Nuclear Fusion of Carbon in Stars : The Reaction Channel with Neutron Emission

Purified Gamma Spectra from Gamma-Particle Coincidences

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Summary

Introduction

- STELLA Experiment
- Experimental Coincidences Investigation
- Simulation Study
- Q values and cross section calculation

Conclusion

Bibliography

Introduction

What is nucleosynthesis ?
→ Nucleosynthesis corresponds to the synthesis of atomic nuclei

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→ Nucleosynthesis corresponds to the synthesis of atomic nuclei

$p + n$	$\rightarrow$	$D + \gamma$
$D + n$	$\rightarrow$	$^{3}H + \gamma$
$D + p$	$\rightarrow$	$^{3}He + \gamma$
$D + D$	$\rightarrow$	$^{3}H + p$
$D + D$	$\rightarrow$	$^{3}He + n$
$D + D$	$\rightarrow$	$^{4}He + \gamma$
$^{3}H + p$	$\rightarrow$	$^{4}He + \gamma$
$^{3}He + n$	$\rightarrow$	$^{3}H + p$
$^{3}He + n$	$\rightarrow$	$^{4}He + \gamma$
$^{3}H + D$	$\rightarrow$	$^{4}He + n$
$^{3}He + D$	$\rightarrow$	$^{4}He + p$
$^{3}He + {}^{3}He$	$\rightarrow$	$^{4}He + 2p$
$^{4}He + D$	$\rightarrow$	$^{6}Li + \gamma$
$^{4}He + {}^{3}H$	$\rightarrow$	$^{7}Li + \gamma$
$^{4}He + {}^{3}He$	$\rightarrow$	$^{7}Be + \gamma$
$^{6}Li + n$	$\rightarrow$	$^{7}Li + \gamma$
$^{6}Li + p$	$\rightarrow$	$^{7}Be + \gamma$
$^{7}Li + p$	$\rightarrow$	$^{4}He + {}^{4}He + \gamma$
$^{7}Be + n$	$\rightarrow$	$^{7}Li + p$
$^{7}Be + e^{-}$	$\rightarrow$	$^{7}Li + \gamma$

Two types

Primordial Nucleosynthesis

- First minutes after the Big Bang
- H, D, He, Li
- $T_{universe} \approx 10^{9}$ K

Introduction

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→ Nucleosynthesis corresponds to the synthesis of atomic nuclei

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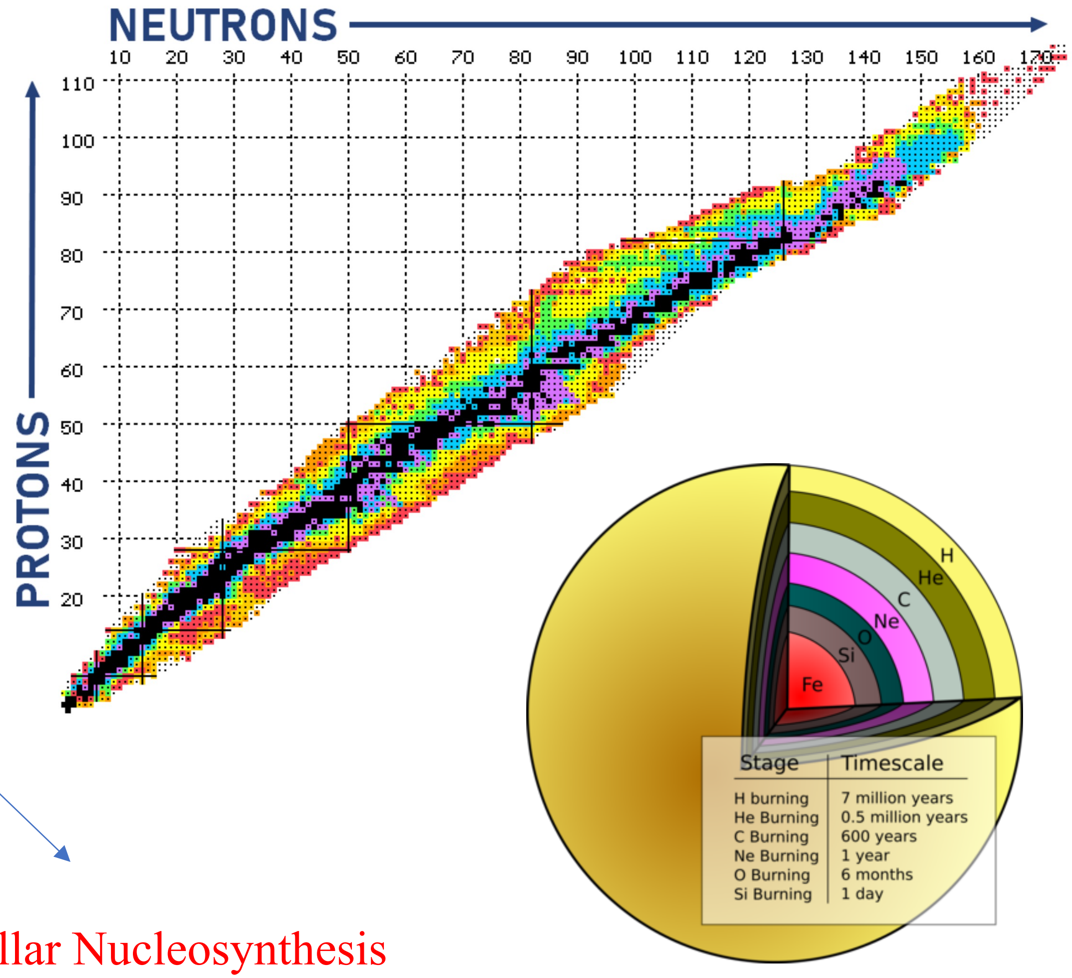
$^7Be + n$	→	$^7Li + p$
$^7Be + e^-$	→	$^7Li + \gamma$



Two types

Primordial Nucleosynthesis

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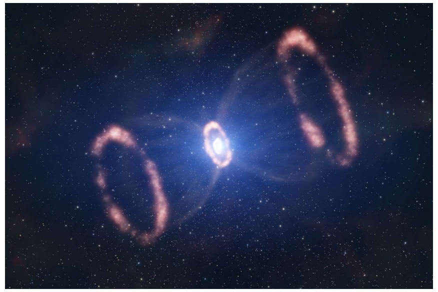
Stellar Nucleosynthesis

- H → Fe
- Explosion phase : heavier elements



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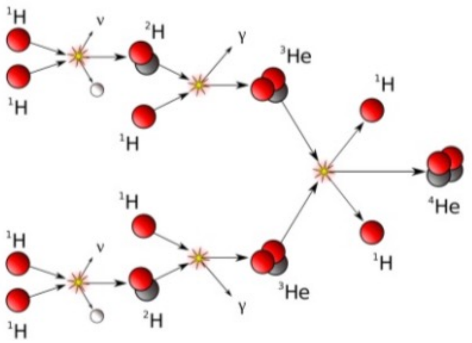
Phase 1 : Hydrogen burning



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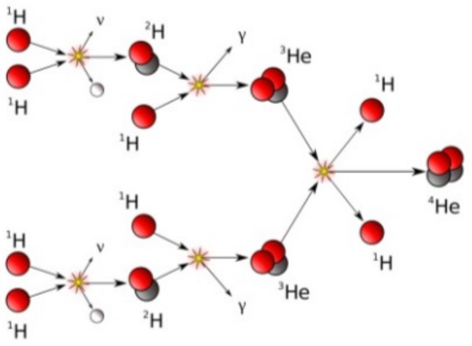

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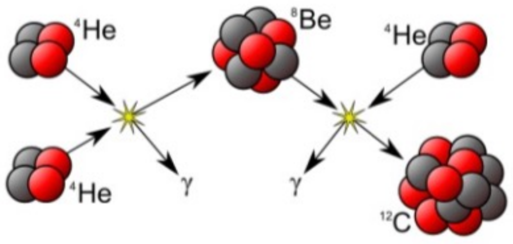
Phase 2 : Helium burning



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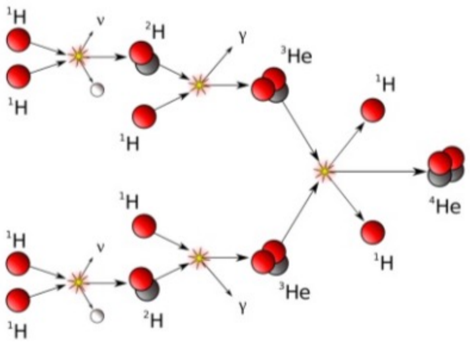

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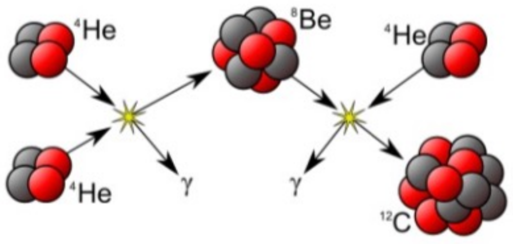

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Phase 3 : Carbon burning

$^{12}C + ^{12}C \rightarrow {}^{23}Na + p + \gamma$ (≈ 440 keV)

${}^{23}Mg + n + \gamma$ (≈ 451 keV)

${}^{20}Ne + \alpha + \gamma$

Experimental interests : $E_{rel} \approx 2.5$ MeV

$T_{fusion} \approx 0.8 \cdot 10^{9}$ K

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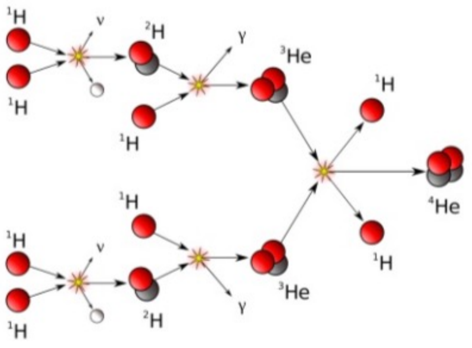

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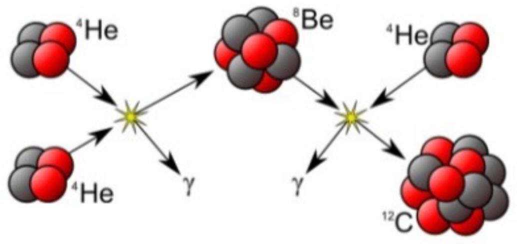

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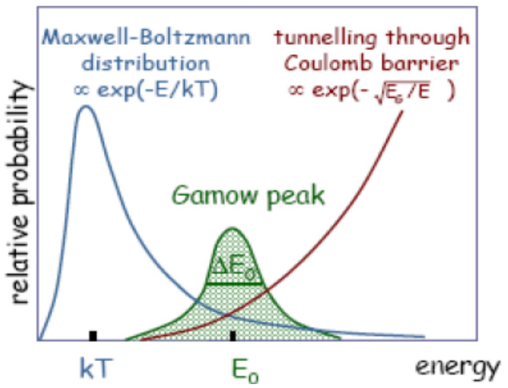
The Tunnel Effect in Nuclear Fusion Reaction



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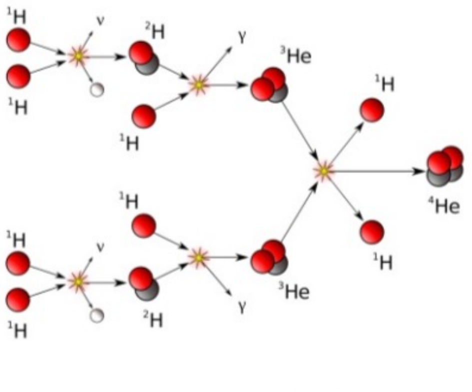

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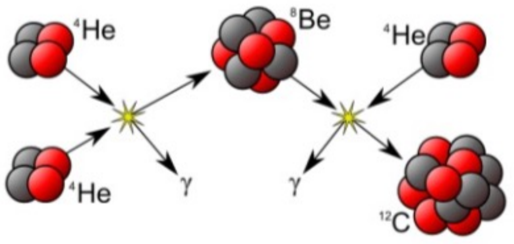

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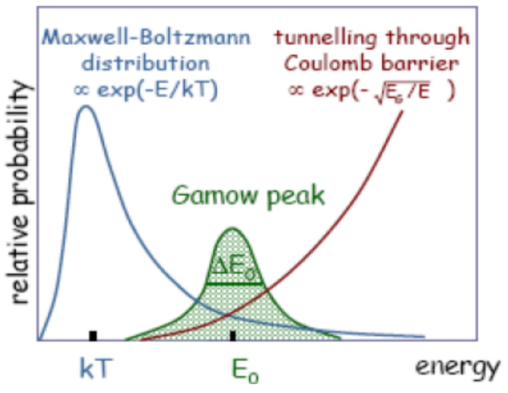

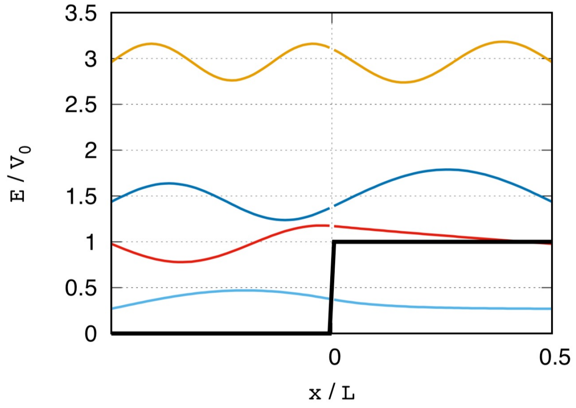

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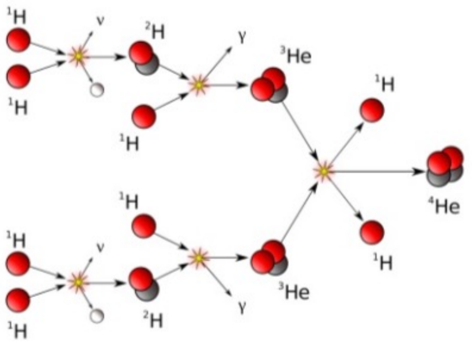

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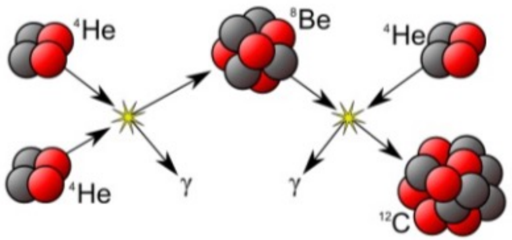

