res(ANC)
$^{13}N(p,\gamma)^{14}O$	$\Gamma\gamma$(Direct/CD); Non-Res(ANC)
$^{14}N(p,\gamma)^{15}O$	Non-Res(Direct/ANC); $\Gamma\gamma$(CoulEx/RD, negligible)
$^{12}C(\alpha,\gamma)^{16}O$	Direct;elastic scattering;β delayed α decay;ANC
$^{16}O(p,\gamma)^{17}F$	Direct; ANC
$^{18}F(p,\gamma)^{19}Ne$	Non-Res(ANC); $\Gamma\gamma$(Direct)

R-Matrix with Asymptotic Normalization Coefficient

$$\sigma \propto \left| M_{DC} \pm i e^{-i\phi} \frac{\Gamma_p^{1/2}\Gamma_\gamma^{1/2}}{(E-E_R)+i\Gamma/2} \right|^2$$

$$M_{DC} \propto C_{lj} \qquad \Gamma_p \propto \left(C_{lj}\right)^2$$

???

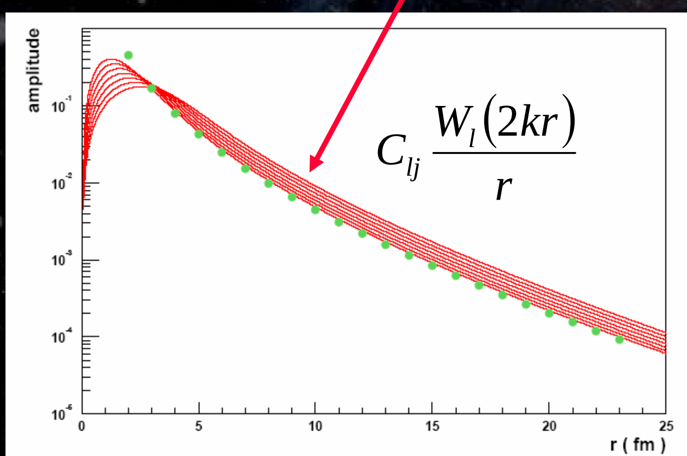
Nucleus interior

For narrow resonance:

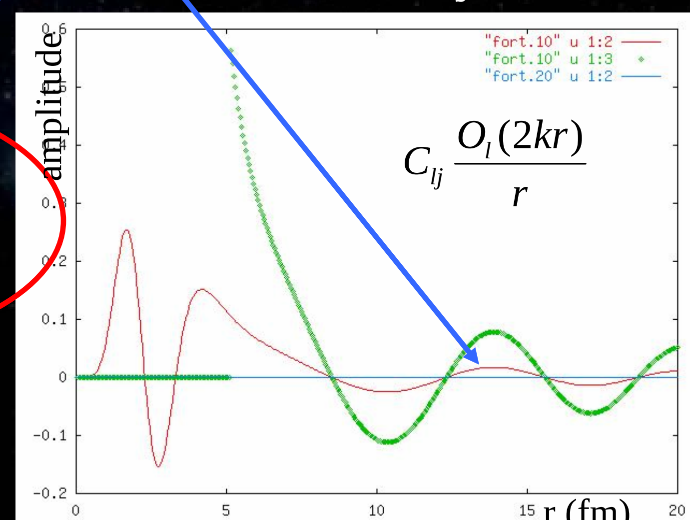
$\Gamma_p \ll \Gamma_\gamma$, $\omega\gamma = \omega\Gamma_p$

