UNDERSTANDING COSMIC ABUNDANCE OF ^{22}NA
GANIL E710

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Introduction

Nova

- ^{22}Na interesting test for Nova model
- E_γ 1.275MeV line never been observed

Resonant reaction

- Main destruction : ^{22}Na(p, γ)^{23}Mg
- Resonance strengths from direct/indirect measurements

GANIL experiment

- GANIL indirect experiment (particle / γ detectors)
- Isolation of ^{23}Mg* γ lines
- First estimation of one ^{23}Mg* lifetime by DSAM

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Astrophysical context : Novae

Nova = white dwarf (WD) star accreting matter from red giant

Thermonuclear events at WD surface

Novae model uncertainties
- Amount of admixed WD material with accreted matter
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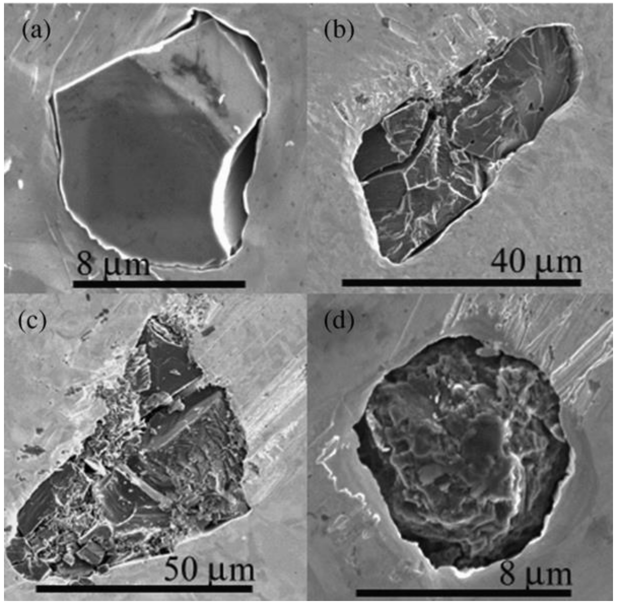

Impact
- Abundances of nuclei
- Test of Nova models
- Isotopic anomaly presolar grains in meteorites
- Excess of ^{22}Ne in the galactic cosmic rays
- Number of supernovae SNIa (dark energy)

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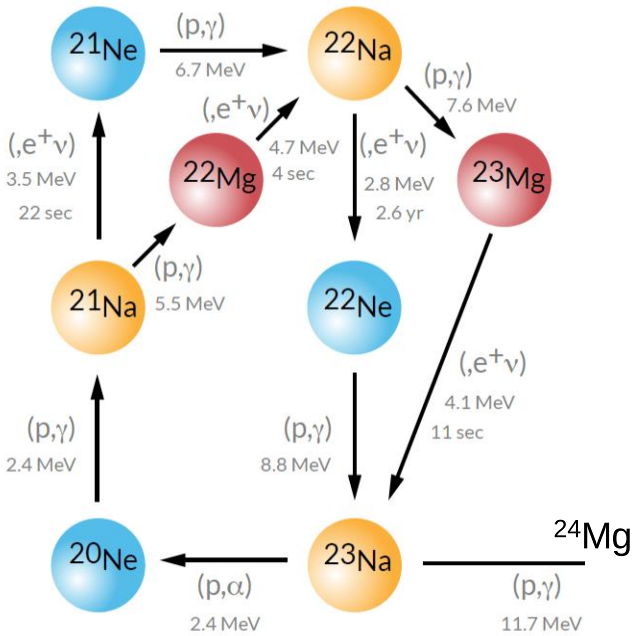


Ne-Na Cycles

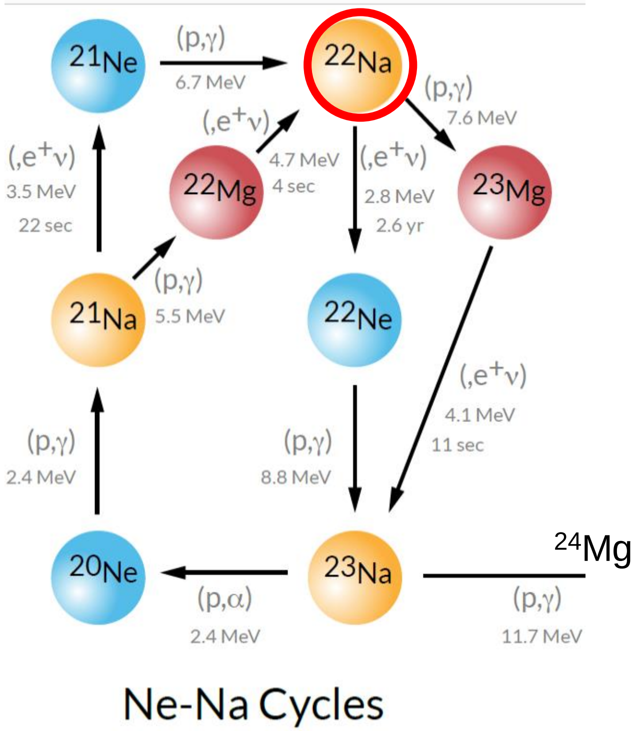
$T_{nova} = 0.04 < T_9 < 0.4$

Astrophysical context : Novae

ONe novae : synthesis of radioactive nuclei

^{22}Na τ=2.6yr

- Transparent to thermonuclear medium
- Space correlation with Nova



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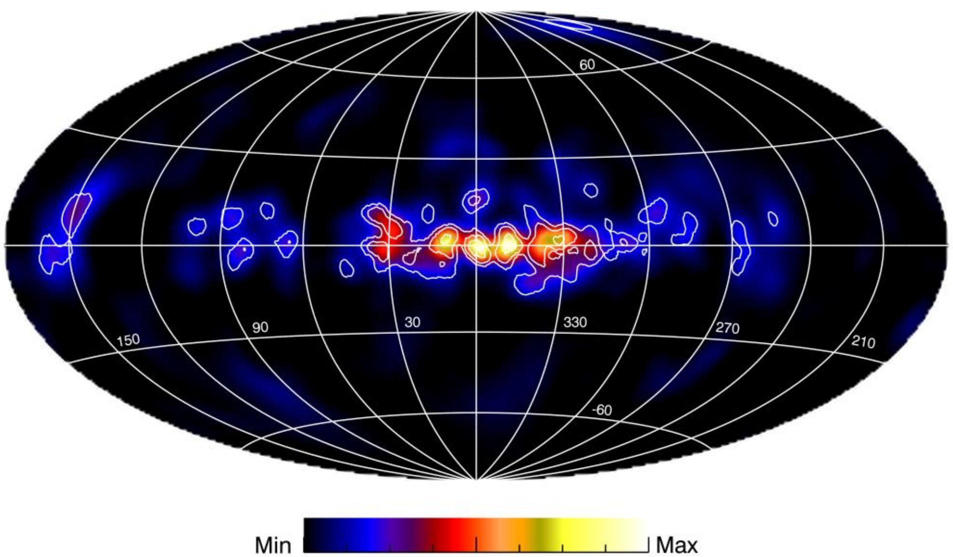
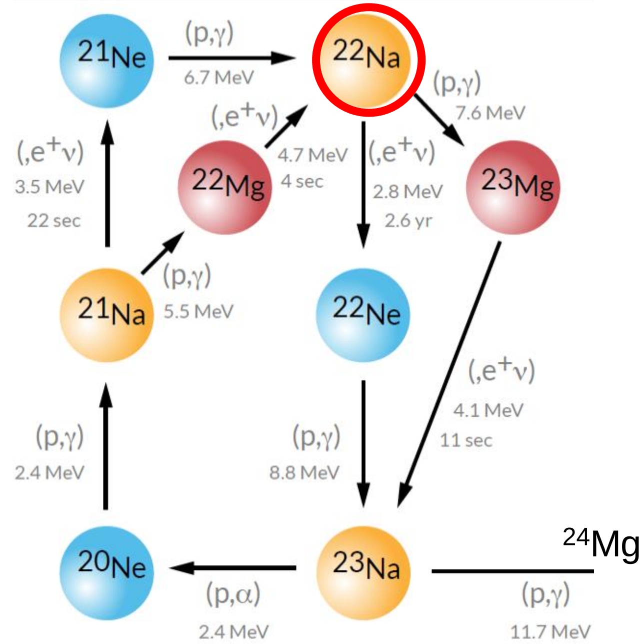
γ-ray telescopes observation
(SPI/INTEGRAL, COMPTEL/CGRO…)



Example : sky map from SPI 3yr exposure at E_γ = 1.809 ^{26}Al (esa)



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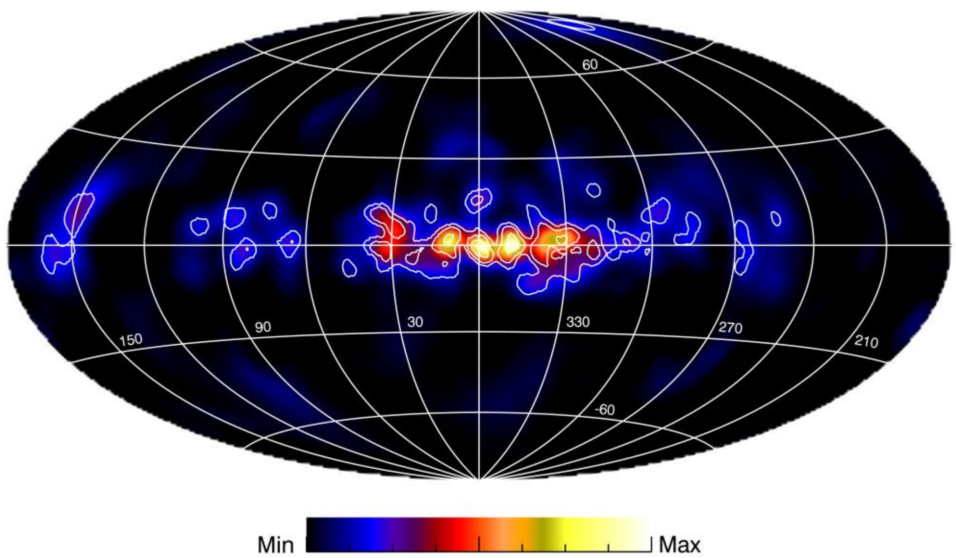

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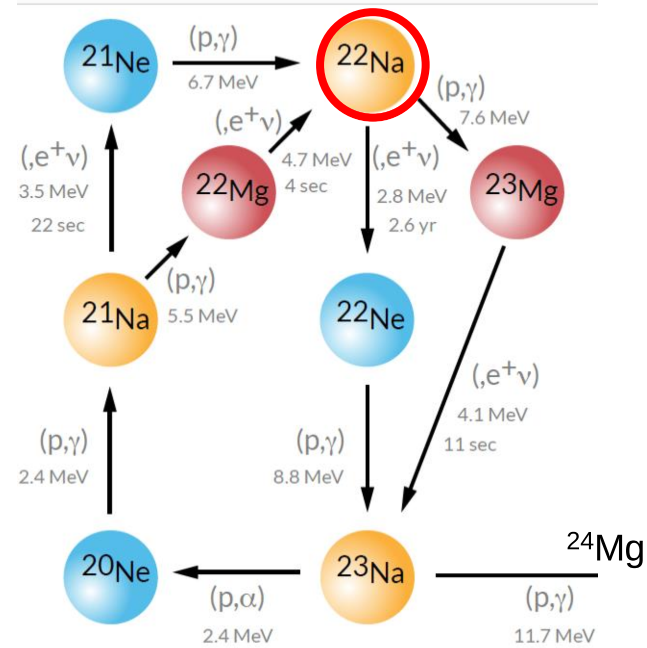

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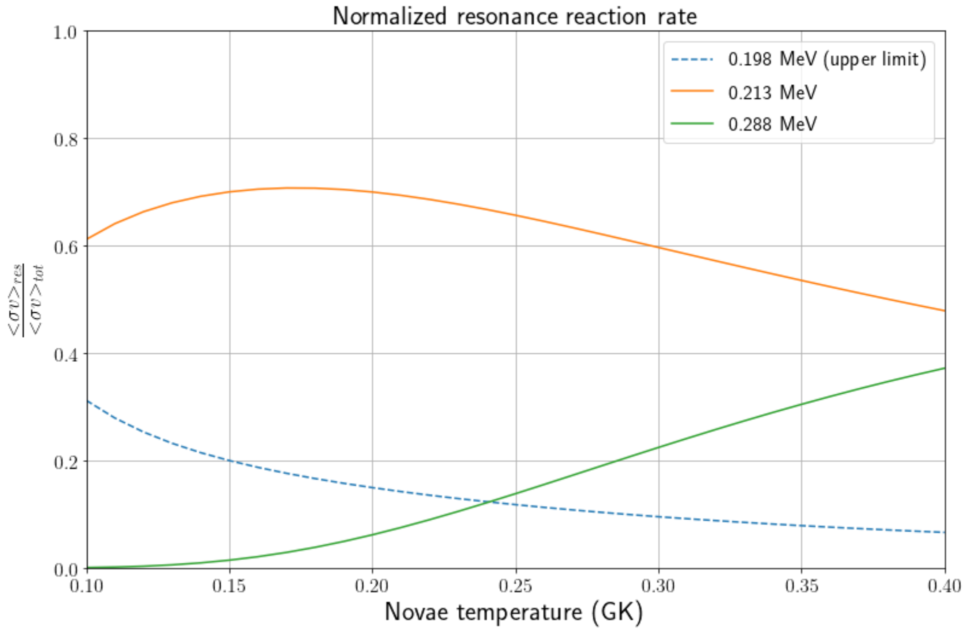

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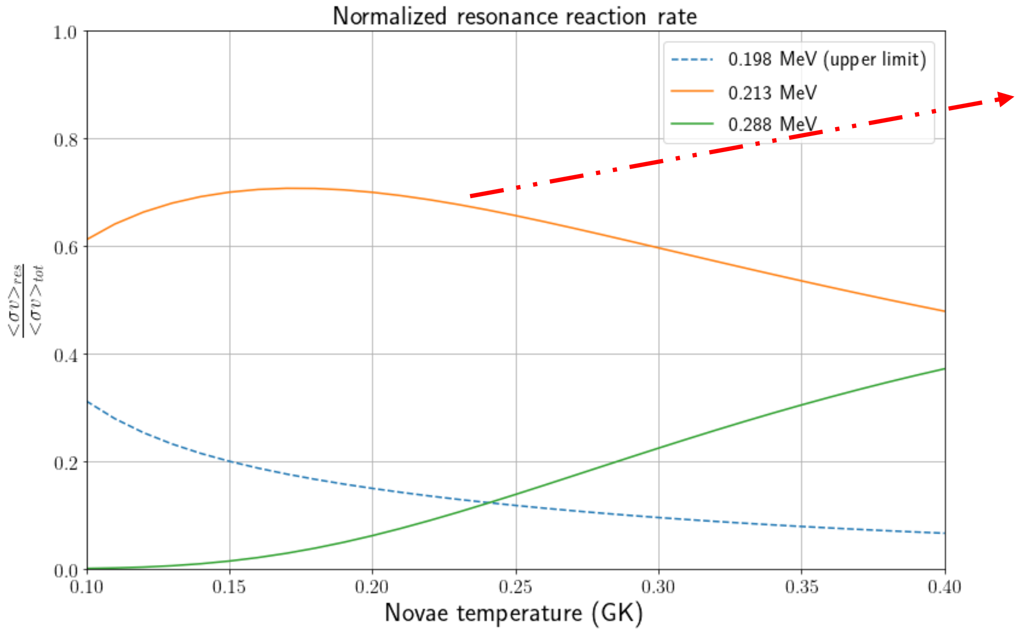

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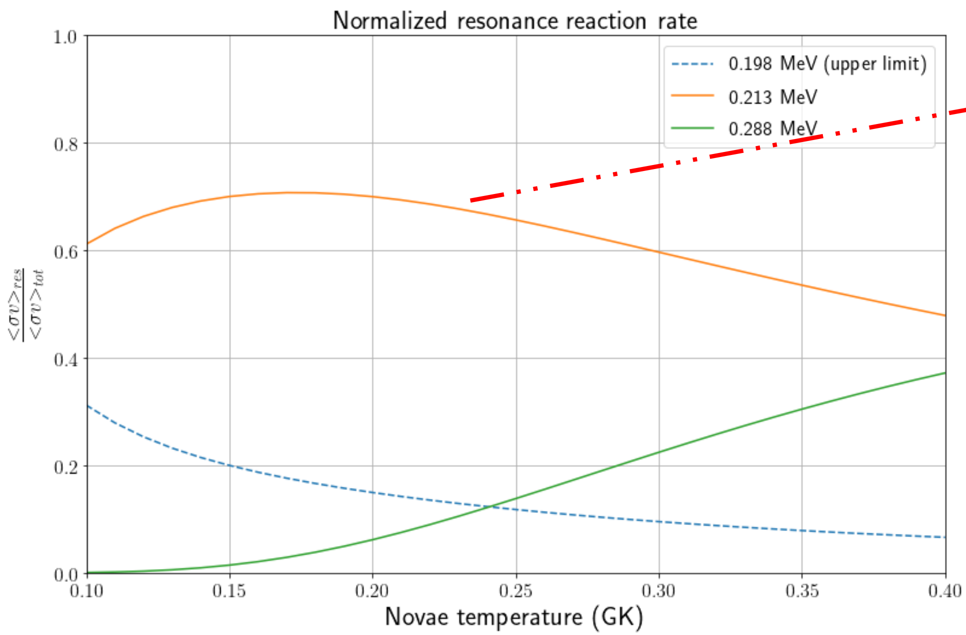

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Measurements	$\omega\gamma$ (meV)
Direct (Bochum, Germany)	1.8 ± 0.7
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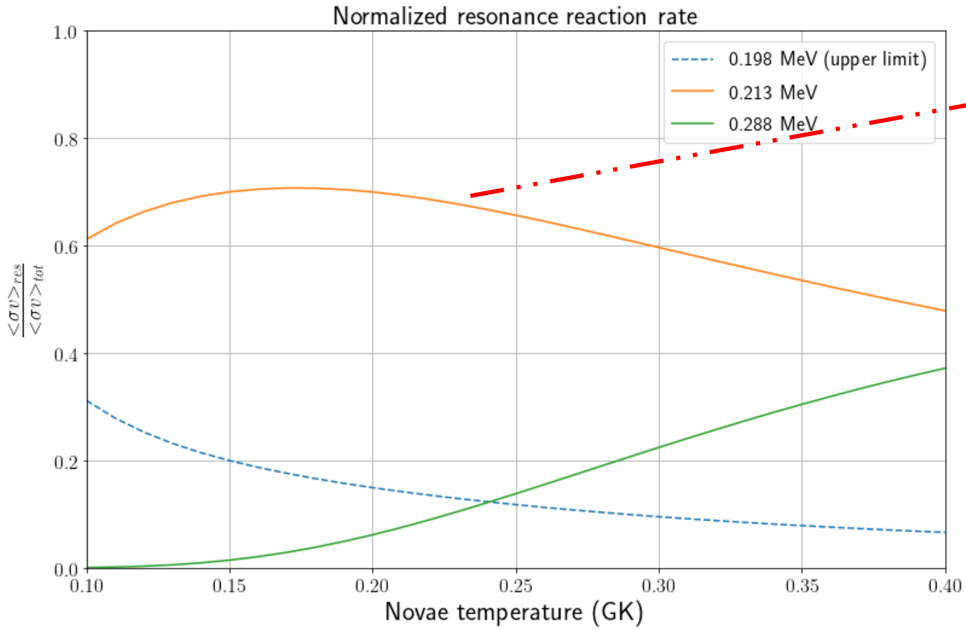

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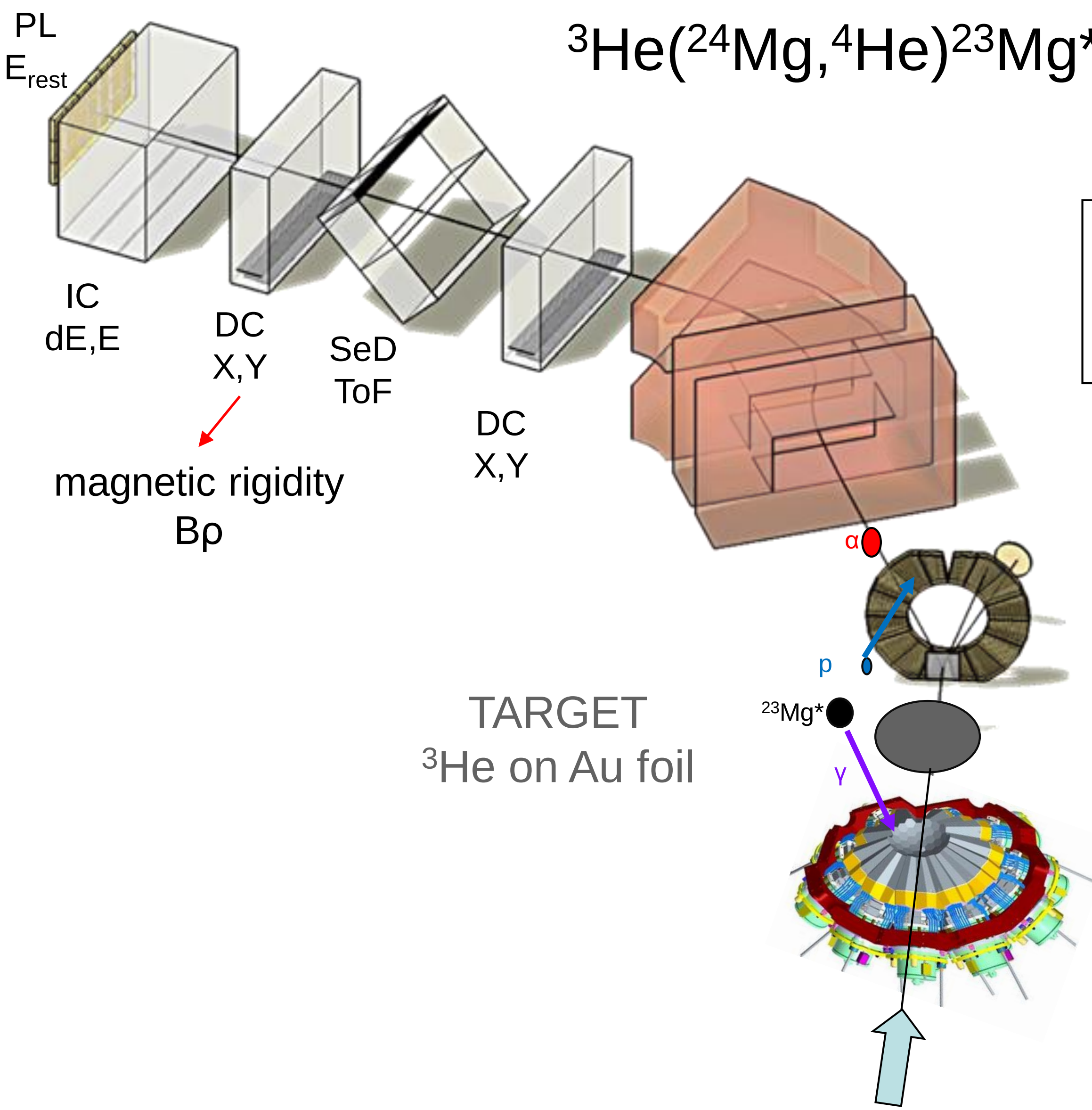
$$\omega\gamma = \frac{2J+1}{(2J_{^{22}Na}+1)(2J_p+1)} * \frac{\hbar}{\tau} * B_p(1-B_p)$$