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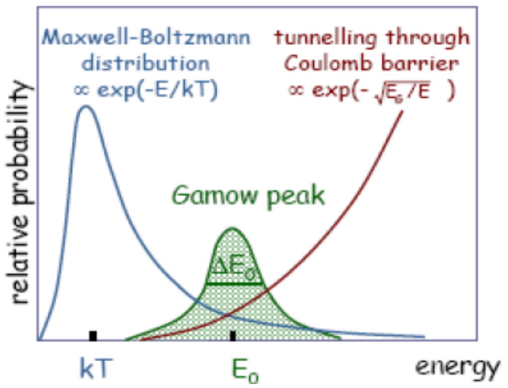
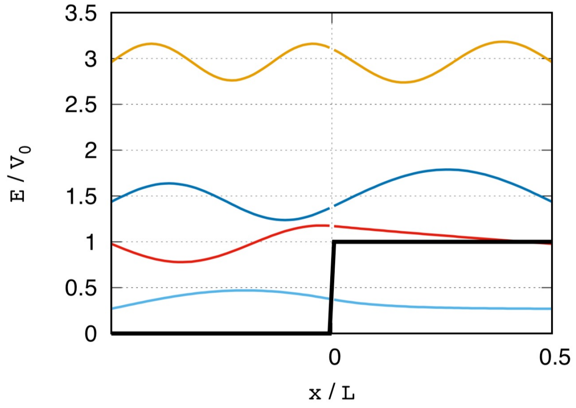
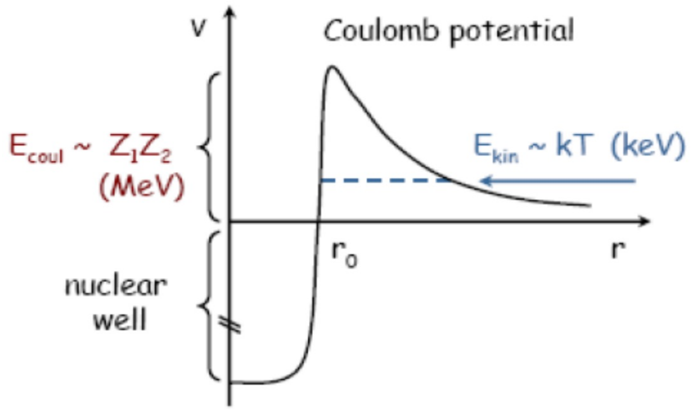
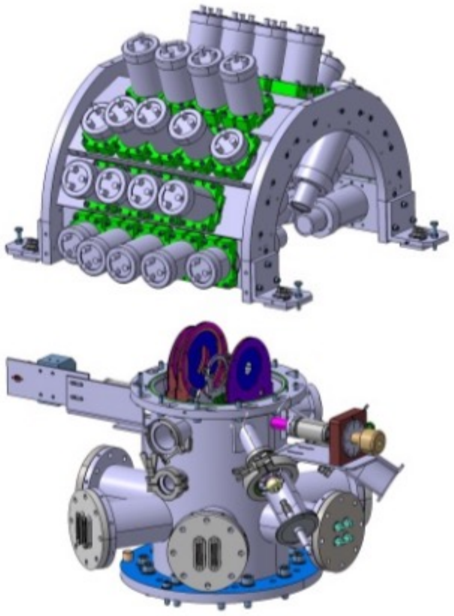




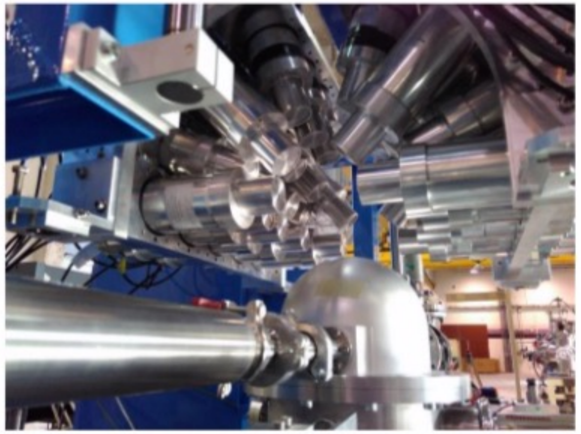


STELLA Experiment

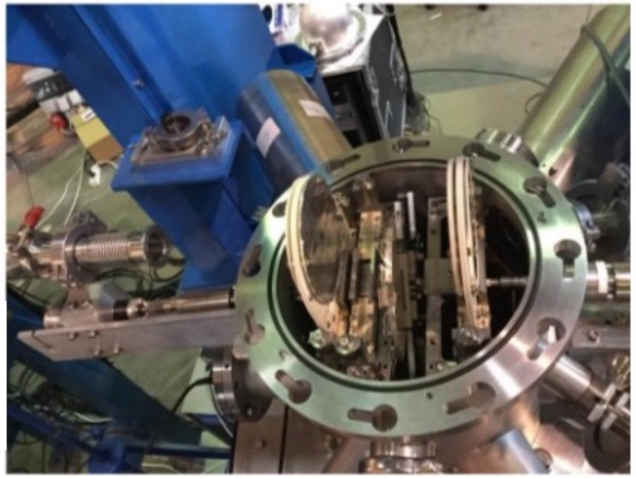


Mechanical design

$LaBr_3$ detectors



Support of rotating target



Silicium detectors
S3B & S3F

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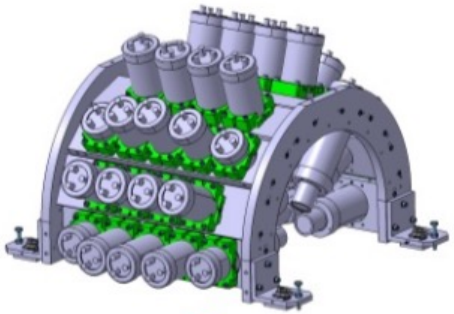
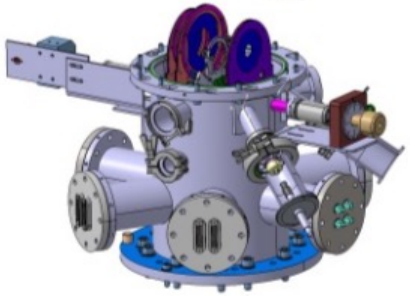
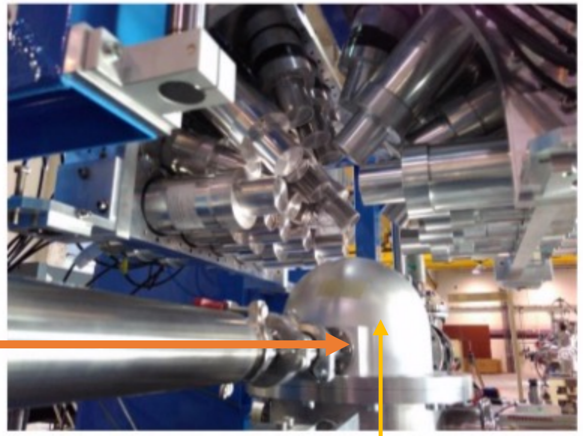




Mechanical design

LaBr$_3$ detectors

Beam of Carbon



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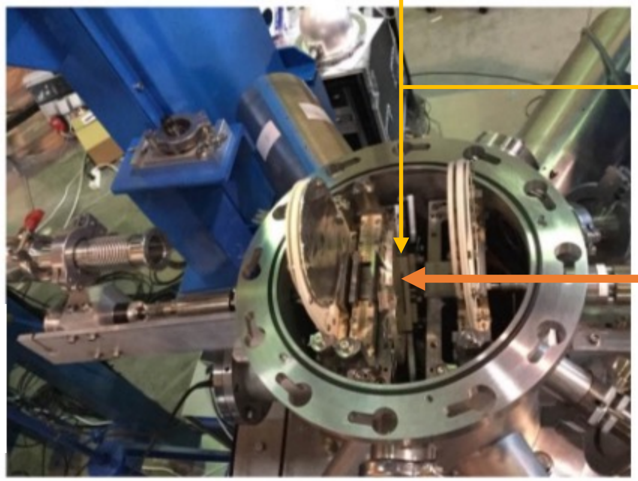
Silicium detectors S3B & S3F

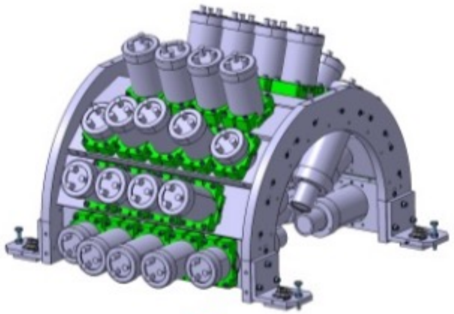


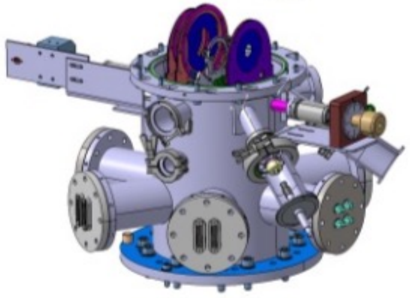
High vaccum chamber ≈ 10^{-8} mbar

Carbon target position

STELLA Experiment

Position of STELLA Experiment





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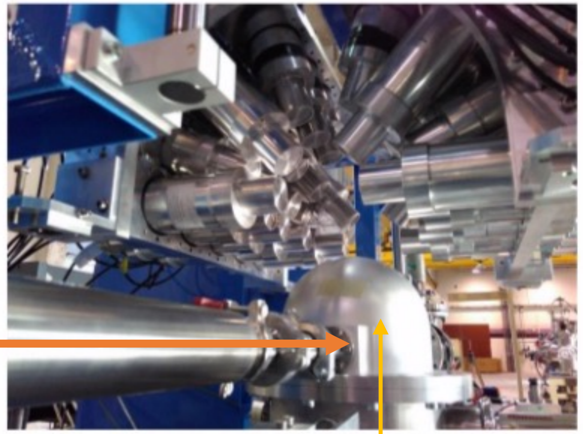

Support of
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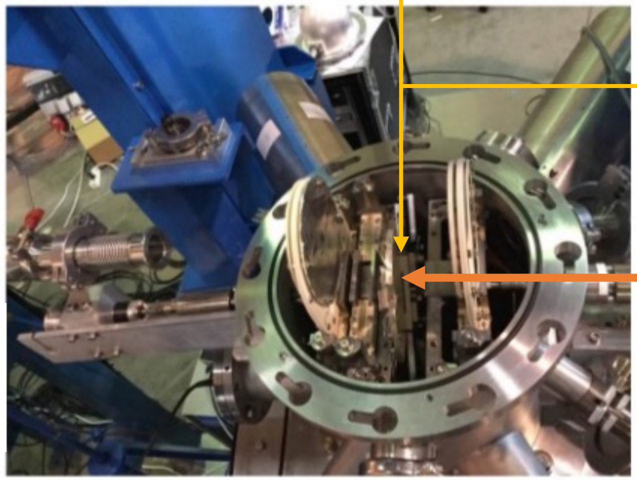
Silicium detectors
S3B & S3F

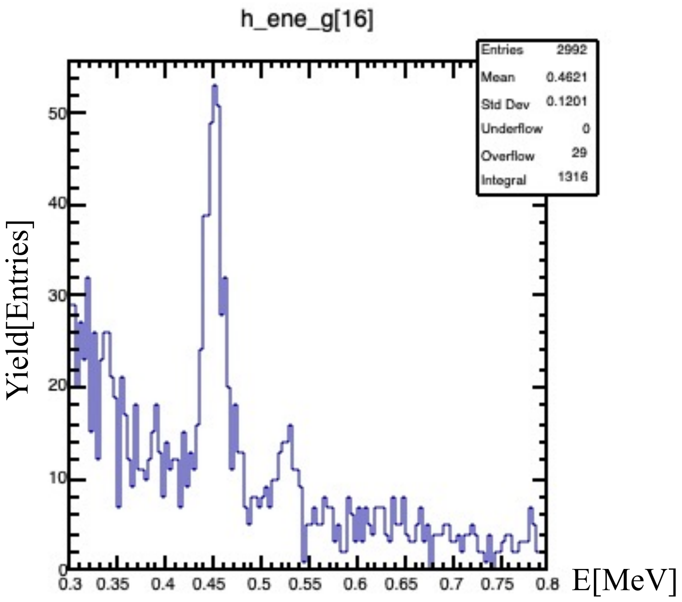


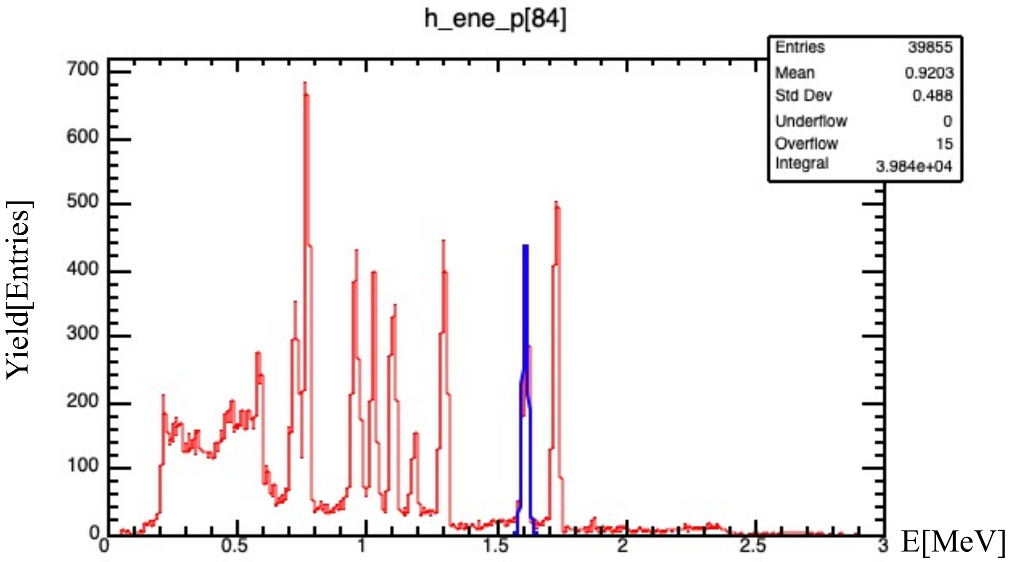
Andromede accelerator
(Orsay)

