The Trojan Horse Method and its main experimental features

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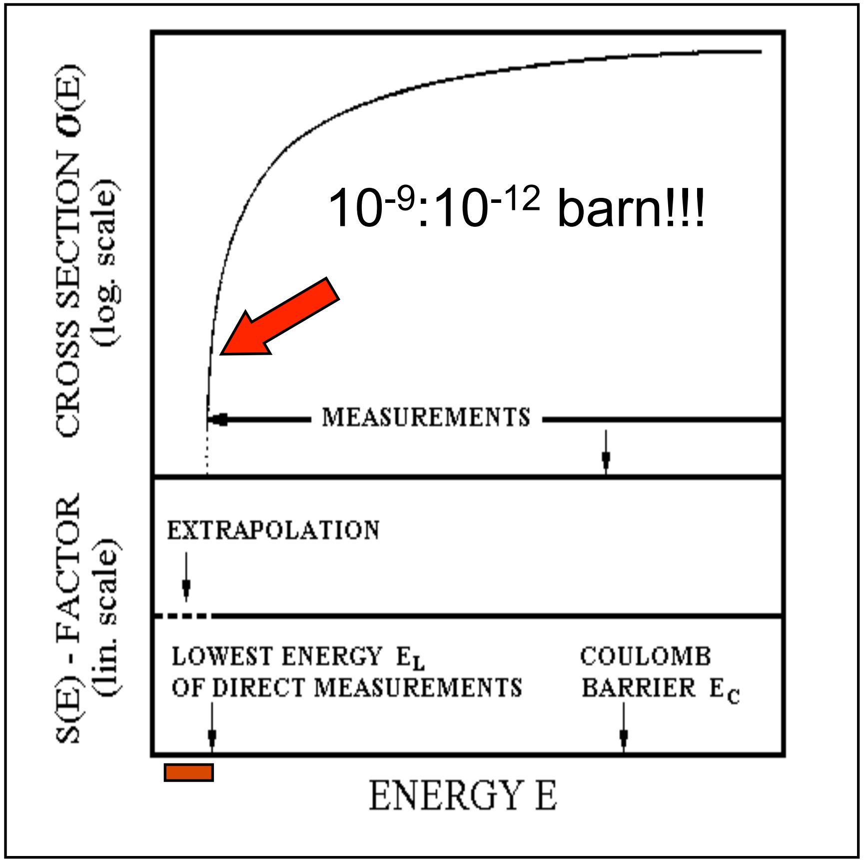
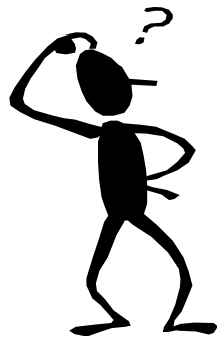
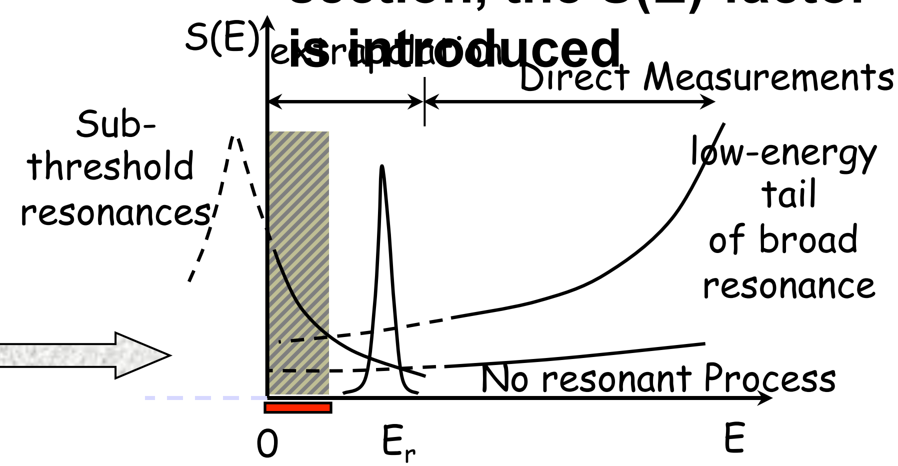
Direct Measurements in Nuclear Astrophysics and related difficulties





- **Very small cross section values reflect in a faint statistic;**
- **Very low signal-to-noise ratio makes hard the investigation at astrophysical energies;**
- **Instead of the cross section, the S(E)-factor is introduced**



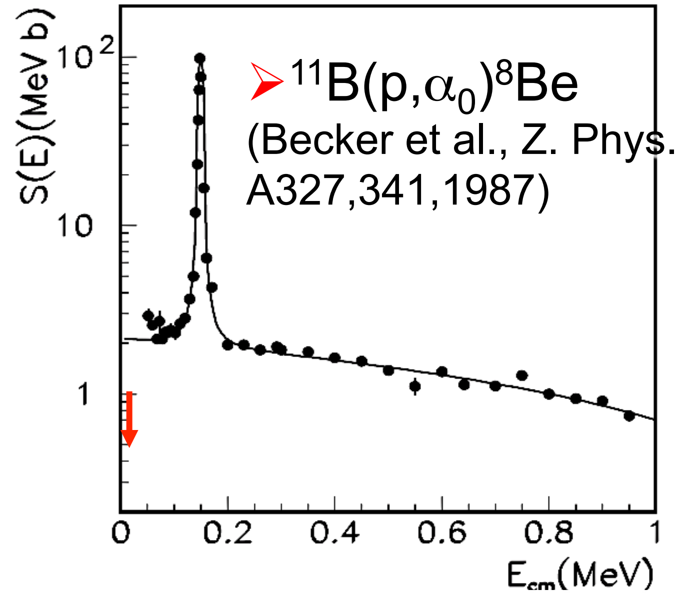
$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

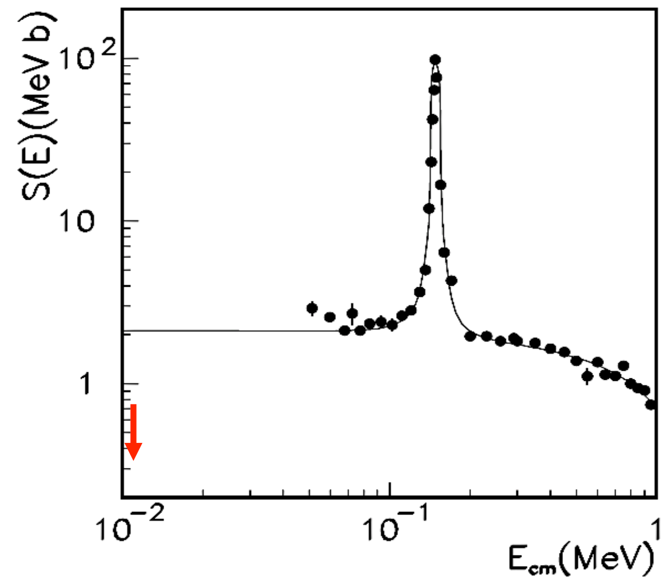
From Stars to the laboratory: direct measurements of charged-particle induced reactions

By considering the typical temperatures of some 10^6 K at which burning (p,α) reactions typically occur in stellar environments, the Gamow peak is at about (for boron case)

$$E_0=1.22(Z^2_x Z^2_y \mu T_6^2)^{1/3}\ \text{keV} \approx 10\ \text{keV}$$

Thus the goal of the experimentalist is to give a measurement of the burning reaction cross section right in correspondence of the energy region of interest for astrophysics……….





Experimental efforts for nuclear astrophysics

Several efforts have been made in the last years in order to **improve the signal-to-noise ratio** for low-energy cross section measurement.
Among them, we have:

IMPROVEMENTS TO INCREASE THE NUMBER OF DETECTED PARTICLES

(t

π detectors

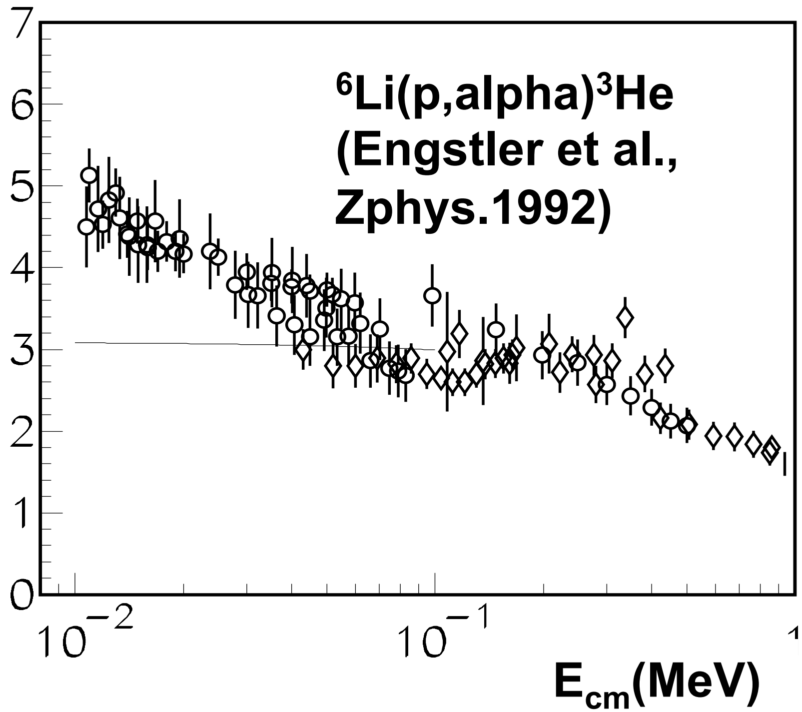
lew accelerator at high beam intensity

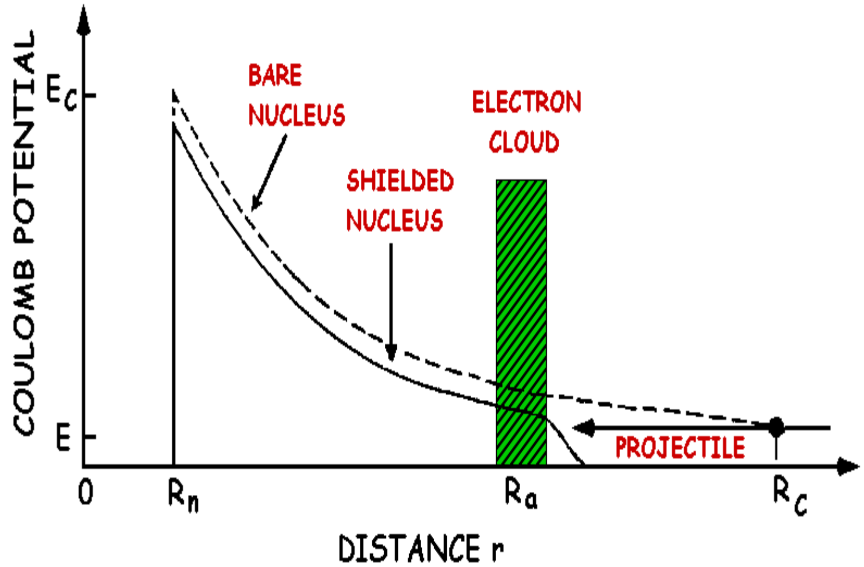
- IMPROVEMENTS TO REDUCE THE BACKGROUND

Use of laboratory with natural shield - (underground physics)

Use of magnetic apparatus (Recoil Mass Separator)

Direct Measurements in Nuclear Astrophysics and related difficulties: electron screening phenomena





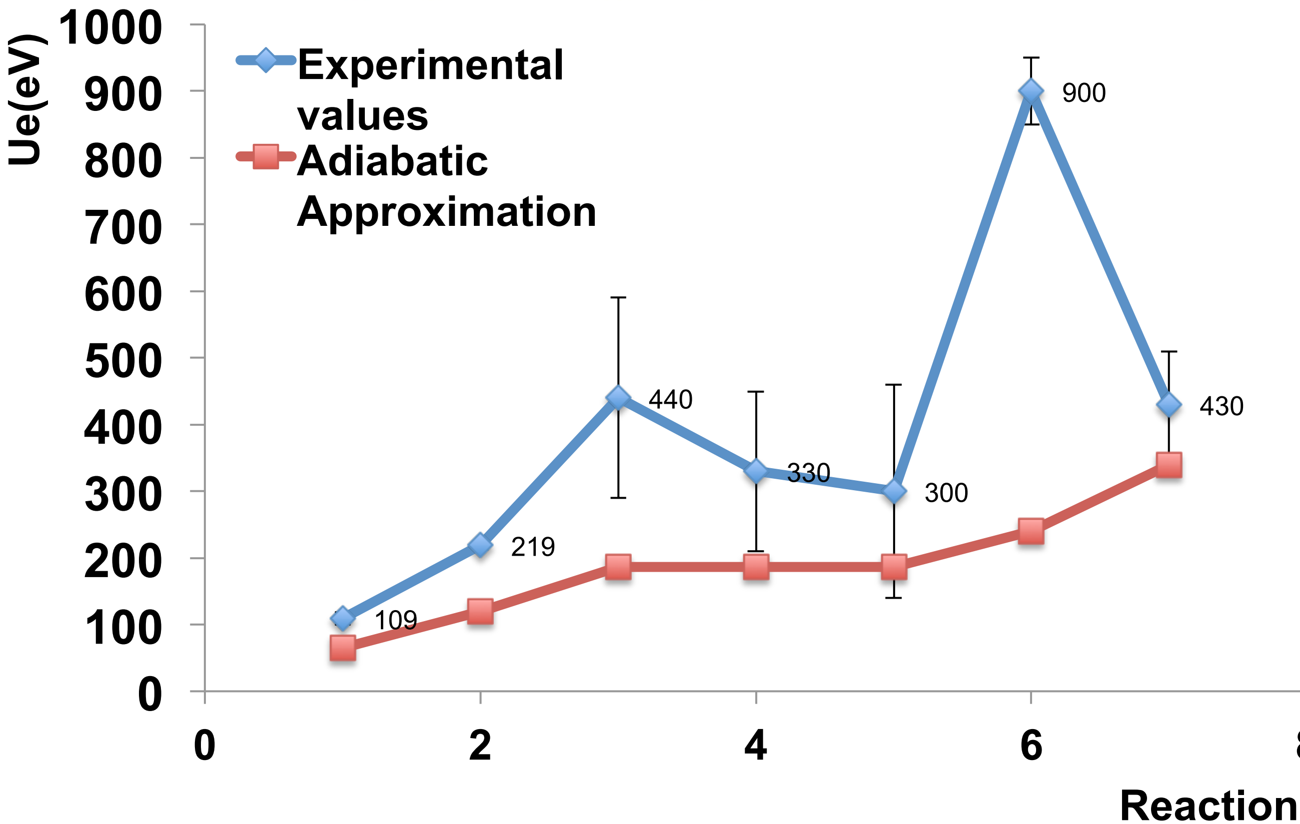
In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{lab}(E)$ –factor in the astrophysical $S_b(E)$-factor has been found. Extensively discussed in several works (e.g. Assembaum et al., 1987)

$$S_{Sh} \propto S_b \cdot e^{\frac{\pi\eta U_e}{E}}$$

Electron screening: present (unsatisfactory)

