ITALY – JAPAN 2012
Milano, 20-23 November 2012

NUCLEAR ASTROPHYSICS AT LABORATORI NAZIONALI DEL SUD

Silvio Cherubini
for ASFIN2
20 November 2012

NUCLEAR ASTROPHYSICS

@

CATANIA

LABORATORI NAZIONALI DEL SUD

Silvio Cherubini
CNS-The University of Tokyo
RIKEN Campus, Wako Dec 17th , 2009

Summary

→ Nuclear Astrophysics and Indirect Methods

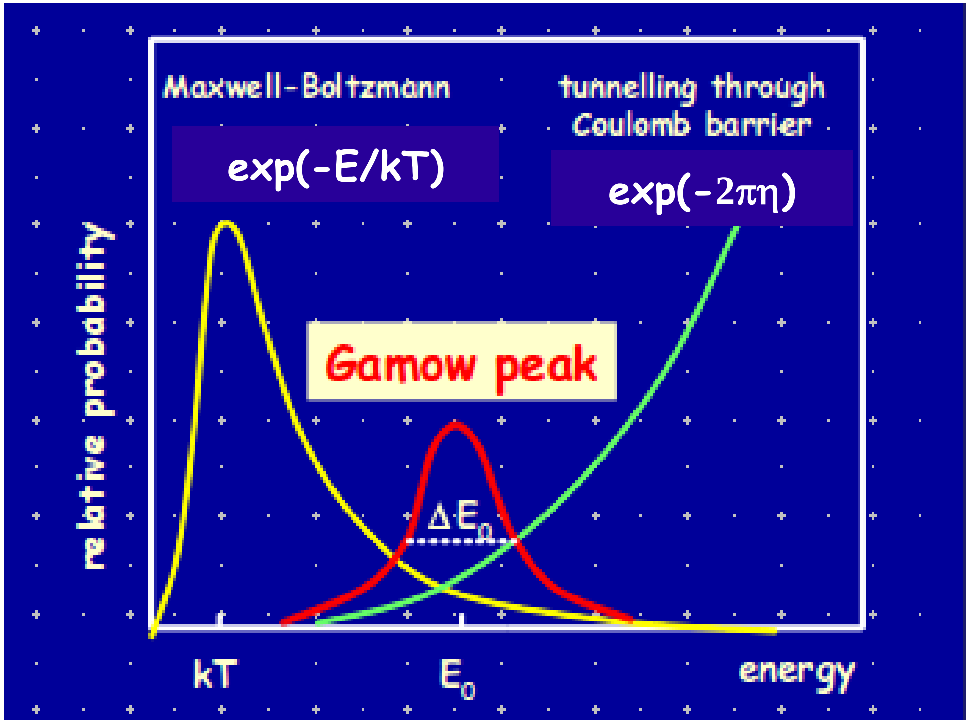
→ Recent applications of THM ^{18}F+p and ^{11}B(p,α)

→ VERY Recent application of VNM

→ Non-THM applications (Big Bang, ^{16}N β–delayed alpha decay)

History of Nuclear Astrophysics in short!

- Eddington, Aston, Gamow, Bethe: “energy production in stars” (1920-1939)
- Gamow introduced the Gamow factor (1928), convoluted with the Maxwell distribution this fixes the typical energy for nuclear reactions in stars

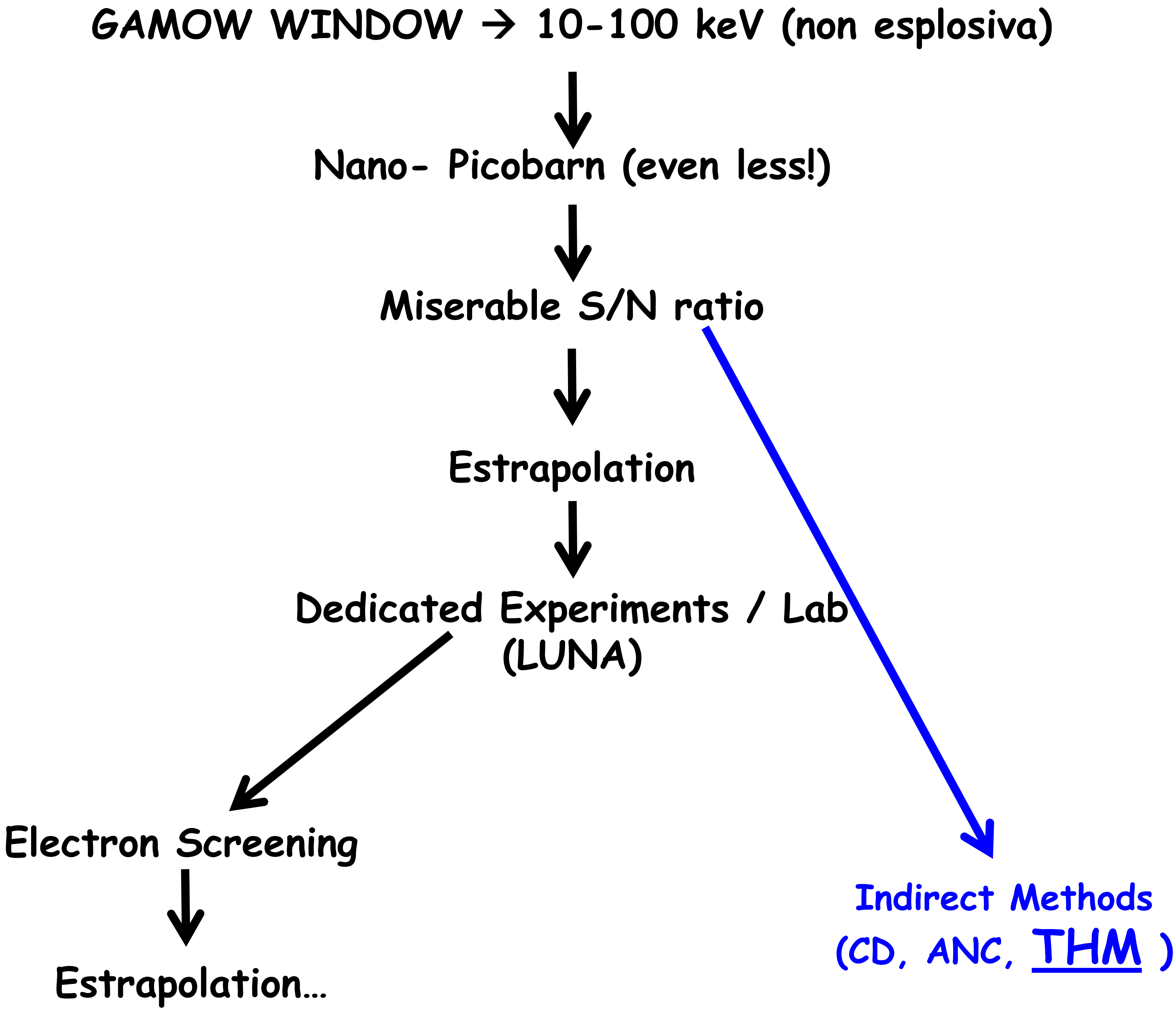


Reaction rate: $r = N_1 N_2 v \sigma(v)$

(# 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)



GAMOW WINDOW → 10-100 keV (non esplosiva)

Nano- Picobarn (even less!)

Miserable S/N ratio

Estrapolation

Dedicated Experiments / Lab
(LUNA)

Electron Screening

Estrapolation...

Indirect Methods
(CD, ANC, THM)

THM: a primer

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

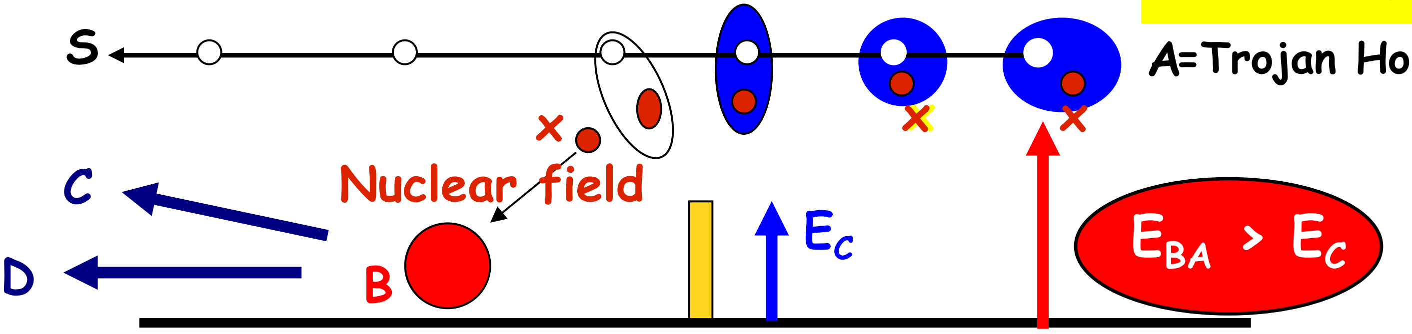
$^{18}F+p\rightarrow{}^{15}O+\alpha$

At astrophysical energies from the QUASI-FREE contribution

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

$^{18}F+d\rightarrow{}^{15}O+\alpha\ +n$

$d = n \otimes p$



A=Trojan Horse nucleus

E_{Bx} = interaction energy B-x

E_C = Coulomb barrier between A and B

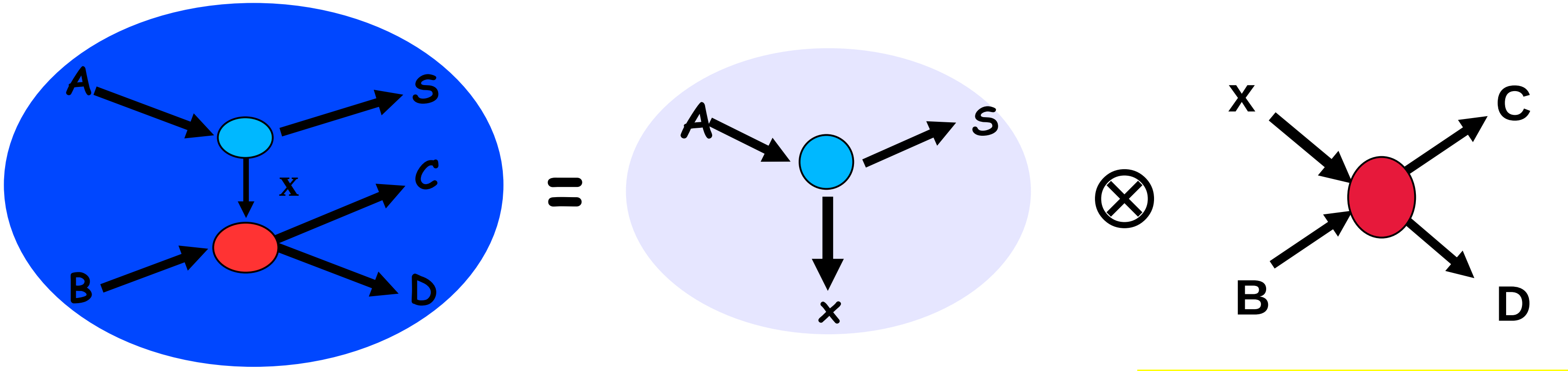
E_{BA} = relative energy between A and B

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

P C P

Electron screening removed by construction

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



3-body Reaction

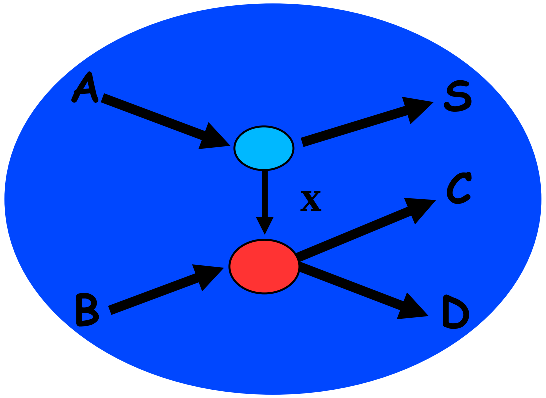
Virtual Decay

Virtual reaction
(astrophysical process)

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

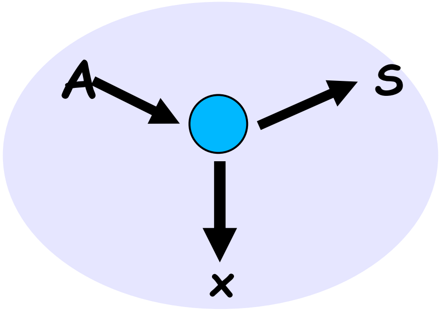
$$E_{Bx} = E_{CD} - Q_{2b}$$

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



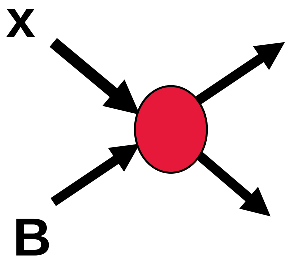
3-body Reaction

$=$



Virtual Decay

$\otimes$



Virtual reaction (astrophysical process)

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

Measured at high energy

Calculated e.g. Montecarlo

Indirectly Measured

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

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 (more in two slides)*
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)

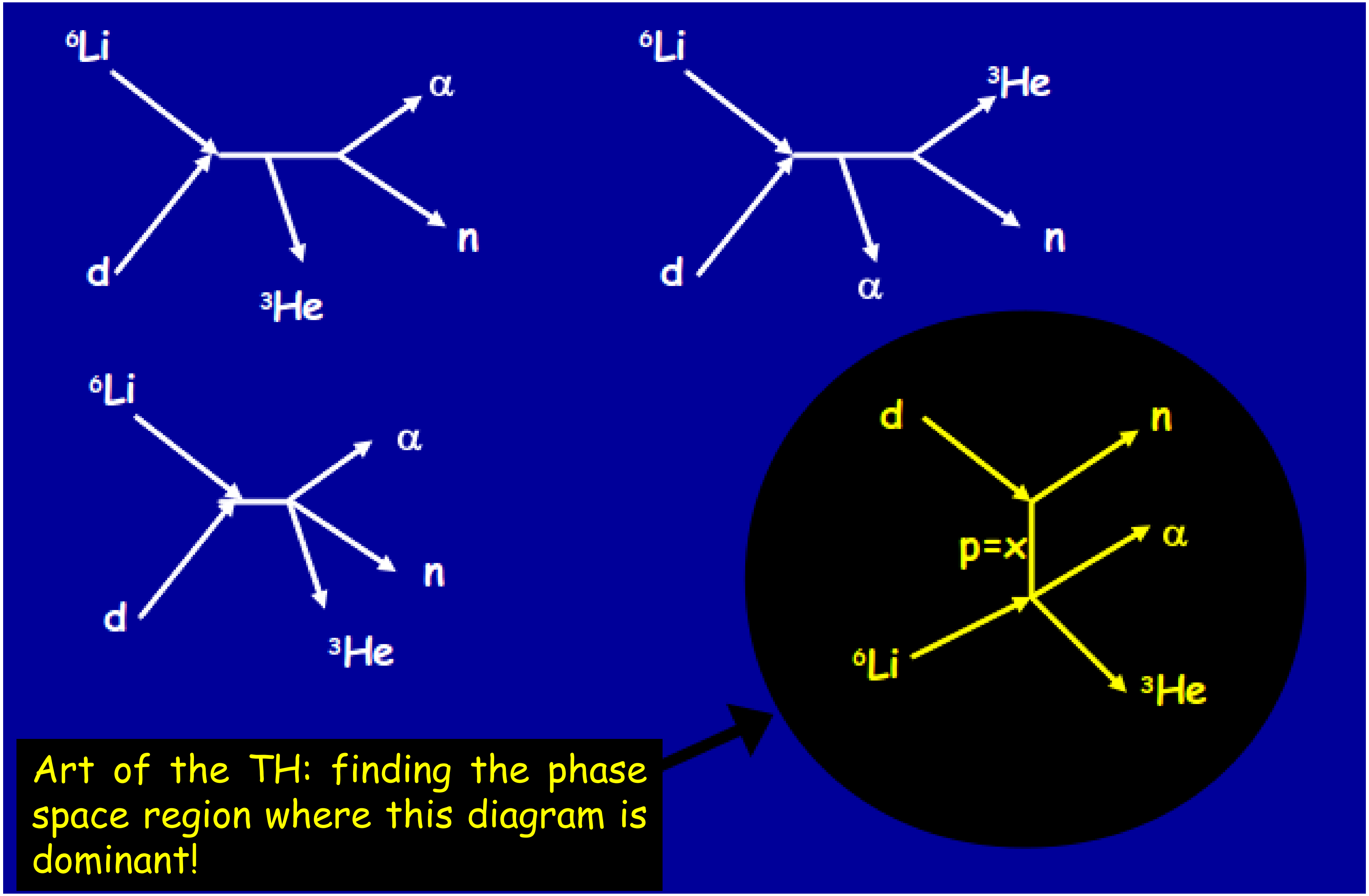
$$\Delta E_{xB} = f(\Delta E_C\ \Delta E_D\ \Delta\theta_C\ \Delta\theta_D)$$

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

3) Avaailability 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

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



Art of the TH: finding the phase space region where this diagram is dominant!