High vaccum chamber ≈ 10^{-8} mbar

Carbon target position

Experimental Coincidences Investigation





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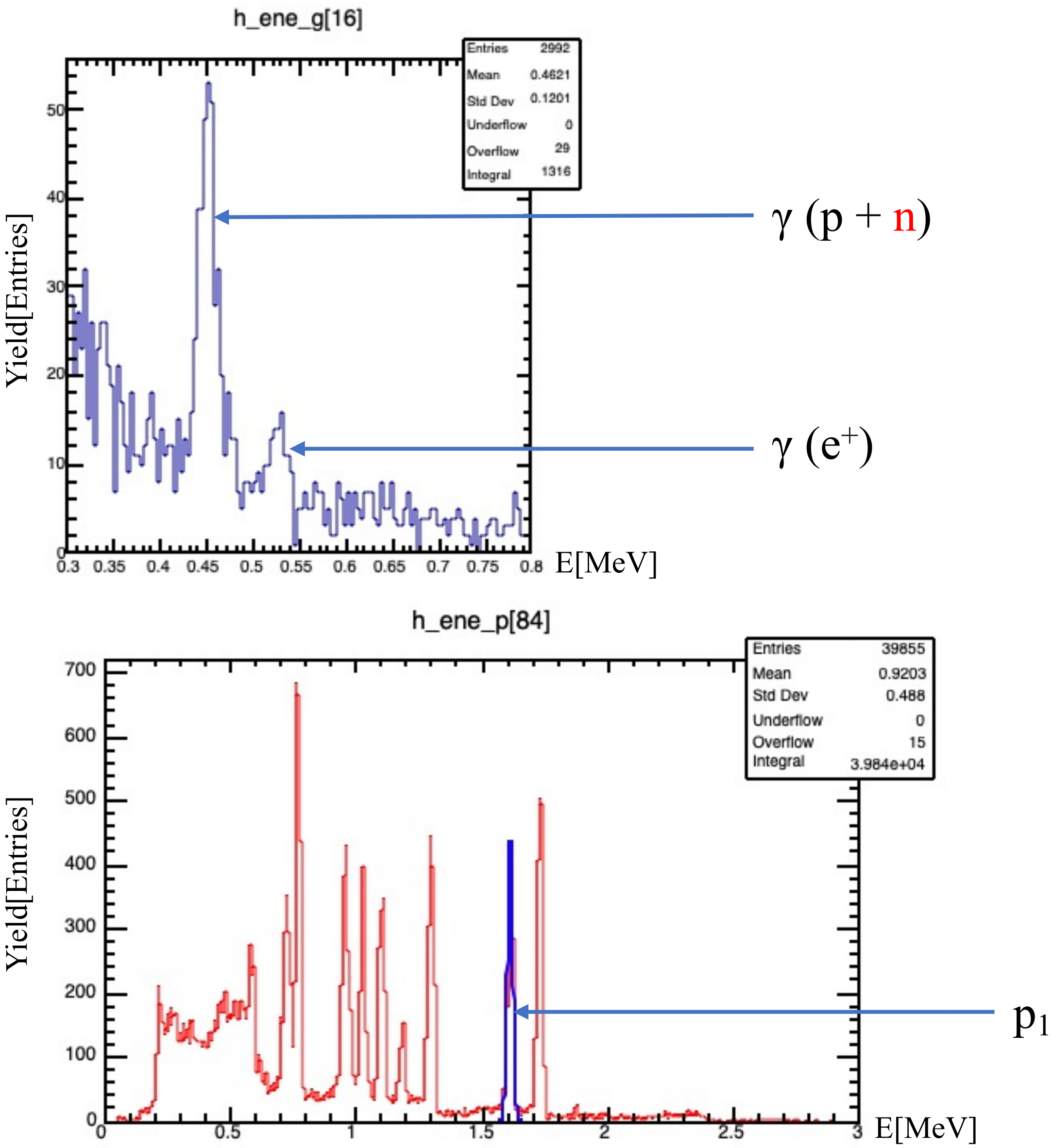

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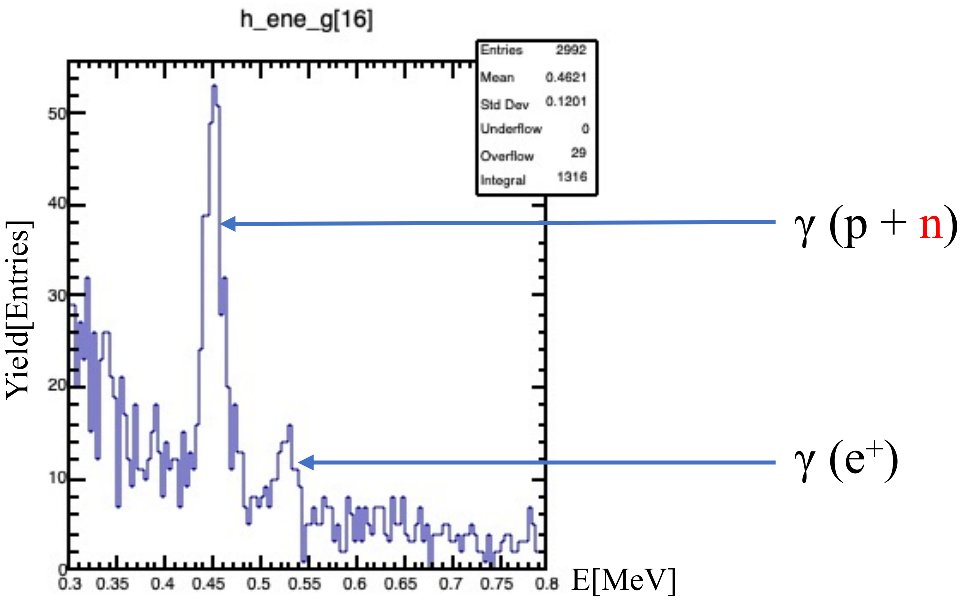

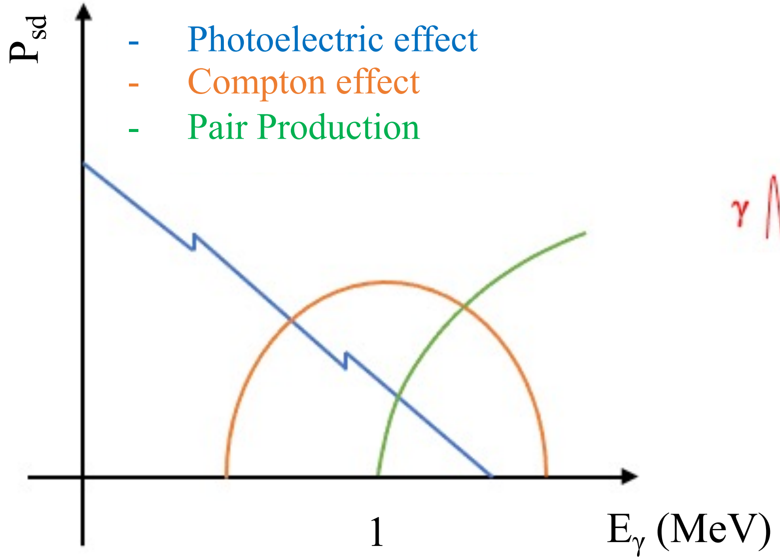

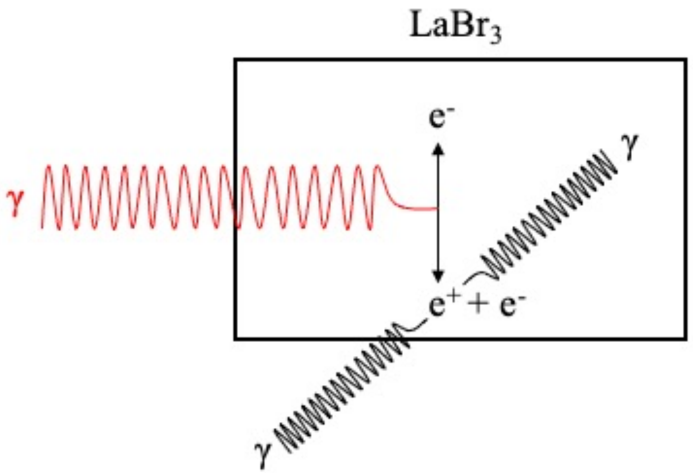

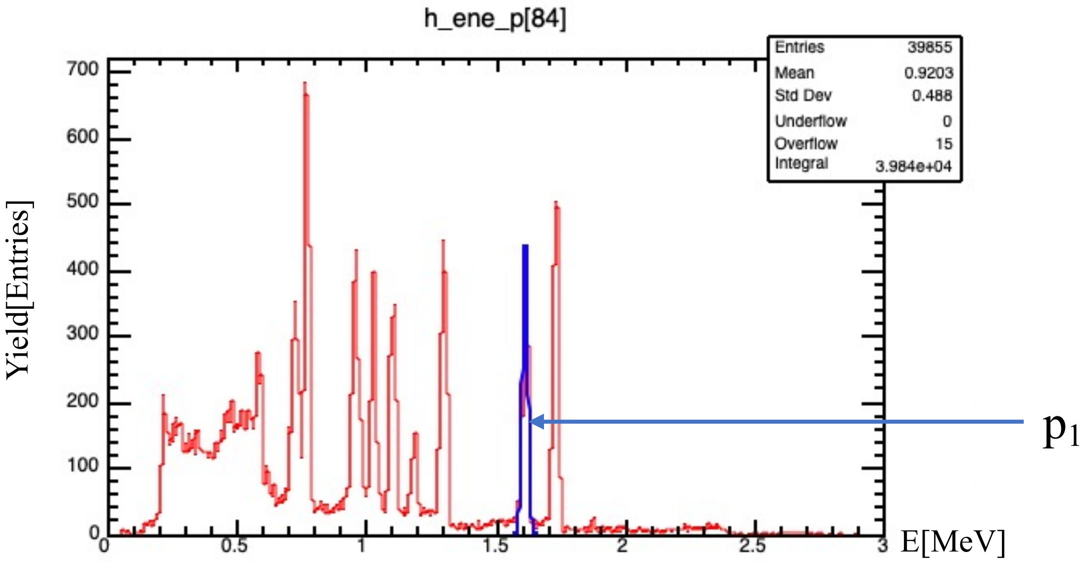

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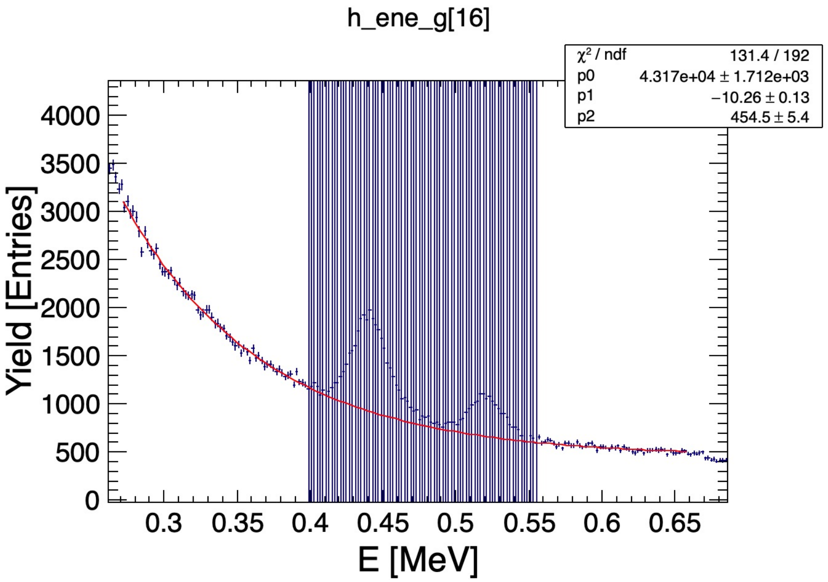
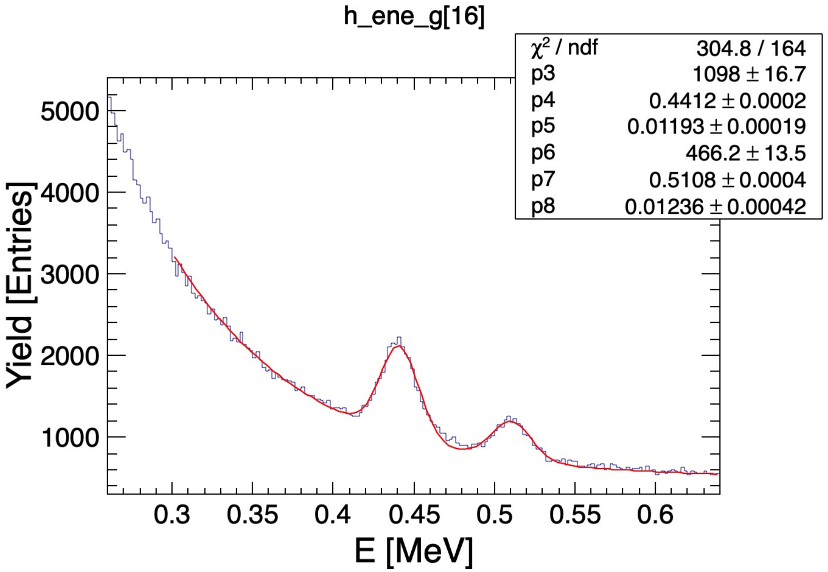
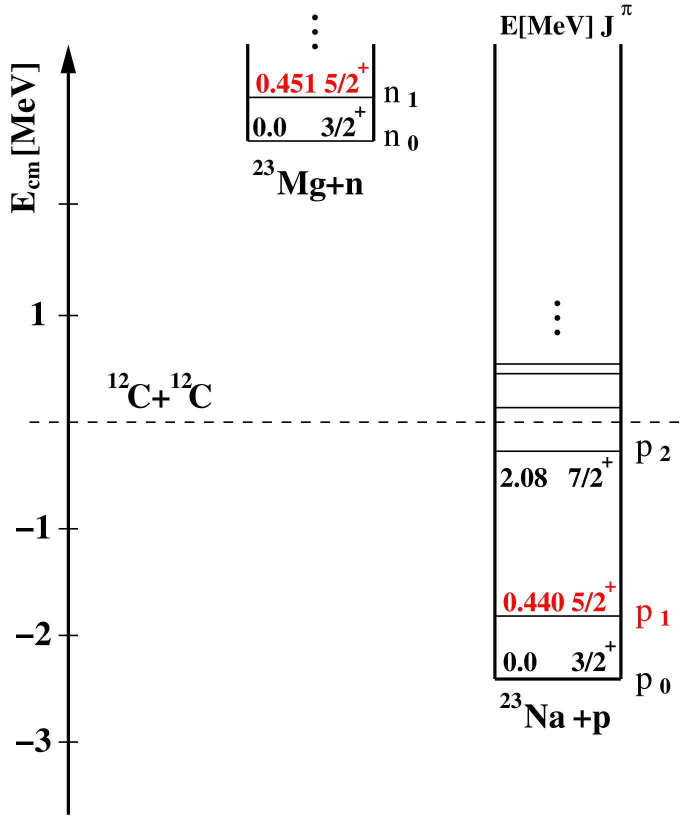
Without Condition : Background + ^{12}C + ^{12}C → ^{23}Na + p + γ, ^{23}Mg + n + γ, ^{20}Ne + α + γ







