Doppler Shift Attenuation Method: The experimental setup at the MLL and the lifetime measurement of the 1st excited state in ^{31}S

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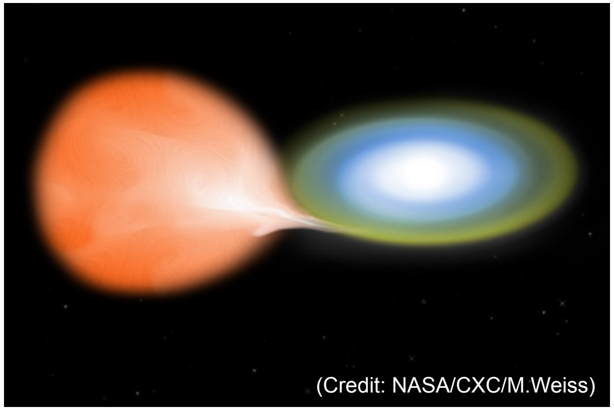
Doppler Shift Attenuation Method: The experimental setup at the MLL and the lifetime measurement of the 1st excited state in ^{31}S

1. Motivation
2. Method, setup and experiment
3. Analysis: simulation and line shape calculation
4. Results and conclusion

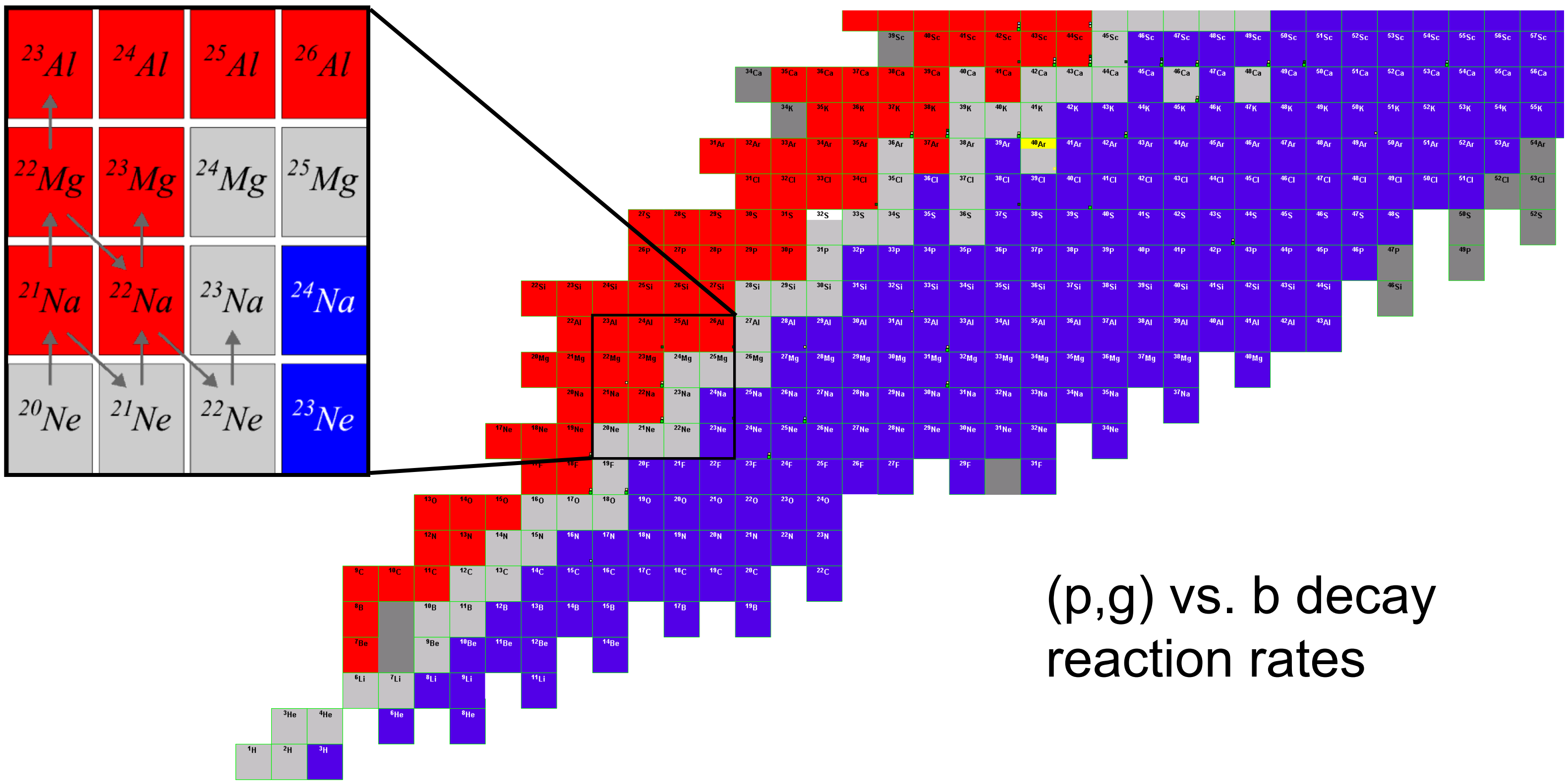
1. Motivation


(Credit: NASA/CXC/M.Weiss)

classical nova illustration

- H-rich material accumulates on surface of white dwarf (C/O or O/Ne core)
- energy production via pp-chain ($e \sim T^4$)
- CNO sets in ($e \sim T^{17}$) pressure overcomes degeneracy
  → ejection of the envelope
- proton capture up to A=40
- competition: p-capture / b decay

1. Motivation



(p,g) vs. b decay
reaction rates

1. Thermonuclear Resonant Reaction Rate

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

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_i \omega\gamma_i \exp\left(\frac{-E_i}{kT}\right)$$

resonance strength

$$\omega\gamma_i = \frac{2J_i+1}{(2J_p+1)(2J_X+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}$$

$$= g(1-B_p)B_p \frac{\hbar}{\tau_i}$$

$$= g(1-B_\gamma)B_\gamma \frac{\hbar}{\tau_i}$$

life time

μ - reduced mass

J_i, J_p, J_X – Spins of: resonance state/ projectile/ target

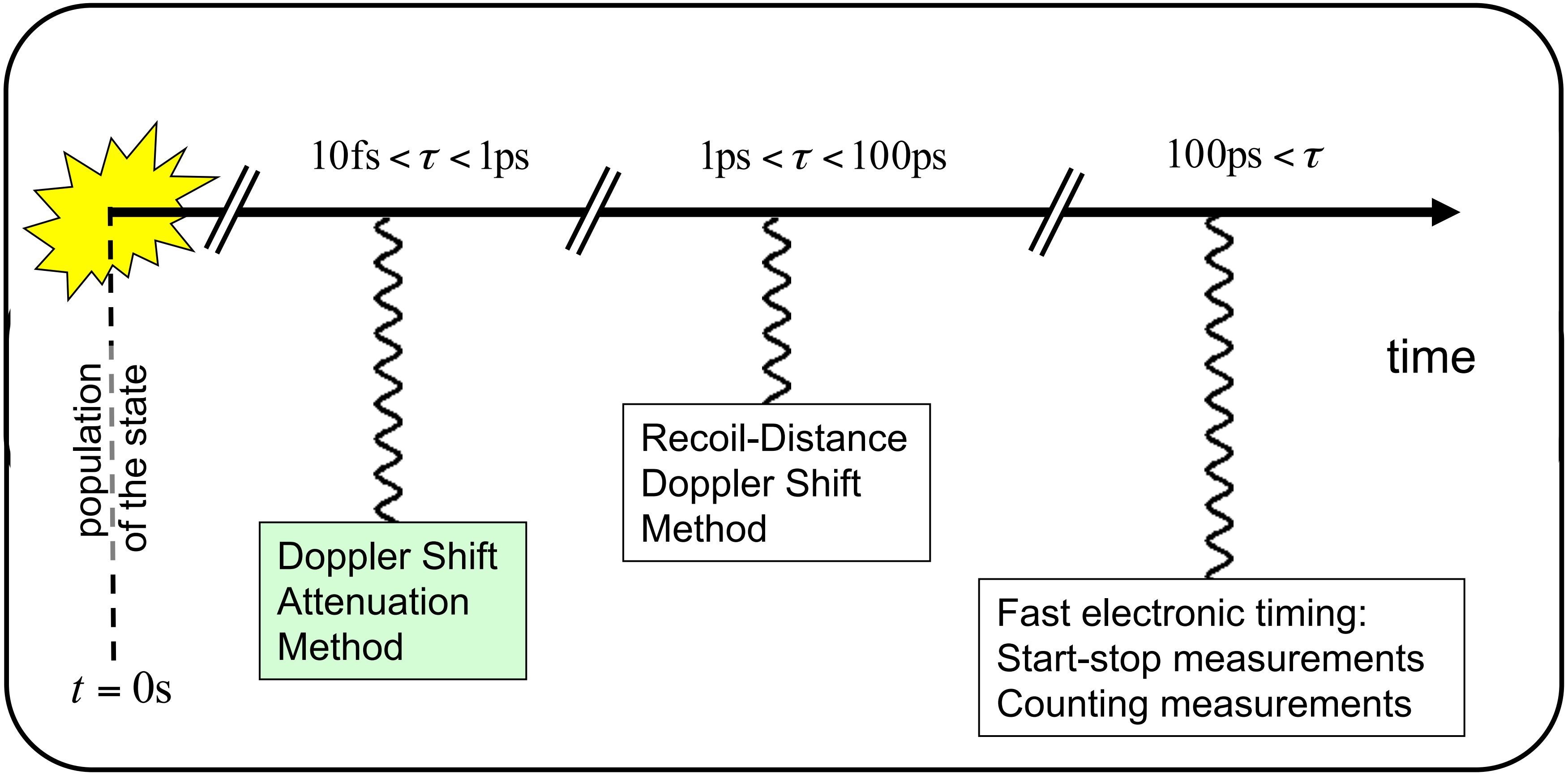
T – temperature

E_i – relative energy of state (to Q)

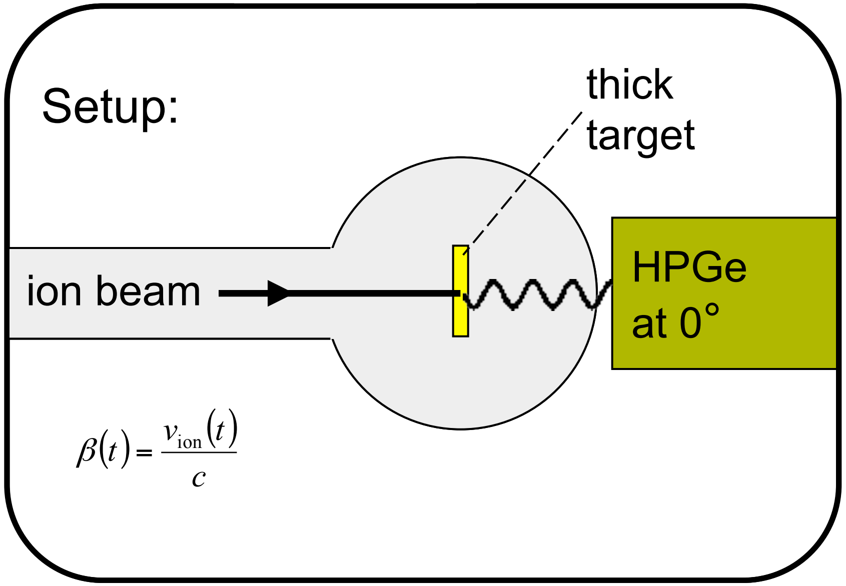
Γ_p, Γ_γ – partial width of p- / γ- decay

$B_p = \Gamma_p / \Gamma$ – branching ratio

2. Lifetime measurements



2. Doppler Shift Attenuation Method



$$\beta(t) = \frac{v_{\text{ion}}(t)}{c}$$

$$E_\gamma^{obs} = E_\gamma^0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha} \overset{v<<c}{\approx} E_\gamma^0 (1+\beta\cos\alpha)$$

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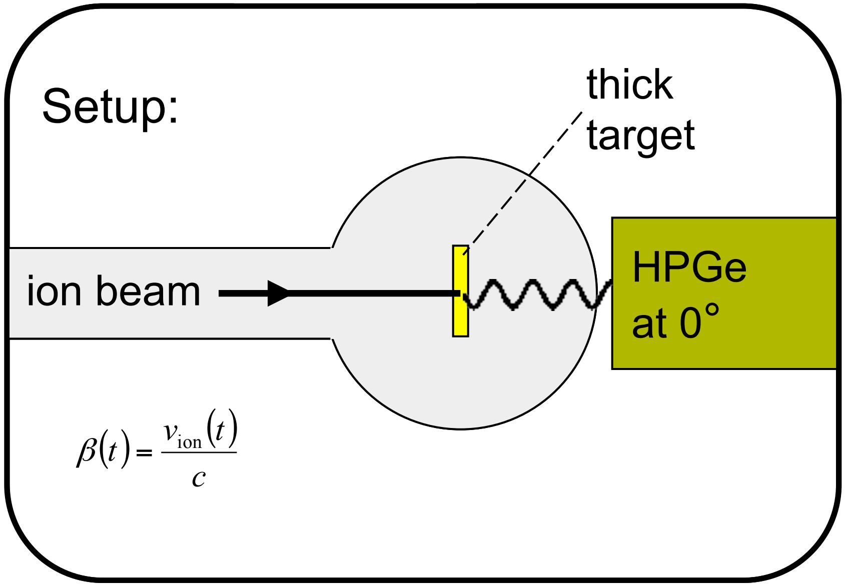
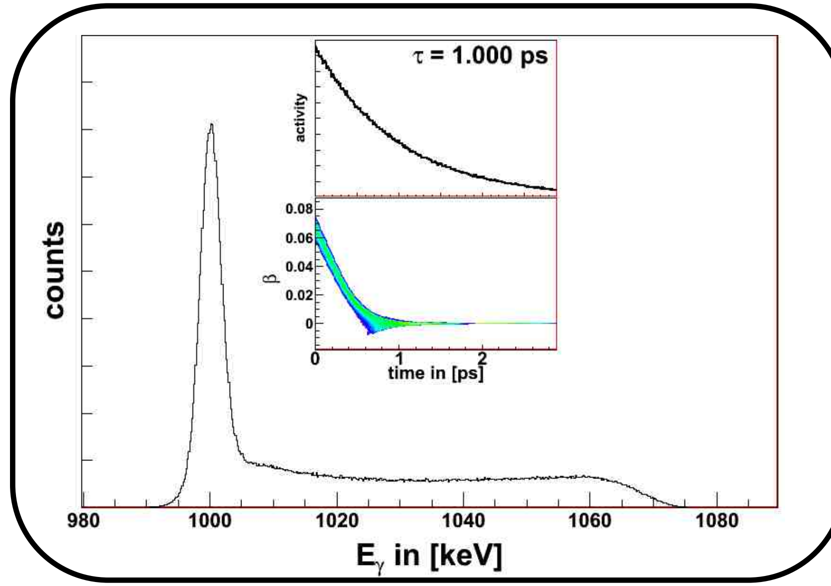
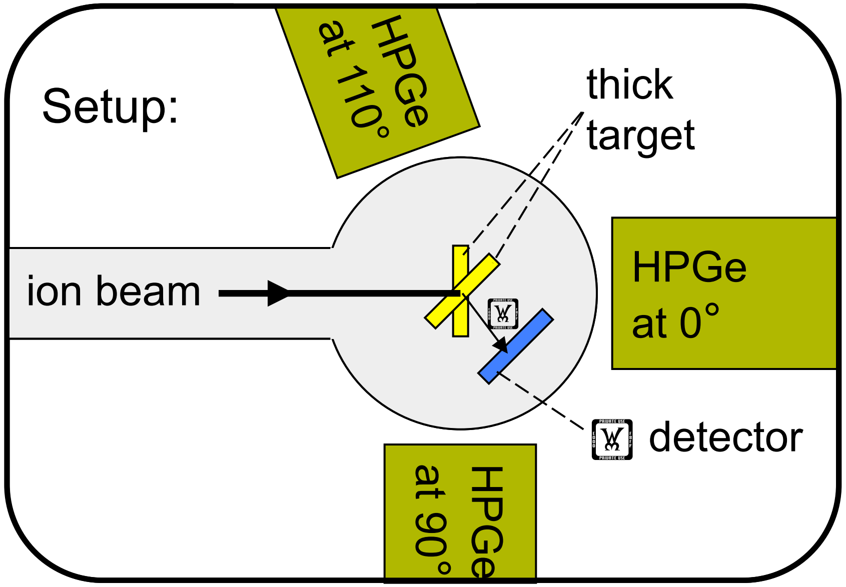




$$E_\gamma^{obs} = E_\gamma^0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha} \overset{v<<c}{\approx} E_\gamma^0 (1+\beta\cos\alpha)$$

2. DSAM setup at the MLL



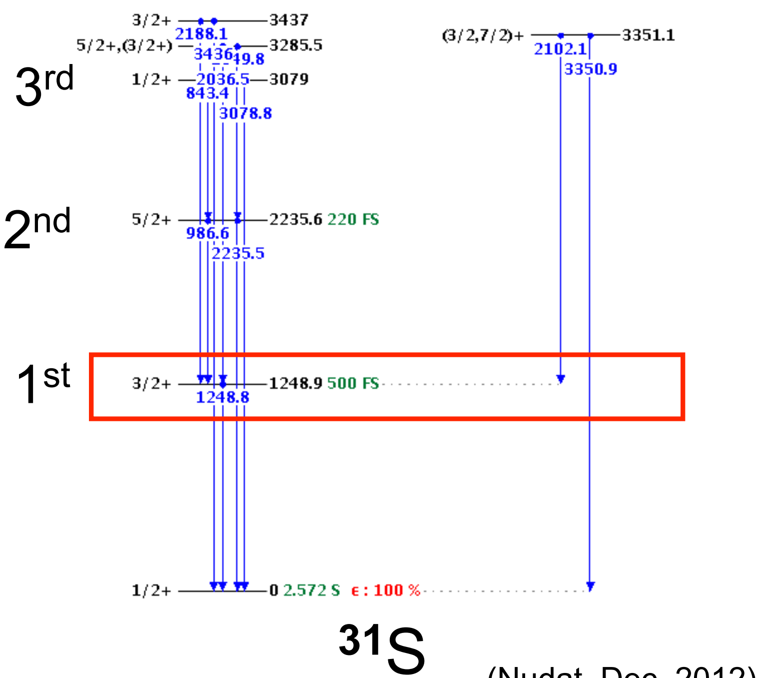
Reaction: $^{32}S(^{3}He,^{4}He)^{31}S^{*}$

Beam: ^{32}S at 85 MeV

Target: ^{3}He implanted Au (stops ^{31}S)

Recoils: ^{31}S with E_{ex} = 1.25 MeV
^{4}He for PID & coinc.