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

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

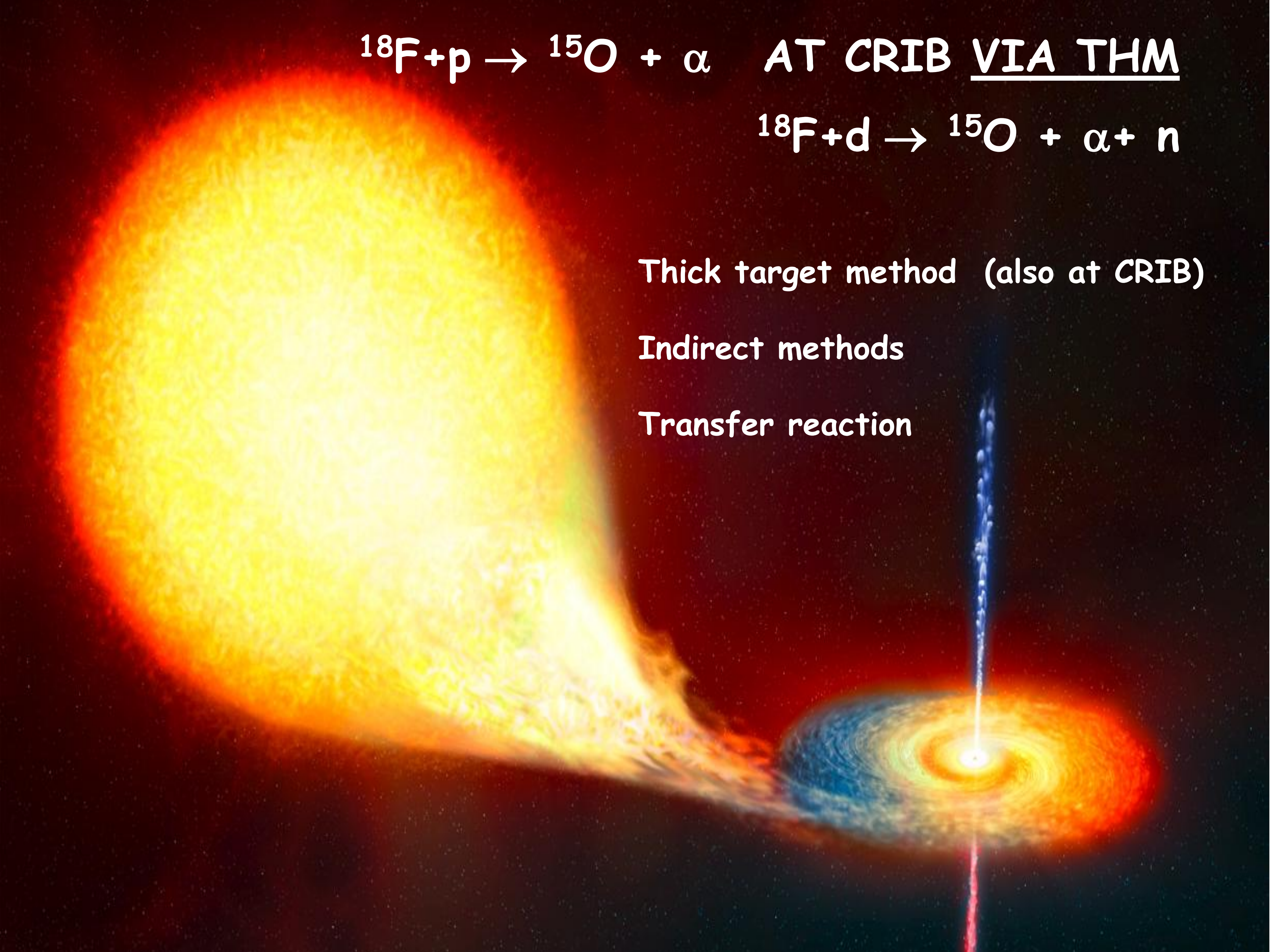
3) No electron screening effect: one can get INDEPENDENT pieces of information on the electron screening potential by comparison with direct data

4) The experimental setup is tipically simple enough

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

$^{18}F+p \rightarrow {}^{15}O + \alpha$ AT CRIB VIA THM

$^{18}F+d \rightarrow {}^{15}O + \alpha + n$

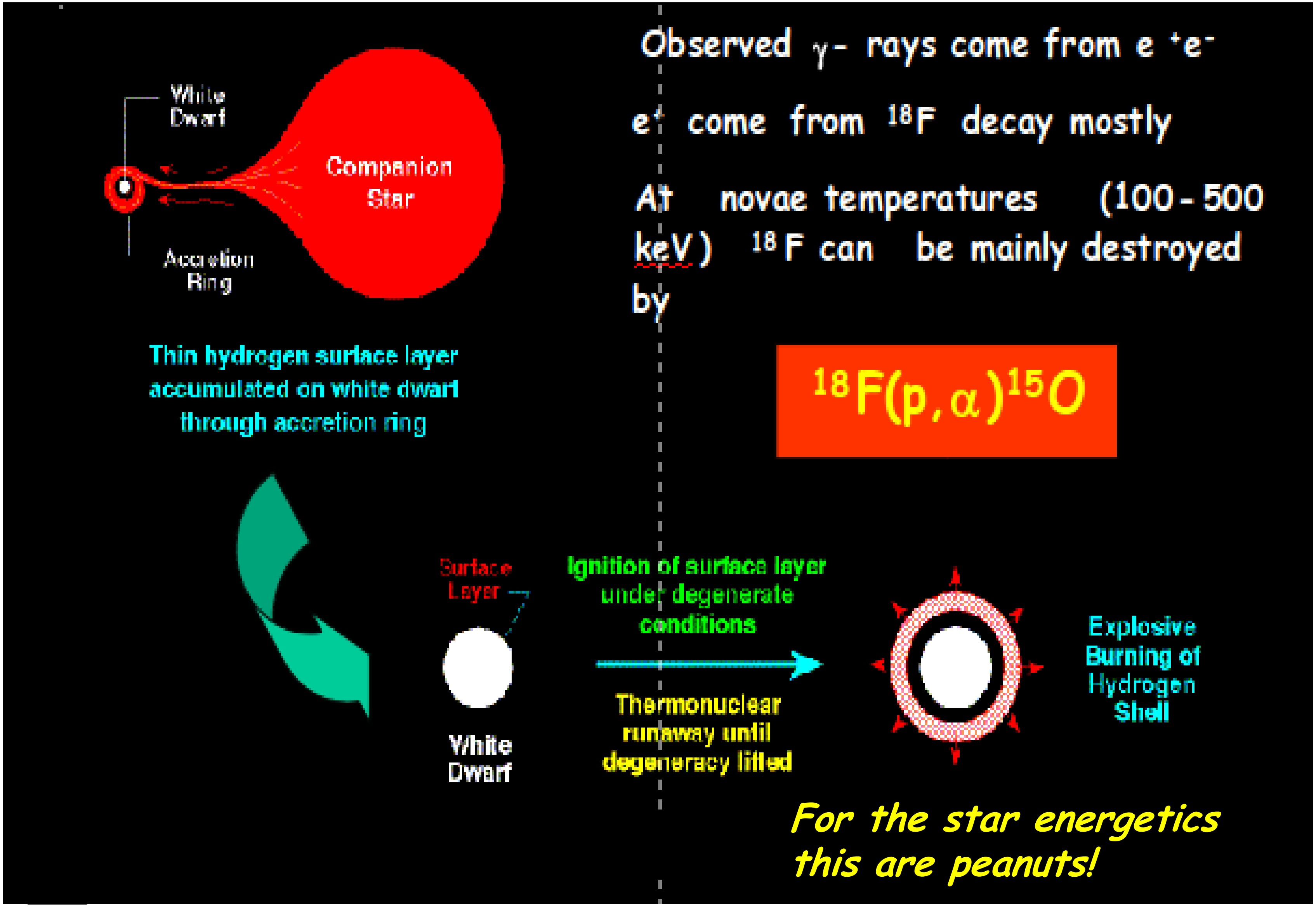


Thick target method (also at CRIB)

Indirect methods

Transfer reaction

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



Observed γ- rays come from e^+e^-

e^+ come from ^{18}F decay mostly

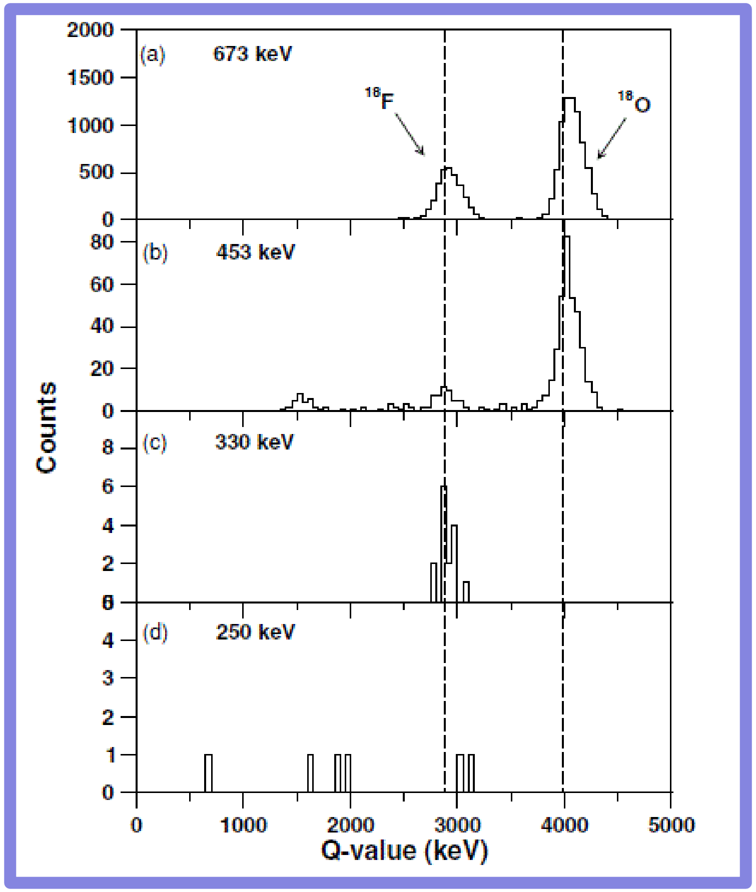
At novae temperatures (100 - 500 keV) ^{18}F can be mainly destroyed by

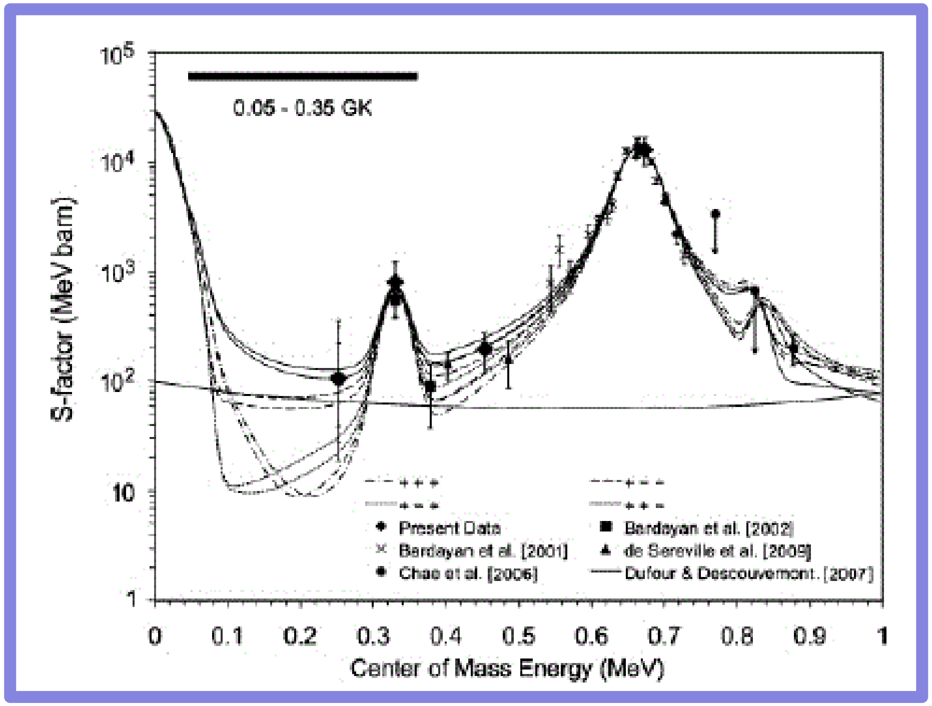
$^{18}F(p,\alpha)^{15}O$

For the star energetics this are peanuts!

STATE OF THE ART DIRECT EXPERIMENT

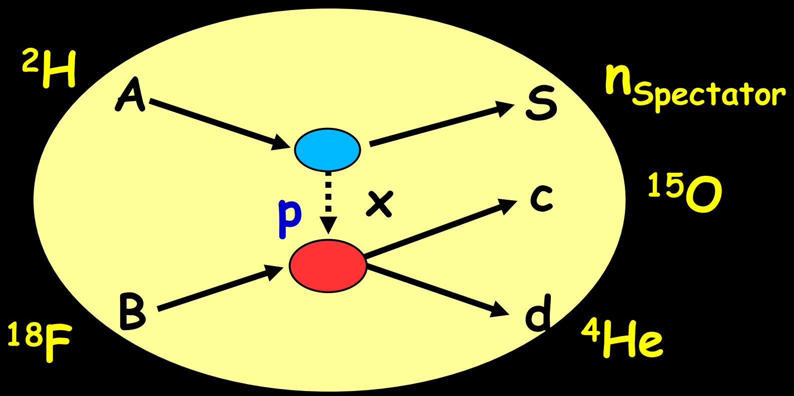
TRIUMF DATA



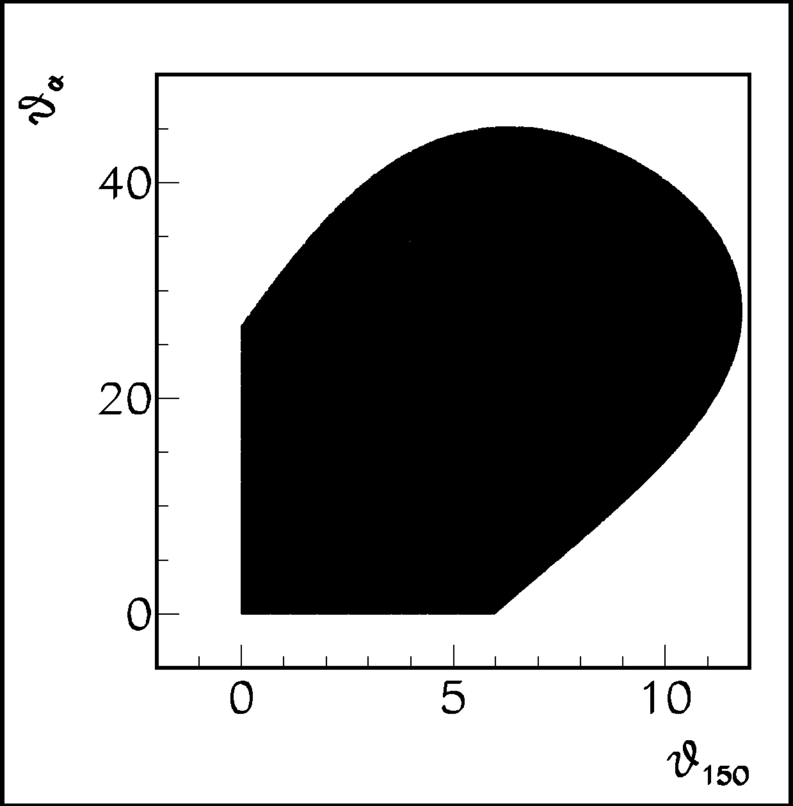


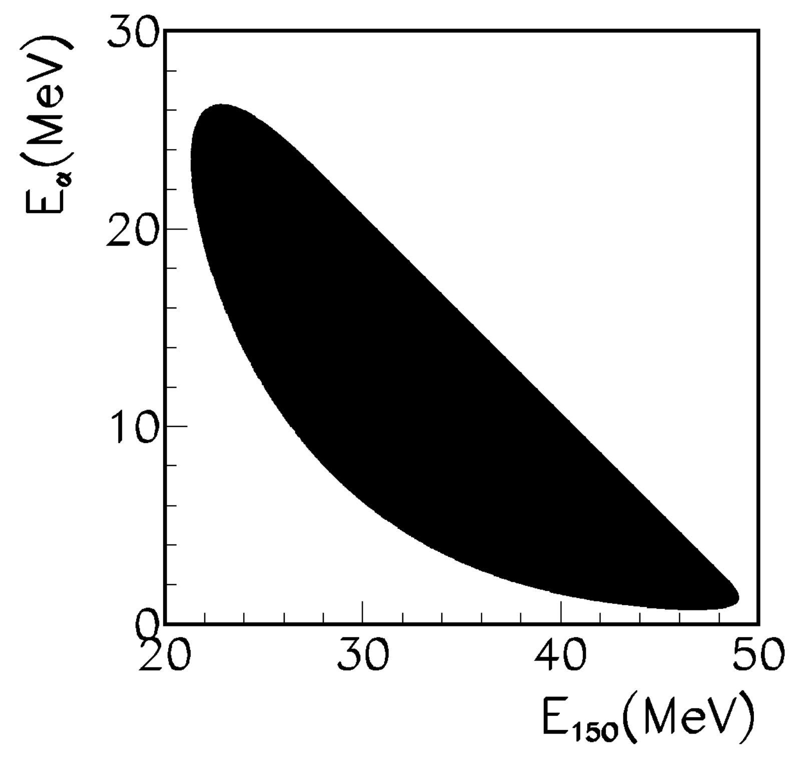
C. E. Beer et al. PHYSICAL REVIEW C 83, 042801(R) (2011)

THM Experiment kinematics… needs all!