Parameter	value	error
p0 : offset	9.67141e+04	Fixed
p1 : slope	-1.18451e+01	Fixed
p2 : adjustment	4.96340e+02	Fixed

All : Background Parameters

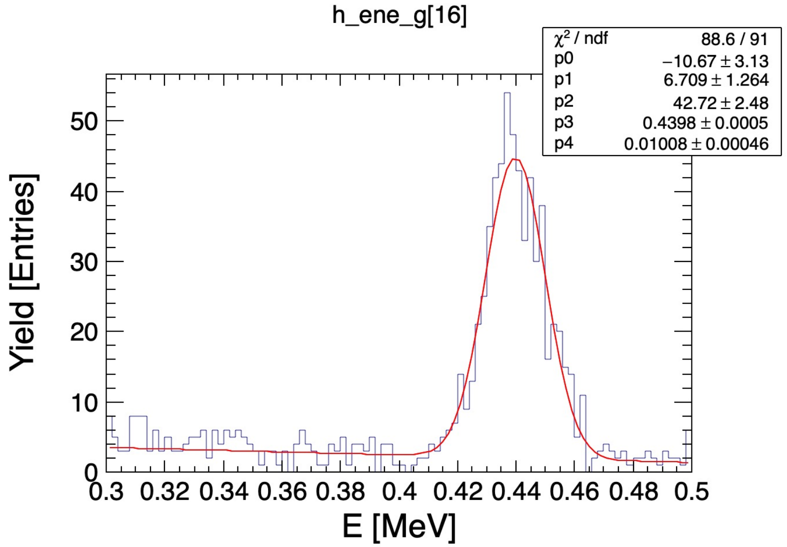
Parameter	value	error
p3 : Amplitude	1.09765e+03	1.69832e+01
p4 : Mean	4.41182e-01	1.86849e-04
p5 : Sigma	1.19319e-02	1.99909e-04

All : γ - Left Peak Parameters

Parameter	value	error
p6 : Amplitude	4.66247e+02	1.34583e+01
p7 : Mean	5.10846e-01	3.52587e-04
p8 : Sigma	1.23562e-02	4.18475e-04

All : γ - 511 keV Parameters

With S3B Particles Coincidences : $^{12}C + ^{12}C \rightarrow ^{23}Na + p_i + \gamma_1$; i = 1…12

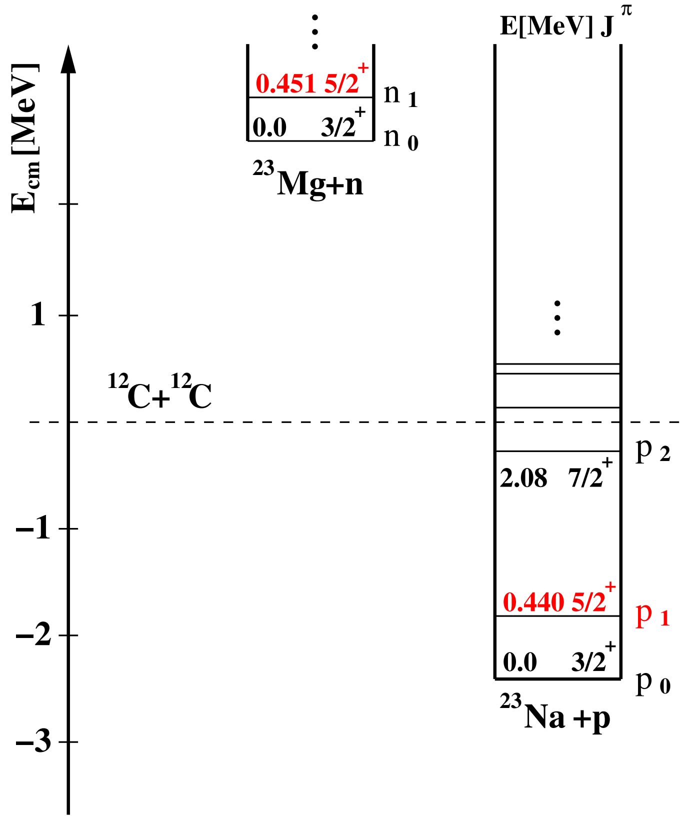


Parameter	value	error
p0 : offset	-1.06682e+01	3.13372e+00
p1 : slope	6.70941e+00	1.26434e+00

S3B : Background Parameters

Parameter	value	error
p2 : Amplitude	4.27163e+01	2.48262e+00
p3 : Mean	4.39838e-01	5.08864e-04
p4 : Sigma	1.00803e-02	4.56043e-04

S3B : γ - 440 keV Parameters



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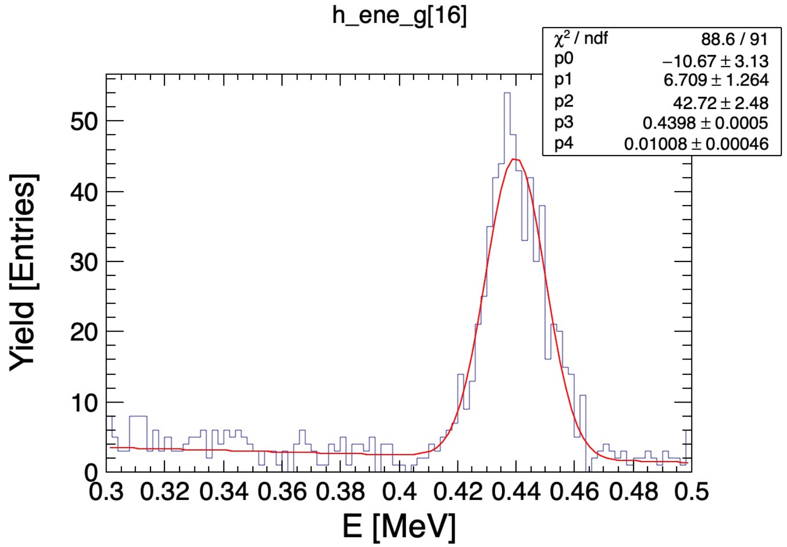

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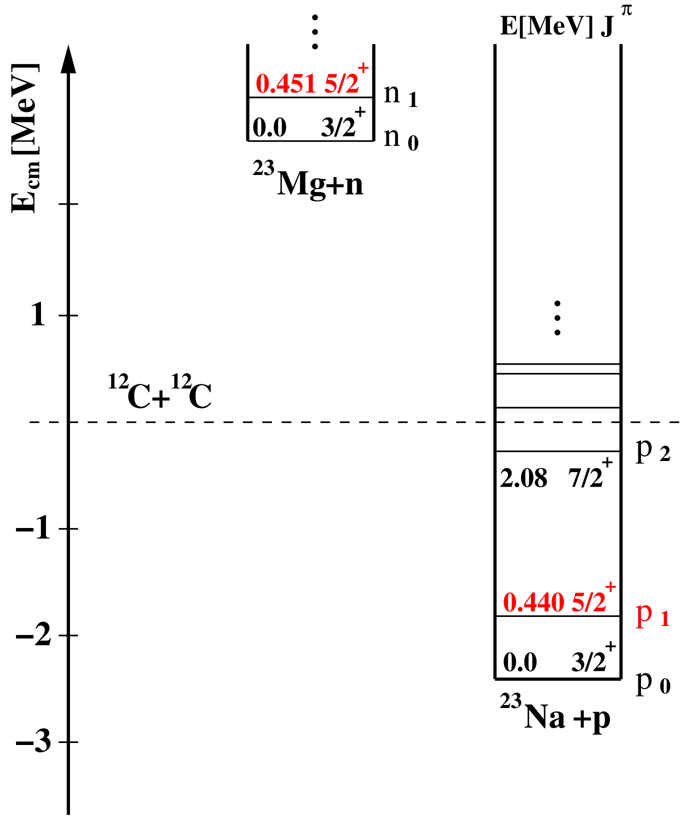
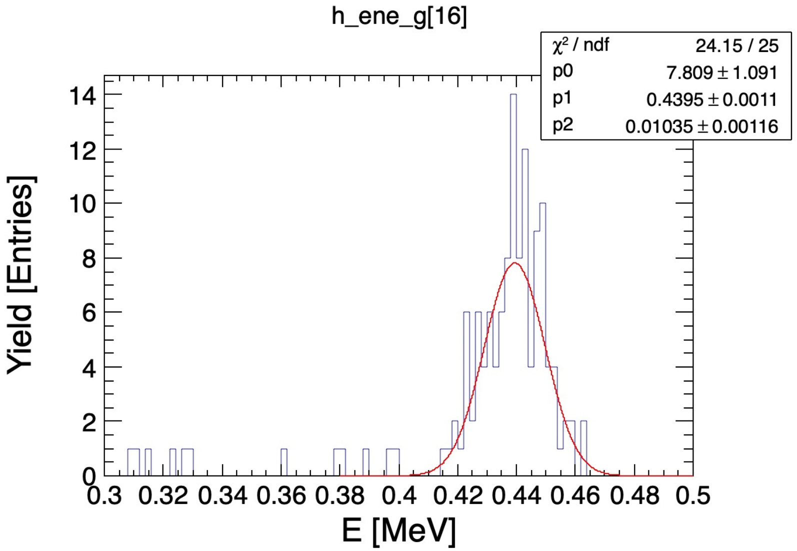
S3B : γ - 440 keV Parameters



With only p_1 Coincidences : $^{12}C + ^{12}C \rightarrow ^{23}Na + p_1 + \gamma_1$



Parameter	value	error
p0 : Amplitude	7.80923e+00	1.09126e+00
p1 : Mean	4.39454e-01	1.12699e-03
p2 : Sigma	1.03548e-02	1.15976e-03

p1 : γ - 440 keV Parameters

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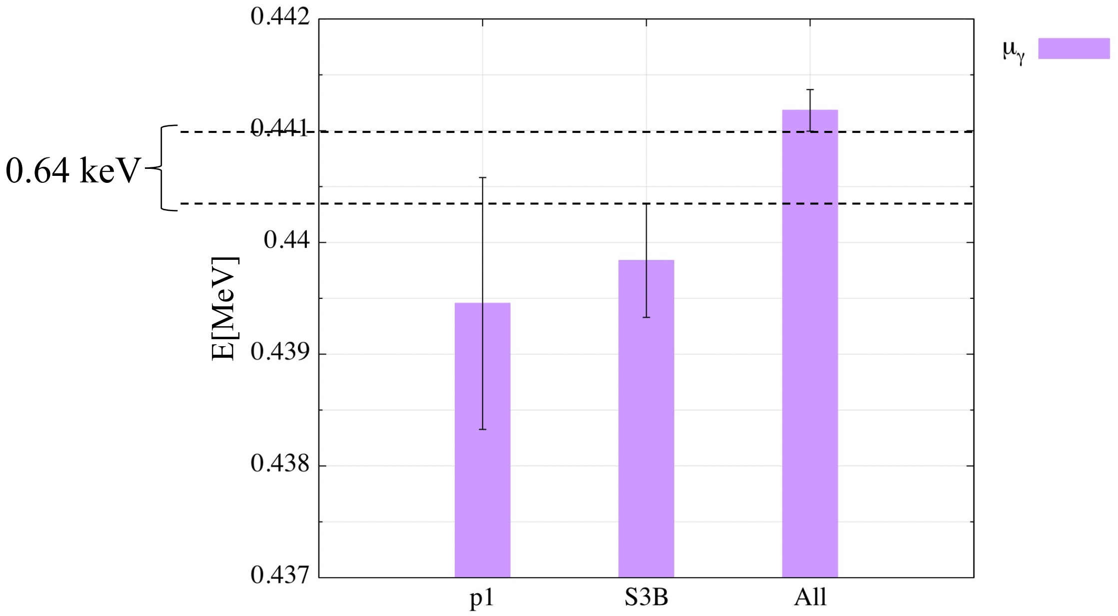
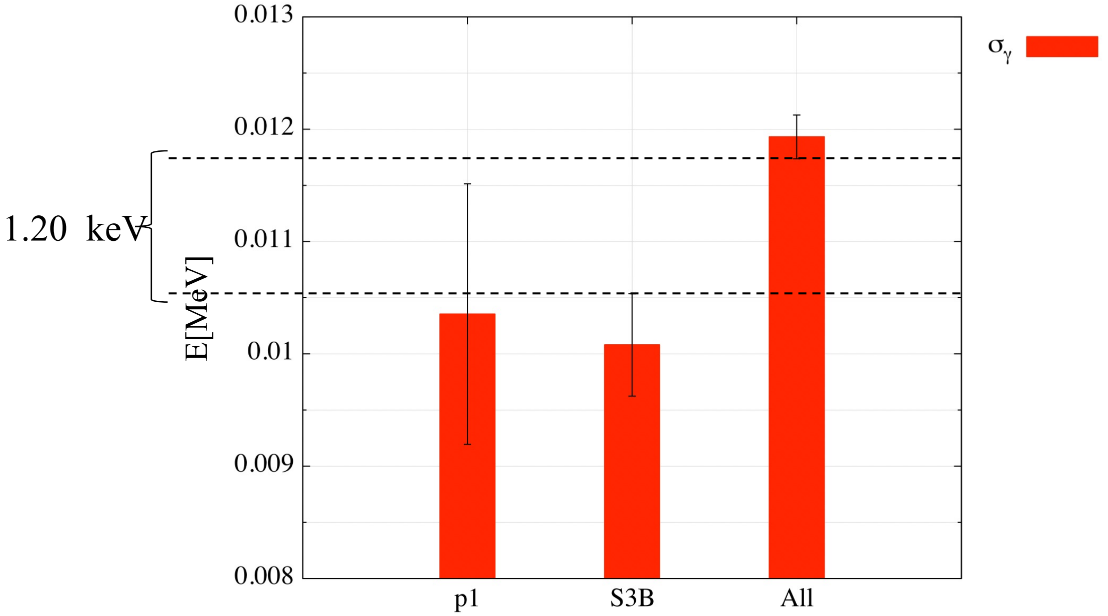