$\Gamma_\gamma \ll \Gamma_p$, $\omega\gamma = \omega\Gamma_\gamma$

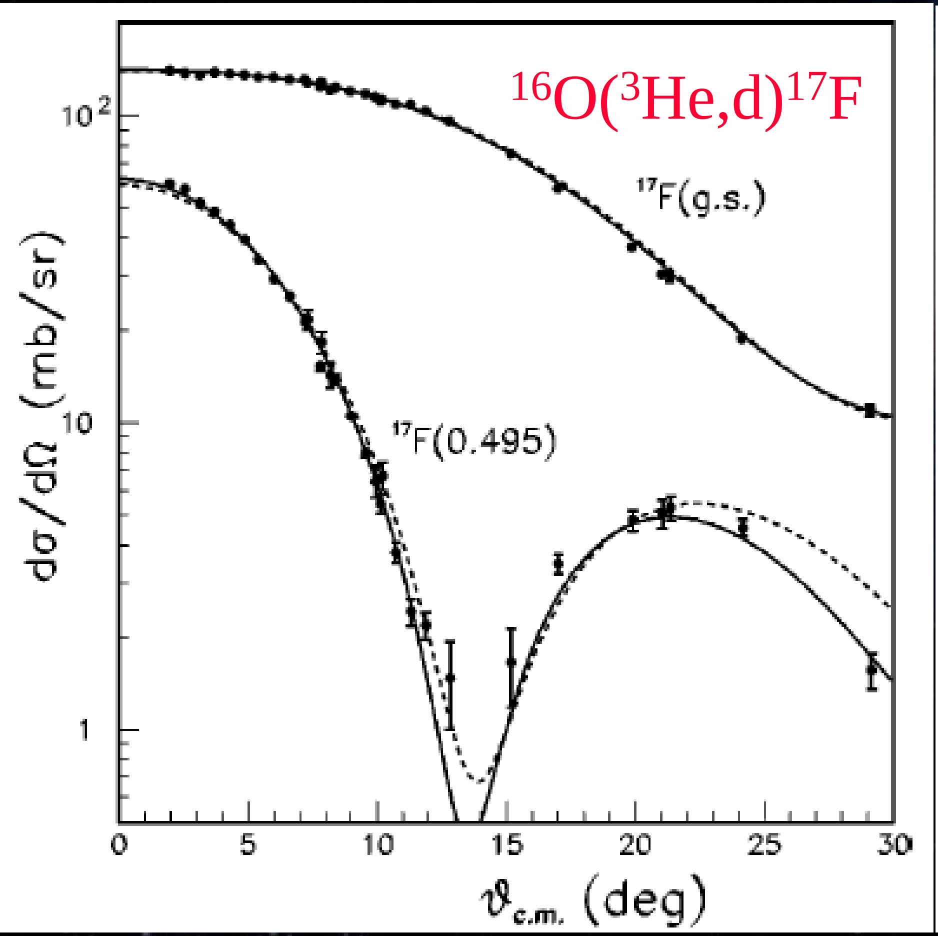
Bound state wave-function (E_b<0)