Reaction	U_{ad} (eV)	U_{exp} (eV)	Reference
$^{6}Li(p,\alpha)^{3}He$	186	440±150	[Engstler et al.(1992)]
$^{6}Li(d,\alpha)^{4}He$	186	330±120	[Engstler et al.(1992)]
$H(^{7}Li,\alpha)^{4}He$	186	300±160	[Engstler et al.(1992)]
$^{2}H(^{3}He,p)^{4}He$	65	109±9	[Aliotta et al.(2004)]
$^{3}He(^{2}H,p)^{4}He$	120	219±7	[Aliotta et al.(2004)]
$H(^{9}Be,\alpha)^{6}Li$	240	900±50	[Zahnow et al.(1997)]
$H(^{11}B,\alpha)^{8}Be$	340	430±80	[Angulo et al. (1993)]

- Large discrepancy between theoretical and experimental values for a large number of reactions

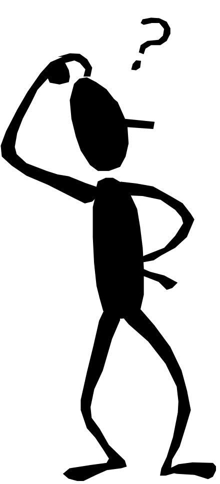


Some idea…

Values of U_e were estimated for several reactions by means of comparison between direct data with extrapolations

Possible explanations:

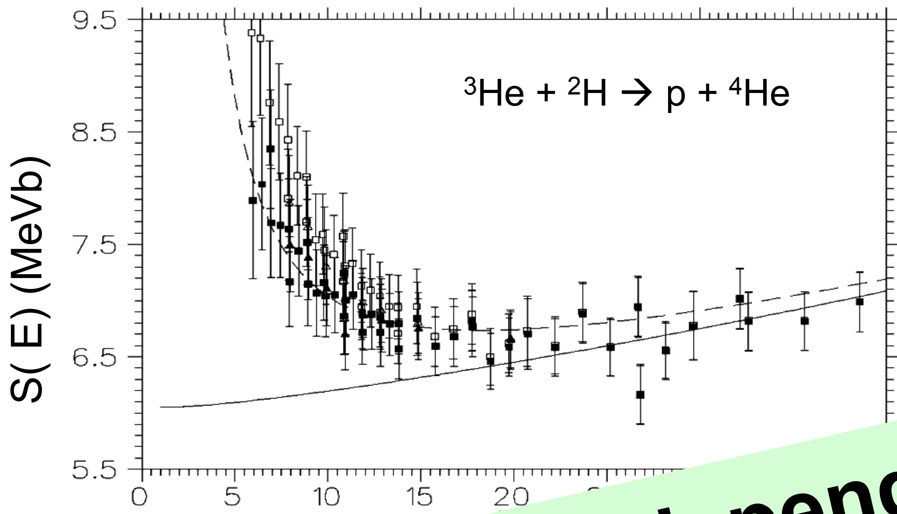
- lack of knowledge for energy loss at E<100 keV;
- extrapolation of $S_b(E)$ at astrophysical energies;
- theoretical models of electron screening (atomic physics and/or solid state physics)



- An independent measure of U_e is needed;
- The bare nucleus astrophysical S(E)-factor needs to be accurately known

Electron screening: laboratory.vs.stars

Direct Measurements



Stellar Screening ≠ Laboratory Screening

Experimental Data (Shielded)

S_b (Bare)
...edure

An experiment...

of U_e a...

- a determination ... b (applications)
- to study electron screening in laboratory conditions and then in stellar plasma

An independent determination of $S_b(E)$ is necessary!

Correction for stellar screening (Debye-Hückel theory)

The Trojan Horse Method (THM) (see C. Spitaleri et al., PAN 2011)

The THM is an indirect technique allowing one to extract the bare-nucleus S-factor for the charged-particle induced reaction

A+x→c+d

at astrophysical energies by performing a surrogate experiment in which a suitable three body reaction

A+a→c+d+s

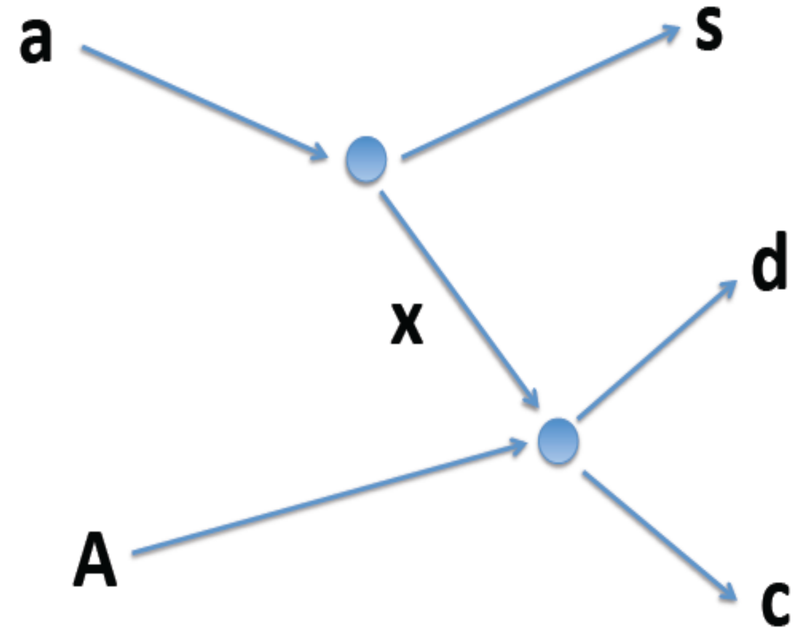
is investigated. The nucleus

. With

respect direct measurements, in which

Indirect tools for nucl.astroph.: The Trojan Horse Method (THM)

- ✓ The QF $a + A \rightarrow c + d + s$ reaction between the projectile A and the target a can be described by the polar-diagram
- ✓ Upper pole describes the break-up process of nucleus a in its "x" and "s" constituents. <u>The break-up is Quasi-Free if *s* maintains in the exit channel the same momentum distribution as in *a*;</u>



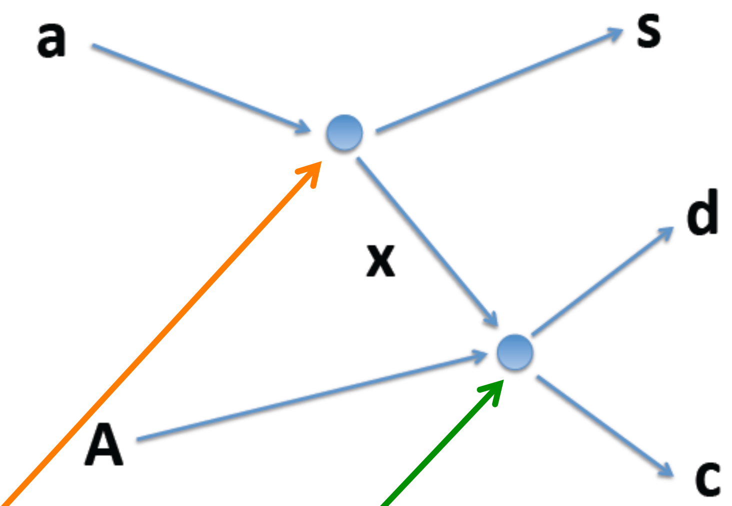
- ✓ Lower pole describes the astrophysically relevant two-body reaction A(x,c)d, induced at the c.m. energy $E_{c.m.}=E_{cd}-Q_{2body}$;
- ✓ The nucleus a (the so-called "TH-nucleus") is chosen because of:
  - its large amplitude in the $a=x\oplus s$ cluster configuration;
  - its relatively low-binding energy;
  - Its known *x-s* momentum distribution $|\Phi(\vec{p}_S)|^2$ in *a.*
- ✓ In this picture, "s" behaves as *spectator* while nucleus "*x*" is the *participant* of the astrophysical A(x,c)d reaction (Impulse Approximation approach).

Indirect tools for nucl.astroph.: The Trojan Horse Method (THM)

The A(a,cd)s is induced at energies of the order of 20-50 MeV, higher than the Coulomb barrier in the entrance A-a channel.

The A-x interaction occurs directly in the nuclear field, thus **Coulomb suppression effects are naturally removed.**

The **cross section** for the A(a,cd)s process can be derived in the simple PWIA approac…



$$\frac{d^3\sigma}{dE_c\, d\Omega_c\, d\Omega_d} \propto KF \cdot |\Phi(\vec{p}_s)|^2 \cdot \left(\frac{d\sigma}{d\Omega}\right)\Bigg|^{N}_{A-x}$$

Indirect tools for nucl.astroph.: The Trojan Horse Method (THM)

THM allows:

- **studying an astrophysically relevant A(x,c)d reaction** in the whole energy range for astrophysics by using only a beam energy;
- **measuring the corresponding bare-nucleus S(E)-factor**, without Coulomb suppression and electron screening effects;
- **overcoming extrapolation procedures** typical of direct measurements
- **establishing the influence of both low-energy or sub-threshold resonances** affecting the total reaction rate.

THM needs:

- **validity test** → devoted studies have been or are currently performed at high energies;
- **introduction of penetrability function** → to determine the S(E)-factor;
- **normalization to direct data** → to extract THM data in absolute units

The Trojan Horse Method (THM): a “To-Do List” for experimentalists

1) Choose the 2-body astrophysical reaction to be studied;

2) Choose the more appropriate TH nucleus;

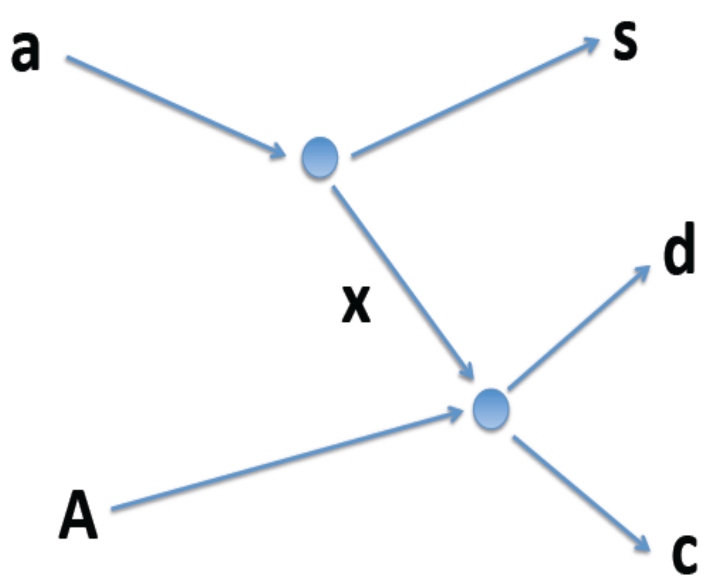
3) Choose the 3-body reaction;

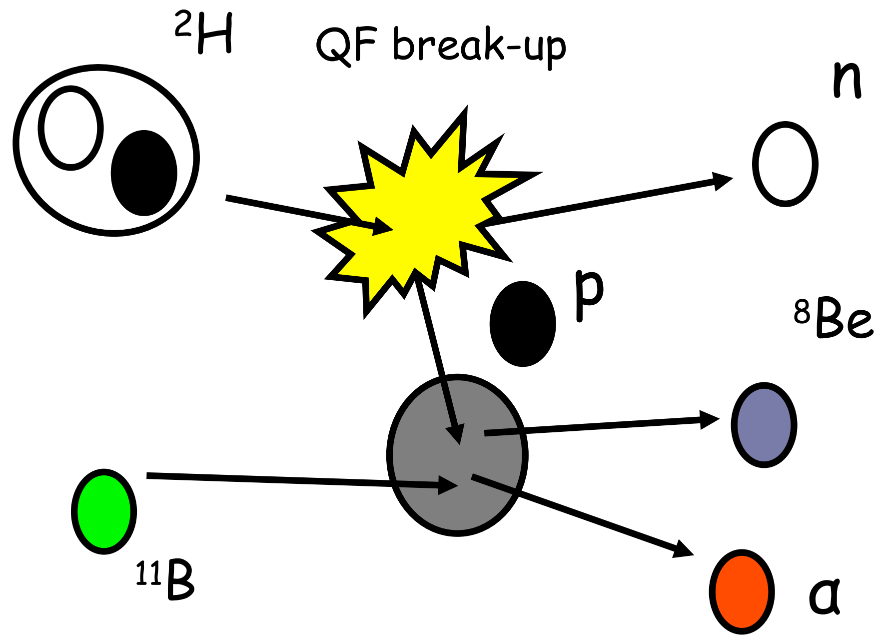
4) Selection of the 3-body channel;

5) Selection of the reaction mechanism;
6) S(E)-factor measurement of th
2body reaction;
7) Reaction rate calculation

B.E.