GANIL E710 indirect method

$^{23}Mg_{7.786}$ lifetime τ (AGATA fs resolution by DSAM (1)) and B_p => $\omega\gamma_{0.213}$

GANIL E710 : Experimental setup

$^{3}He(^{24}Mg,^{4}He)^{23}Mg^{*}$



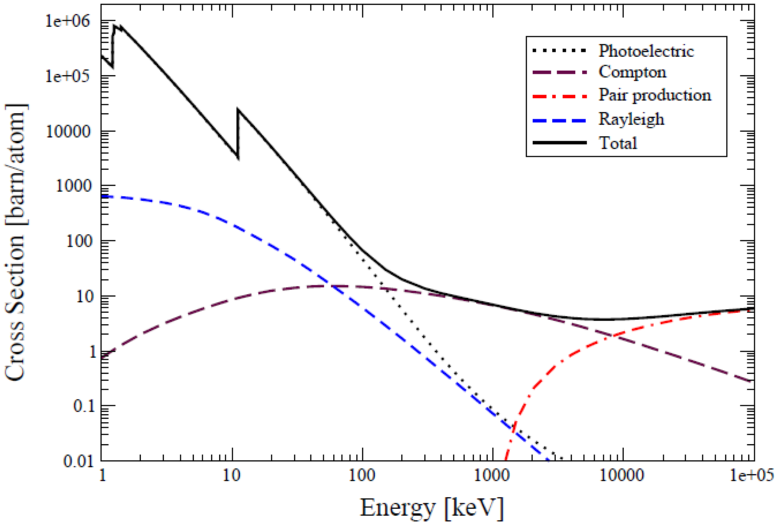
VAMOS
magnetic spectrometer
=> ^{4}He

SPIDER
dE-E Si detector
=> p

AGATA
segmented Ge array
=> γ from $^{23}Mg^{*}$

γ in AGATA coïncidence with particles in VAMOS or SPIDER

GANIL E710 : main detector AGATA



Gamma interaction cross-section in Ge (from (1))
=> [1,10]MeV Compton Scattering dominant

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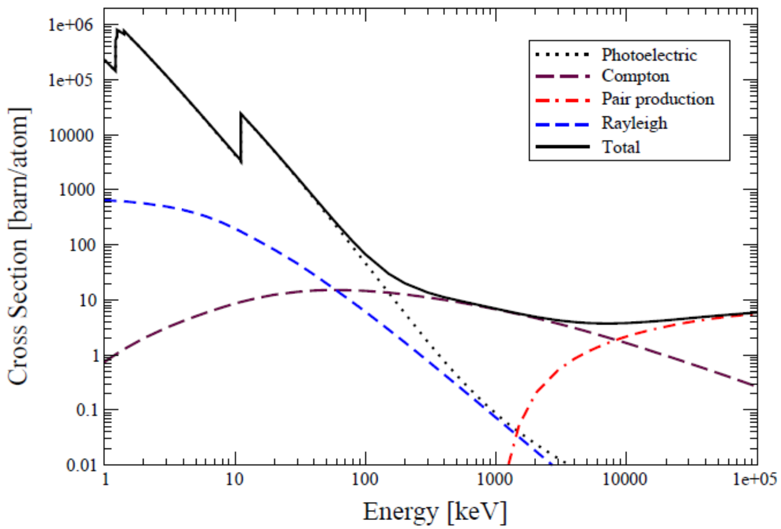

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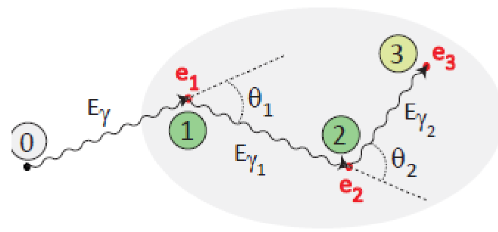

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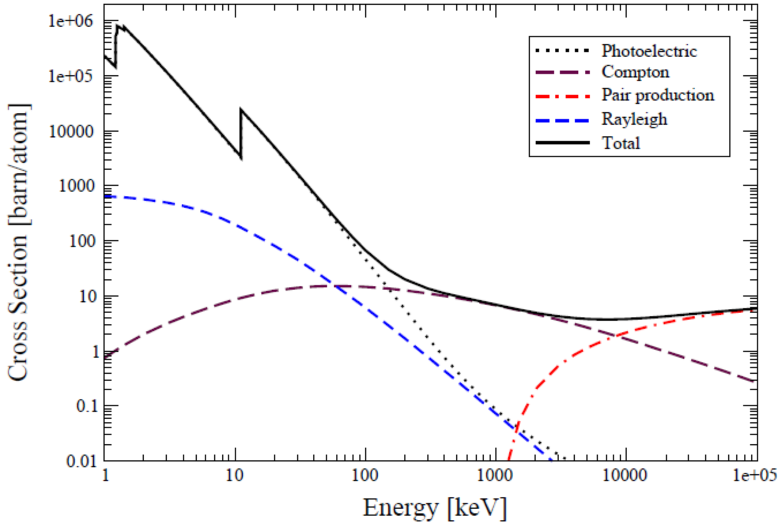

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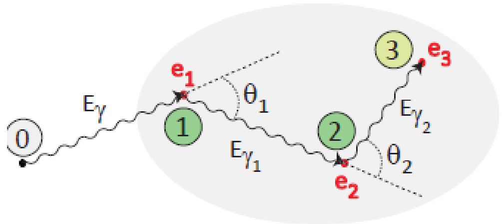

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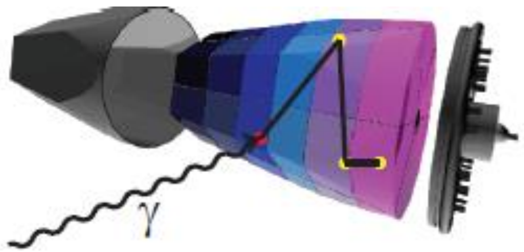

32 Crystals

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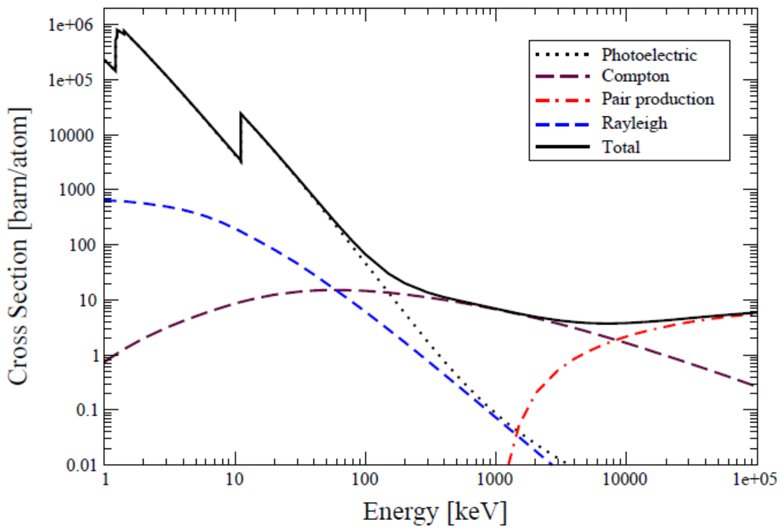

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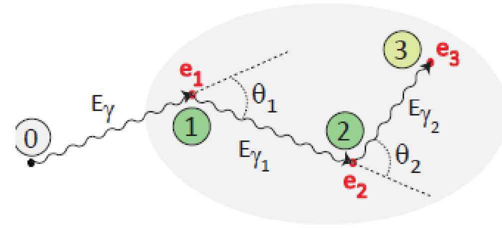

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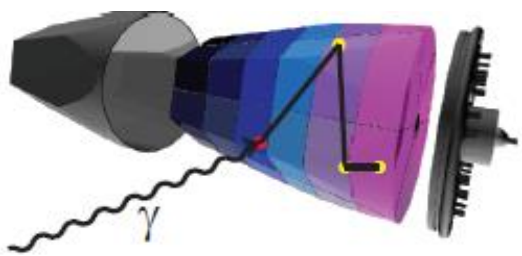

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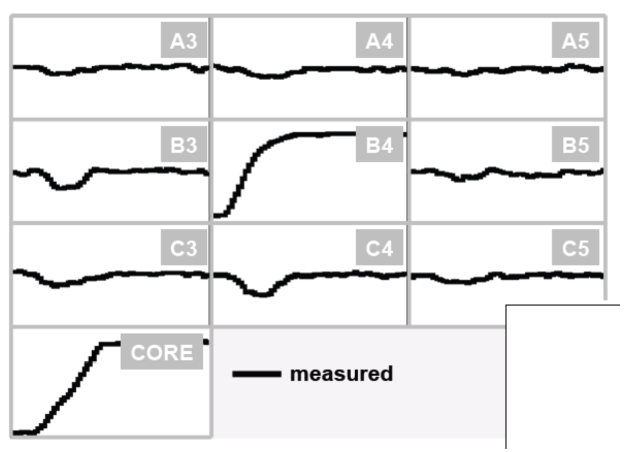

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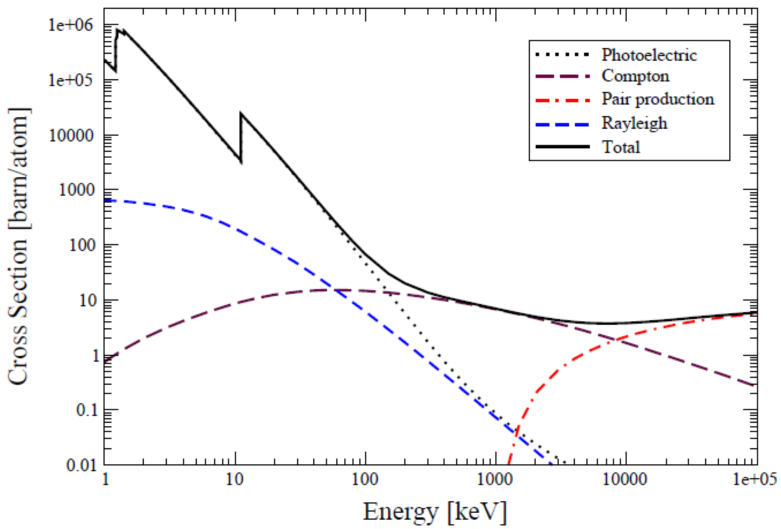

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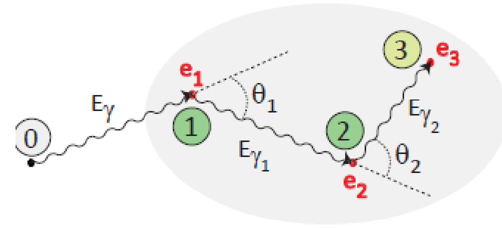

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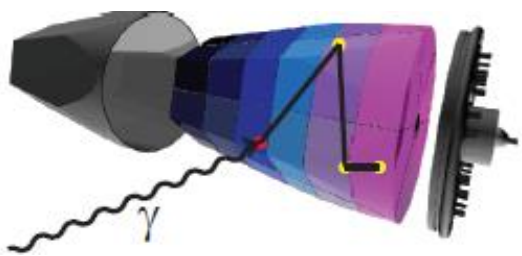

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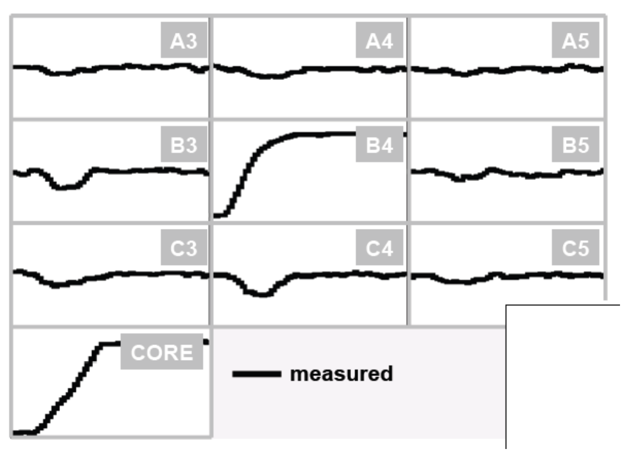

Individual interaction points $(X,Y,Z,E,t)_i$

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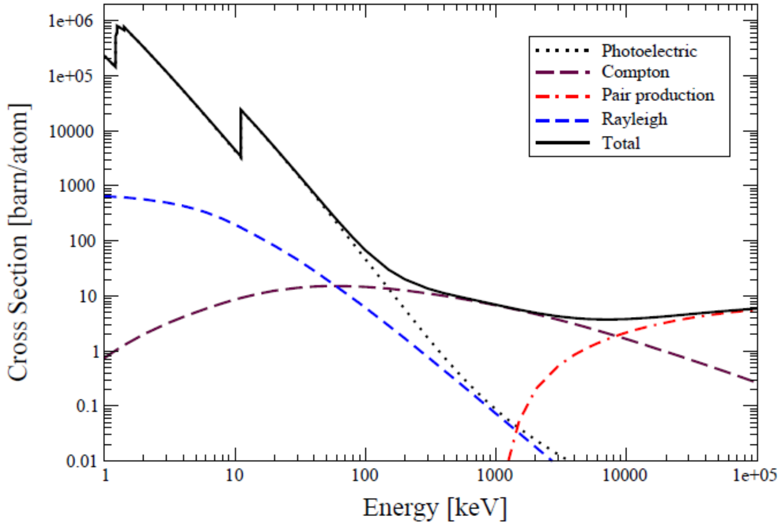

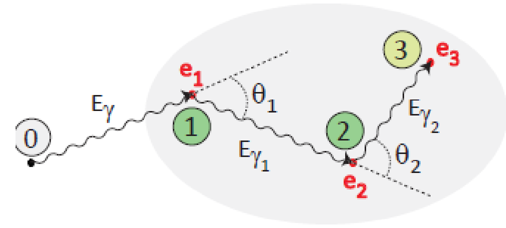

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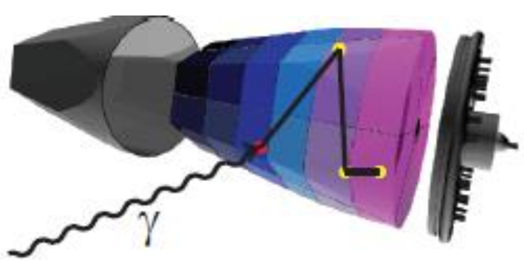

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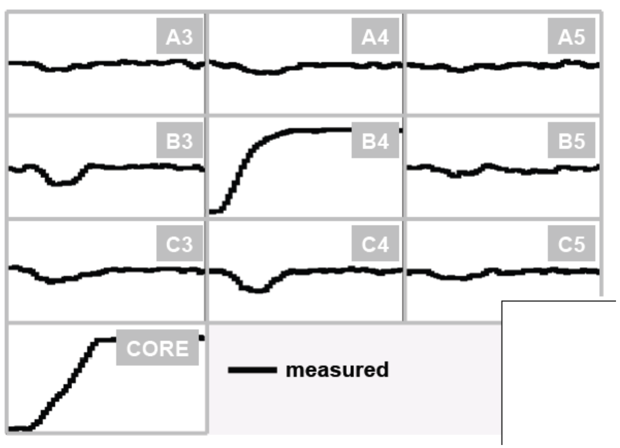

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Tracking algorithm
(based on Compton Scattering)

(E_γ, θ)
d(2keV, 2 degrees)

SPIDER first results

Identification of light reaction elements (p, ^{4}He)

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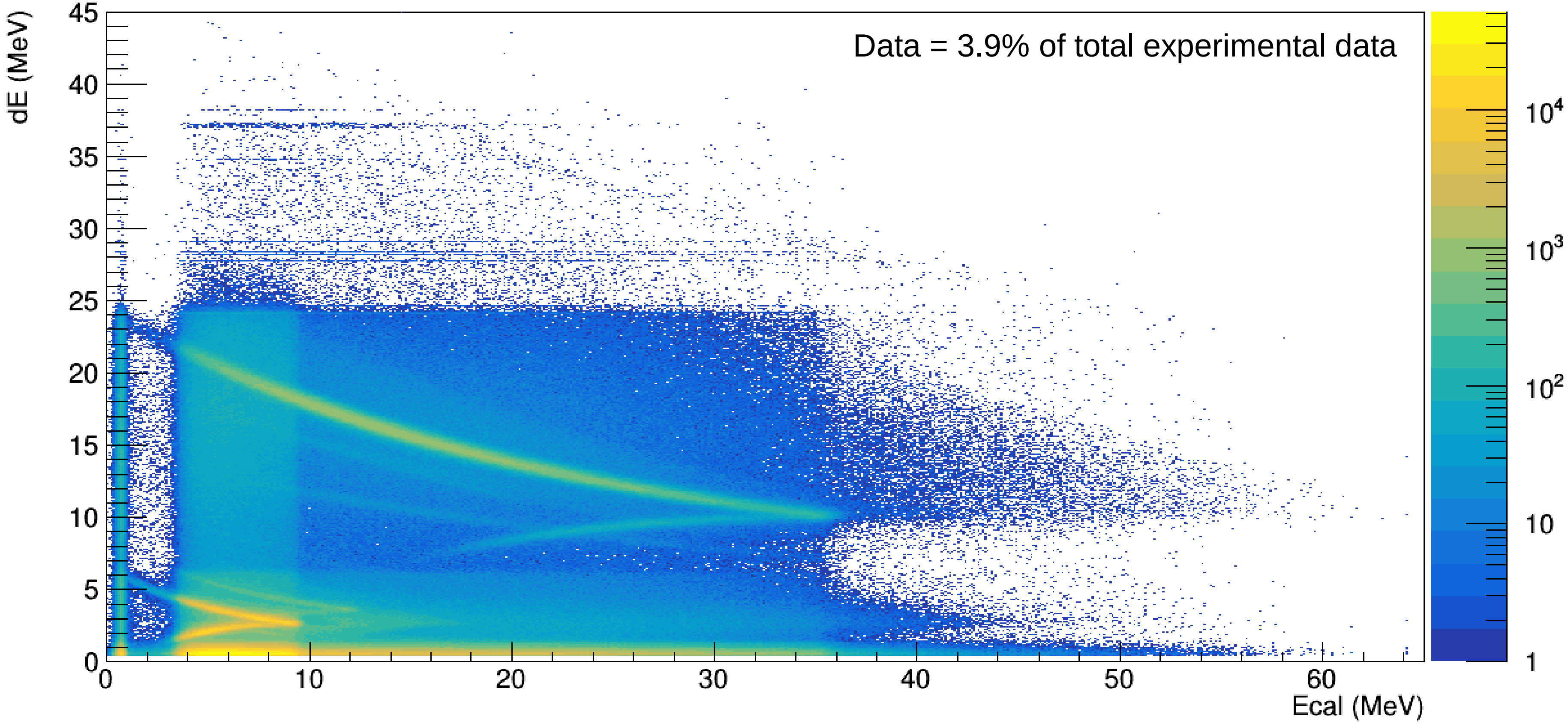

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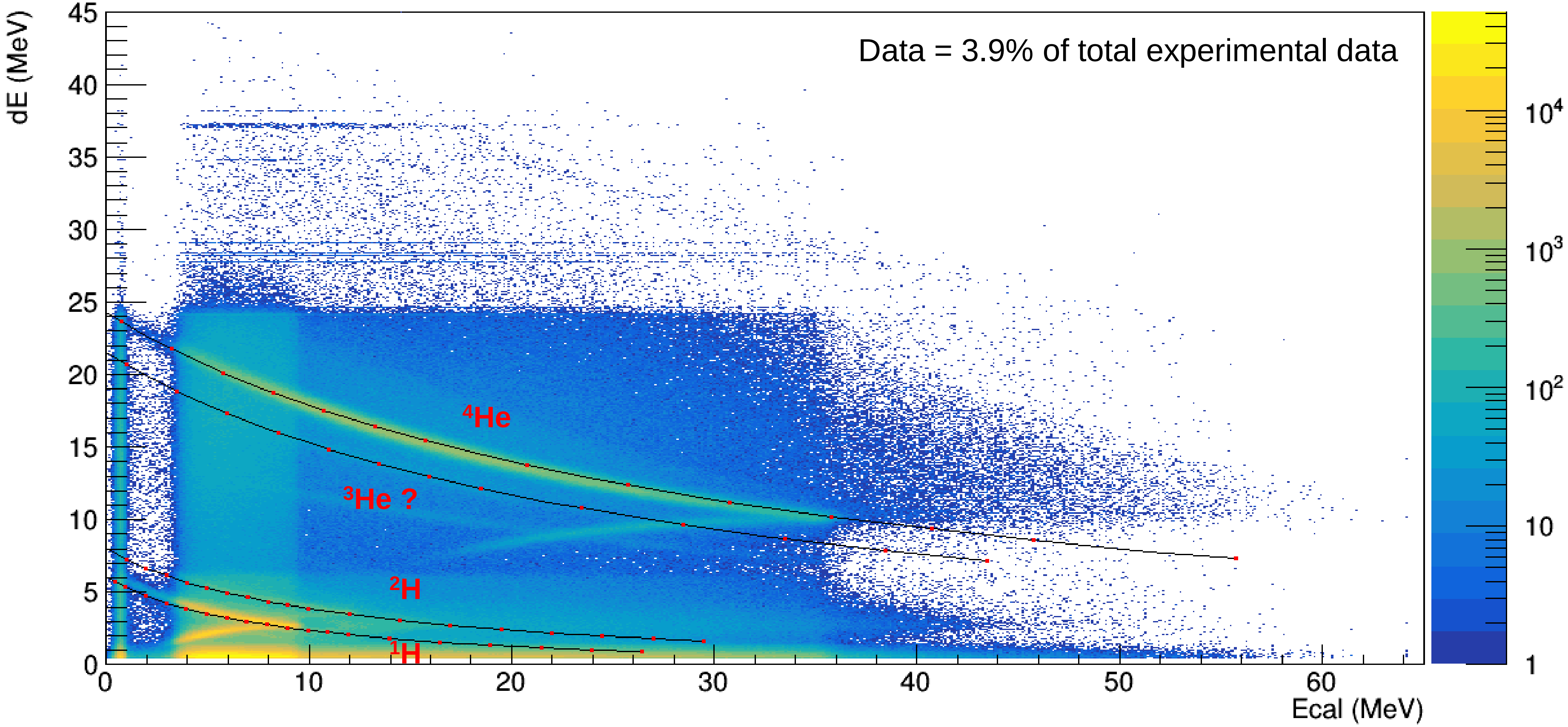