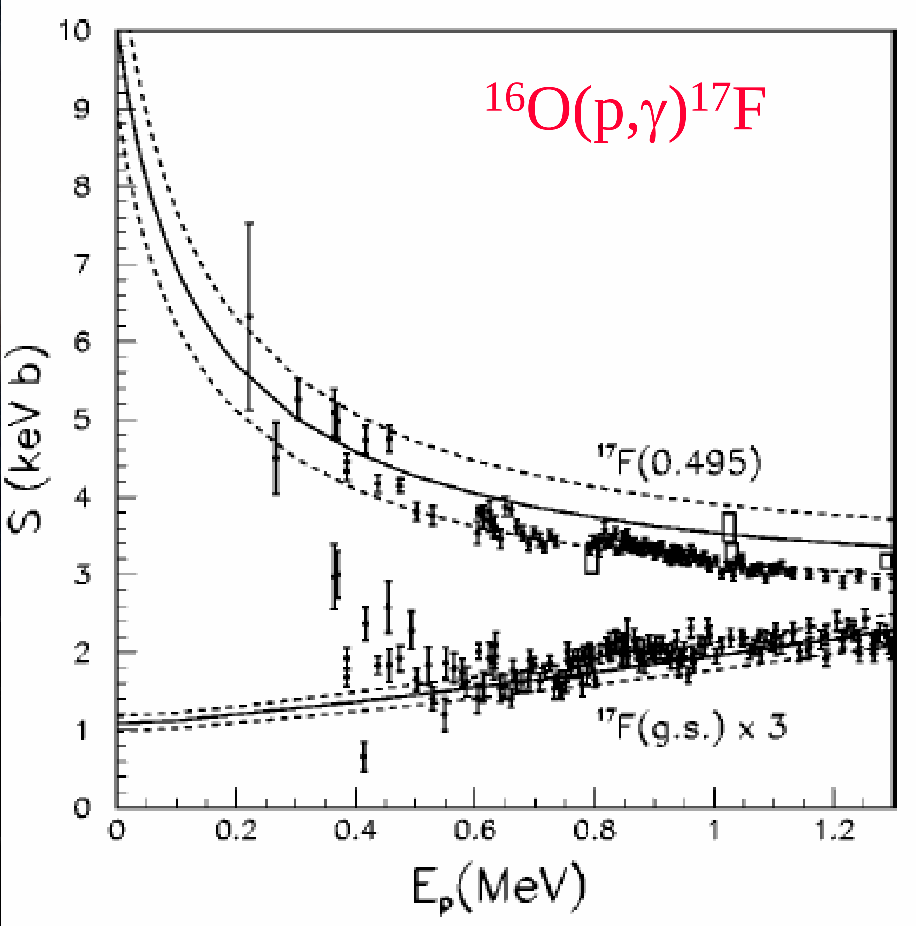


Quasi-bound state wave-function (E_b>0)