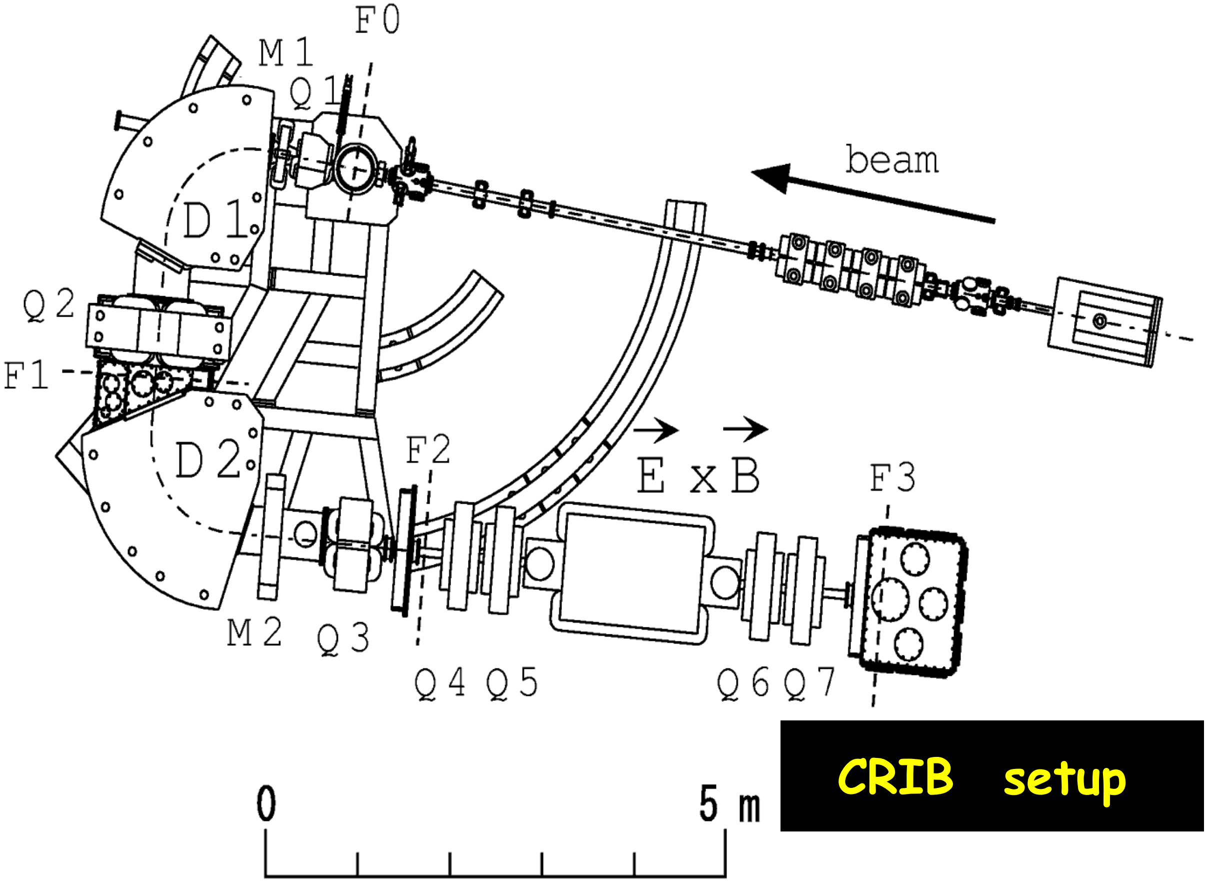


$E(^{18}F) = 50$ MeV





BEAM PRODUCTION AT CRIB

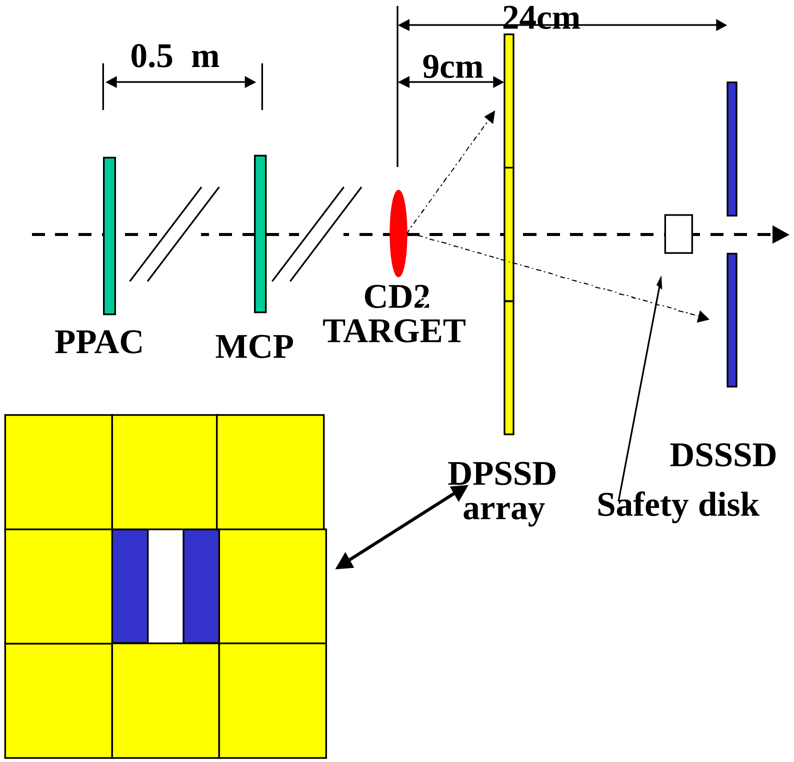


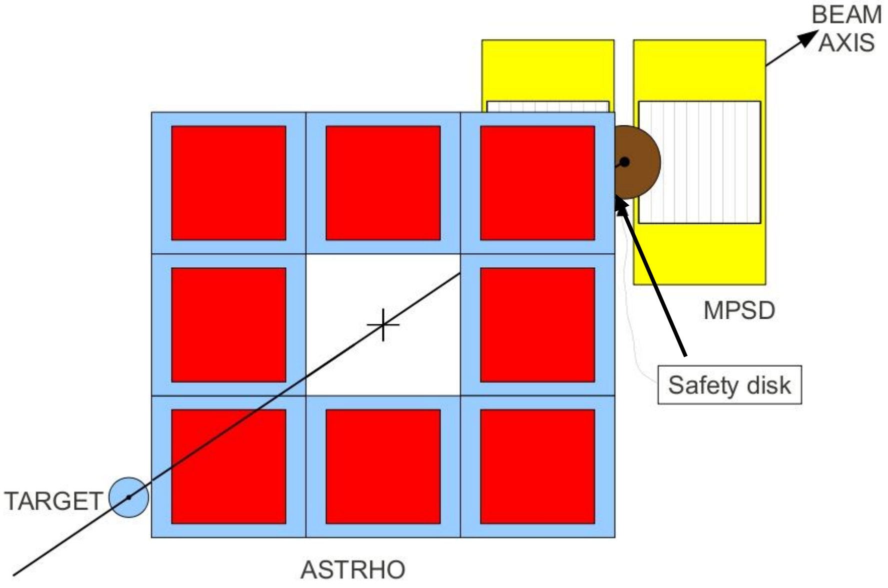
CRIB setup

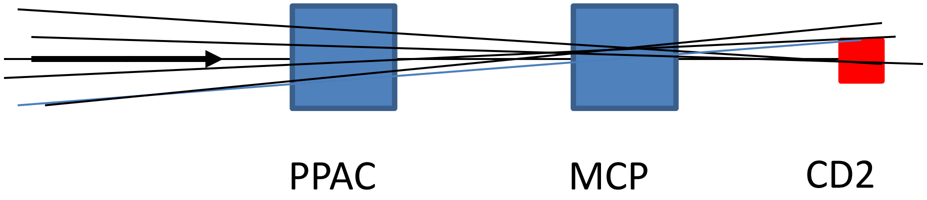
1. Two beam production tests performed (Nov 2005, June 2006)
2. 3*10^5 pps obtained, 10^6 pps within the capabilities of the machine
3. Beam purity > 98%
4. Normalization and deffinitionof the beam particle by particle (PPACs)

EXPERIMENTAL SETUP

(other then CRIB.....)

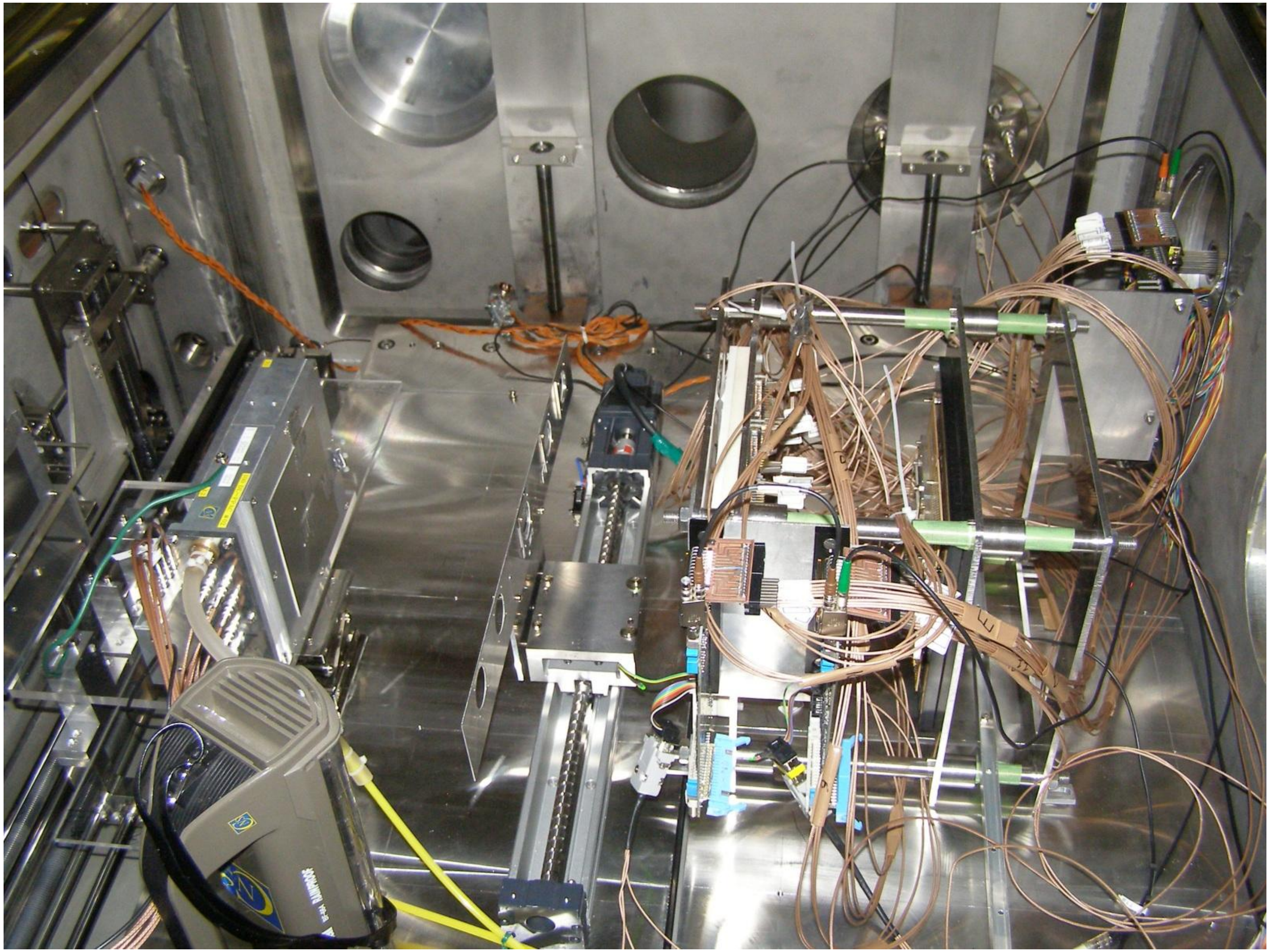






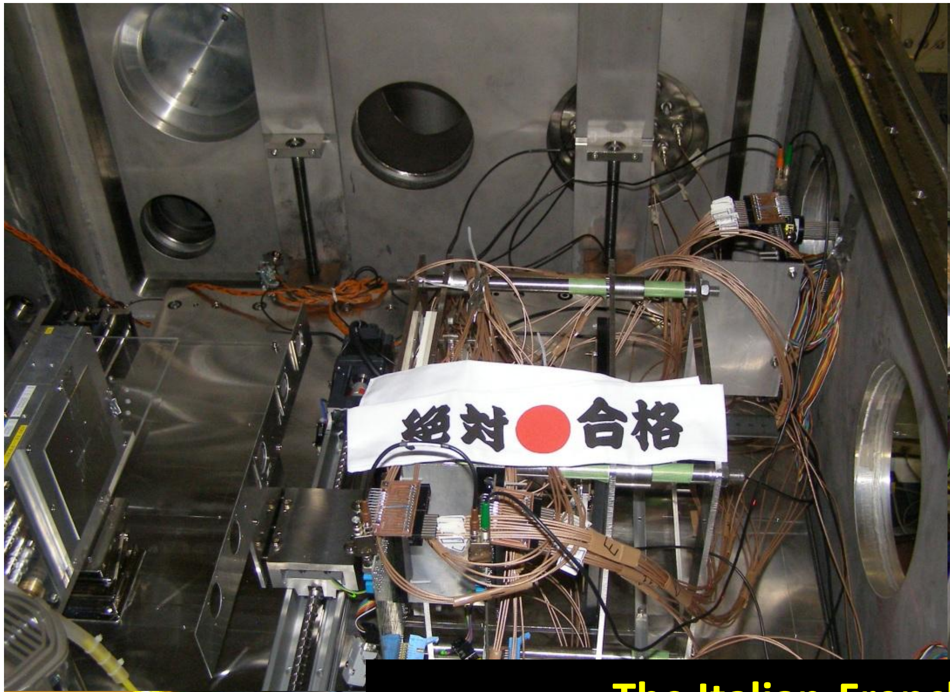
particle by particle beam reconstruction

ASTRHO:
Array of Silicons for TRojan HOrse



How ASTRHO looks like in reality
(before PPAC explosion...)

The Italian-French-Japanese connection



Q-VALUE SPECTRUM

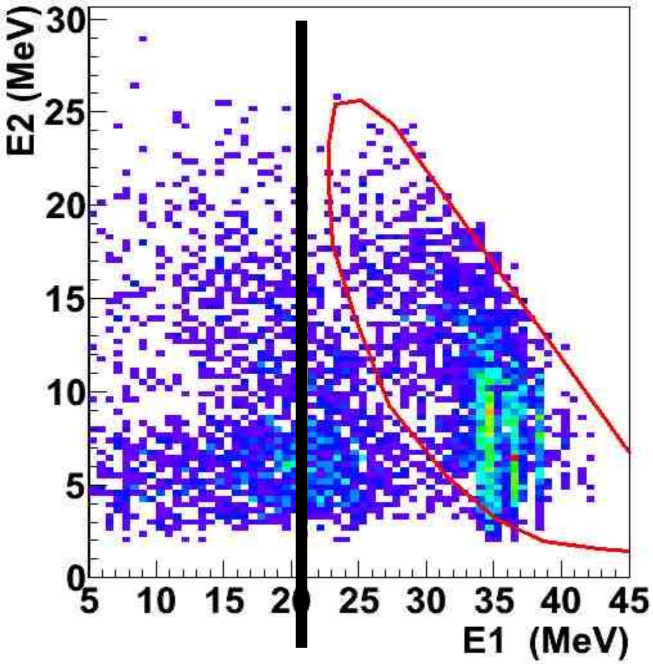
$^{18}F+d \rightarrow {}^{15}N+\alpha+p$ @ q=4.194

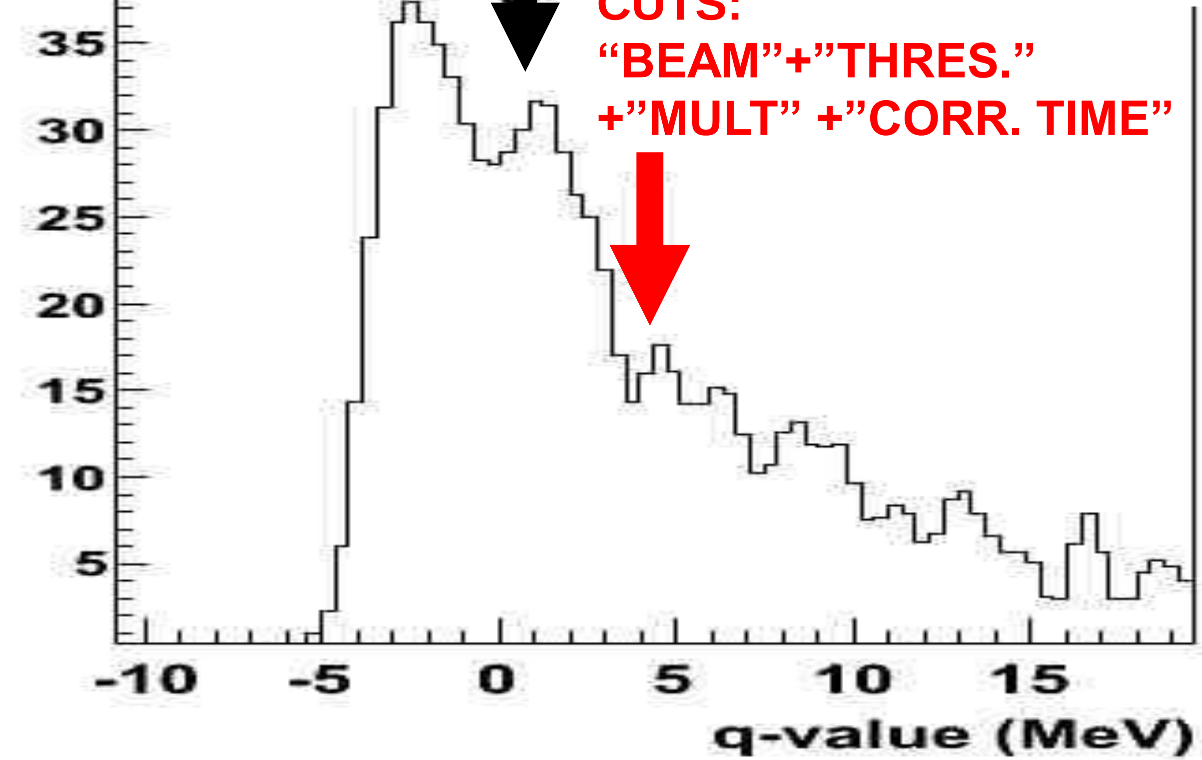
$^{18}F+d \rightarrow {}^{15}O+\alpha+n$ @ q=0.658

$^{18}F+d \rightarrow {}^{18}O+p+p$ @ q=0.213

$^{18}F+d \rightarrow {}^{18}F+p+n$ @ q=-2.225

VNM+RIB!!!