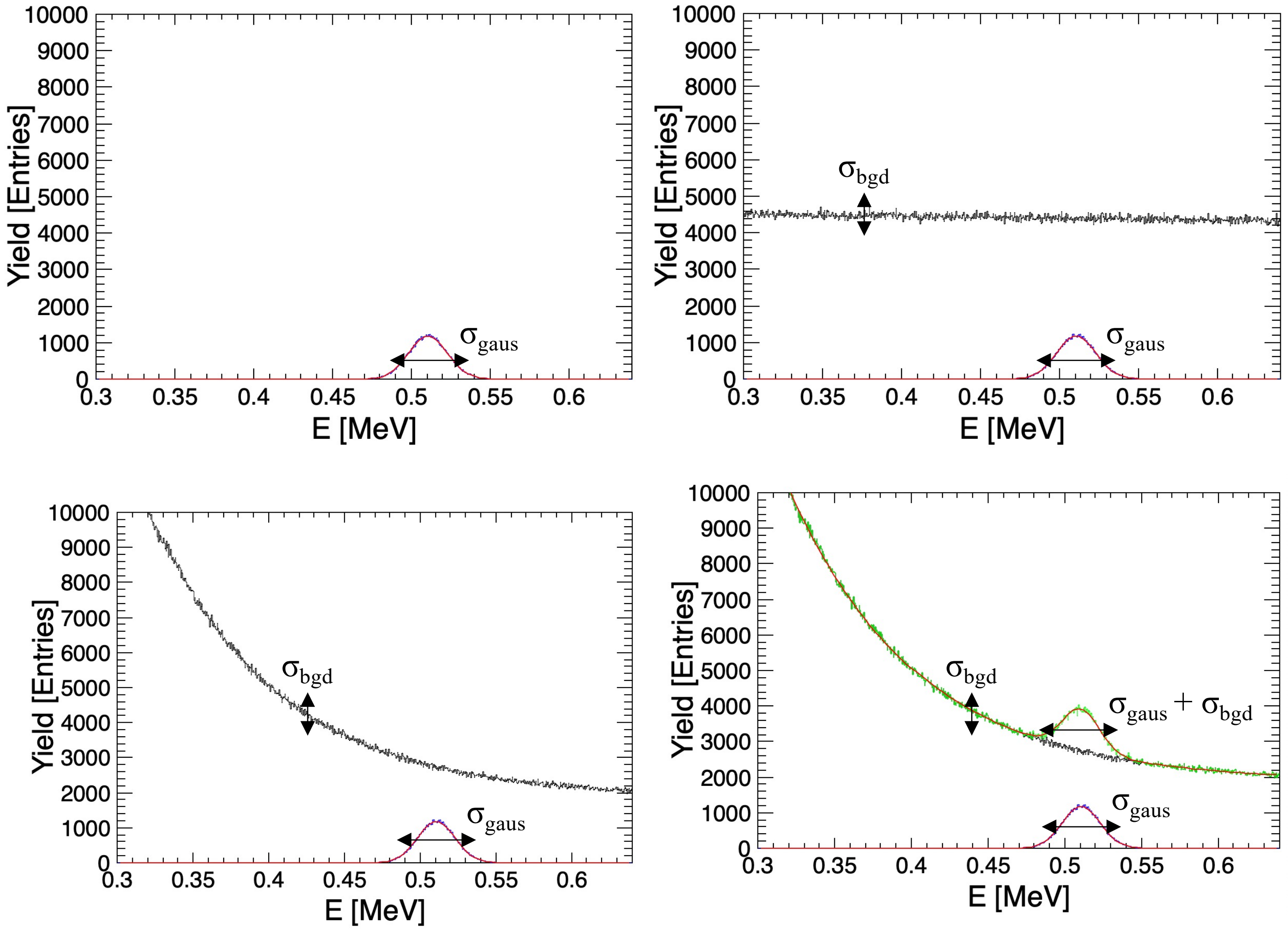
→ Differences between All-parameters and coincidence spectra parameters : $\mu_{\gamma\text{-All}} > \mu_{\gamma\text{-S3B,p1}}$

$\sigma_{\gamma\text{-All}} > \sigma_{\gamma\text{-S3B,p1}}$

→ The data are shifted to the right : larger mean and sigma due to the additional contribution of the possible neutron *(440 keV : p_1 + 451 keV : n_1)*

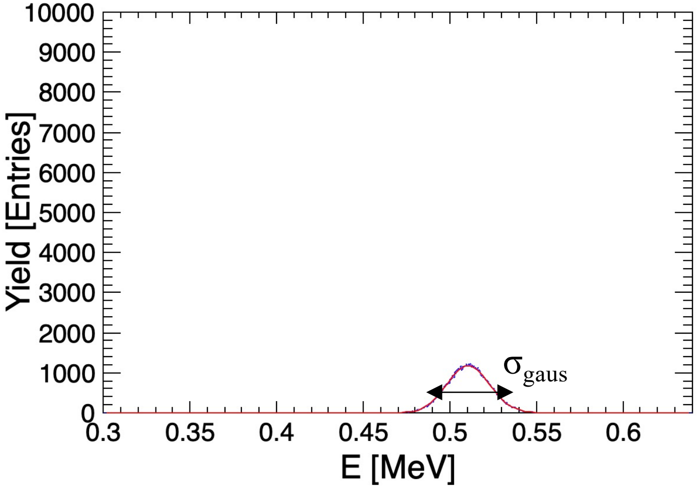
Simulation Study

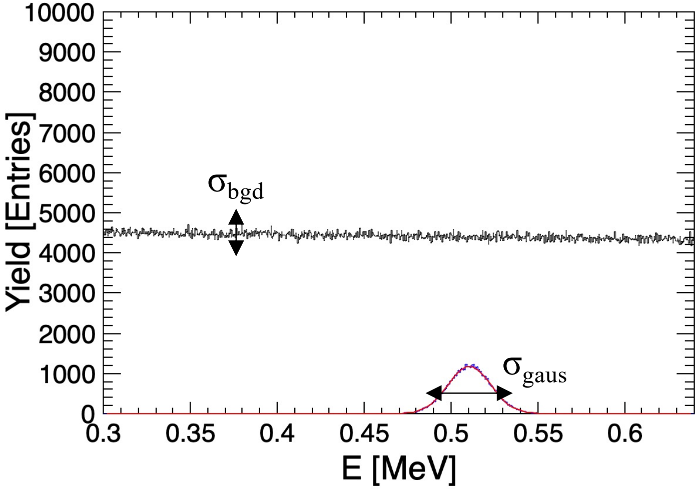
Study of the impact of statistical fluctuations

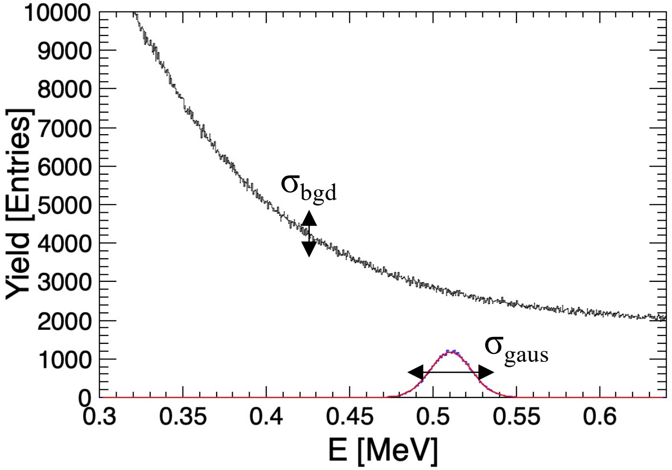


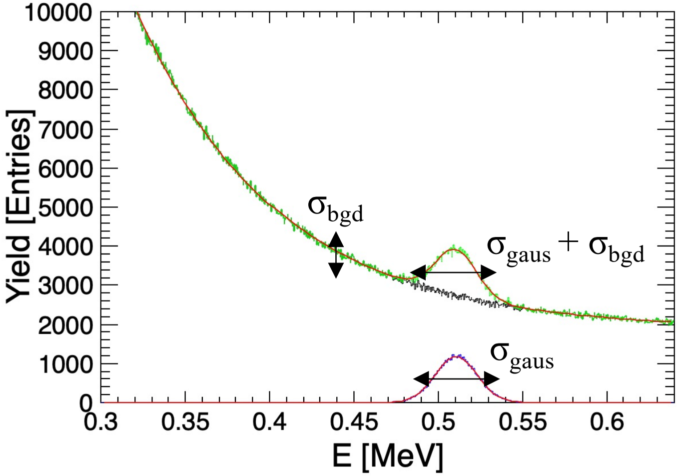
Simulation Study

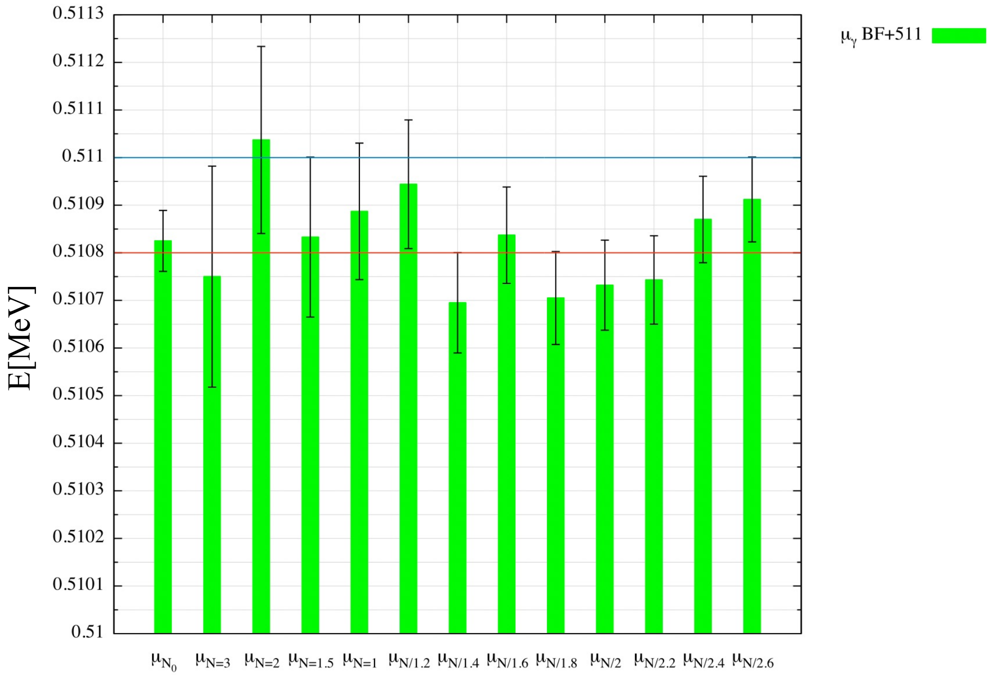
Study of the impact of statistical fluctuations