The indirect study of the $^{11}B(p,\alpha_0)\,^{8}Be$ via the THM applied to the $^{2}H(^{11}B,\alpha_0\,^{8}Be)n$ reaction

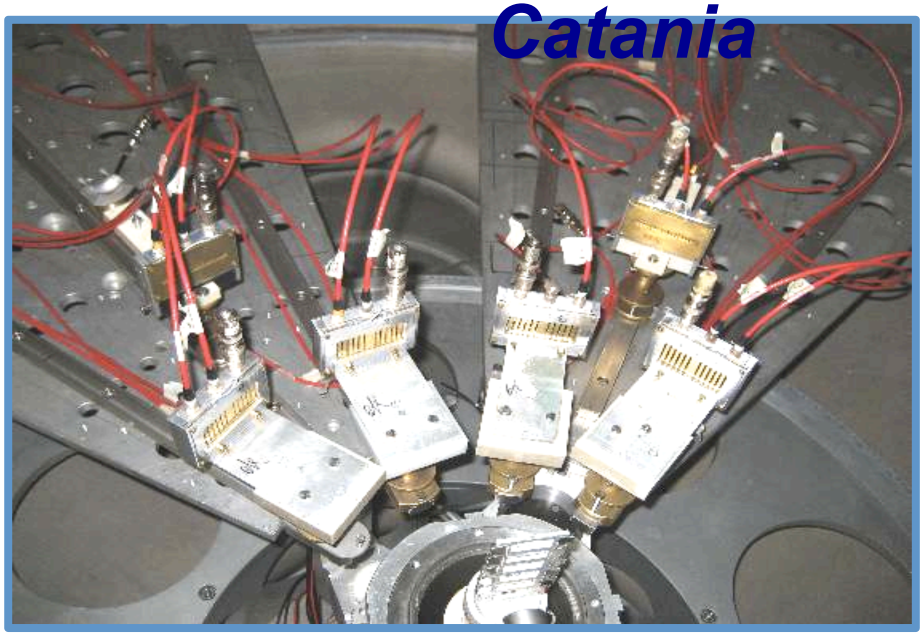


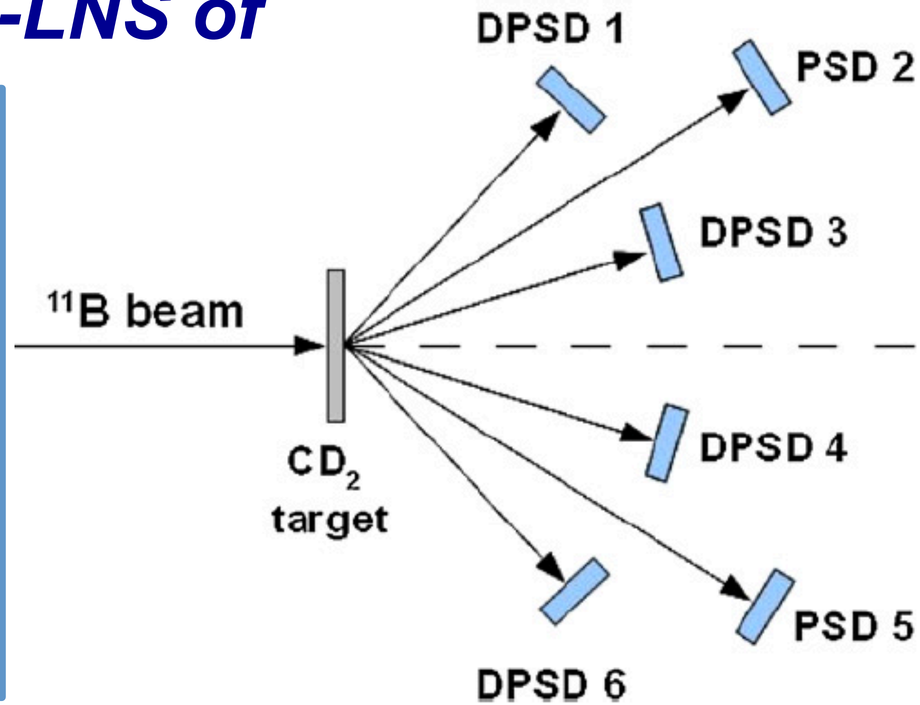


THM→ Baur et al. PLB, 1986; Spitaleri et al., 1990; Cherubini et al. ApJ 1996, Spitaleri et al. PRC 1999; Tumino et al. PRC 2003, Spitaleri et al. PRC 2004, Spitaleri C. et al., Phys. Atom. Nuclei, 74, 2011 and ref. ther….

THM recent applications→ La Cognata et al., ApJ 2013; Pizzone et al., PRC 2013; Tumino et al. ApJ 2013, Lamia et al. ApJ 2013; Gulino et al. PRC 2012; Sergi et al. PRC 2010;….

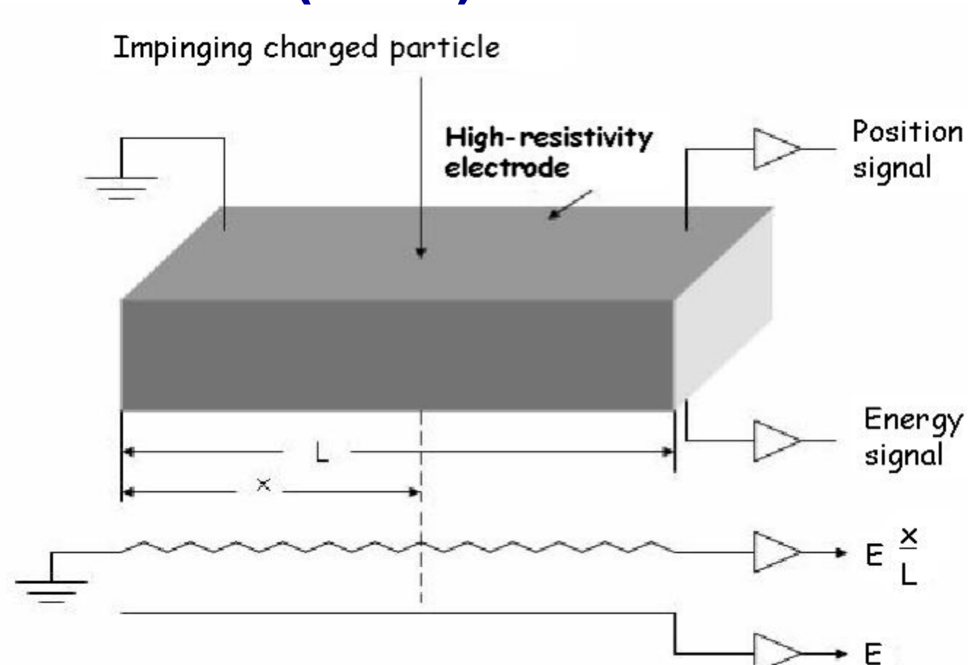
The Experiment at INFN-LNS of Catania





- Study of the $^{11}B(p,\alpha)^{8}Be$ reaction (Q=8.59 MeV) through the QF $^{2}H(^{11}B,\alpha^{8}Be)n$ reaction (Q=6.36 MeV);
- $E_{beam}(^{11}B)$=27 MeV & $I_{beam}(^{11}B)$=2-5 nA;
- Target thickness CD_2 ~190 μg/cm^2;
- Use of standard position sensitive silicon detectors, placed at about 300 mm from the target position;
- Displacement of the detectors around the *QF-angular* range
- Detection of alpha and beryllium particles. No detection of the exiting

Position sensitive silicon detectors (PSD) and their use for THM purpose



Typical Dimensions→ 50*10 mm^2

Thickness→ from 500 μm to 1000 μm

Energy resolution→ 1% (5 MeV alpha-source, maximum)

Spatial resolution→ 0.5 mm (FWHM) (maximum)

Placed at 60-30 cm far from the target→0.1°-0.2° angular resolution

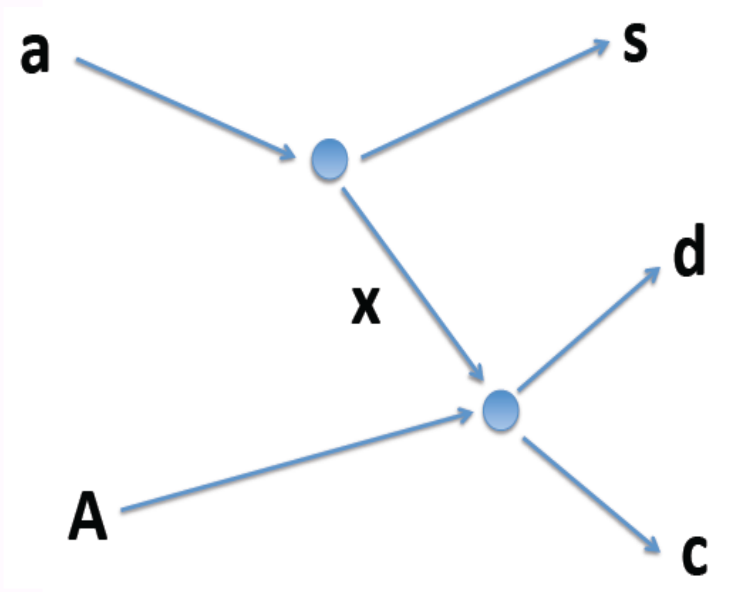
Detectors placement around the quasi-free angles: what does it mean?

For a deeper discussion, by considering the energy and momentum conservation laws for a general reaction A(a,c d)s, it is possible to write the following system 5.9:

$$\begin{cases} E_A + Q = E_c + E_d + E_s \\ \vec{P}_A = \vec{P}_c + \vec{P}_d + \vec{P}_s \end{cases} \quad (5.9)$$

where E_i and P_i represent the values of energy and momentum for the i-th particle. If the relative motion of the spectator particle occurs mainly with l=0, it will possible to assume P_s=0, that is E_s=0. By using this assumption, the system 5.9 can be written as

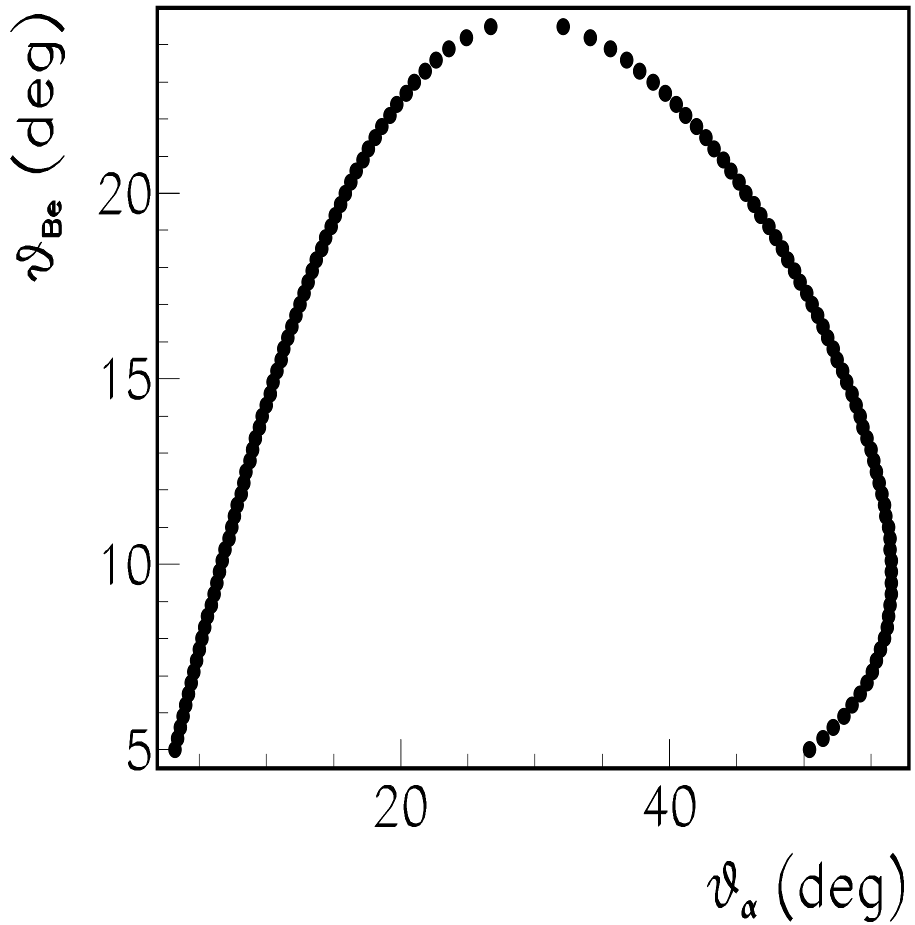
$$\begin{cases} E_a + Q = E_c + E_d \\ P_a = P_c cos\theta_c + P_d cos\theta_d \\ 0 = P_c sen\theta_c + P_d sen\theta_d \end{cases} \quad (5.10)$$



Thus, it is possible to determine a couple of angles for the two particles "c" and "d" corresponding to zero-momentum for "s"

Detectors placement around the quasi-free angles: what does it mean?

Table 5.1: QF-angular pair in th hypothesis of a break-up process for the $^{2}H(^{11}B,\alpha^{8}Be)n$ induced with an energy of $E_{11B}=E_{beam}=27$ MeV.