2. Commissioning experiment: $^{32}S(^{3}He,^{4}He)^{31}S^{*}$



(Nudat, Dec. 2012)

Reaction: $^{32}S(^{3}He,^{4}He)^{31}S^{*}$

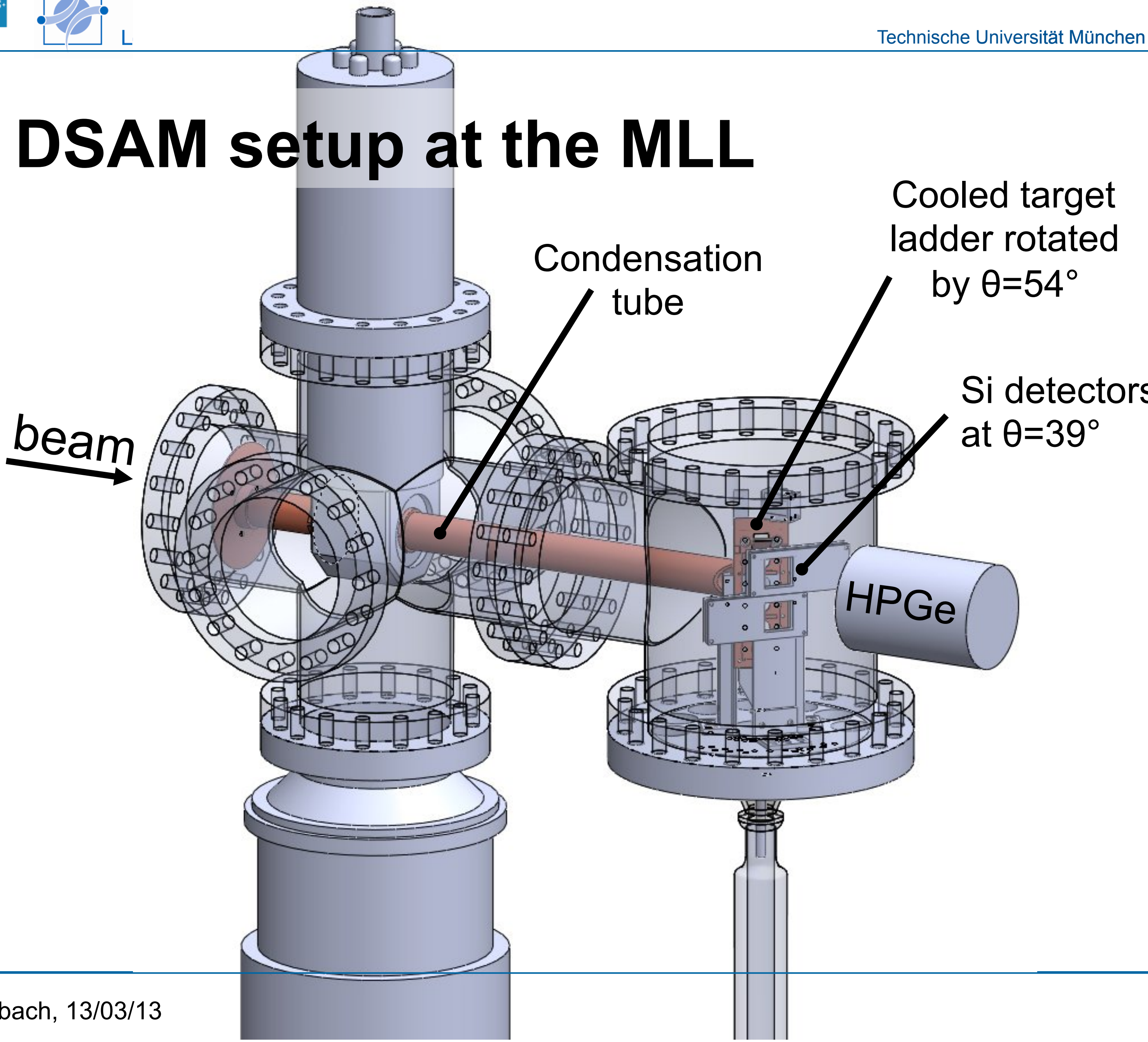
Beam: ^{32}S at 85 MeV

Low trans. strength:
2nd → 1st, 3rd → 1st

High trans. strength:
4th → 1st, 5th → 1st

levels nicely separated
Detector response function known
known lifetime
no feeding

2. DSAM setup at the MLL



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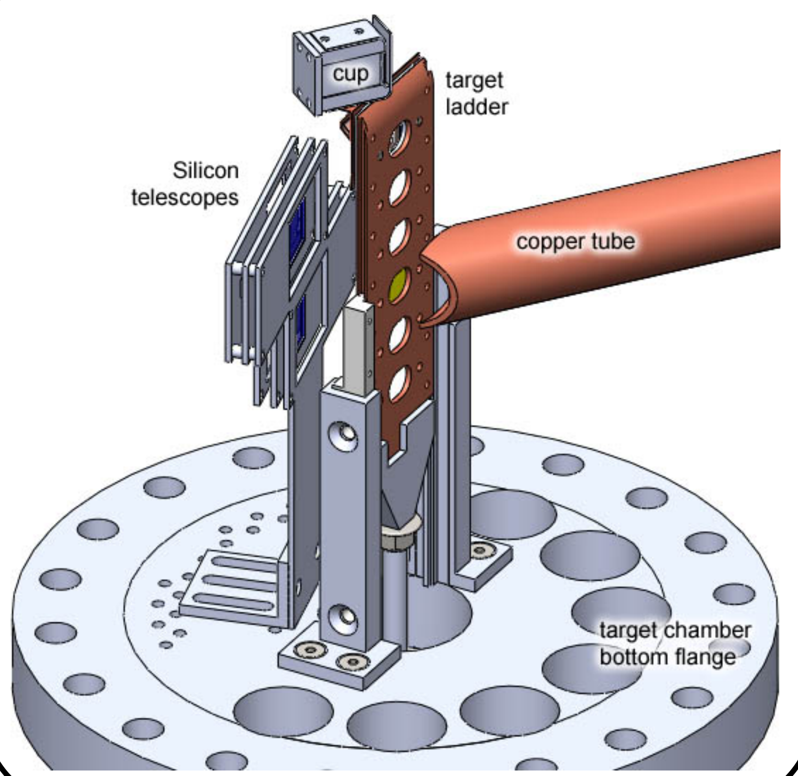

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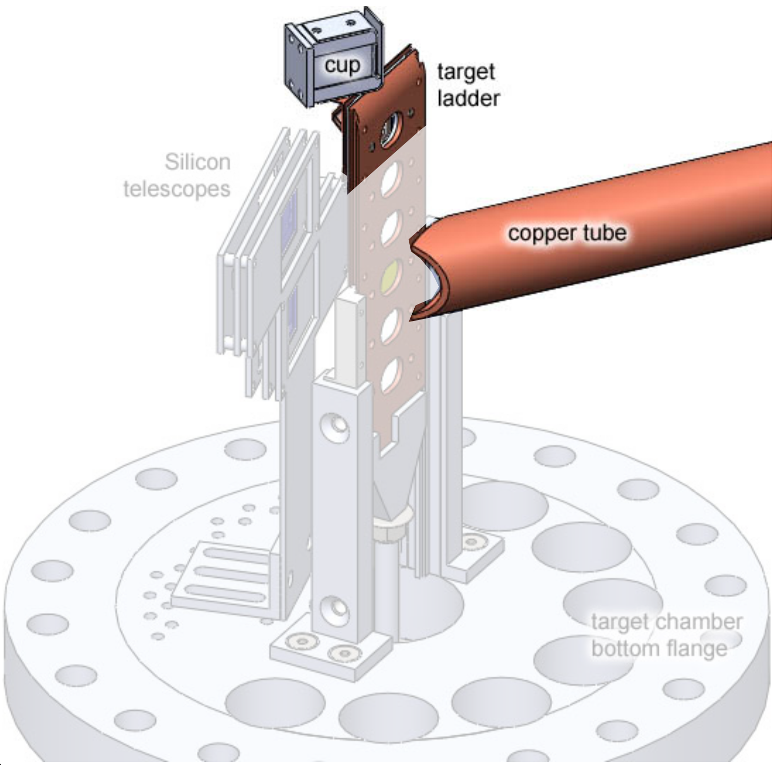
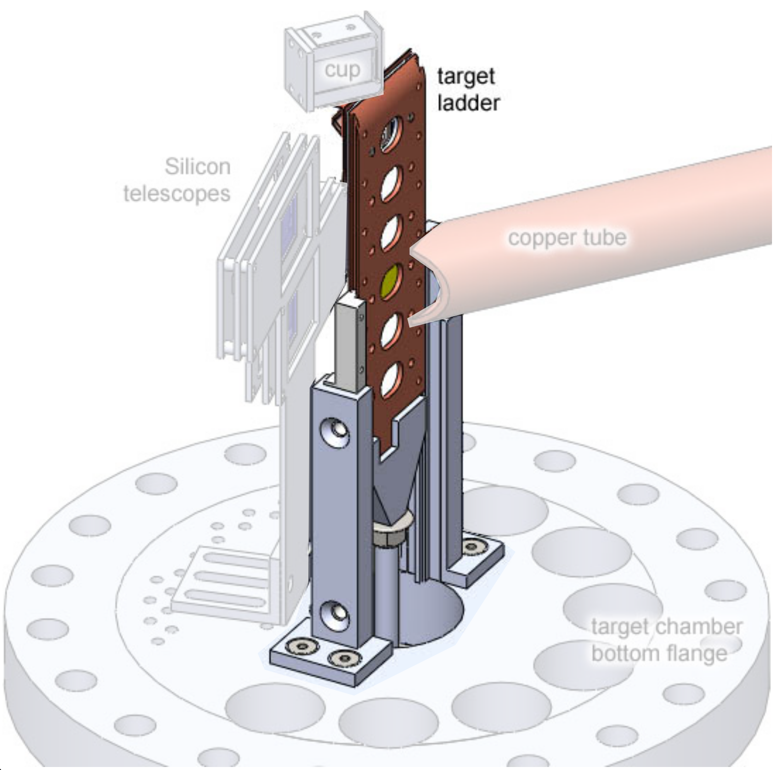


Features: beam diagnostic

- mini cup with suppressing voltage
- optional collimator in Cu tube
- CsI crystal for visual diagnostic

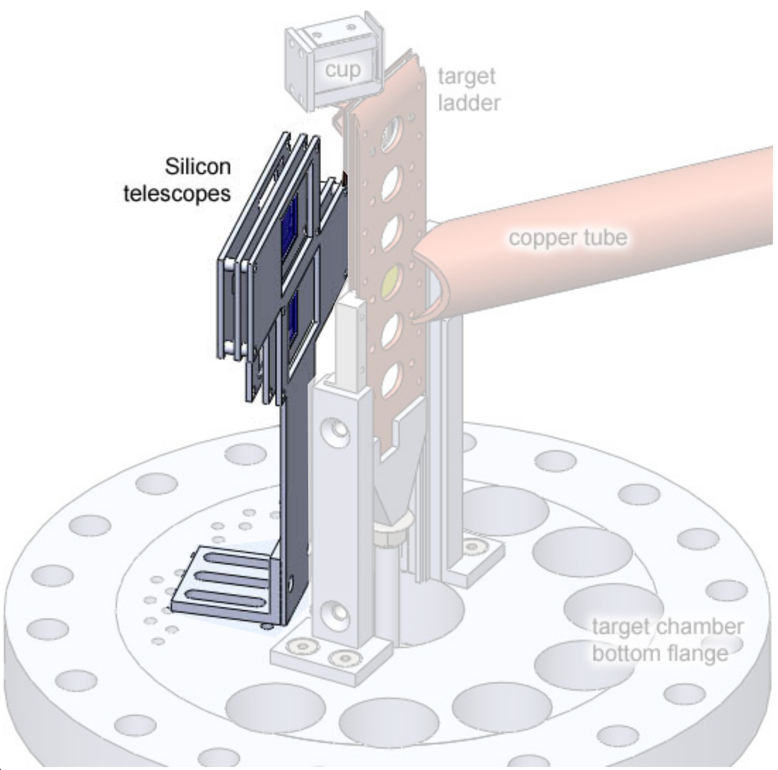
2. DSAM setup at the MLL



Features: target ladder

- 5+2 positions
- linear translator
- rotation angle 54°
- coolable to T = -100 °C

