INDIRECT METHODS IN NUCLEAR ASTROPHYSICS

Silvio Cherubini

DFA "E. Majorana" – Università di Catania and INFN-LNS

18. ZIMÁNYI SCHOOL

WINTER WORKSHOP ON HEAVY ION PHYSICS

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SUMMARY

1) HISTORY OF NUCLEAR ASTROPHYSICS (IN SHORT)

2) why do we go for INDIRECT METHODS?

3) CD, ANC: just a glance

4) Trojan Horse Method 😍😍😍

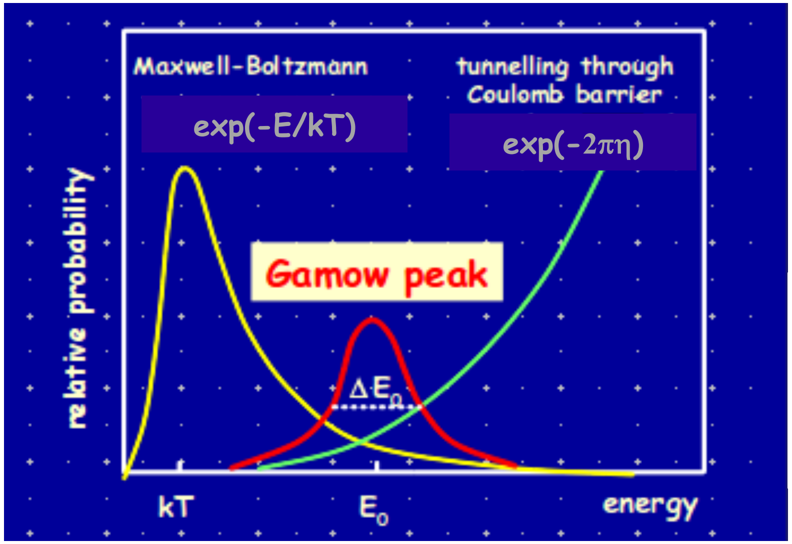
5) THM and RIBs

6) THM and n-induced reactions

History of Nuclear Astrophysics in short!

- Eddington, Aston, Gamow, Bethe: “energy production in stars” (1920-39)

- Gamow introduced the Gamow factor (1928), convoluted with the Maxwell distribution: this fixes the typical energy for nuclear reactions in stars



Reaction rate: $r = N_1 N_2 v \sigma(v)$

(# reactions volume^{-1} time^{-1})

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

- B^2FH: kind of formal definition of nucleosyntesis in stars (1957)

What is the LAB rate???

Let's solve an exercise

Data:

Typical x-section: $\sigma = 10^{-12}$ **barn = 1 pb**

Target density: $d = 10^{18}$ **atoms/cm^2**

Beam intensity: $I = 100\ \mu A$ **(but RIBs…)**

VERY OPTIMISTIC !!!

Question:

Event rate: $r = ?$

X-sec $\sigma = 10^{12}$ barn $= 10^{-36}\ cm^2$

$\rightarrow (10\ fm)^2 = 100\ fm^2$

$1\ barn = 10^{-28}\ m^2 = 10^{-24}\ cm^2$

$100\ \mu A = 10^{-4}\ A \simeq (6.24 \times 10^{18}) \times 10^{-4}$ pps

$\simeq 10^{+15}$ pps

target density (# of scatterers) $= 10^{18}\ \frac{atoms}{cm^2}$

$event/s = d\, I\, \sigma\, \eta$

η = detection efficiency = 100% !

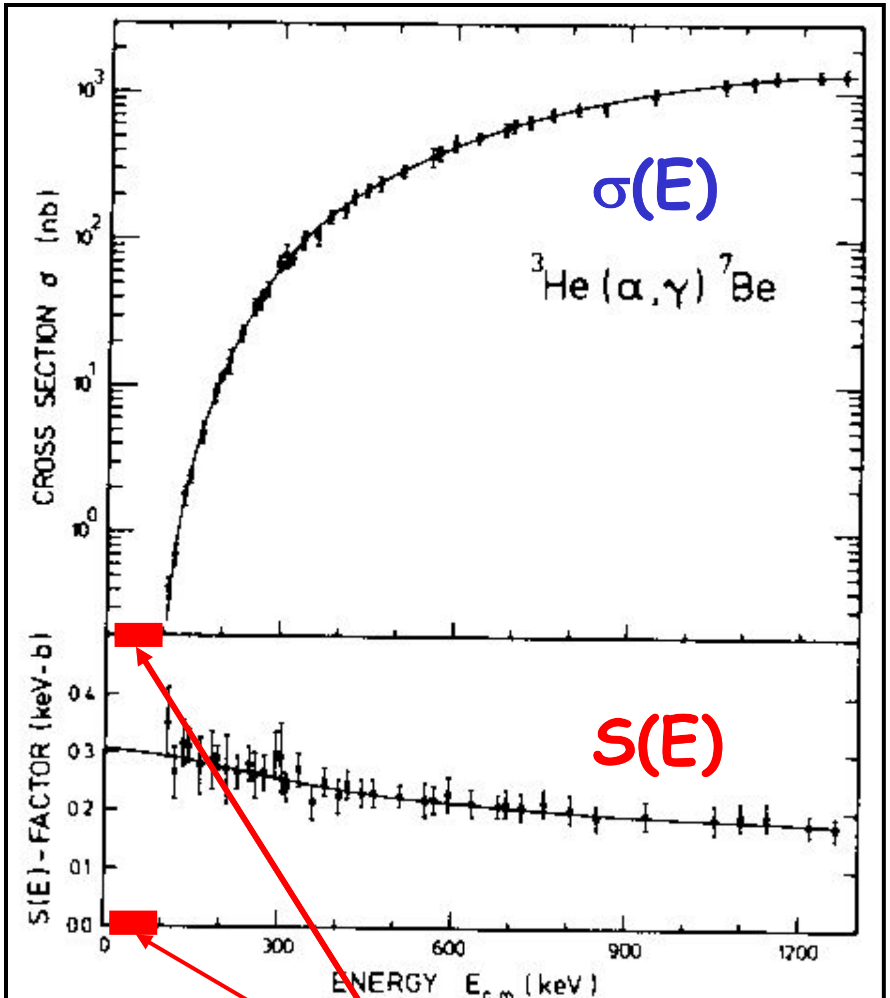
$events/s = 10^{18}\ \frac{atoms}{cm^2} \cdot 10^{15}\ pps \cdot 10^{-36} \cdot 1$

$\simeq 10^{-3}$ Hz (event/s)

$\rightarrow \sim 3-4$ ev/h

Is something missing???
Answer is “yes”, but what?

Why one wants to go indirect?



Astrophysical energies (Gamow energies)

A few reactions measured down in the Gamow window. For all others:

- Data EXTRAPOLATION down to astrophysical energies REQUIRED!