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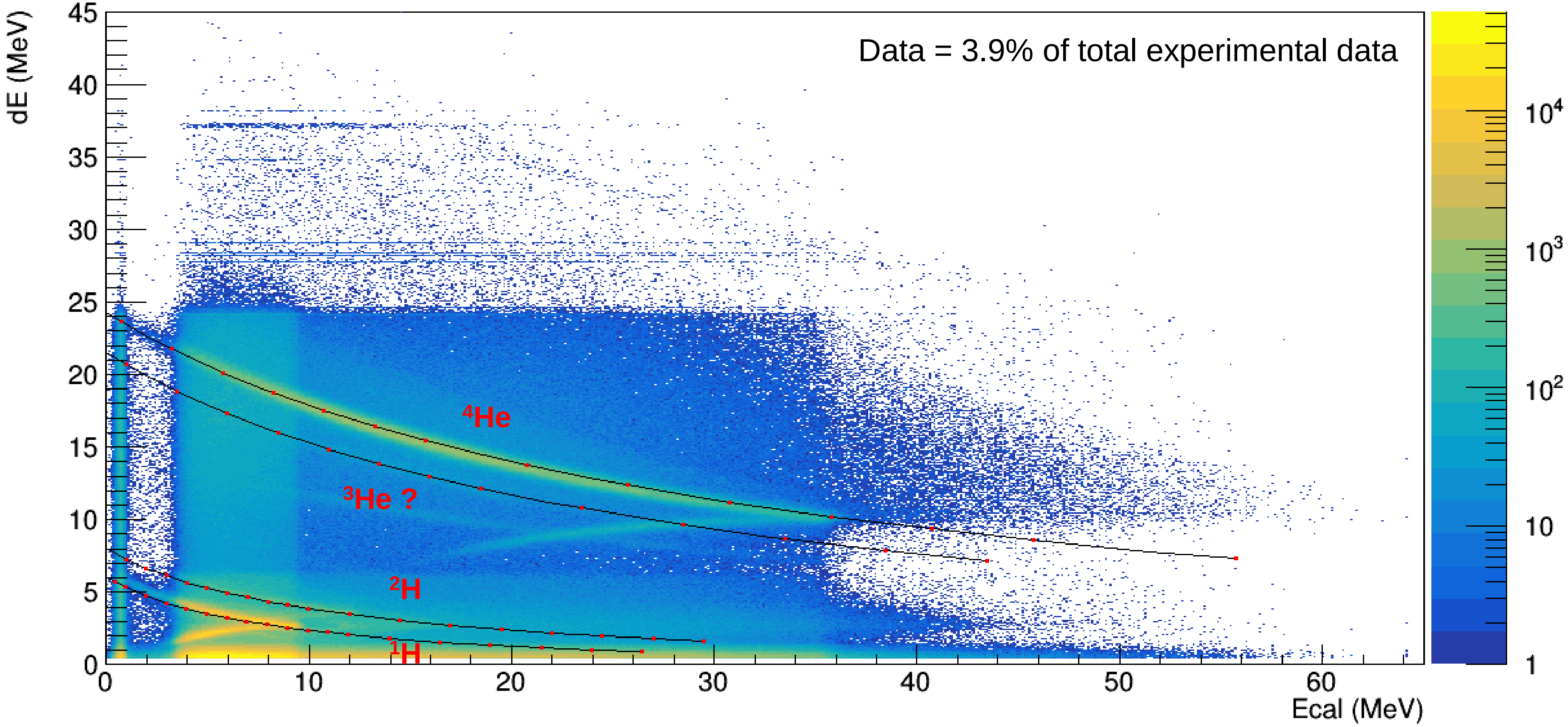

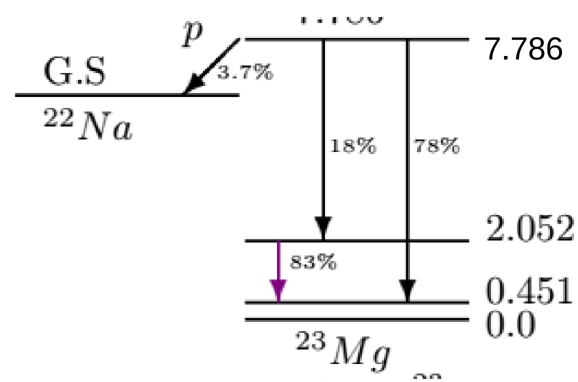

- Quantify independently B_p branching ratio
- Constrain coïncidence γ spectra with E_{4He}

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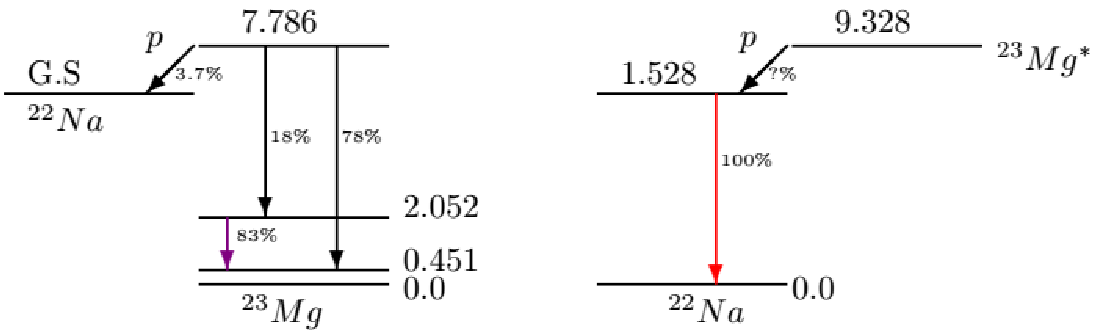
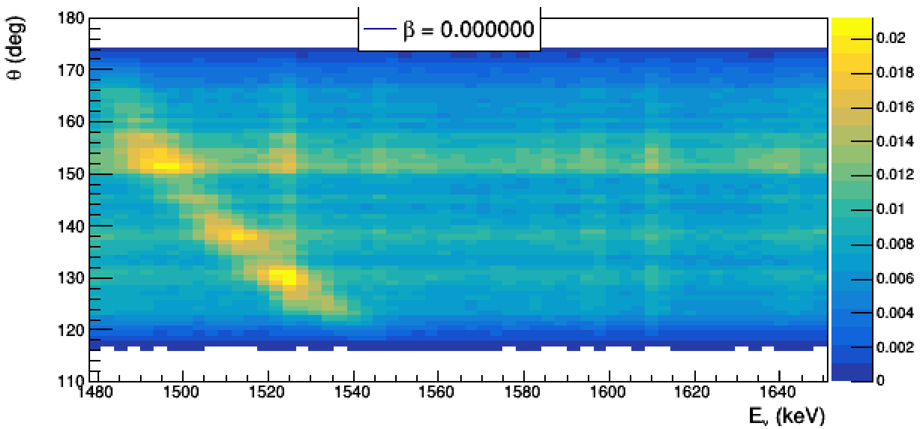
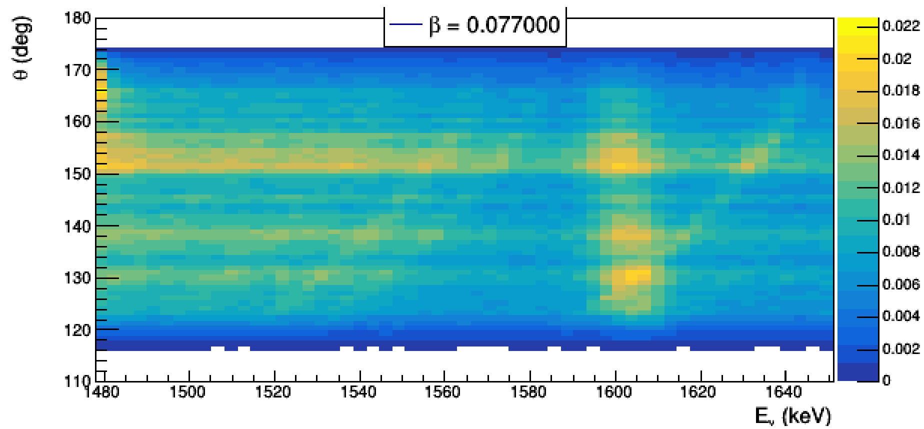


Figure 4: Decay scheme of two ^{23}Mg* states, at (E = 7.786 MeV, E = 9.238 MeV).





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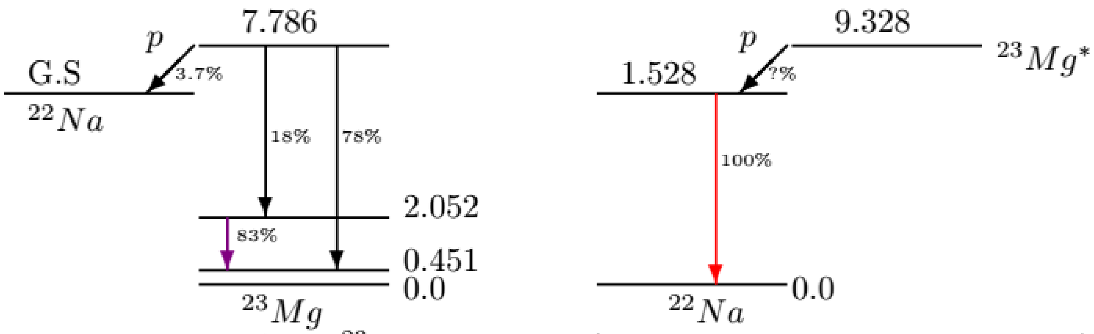

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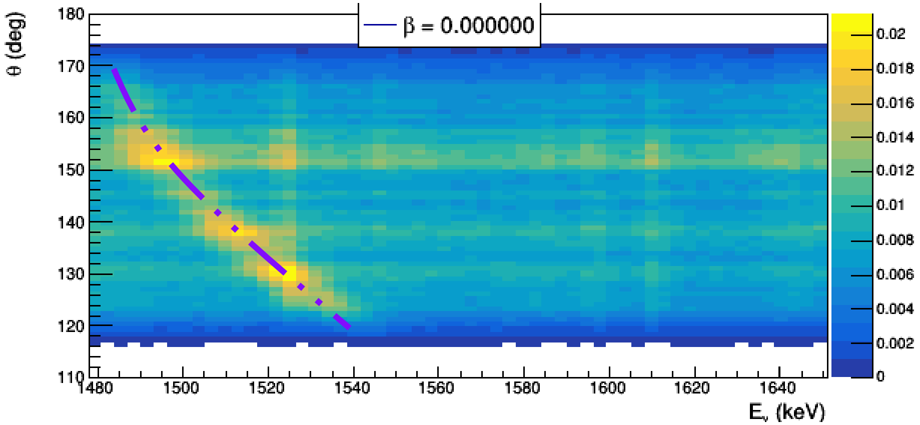

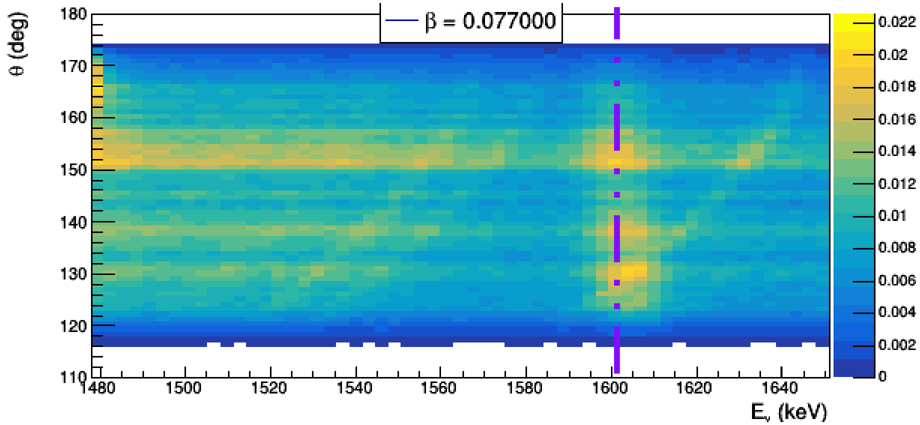

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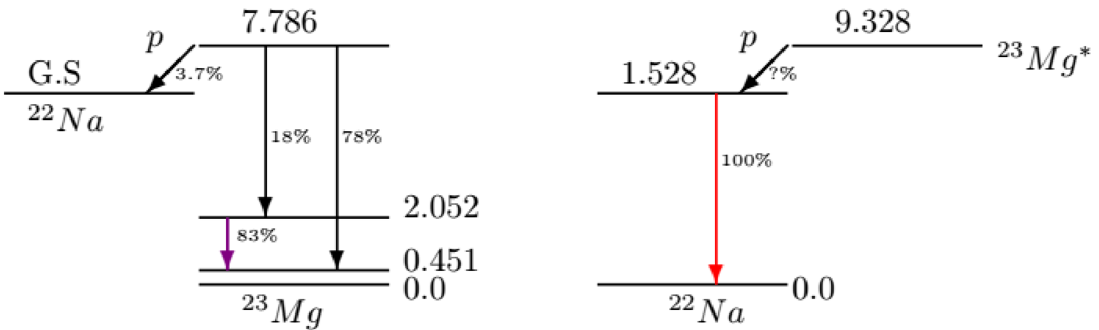

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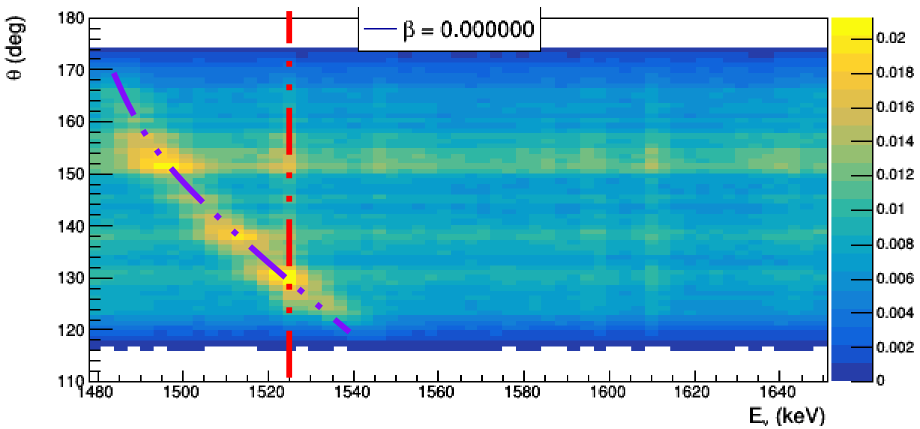

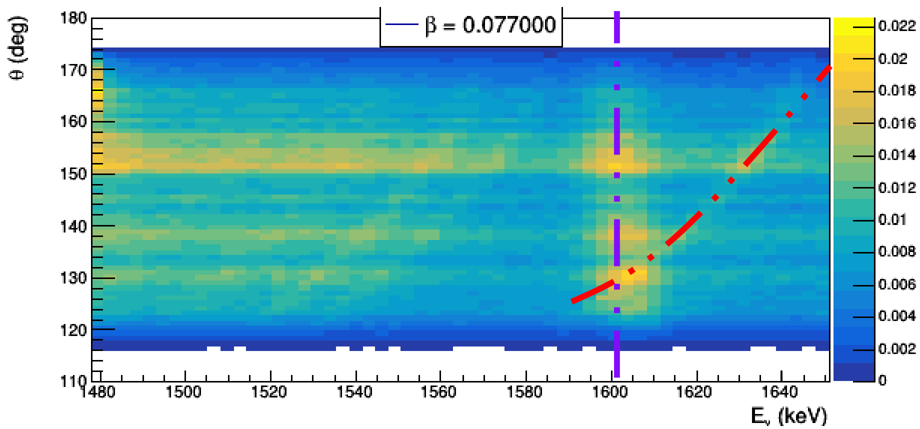

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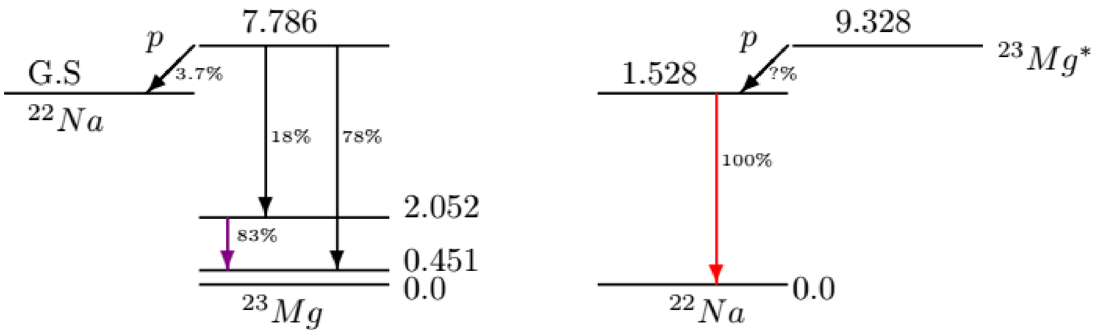

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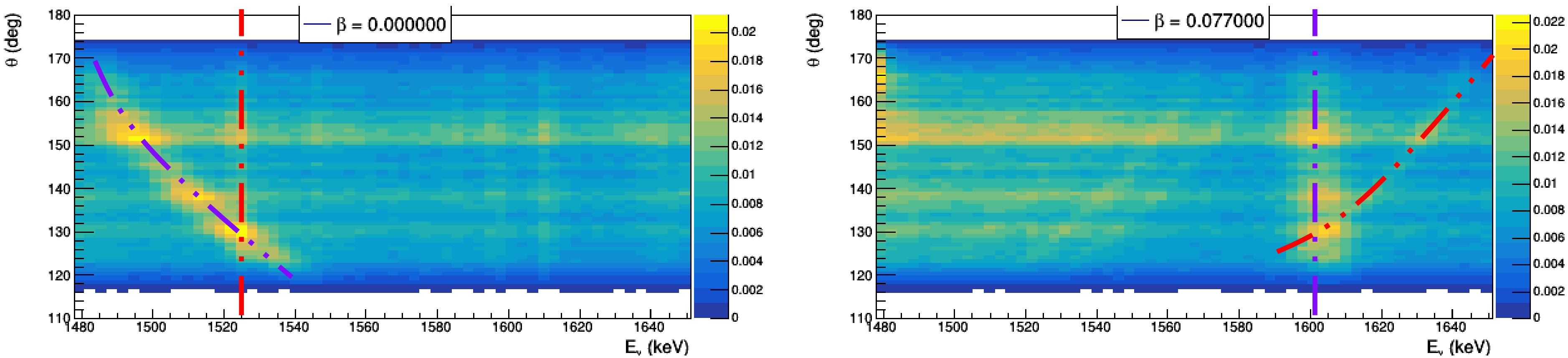

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^{23}Mg* short lifetime : γ emission before stopping by Au medium

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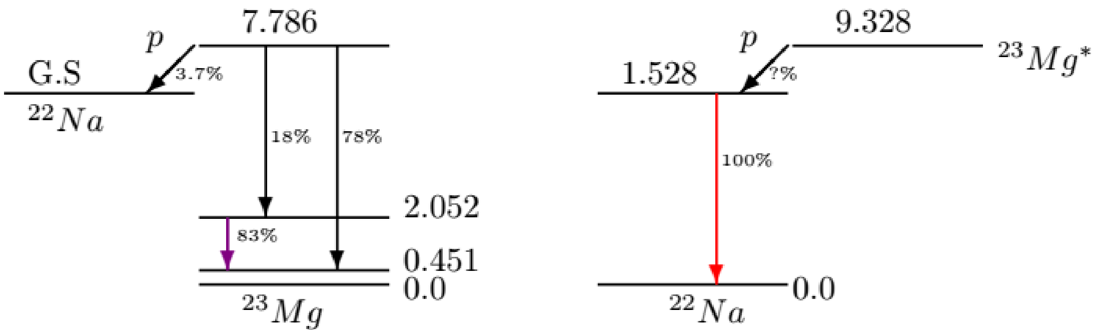

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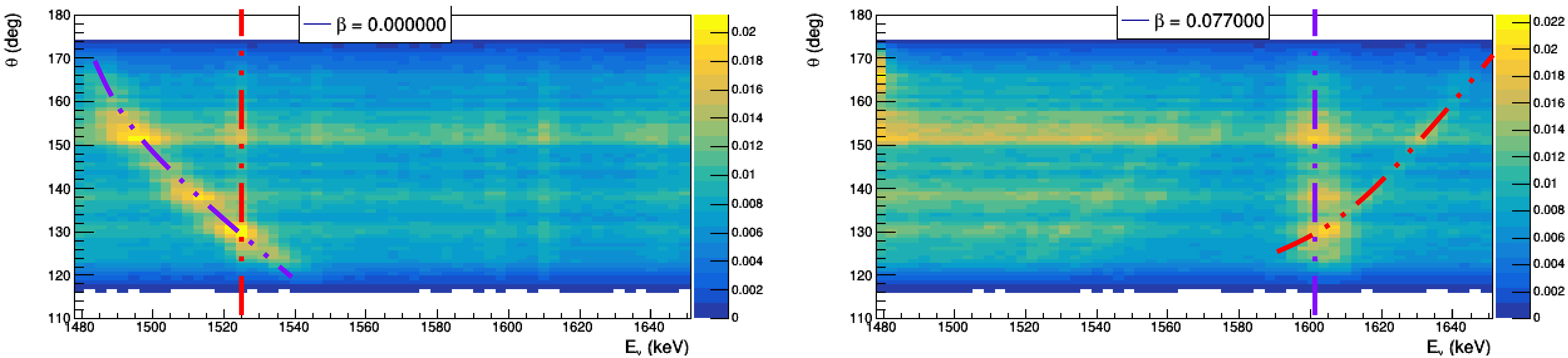