$E_{beam}\,(MeV)$	$\theta_{\alpha}\,(deg)$	$\theta_{^8Be}\,(deg)$	$E_{\alpha}\,(MeV)$	$E_{^8Be}\,(MeV)$
27	12	16.6	26.08	6.94
27	15	19.4	25.34	7.73
27	17	21	24.7	8.38
27	19	22.2	24	9.06

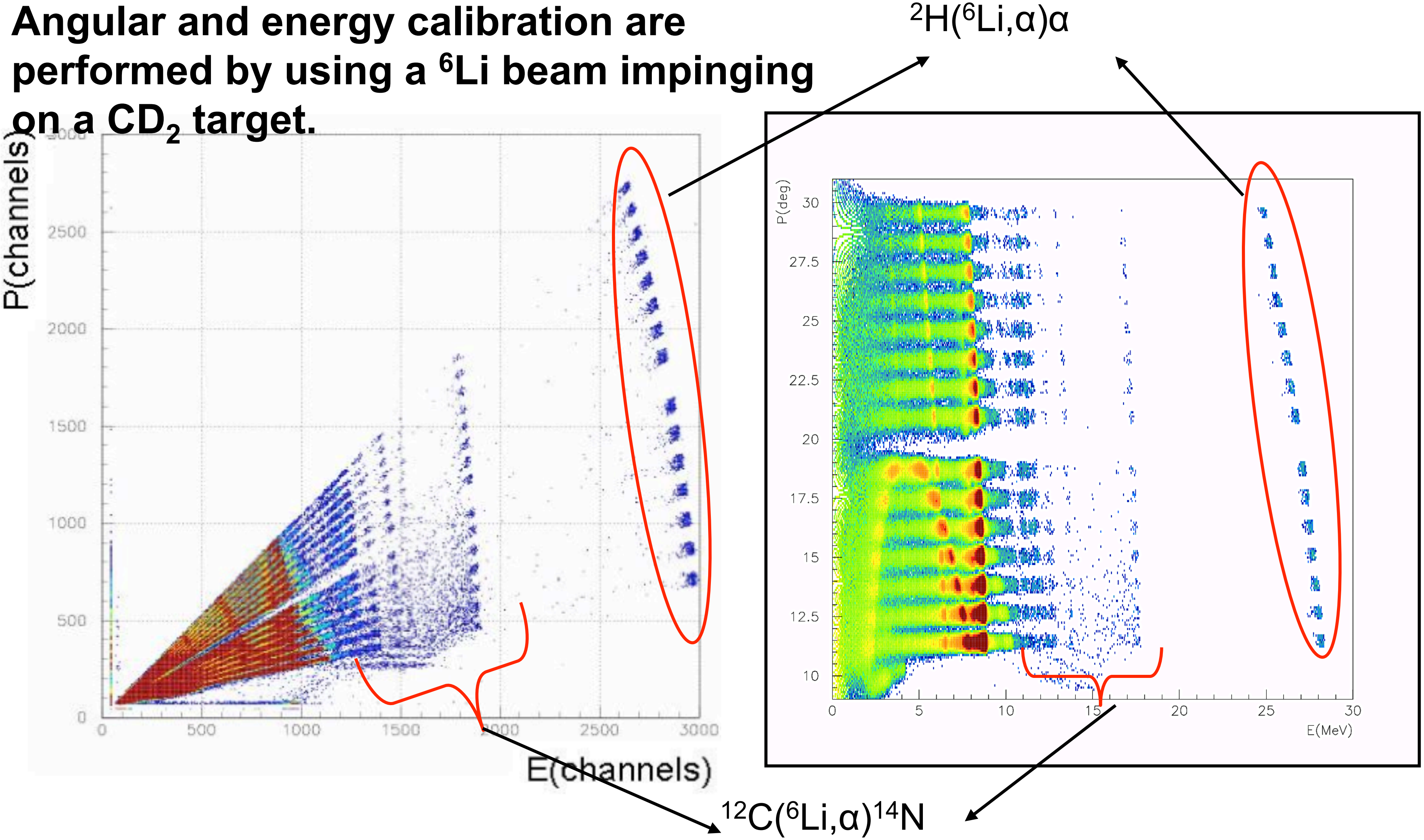
This allows then to determine the experimental apparatus:

^{8}Be detection→ 10°<θ_{Be}<30°;

α detection→10°<θ_{α}<24°;
→30°<θ_{α}<44°;
→50°<θ_{α}<64°;

Position sensitive silicon detectors (PSD): angular and energy calibration

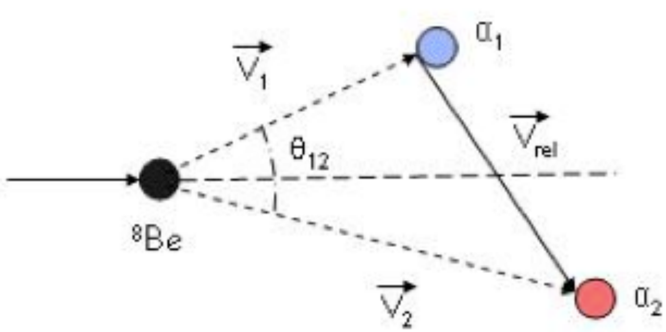
Angular and energy calibration are performed by using a ^{6}Li beam impinging on a CD_2 target.



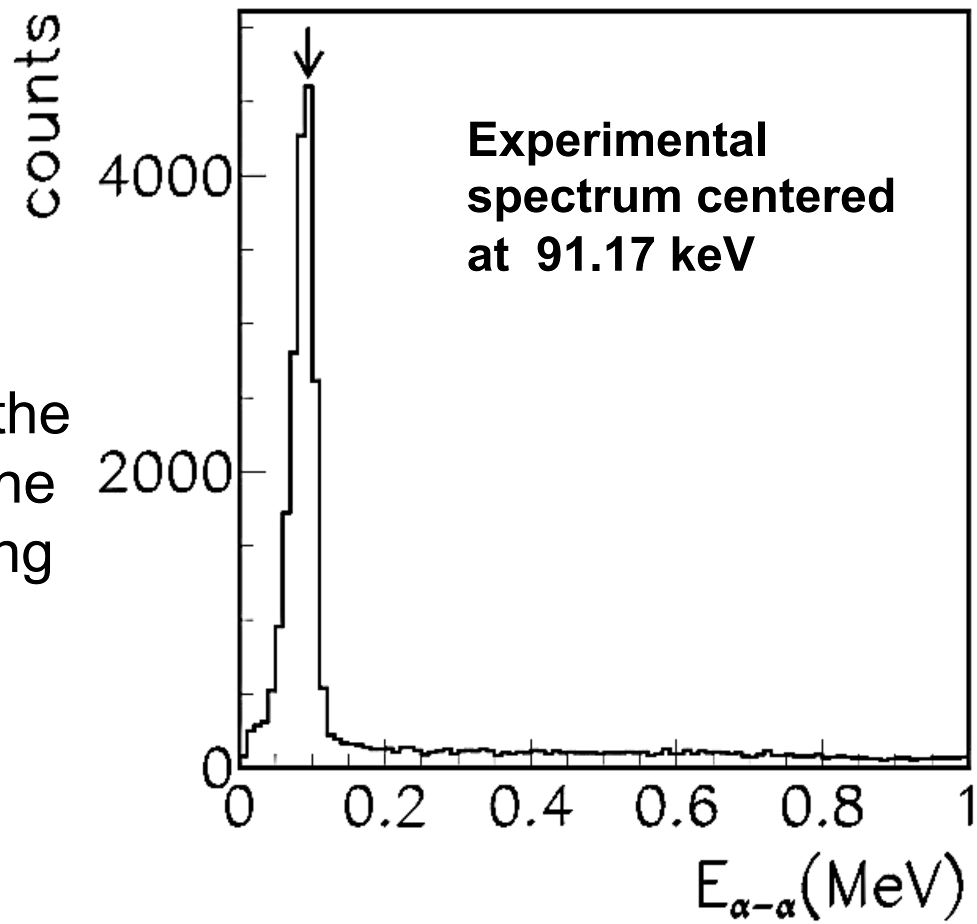
Selection of the 2->3 $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ channel:

^{8}Be determination

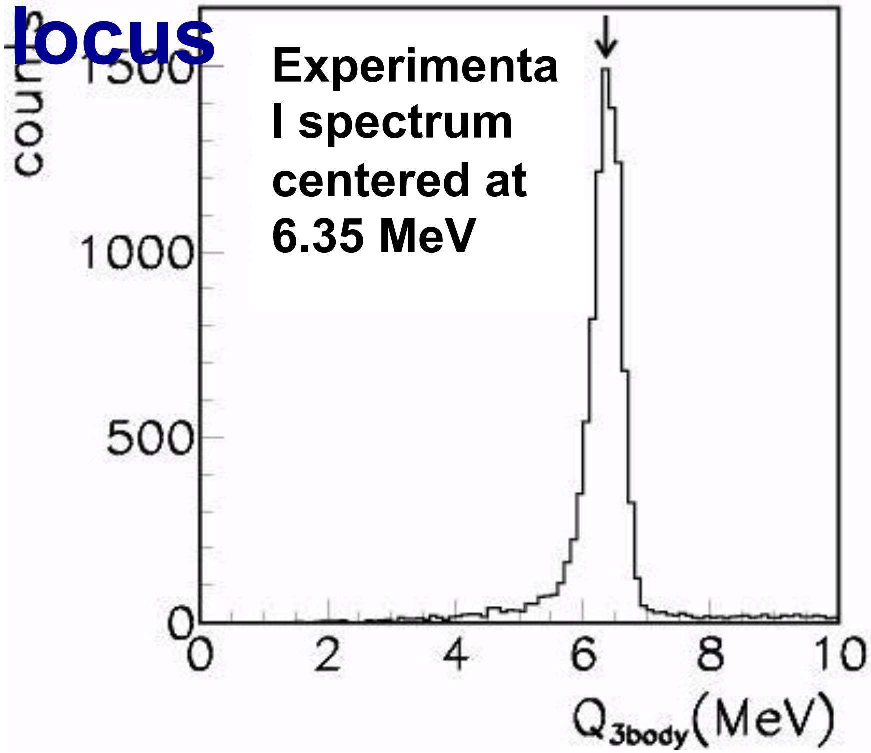
^{8}Be(g.s.) decays in 2 alphas (Q^{th}_{dec} 92 keV). These have been detected in coincidence on a Dual Position Sensitive Detector,



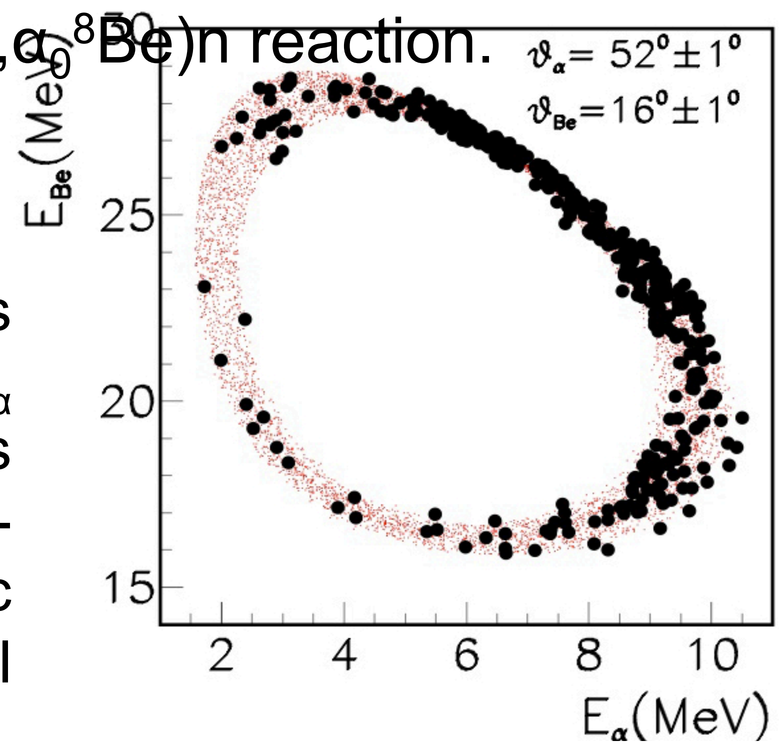
Off-line reconstruction of the relative energy between the detected α-particles. Gating on this relevant peak, emission energies and angles of ^{8}Be have been reconstructed.



Selection of the 2->3 $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ channel: experimental Q-value and kinematical locus



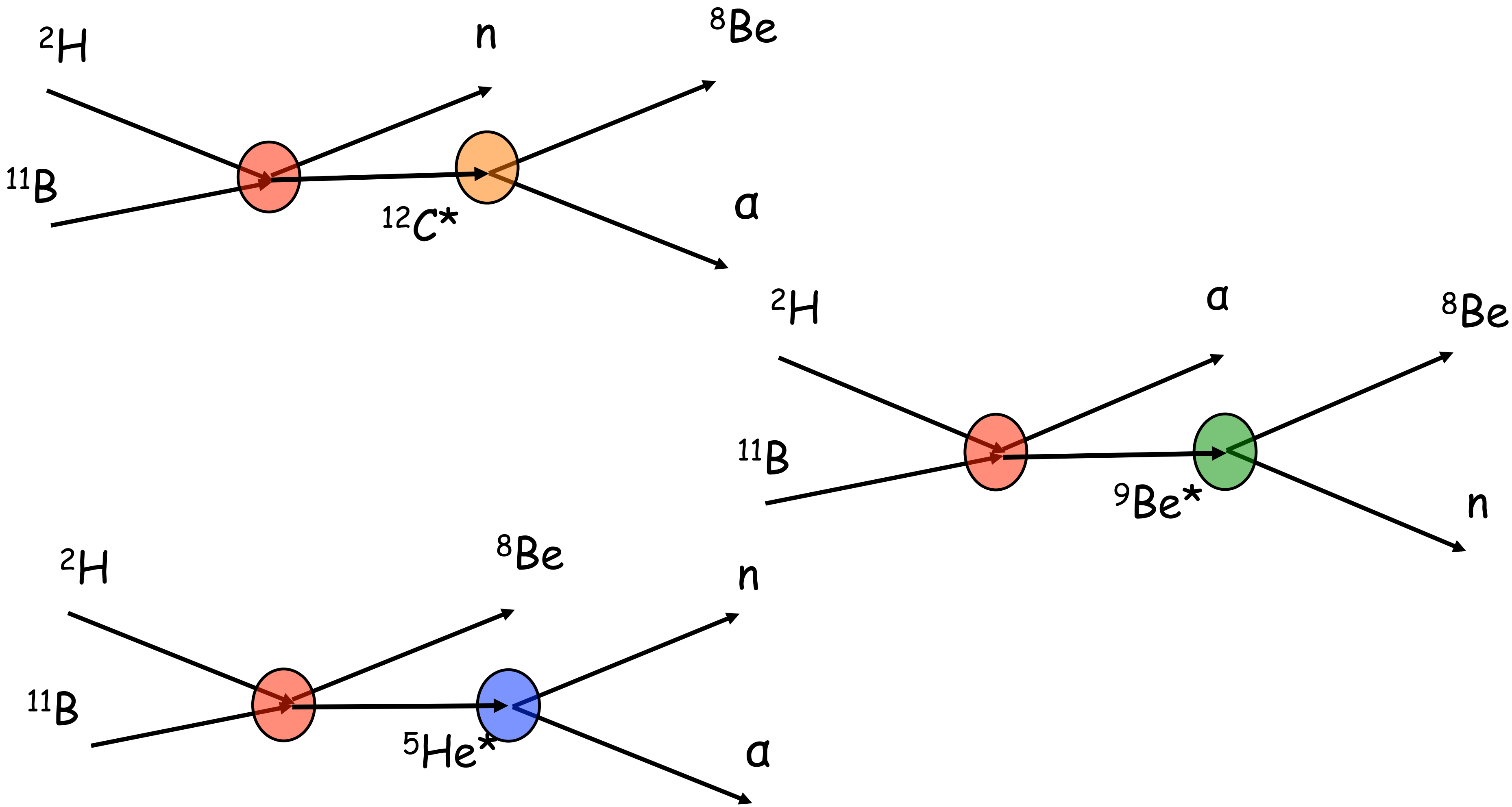
After the identification of ^{8}Be events and in the hypothesis of an undetected neutron particle, the **experimental Q_{value}** has been reconstructed for the detected events. The clear peak at about 6.36 MeV marks the occurrence of the $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ reaction.