- S(E) is a smoothly varying function of the energy than the cross section σ(E)

$$S(E)=E\,\sigma(E)\,\exp(2\pi\eta)$$

- much easier extrapolation with the astrophysical S(E)-factor

BUT

- Resonances can give contribution to X-sections in NASTY ways

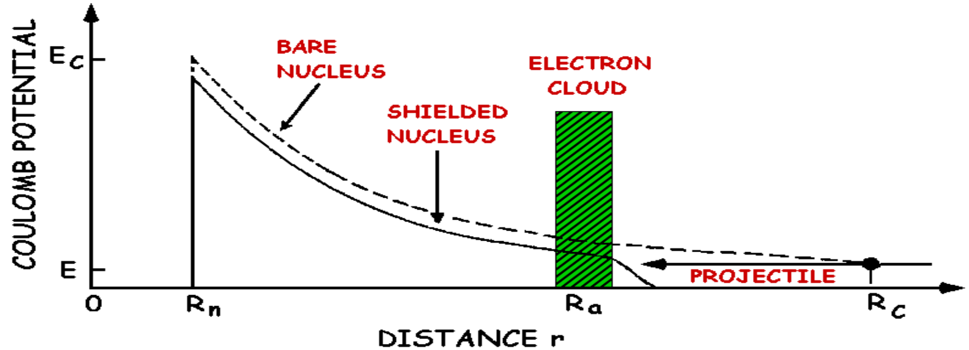
- the "something else"

ELECTRON SCREENING

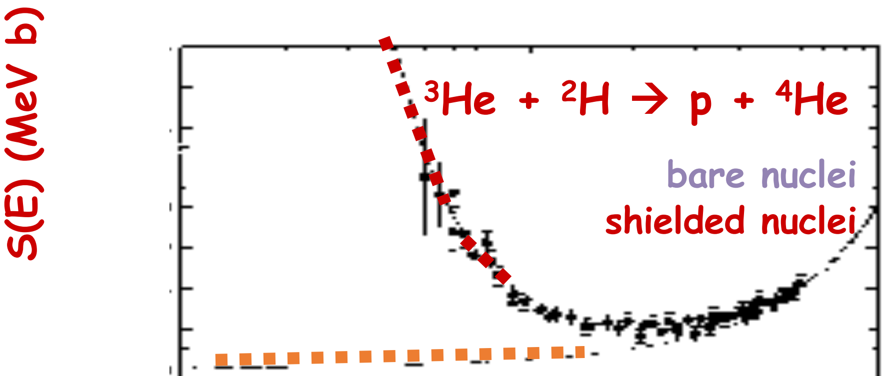
brings

extrapolation back again

ELECTRON SCREENING:



$E_{eff}=E_{projectile}+U_e$



R.Bonetti et al:
Phys. Rev. Lett. 82, (1999),5205

In spite of all efforts… Extrapolation back again

WHY IS THIS A PROBLEM?

One need The right $\sigma(E)$ or $S(E)$ as an input for stellar models!!!

It is a problem because electron screening in STARS and in LABORATORIES is not the same (nor in LABS and TFR) !

…and the effect is quite remarkable

RECAPITULATING:

GAMOW WINDOW → 10-100 keV (non-explosive scenarios)

↓

Nano- Picobarn (even less!)

↓

Miserable S/N ratio

↓

Estrapolation

↓

Dedicated Experiments / Lab
(LUNA)

↓

Electron Screening

↓

Estrapolation BACK AGAIN

Indirect Methods
(CD, ANC, <u>THM</u>)

INDIRECT METHODS

In order to solve some of the problem cited above (low X-sections, electron screening) some indirect approaches were proposed.

Just to name a few of them:

- Asymptotic Normalisation Coefficients (ANC) method (radiative capture reactions).

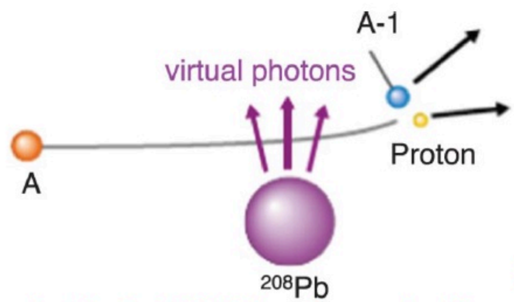
- Coulomb Dissociation method (radiative capture reactions).

- **Trojan Horse Method** (thermonuclear reactions induced by light particles)

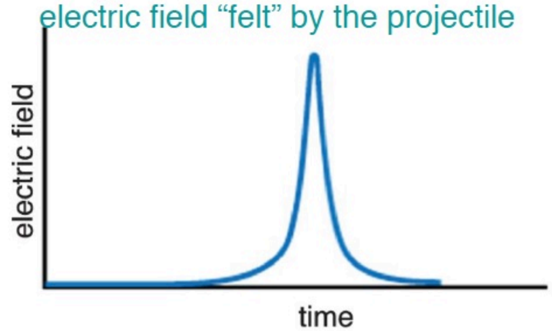
Schematic picture of the Coulomb dissociation.

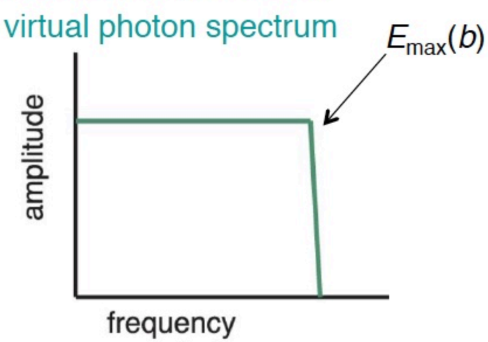
(γ Trojan Horse)

Thanks and full credits to Prof. Tohru Motobayashi



Fermi, Z. Phys. 29 (1924) 315



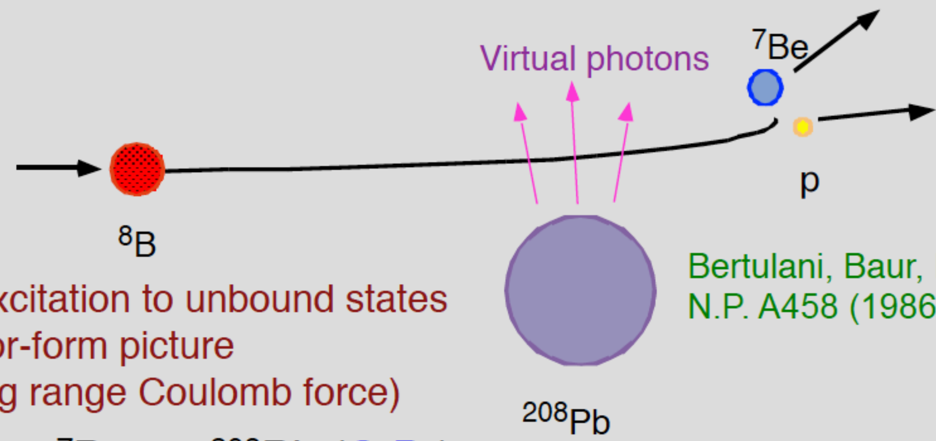


"Fast beam" can cover the energy range of nuclear excitation.

Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP
Progress of Theoretical and Experimental Physics

Coulomb dissociation   successfully applied to astrophysical capture reactions



Bertulani, Baur, Rebel
N.P. A458 (1986) 188

= Coulomb excitation to unbound states
(in the prior-form picture
-- long range Coulomb force)

^{8}B+^{208}Pb -> ^{7}Be+p+^{208}Pb (C.D.)

↓ Virtual photon theory or DWBA A

^{8}B(γ,p)^{7}Be (abs.)

↓ Detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ, thick target (intermediate energy)

experiments with weak RI beams

Coulomb dissociation efficient tool ← σ enhancement and experimental advantages

detailed balance

$$\sigma_{(\gamma,\mathrm{p})} = \frac{(2j_7+1)(2j_1+1)}{2(2j_8+1)} \frac{k_{17}^2}{k_\gamma^2} \sigma_{(\mathrm{p},\gamma)}$$

100 ~ 1000 for inverse process

virtual photon number (intermediate energy)

$$\left(\frac{d\sigma}{dE_\gamma}\right)_{\mathrm{C.D.}} = \frac{n}{E_\gamma}\sigma_{(\gamma,\mathrm{p})}$$