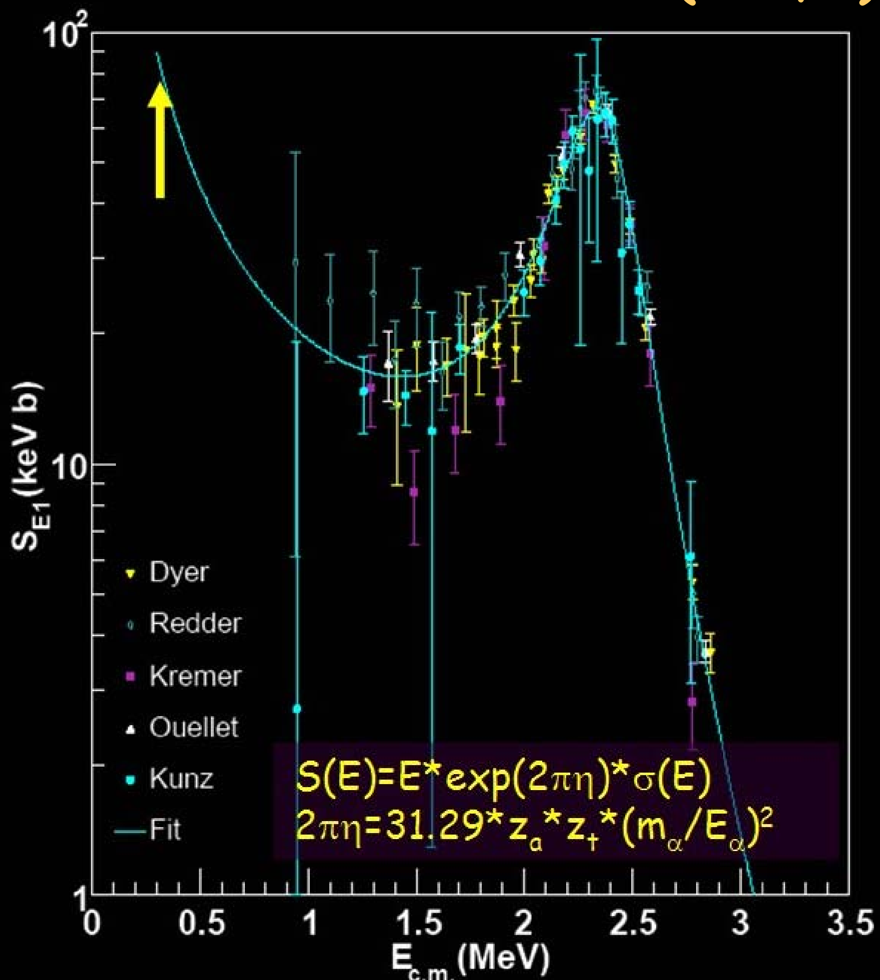


The $^{16}O(p,\gamma)^{17}F$ Reaction





Subthreshold resonance:
From $^{12}C(^{6}Li,d)^{16}O$ to $^{12}C(\alpha,\gamma)^{16}O$



C. R. Brune *et al.*, Phys. Rev. Lett. **83**, 4025 (1999).

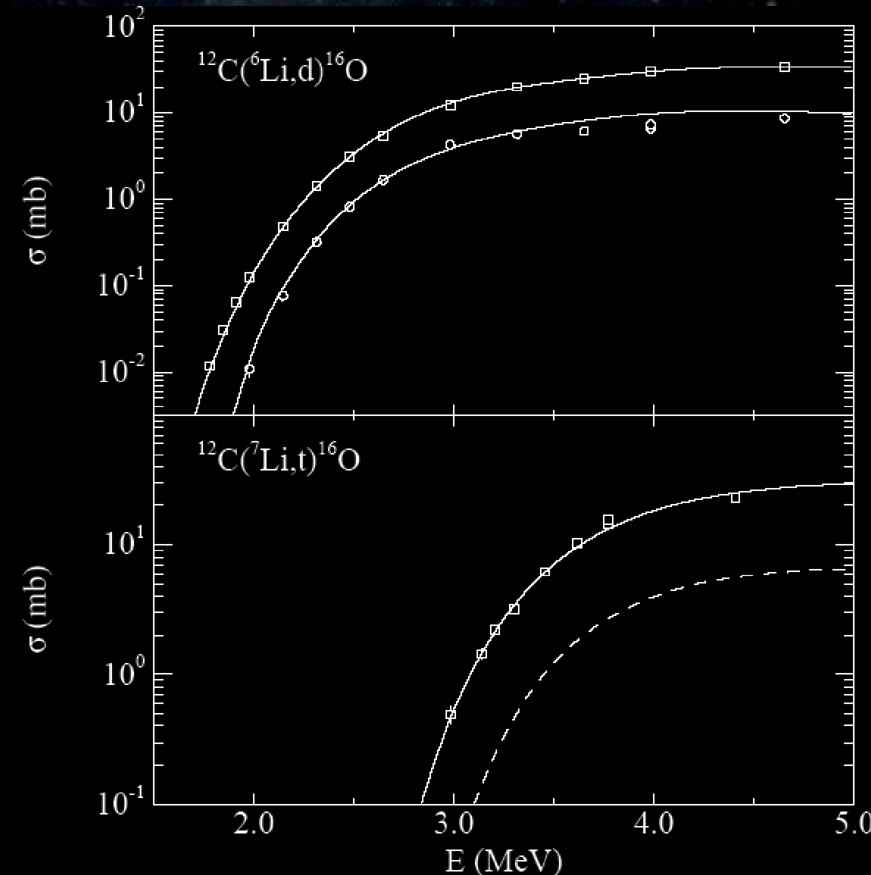
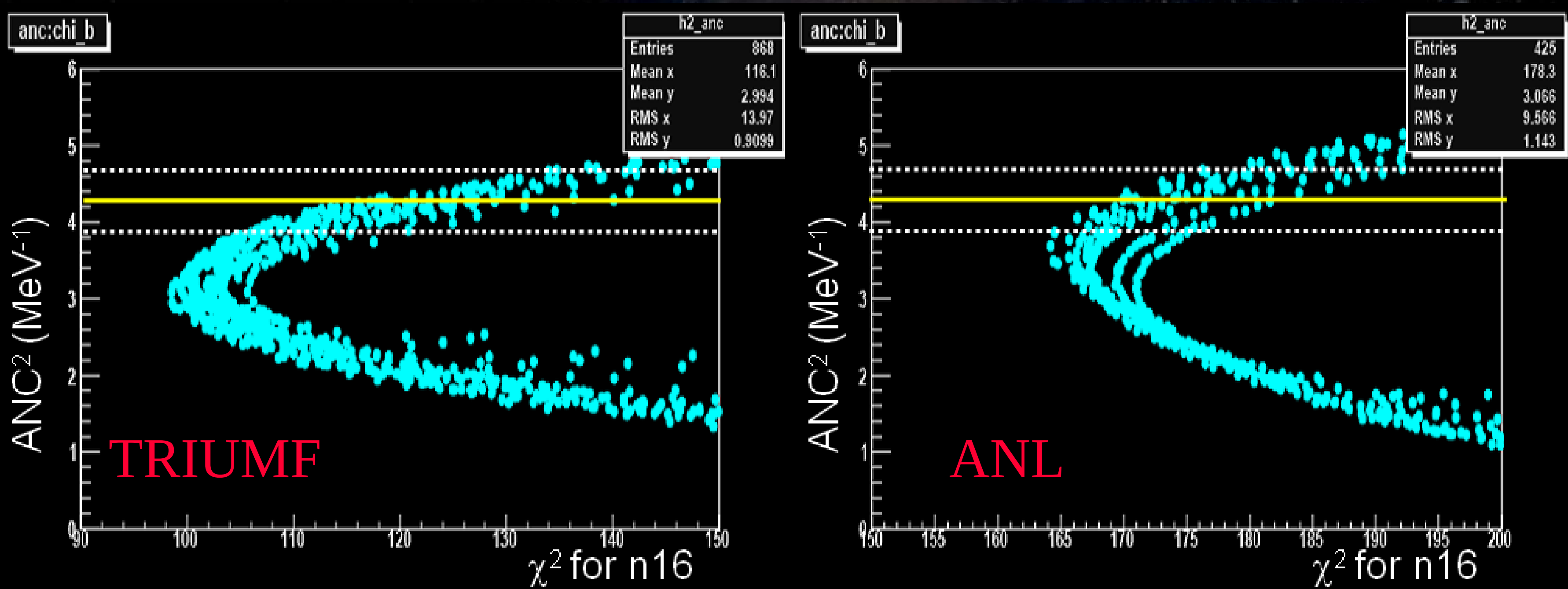