DETECTOR PAIRS:
8-1;7-1
CUTS:
"BEAM"+"THRES."
+"MULT" +"CORR. TIME"

EVENT SELECTION

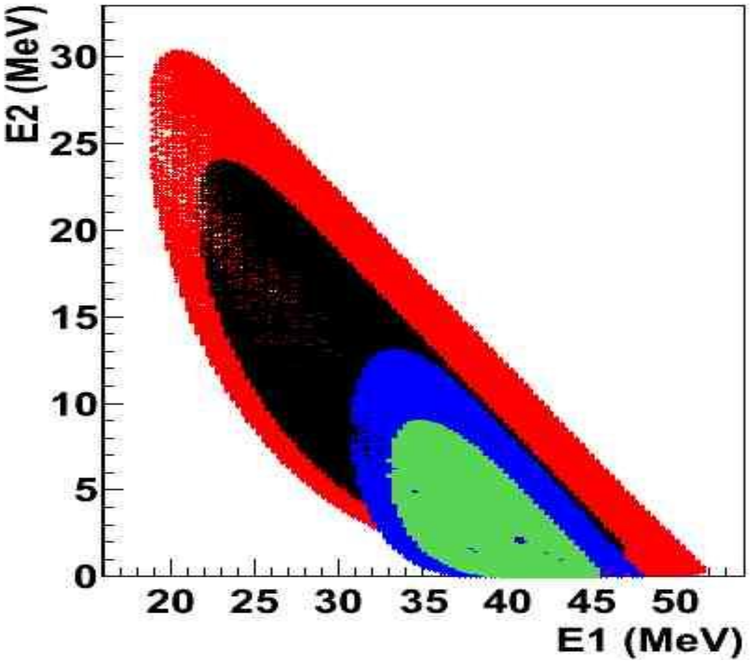
Red : ^{18}F + d → ^{15}N + α + p

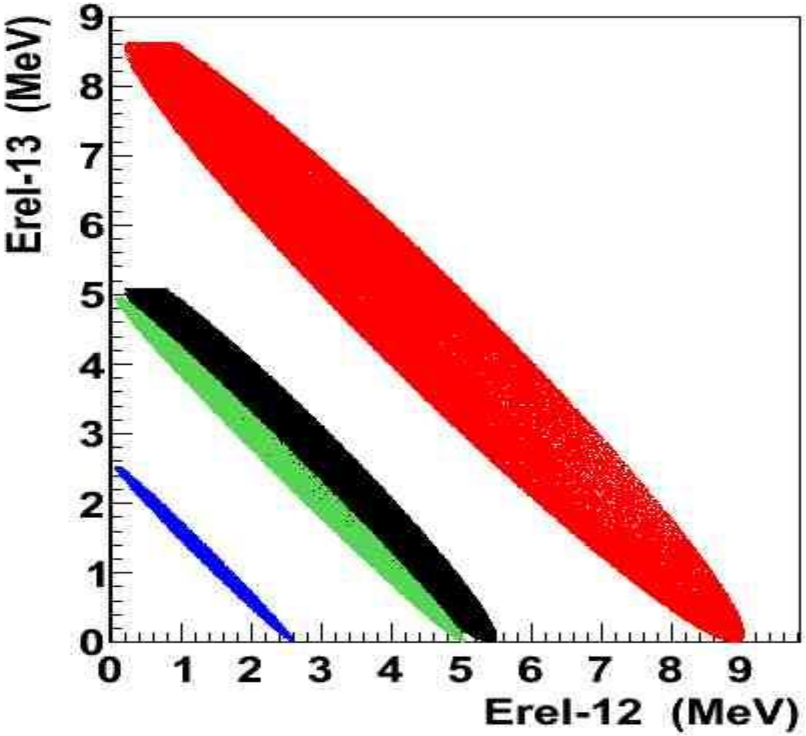
Black: ^{18}F + d → ^{15}O + α + n

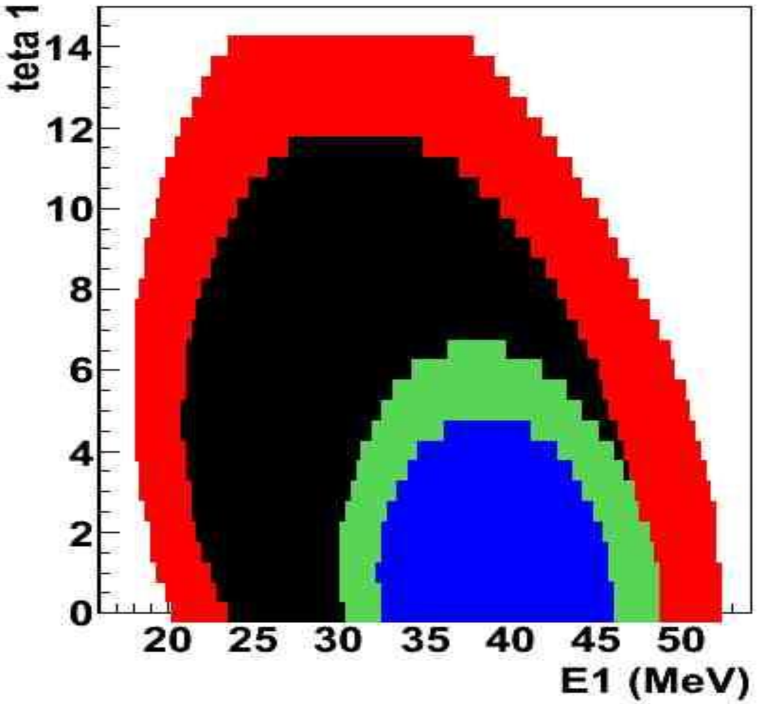
Blue: ^{18}F + d → ^{18}F + p + n

Green: ^{18}F + d → ^{18}O + p + p

“1”+“2”+“3”

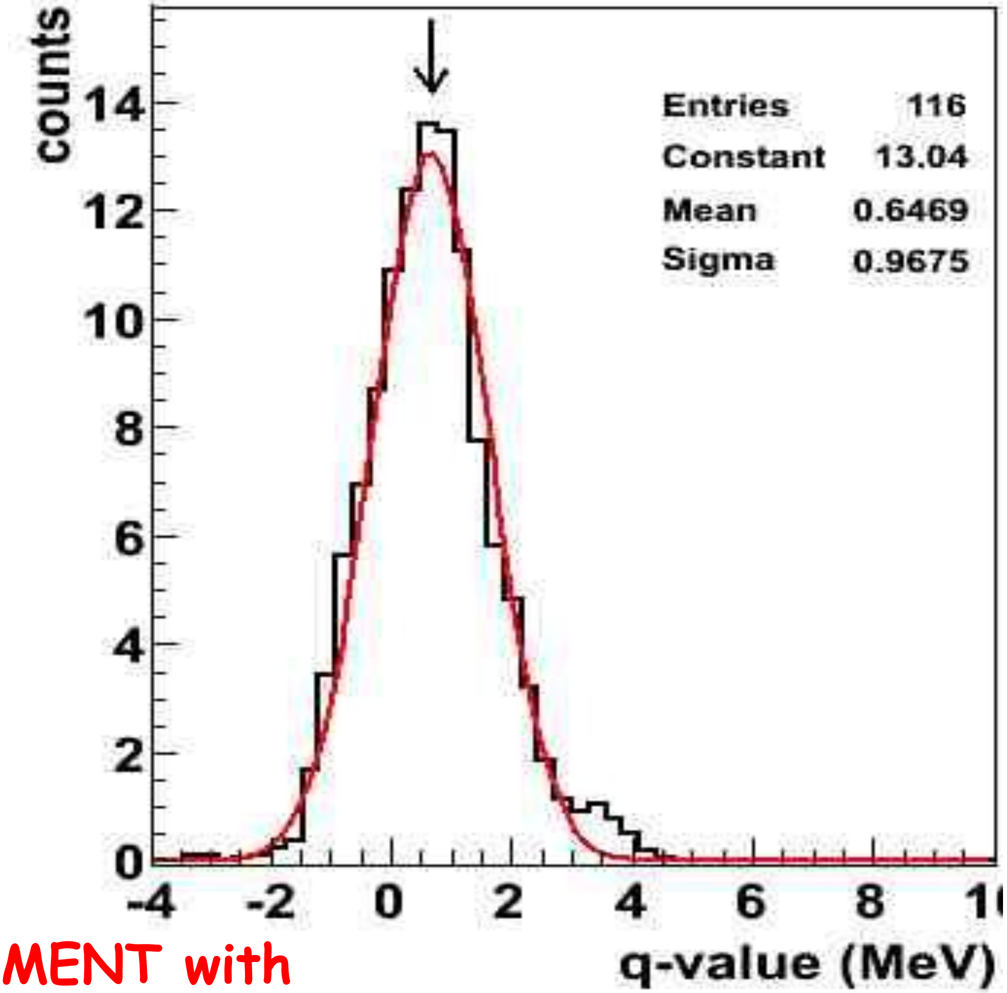






Q-VALUE SPECTRUM

Previous cuts + Erel-Erel correlation +E-Theta correlation

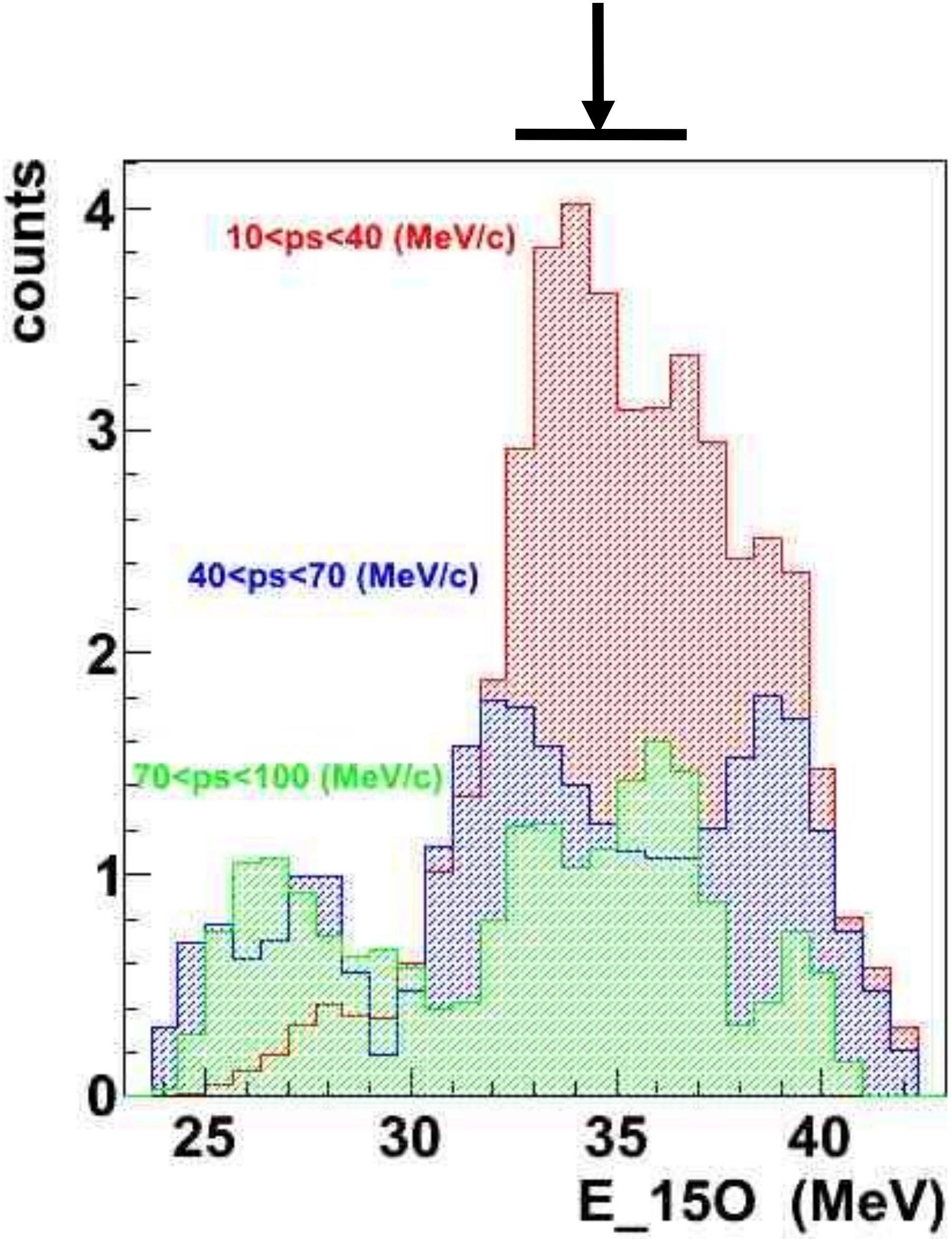


GOOD AGREEMENT with

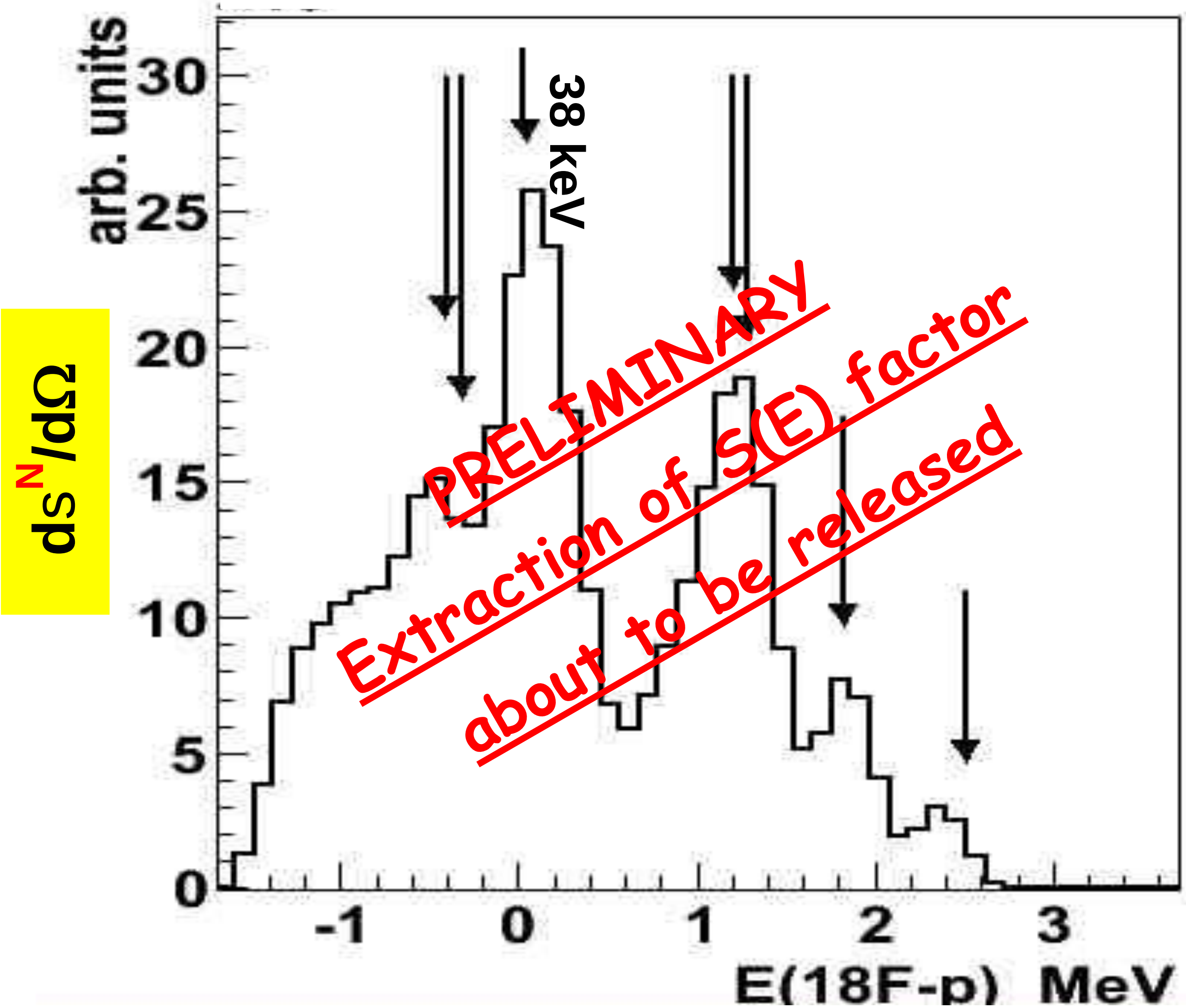
Q-value expected position (0.658 MeV)

And energy beam profile (exp. Sigma 0.8 MeV)

HINTS FOR QF MECHANISM



BARE NUCLEUS CROSS SECTION



PRELIMINARY

Extraction of S(E) factor about to be released

FIRST TROJAN HORSE MEASUREMENT WITH RIBs !!!