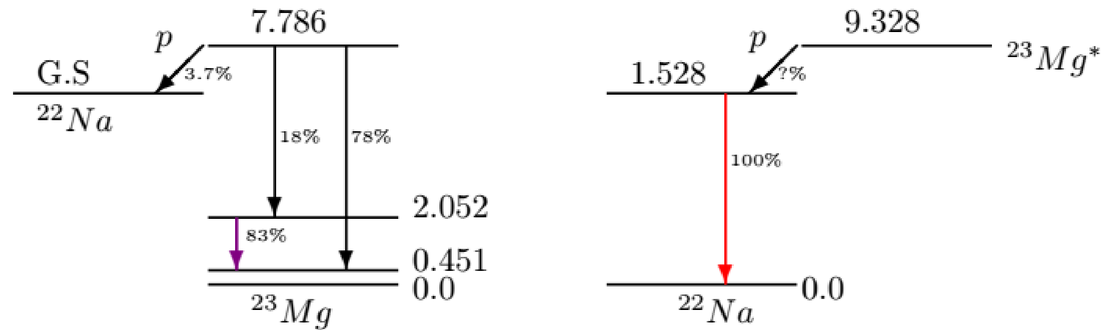
Preliminary measurement of β = 0.077 +/- 0.005

^{23}Mg* short lifetime : γ emission before stopping by Au medium => Rhum Road Sailing Cup (2018)

Identification of γ lines from ^{23}Mg

γ rays = Doppler redshifted

$$E_\gamma = E_{\gamma,0} \frac{(1-\beta^2)^{\frac{1}{2}}}{1-\beta \ cos\theta_\gamma}$$



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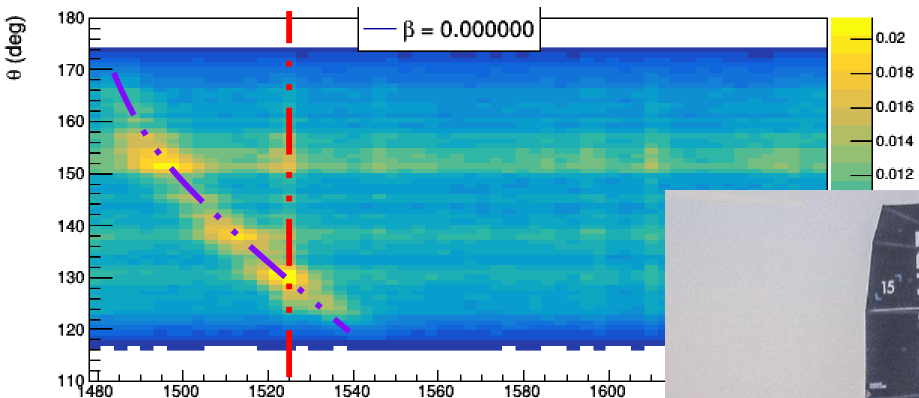

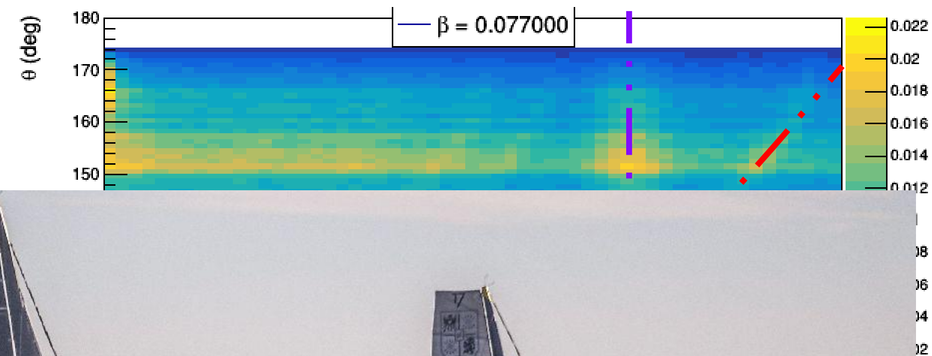

Prelimin

^{23}Mg* short lifetime : γ emission b 3)

γ rays = Doppler redshifted

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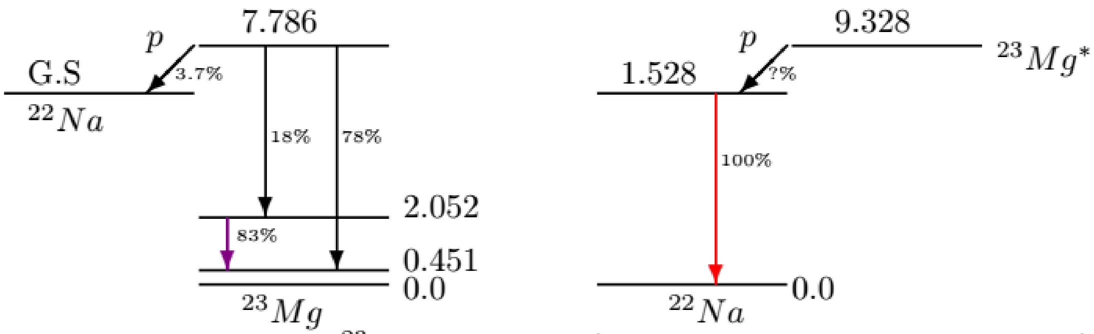

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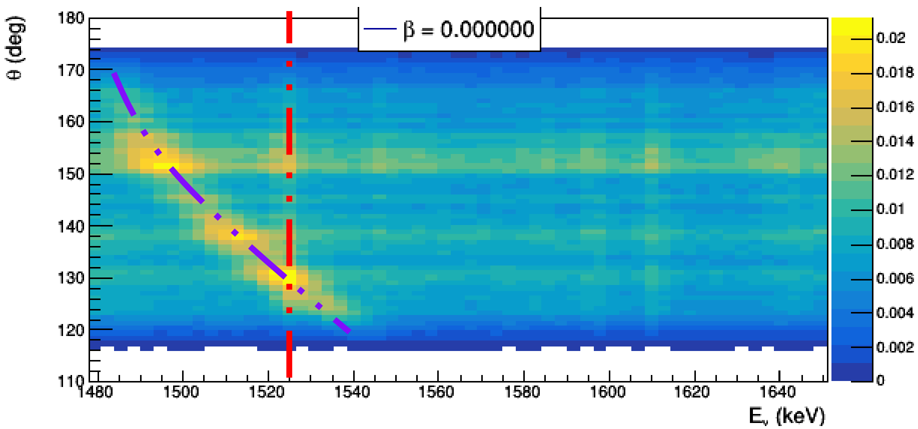

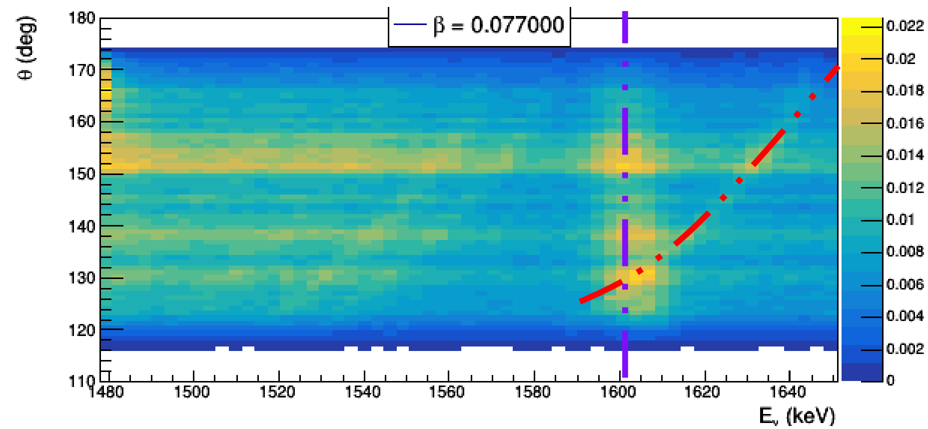

Preliminary measurement of β = 0.077 +/- 0.005

^{23}Mg* short lifetime : γ emission before stopping by Au medium => Rhum Road Sailing Cup (2018)

^{22}Na* long lifetime : γ emission at rest

Identification of γ lines from ^{23}Mg

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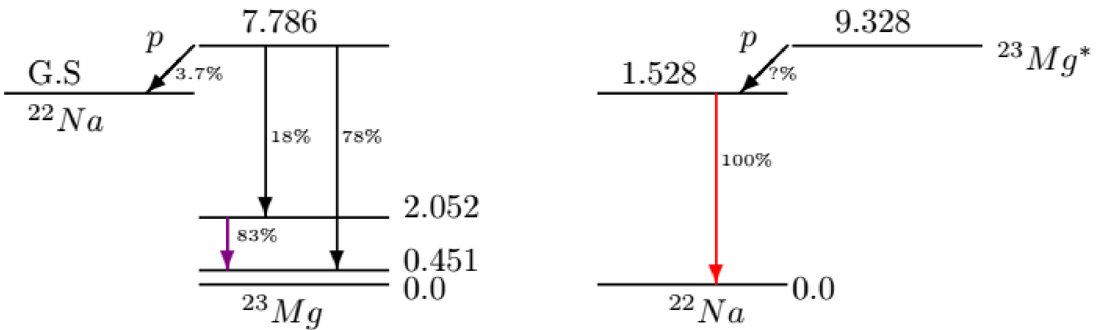

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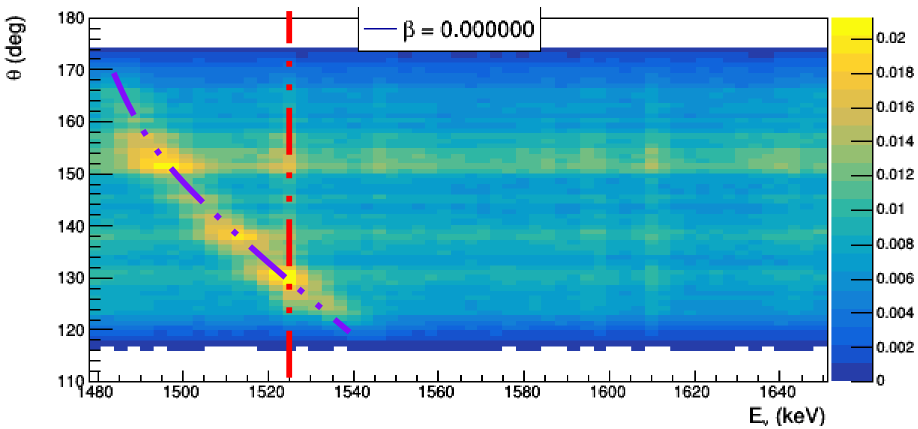
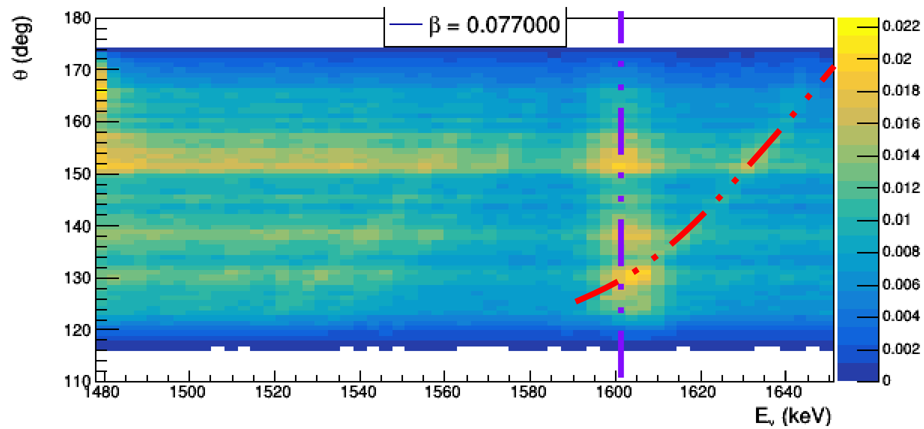




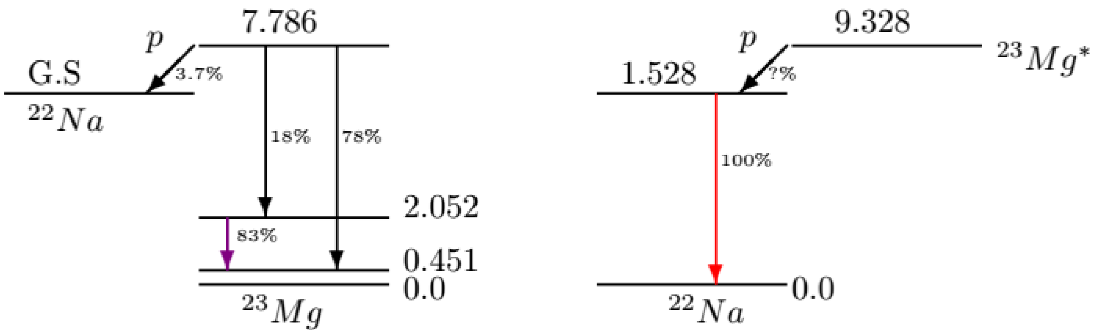
Preliminary measurement of β = 0.077 +/- 0.005

^{23}Mg* short lifetime : γ emission before stopping by Au medium => Rhum Road Sailing Cup (2018)
^{22}Na* long lifetime : γ emission at rest => wonderful Kouign Amann

Identification of γ lines from ^{23}Mg

γ rays = Doppler redshifted

$$E_\gamma = E_{\gamma,0}\frac{(1-\beta^2)^{\frac{1}{2}}}{1-\beta\ cos\theta_\gamma}$$



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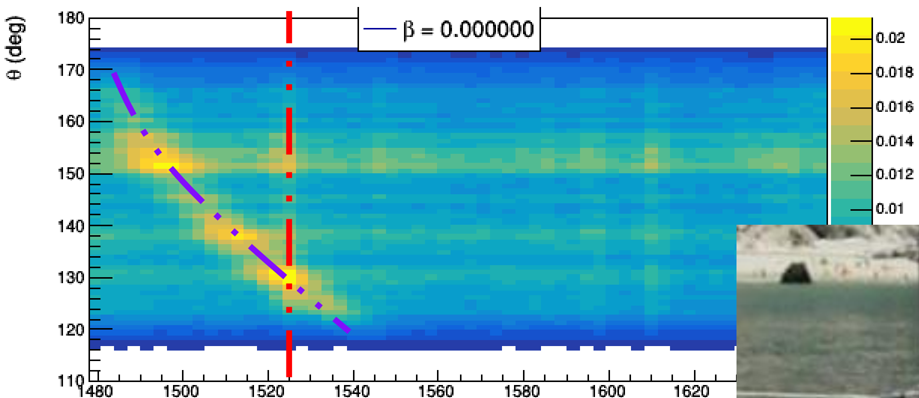
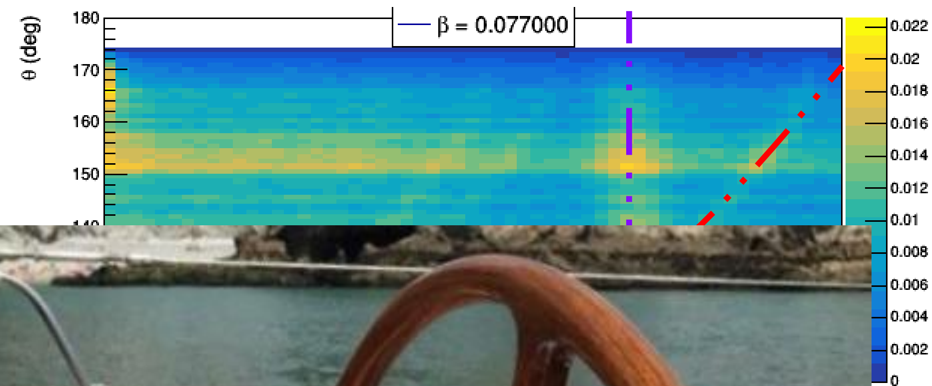




Preliminary

^{23}Mg* short lifetime : γ emission before … 18)

^{22}Na* long lifetime : γ emission at rest

Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

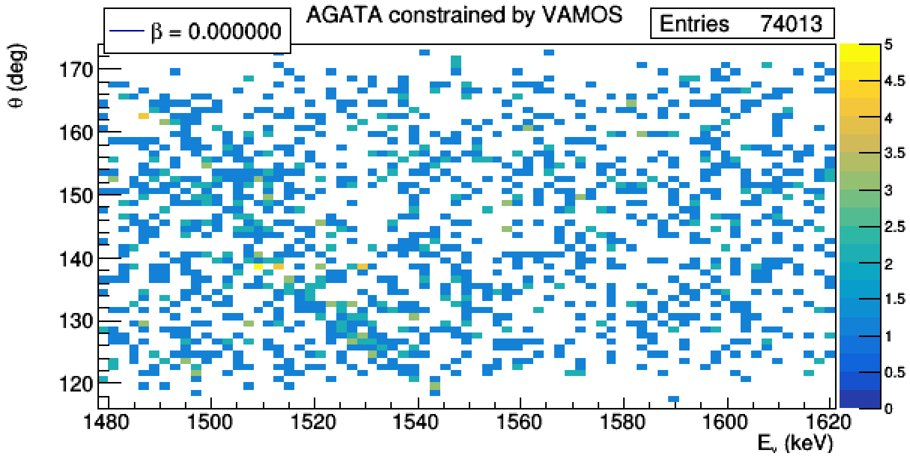
$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c * m_{^4He}}\right)^2}} - 1\right)$$

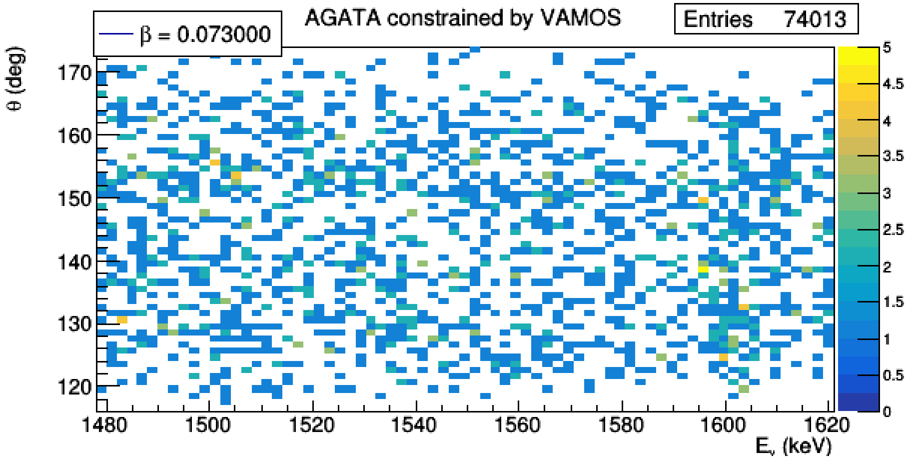
Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c * m_{^4He}}\right)^2}} - 1\right)$$

^{4}He E* ϵ [50.45;51.03] MeV





Background reduction in γ spectra

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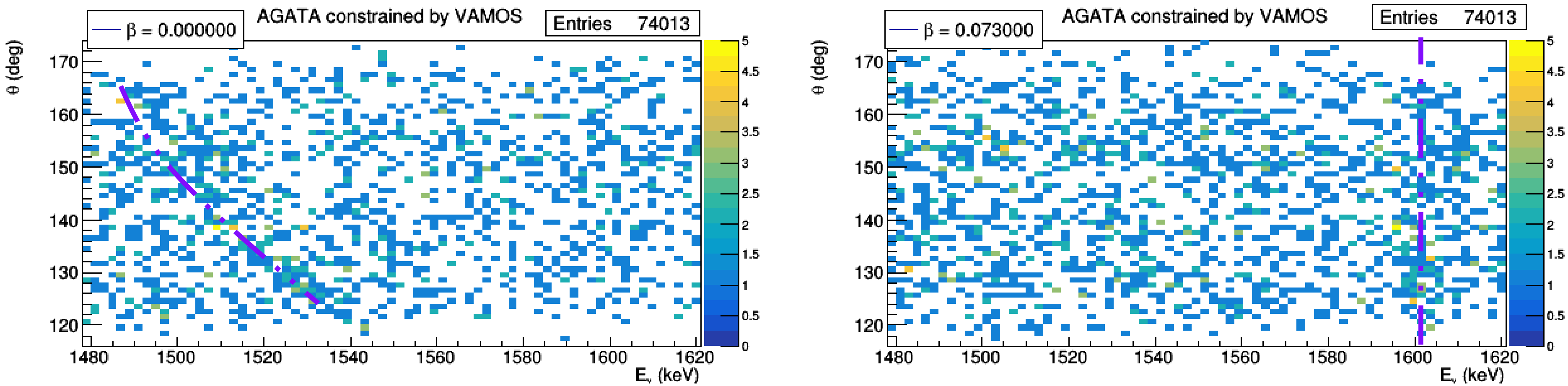