100 ~ 1000 for inverse process

thick target

charged particle detection

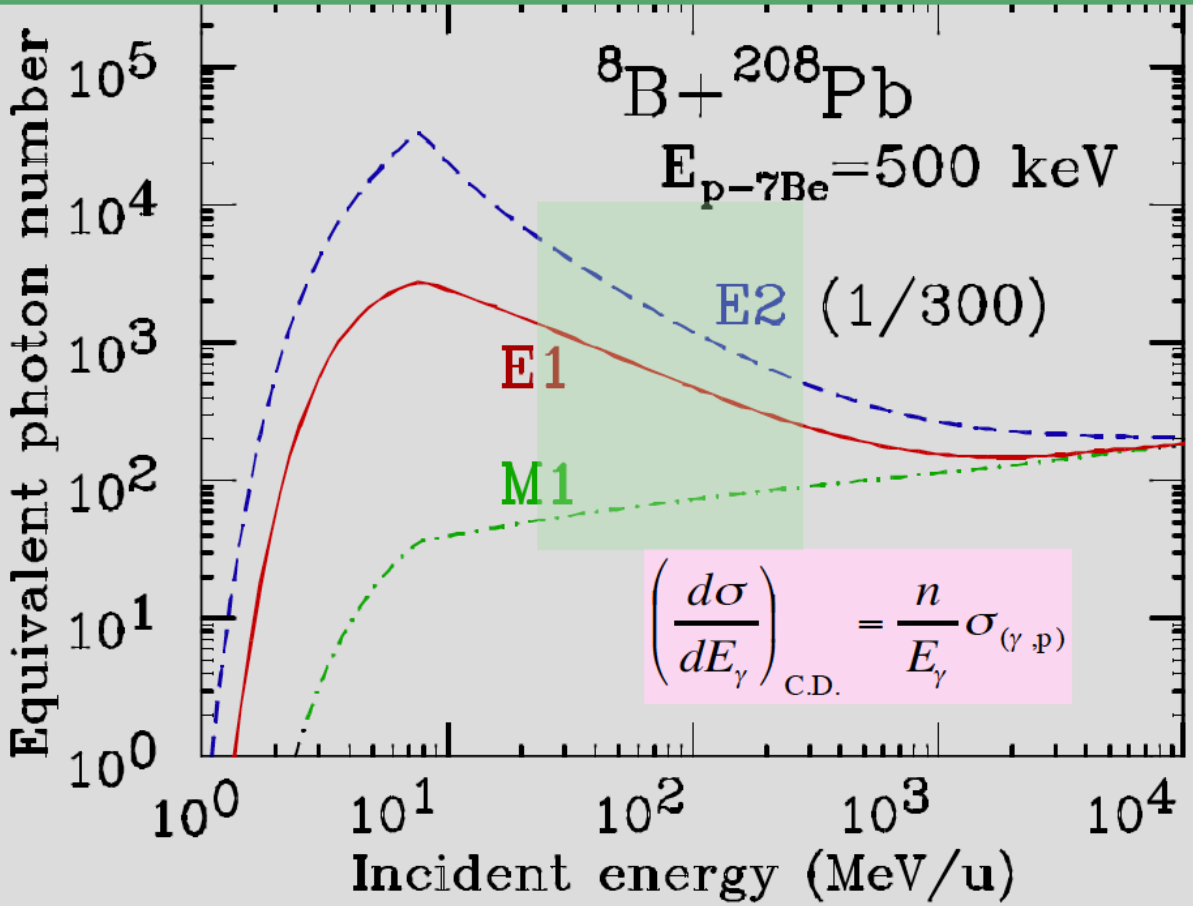
but

Indirect --- nucl. force / higher order / E2 / 3 body /relativistic…

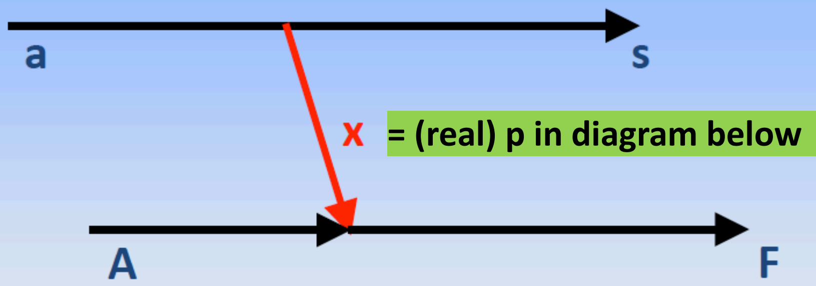
← reaction theory

only for (x,γ) to the ground state / only E1 (or E2) practical

Virtual photon intensity depends on the multipolarity.

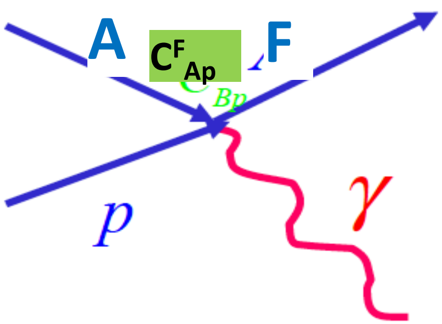


$$\left(\frac{d\sigma}{dE_\gamma}\right)_{C.D.} = \frac{n}{E_\gamma}\sigma_{(\gamma,p)}$$



In the **Asymptotic Normalization Coefficient (ANC) approach**, a transfer reaction to a bound state is measured to deduce the normalization constant of the bound state wave function, prop. to the A(x,γ)F c.s.

Proposed by A. Mukhamedzhanov



Direct Radiative proton capture

$$\sigma \propto |M|^2 \qquad [S(E) = E e^{2\pi\eta}\sigma]$$

$$M = \left\langle \phi_A(\xi_B, \xi_p, \xi_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \phi_B(\xi_B)\phi_p(\xi_p)\psi_i^{(+)}(r_{Bp}) \right\rangle$$

Integrate over ξ: $$M = \left\langle I^A_{Bp}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

Low B.E.: $$I^A_{Bp}(r_{Bp}) \overset{r_B > R_N}{\approx} C^A_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

$$\sigma_{capture} \propto (C^F_{Ap})^2$$

Slide built using stolen material from Marco La Cognata and Akram Mukhamedzanov!

Trojan Horse Method

Main application:

measurements of charged particle cross sections at astrophysical energies

Volume 176, number 2,3 PHYSICS LETTERS B 2 October 1986

BREAKUP REACTIONS AS AN INDIRECT METHOD TO INVESTIGATE LOW-ENERGY CHARGED-PARTICLE REACTIONS RELEVANT FOR NUCLEAR ASTROPHYSICS

G. BAUR

Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, Fed. Rep. Germany

Received 18 April 1986; revised manuscript received 10 July 1986

It is proposed to use breakup reactions as a means to extract information on charged-particle induced reactions at low relative energies. The Coulomb penetration factor, which diminishes tremendously the two-particle cross section, is overcome in the three-body scattering approach. The assumptions and possibilities of such a method are discussed and applications to astrophysically relevant nuclear reactions are indicated.

The study of charged-particle reactions at low relative energies is of special interest for the synthesis of the elements in the universe [1]. A great problem in the direct experimental study of such reactions at the relevant astrophysical energies is the very low cross section due to the Coulomb barrier of the incident particles. Usually a mixture of experimental information at higher energies and theoretical arguments and calculations is used in order to extrapolate the astrophysical S-factor down to the relevant energies.