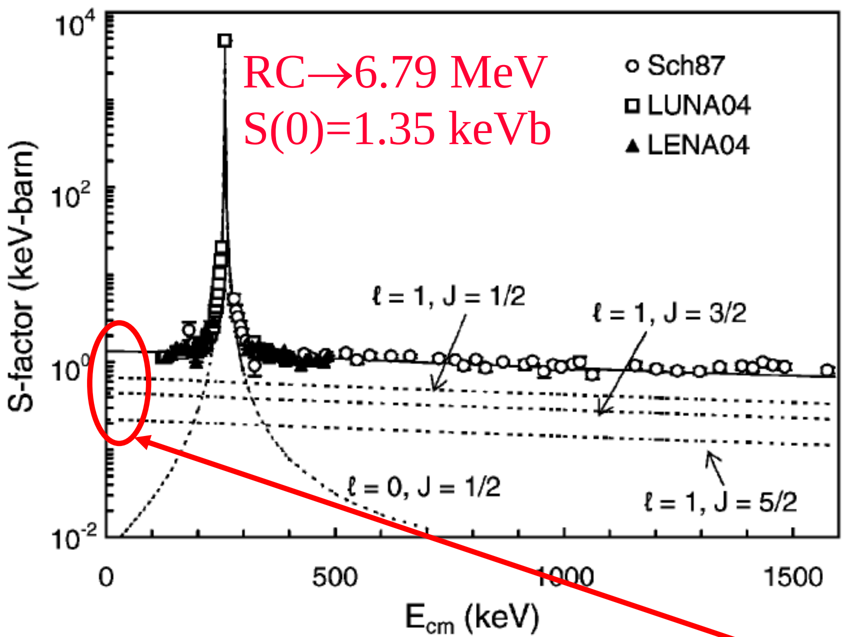
FIG. 2. … panel) and ^{7}L… te of ^{16}O (□ … The solid cu… ; the dashed …