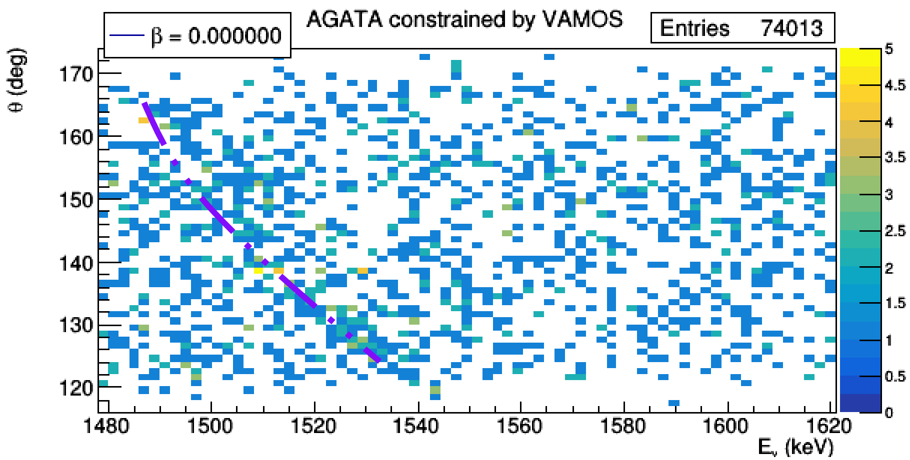
^{23}Mg* E$_γ$ = 1.601MeV

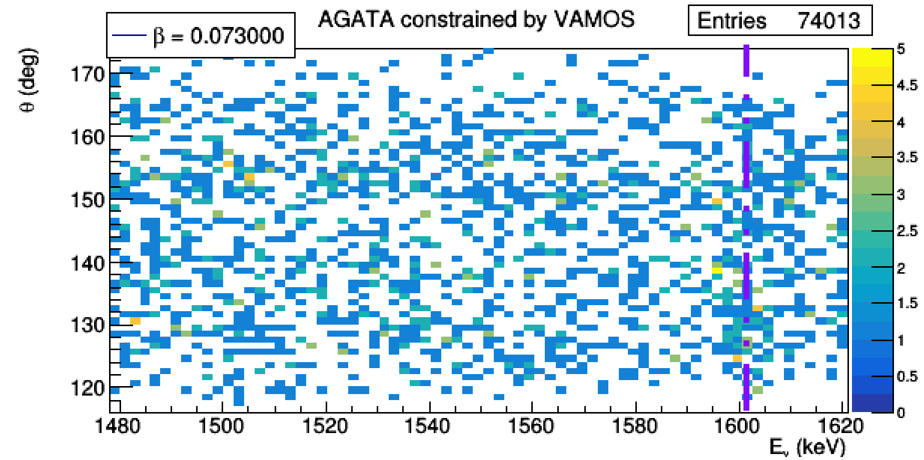
Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

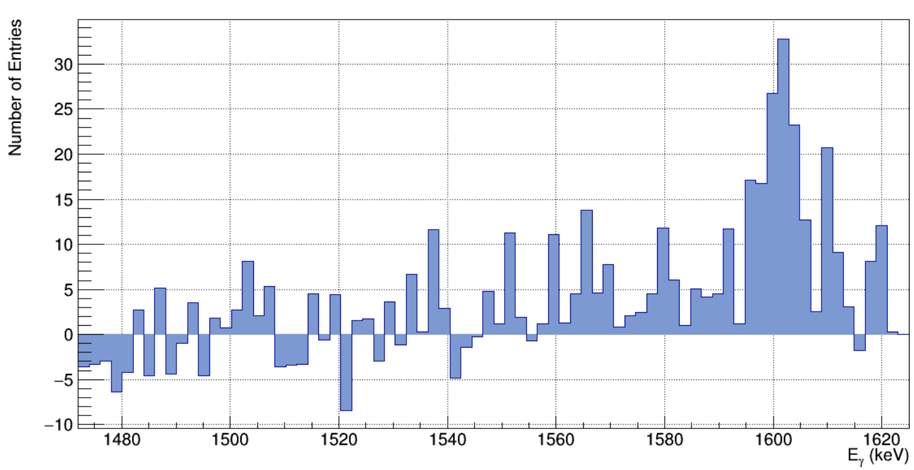
$$E^* = m_{^4He} c^2 \left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c * m_{^4He}}\right)^2}} - 1 \right)$$

^{4}He E* ϵ [50.45;51.03] MeV





^{23}Mg* $E_γ$ = 1.601MeV



Projected difference between constrained and free γ Doppler corrected matrices

⇒ 1.601 MeV γ ray highlighted by coïnciding ^{4}He* not a statistical effect

Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

$$E^* = m_{^4He} c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{B\rho * q_{^4He}}{c * m_{^4He}} \right)^2}} - 1 \right)$$

Background reduction in γ spectra

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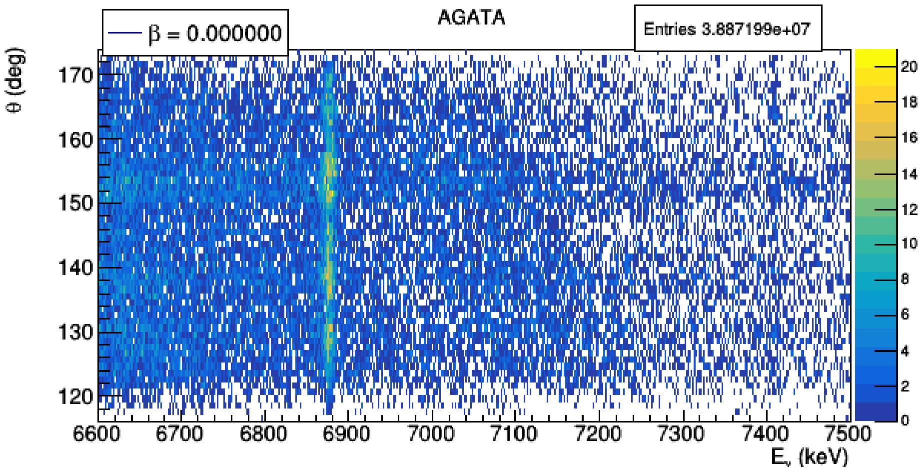
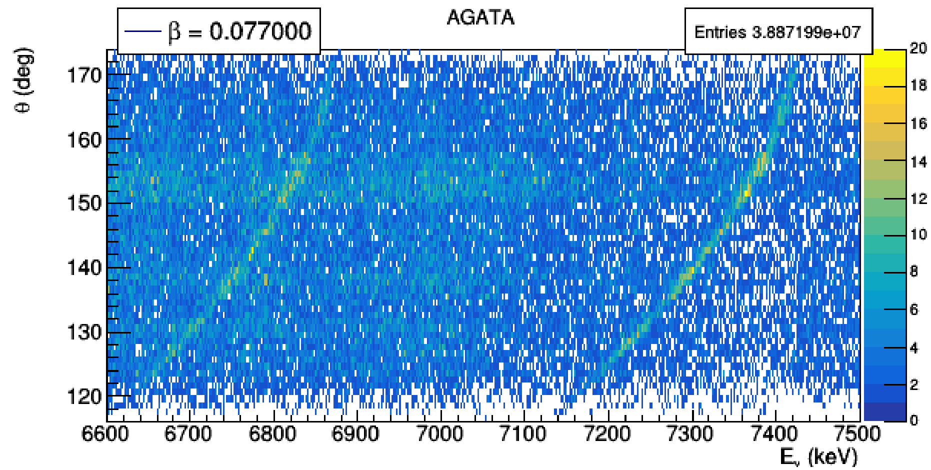
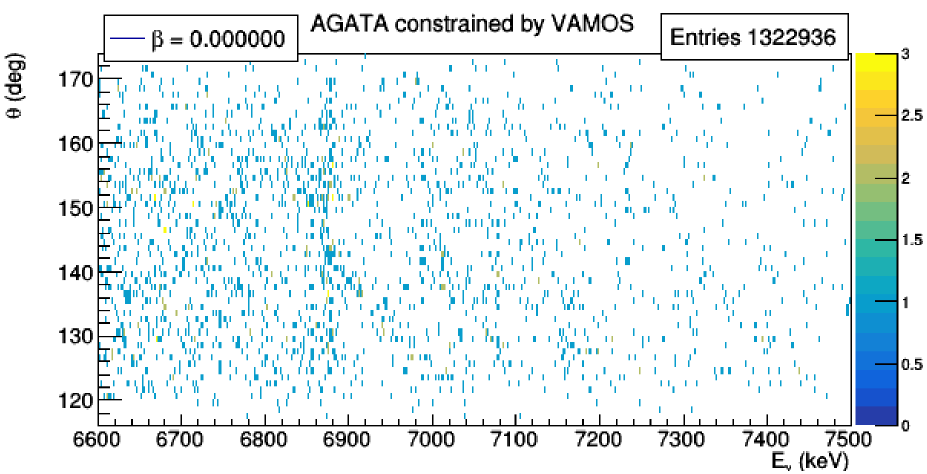
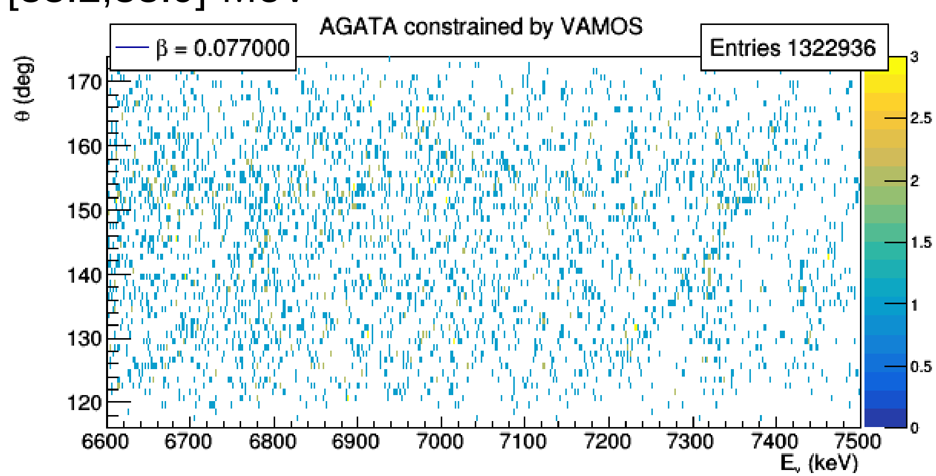




^{4}He E* ∈ [38.2,38.9] MeV

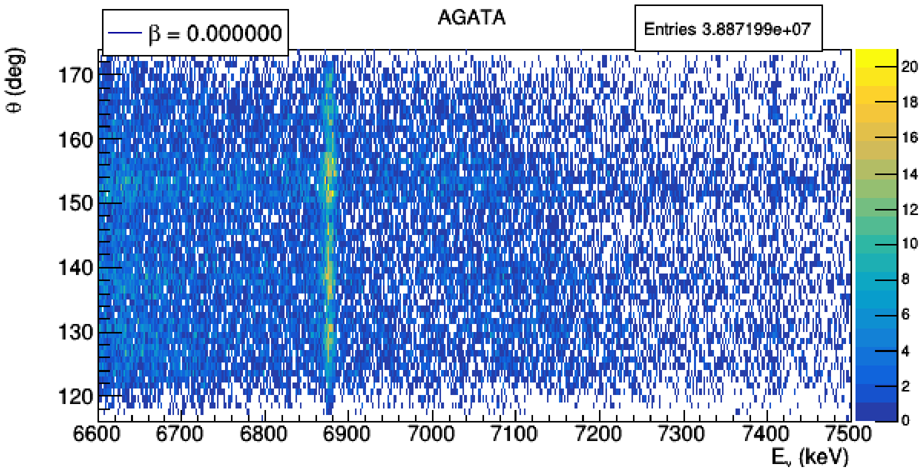


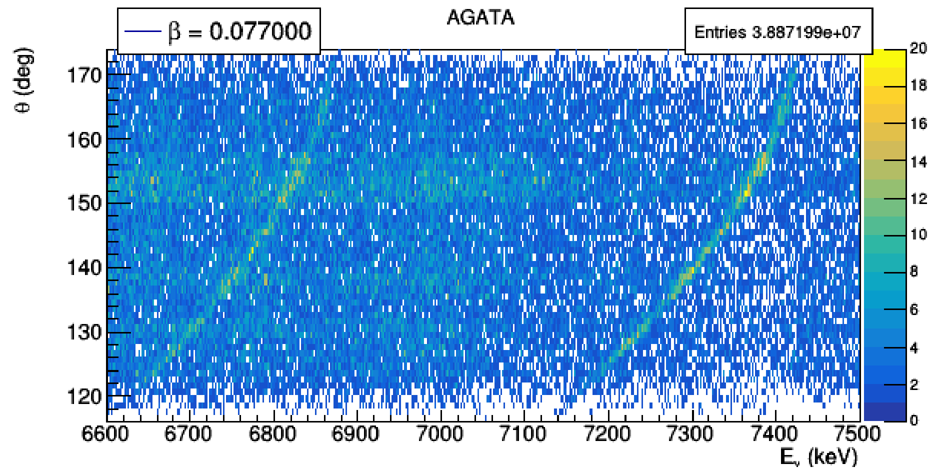


Background reduction in γ spectra

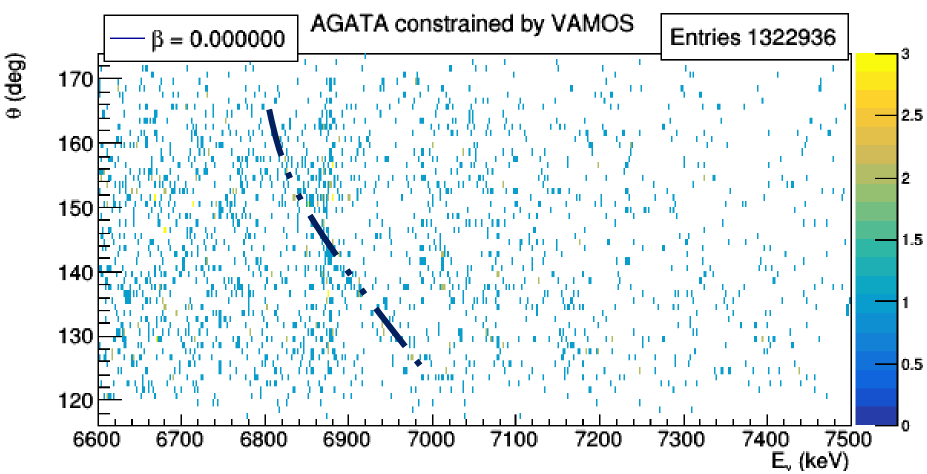
Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

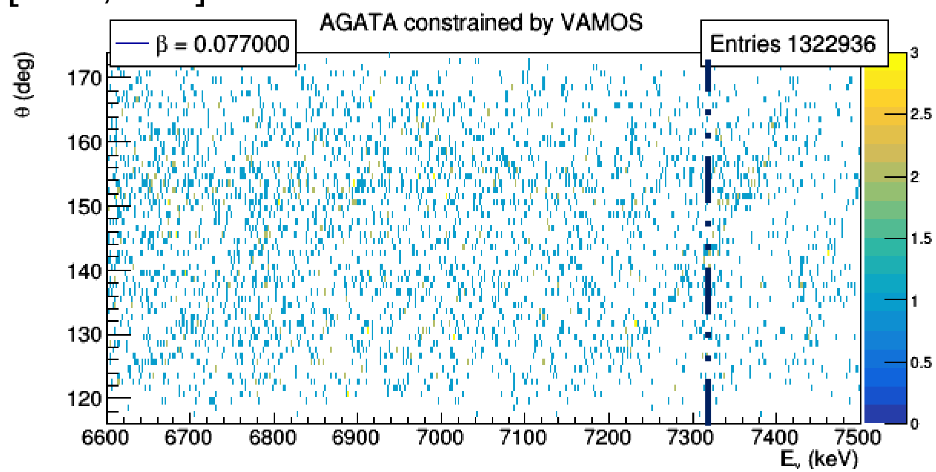
$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c*m_{^4He}}\right)^2}} - 1\right)$$





^{4}He E* є [38.2,38.9] MeV



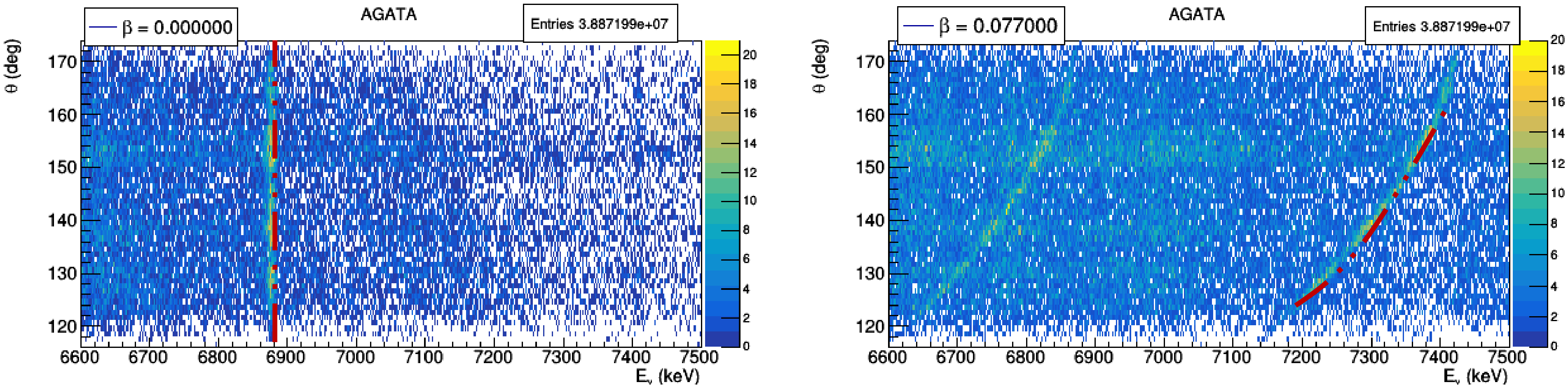


^{23}Mg* E_γ = 7.333MeV

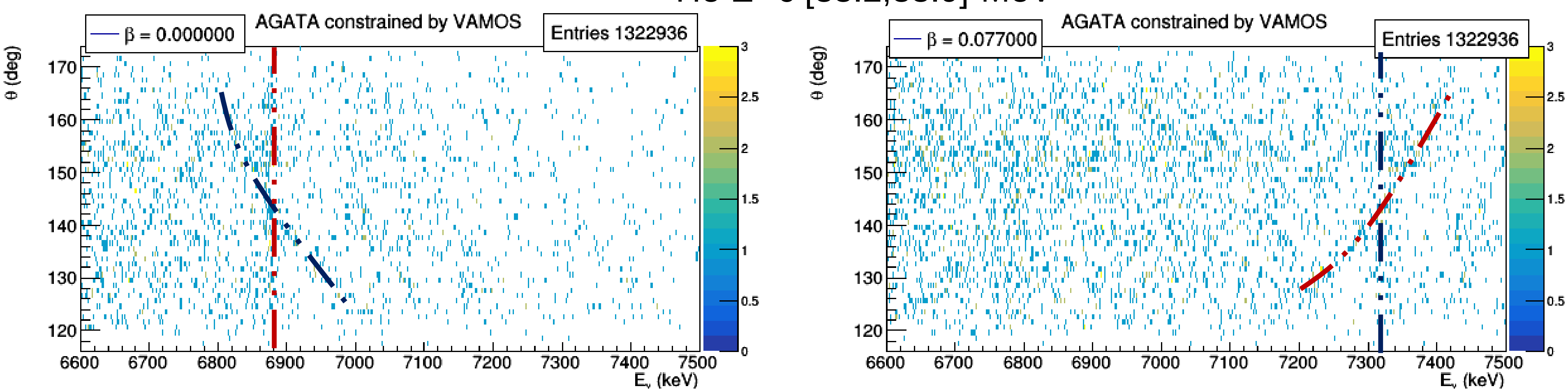
Background reduction in γ spectra

Coïncidence with VAMOS ^4He excitation energy (resolution 2.10^{-3})

$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c * m_{^4He}}\right)^2}} - 1\right)$$



^4He E* ∊ [38.2,38.9] MeV



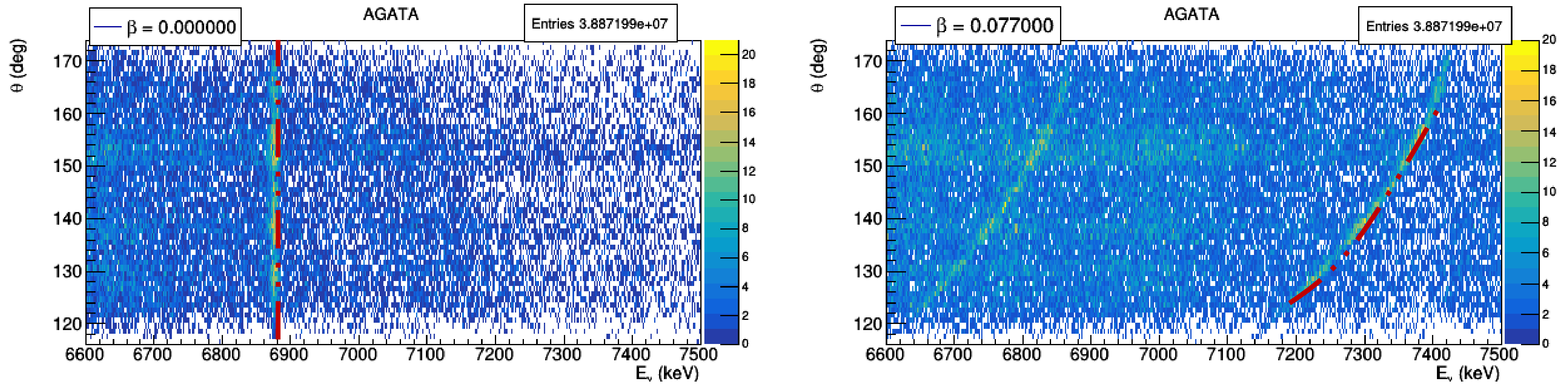
^{23}Mg* E $_γ$ = 7.333MeV

^{28}Si* E $_γ$ = 6.880MeV (fusion-evaporation unwanted product !)