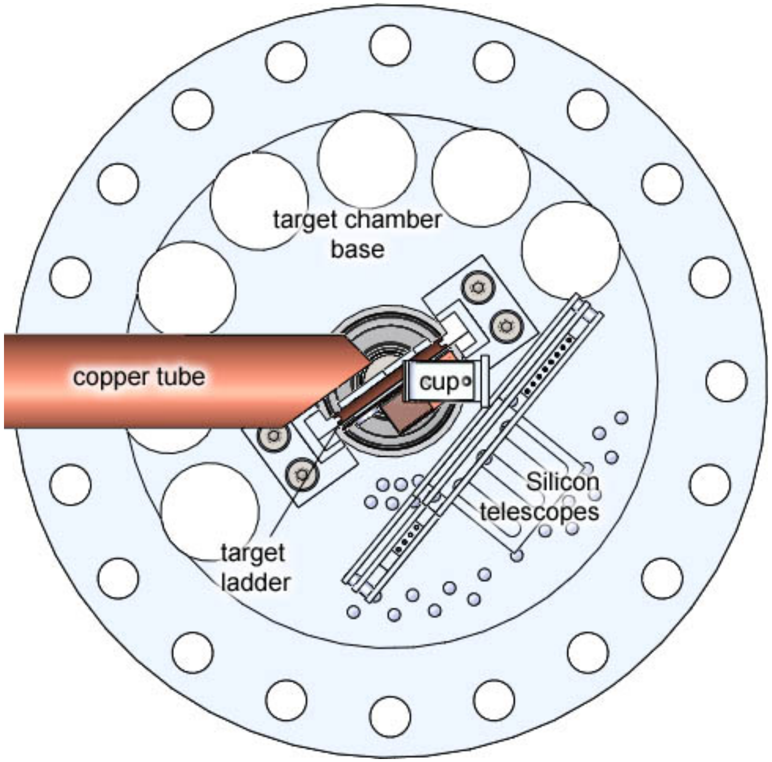
2. DSAM setup at the MLL

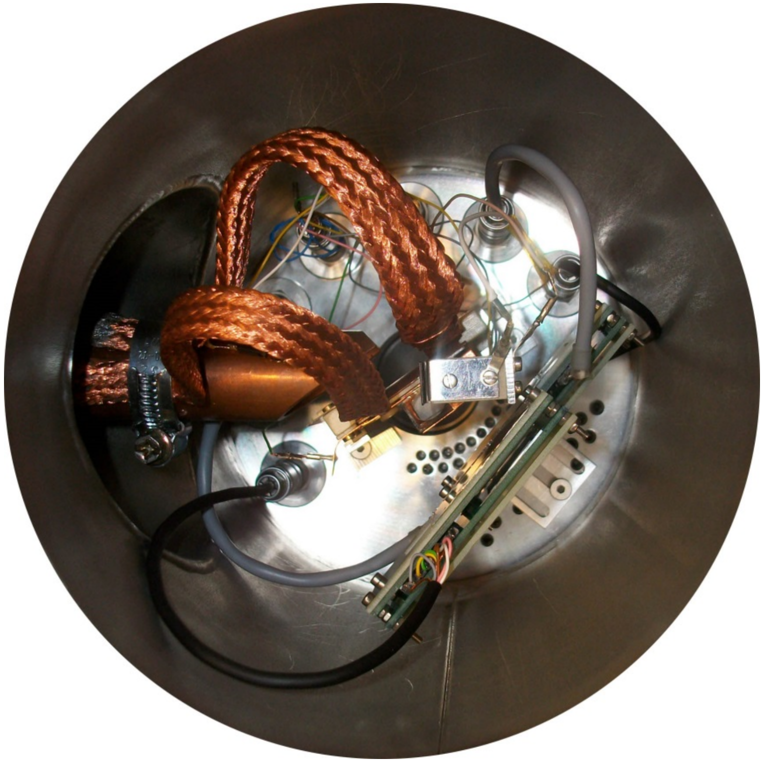


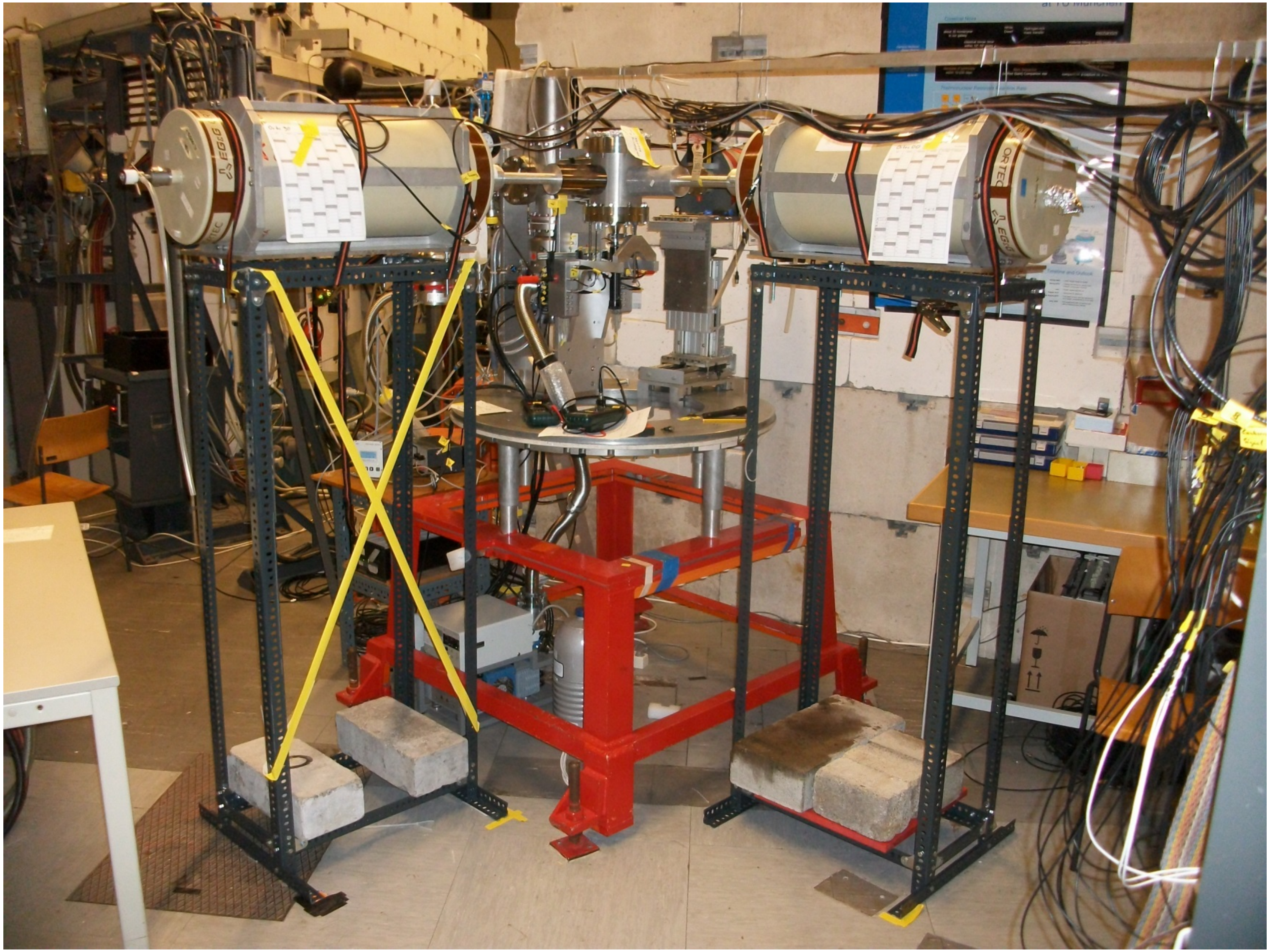
Features: Silicon telescopes

- $\Delta E/E$ (50 μm/1mm) for PID
- polar angles: 25°< θ < 60°
- distance: 32 mm
- 20 $\times$ 20 mm^2
- position sensitive

2. DSAM setup at the MLL

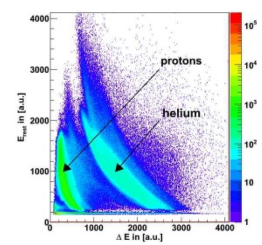




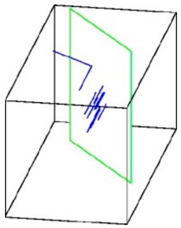


3. Analysis: Simulation and lineshape calculation

Three major analysis steps:



3.1 Proceeding the acquired data of the experiment
→ calibration
→ background reduction in the E_g spectra



3.2 Simulation of the Stopping process: Geant4

3.3 Line shape analysis: Fitting with APCAD

3.1 Proceeding the experimental data

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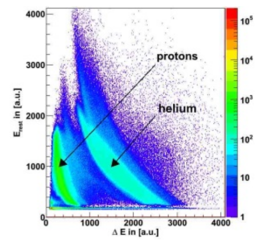
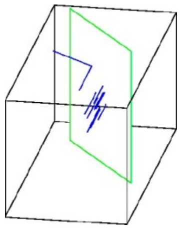




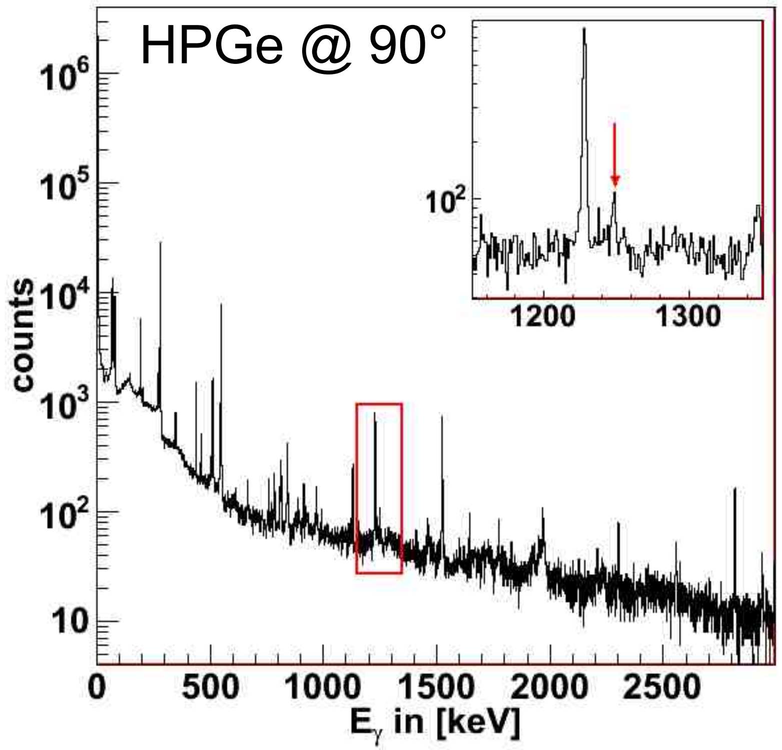
3.2 Simulation of the Stopping process: Geant4

3.3 Line shape analysis: Fitting with APCAD

3.1 Proceeding the experimental data

Raw data:

- ~90 hours (with 2.3 pnA)
  $^{32}S \rightarrow$ "^{3}He + Au" target
- ~30 hours (with 6.3 pnA)
  $^{32}S \rightarrow$ "Au-only" target
- global trigger on charged particles in the Si telescopes

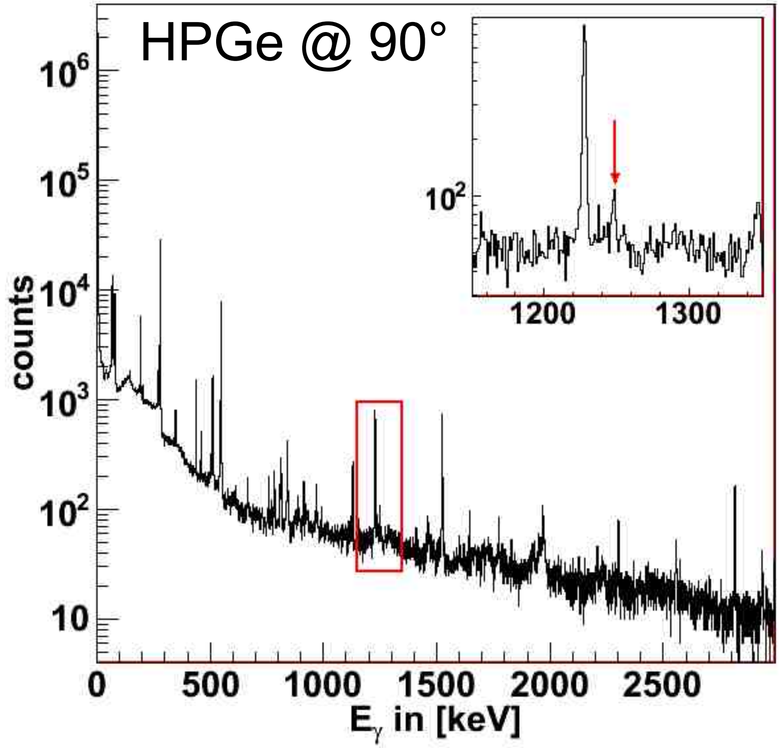


3.1 Proceeding the experimental data

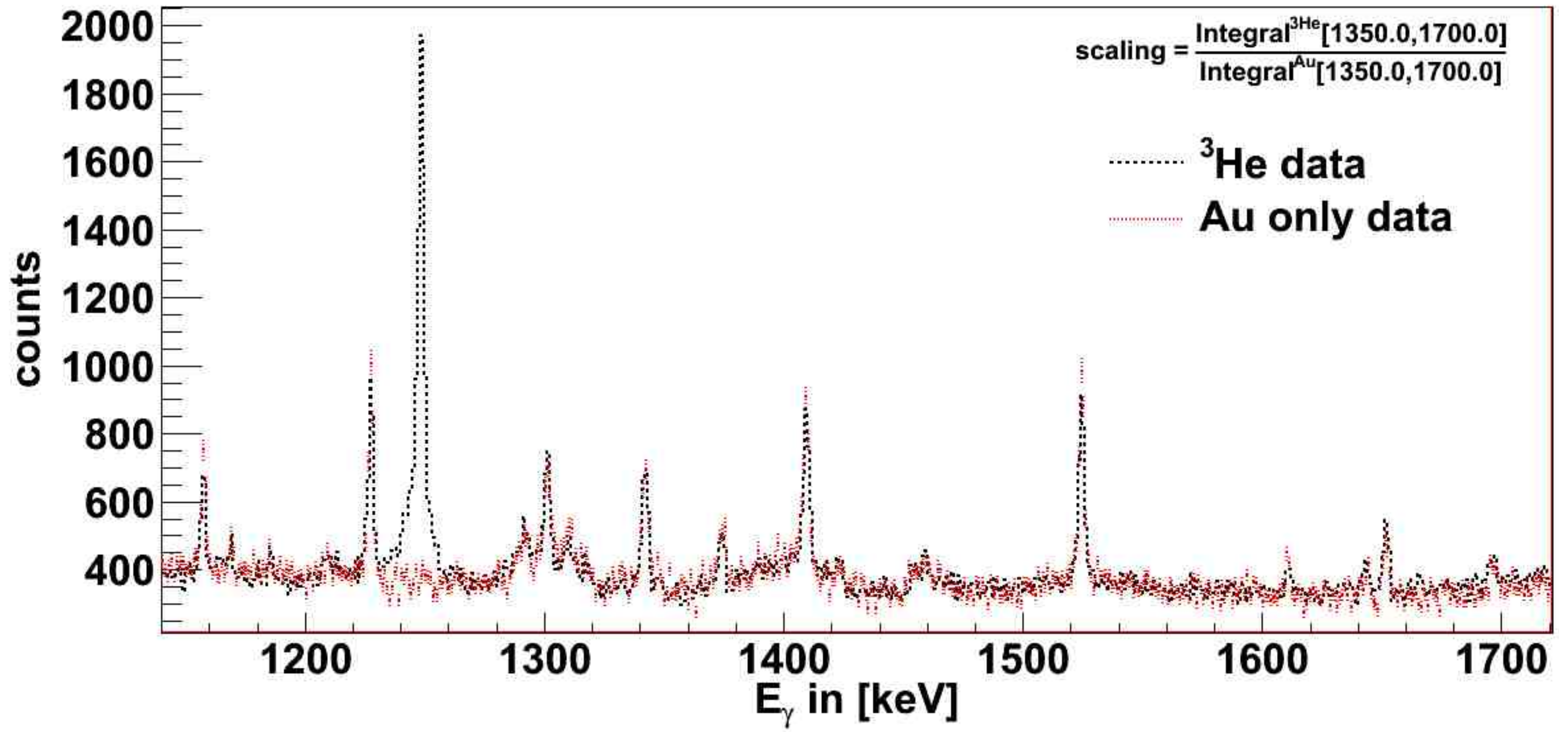
Proceeding:

•Particle identification in the dE/E Si telescopes

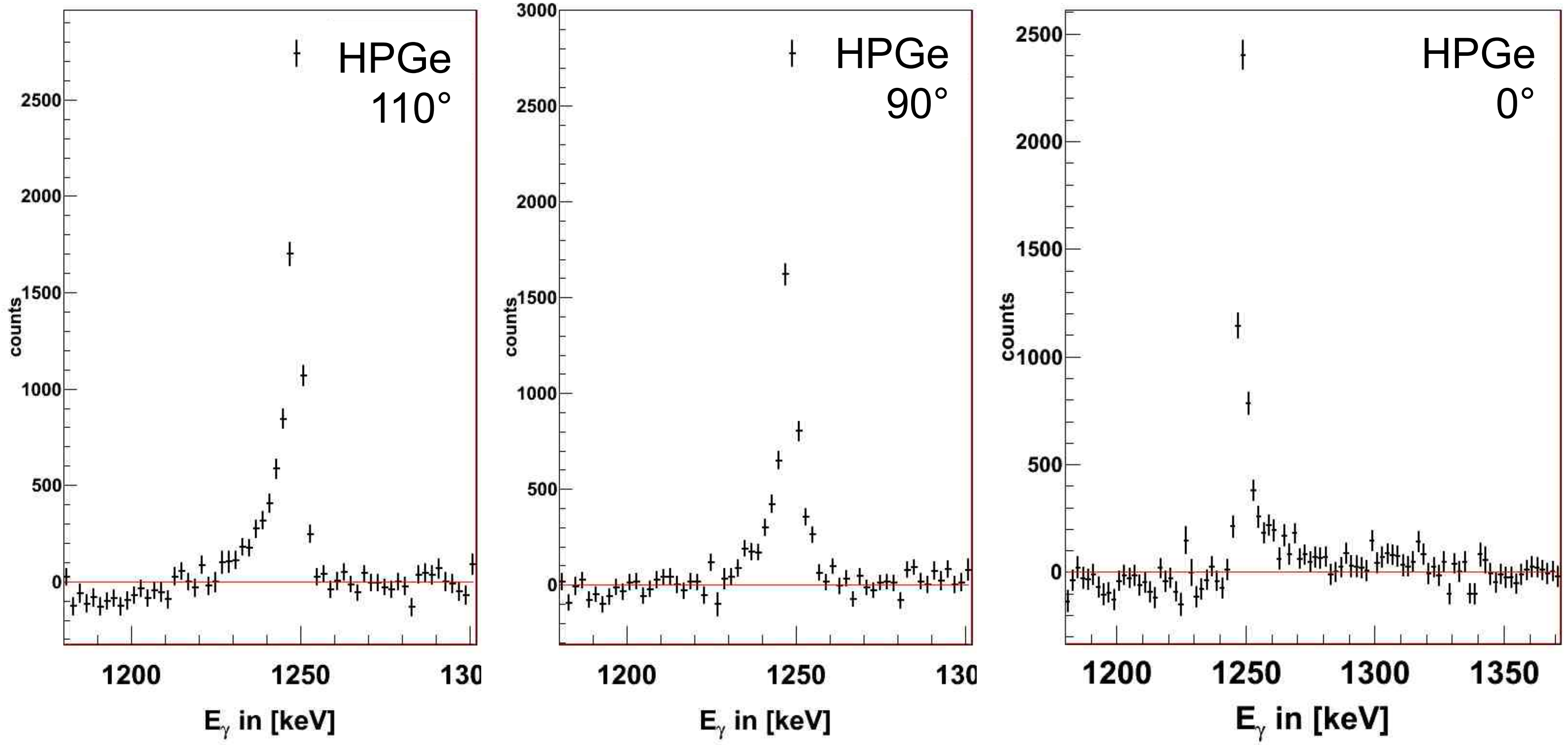
•Background subtraction



3.1 E_γ background subtraction



3.1 E_γ spectra for lineshape analysis



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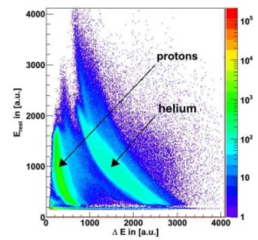