In this letter it is proposed to obtain information about the low-energy charged-particle induced reaction

$$A+x \to c+C \qquad (1)$$

by means of the three-body type of reaction

$$A+(b+x) \to b+c+C. \qquad (2)$$

A "spectator" particle b is attached to particle x, to form a projectile a = (b+x). The bombarding energy E_a is chosen to overcome the Coulomb barrier in the incident channel of reaction (2). In this way, particle x can be brought into the nuclear reaction zone to induce the reaction (1) of particle x with A. If the Fermi motion of particle x inside a compensates for the initial projectile velocity v_a, this reaction (1) is induced at very low (even vanishing) relative energy between A and x. This "trojan horse method" is illustrated schematically in fig. 1. It is now suggested to study reac-

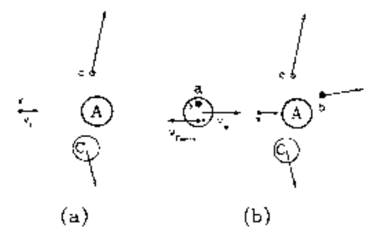


Fig. 1. At astrophysically relevant energies the two-particle reaction $A+x \to c+C$ is strongly hindered by the Coulomb potential (part (a)). In the three-body approach (b), particle x is brought into the nuclear reaction zone of the target nucleus A inside the projectile a = (b+x) with velocity v_a and it induces the reaction at the low relative energies corresponding to $v_x = v_a - v_{\mathrm{Fermi}}$ in which one is interested.

tion (2) experimentally under conditions which correspond to astrophysically relevant energies between x and A. The problem is then to obtain, from the experimentally determined coincidence cross section $d^3\sigma/d\Omega_c d\Omega_b dE_b$, information about the astrophysically interesting cross section

$$\sigma_{Ax\to cC} = \frac{\pi}{q_x^2} \sum_l (2l+1)\,|S_{lc}|^2. \qquad (3)$$

THM: a primer

Idea: get the 2-body cross-section of the process

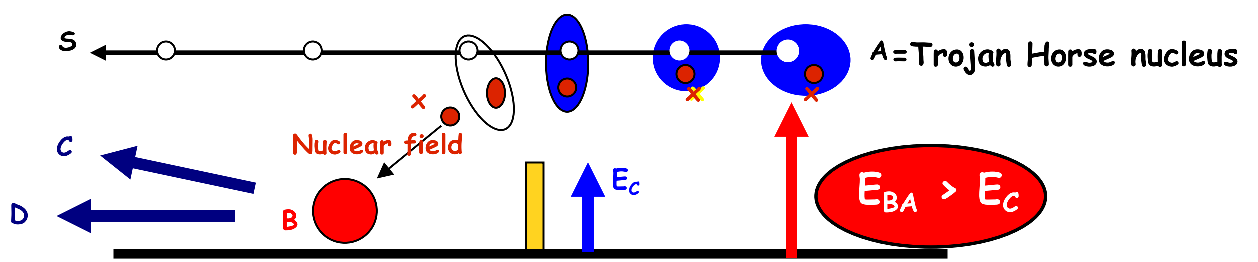
$$\boxed{B + x \rightarrow C + D}$$

***At astrophysical energies from the* QUASI-FREE contribution**

of a 3-body reaction *(C. Spitaleri, Folgaria 1990)*

$$\boxed{B + A \rightarrow C + D + S}$$

$$A = x \otimes S$$



E_{Bx} = interaction energy B-x

E_C = Coulomb barrier between A and B

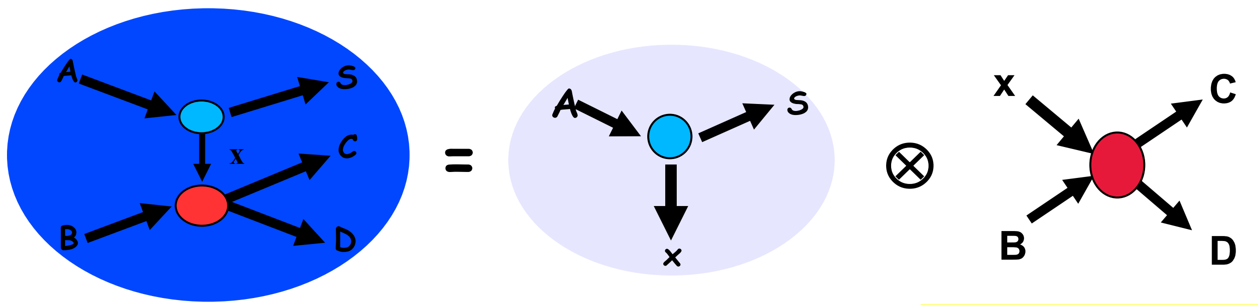
E_{BA} = relative energy between A and B

$$E_{Bx} = E_{CD} - Q_2$$

P C P

Electron screening removed by construction

Assuming that a Quasi-free mechanism is dominant one can use the PWIA:



3-body Reaction

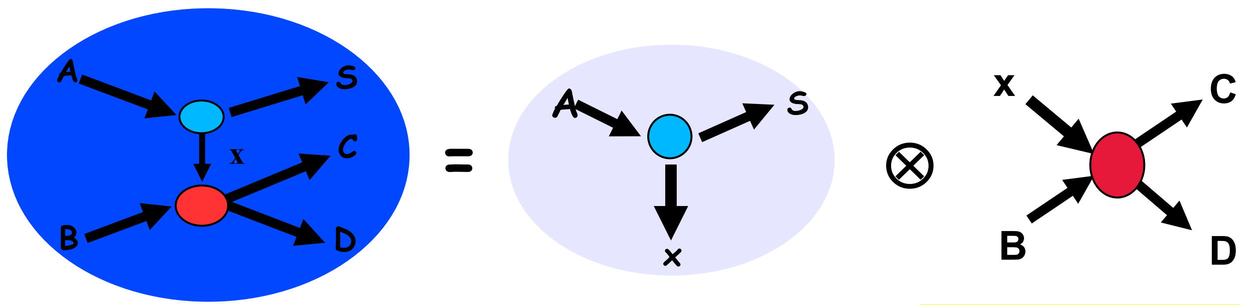
Virtual Decay

Virtual reaction
(astrophysical process)

$$\frac{d^3\sigma}{d\Omega_C\, d\Omega_D\, dE_{cm}} \propto KF \cdot |\Phi(P_s)|^2 \bullet \frac{d\sigma}{d\Omega}^{N}$$

$E_{Bx} = E_{CD} - Q_{2b}$

Assuming that a Quasi-free mechanism is dominant one can use the PWIA:



3-body Reaction | Virtual Decay | Virtual reaction (astrophysical process)

$$\frac{d^3\sigma}{d\Omega_C \, d\Omega_D \, dE_{cm}} \Big/ \boxed{KF \cdot |\Phi(P_s)|^2} \propto N \frac{d\sigma}{d\Omega}$$

<u>Measured at high energy</u> | <u>Calculated e.g. Montecarlo</u> | <u>Indirectly Measured</u>

$E_{Bx} = E_{CD} - Q_{2b}$

APPLICATION OF THE METHOD and tricky points

From the theoretical/phenmenological point of view

1. Selection of the three body reaction and of the Trojan Horse Nucleus depending on its cluster structure properties. *This affects the number and type of reaction mechanisms competing with the QF one and the cross section value of the QF channel itself*

2. Check of the presence/dominance of the QF mechanism (impulse distribution reconstruction, study of the angular distribution, Treiman-Yang criterion)

3. Reliability of the "ingredients" used in $d^2\sigma$ derivation, e.g. of impulse distribution of the THI nucleus.

4. If one is measuring a cross section below the Coulomb barrier, then has to correct the THM x-sec for penetration factor before comparing the THM results with the direct ones.

From the experimental point of view:

1) Optimization of the energy and angular resolution of the experiment to obtain the necessary resolution in the E_{xB} variable (relative energy of x-B (related to the cm energy of the astrophysical process)