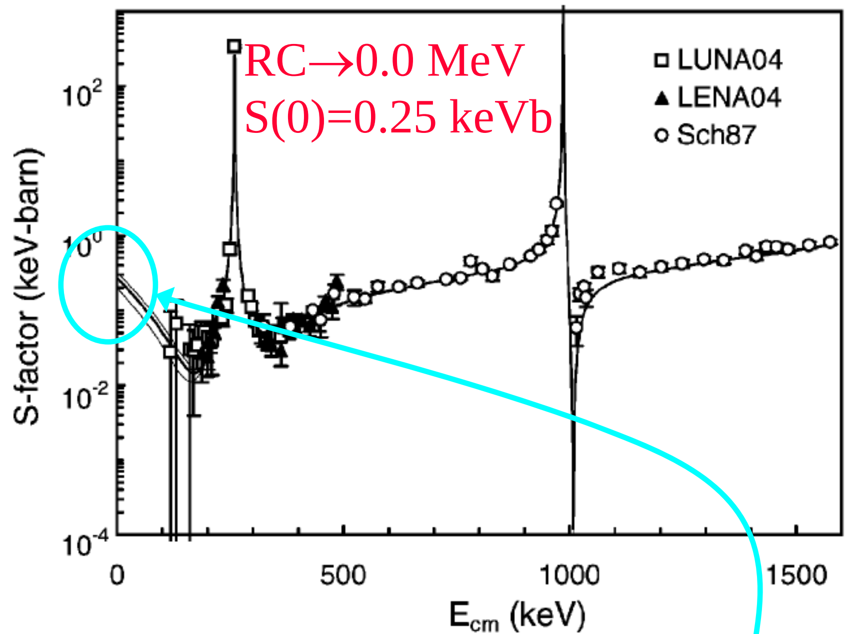
$$C_i^2 = \frac{2\mu a}{\hbar^2 W^2(a)} \left(\frac{\gamma_i^2}{1 + \gamma_i^2 \frac{dS}{dE}} \right),$$