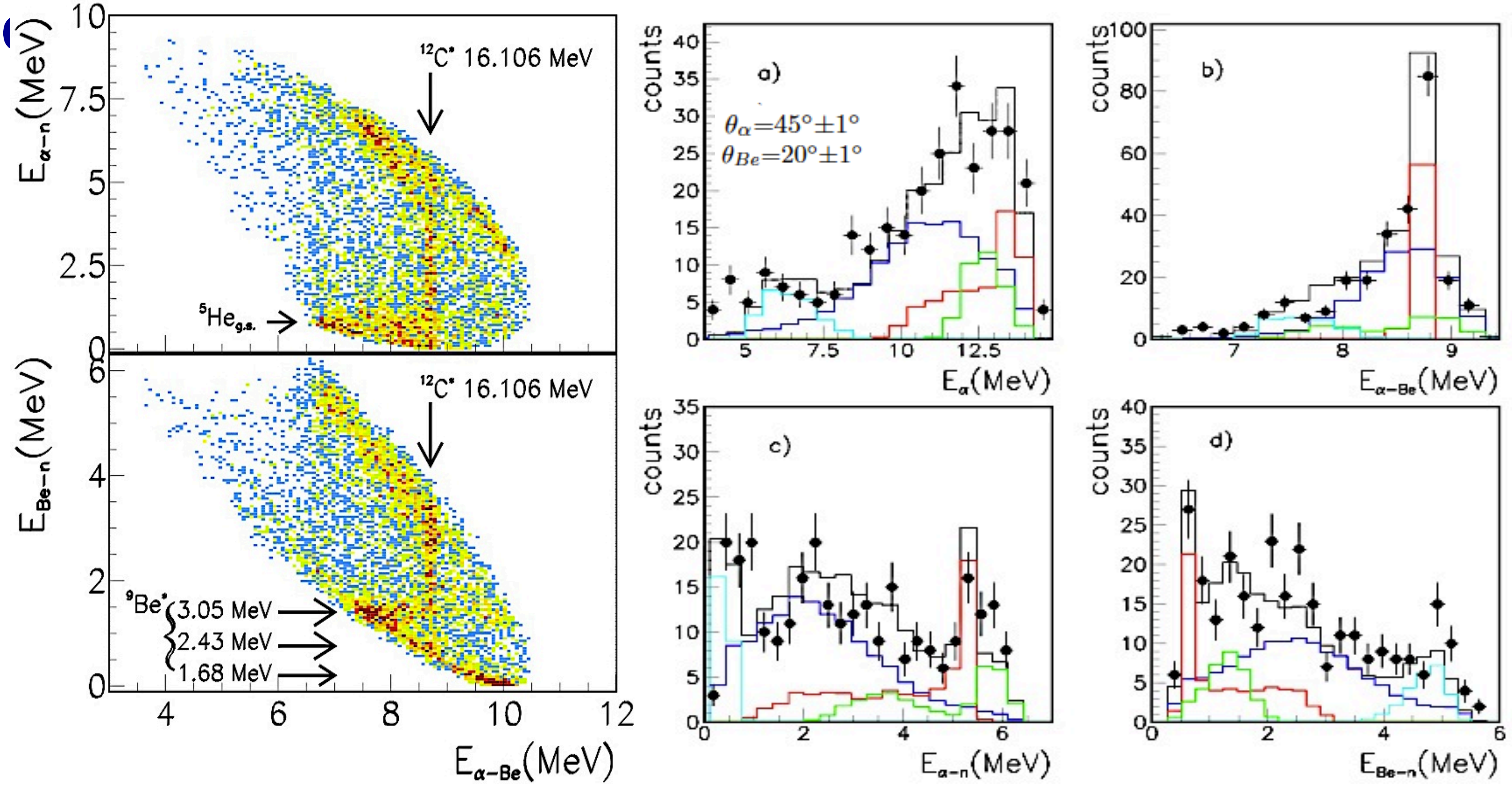
The **kinematical locus** of events E_{Be} .vs.E_α for the $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ reaction was compared with the corresponding three-body kinematic calculation, appearing to be very well reconstructed.

The $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ reaction channel: are the data contaminated by Sequential Mechanism (SM)?

The same particles α, ^{8}Be and neutron can be produced via the decays of intermediate nuclei. Study of the relative energies is then needed.



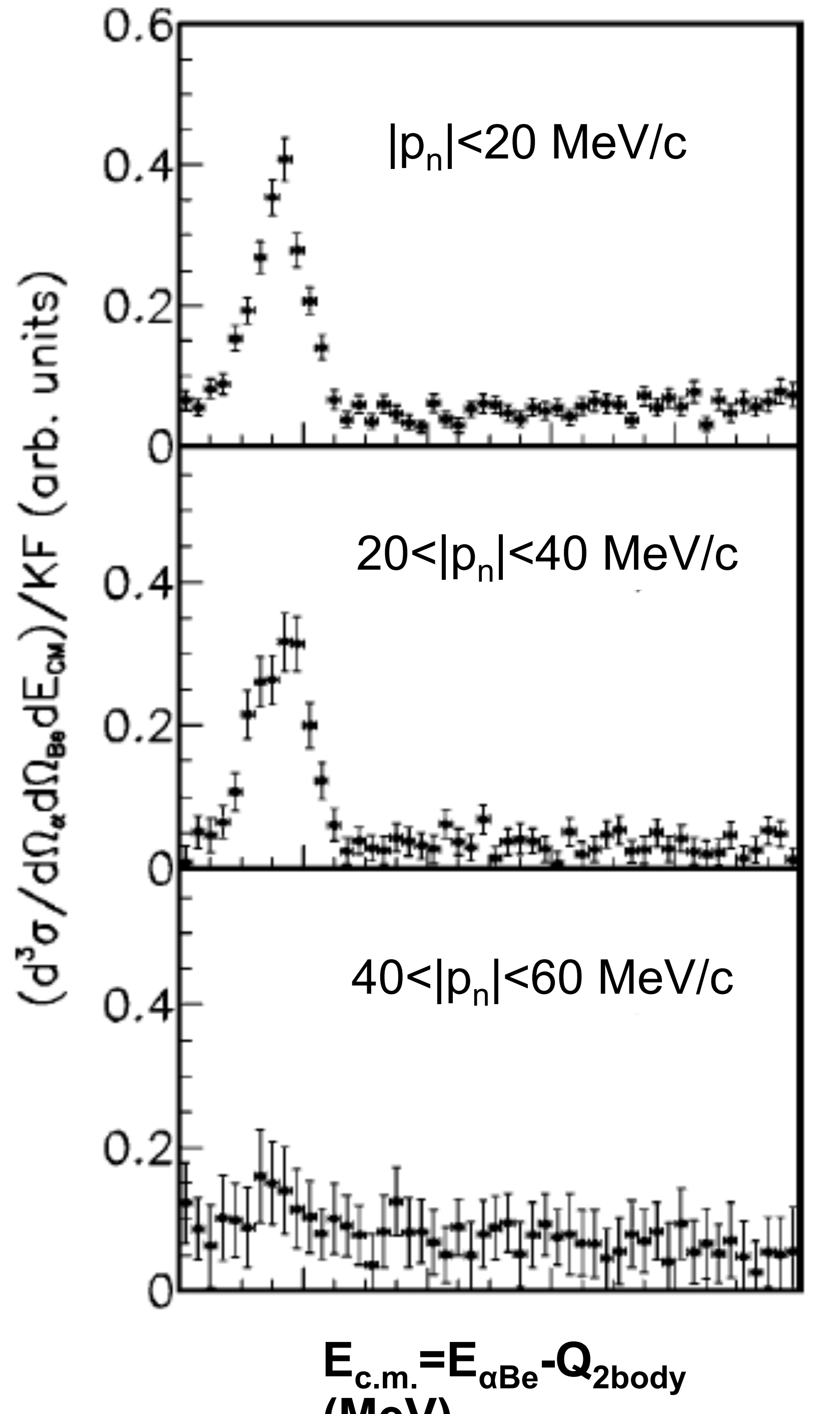
Are Sequential Mechanism (SM) present in THM



reaction mechanism.

Selection of the QF-mechanism: data as a function of p_n

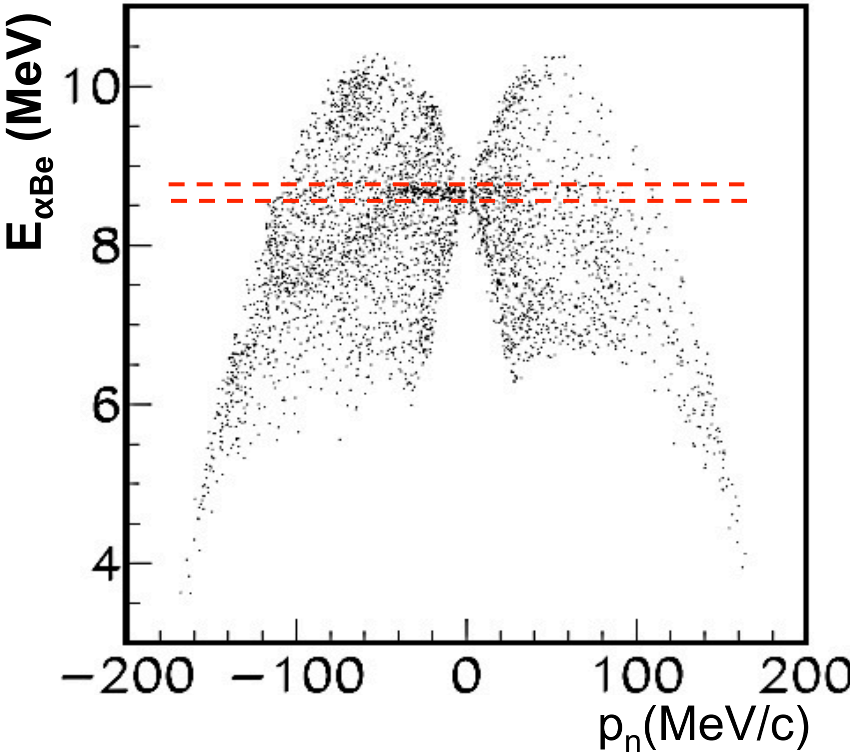
1) Spectra are obtained with different condition on the *undetected* neutron momentum;
2) The yield is enhanced around low-neutron momenta and decrease for p_n>50 MeV/c. This finally underlines that the experimental yield is affected by the behaviour of the p-n momentum distribution in the deuteron (having its maximum at 0 MeV/c);
3) The coincidence yield appears strongly influenced by the momentum-distribution of the exiting neutron. This strong correlation is an unambiguous signature of the presence of the QF-reaction



QF selection via Momentum Distribution investigation

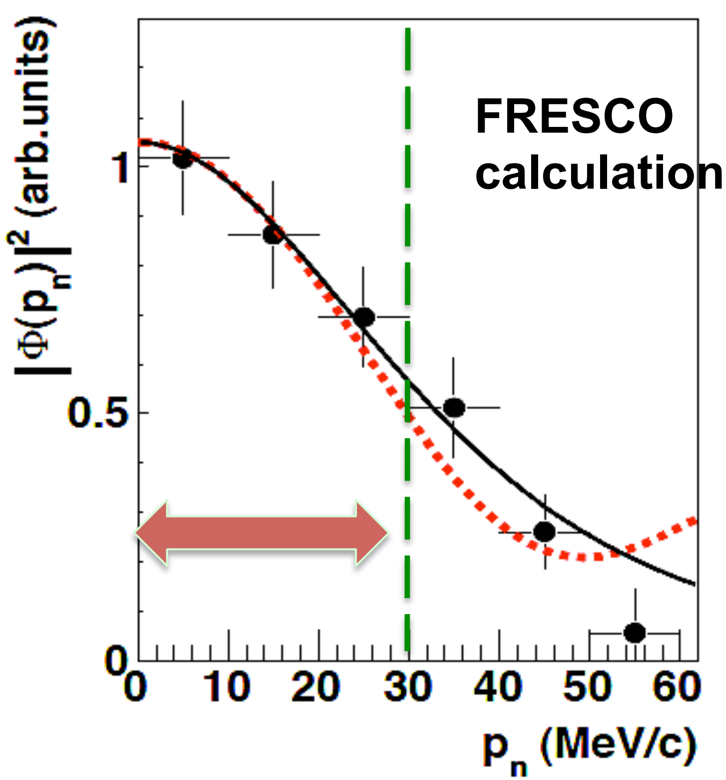
✓ The PWIA approach allows one to exctract the experimental momentum distribution via the relation:

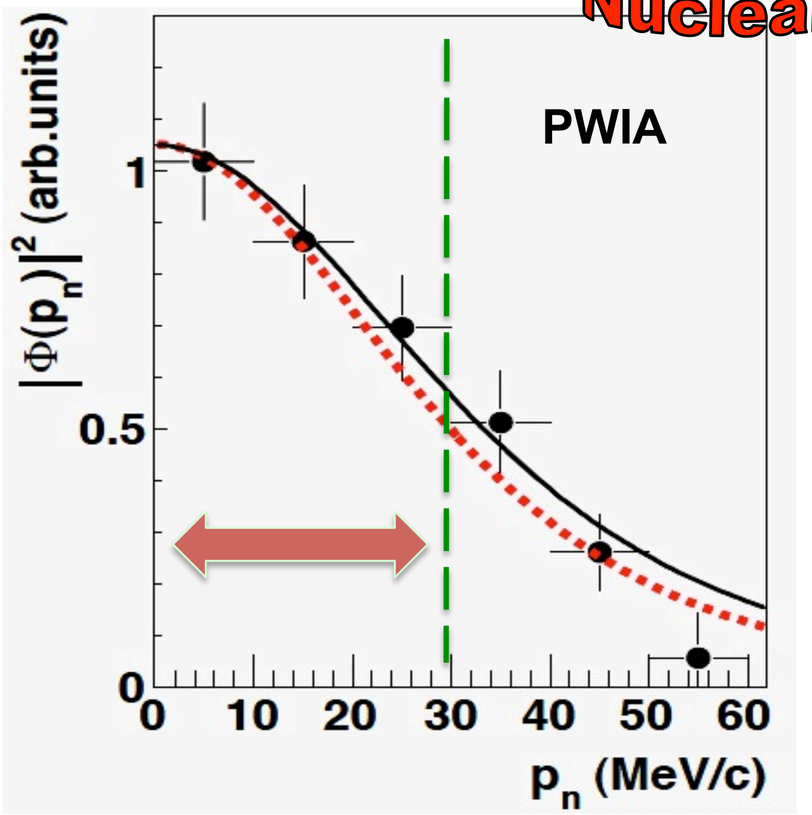
$$|\Phi(\vec{p_n})|^2 \propto \frac{\frac{d^3\sigma}{d\Omega_\alpha \, d\Omega_{8Be} dE_{cm}}}{KF}$$



QF selection via Momentum Distribution investigation: PWIA vs DWBA

AstroFIsica Nucleare





Exp. Fit→ FWHM=65±10 MeV/

Hulthén→FWHM=58 MeV/c

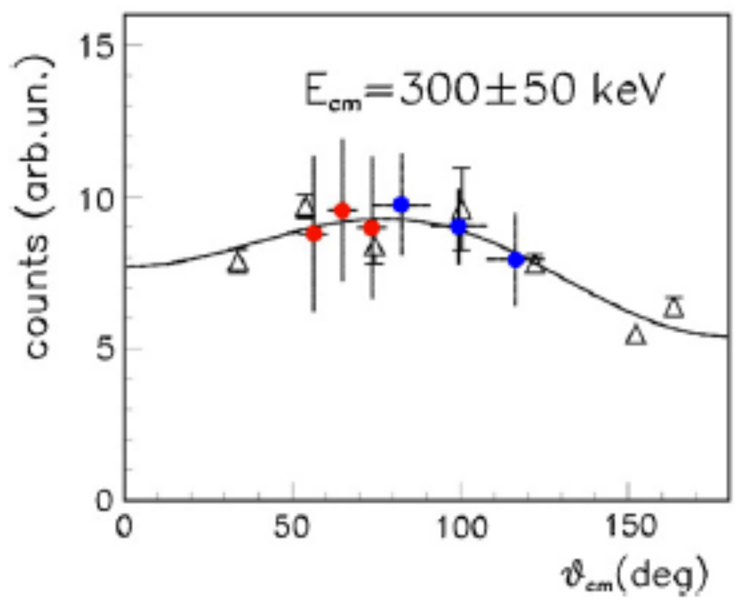
$$|\Phi(\vec{p}_n)|^2 = \frac{1}{2\pi}\sqrt{\frac{ab(a+b)}{(a-b)^2}}\left(\frac{1}{a^2+p_n^2} - \frac{1}{b^2+p_n^2}\right)$$

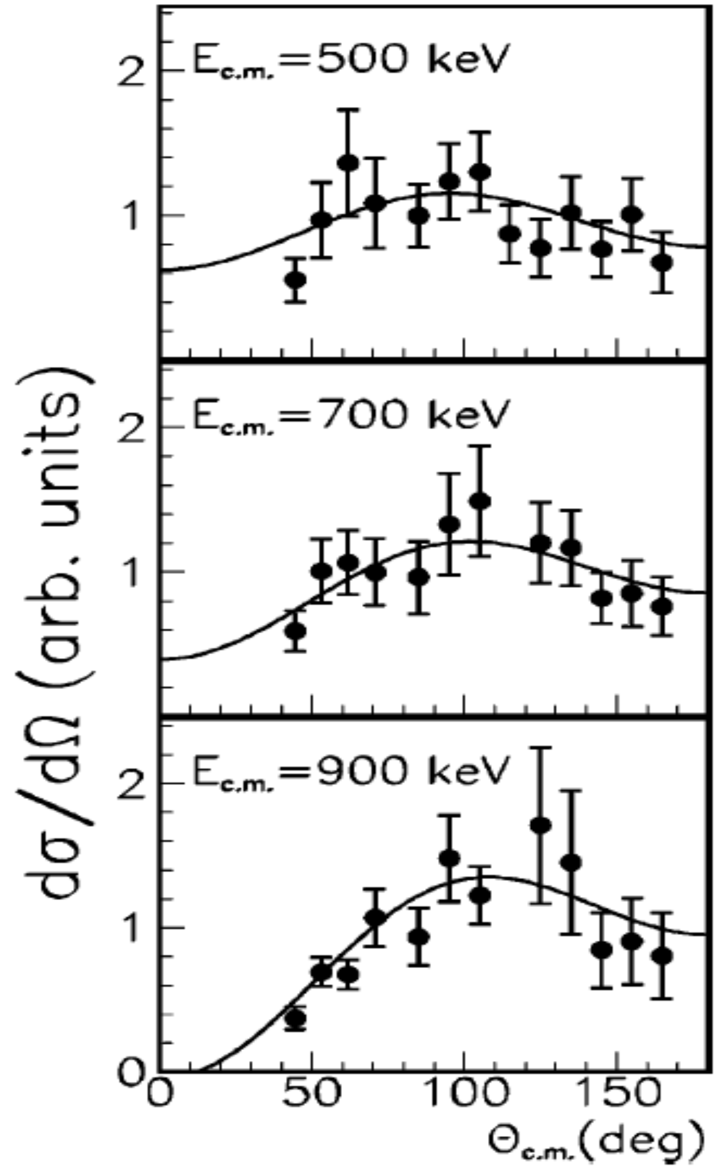
Data selection: from the $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ to the $^{11}B(p,\alpha_0)^{8}Be$

Angular distributions need to be extracted, by means of the derived

$$\theta_{cm} = \arccos \frac{(\mathbf{v}_B - \mathbf{v}_p)\cdot(\mathbf{v}_{Be} - \mathbf{v}_\alpha)}{|\mathbf{v}_B - \mathbf{v}_p||\mathbf{v}_{Be} - \mathbf{v}_\alpha|},$$

Center-of-mass alpha-^{8}Be emission angle.





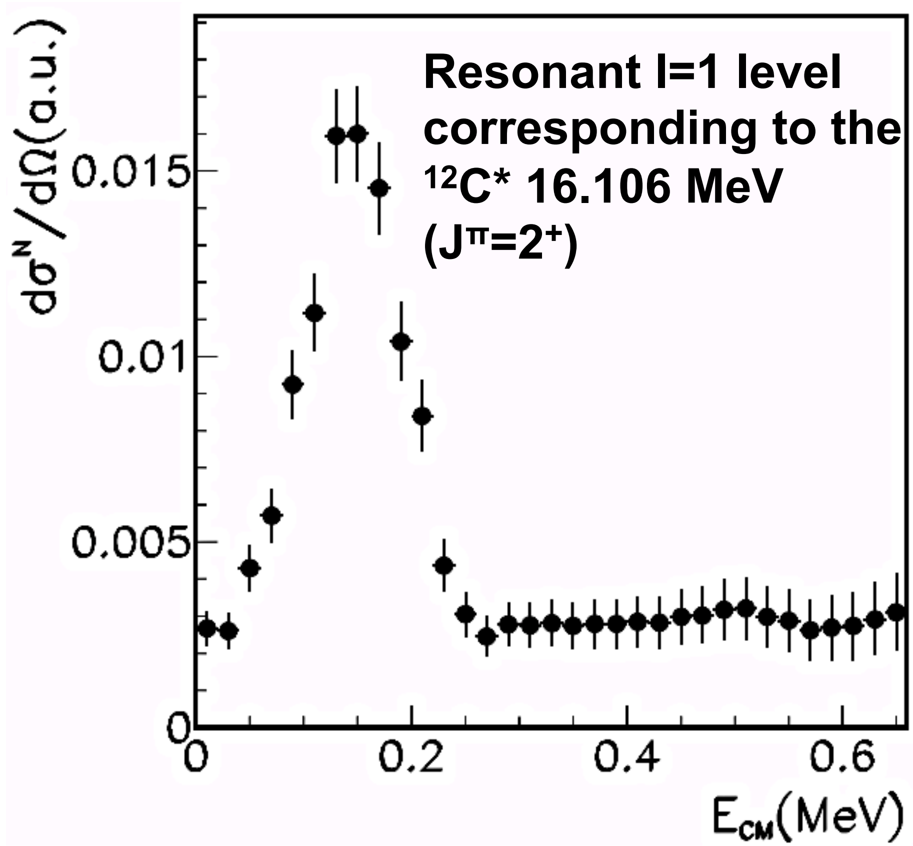
Data selection: from the $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ to the $^{11}B(p,\alpha_0)^{8}Be$

- ✓ Only the events belonging to the condition $|p_n|<30$ MeV/c (quasi-free selection) will be taken into account;
- ✓ By using the simple PWIA formulation, the HOES cross section can be obtained via the factorization:

$$\frac{d\sigma^N}{d\Omega} \propto \frac{\dfrac{d^3\sigma}{d\Omega_\alpha\, d\Omega_{8Be} dE_{cm}}}{KF \cdot |\Phi(\overrightarrow{p_n})|^2}$$

- ✓ The energy in the center-of-mass ^{11}B-p is determined by the relation:

$E_{CM}=E_{\alpha Be}-Q_2=E_{\alpha Be}-8.59$ MeV



- ✓ No penetrability or electron screening effects influence the TH "bare-nucleus" cross section.

Energy Resolution on E_{cm}: evaluation via error propagation

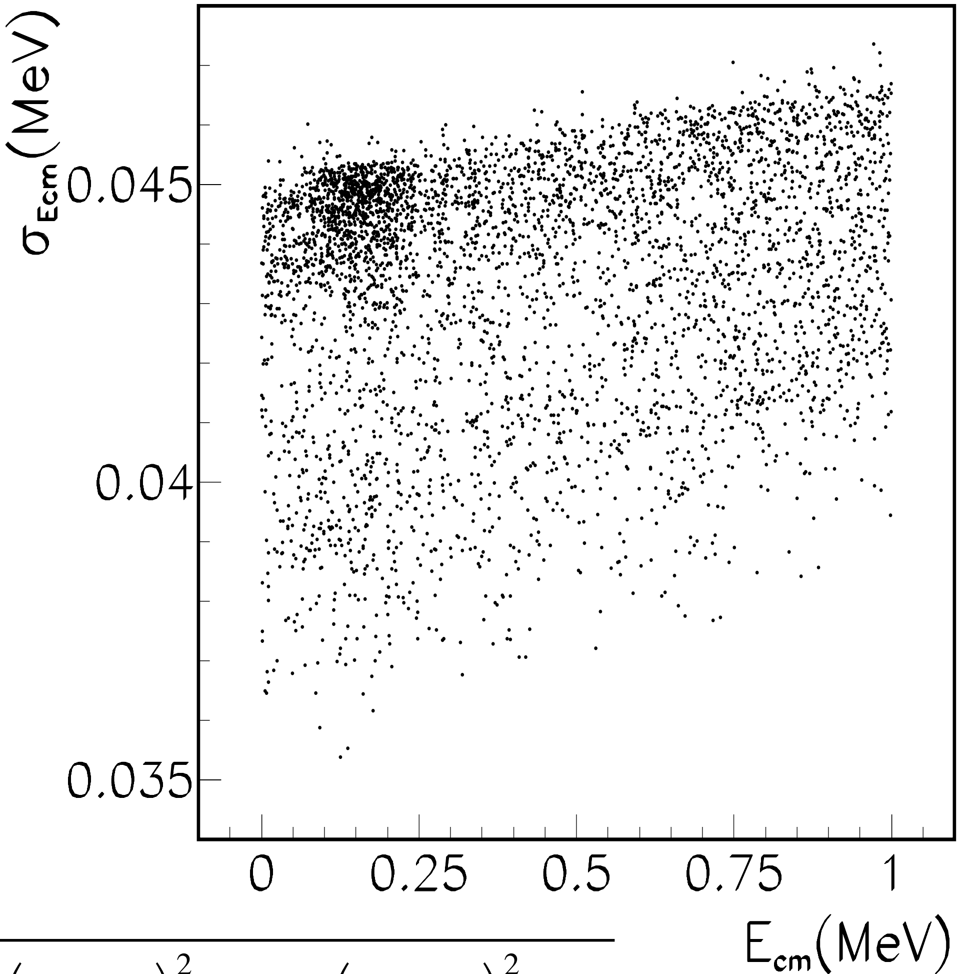
THM allows one to determine the astrophysically relevant 2body reaction at energies:

$E_{c.m.} = E_{\alpha Be} - Q_{2body} = E_{\alpha Be} - 8.59$ MeV

However, the variable $E_{\alpha Be}$ represents the relative energy between the detected α and Be particle, thus:

$$E_{\alpha Be} = \frac{(\vec{p}_{\alpha Be})^2}{2\mu} = \frac{(\vec{p}_{\alpha} - \vec{p}_{Be})^2}{2\mu} =$$

$$\frac{\left(p_\alpha^2 + p_{Be}^2 - 2 p_\alpha p_{Be} \cdot \cos\theta_{\alpha Be}\right)}{2\mu}$$



$$\sigma_{E_{\alpha Be}} = \sqrt{\left(\frac{\partial E_{\alpha Be}}{\partial E_\alpha}\right)^2 \delta E_\alpha^2 + \left(\frac{\partial E_{\alpha Be}}{\partial E_{Be}}\right)^2 \delta E_{Be}^2 + \left(\frac{\partial E_{\alpha Be}}{\partial \theta_\alpha}\right)^2 \delta\theta_\alpha^2 + \left(\frac{\partial E_{\alpha Be}}{\partial \theta_{Be}}\right)^2 \delta\theta_{Be}^2}$$

Considering an energy resolution of about 1% and a 0.1°-0.2° on angular resolution, an average error of about 40 keV is expected on the quantity $E_{c.m.}$.