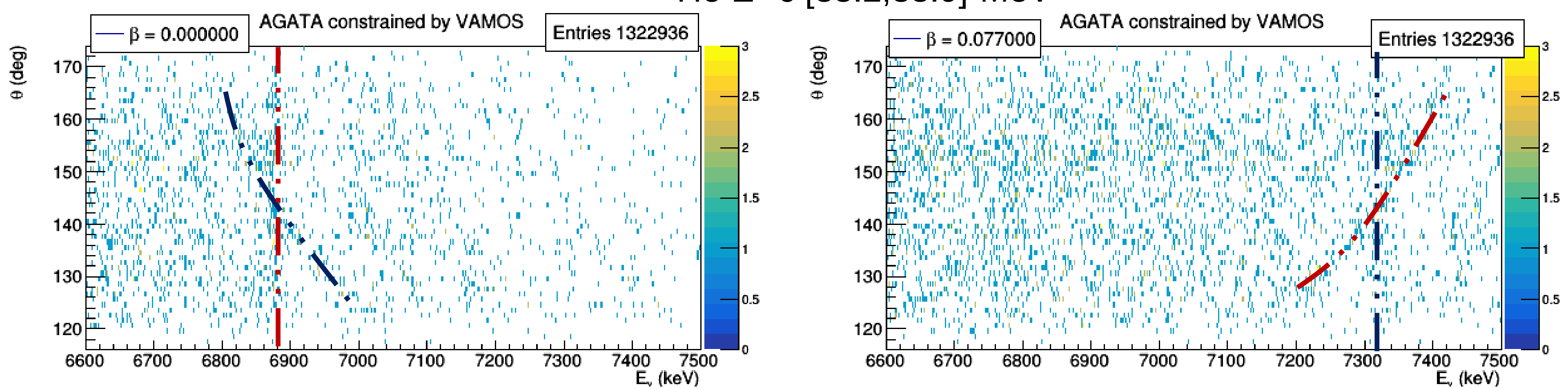
Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c*m_{^4He}}\right)^2}} - 1\right)$$



^{4}He E* ∈ [38.2,38.9] MeV



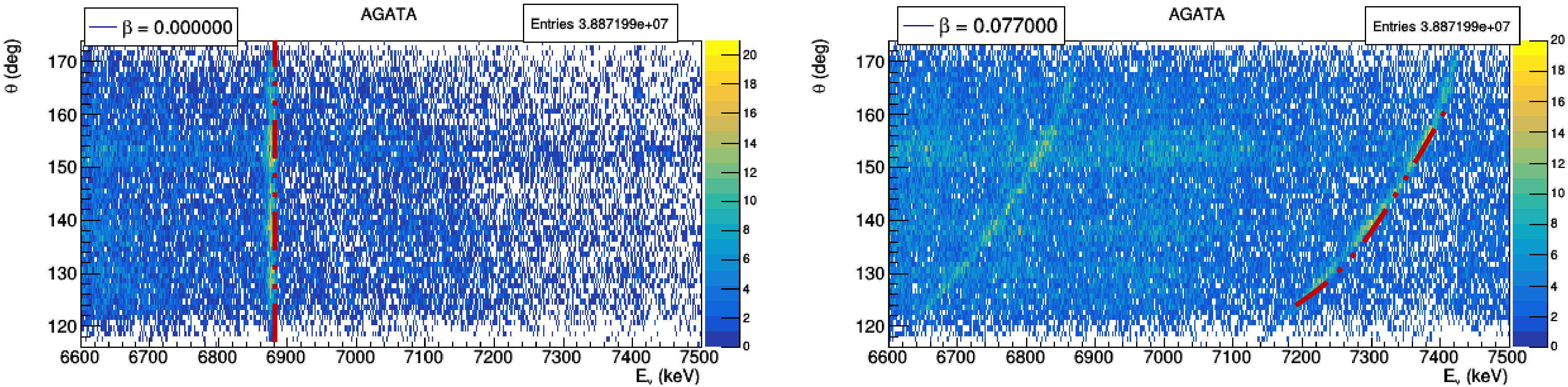
^{23}Mg* E $_\gamma$ = 7.333MeV => Kouign Amann

^{28}Si* E $_\gamma$ = 6.880MeV

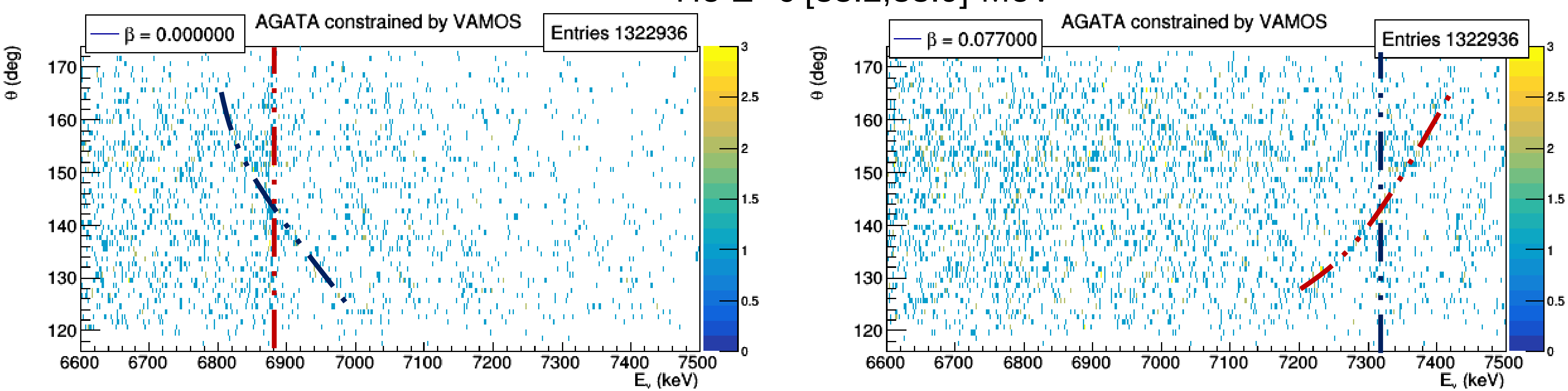
Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c*m_{^4He}}\right)^2}} - 1\right)$$



^{4}He E* ϵ [38.2,38.9] MeV



^{23}Mg* E $_γ$ = 7.333MeV => Kouign Amann

^{28}Si* E $_γ$ = 6.880MeV => Tourte aux Blettes

Background reduction in γ spectra

Coïncidence with VAMOS ^{4}He excitation energy (resolution 2.10^{-3})

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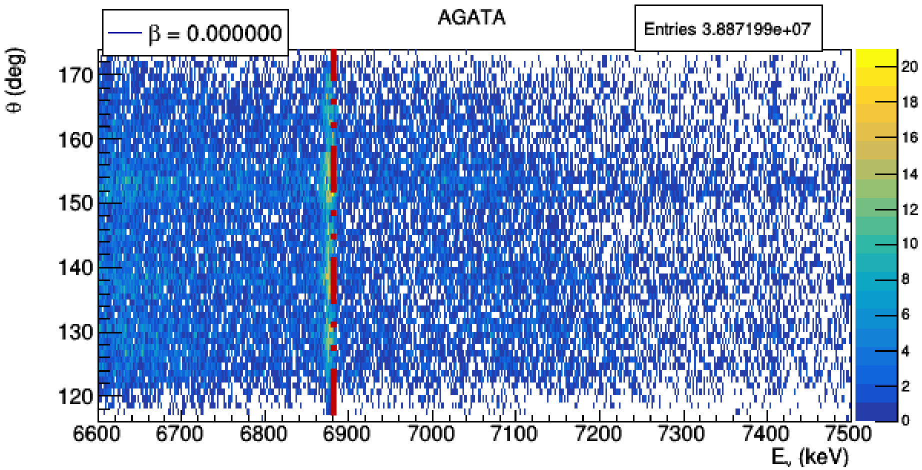
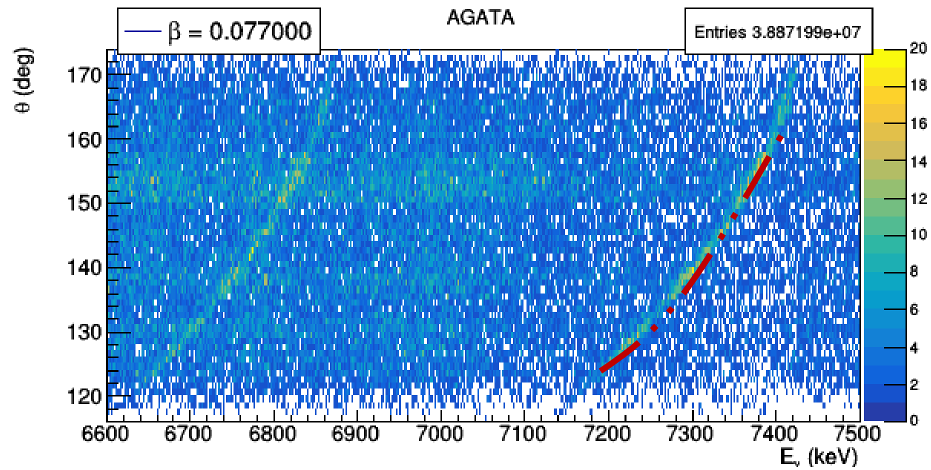
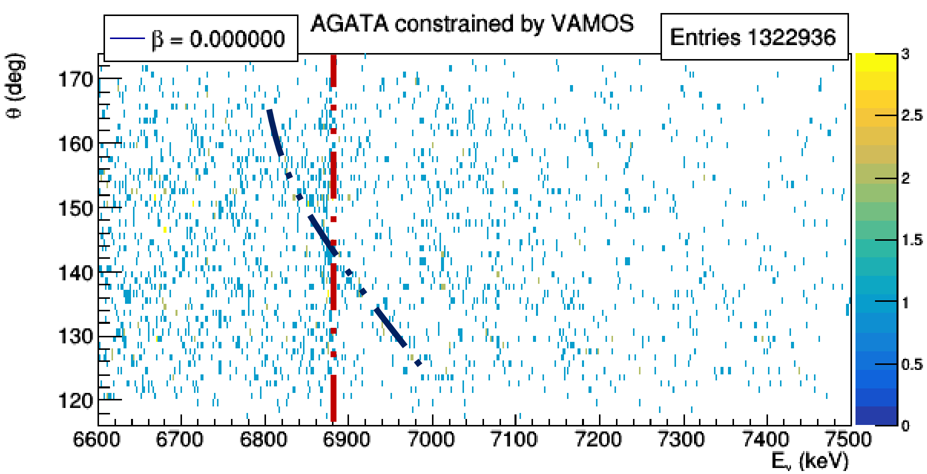
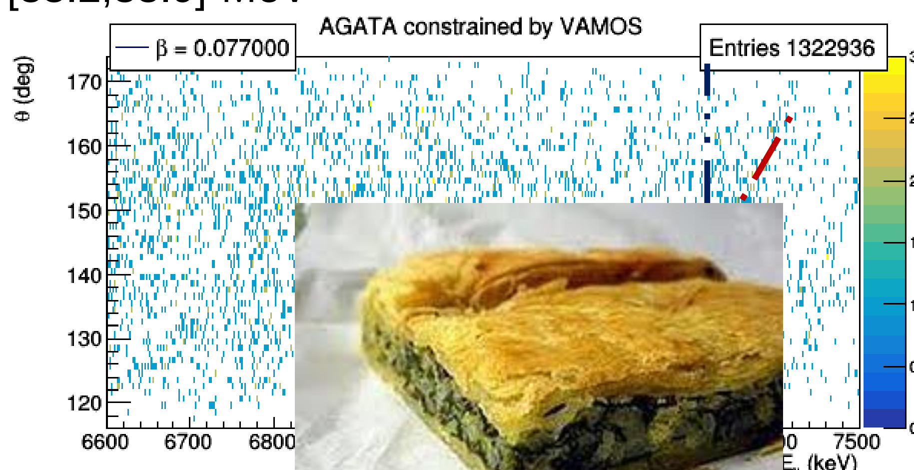




^{4}He E* ϵ [38.2,38.9] MeV





^{23}Mg* E $_γ$ = 7.333MeV => Kouig

^{28}Si* E $_γ$ = 6.880MeV => Tourte aux Blettes

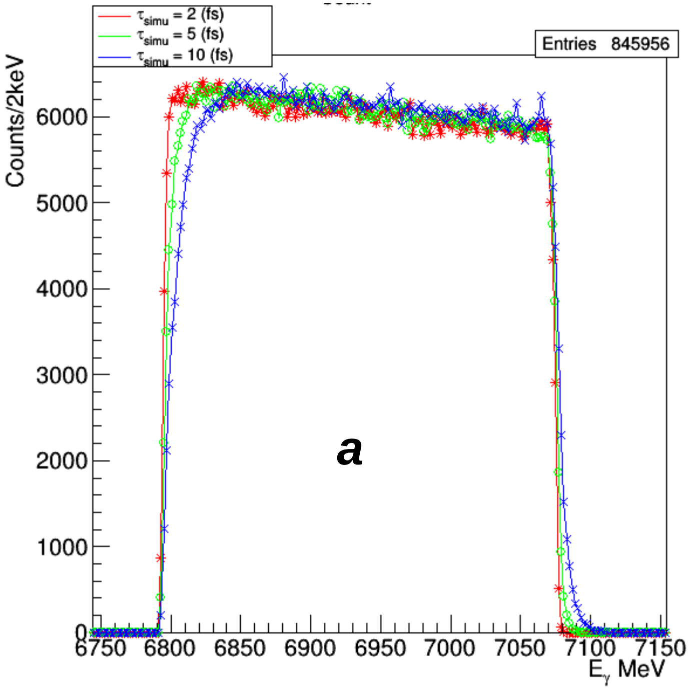
Preliminary results on τ

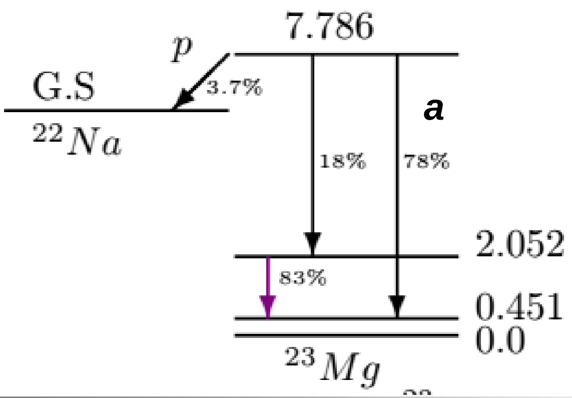
Simulated γ spectra as a function of τ ^{23}Mg* states

Preliminary results on τ

Simulated γ spectra as a function of τ $^{23}Mg^{*}$ states

=> Doppler shifted simulated γ peak broader as τ larger

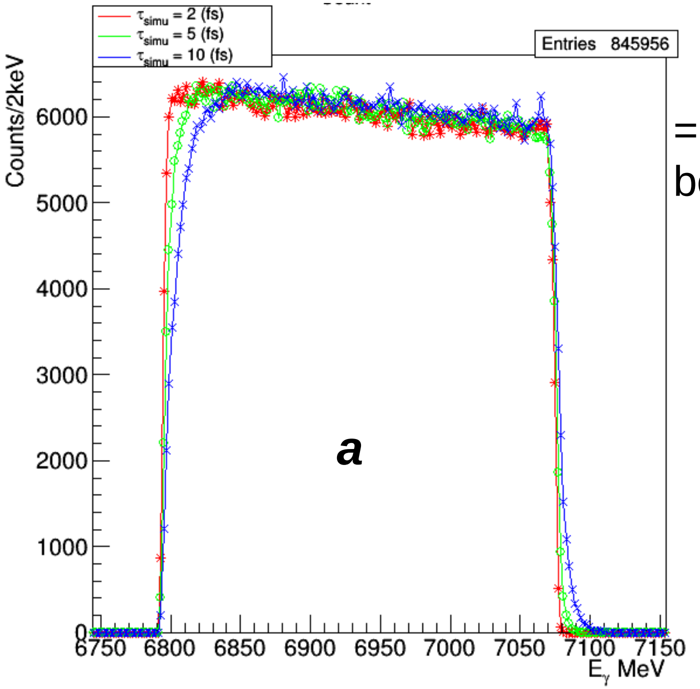




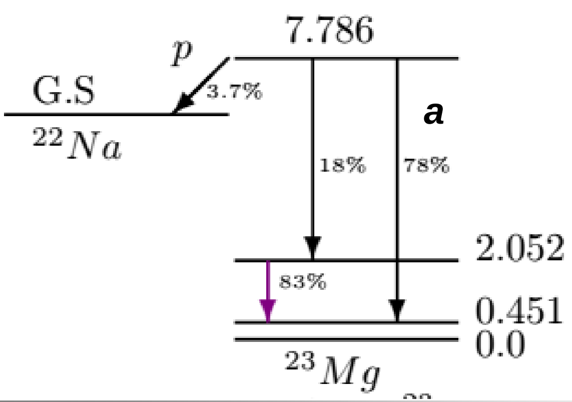
Preliminary results on τ

Simulated γ spectra as a function of τ $^{23}Mg^*$ states

=> Doppler shifted simulated γ peak broader as τ larger



=> sensibility below 10fs



Preliminary results on τ

Simulated γ spectra as a function of τ ^{23}Mg* states

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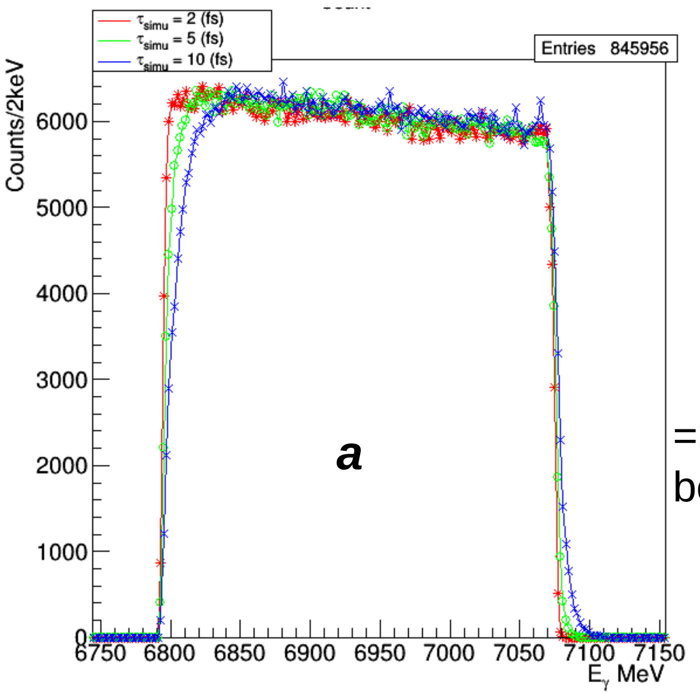

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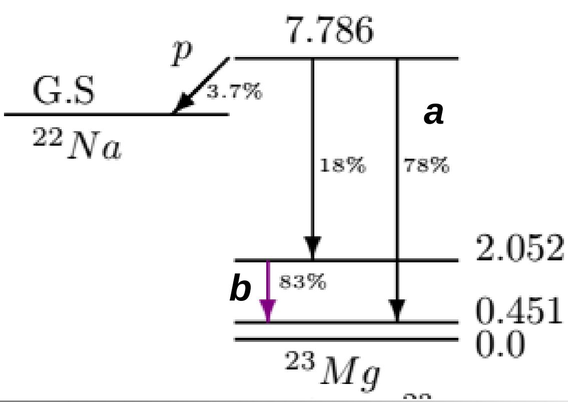
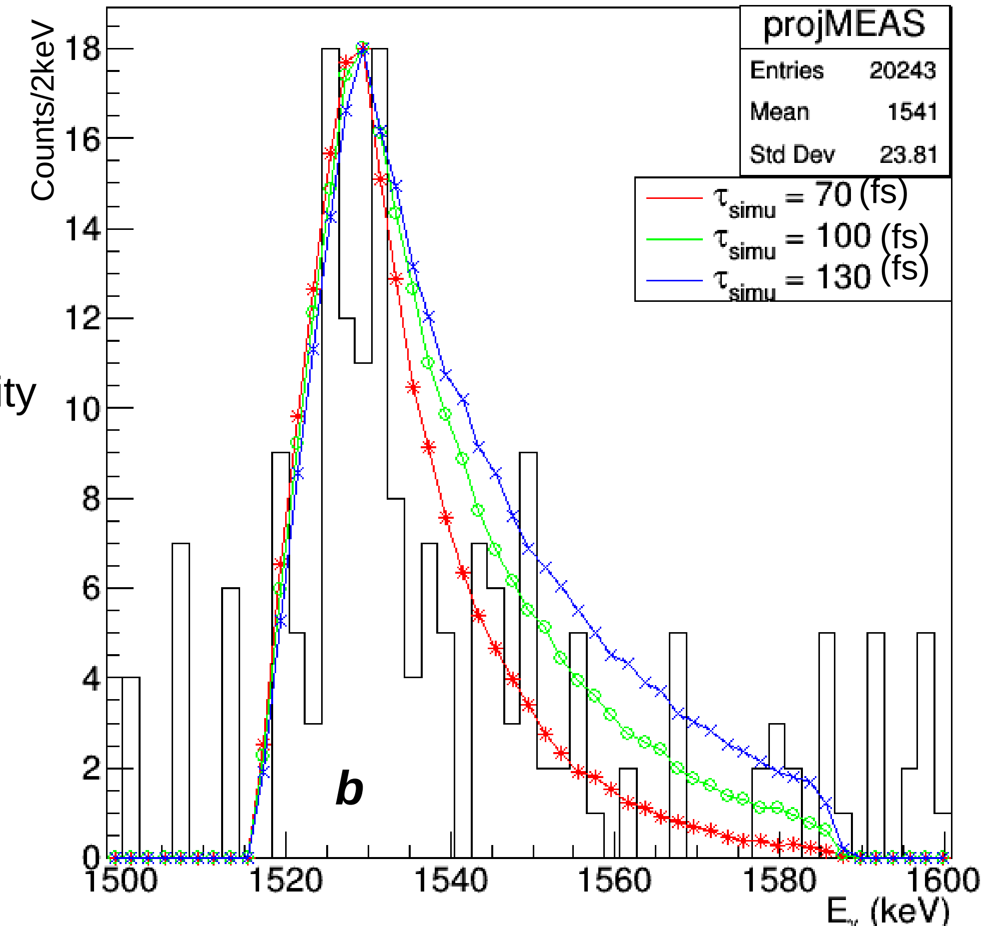


θ_γ = [124;133]°

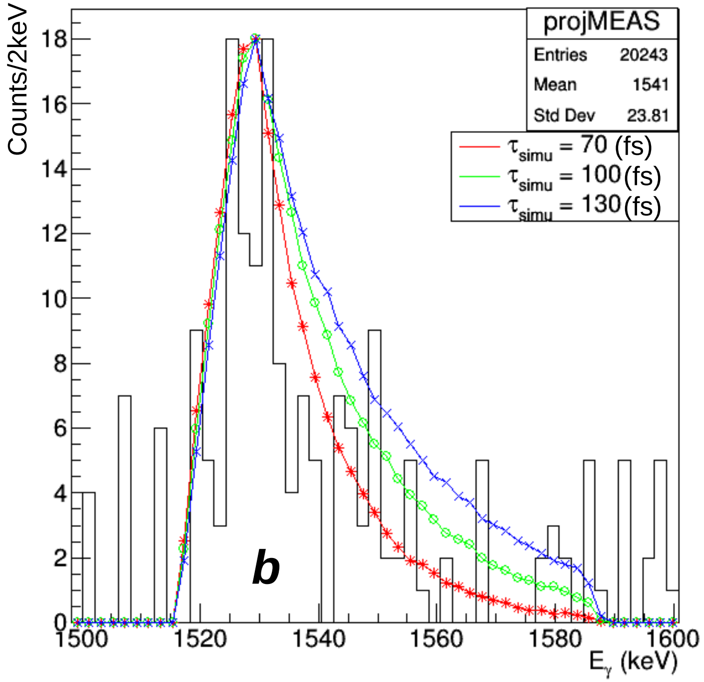
^{4}He E* ϵ[50.45;51.03] MeV



Background local substraction on peak (barycentric equation)