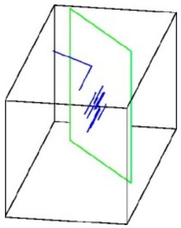

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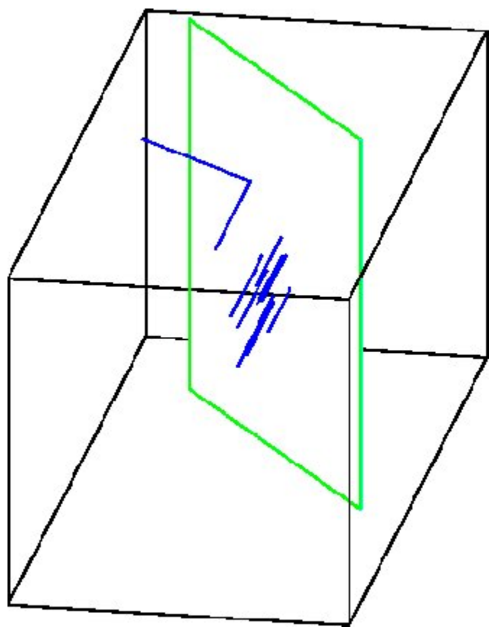
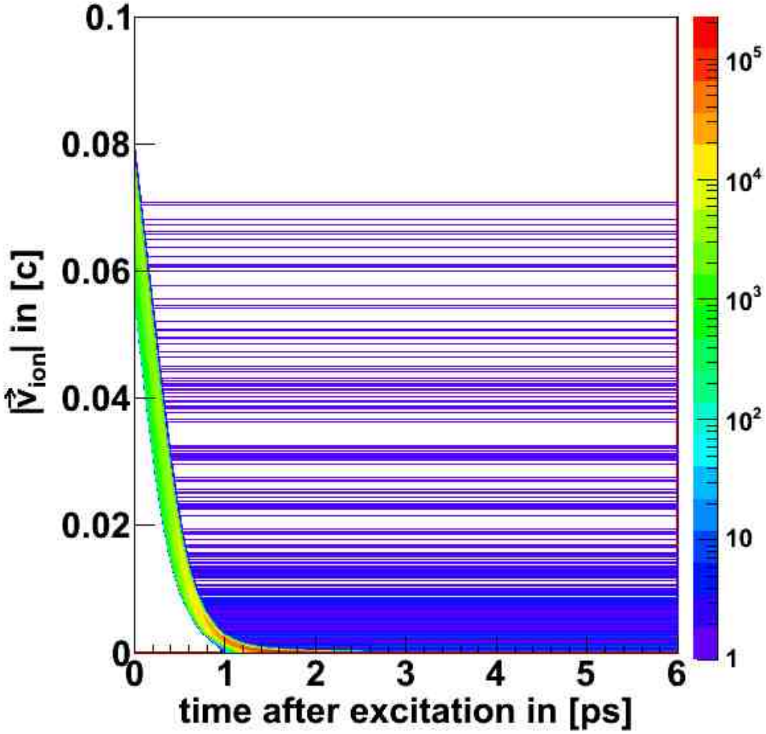


Monte Carlo simulation:

- beam:
  - energy
  - elliptical spot
- target:
  - 1^{st} layer: ^{3}He in gold
  - 2^{nd} layer: Au only
  - rotation
- transfer reaction

3.2 Simulation of the stopping process: Geant4



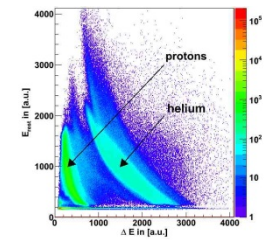
Output file:

- if transfer reaction occurs:
  - save ^{31}S vector
  - save ^{4}He vector

  for each time step

3.1 Proceeding the experimental data

Three major analysis steps:



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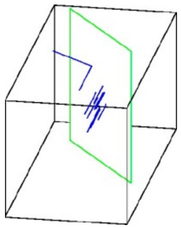

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3.3 Line shape analysis: APCAD

Analysis **P**rogram for **C**ontinuous **A**ngle **D**SAM

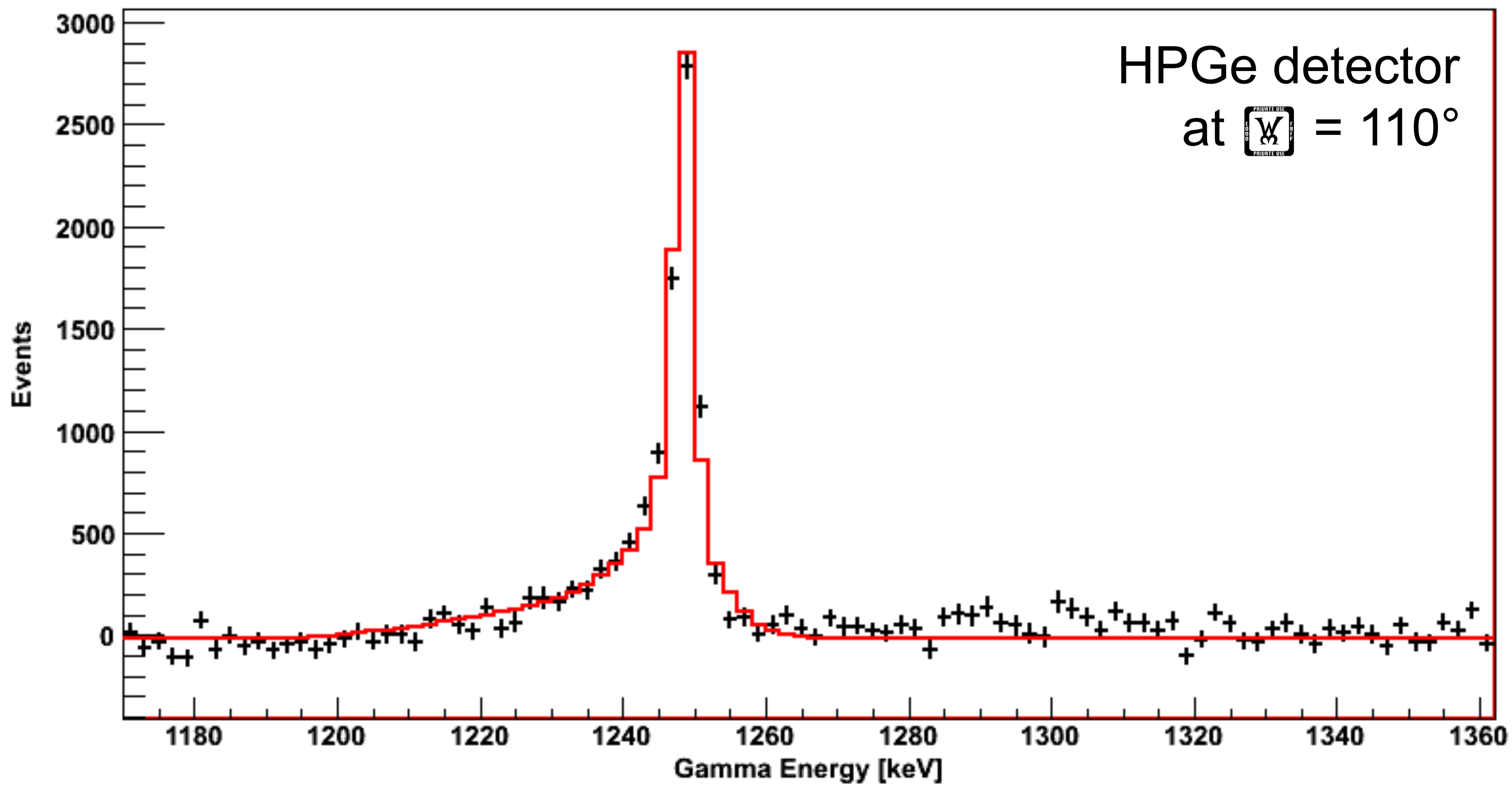
- Christian Stahl, TU Darmstadt, AG Pietralla

Idea:

1. Simulate stopping process $v_{ion}(t)$
2. Determine observed Doppler Shift distribution $m_{det}(t)$
3. Assume lifetime and covolve it with $m_{det}(t)$

4. Fit experimental line shape by varying assumed lifetime

3.3 Fitting the experimental data



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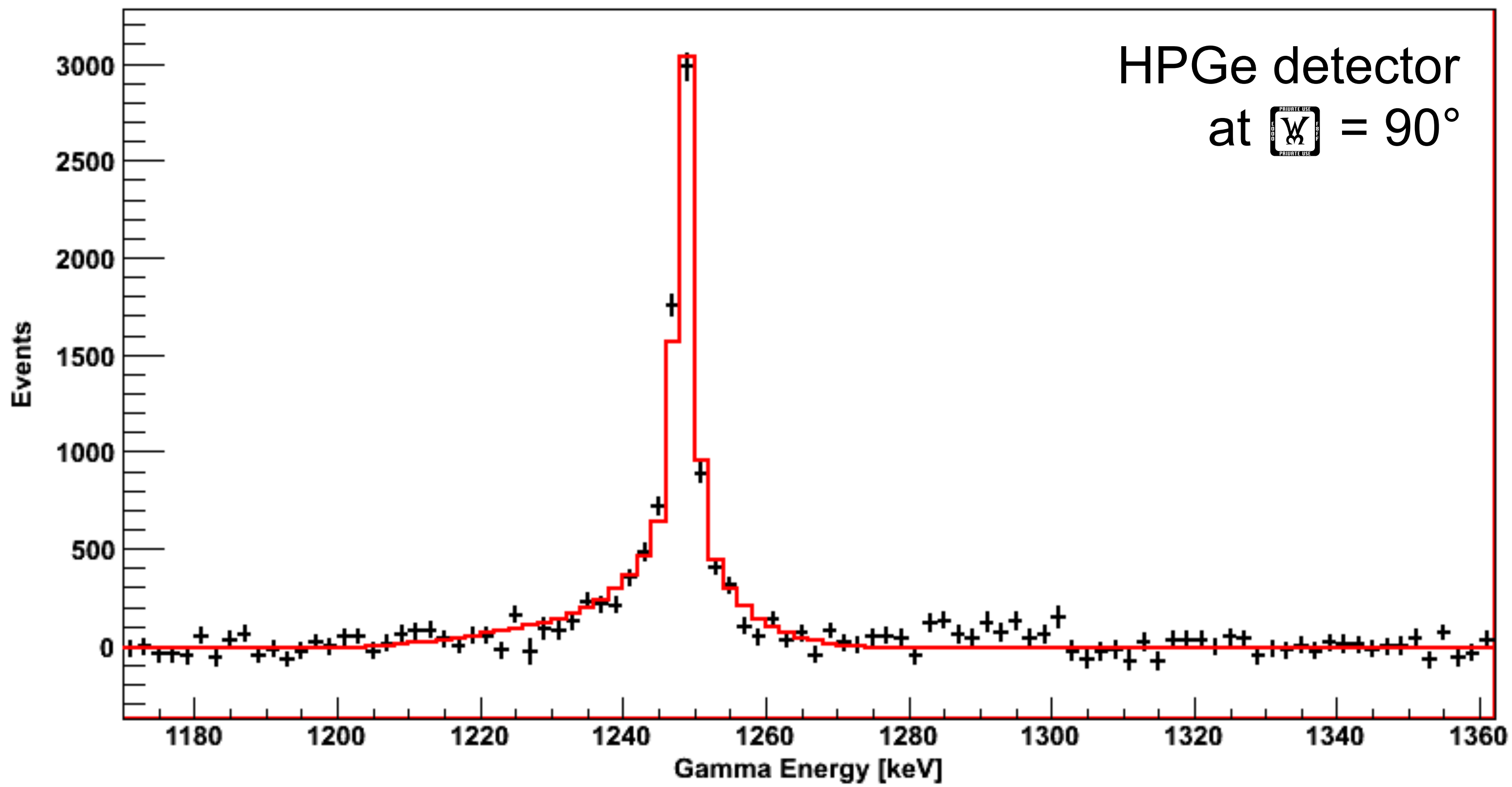

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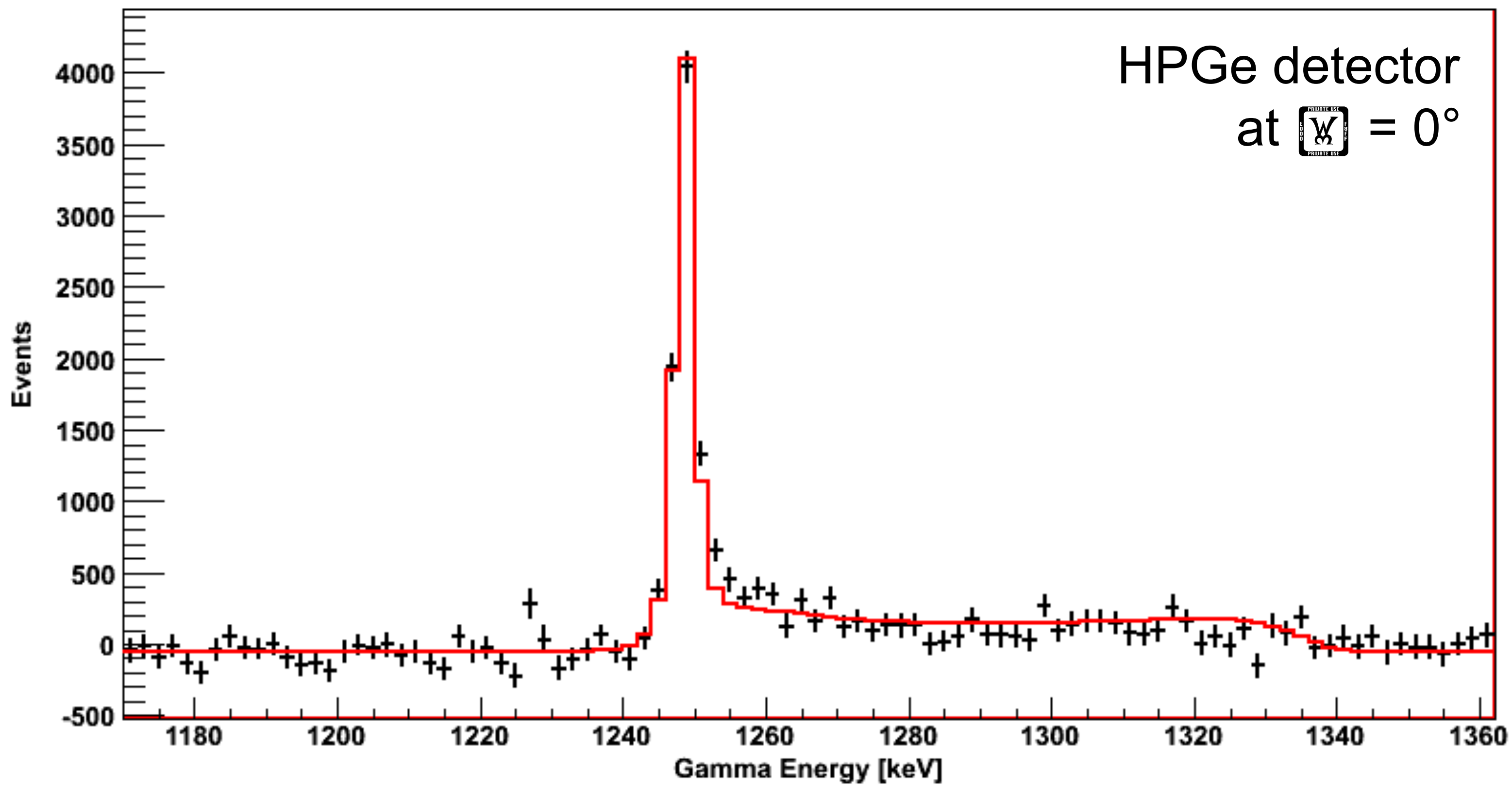