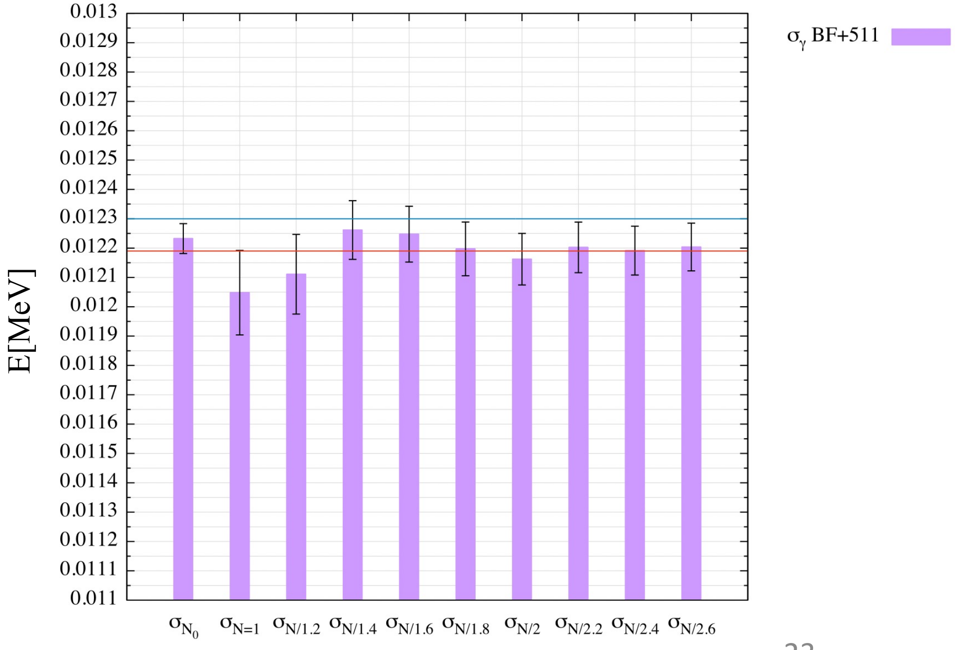










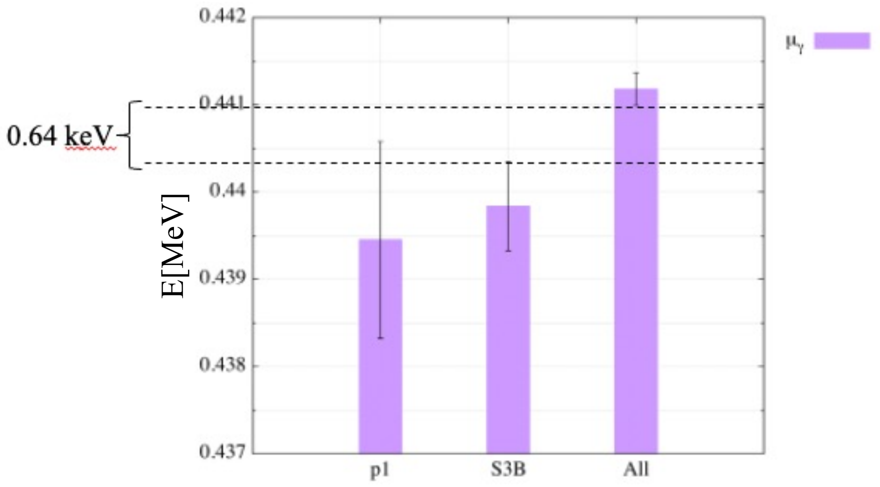


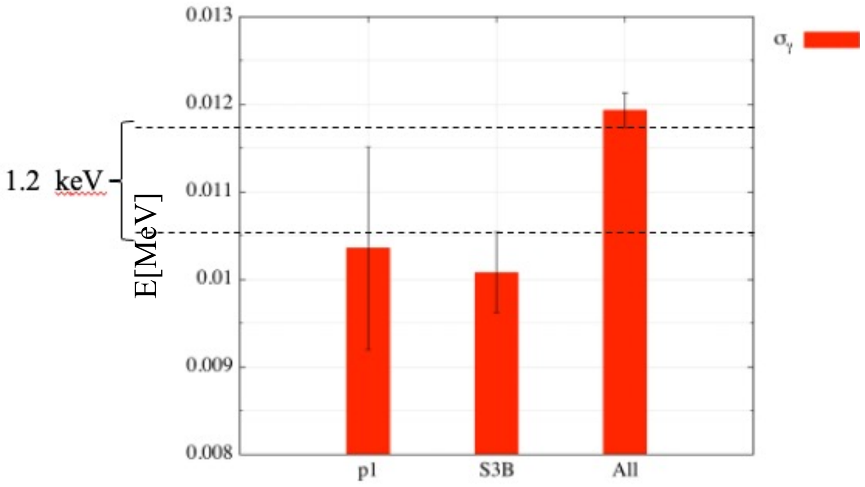
Simulation Study

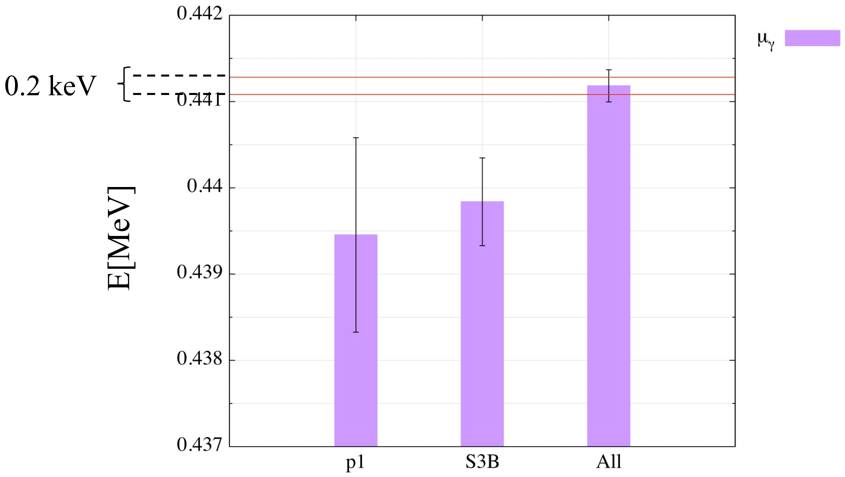
Study of the impact of statistical fluctuations

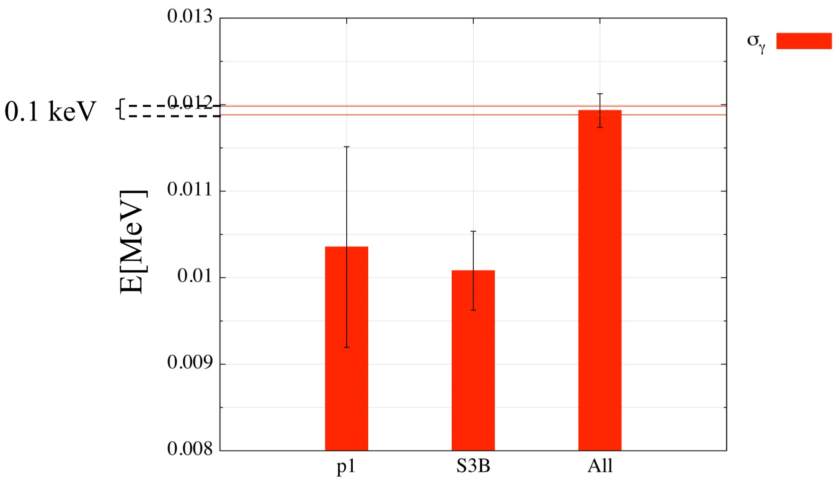
$\Delta\mu$: 0.20 keV < 0.64 keV
$\Delta\sigma$: 0.11 keV < 1.20 keV

→ Statistical fluctuations are not the cause of the energy shift and widening









Simulation Study

Study of the impact of statistical fluctuations

$\Delta\mu$: 0.20 keV < 0.64 keV
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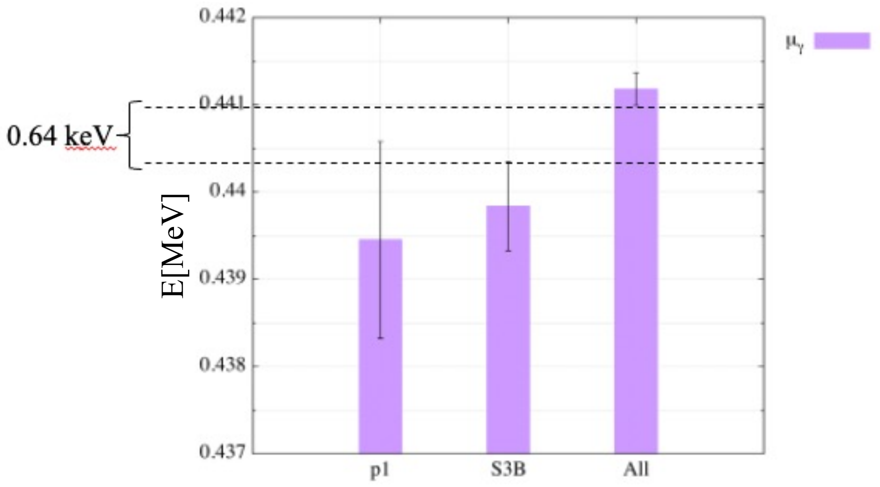
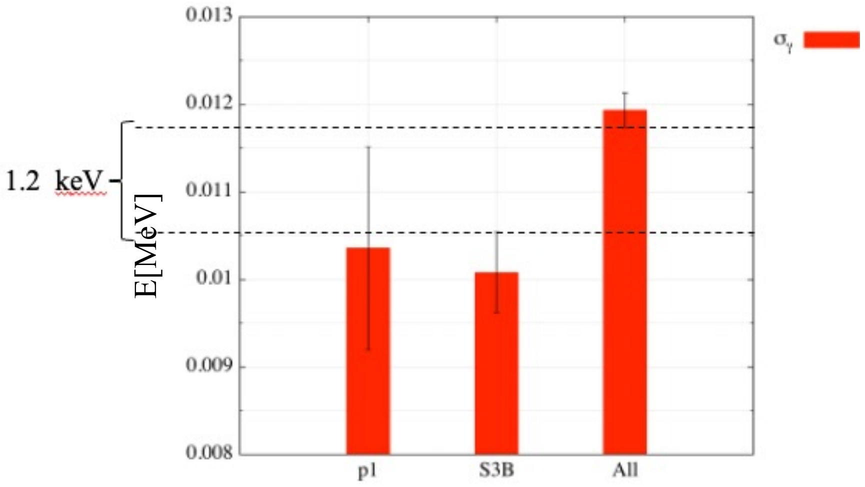
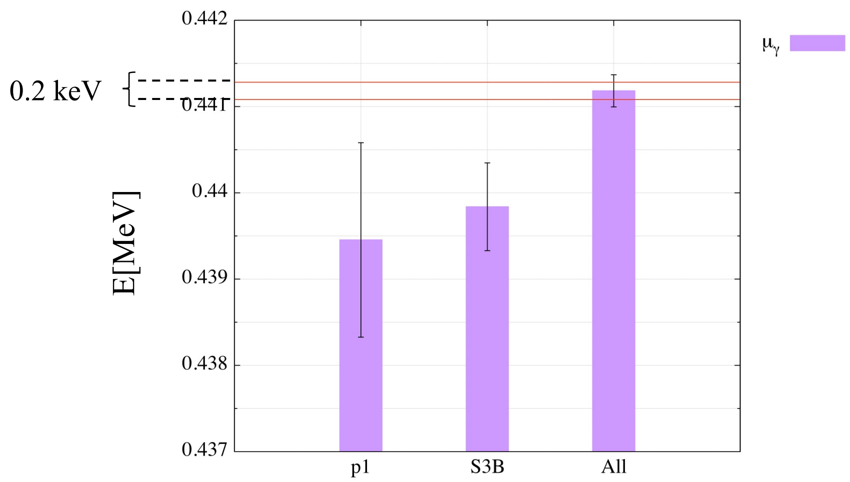
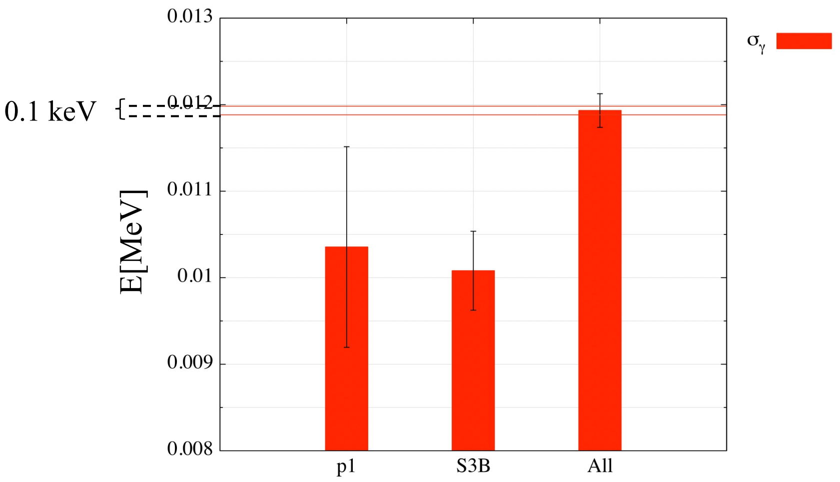
→ Statistical fluctuations are not the cause of the energy shift and widening

→ We can now look for the neutron contribution in the first peak









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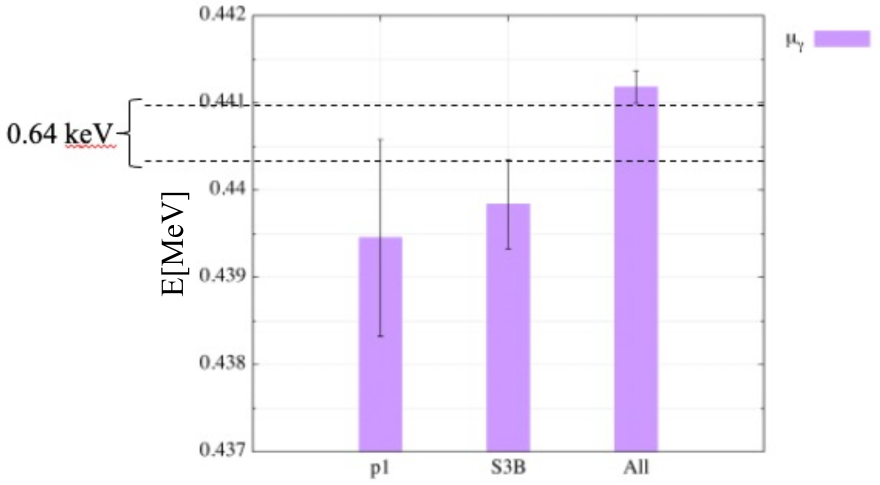
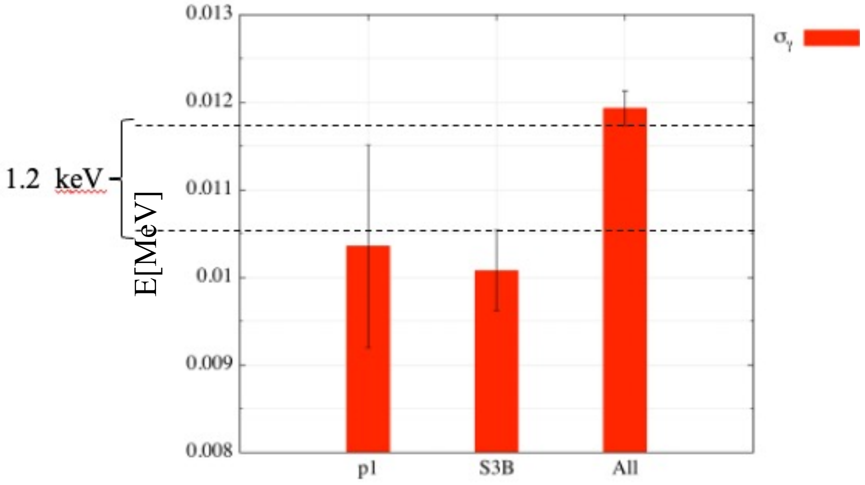
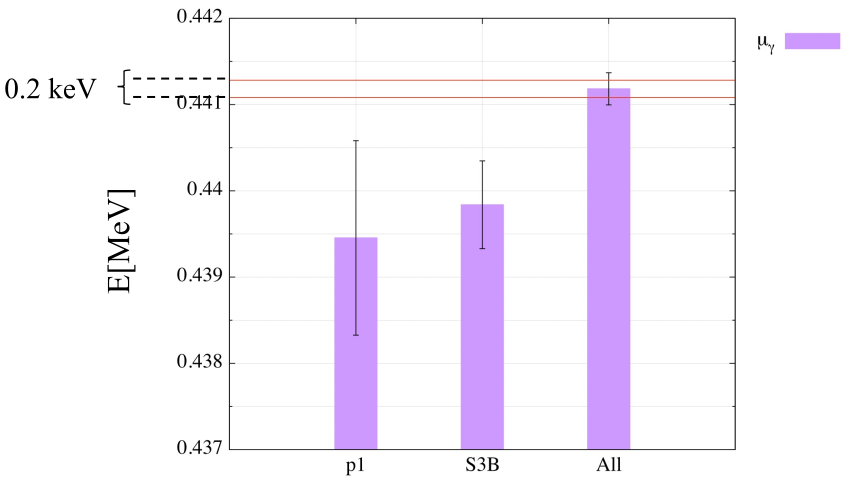
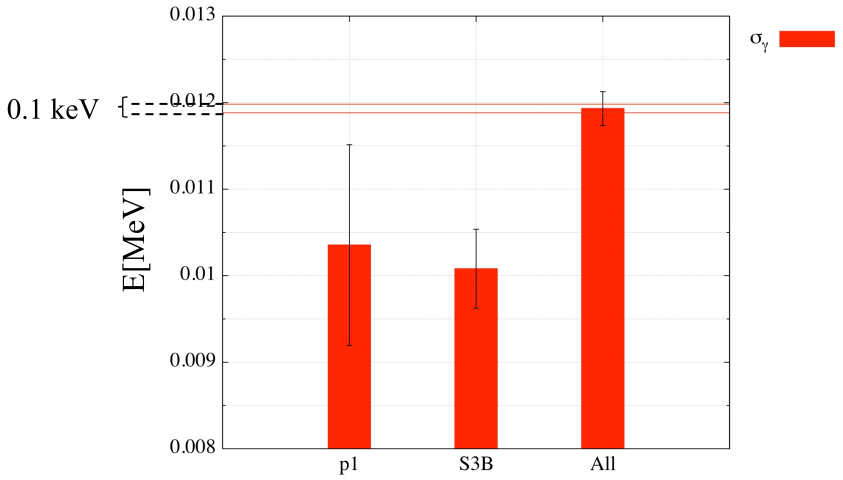