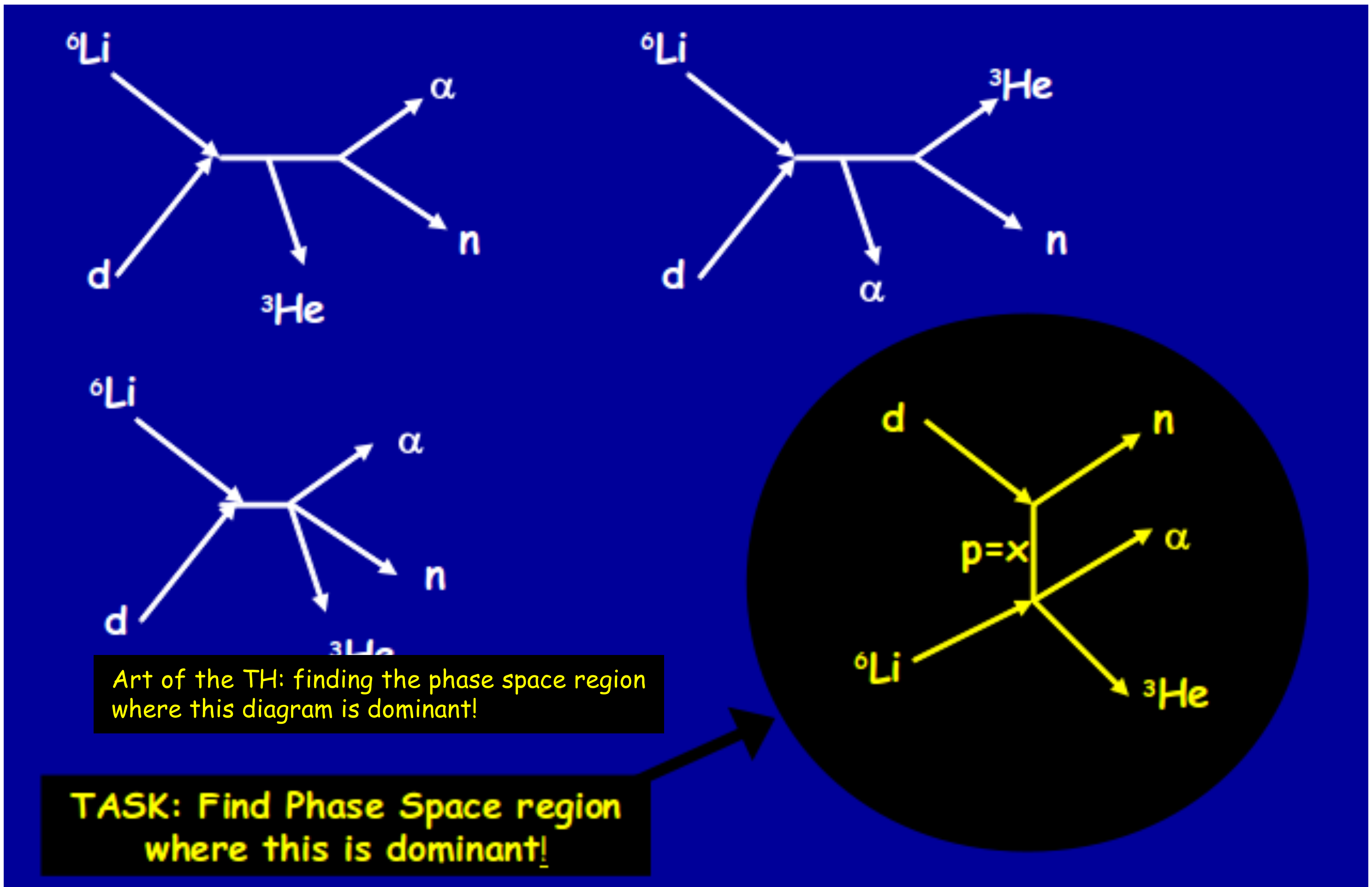
$$\Delta E_{xB} = f(\Delta E_C \; \Delta E_D \; \Delta\theta_C \; \Delta\theta_D)$$

2) Background noise suppression (this is not THM specific...) including the PHYSICAL background (see next slide)

3) Availability of direct measurements (above the region where Electron Screening effects start to show up and if possible also above the Coulomb barrier).

PHYSICAL BACKGROUND: an example

$^6Li+p \rightarrow {}^3He+\alpha$ from $^6Li+d \rightarrow {}^3He+\alpha+n$



ADVANTAGES of the Method

1) The cross sections in the experiment are typical QF processes ones (mbarn/sr) though one is measuring a nuclear reaction at astrophysical energies and 3 body kinematics offers other benefits

2) The THM x-section is purely NUCLEAR: no suppression effect due to Coulomb barrier

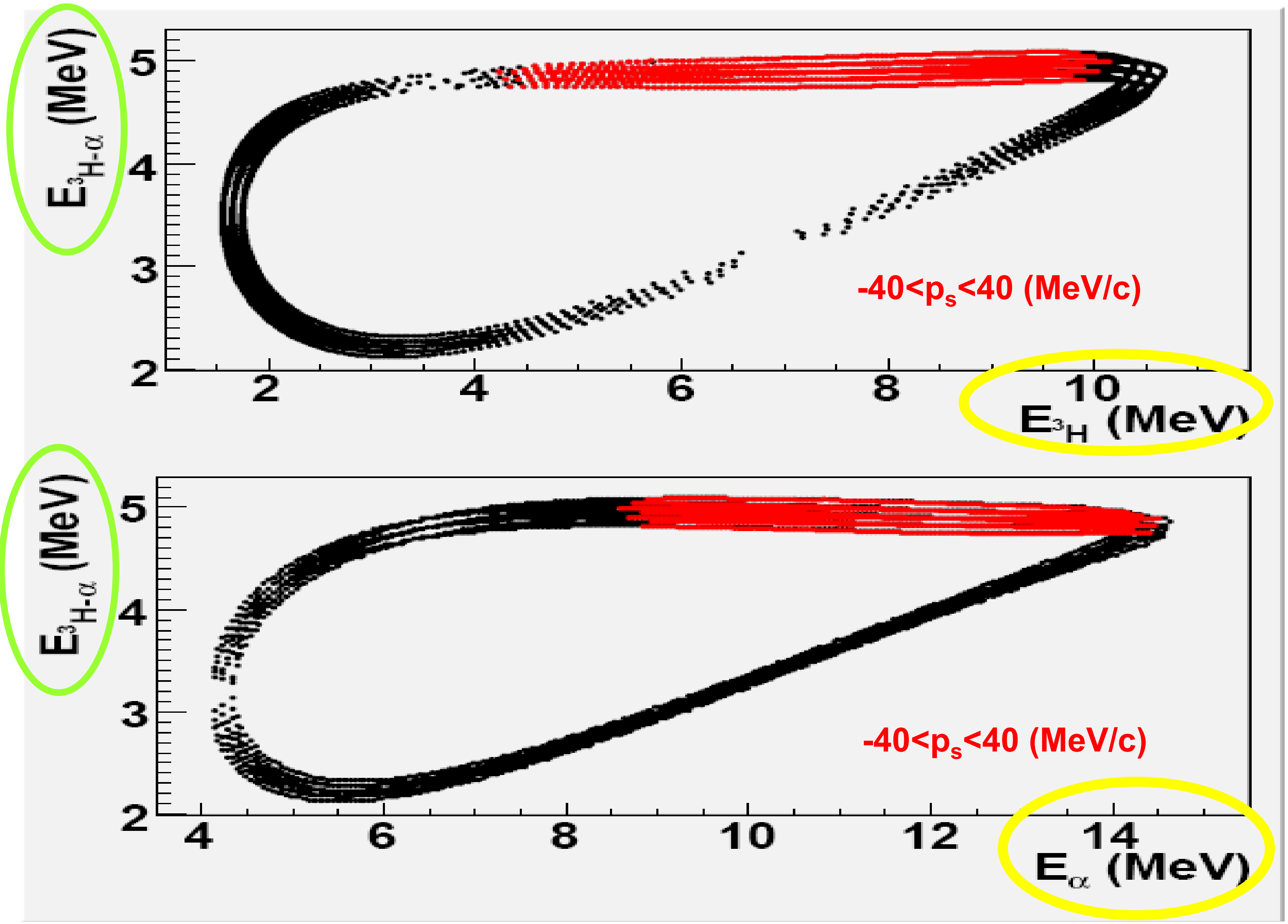
3) No electron screening effect: one can get INDEPENDENT pieces of information on the electron screening potential by comparison with direct data