Preliminary results on τ :

^{23}Mg* 2.052 MeV state : first estimation of lifetime τ by DSAM



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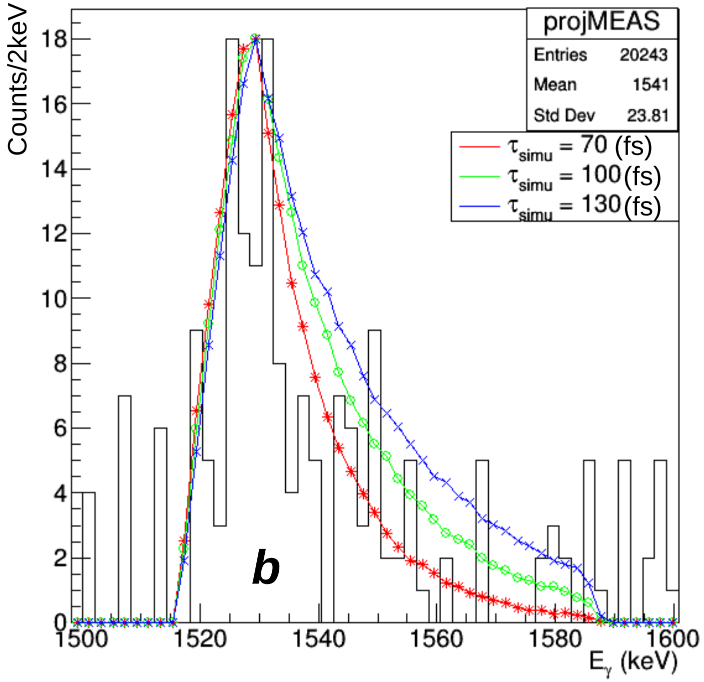

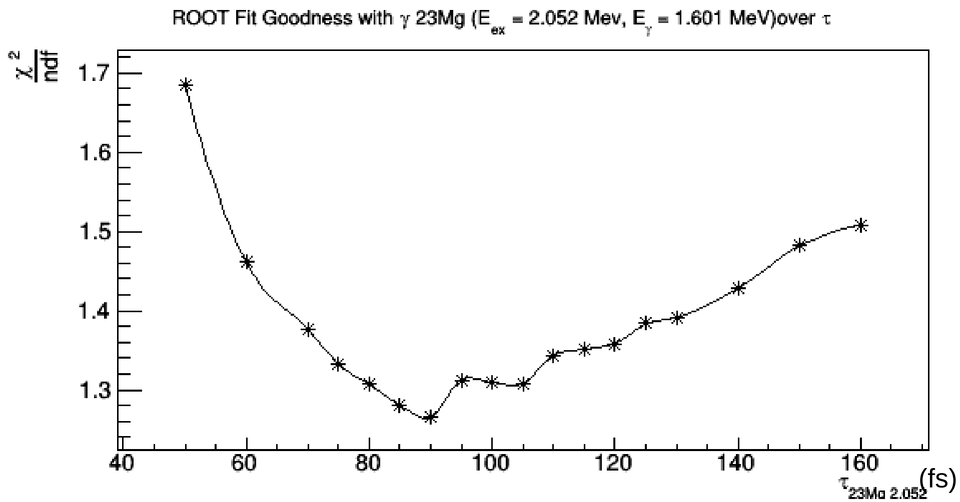

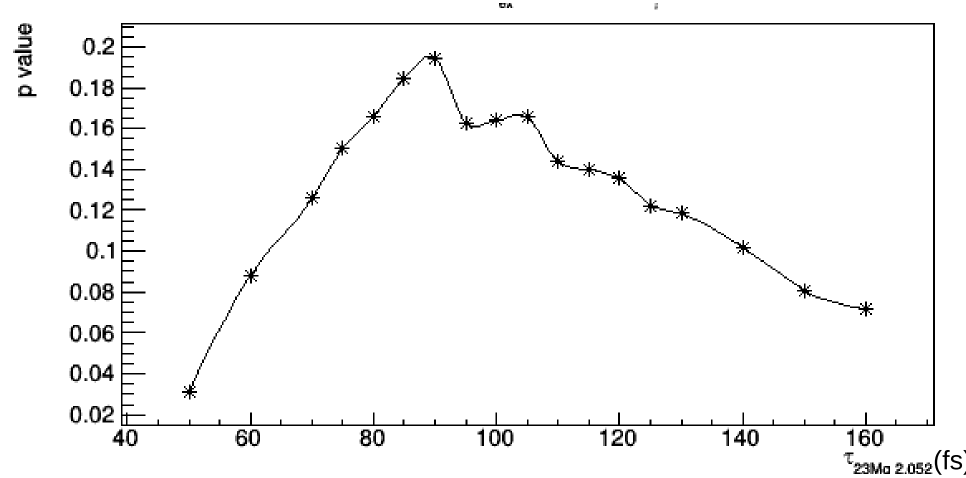

Preliminary results on τ :

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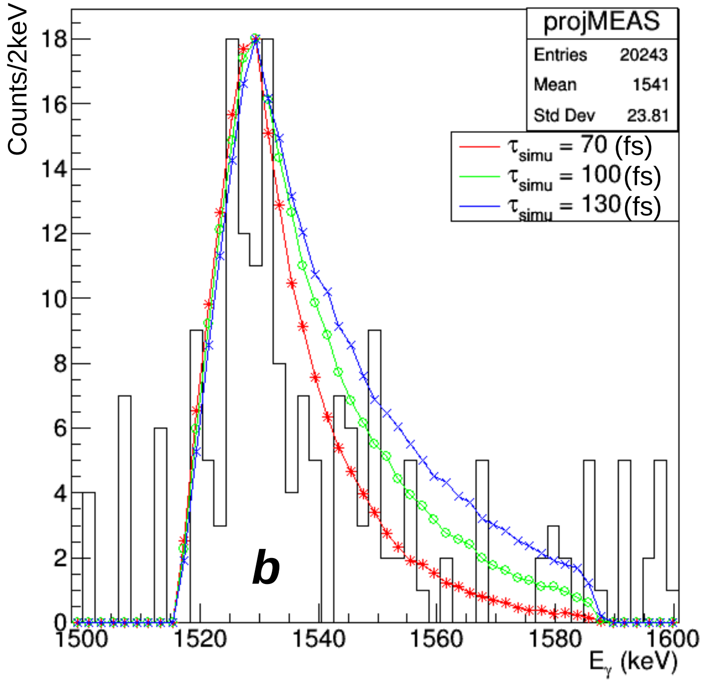
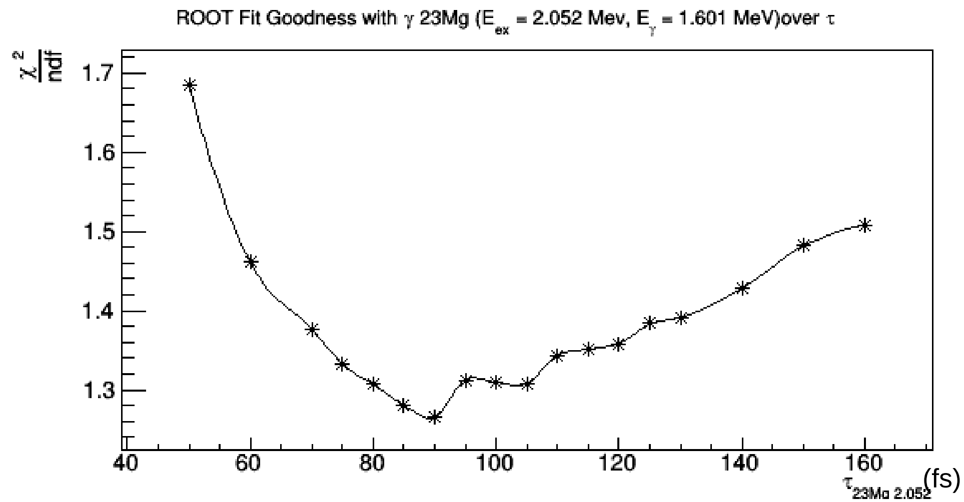
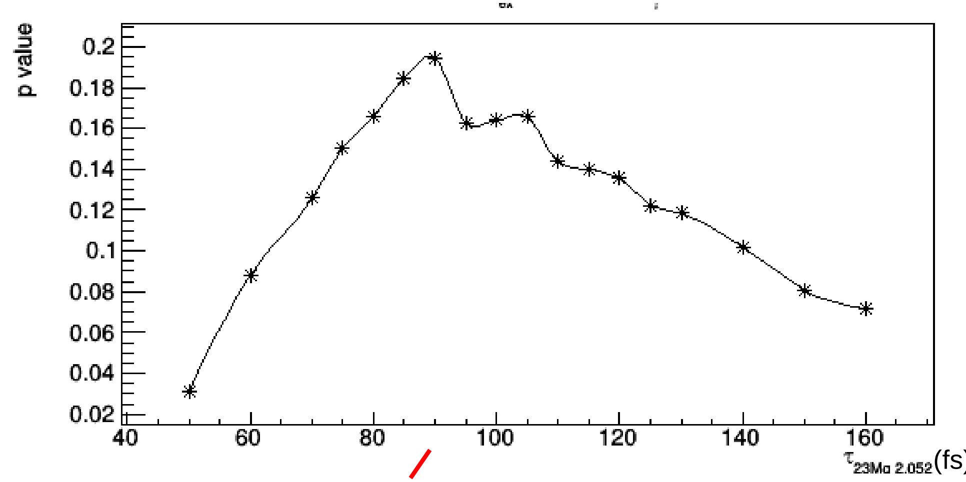


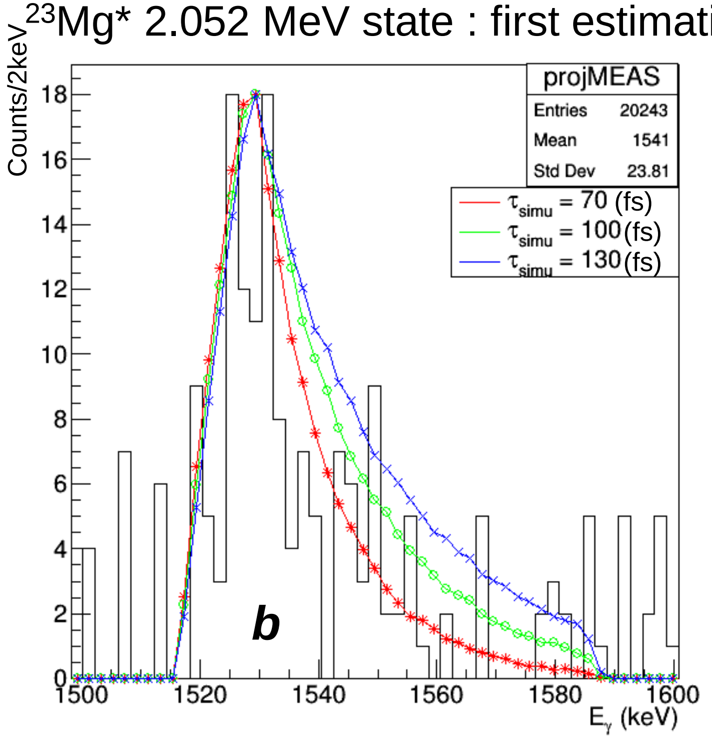


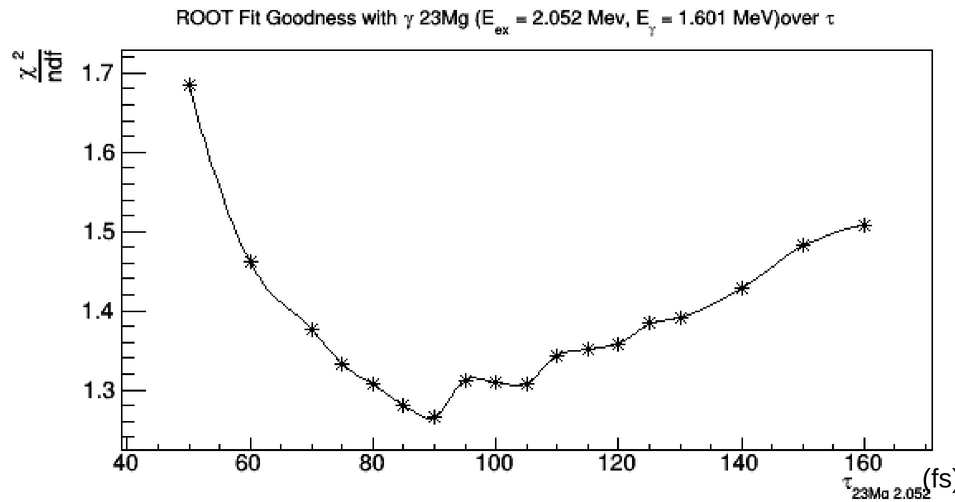


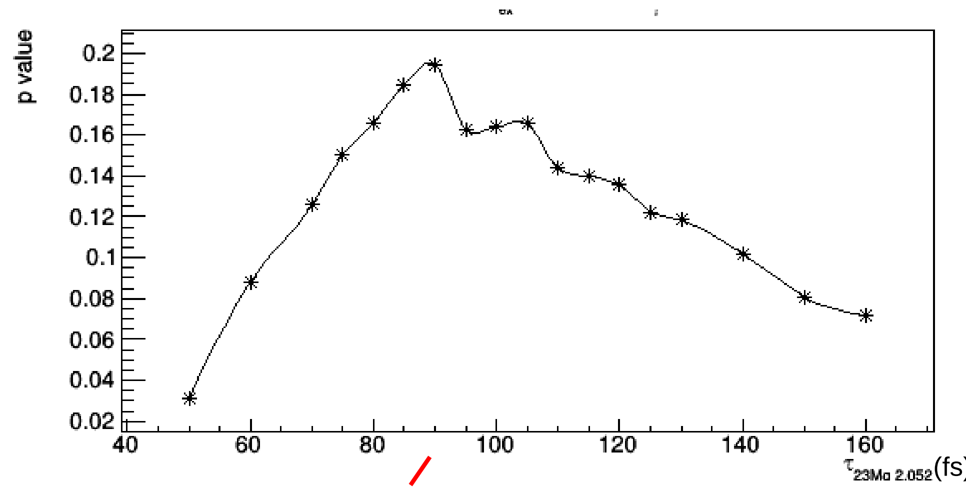
τ = 90 +/- 5 fs (E_{23Mg} = 2.052 MeV)

Preliminary results on τ :

^{23}Mg* 2.052 MeV state : first estimation of lifetime τ by DSAM







Reference values :

- τ = 55 +/- 14 fs (NNDC)
- τ = 105 +/- 18 fs (2)

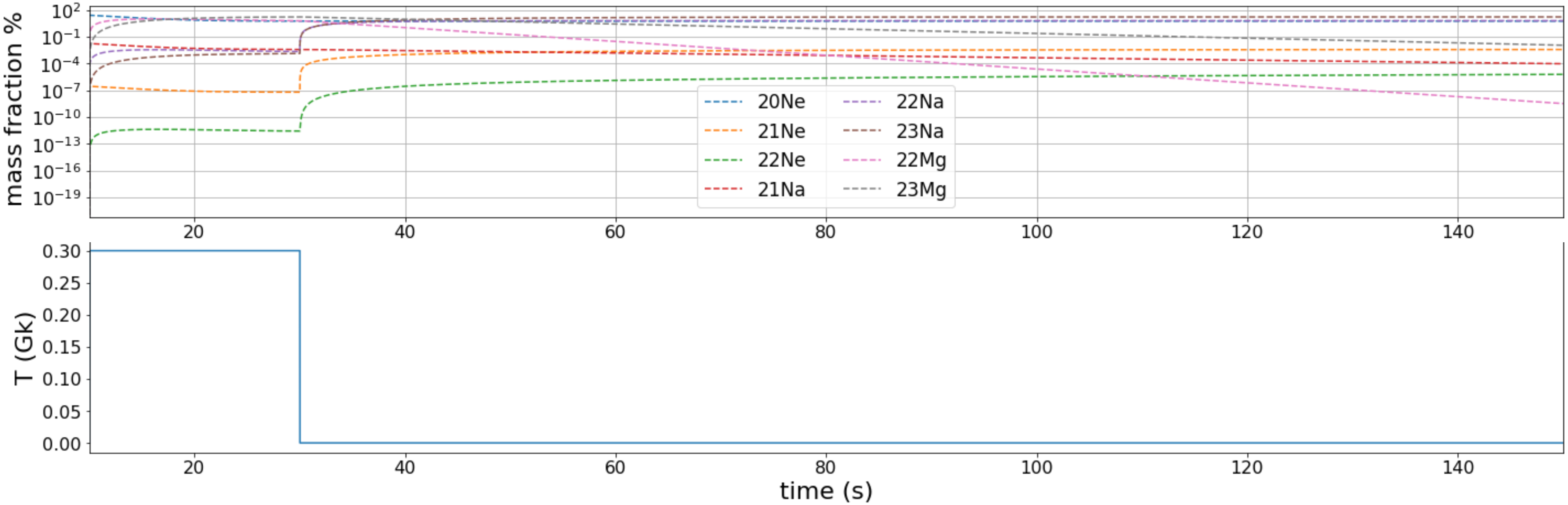
τ = 90 +/- 5 fs (E_{23Mg} = 2.052 MeV)

My Nova simulation : heuristic model

NeNaMg nuclear network simulation (T_{nova} = 0.3 GK during 20s)

My Nova simulation : heuristic model

NeNaMg nuclear network simulation (T_{nova} = 0.3 GK during 20s)



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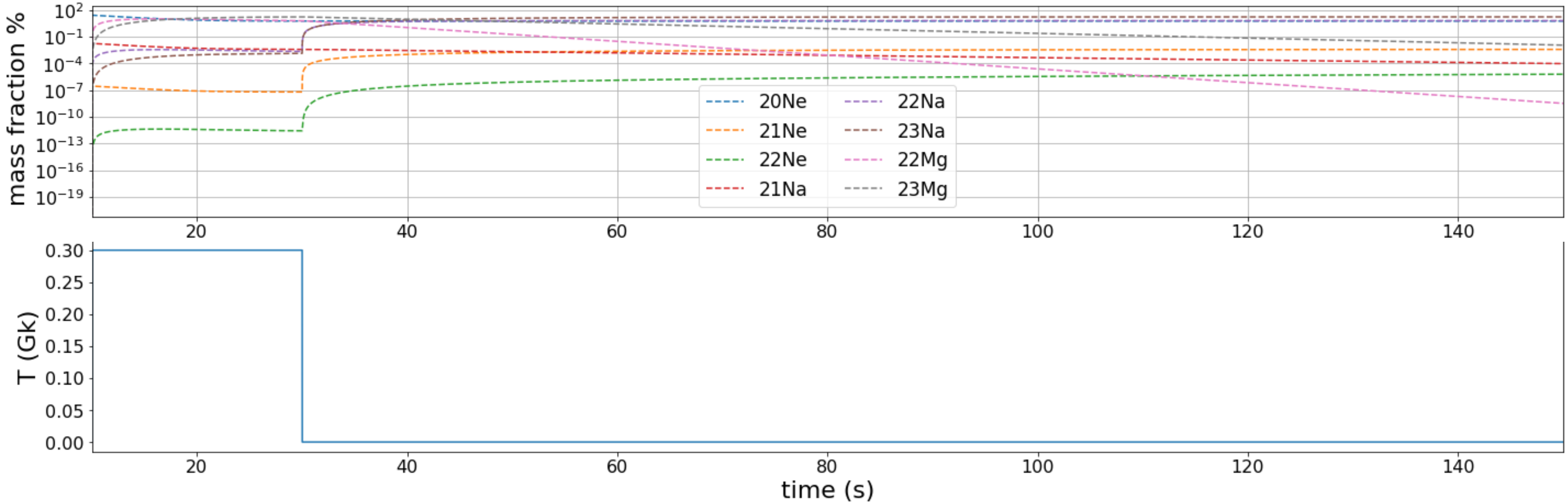

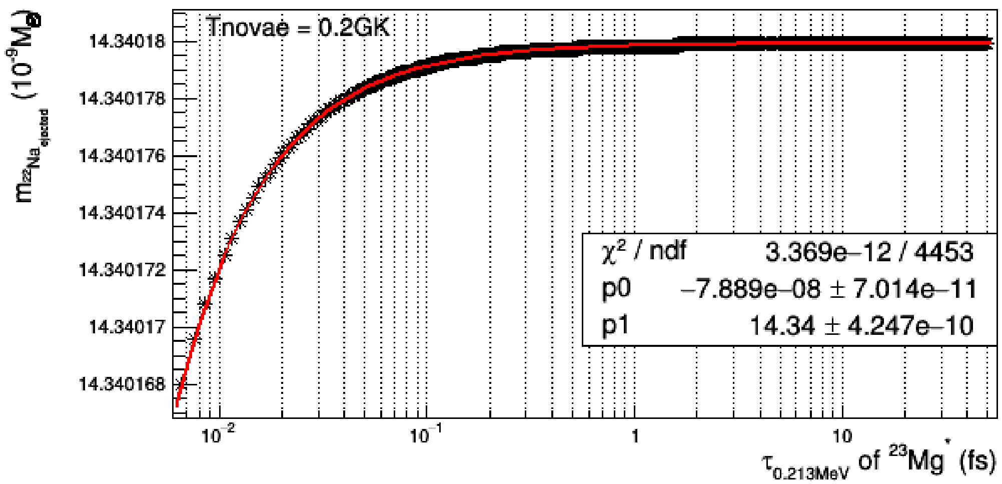

- Nucleus mass fraction = constant at the end of nova explosion

- Nova ejected ^{22}Na mass ~ 10^{-8} $M_{\odot}$
  Law with τ ($^{23}Mg^{*}_{7.786}$)

m_{22Na}(ejected) = A - $\frac{B}{T}$

Conclusion

1. **ONe Nova nuclear network :** 0.213MeV dominant resonance on destruction $^{22}Na(p, \gamma)^{23}Mg$ confirmed
   Nova simulation : ^{22}Na ejected matter dependence on τ ($^{23}Mg^*_{7.786}$)
   $\Rightarrow$ τ =10fs, Flux = **2.47 10^{-5} ph.cm^{-2}.s^{-1}** (Nova 1kpc) vs SPI sensitivity **3.10^{-5} ph.cm^{-2}.s^{-1}**