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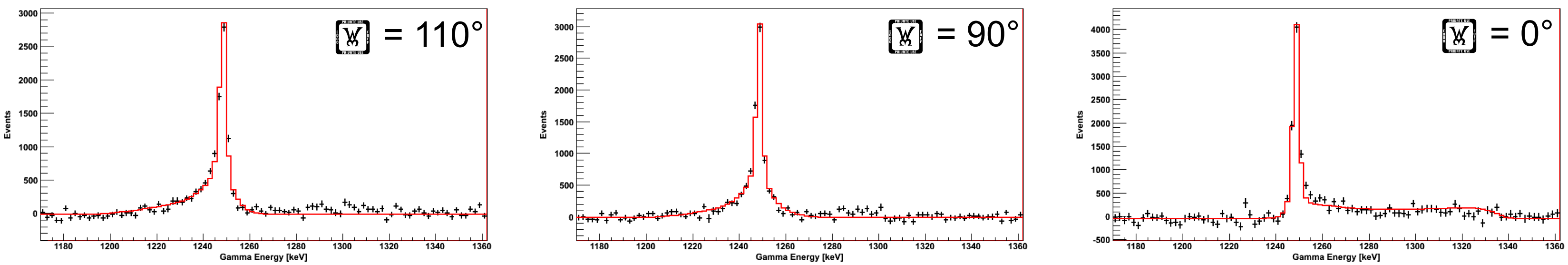
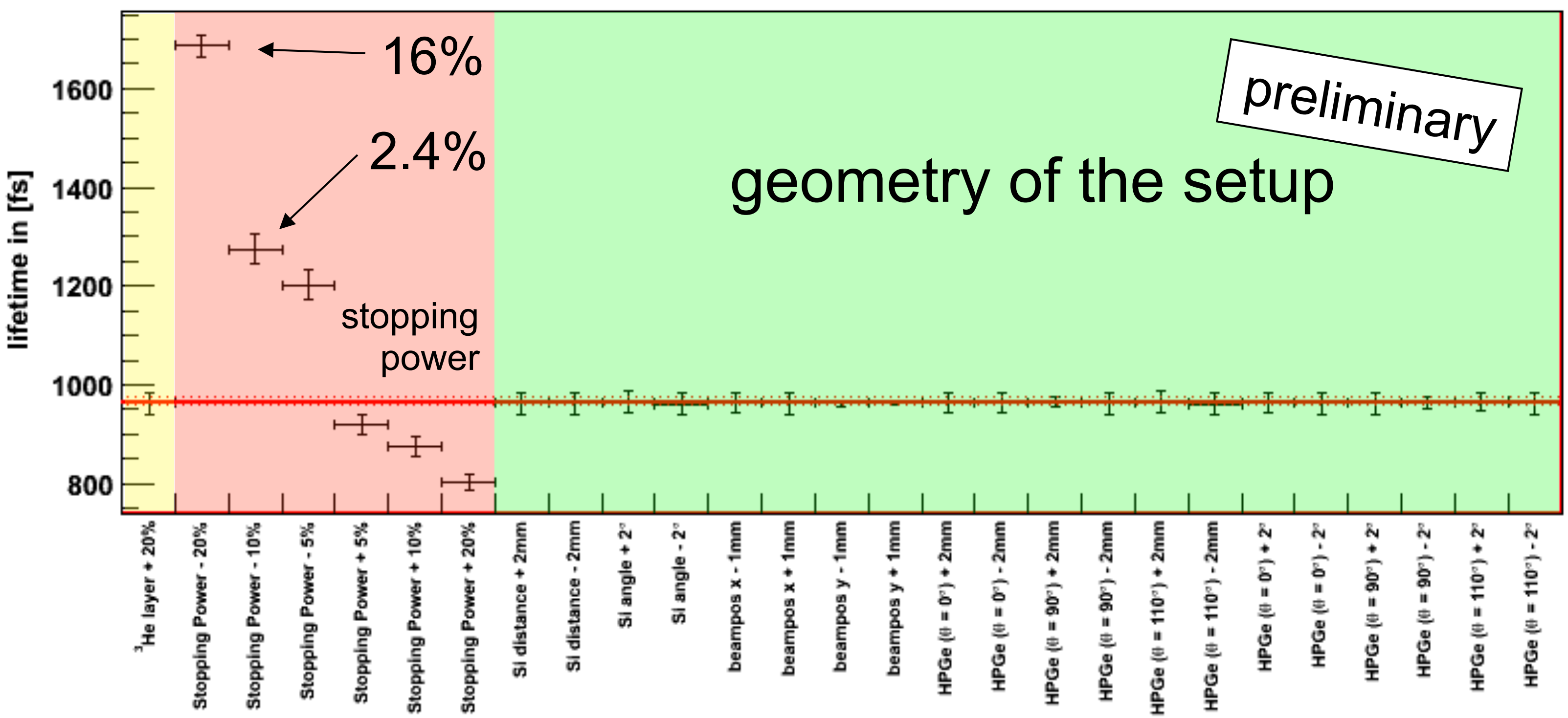


- simultaneous fit of all angles

$$\tau = \left(964 \pm 19_{stat} \pm \mathrm{Error}_{syst}\right)\mathrm{fs}$$

preliminary

4. Results and error discussion



4. Conclusion and outlook

- Successful commissioning of the new DSAM setup at the MLL
- 1st excited state in ^{31}S:

$$\tau = \left(964 \pm 19_{stat} \pm {}^{311}_{89}\,{}_{syst} \right) \mathrm{fs}$$

- The error is dominated by systematic uncertainties of the stopping power

Outlook:

- Neutron detector for access to additional reaction channels
- DAQ: digitizer
- Ice target (hydrogen target)
- Miniball @ MLL
- CRYRING @ GSI

5. Additional slides

5.1 previous measurements:

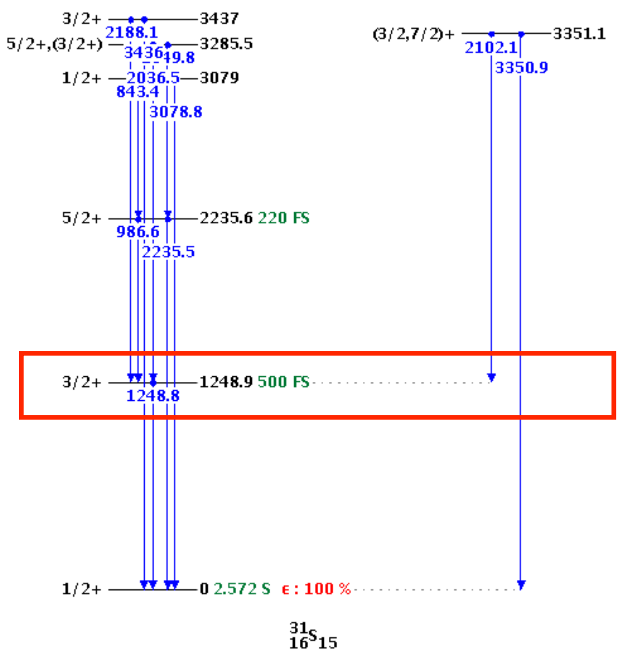
	τ	$\Delta\tau$	$\Delta\tau_{stat}$	$\Delta\tau_{syst}$
Engmann et al. 1970	720fs	180fs		20%
Doornenbal et al. 2012 A	1.2ps		0.7ps	+1.3 ps -0.9 ps
Doornenbal et al. 2012 B	3.2 ps		4.8ps	5.2ps
Tonev et al. 2011	624fs	24fs		10%

$^{32}S(^{3}He,^{4}He)^{31}S$,
7MeV, direct kinematic

2-step fragmentation,
$^{40}Ca+^{9}Be->^{37}Ca$
$^{37}Ca+^{9}Be->^{31}S$
Miniball,

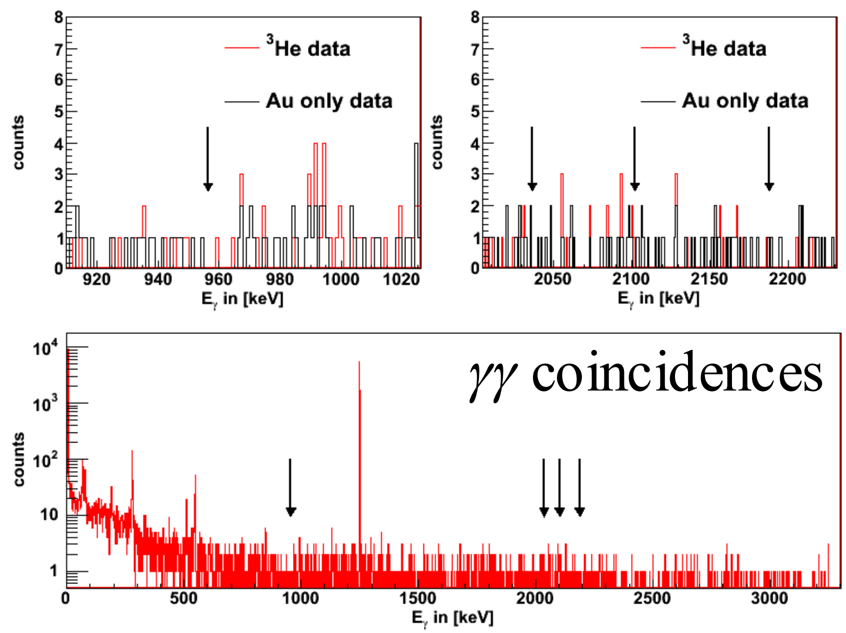
Fusion evaporation,
$^{20}Ne+^{12}C->^{31}S+n$

5.2 feeding

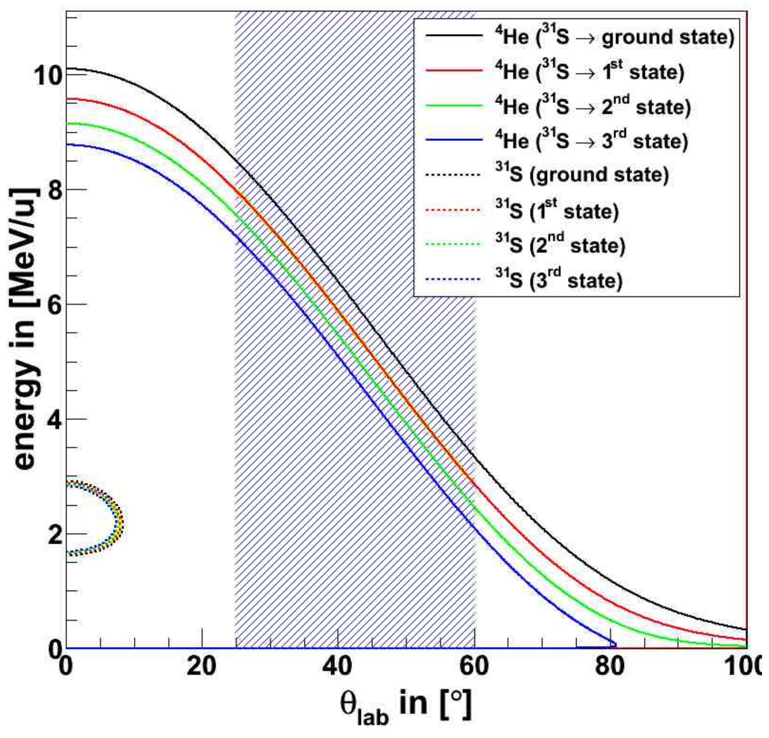


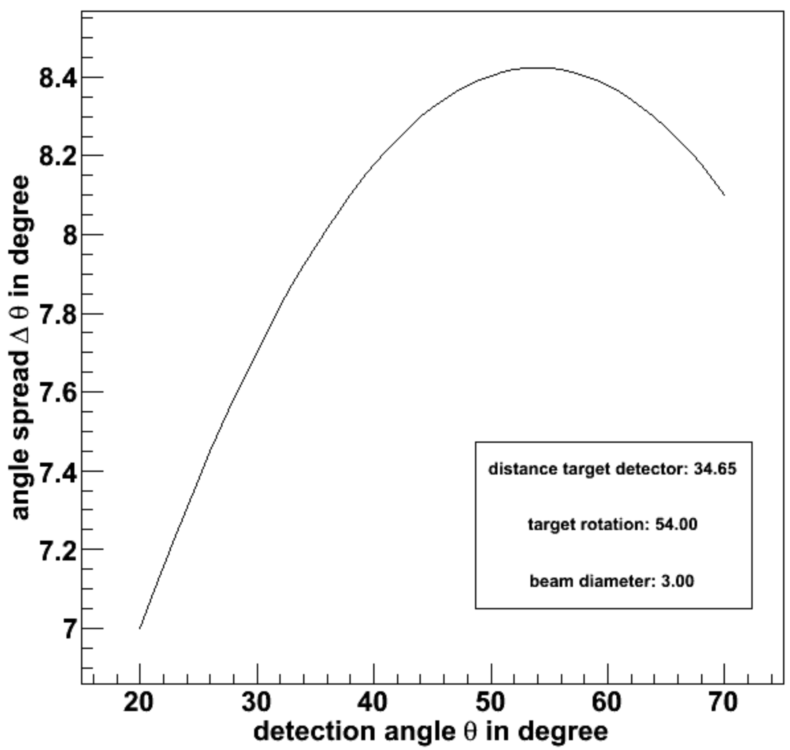
High trans strength:

$4^{th} \rightarrow 1^{st}$, $5^{th} \rightarrow 1^{st}$

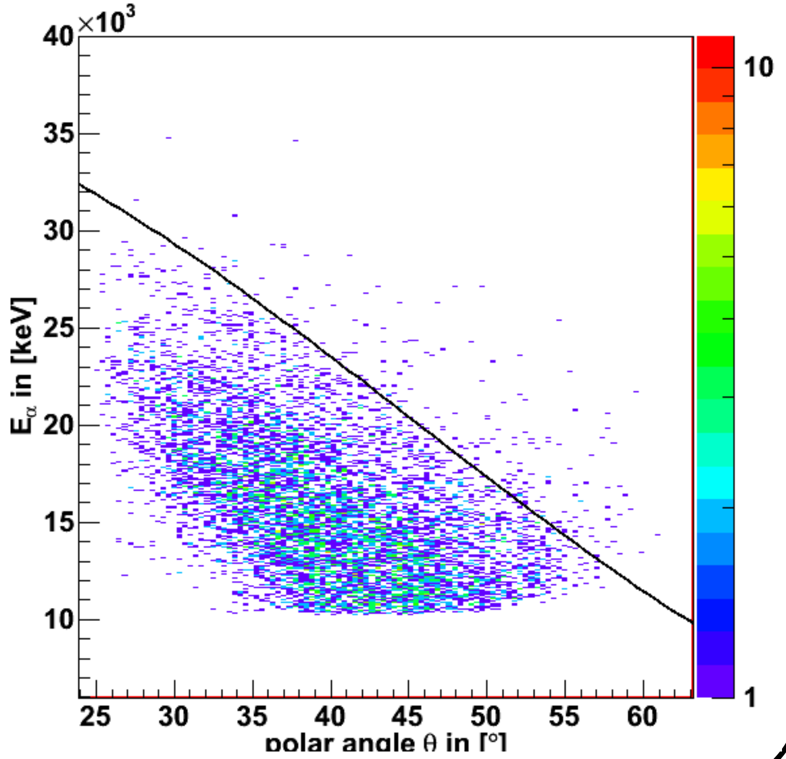


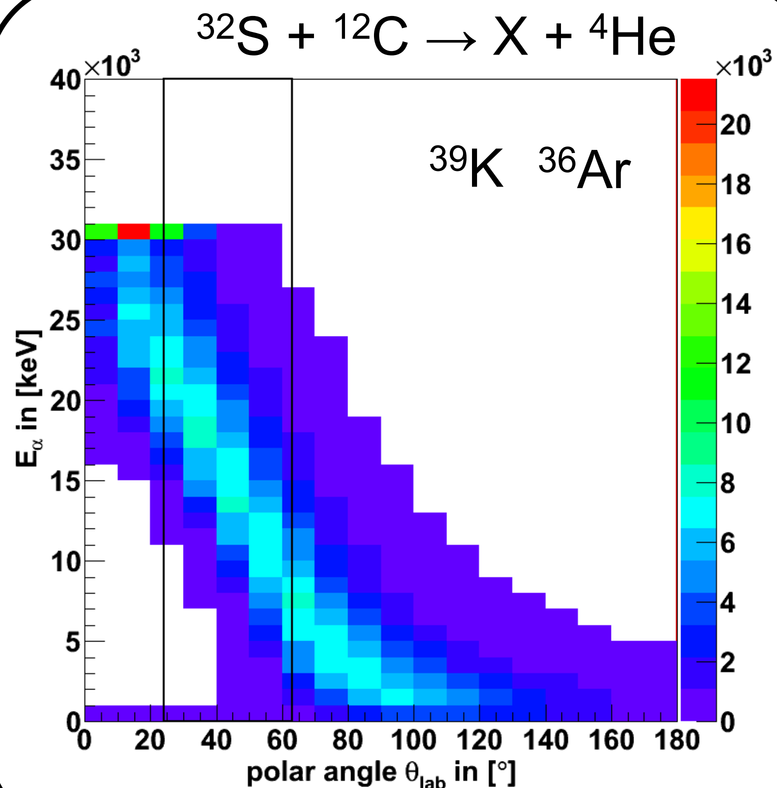
5.2 Energy of ^{4}He particles





5.3 Fusion evaporation





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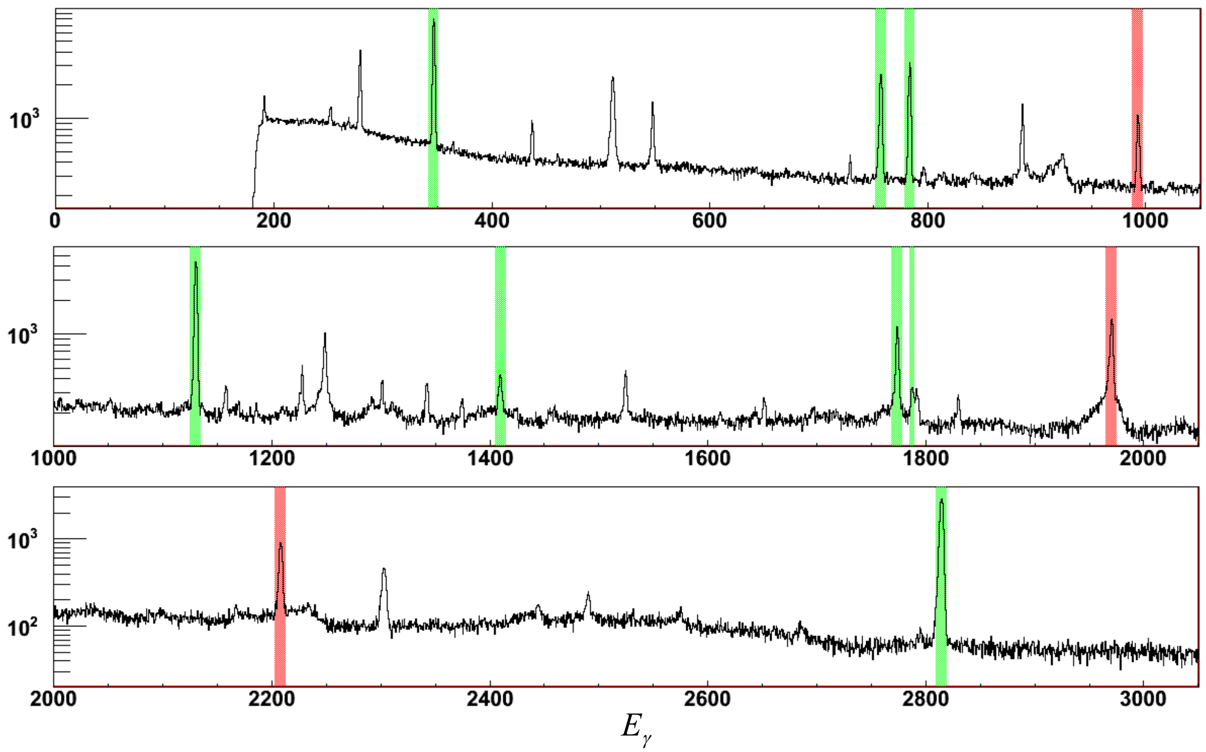
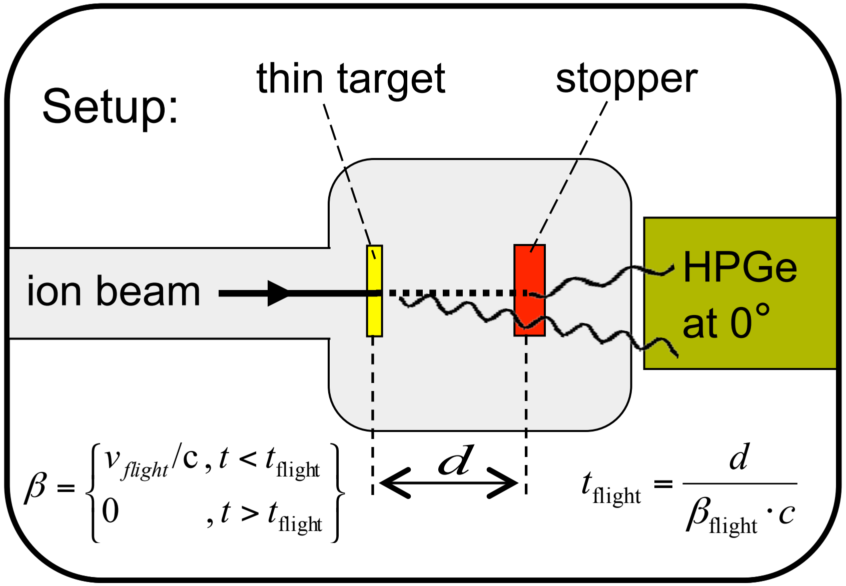


2. Recoil-Distance Doppler Shift Method



$$E_\gamma^{obs} = E_\gamma^0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha} \overset{v<<c}{\approx} E_\gamma^0 (1+\beta\cos\alpha)$$

$$N_{\text{shifted}} = \int_{t=0}^{t_{flight}} N_{\text{all}} \exp\left(-\frac{t}{\tau}\right)$$

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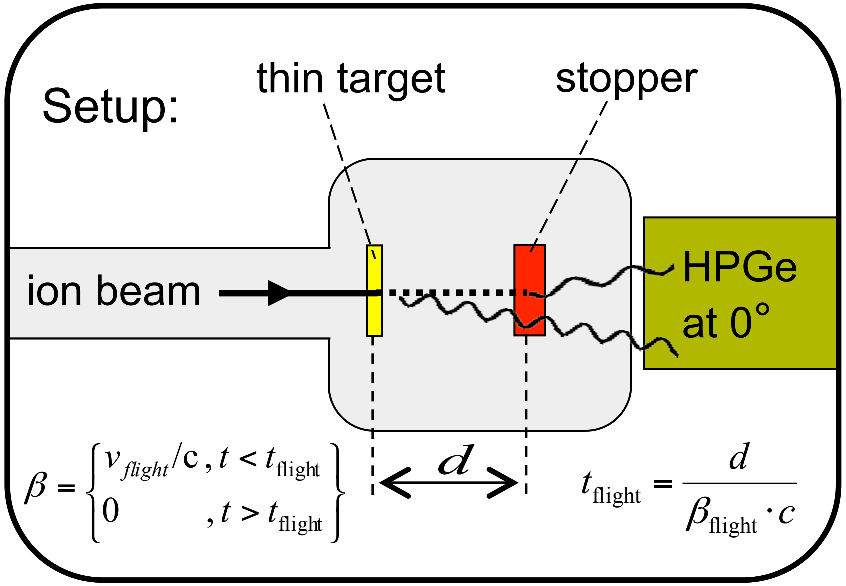
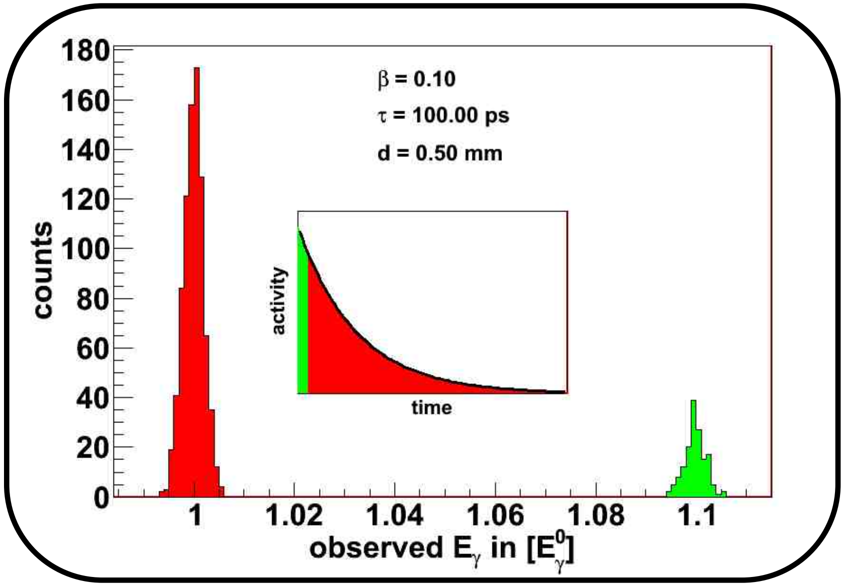


$$\beta = \begin{cases} v_{flight}/c, & t < t_{\text{flight}} \\ 0, & t > t_{\text{flight}} \end{cases}$$

$$t_{\text{flight}} = \frac{d}{\beta_{\text{flight}} \cdot c}$$



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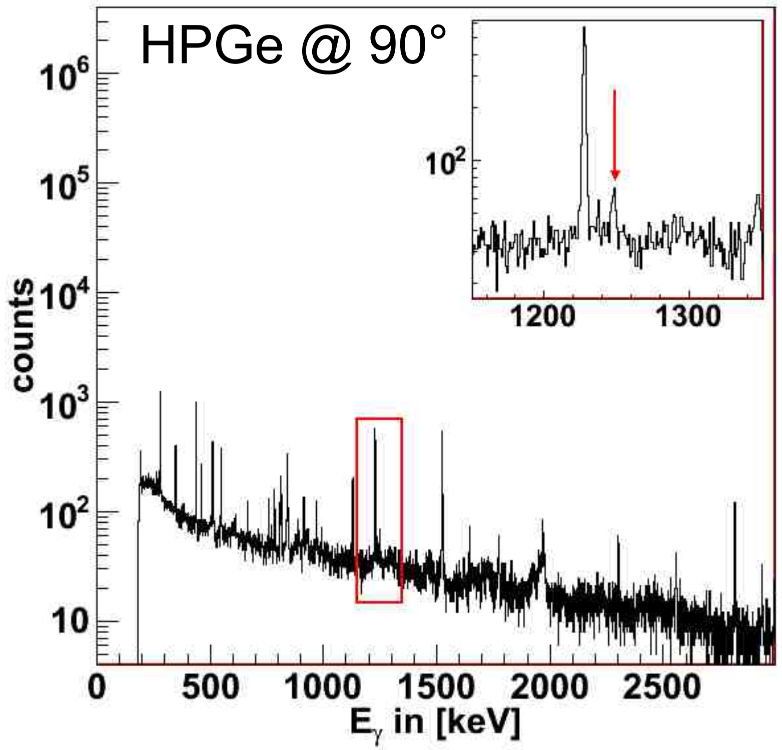
$$N_{\text{shifted}} = \int_{t=0}^{t_{flight}} N_{\text{all}} \exp\left(-\frac{t}{\tau}\right)$$

3.1 TDC gate

TDC data

- common start:
  trigger Si telescopes
- individual stop:
  - delayed Si telescopes
  - HPGe @ 0°
  - HPGe @ 90°
  - HPGe @ 110°

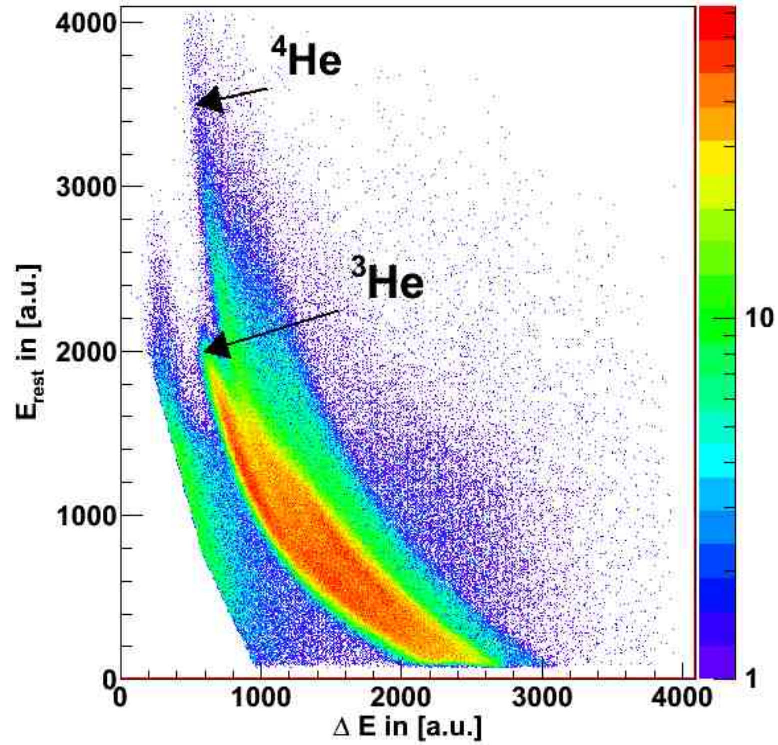


3.1 charged particle identification

PID gate
with ΔE/E Si telescopes

two groups:
- protons
- ^3He, ^4He

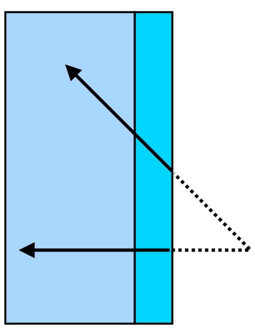
→ ^3He and ^4He can not be separated



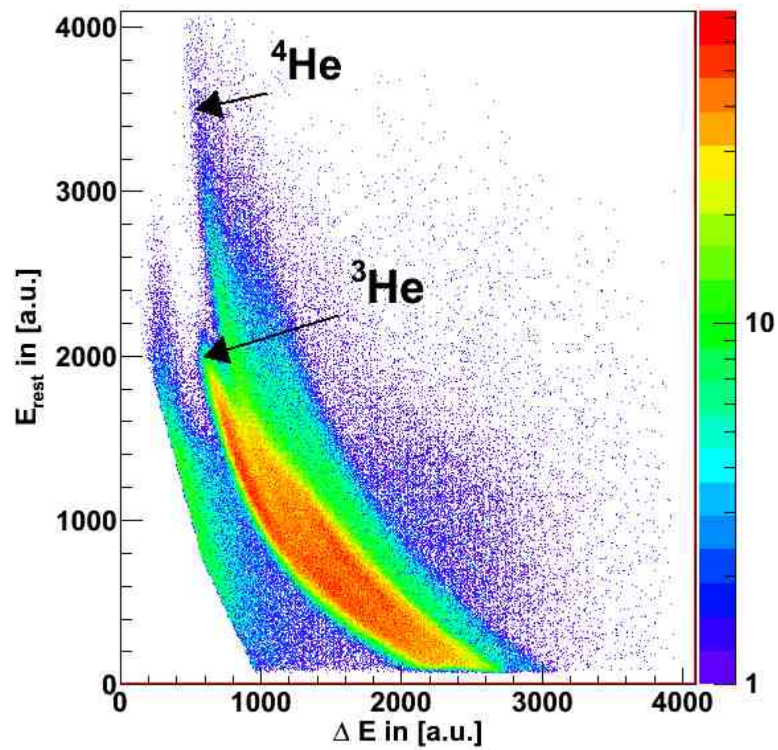
3.1 charged particle identification

PID gate
with ΔE/E Si telescopes

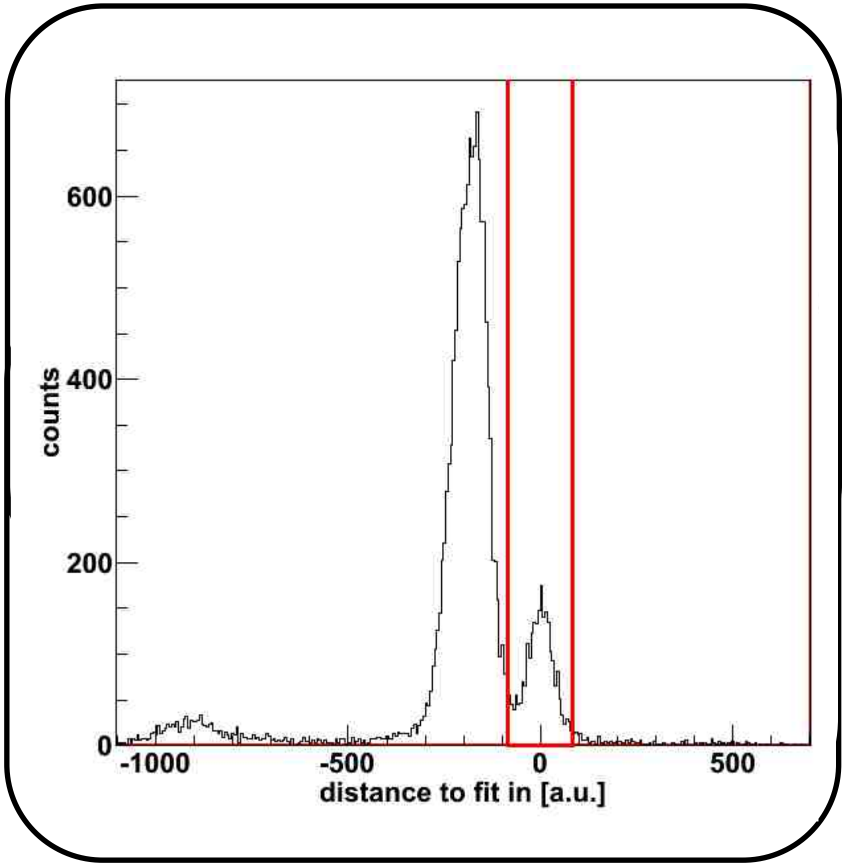
effective thickness d_{eff} of
ΔE depends on (θ,φ)