$^{11}B(p,\alpha_0)^8Be$: TH S(E)-factor determination

- Extraction of the bare-nucleus S(E)-factor: $S(E) = E{*}P_l\sigma^N(E){*}\exp(2\pi\eta)$

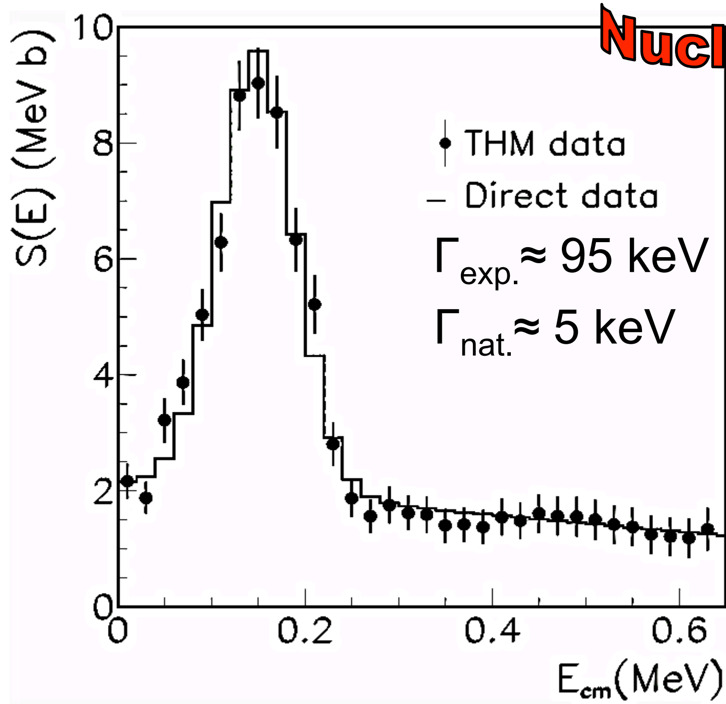
-^{9}Be & ^{5}He (SM) evaluation;

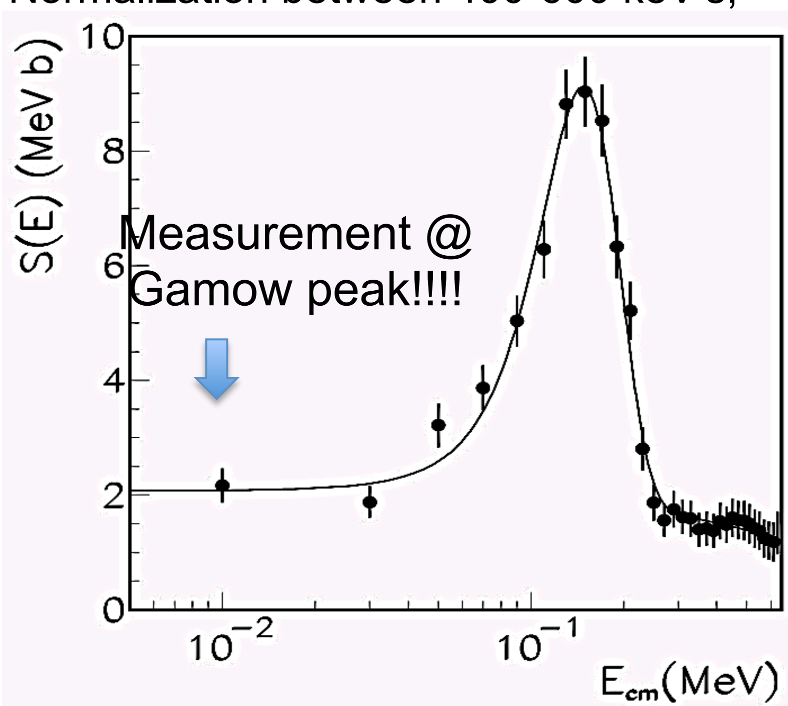
-Separation between resonant l=1 (16.106 MeV ^{12}C) and no-resonant contribution;

-Integration via angular distributions;

-Smearing procedure for the direct data (40 keV energy resolution);

-Normalization between 400-600 keV's;





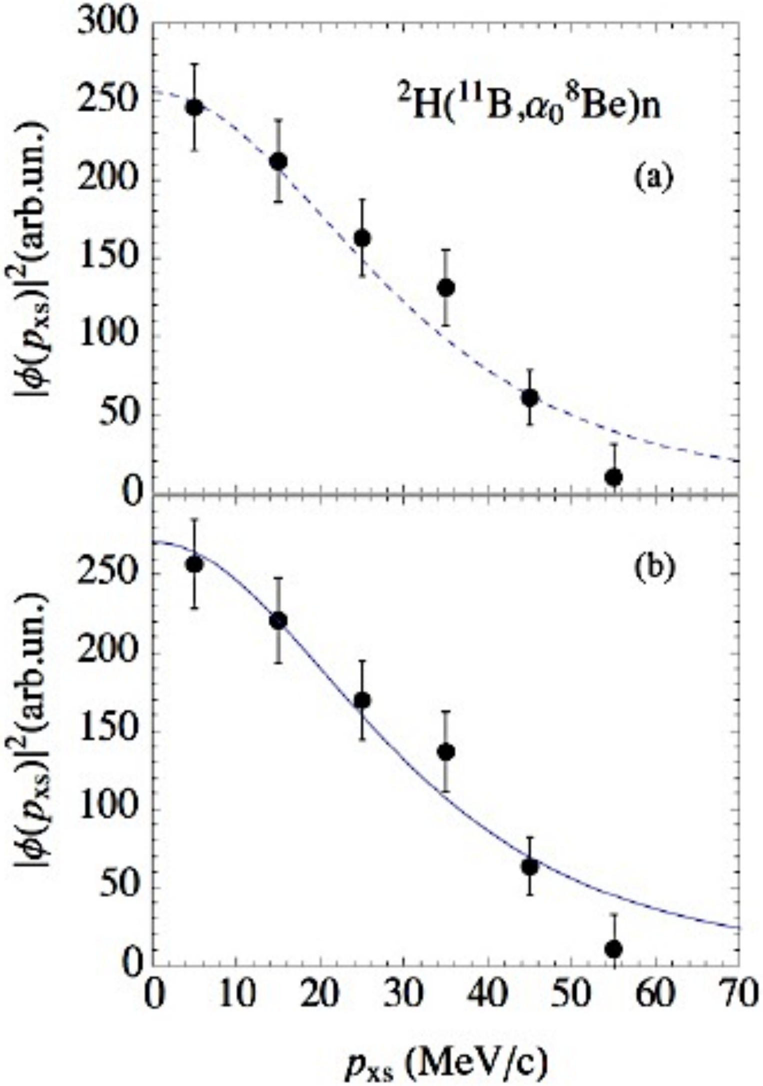
- The bare-nucleus S(E)-factor has been described as:

$$S(E)_b = 2.04 - 1.37{*}E + 0.12{*}E^2$$

$$+7.28\times\exp[-0.5((E-0.148)/0.044))^2]$$

S(0)=2.07±0.41 (MeV b)

How much the d-state component in deuteron alters the THM result?



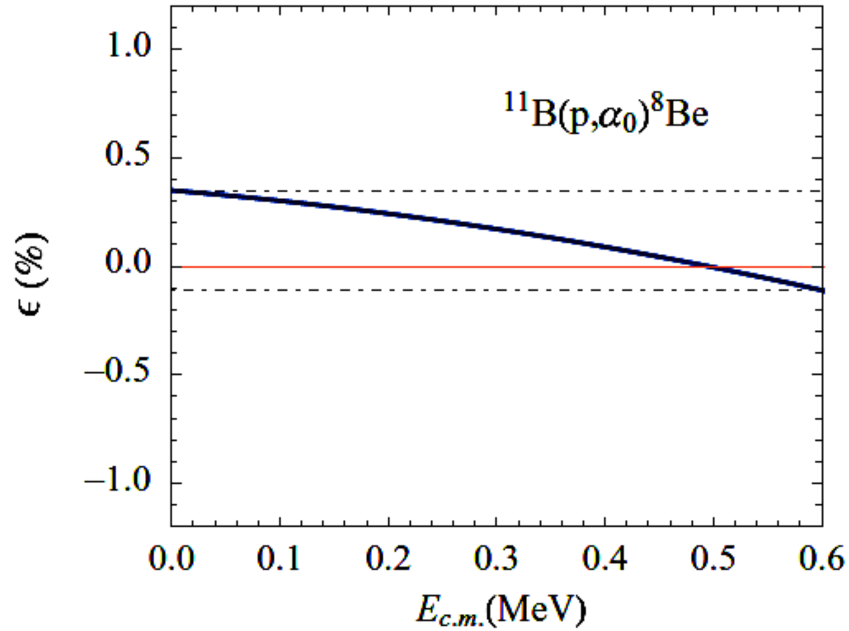


FIG. 9. (Color online) The $^{11}B(p,\alpha)^8Be$ case: The discrepancy ϵ, as given in Eq. (13) (blue line), is shown as the center-of-mass energy $E_{c.m.}$ varies. The higher and lower value of ϵ are also marked (blue dot-dashed line).

Panel a)→ The deuteron wave function (including s and d state) in momentum space

Panel b)→ The asymptotic form of the deuteron wave function

D-wave as

V. A. Babenko, Phys. At. Nucl. 74, 352 (2011)
R. J. Adler *et al.*, Phys. Rev. C 16, 3 (1977).

$^{11}B(p,\alpha_0)^8Be$: electron screening potential U_e determination via the TH

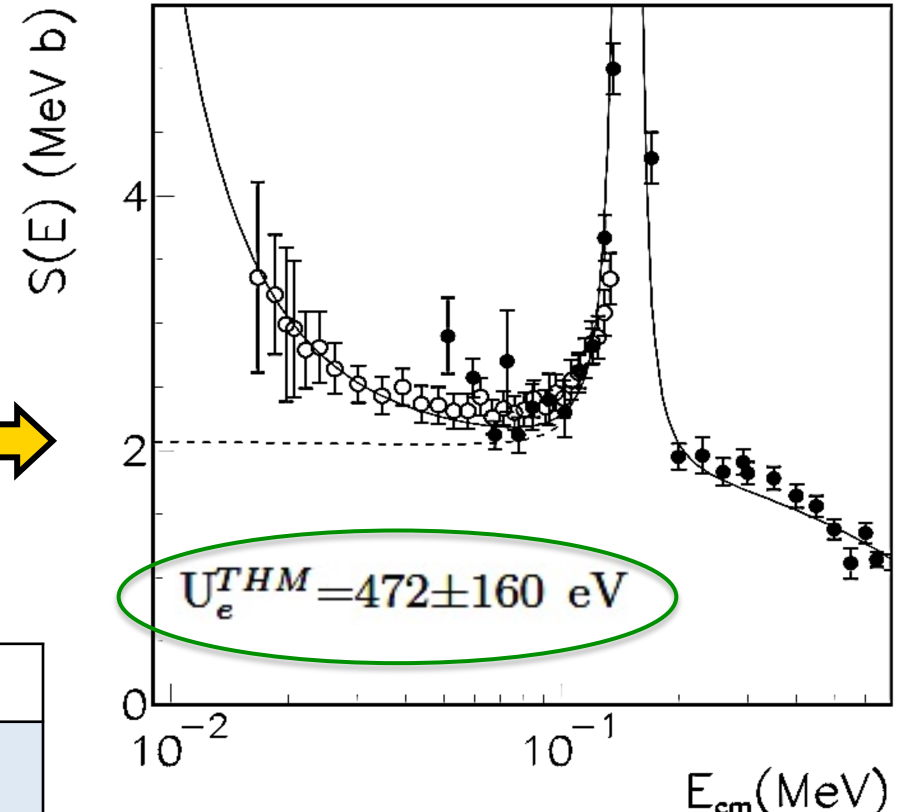
- The TH S(E)-factor (non-resonant) can be used for evaluating the electron screening potential;
- The shielded direct data can be fitted via the relation:

$$S(E)_{sh} = S(E)_b \times \exp(\pi \eta U_e / E)$$

leaving U_e as the only free parameter.