Two subthreshold particle widths
^{16}N decay vs. $^{12}C(^6Li,d)^{16}O$



The $^{14}N(p,\gamma)^{15}O$ Reaction





$$\sigma_{DC} \propto C^2_{6.79}$$

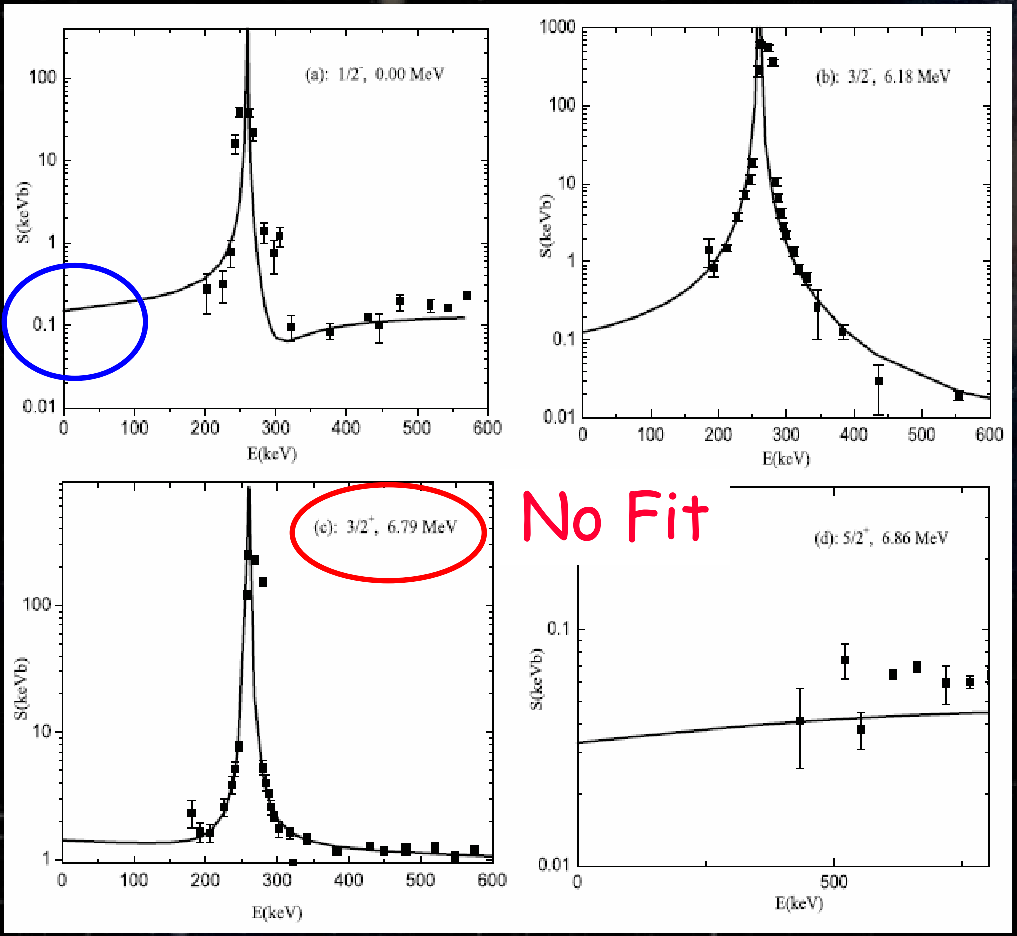
S(0)=1.70±0.07 ±0.10 keVb

$$\sigma(6.79 \to 0.0) \propto \left(\gamma_p^2 \gamma_\gamma^2\right)_{Er=6.79MeV}$$

$$C^2_{6.79} = \frac{2\mu a}{\hbar^2 W^2(a)} \gamma^2_{6.79}$$

C. Angulo, A.E. Champagne and H.-P. Trautvetter NPA758 (2005)391c

Coincidence?



TAMU(ANC)
$^{14}N(^{3}He,d)^{15}O$
S_{tot}=1.70±0.22 keV b
A.M.Mukhamedzhanov et al., PRC 67, 065804 (2003)

LUNA(Direct measurement)
$^{14}N(p,\gamma)^{15}O$
S_{tot}=1.7±0.1 ±0.2 keV b
LUNA Collaboration
Phys. Lett. B591 (2004) 61

Need lower energy data to constrain the sign of interference.