4) The experimental setup is tipically simple enough

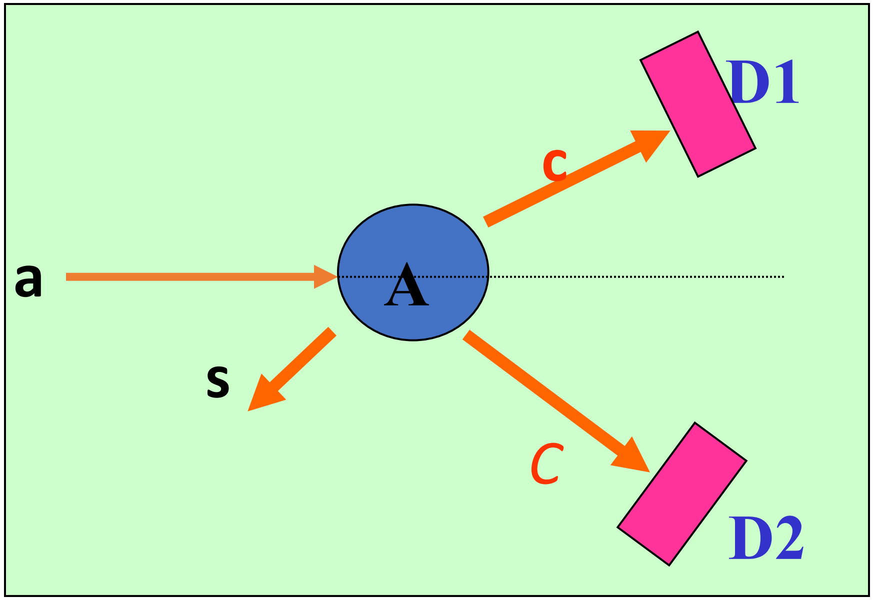
5) The THM can be extended to use QFR in studying NEUTRON induced reaction (aka VNM Virtual Neutron Method)

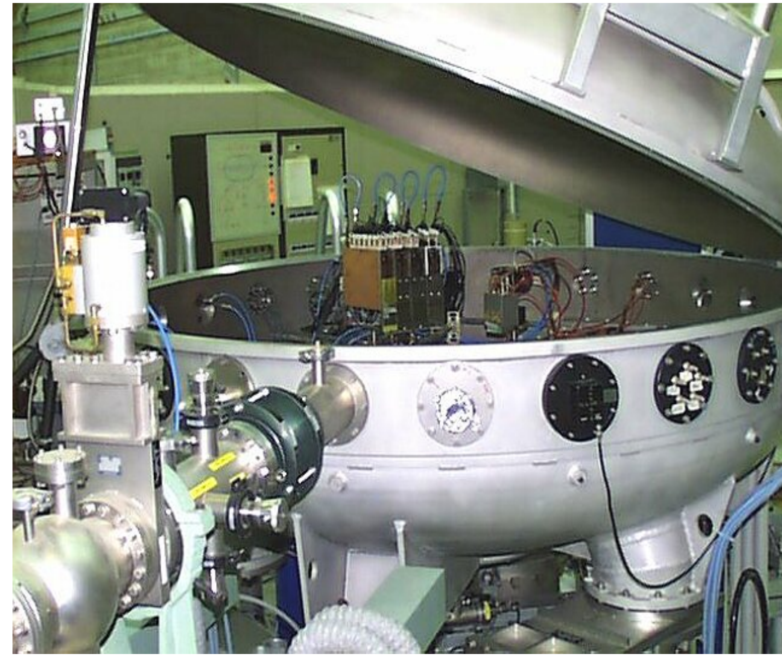
Benefits of 3-body kin. (#1): Magnifying glass effect

6Li+n→ α+t via 6Li+d→ α+t+p



Schematic view of a typical THM experimental setup. SIMPLE (#4)





D1,D2: (typically) Position Sensitive Detectors centred at Quasi-Free angular pairs

Trigger: D1_ AND _ D2

Note: measuring E_1, E_2, θ_1, θ_2 over-determines the full three-body kinematics in a coplanar geometry.

p-p SCATTERING from p+d →p+p+n_s PURE NUCLEAR #2

Jackson & Blatt question, Rev. Mod. Phys., 22 (1950), p. 77, is the "smoking gun" of THM!

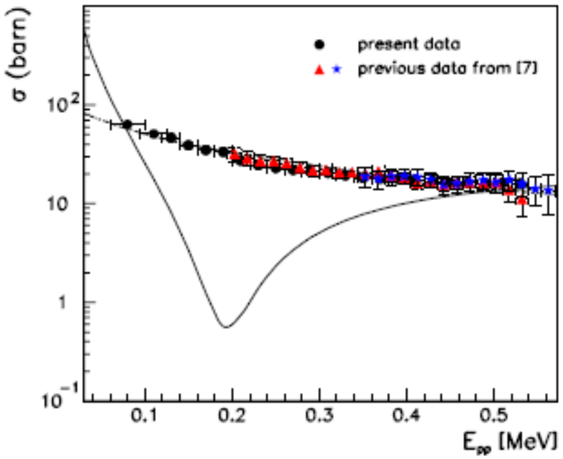


FIG. 3 (color online). THM two-body cross section (black dots from present experimental work, red triangles, and blue stars from previous work [7]) vs E_{pp}. Solid line represents the theoretical OES $p-p$ cross section calculated as explained in the text. The dashed-dotted line is the HOES cross section calculated using Eq. (3).

PRL 98, 252502 (2007) PHYSICAL REV

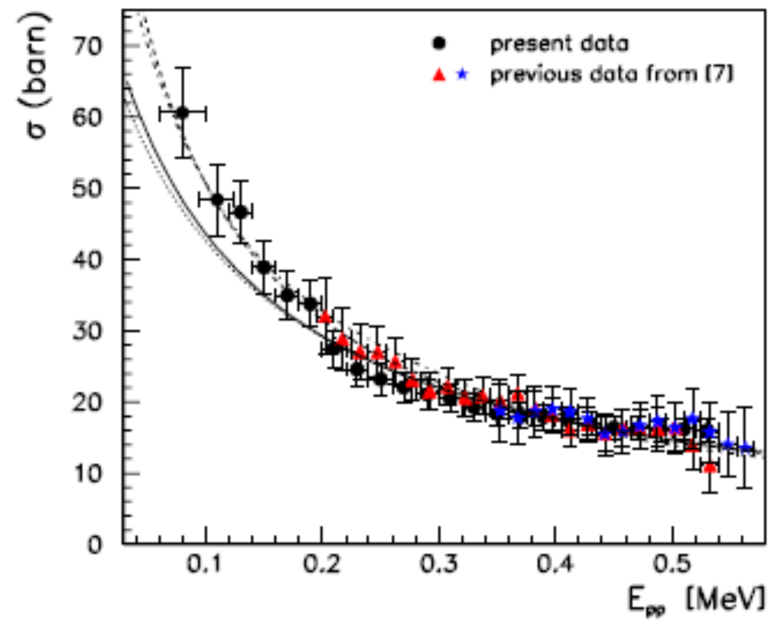


FIG. 4 (color online). THM two-body cross section (black dots from present experimental work, red triangles, and blue stars from previous work [7]) vs $p-p$ relative energy E, compared with the on-shell $n-n$ (solid line), $p-n$ (dashed line), and pure nuclear $p-p$ (dotted line) ones. The HOES calculated cross section is also reported as the dashed-dotted line.