- RESULTS

$^{11}B(p,\alpha_0)^8Be$	S(0)	U_e
THM	2.07±0.41 (MeV b)	472±160 eV
Becker et al., 1987	2.10±0.13 (MeV b)	-----------
Angulo et al.,	------------	430±80 eV



Lamia L. et al, JpG, 2012

Recent TH results: Coulomb barrier

PHYSICAL REVIEW C **78**, 064001 (2008)

Off-energy-shell *p*-*p* scattering at sub-Coulomb energies via the Trojan horse method

A. Tumino,[1,2,3,*] C. Spitaleri,[1,2] A. Mukhamedzhanov,[4] G. G. Rapisarda,[1,2] L. Campajola,[5] S. Cherubini,[1,2] V. Crucillá,[1,2] Z. Elekes,[7] Z. Fülöp,[7] L. Gialanella,[6] M. Gulino,[1,2] G. Gyürky,[7] G. Kiss,[7] M. La Cognata,[1,2] L. Lamia,[1,2] A. Ordine,[6] R. G. Pizzone,[1,2] S. Romano,[1,2] M. L. Sergi,[1,2] and E. Somorjai[7]
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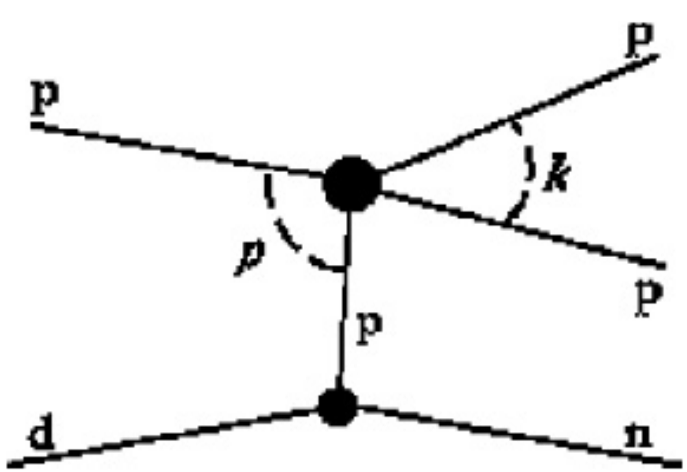
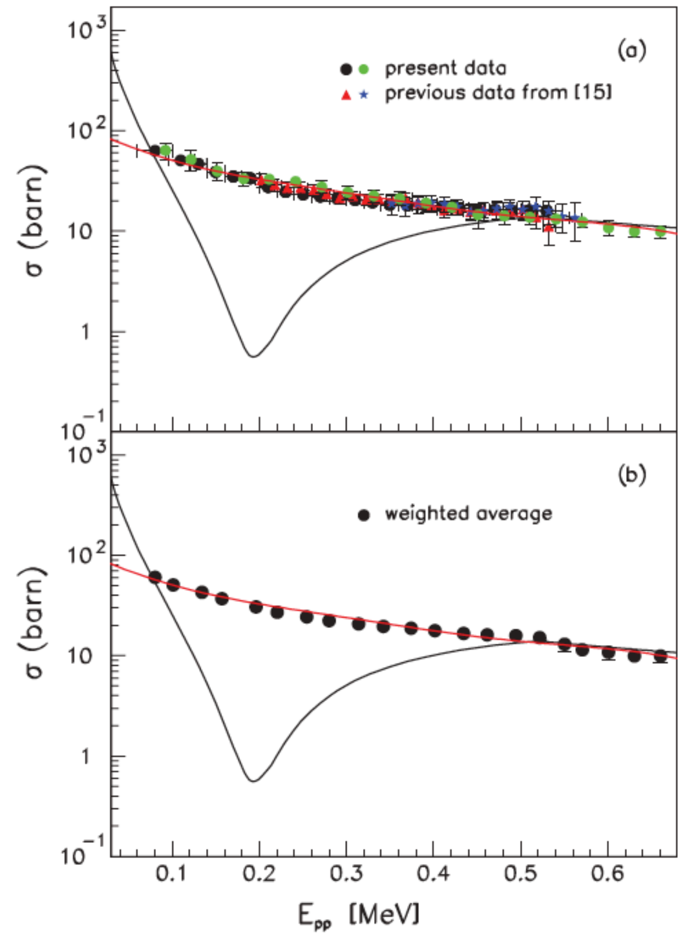
[7]*ATOMKI, Debrecen, Hungary*





Recent TH results: pole-invariance

PHYSICAL REVIEW C **87**, 025805 (2013)

Updated evidence of the Trojan horse particle invariance for the $^{2}H(d, p)^{3}H$ reaction

R. G. Pizzone,[1] C. Spitaleri,[1,2] C. A. Bertulani,[3] A. M. Mukhamedzhanov,[4] L. Blokhintsev,[5] M. La Cognata,[1]
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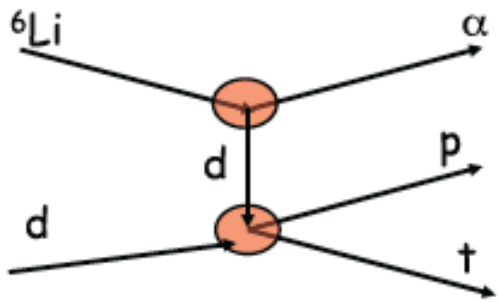
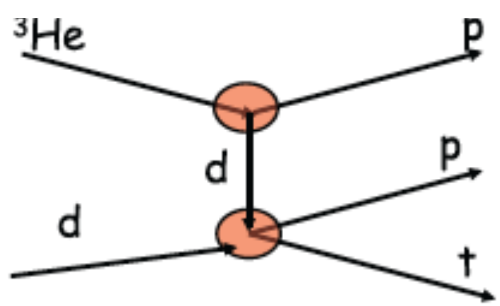
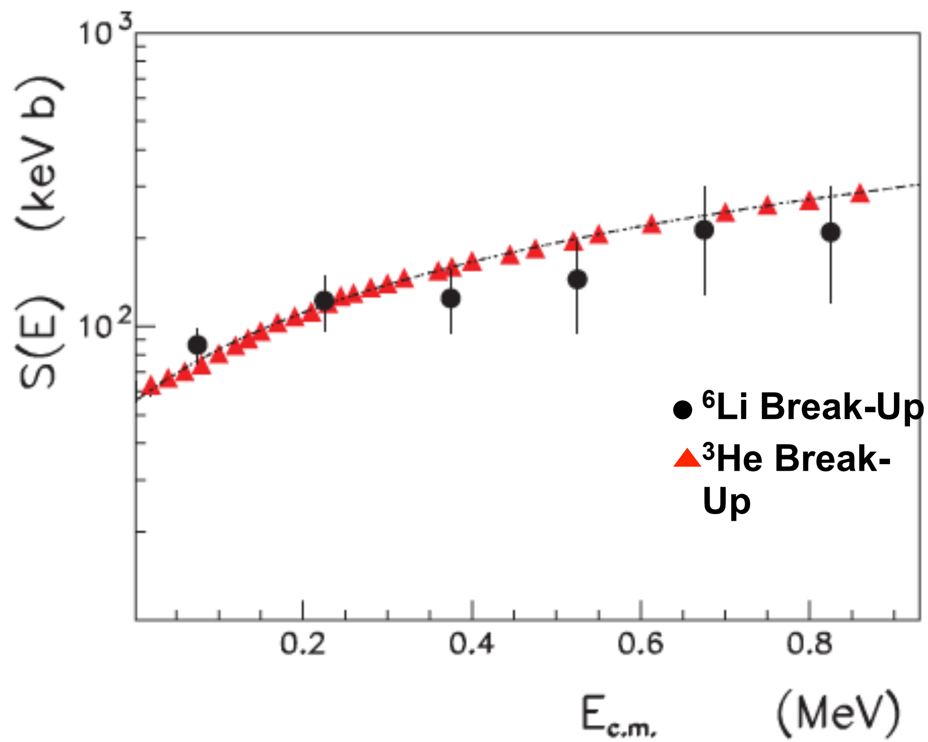
Kore, Enna, Italy



(a)



(b)



Recent TH results: CNO reactions

PHYSICAL REVIEW C **82**, 032801(R) (2010)

New high accuracy measurement of the $^{17}O(p,\alpha)^{14}N$ reaction rate at astrophysical temperatures

M. L. Sergi,[1,*] C. Spitaleri,[1,†] M. La Cognata,[1] A. Coc,[2] A. Mukhamedzhanov,[3] S. V. Burjan,[4] S. Cherubini,[1] V. Crucillá,[1] M. Gulino,[1] F. Hammache,[5] Z. Hons,[4] B. Irgaziev,[6] G. G. Kiss,[1] V. Kroha,[4] L. Lamia,[1,*] R. G. Pizzone,[1] S. M. R. Puglia,[1] G. G. Rapisarda,[1] S. Romano,[1] N. de Séréville,[5] E. Somorjai,[7] S. Tudisco,[1] and A. Tumino[1,‡]

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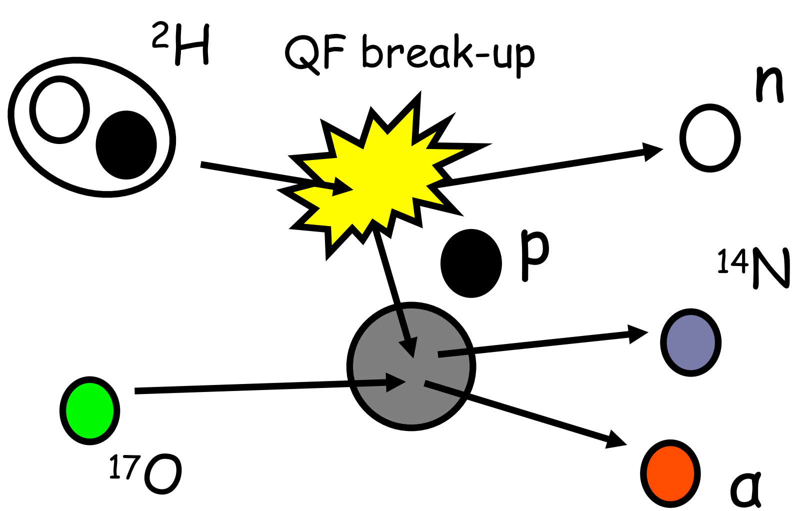

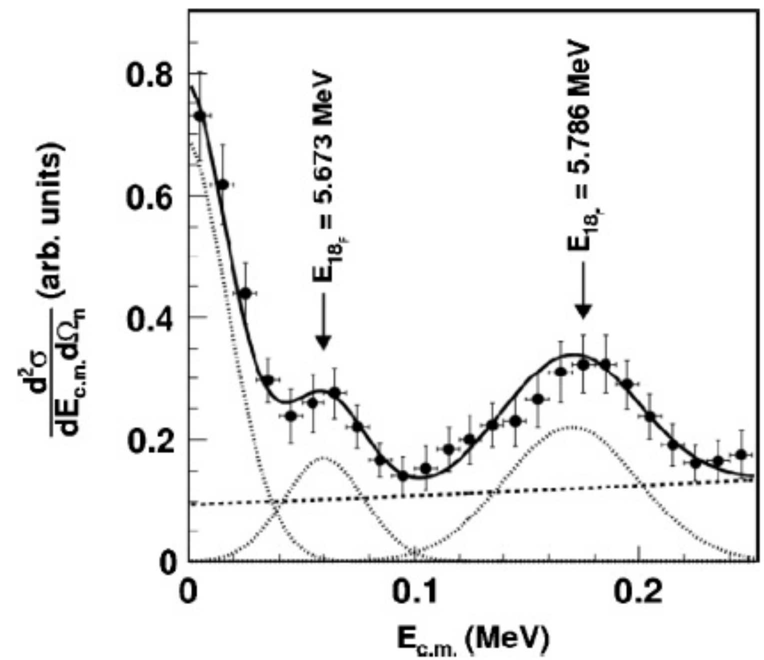

Recent TH results: n-destroying

PHYSICAL REVIEW C **87**, 012801(R) (2013)

Suppression of the centrifugal barrier effects in the off-energy-shell neutron + ^{17}O interaction

M. Gulino,[1,2] C. Spitaleri,[1,3] X. D. Tang,[4] G. L. Guardo,[1,3] L. Lamia,[1,3] S. Cherubini,[1,3] B. Bucher,[4] V. Burjan,[5] M. Couder,[4] P. Davies,[4] R. deBoer,[4] X. Fang,[4] V. Z. Goldberg,[6] Z. Hons,[5] V. Kroha,[5] L. Lamm,[4,*] M. La Cognata,[1] C. Li,[7] C. Ma,[4] J. Mrazek,[5] A. M. Mukhamedzhanov,[6] M. Notani,[4] S. O'Brien,[4] R. G. Pizzone,[1] G. G. Rapisarda,[1,3] D. Roberson,[4] M. L. Sergi,[1,3] W. Tan,[4] I. J. Thompson,[8] and M. Wiescher[4]

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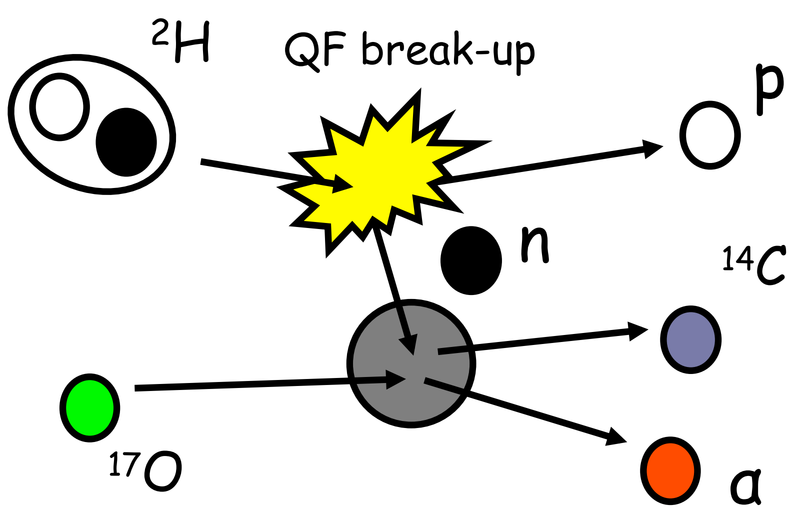

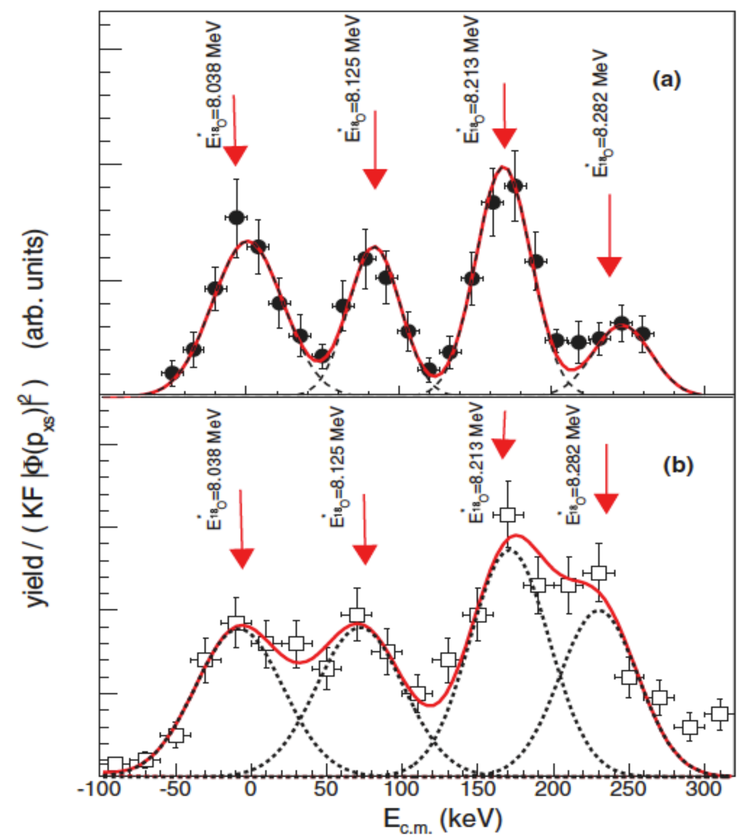

Thank you and see you in Catania…