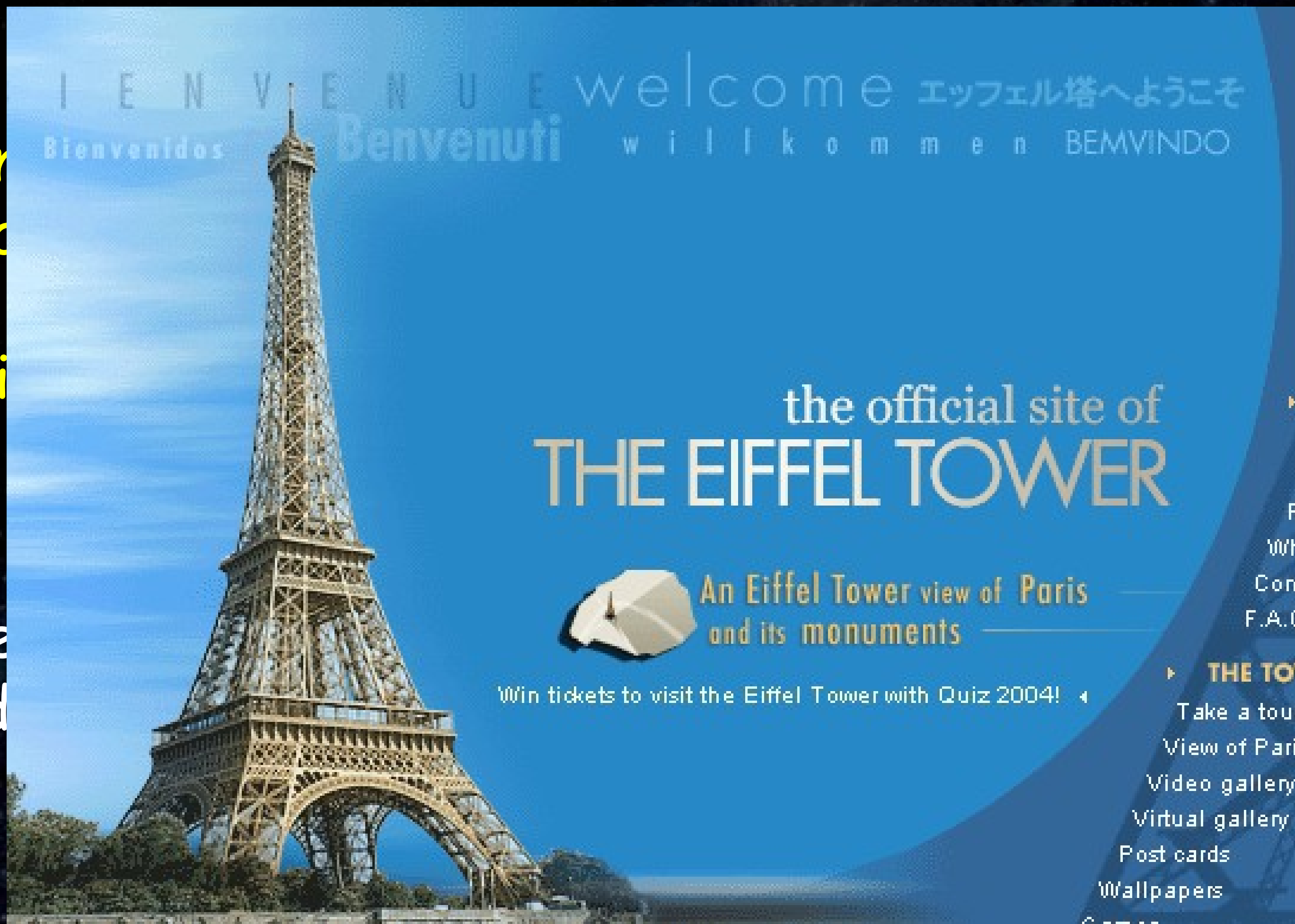
Conclusion on ANC

- Direct captures ($^{16}O(p,\gamma)^{17}F$, $^{14}N(p,\gamma)^{15}O$)
- Sub-threshold resonances ($^{12}C(\alpha,\gamma)^{16}O$, $^{14}N(p,\gamma)^{15}O$)
- Charge symmetry (Using stable nuclei to study unstable nuclei involving system)

Pros : Large cross section ~mb; No γ detection; No screening effect; Good for direct capture, subthreshold resonances, and for states near the thresholds ($\Gamma_p << \Gamma_\gamma$) ;

Cons : Optical model dependence (~10%, less for sub-coulomb barrier energies); Multi-step contributions;

Collaborative Efforts



- ➢In…
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Thank you!

A. M. Mukhamedzhanov (TAMU)