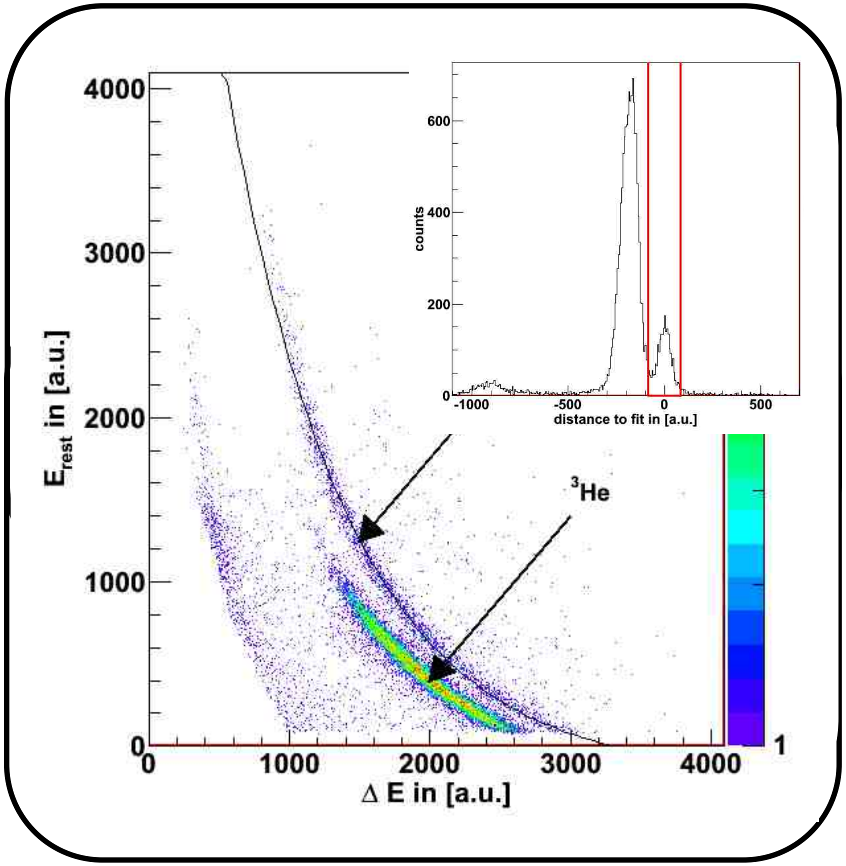


$$d_{eff} = \frac{d_{norm}}{\vec{p} \cdot \vec{n}}$$

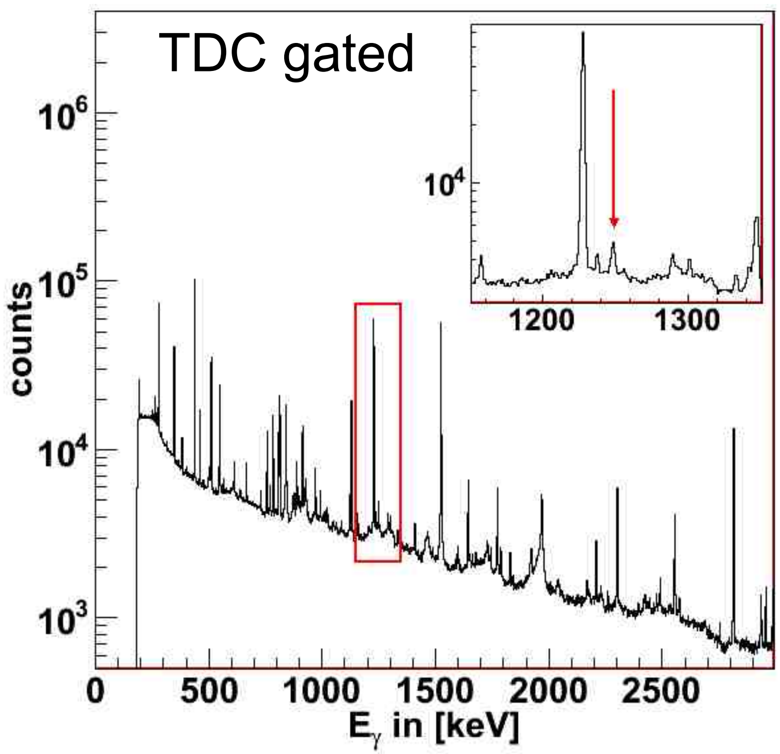


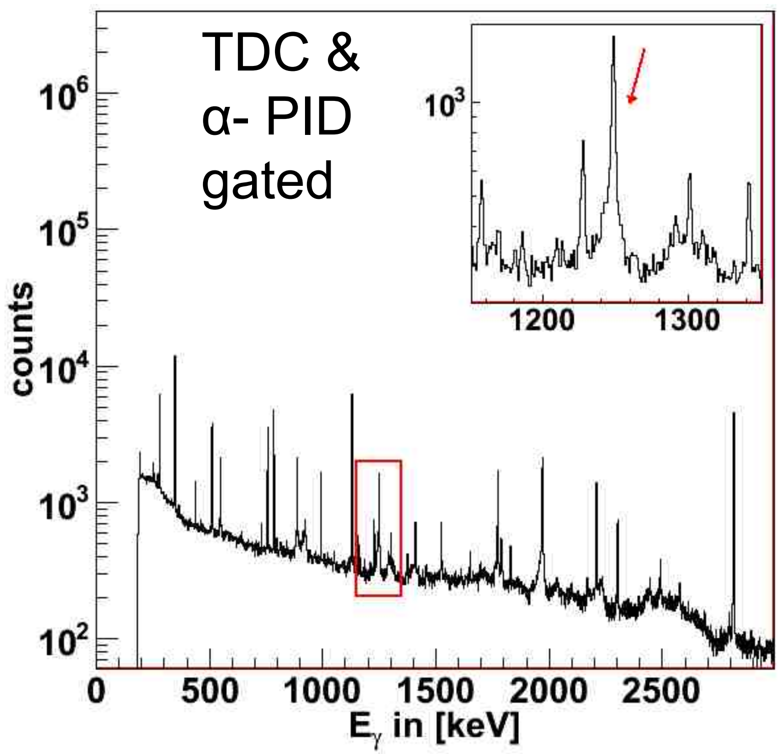
3.1 charged particle identification





3.1 PID α gate on E_γ spectra





3.3 Projection on a HPGe detector

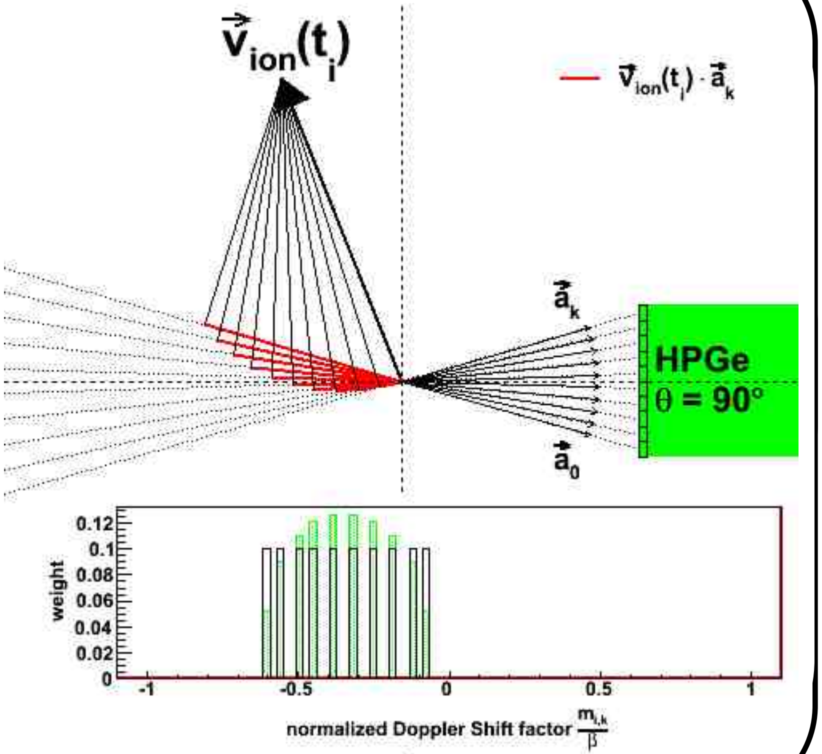
Observed Doppler shift is determined by the ion's velocity component in the direction of observation

$$E_\gamma^{obs} = E_\gamma^0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha}$$

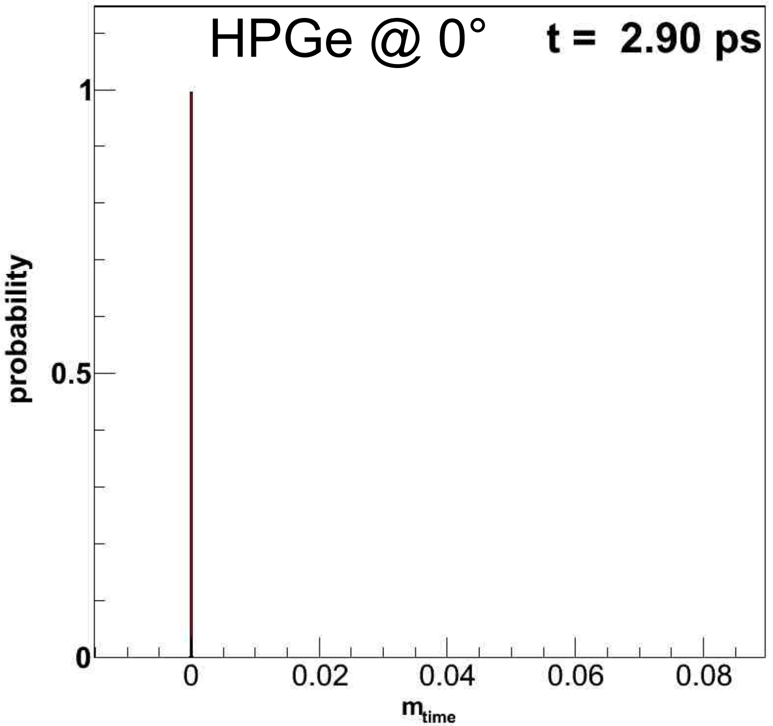
$$\approx E_\gamma^0 (1+\beta\cos\alpha)$$

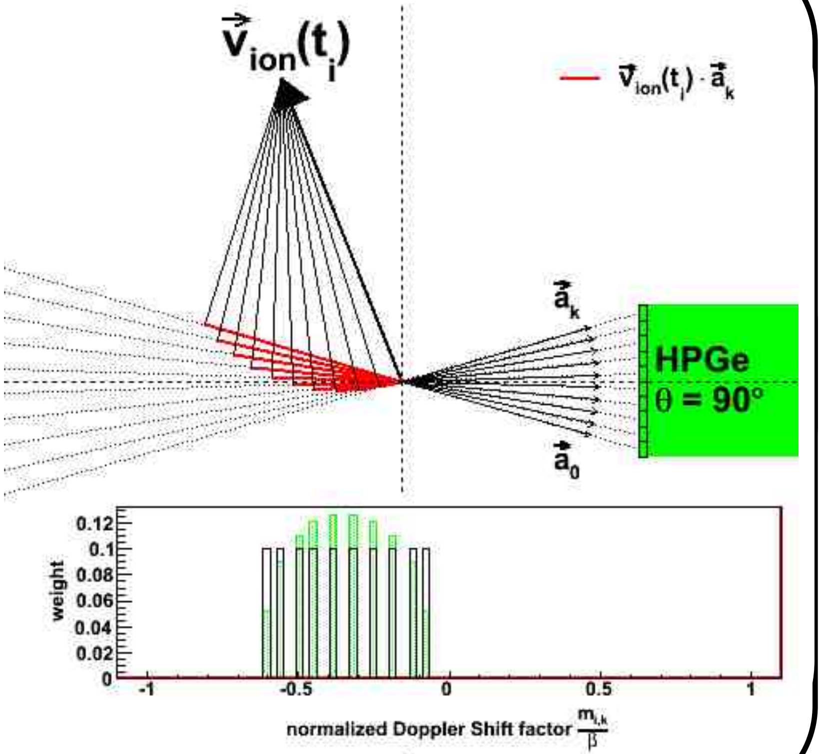
$$E_\gamma^{obs} = E_\gamma^0 (1+m)$$

$$m = \frac{E_\gamma^0}{E_\gamma^{obs}} - 1 = \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha} - 1$$

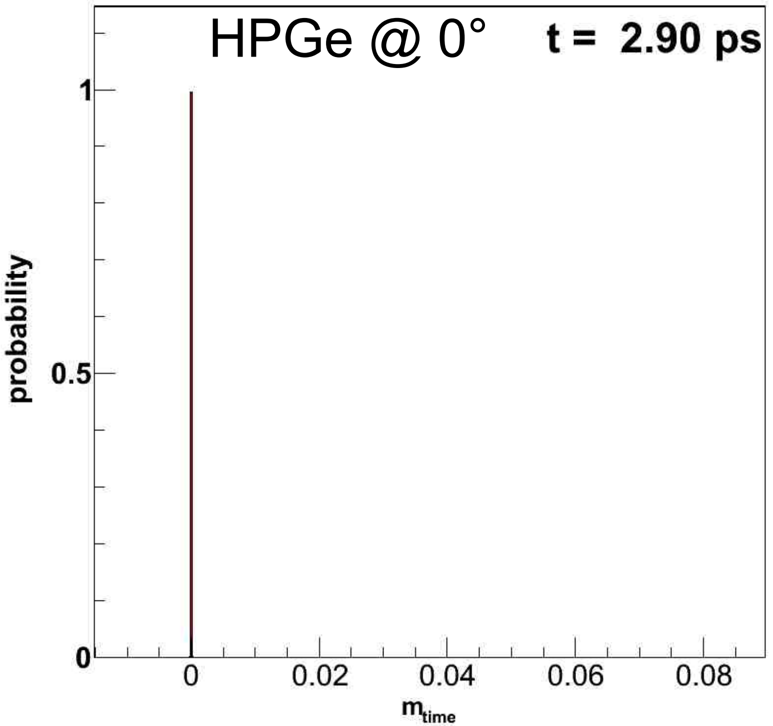


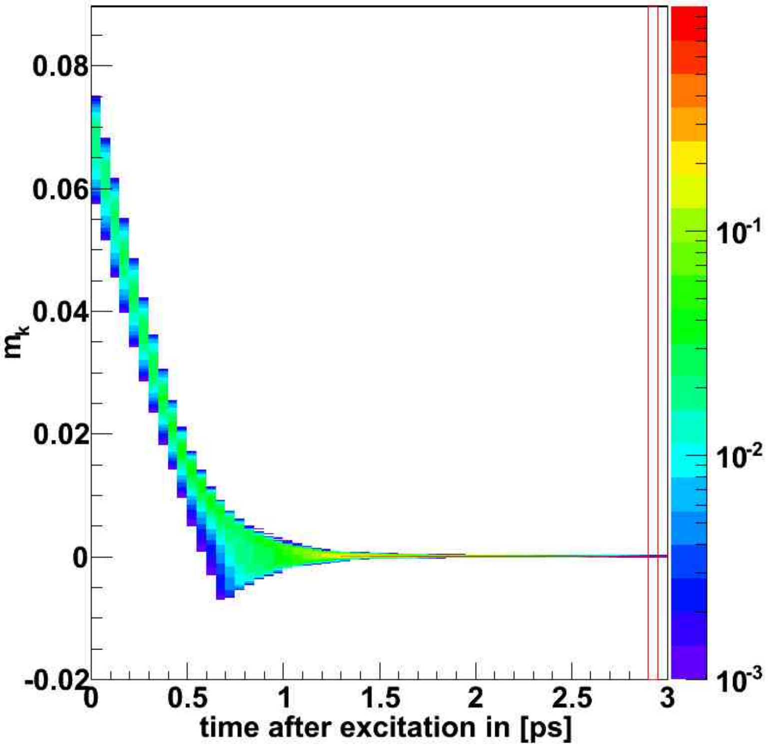
3.3 Projection on a HPGe detector



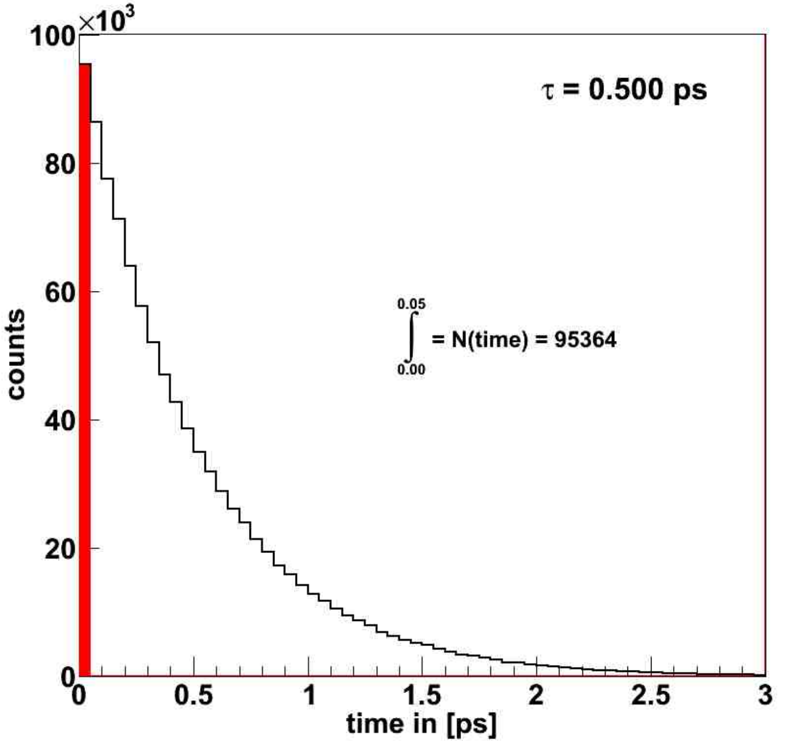


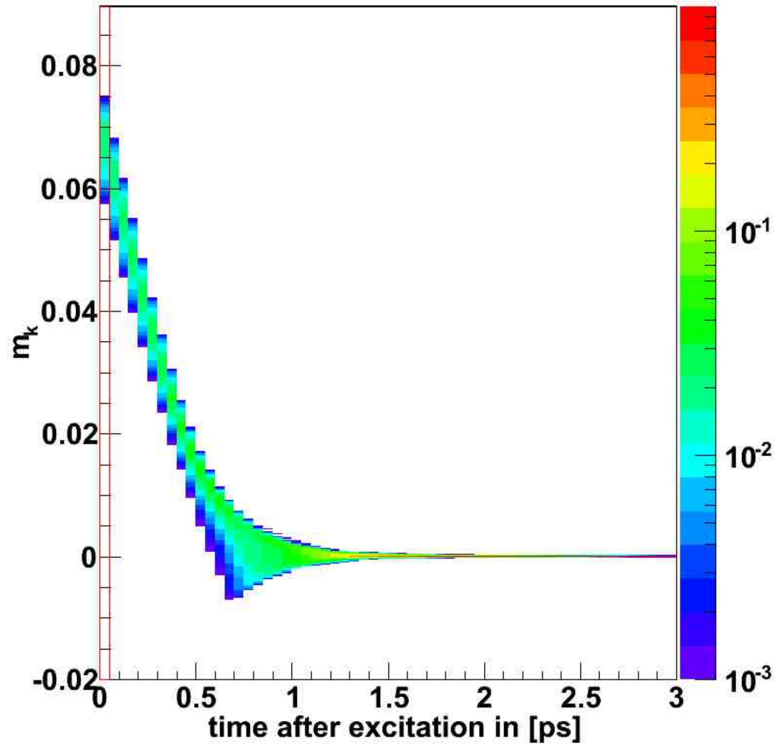
3.3 Doppler Shift distribution: projection