Tesi Laurea G.G. Rapisarda (2005)

Tumino et al. PRL 98, 252502 (2007)

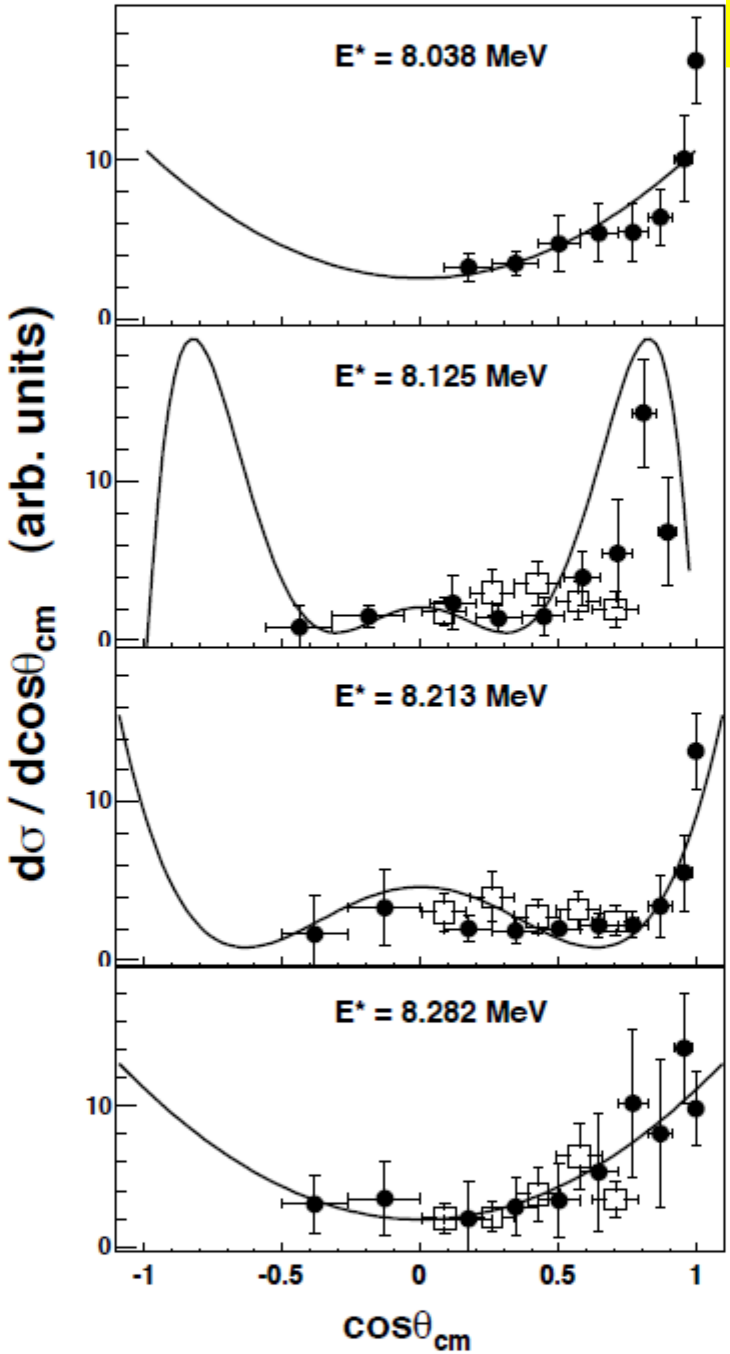
Electron Screening potentials studied using THM (#3)

U_e (ad)	$U_e^{(THM)}$ ^{6}Li+d	$U_e^{(Dir)}$ ^{6}Li+d	$U_e^{(THM)}$ ^{7}Li+p	$U_e^{(Dir)}$ ^{7}Li+p
186 eV	340 ± 50 eV	330 ± 120 eV	330 ± 40 eV	300 ± 160 eV

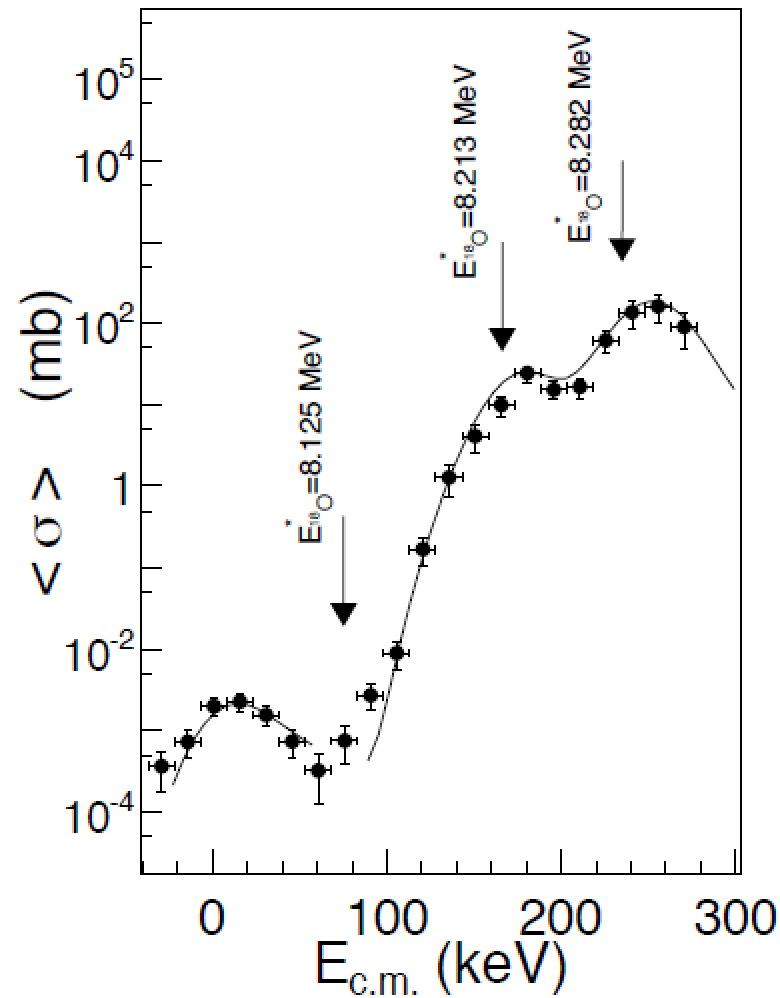
$U_e^{(THM)}$ ^{6}Li+p	$U_e^{(Dir)}$ ^{6}Li+p
435 ± 40 eV	440 ± 150 eV

Owing to “high” bombarding energy the elctron cloud is ineffective.
Electron screening is removed by construction

$^{17}O+n \rightarrow {}^{14}C+\alpha$ via $^{17}O+d \rightarrow \rightarrow {}^{14}C+\alpha+p_s$