$^{11}B(p,a_0)^8Be$ via $^{11}B(d,a_0\,^8Be)n$

L. Lamia et al.

among «al.»:
S. Kubono,
Y. Wakabayashi,
H. Yamaguchi

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015106 L Lamia *et al*

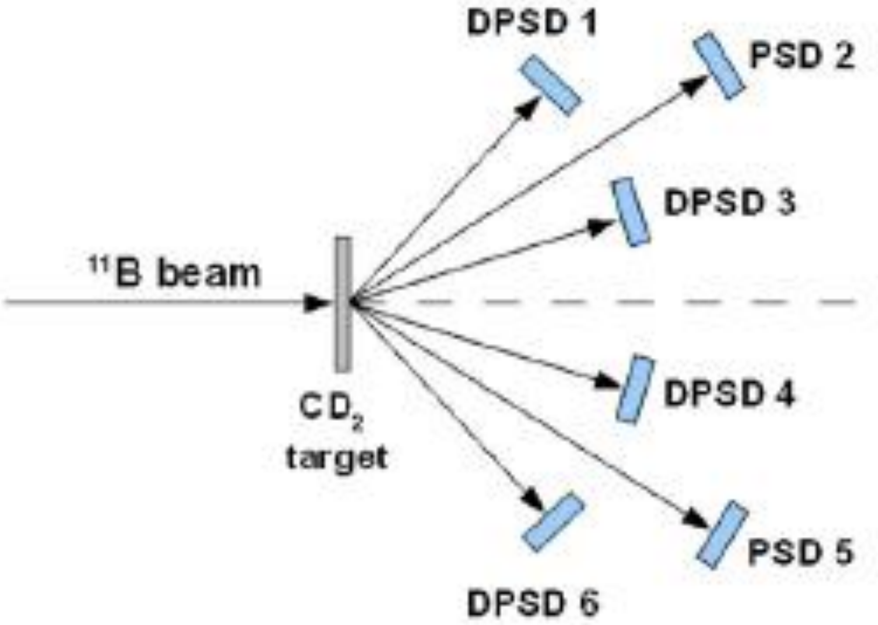


Figure 2. Sketch of the experimental setup discussed in the text. A 27 MeV ^{11}B beam impinges on a CD_2 ~ 170 $\mu g\ cm^{-2}$ thick target. The outgoing ^8Be and α particles were detected by means of DPSD and PSD detectors, respectively. The displacement of the setup inside the CAMERA 2000 scattering chamber was chosen in order to cover the QF angular range predicted by kinematical calculations.

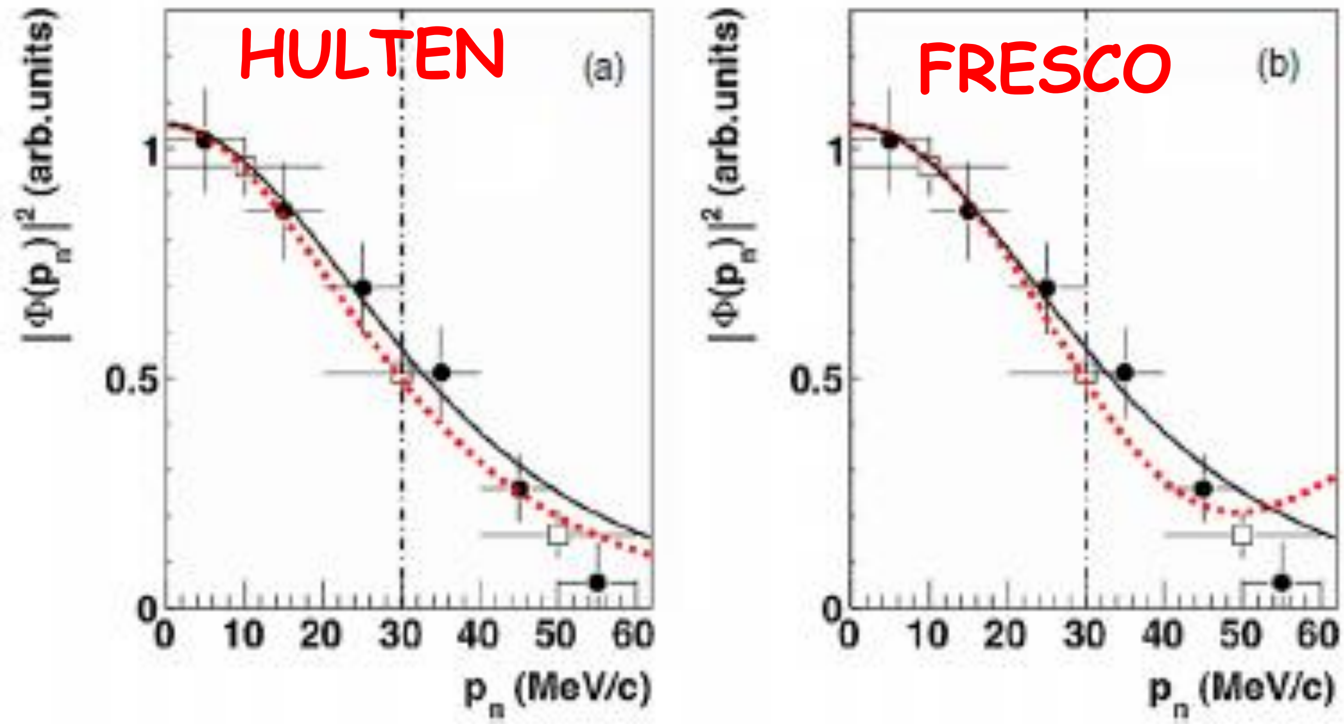


Figure 9. (a) The experimental momentum distribution (full circles and open squares) with their fit (black solid line) compared with the square of the theoretical Hulthén function, in momentum space, in the PWIA (red dashed line). (b) The same experimental momentum distribution (full circles and open squares) with their fit (black solid line) compared with the DWBA momentum distribution evaluated using the FRESCO code (red dashed line). The vertical dot-dashed lines, in both panels, mark the position of the strict selection on the experimental data needed for the TH application (see the text and [50]).

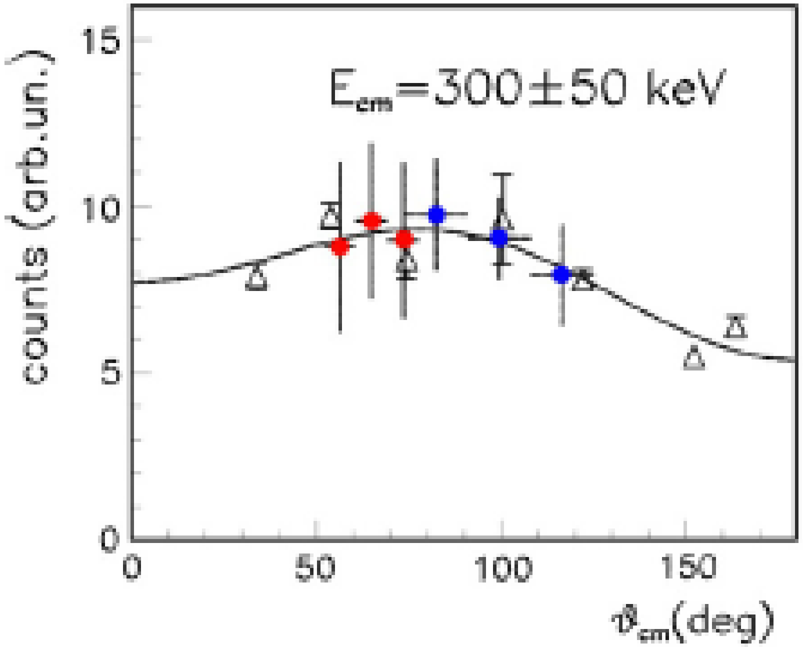


Figure 11. Experimental angular distributions at the energy $E_{\rm cm} = 300 \pm 50$ keV. The full dots are the THM data extracted from the experiment discussed in the text (red points) and those from a previous THM experiment (blue points). The error bars include only the statistical errors. The empty triangles are the direct data of [28] while the full line represents their fit by means of Legendre polynomials [28].

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015106 L Lamia *et al*

S(E) by THM

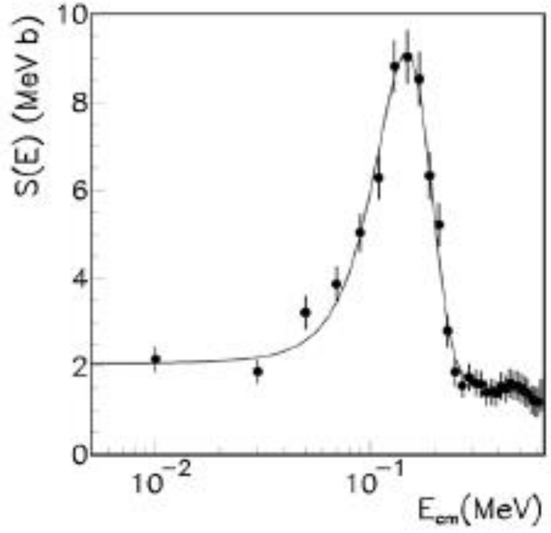


Figure 14. $S(E)$-factor for the $^{11}B(p,\alpha_0)^8Be$ reaction extracted by means of the THM (black points) with its fit given in terms of equation (11).

S(E) by THM vs Direct measurement → electron screening extraction

U_e^{THM} =472+-160 eV

U_e^{dir} =430+-80 eV

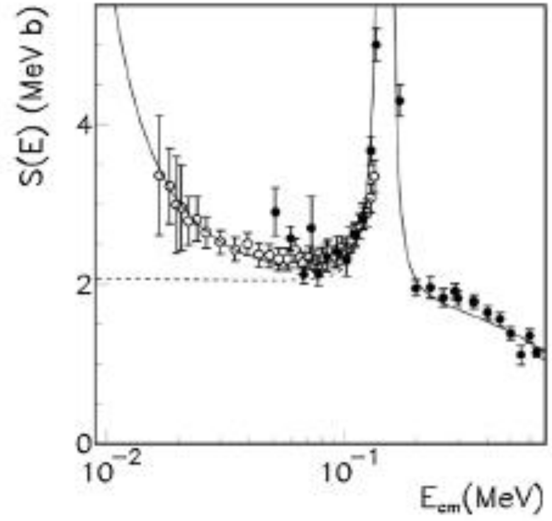
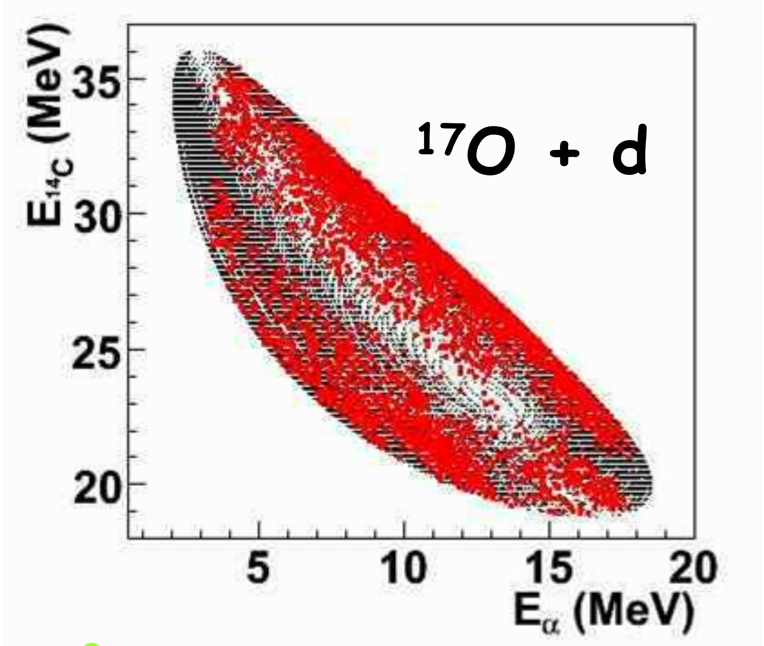
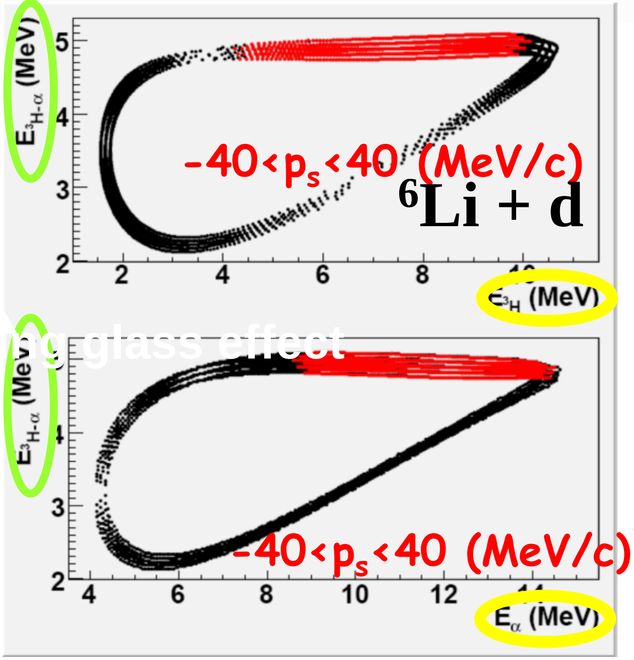


Figure 15. Experimental data from [29] (empty circles) 're-scaled' to the experimental data from [28], shown as full circles. The dotted line represents the bare nucleus $S(E)$-factor from equation (13) while the full line is the results of our fit taking into account the exponential increase due to the presence of the electron screening potential (see text for details).

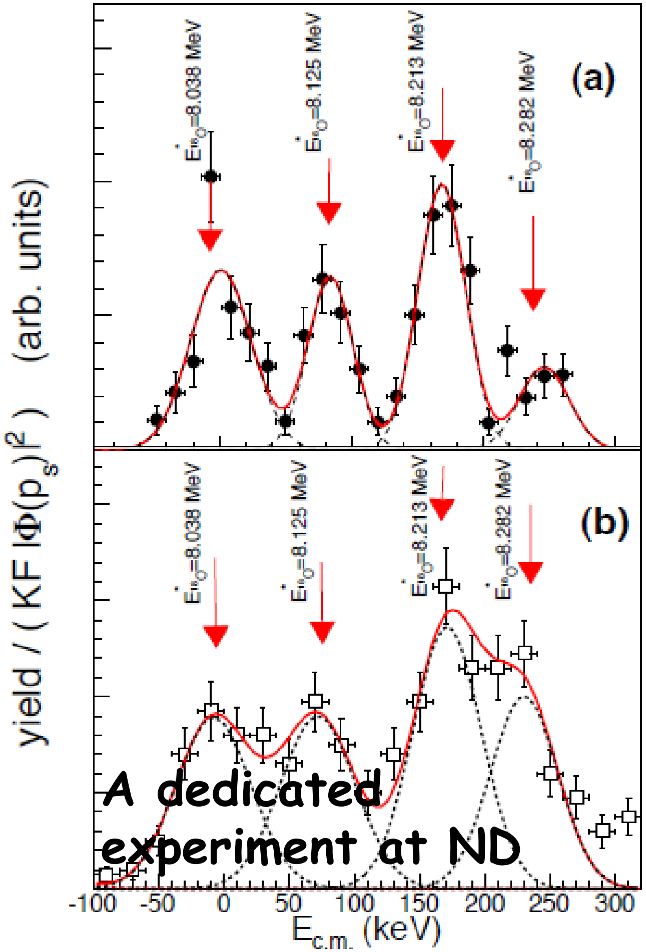
V N M: $^{17}O(n,\alpha)^{14}C$ via $^{17}O + d \rightarrow \alpha + ^{14}C + p$