Δμ : 0.20 keV < 0.64 keV
Δσ : 0.11 keV < 1.20 keV

→ Statistical fluctuations are not the cause of the energy shift and widening

→ We can now look for the neutron contribution in the first peak

→ Normalisation : Same statistical relevance

$$I_{gaus} = \int_{-\infty}^{+\infty} A \exp\left(-\frac{1}{2}\frac{(x-\mu)^2}{\sigma}\right) \mathrm{d}x$$

With A : Amplitude, μ : Mean and σ : Sigma

$I_{gaus} = 32830$: Left peak

$I_{gaus} = 14435$: Right peak

$$I_{bgd} = \int_a^b (O\exp(Sx) + A)\,\mathrm{d}x$$

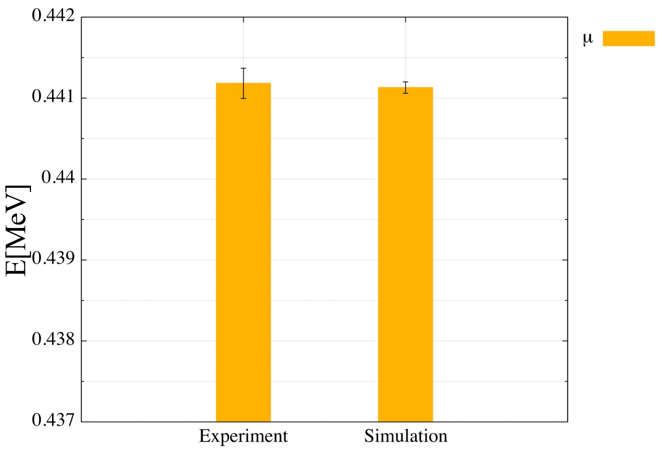
With O : Offset, S : Slope and A : Adjustment

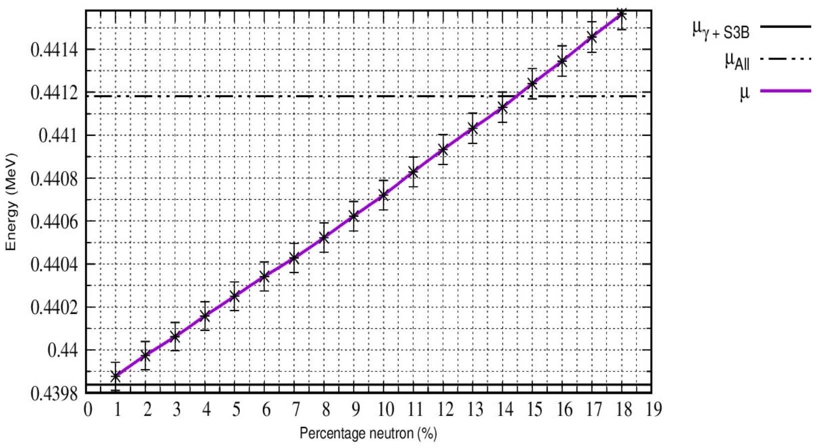
With a and b : interval normalisation

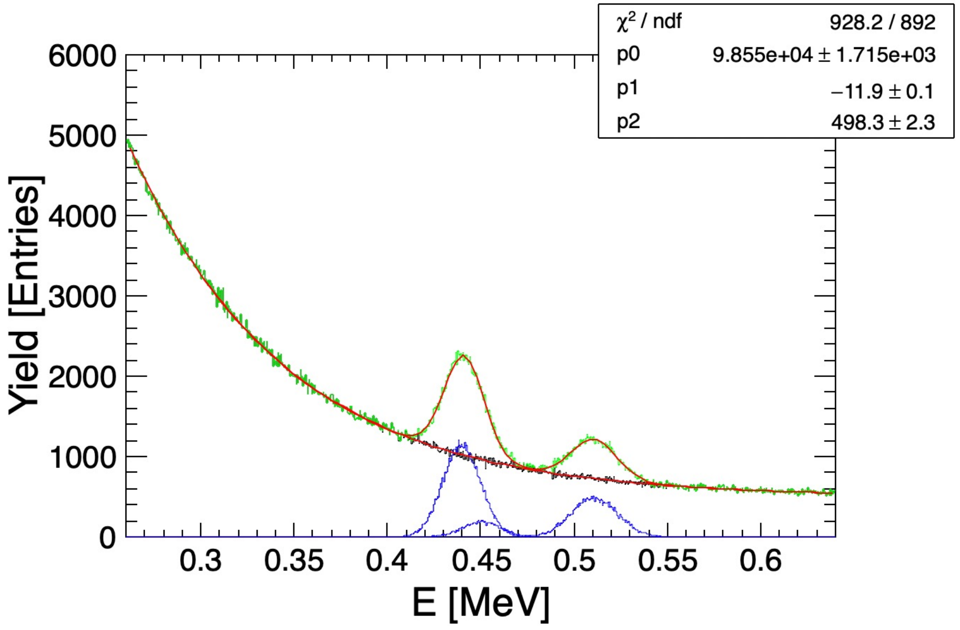
$I_{bgd} = 559836$: Background

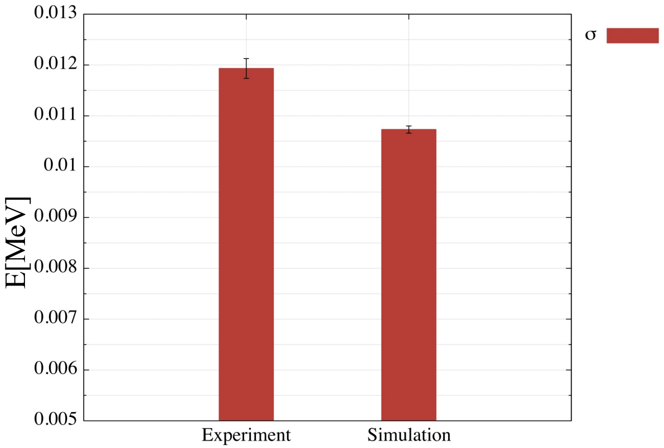
Simulation Study

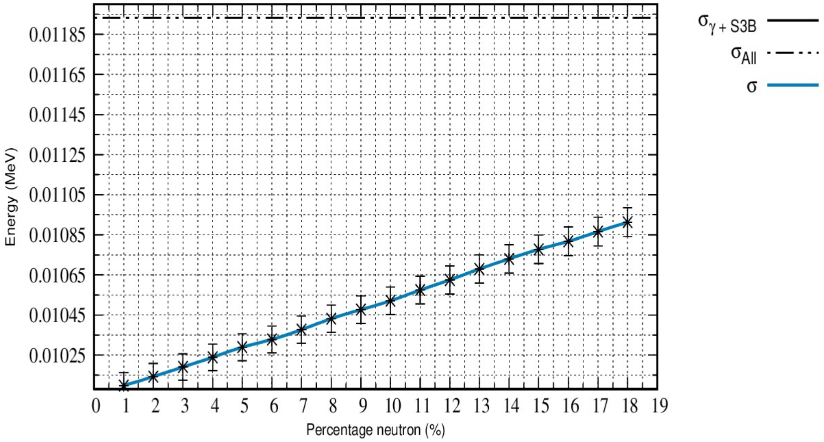
Study of the neutrons contribution







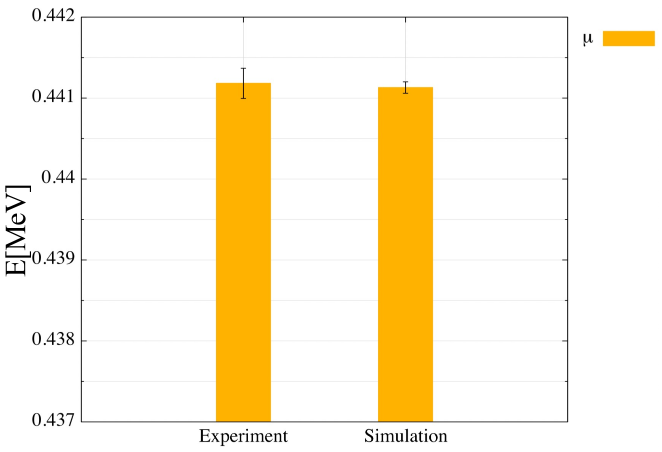


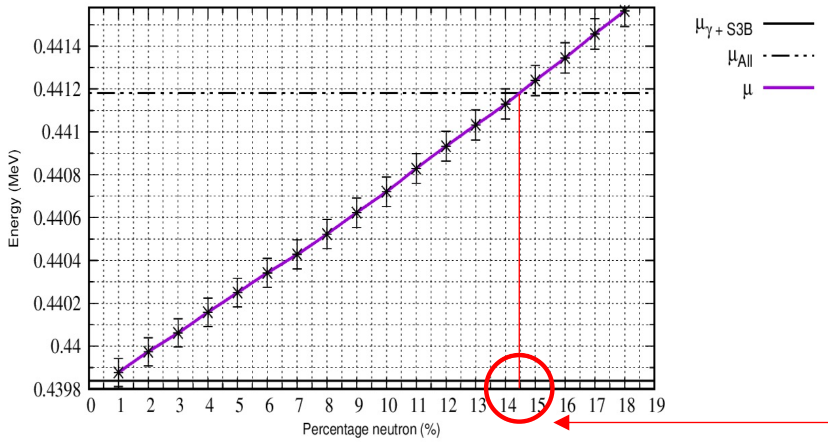


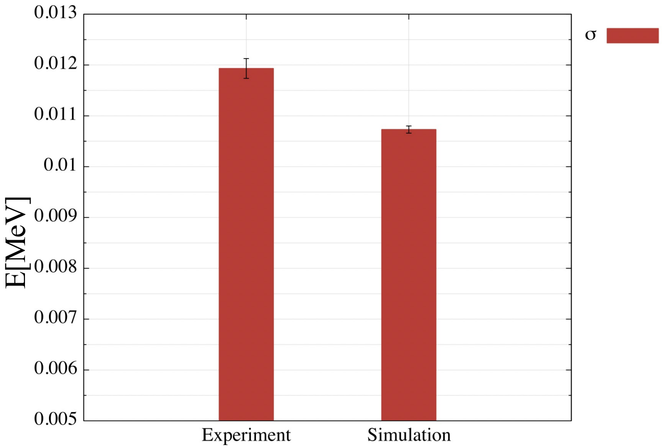
<u>Idea</u> : Reproduce total spectrum with proton gated parameters, to find the contribution of the neutron in the left peak

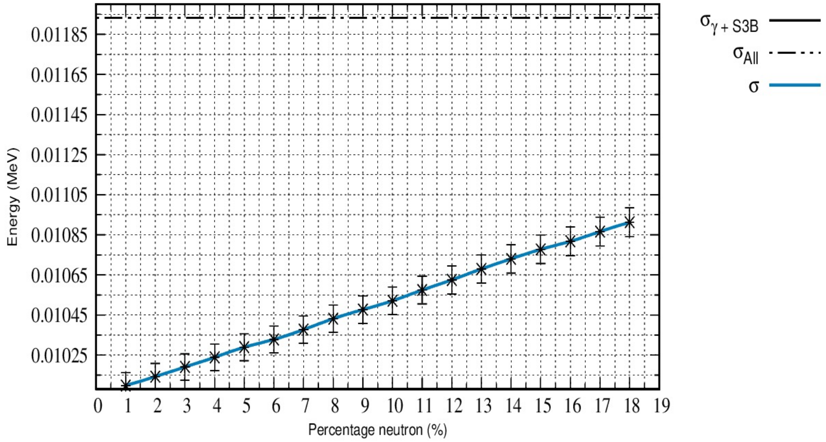
Simulation Study

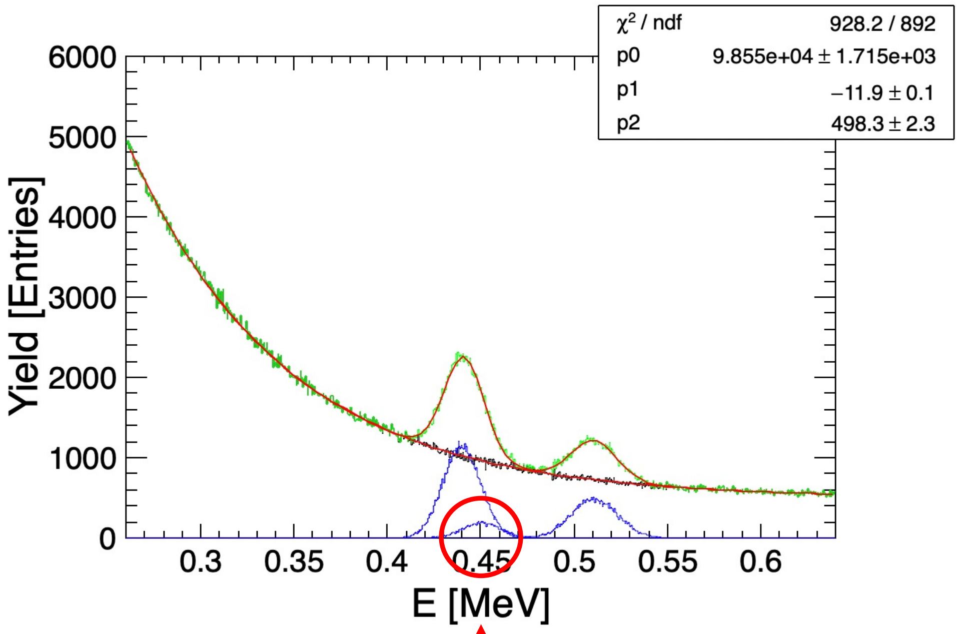
Study of the neutrons contribution











Idea : Reproduce total spectrum with proton gated parameters, to find the contribution of the neutron in the left peak