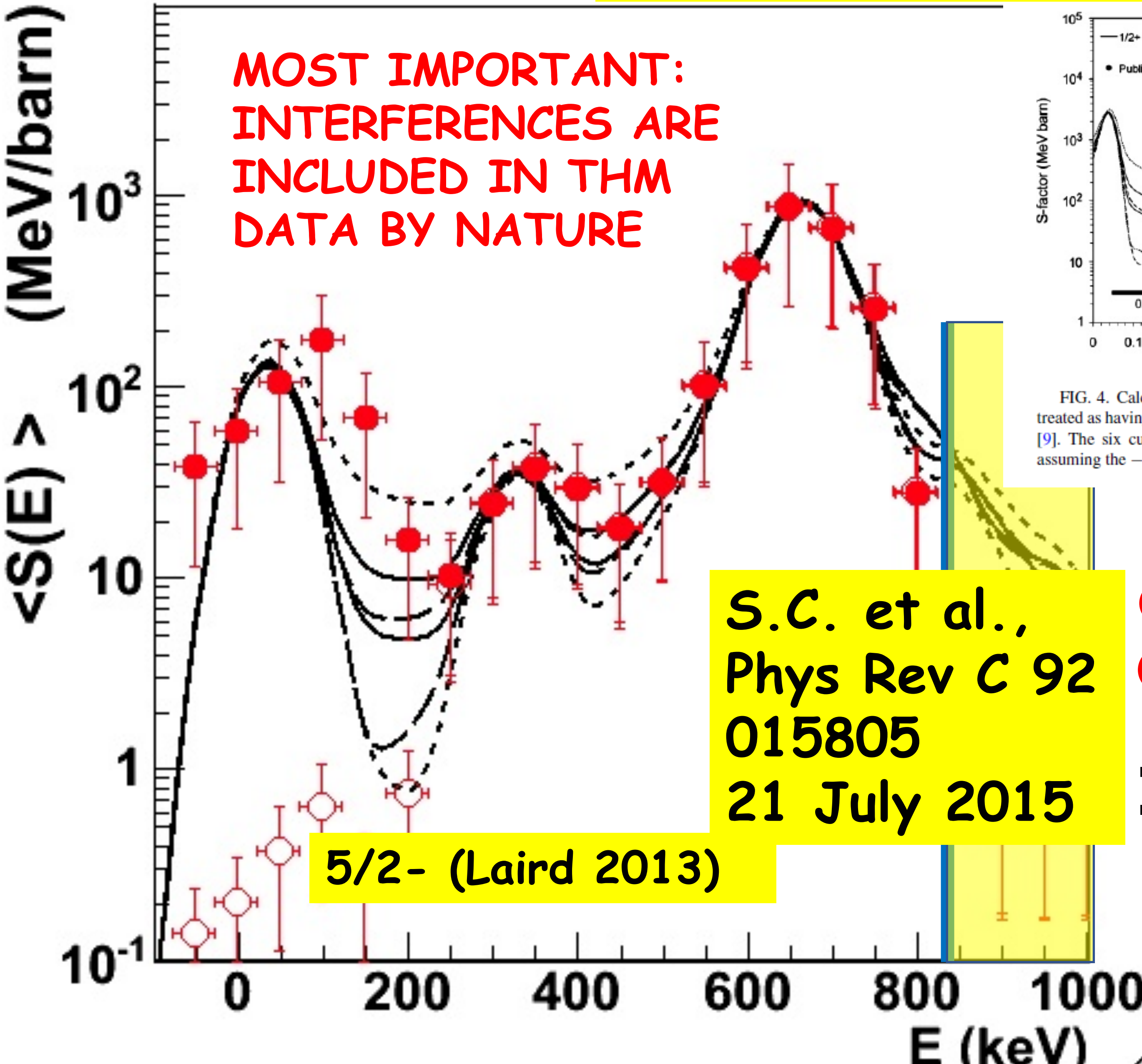


angular distributions



Gulino et al. PRC Rapid Communication (2013)

$^{18}F+p \rightarrow ^{15}O+\alpha$ via $^{18}F+d \rightarrow \rightarrow ^{15}O+\alpha+n_s$



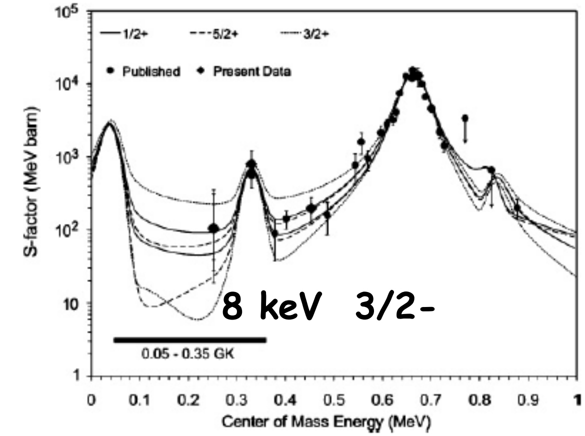
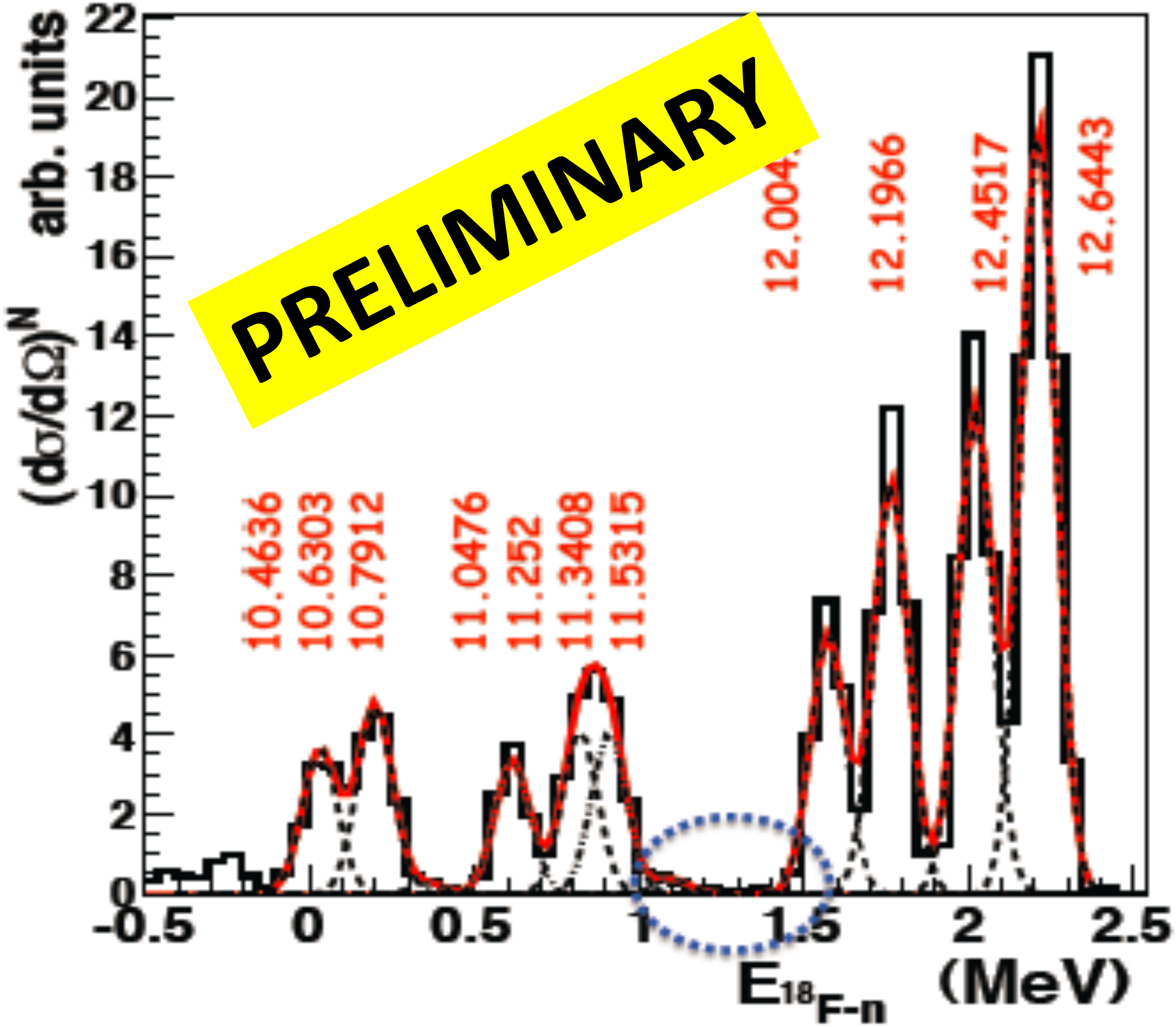


FIG. 4. Calculated $^{18}F(p,\alpha)^{15}O$ S factors with the 8 keV state treated as having a spin-parity of $3/2^-$ using the Adekola parameters [9]. The six curves correspond to the upper and lower S factors, assuming the −121 keV resonance to be $1/2^+$, $5/2^+$, or $3/2^+$.

THM data

C.E. Beer, Phys. Rev. C 83, 042801(R) (2011)
Smeared to THM resolution

18F+n→15N+α



M. Gulino, Analysis in Progress

THANKS FOR YOUR ATTENTION

THM was developped by the ASFIN Collaboration since 1990.

Presently: S.C., M. La Cognata, M. Gulino, R. Spartà, L. Guardo, RG Pizzone, A. Tumino, S. Romano, G. D'Agata, GG Rapisarda, I. Indelicato, L. Pumo, G. Manicò, A. Di Pietro, P. Figuera, M. Lattuada, D. Lattuada, S. Palmerini, M. Busso, M. Limongi, A. Chieffi…

… and The Boss: C. Spitaleri