VIRTUAL neutron source

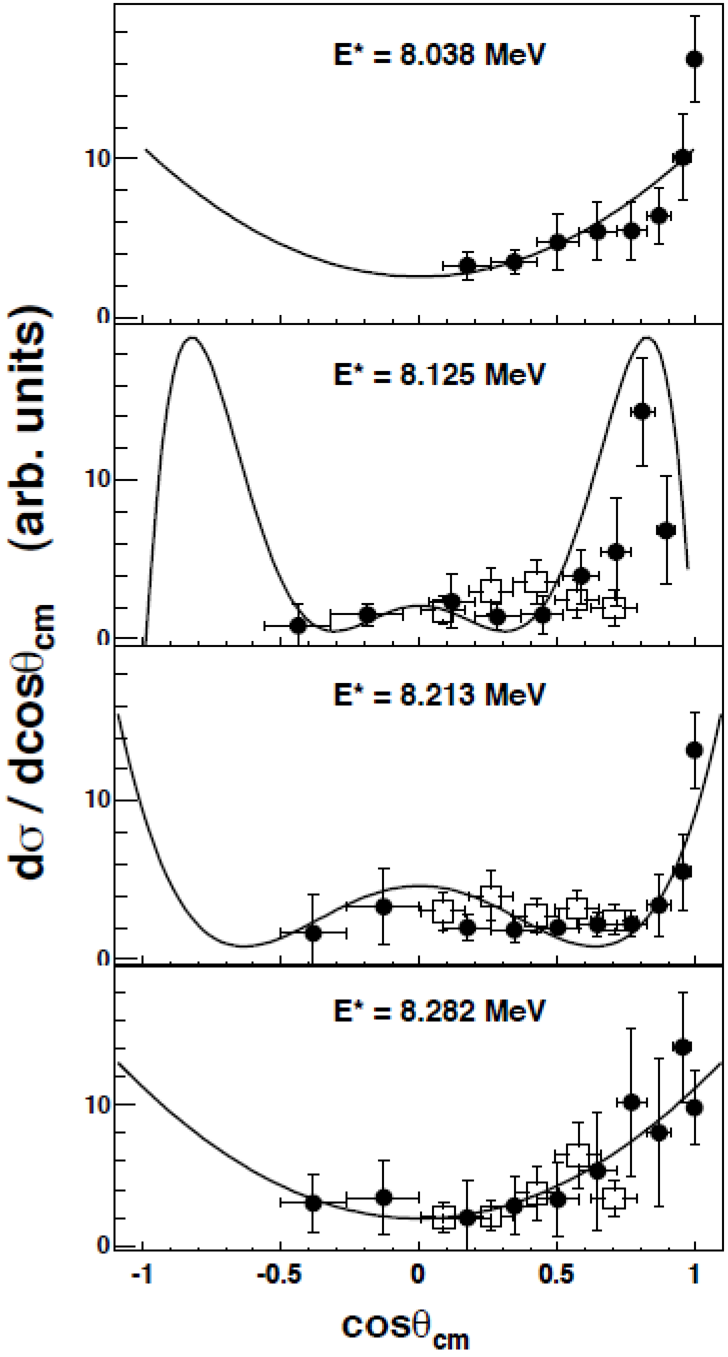




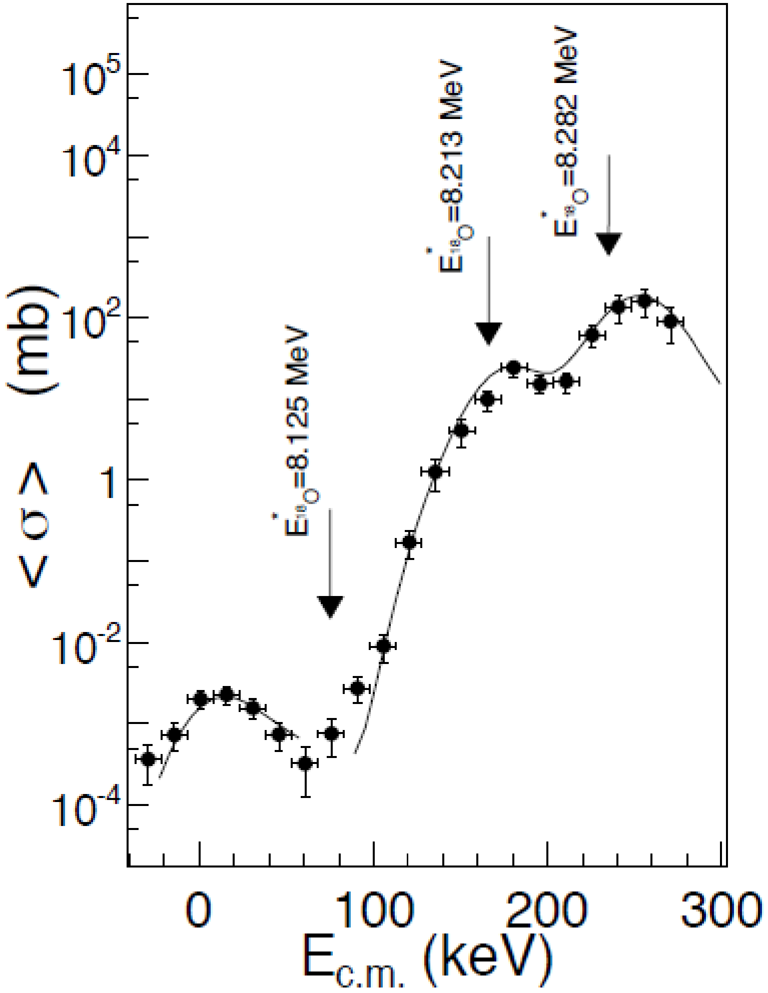
A parasitic experiment performed @ LNS, Catania



A dedicated experiment at ND



angular distributions



Gulino et al. accepted for publication on PRC Rapid Communication today!!!

Univ. Catania and INFN-LNS:
C. Spitaleri, S. C., L. Guardo, *M. Gulino*, S. Hayakawa, I. Indelicato, M. La Cognata, L. Lamia,R.G. Pizzone, S. Puglia, G.G. Rapisarda, S. Romano, M.L. Sergi, R. Spartà, *A. Tumino*

CNS, The University of Tokyo:
S. Kubono, H. Yamaguchi, Y. Wakabayashi, D.N. Binh,

RIKEN, Tohoku-, Tsukuba-, Yamagata-, Kyushu- University:
N. Iwasa, S. Kato, H. Komatsubara, S. Nishimura, T. Teranishi

CSNSM, IN2P3/CNRS and Université Paris Sud:
A. Coc, N. de Séréville, F. Hammache

Texas A&M University
R. Tribble, A. Mukhamedzanov, L. Trache

RUB: Claus Rolfs

...I apologize with those
I surely forgot!

Direct Measurements and inhomogeneous Big Bang

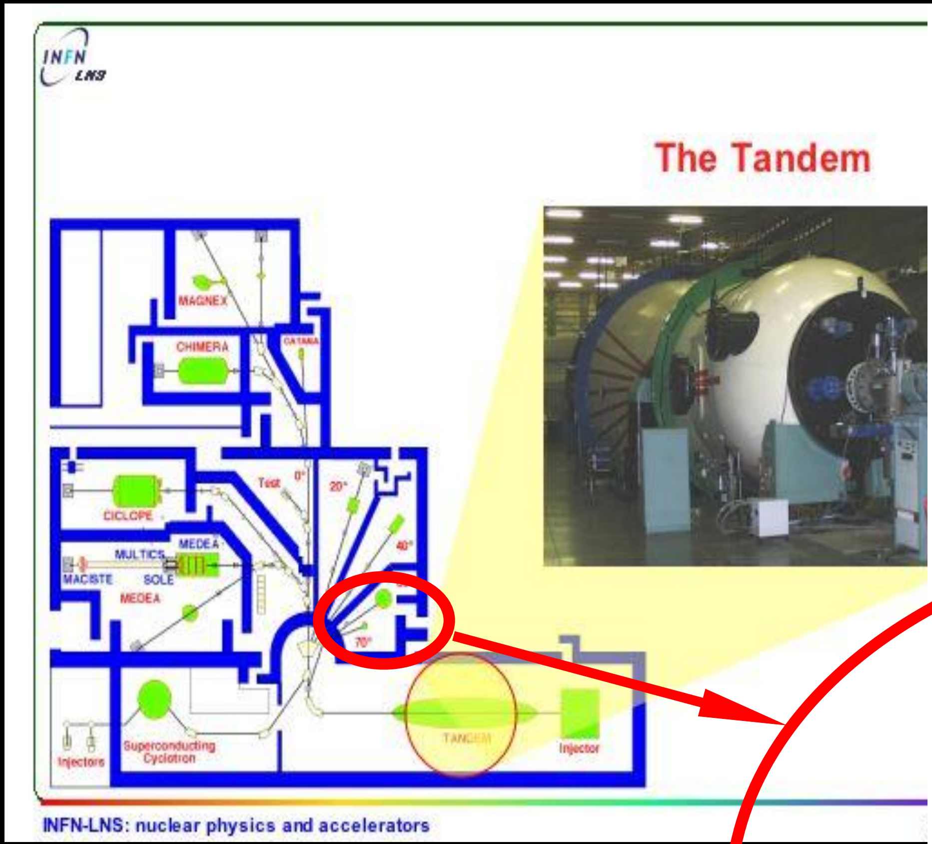
LINCHPINS OF BIG BANG:

expansion, Cosmic Microwave Background, primordial nucleosynthesis…

BIG BANG SCENARIOS (depending on the phase transition from QGP to Hadronic Universe):

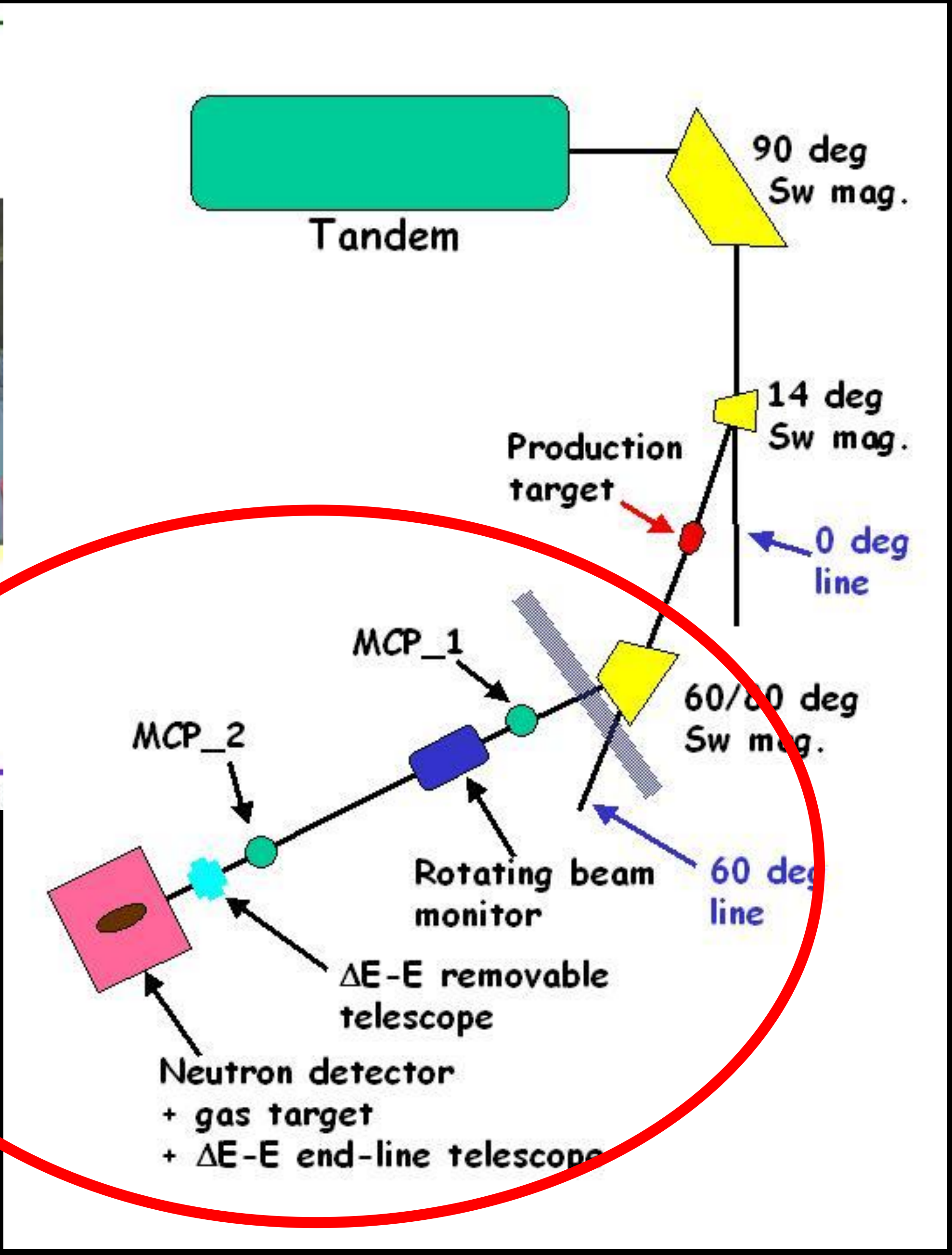
- **HOMOGENOUS Big-Bang**
  - **synthesis of elements stops at lithium**
- **INHOMOGENEOUS Big-Bang**
  - **much wider set of primordial elements (up to carbon)**
  - **via the reaction chain:**

$${}^{1}H(n,\gamma){}^{2}H(n,\gamma){}^{3}H(d,n){}^{4}He(t,\gamma){}^{7}Li(n,\gamma)\boxed{{}^{8}Li(\alpha,n){}^{11}B}(n,\gamma){}^{12}B(\beta\nu){}^{12}C$$



The Tandem

INFN-LNS: nuclear physics and accelerators



EVERYTHING OK ?

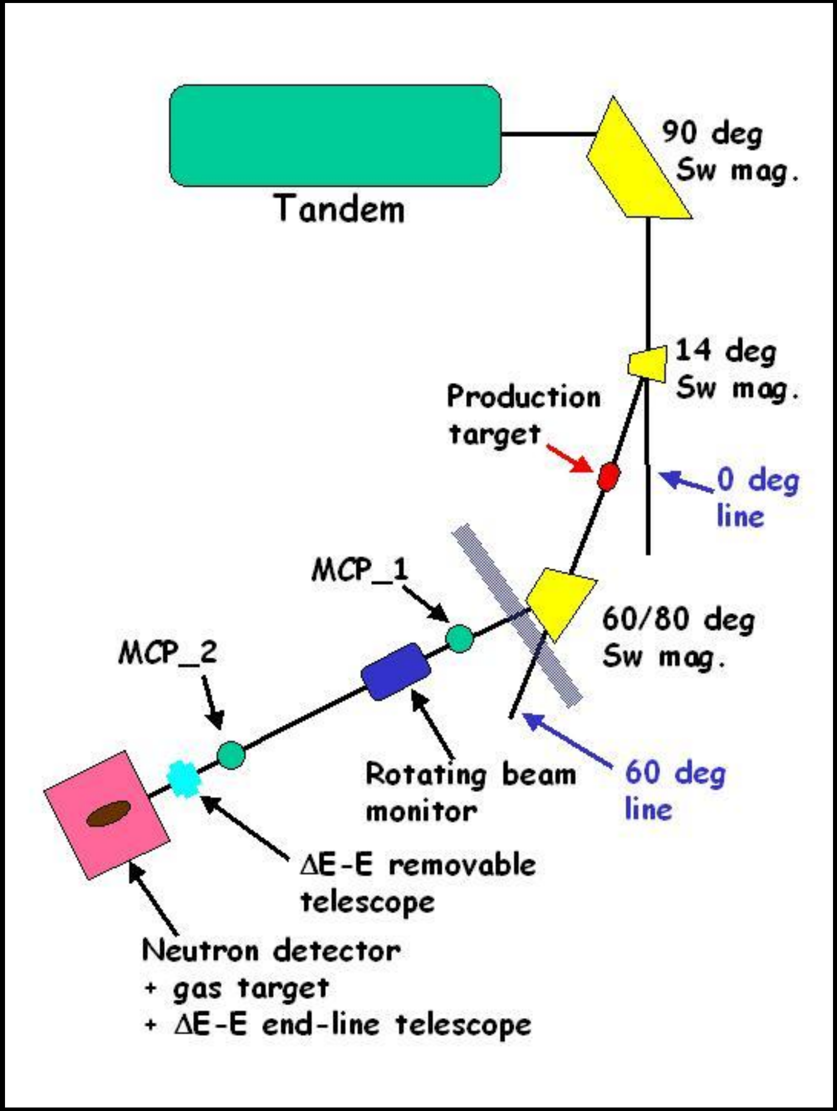
Not really welcome guests…..

1) **Leaky ^{7}Li beam** (no matter what you do, it is there!)

- 2) **Neutrons** from cyclotron and

- 3) **Neutrons** primary-beam induced *(really nasty ones)*

The experimental technique



The principle: we can suppress via "software" what was not suppressed by the "hardware" *(S. Cherubini)*

How?

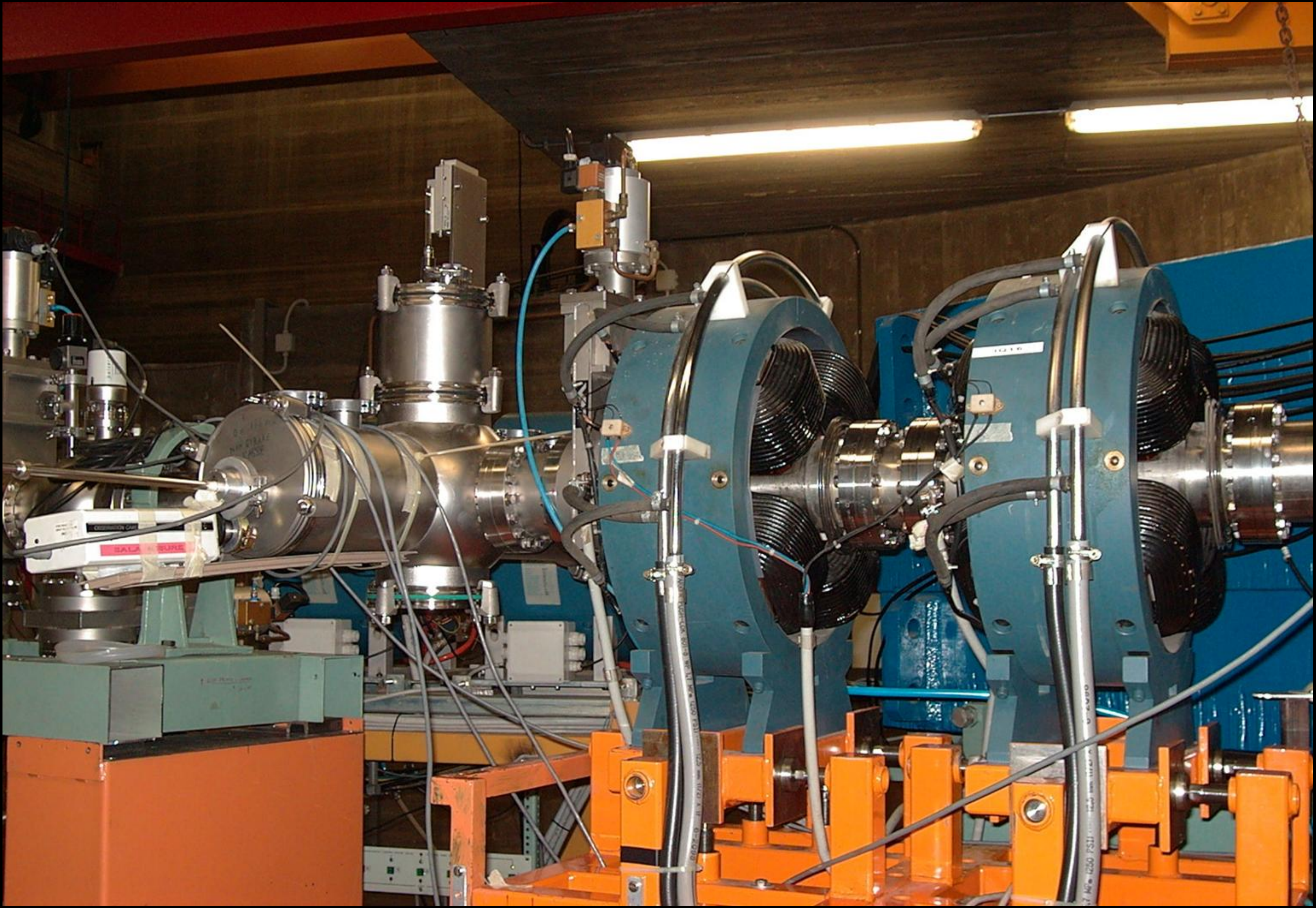
The Recipe:

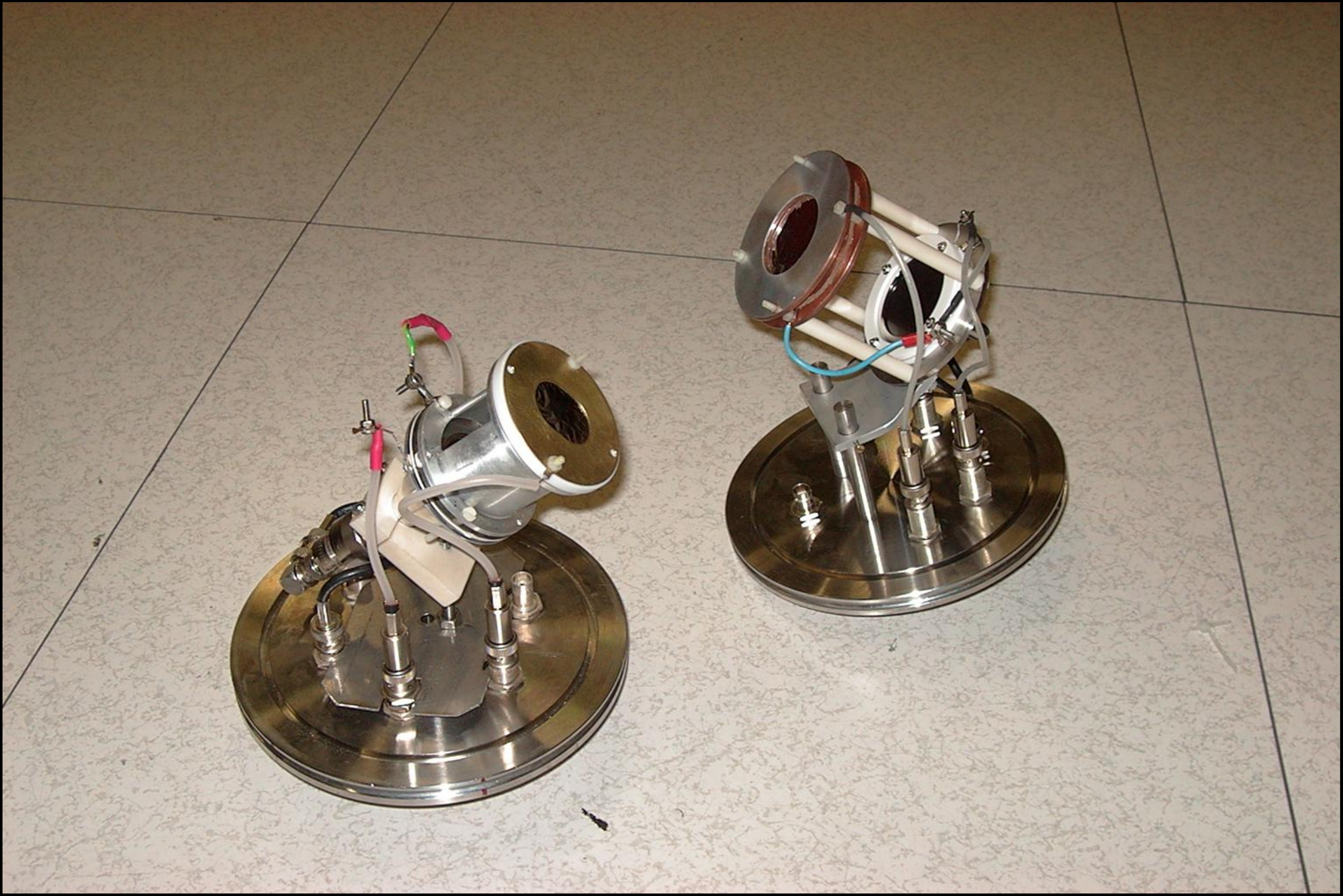
1 Apply a tagging procedure to the incoming ^{8}Li ions using the MCP pair,

2 use this information to "switch on" the neutron detector only when a ^{8}Li has been detected.

This allow for a dramatic reduction of the background neutrons, owing to their de-correlation with the MCP trigger signal

Beam time needs (from known X-sec.)


IQ16

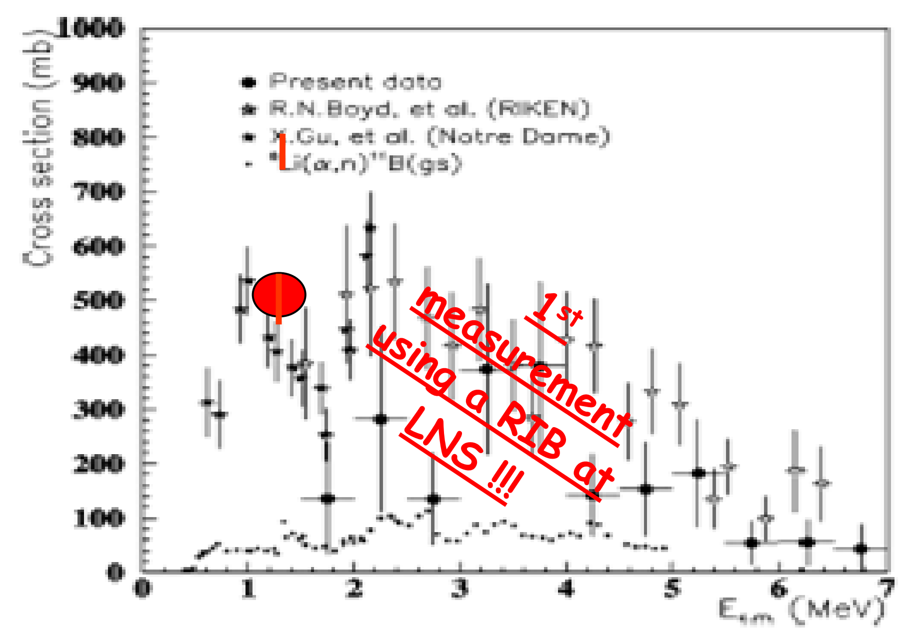


Direct measurements & Inhomogeneous BigBang

BIG BANG result for ^{8}Li(α,n)^{11}B x-sec

500 mbarn +- 170 mbarn +- 70 mbarn

Stat. *Syst.*



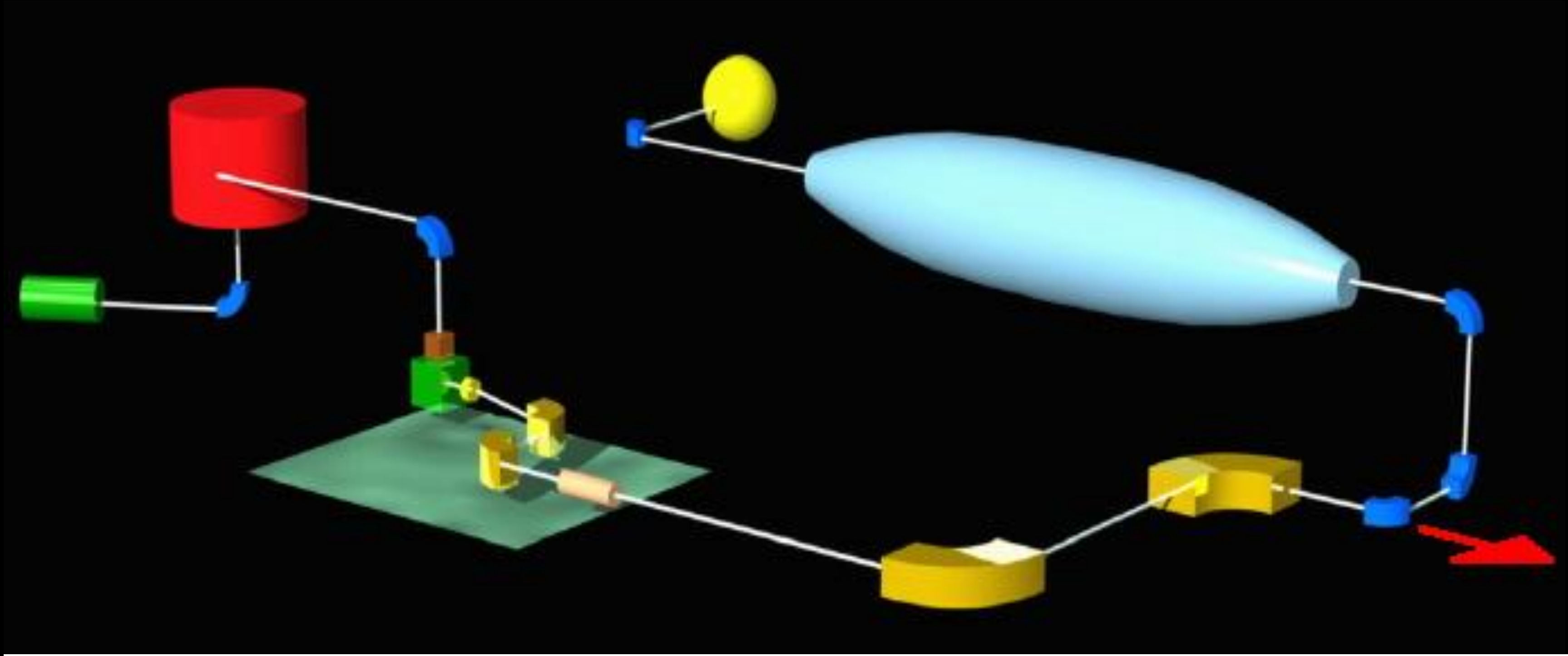
1st measurement using a RIB at LNS !!!

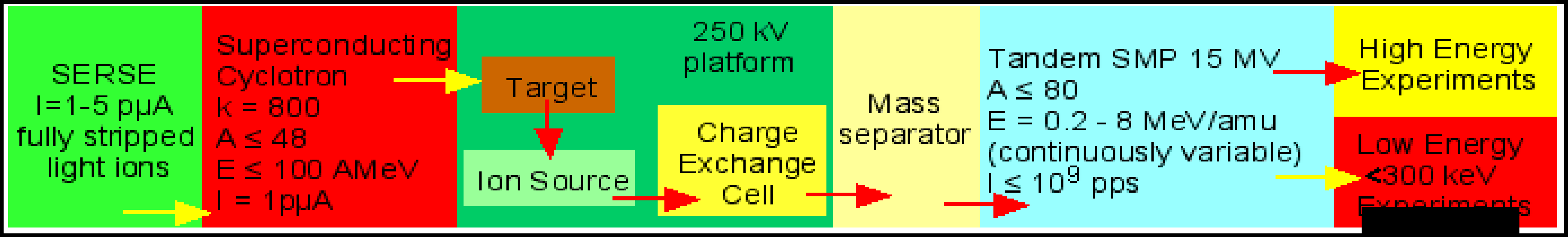
EPJ A-20, S. Cherubini et al.

+ series of papers

New runs of BIGBANG were the first experiment at

EXCYT





SERSE
I=1-5 pμA
fully stripped
light ions

Superconducting
Cyclotron
k = 800
A ≤ 48
E ≤ 100 AMeV
I = 1pμA

Target

Ion Source

250 kV
platform

Charge
Exchange
Cell

Mass
separator

Tandem SMP 15 MV
A ≤ 80
E = 0.2 - 8 MeV/amu
(continuously variable)
I ≤ 10^9 pps

High Energy
Experiments

Low Energy
<300 keV
Experiments

BUT the X-sec puzzle remined there...

Inclusive measurements → high
Exclusive measurement → low ...

La Cognata et al.,
The Astrophysical Journal,
706:L251–L255,
2009 December 1

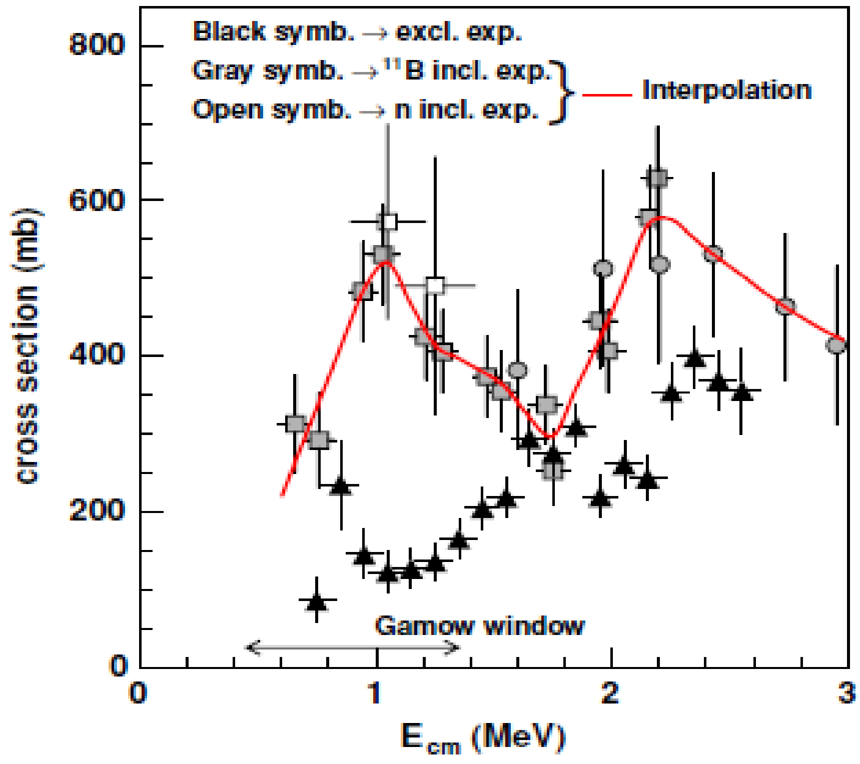
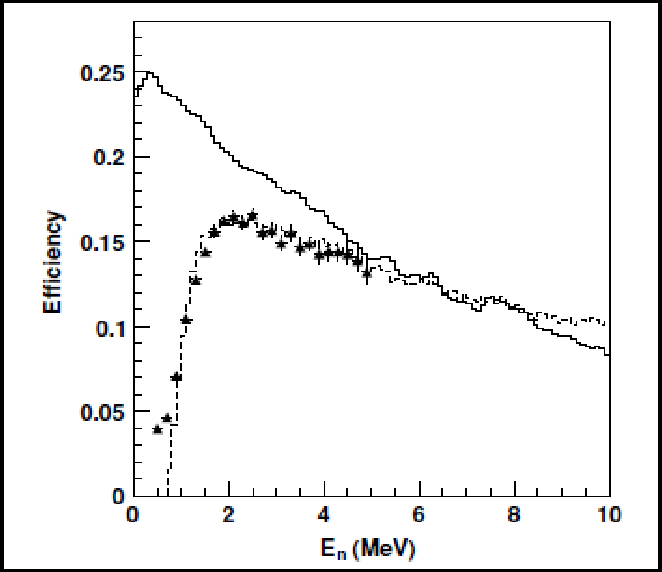
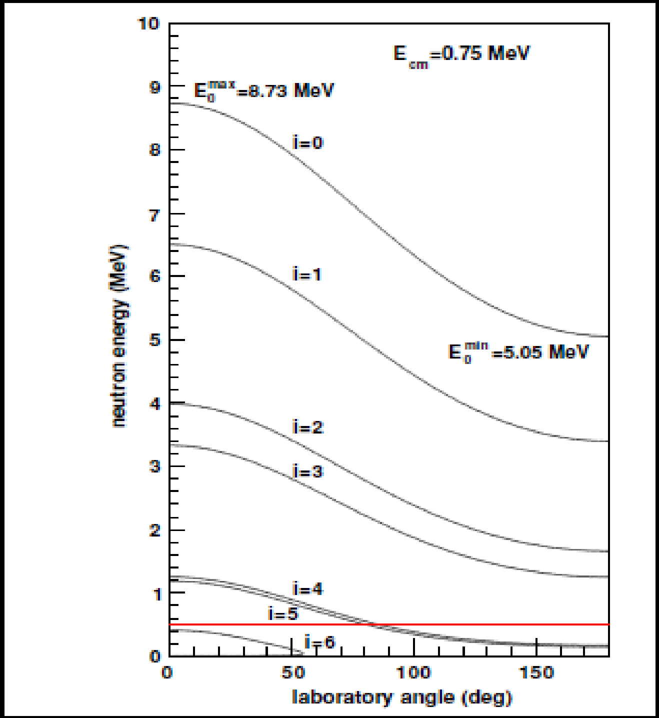
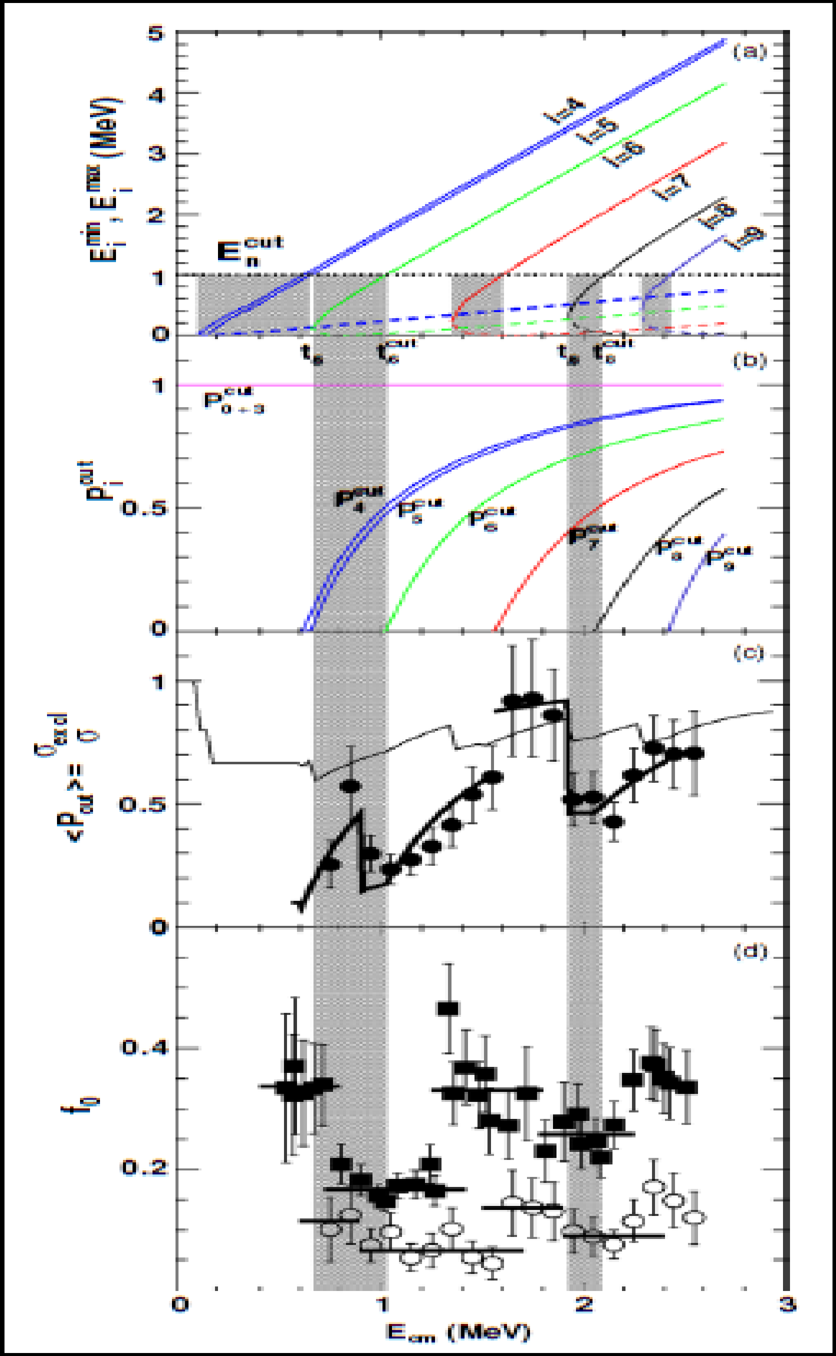