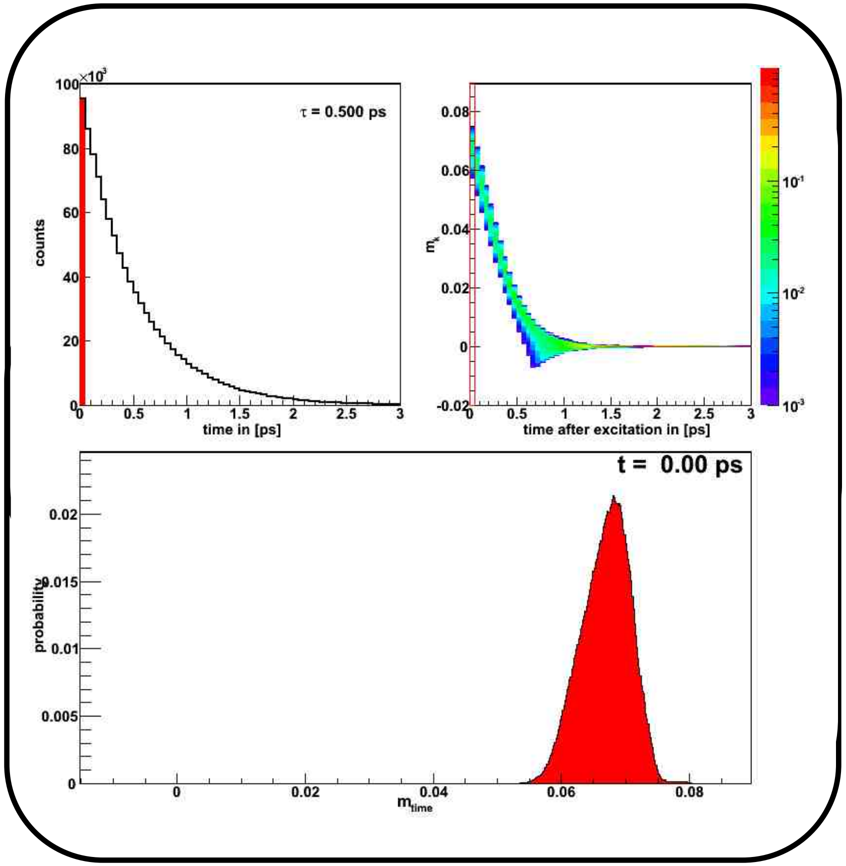


3.3 Line shape modeling

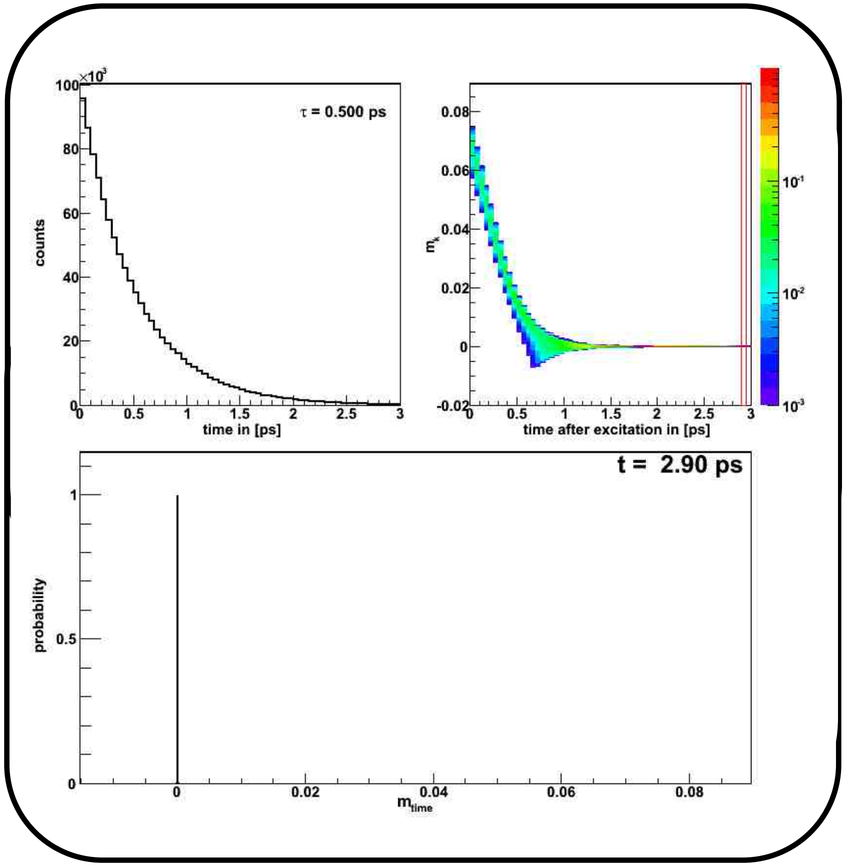


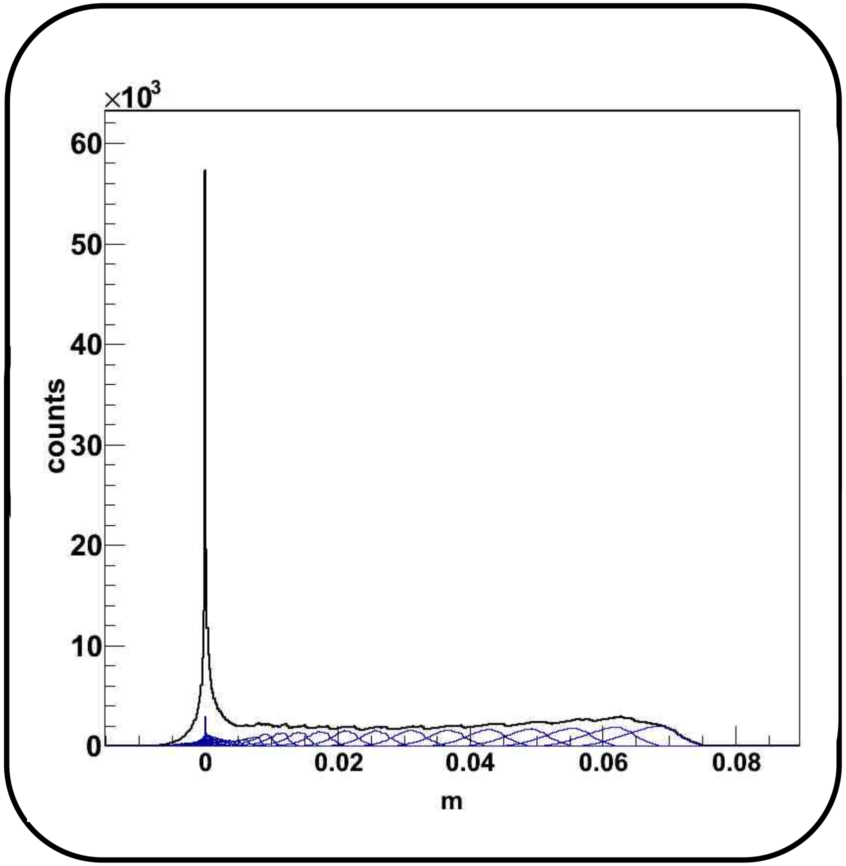


3.3 Line shape modeling

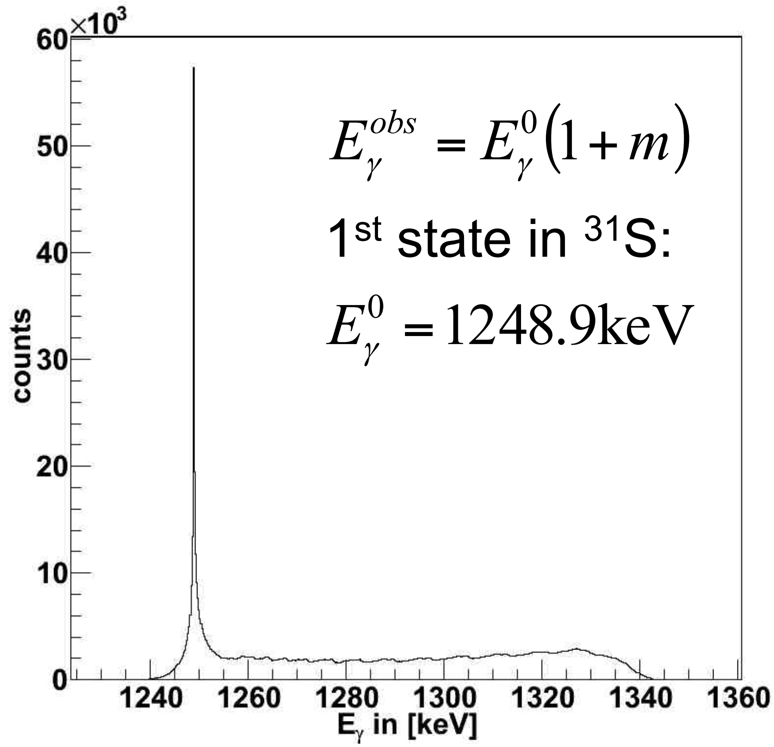


3.3 Line shape modeling





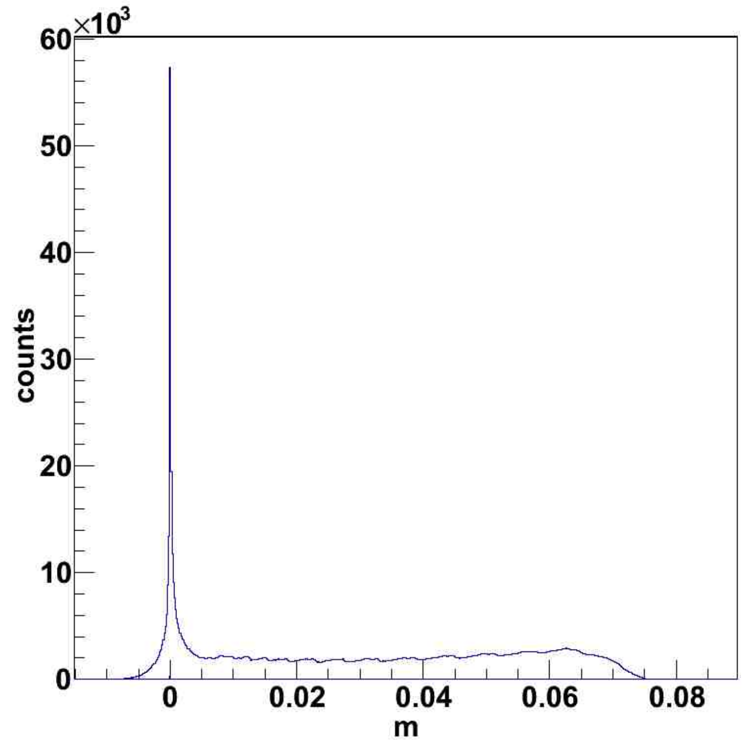
3.3 Physical energy in the HPGe



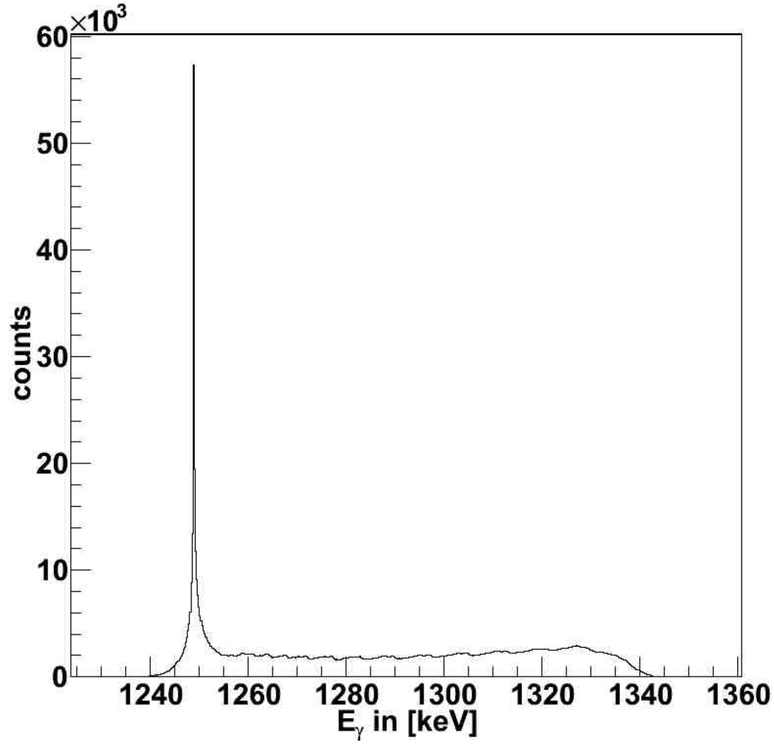
$$E_\gamma^{obs} = E_\gamma^0 (1 + m)$$

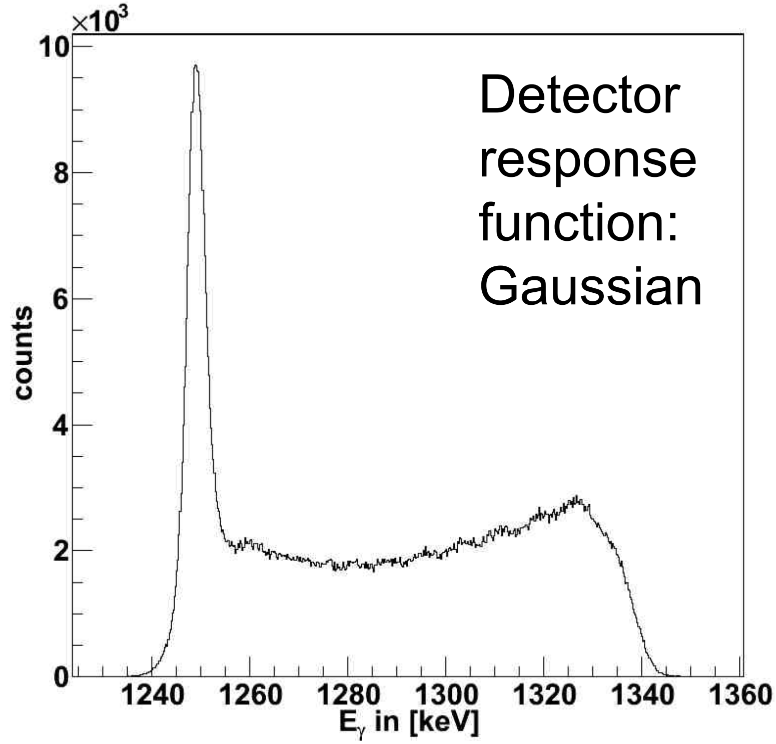
1st state in ^{31}S:

$$E_\gamma^0 = 1248.9\,\text{keV}$$



3.3 HPGe detector response





3.3 Fitting the experimental data

Optimize χ^2

free parameters:
- lifetime τ
- transition energy E_γ^0
- number of events
- background offset

Fixed parameters:
- HPGe detector response
- background slope