2. **E710 GANIL indirect experiment :** $^{3}He(^{24}Mg,^{4}He)^{23}Mg^*$ with particle detectors (SPIDER/VAMOS) and γ ray detector AGATA

3. **E710 first results** on particle/γ data
   - SPIDER : identification of (p, ^{4}He) dE-E curbs
   - AGATA constrained by VAMOS : DS lines from $^{23}Mg^*$
     preliminary estimations of β ($^{23}Mg^*$) and τ ($^{23}Mg^*_{2.052}$)

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Outlooks

1. Proton branching ratio B_p
2. Excited $^{23}Mg_{7.786}$ lifetime (shape analysis with simulated γ spectra)
3. Impact of derived resonant destruction rate on nova ^{22}Na abundance (simulation with more complex models)

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Thank you for your attention

References

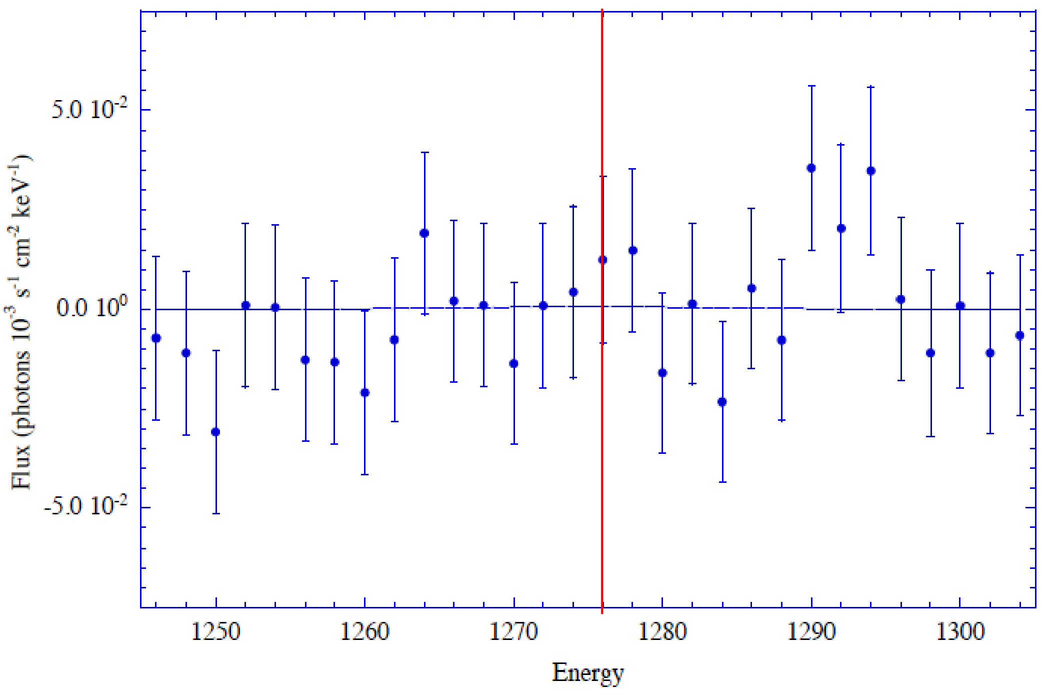
(1) - The lifetime of the 6.79 MeV state in ^{15}O as a challenge for nuclear astrophysics and γ–ray spectroscopy : a new DSAM measurement with the AGATA Demonstrator array.
C. Michelagnoli, Thesis (2013)

(2) - Measurements of lifetimes in ^{23}Mg.
O.S Kirsebom et al. Physical Review Letters (2016)

- Direct Measurements of ^{22}Na(p, γ)^{23}Mg Resonances and Consequences for ^{22}Na Production in Classical Novae.
A.L Sallaska et al, Physical Review Letters (2010)

Appendice

Astrophysical search for ^{22}Na line at 1.275 MeV



Gamma spectrum resulting from observation with SPI over 3years (1). The flux represents cumulative emission toward Galatic Center fitted by novae assumed spatial distribution.

⇒ Line at 1.275 hardly seen : 1.3 10^{-5} ph.cm^{-2}.s^{-1} (1σ)

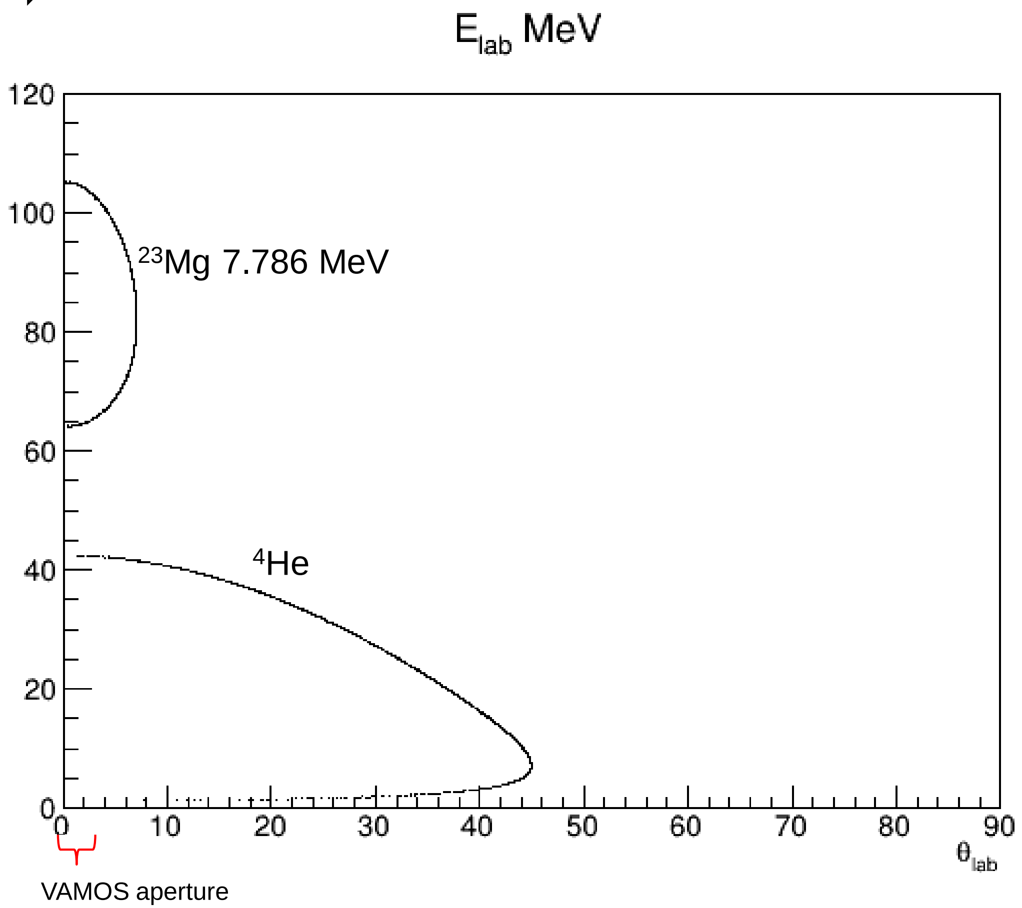
⇒ With 1/3 One novae at rate 30 per year, derived ejected mass upper limit 2.5-5.7 10^{-7} $M_{\odot}$ per outburst

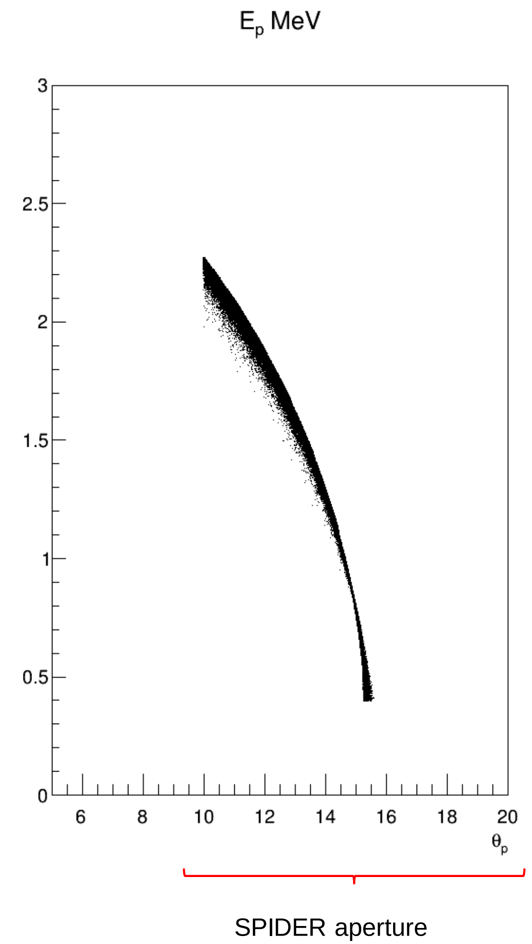
Important issue to tackle : instrument background level high at the energy looked at (activation by Cosmic Rays of aluminium material near detector)

(1) Cosmic Gamma-Ray Spectroscopy, R. Diehl (2013)

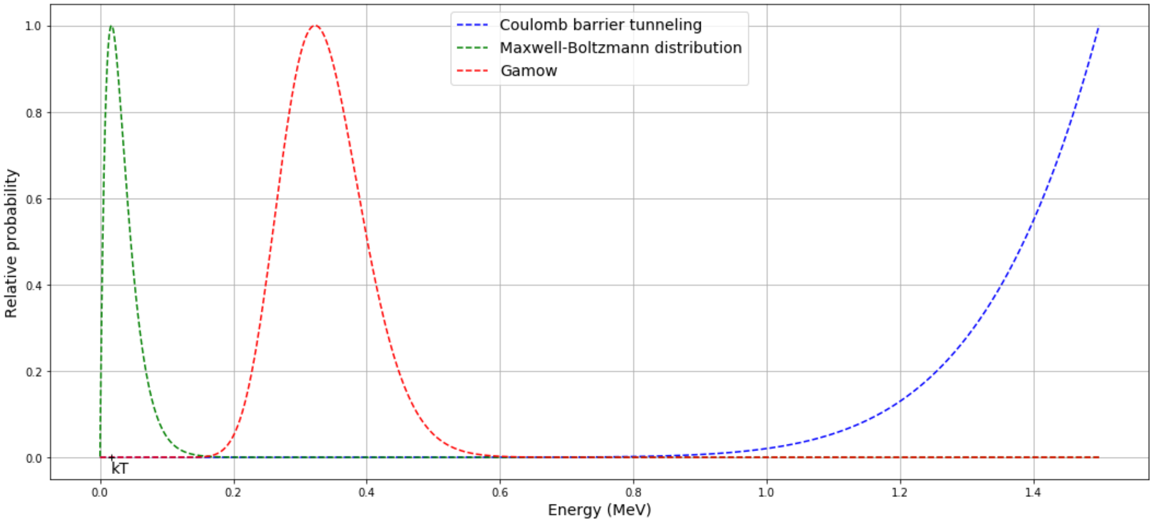
A. Reaction kinematics

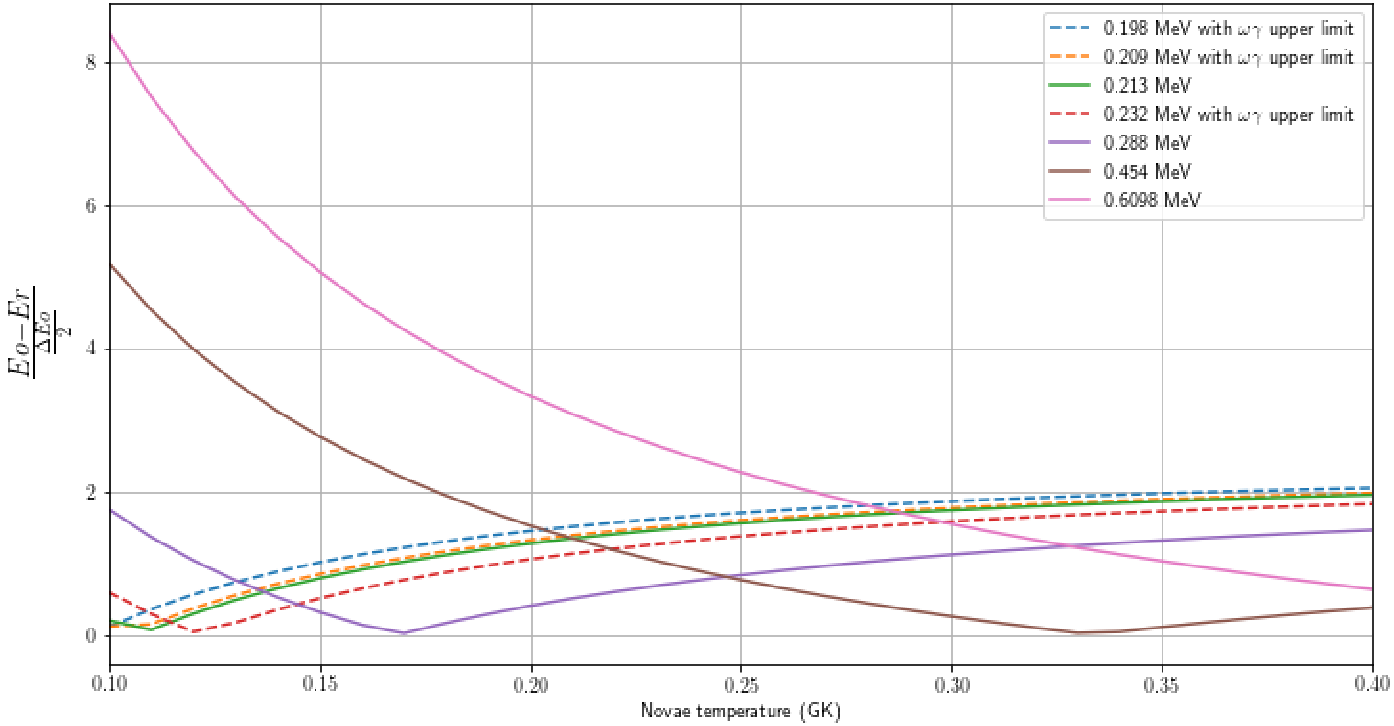
Simulation of reaction products (^{23}Mg, ^{4}He) and p





A. Gamow window

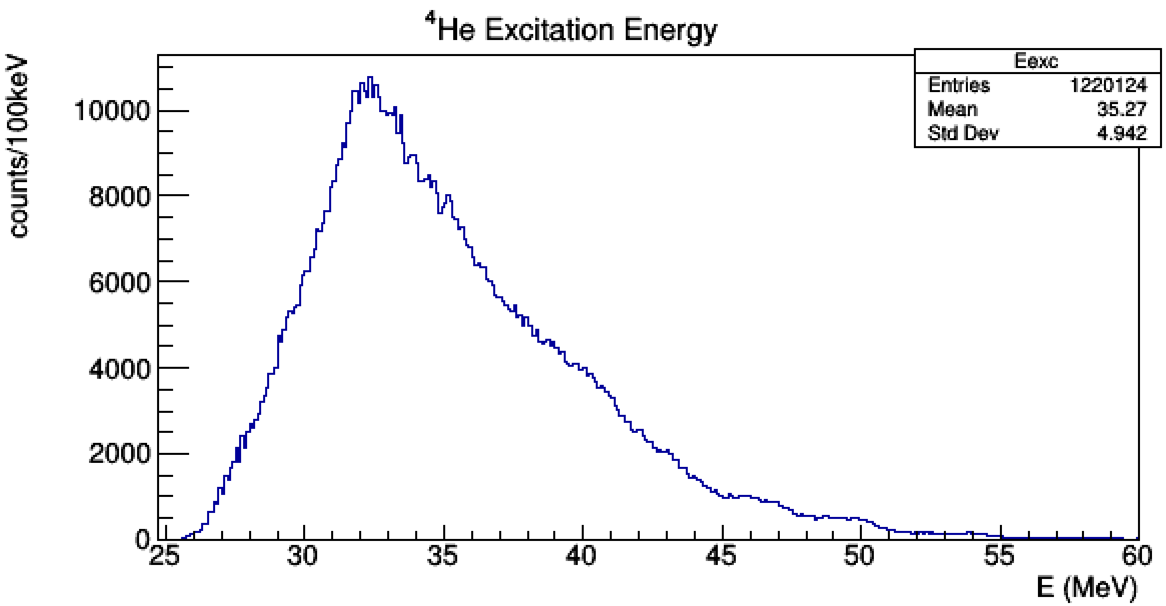




A. Coïncidence with ^{4}He

VAMOS ^{4}He excitation spectrum from reconstruct Bρ with Drift Chambers
=> resolution 2.10^{-3}

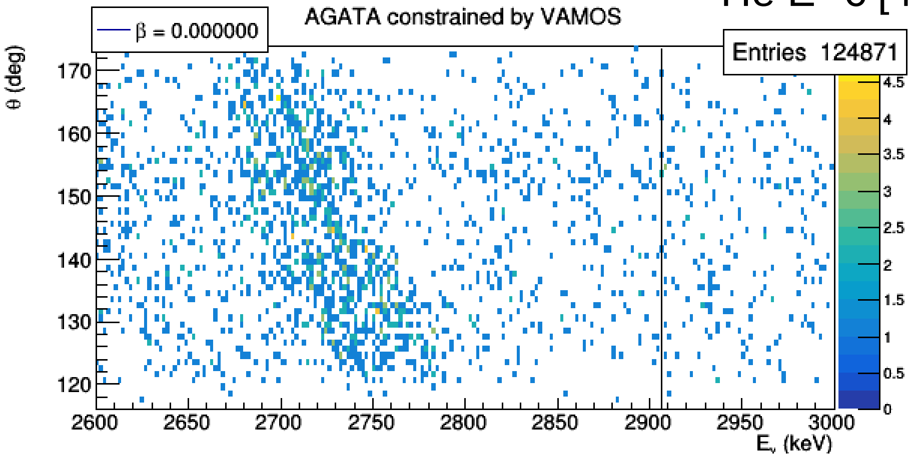
$$E^* = m_{^4He}c^2\left(\frac{1}{\sqrt{1-\left(\frac{B\rho * q_{^4He}}{c*m_{^4He}}\right)^2}} - 1\right)$$

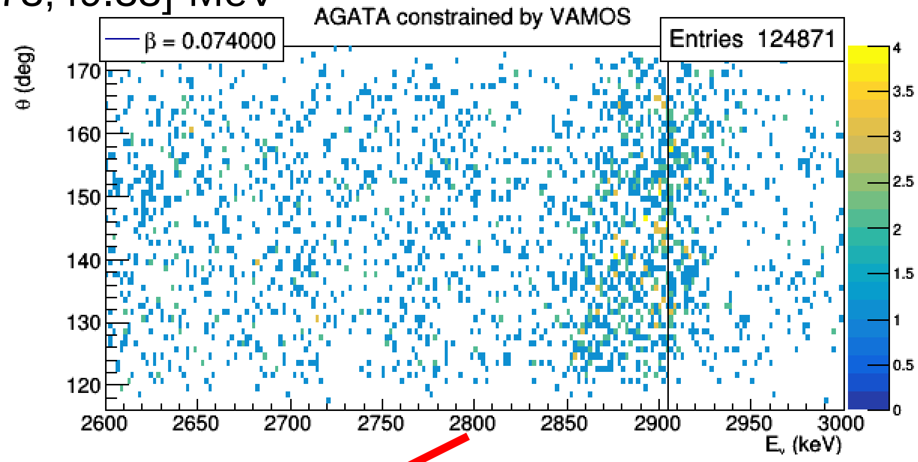


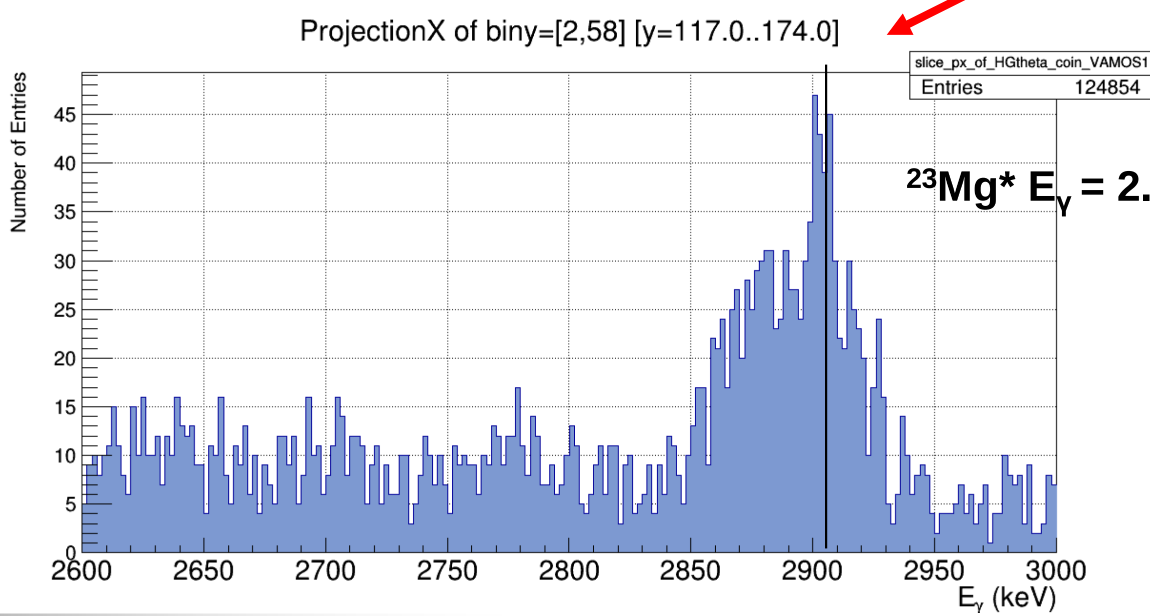
A. Fusion-Evaporation products

$^{24}Mg(^{12}C,2\alpha)^{28}Si^*$ or $^{24}Mg(^{16}O,3\alpha)^{28}Si^*$ => overlapping with 23Mg* γ lines

^{4}He E* є [48.73;49.33] MeV







$^{23}Mg^*$ E_γ = 2.90MeV

A. Lifetime vs resonance strength