Figure 1. ^{8}Li + ^{4}He → ^{11}B + n reaction cross section data vs. E_{cm}: "□" (La Cognata et al. 2008), "●" (Boyd et al. 1992), "■" (Gu et al. 1995), and "▲" (Ishiyama et al. 2006). The curve depicts the interpolated inclusive cross section σ_{incl}. The Gamow energy region at $T = 2 \times 10^{9}$ K is shown.

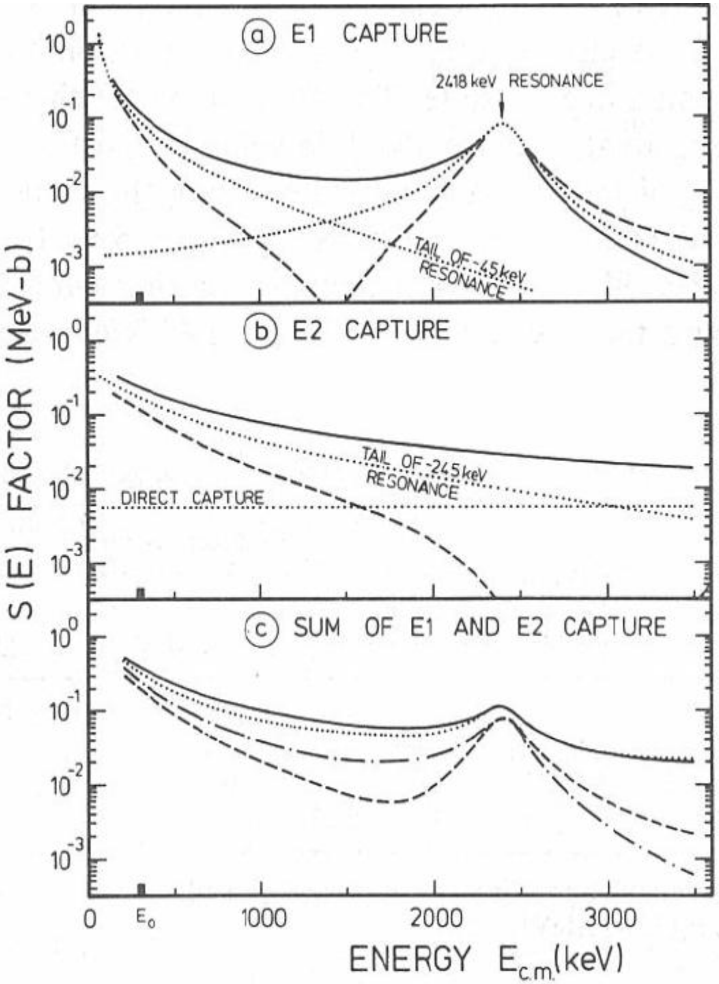
We proposed the following solution to the puzzle


Efficiency
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
E_n (MeV)


E_{cm}=0.75 MeV
E_0^{max}=8.73 MeV
E_0^{min}=5.05 MeV
i=0
i=1
i=2
i=3
i=4
i=5
i=6
neutron energy (MeV)
10
9
8
7
6
5
4
3
2
1
0
0
50
100
150
laboratory angle (deg)


(a)
(b)
(c)
(d)
E_i^{min}, E_i^{max} (MeV)
5
4
3
2
1
0
i=4
i=5
i=6
i=7
i=8
i=9
E_n^{cut}
t_s
t_s^{cut}
t_s
t_s^{cut}
P_{0+3}^{cut}
P_i^{cut}
1
0.5
0
P_4^{cut}
P_5^{cut}
P_6^{cut}
P_7^{cut}
P_8^{cut}
P_9^{cut}
$<P_{cut}> = \frac{\sigma_{excl}}{\sigma}$
1
0.5
0
f_0
0.4
0.2
0
1
2
3
E_{cm} (MeV)

Study of the beta-delayed alpha decay of ^{16}N



.... contribution from E1 levels
at 2418 and -45 keV
----- destructive interference
—— constructive interference

.... contribution from E2 level
at -245 keV and direct capture
----- destructive interference
—— constructive interference

C. E. Rolfs & W.S. Rodney
Cauldrons in the cosmos

FIGURE 7.6. The capture reaction $^{12}C(\alpha, \gamma_0)^{16}O$ can have contributions from both E1 and E2 amplitudes. (*a*) In the case of E1 capture, the resonances at $E_R = 2418$ and -45 keV can both contribute to the yield (*dotted lines*), where constructive or destructive interference between the two E1 sources may occur (*solid or dashed lines*). (*b*) Similarly, the two E2 sources arising from the $E_R = -245$ keV subthreshold resonance and the direct-capture process (*dotted lines*) lead to interference effects (*solid and dashed lines*). (*c*) The total capture cross section is the incoherent sum of the E1 and E2 yields, leading to four possible curves depending on the sign of the interference effects.

Determination of the $E1$ component of the low-energy $^{12}C(\alpha,\gamma)^{16}O$ cross section

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R. V. F. Janssens,[1] C. L. Jiang,[1] L. Jisonna,[5] D. Kahl,[1,*] E. F. Moore,[1] M. Notani,[1,†] R. C. Pardo,[1] N. Patel,[1,6] M. Paul,[7]
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(Received 30 December 2009; published 29 April 2010)

A measurement of the β-delayed α decay of ^{16}N using a set of twin ionization chambers is described. Sources were made by implantation, using a ^{16}N beam produced via the In-Flight Technique. The energies and emission angles of the ^{12}C and α particles were measured in coincidence and very clean α spectra, down to energies of 450 keV, were obtained. The structure of the spectra from this experiment is in good agreement with results from previous measurements. An analysis of our data with the same input parameters as used in earlier studies gives $S_{E1}(300) = 86 \pm 22$ keVb for the $E1$ component of the S-factor. This value is in excellent agreement with results obtained from various direct and indirect measurements. In addition, the influence of new measurements including the phase shift data from Tischhauser *et al.* on the value of $S_{E1}(300)$ is discussed.

DOI: 10.1103/PhysRevC.81.045809 PACS number(s): 21.10.Pc, 23.60.+e, 2

I. INTRODUCTION

The isotopes ^{16}O and ^{12}C are, after ^{1}H and ^{4}He, the third- and fourth-most abundant nuclei in the visible universe. Most of the carbon and oxygen which we observe today is produced by helium burning in red giant stars. Carbon and oxygen are not only crucial for all living organisms, but their relative abundances, which are determined by the competition between the triple α and the $^{12}C(\alpha,\gamma)^{16}O$ reactions, is also an important parameter for the evolution of a massive star at the end of its lifetime during the carbon-, neon-, and oxygen-burning phases [1–3]. While the cross section for the triple-α process is experimentally quite well determined [4], our knowledge of the $^{12}C(\alpha,\gamma)^{16}O$ reaction under typical helium burning conditions [$T_9 \sim 0.2$ or $E_{c.m.} \sim 300$ keV] is still limited by its small cross section and by the crucial role played by two subthreshold states in ^{16}O [5].

The history of experiments studying the $^{12}C(\alpha,\gamma)^{16}O$ reaction goes back more than four decades [6,7]. The magnitude of this cross section, however, is still a hotly debated issue, both experimentally and theoretically, and many recent publications can be found in the literature [8–16].

The $^{12}C(\alpha,\gamma)^{16}O$ reaction proceeds mainly through two radiative capture modes to the ^{16}O ground state (see Fig. 1). One is $E1$ capture with contributions from the 1^- state at $E_x = 9.585$ MeV ($E_r = 2.418$
state at $E_x = 7.117$ MeV (E_r
capture, which is dominated by
capture, and the subthreshold
($E_r = -245$ keV). At energies
window for red giant stars (
sections are of the order of
direct measurements so far were
$E_{c.m.} = 890$ keV [4]. These d
the energy region of astrophy
theory. Since the higher-energy
the contributions from subthres
S factors in the past 30 years
$S_{E1}(300)$ and 7 to 120 keVb f
the reliability of the extrapolati
experiments, such as elastic α scattering on C [18,19], α-transfer reactions to ^{16}O [20], and ^{16}N decay are usually included in the analyses [21].

A measurement of the β-delayed α decay of ^{16}N is considered to be the best method presently available to provide a constrain for the $E1$ component, $S_{E1}(300)$, of the $^{12}C(\alpha,\gamma)$ reaction [21]. For nuclear astrophysics, this decay has been studied in the past by two groups [11,21–23]. The S-factor $S_{E1}(300)$ is extracted from the relative height of a satellite peak in the α energy spectrum located at $E_\alpha \sim 0.9$ MeV, which originates from the interference of the subthreshold 1^- state with the higher-lying 1^- state in ^{16}O at $E_x = 9.585$ MeV [24].

In all previous experiments [11,21–23,25] the α particles were detected in thin Si surface-barrier detectors. The very small α/β ratio of the ^{16}N decay ($\sim 10^{-5}$), however, results in a very high background from β particles that strongly affects the low-energy part of the energy spectrum from which $S_{E1}(300)$

---

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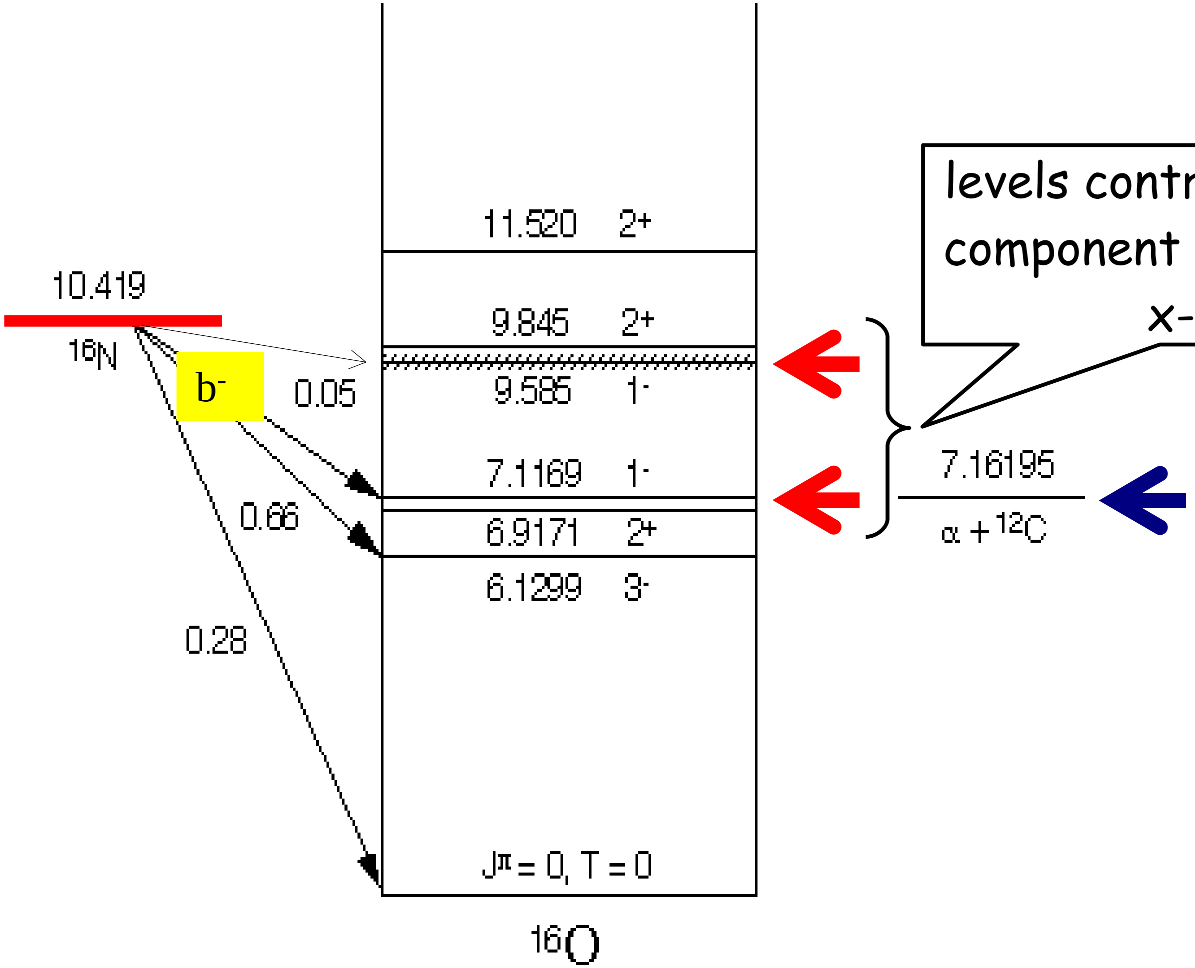
“A measurement of the β-delayed α decay of ^{16}N is considered to be the best method presently available to provide a constrain for the E1 component, SE1 (300), of the ^{12} C(α,γ) reaction”



levels contributing to E1 component in $^{12}C(a,g)^{16}O$ x-sec

“In a study of the 16N b-delayed decay, three aspects are important:

~~**(1)a particles with energies down to 0.6 MeV have to be detected in coincidence with 12C ions of even lower energies (0.1 MeV). Any significant energy loss of the outgoing particles in the catcher foil will deform the shape of the spectrum.**~~

~~**(2) If a particle, emitted from the foil, is stopped in the support frame, only a part of the energy is deposited in the gas. Such events must be clearly separated from the true coincidence events producing the interference peak.**~~

~~**(3) The detection efficiency must be constant over the energy range from 0.2 MeV to 2 MeV.”**~~

1), 2) No foil, no frame: NO PROBLEMS

3) Monitor the energy response of the detector event by event

Univ. Catania and INFN-LNS:
C. Spitaleri, S. C., L. Guardo, *M. Gulino*, S. Hayakawa, I. Indelicato, M. La Cognata, L. Lamia,R.G. Pizzone, S. Puglia, G.G. Rapisarda, S. Romano, M.L. Sergi, R. Spartà, *A. Tumino*

CNS, The University of Tokyo:
S. Kubono, H. Yamaguchi, Y. Wakabayashi, D.N. Binh,

RIKEN, Tohoku-, Tsukuba-, Yamagata-, Kyushu- University:
N. Iwasa, S. Kato, H. Komatsubara, S. Nishimura, T. Teranishi

CSNSM, IN2P3/CNRS and Université Paris Sud:
A. Coc, N. de Séréville, F. Hammache

Texas A&M University
R. Tribble, A. Mukhamedzanov, L. Trache

RUB: Claus Rolfs

domo arigato!

...I apologize with those
I surely forgot!