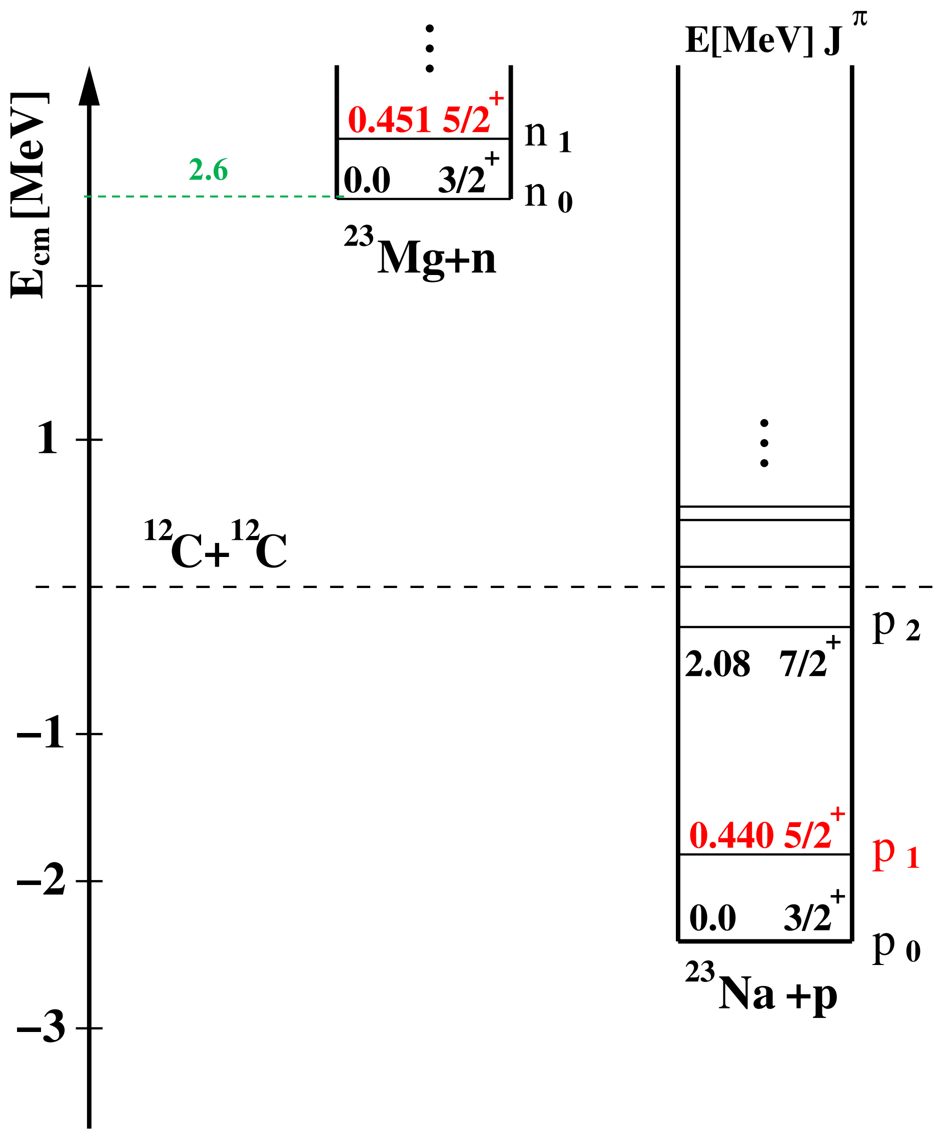
Blue : Peak γ_{p1} 440 keV (S3B)

Peak γ_{n1} 451 keV : 14.5% ± 0.5 %

Peak γ_{e+} 511 keV

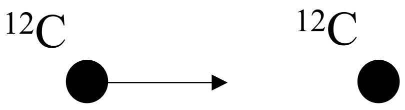
Green : Superposition Background + All

Q values and cross section calculation



Q_{values} : $E_{rel} - E_{state}$

$Q(n_0) = 2.90$ MeV
$Q(n_1) = 2.45$ MeV
$Q(n_2) = 0.85$ MeV
$Q(n_3) = 0.54$ MeV
$Q(n_4) = 0.18$ MeV
$Q(n_5) \approx 0.13$ MeV



$E_{rel} = 5.5$ MeV
$E_{beam} = 11$ MeV

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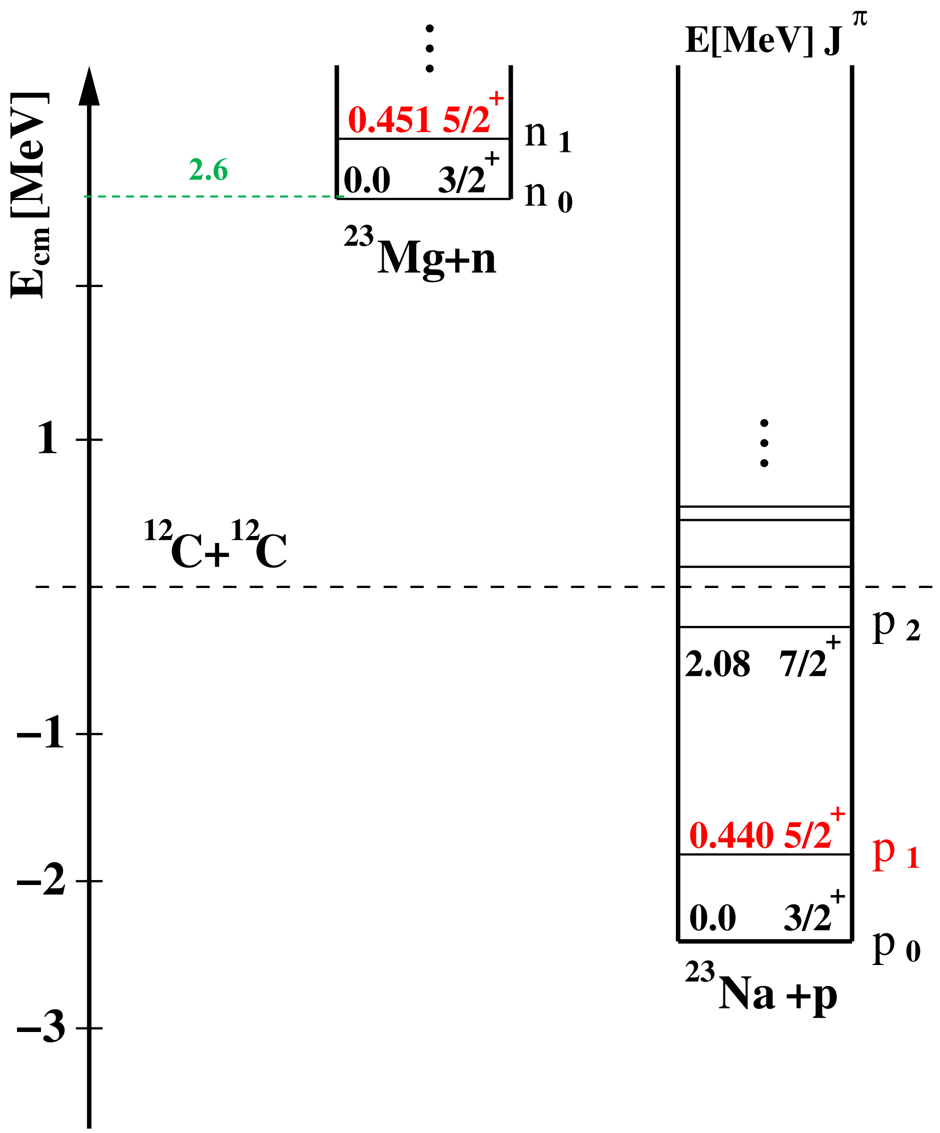

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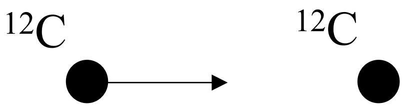

$E_{rel} = 5.5$ MeV
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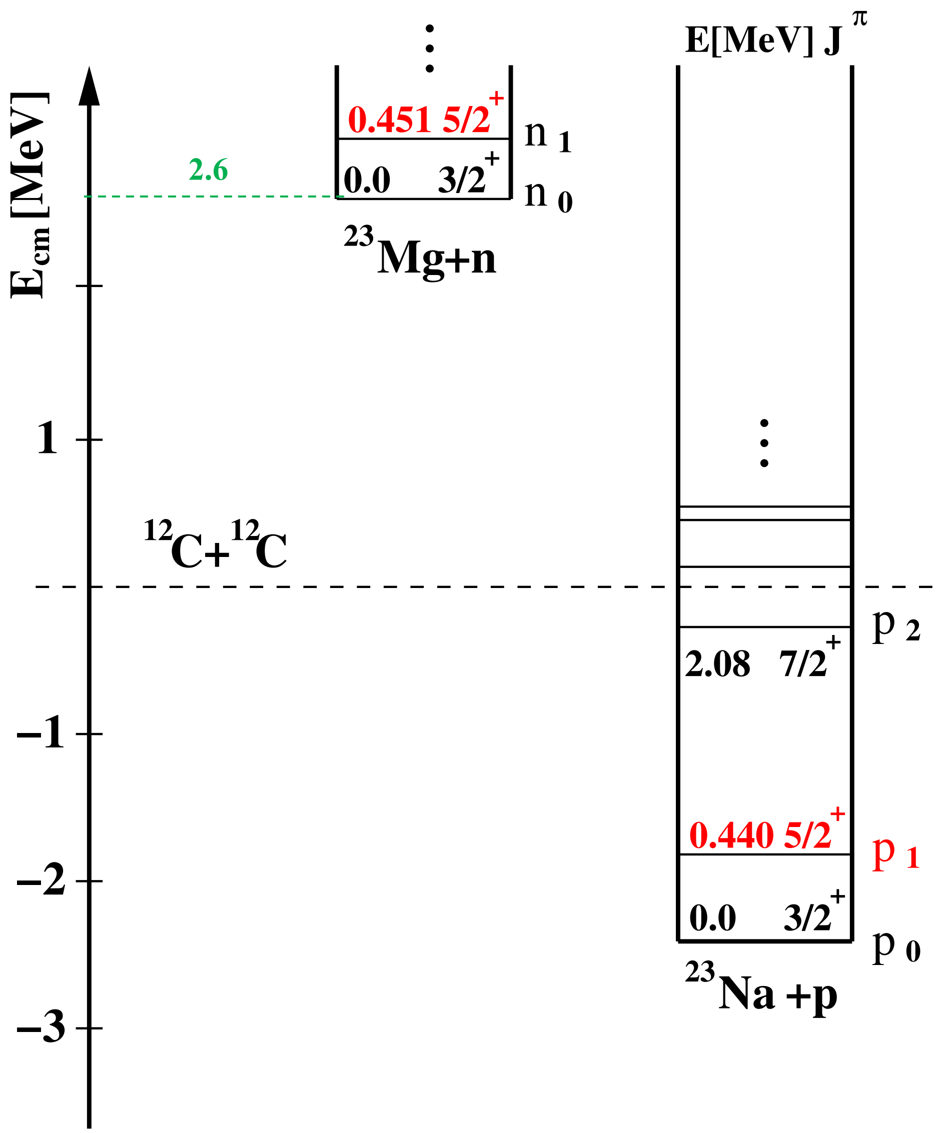
$$\sigma(\Sigma\sigma_i,\ 5.5\ \text{MeV}) = N_R \frac{1}{\frac{N_T}{A}} \frac{1}{N_P} \frac{1}{\epsilon} \frac{1}{\Delta t} = 1.7\ \text{mbarn}$$

N_R : Number of reactions
$N_{T/A}$: Number of targets per surface
N_P : Number of particles in the beam
ε : Efficiency of gamma ray detection in $LaBr_3$
Δt : Data acquisition time

Q values and cross section calculation



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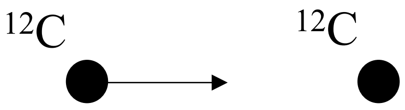

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$$\sigma(\Sigma\sigma_i + \sigma_0,\ 5.5\ \text{MeV}) = 1.6\ \text{mbarn}$$

B. Bucher *et al.*, Journal of Physics 2013

→ 1.7 mbarn > 1.6 mbarn but very encouraging

Conclusion

→ Characterization of experimental γ-spectra : All + Coincidences
→ Mismatch of peak parameters μ and σ
→ Simulation study for statistical relevance $\Delta\mu$ and $\Delta\sigma$
→ Simulation to reproduce full γ-spectra with gated parameters : First evidence of the 14.5 % $\pm$ 0.5 % neutron proportion in the ^{12}C + ^{12}C fusion reaction chain in this dataset
→ Calculation of cross-section + comparison with literature : near-matching result 1.7 mbarn > 1.6 mbarn

→ ROOT scripts : experimental data + simulation
→ Gnuplot : display
→ Modelisation of experimental data
→ Mathematica calculations

→ Model too simple : simulation
→ Analyse all 30 detetctors of STELLA
→ Study to be further developed for possible publication
→ Choose an energy with only allows population of the n_1 level

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