WE Heraeus-Seminar on Astrophysics with small-scale accelerators

6-10 February 2012 - Physikzentrum Bad Honnef - Germany

Lifetime measurement of the 6.792 MeV state in ^{15}O with the AGATA Demonstrator

R. Depalo[1,2], C. Michelagnoli[1,2], R. Menegazzo[1], C. A. Ur[1], D. Bazzacco[1], D. Bemmerer[3], C. Broggini[1], A. Caciolli[1], M. Erhard[4], E. Farnea[1], Zs. Fülöp[5], N. Keeley[6], S. Lunardi[1,2], M. Marta[3], T. Szücs[5], and the AGATA collaboration

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[3] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

[4] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

[5] ATOMKI, The Debrecen, Hungary. [6] Andrzej Soltan Institute for Nuclear Studies, Warsaw, Poland

Outline

Astrophysical motivation

The Solar composition problem

CNO neutrinos and $^{14}N(p,\gamma)^{15}O$ cross section

The lifetime of the 6.79 MeV state

The Experiment

The Doppler Shift Attenuation Method

The AGATA Demonstrator array

Experimental setup

Data Analysis

Data sorting

Simulations of gamma ray emission and detection

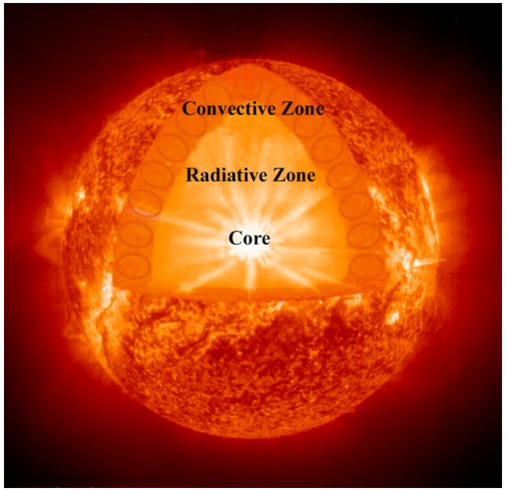
Reaction mechanism

Lifetime evaluation: simulations VS experiment

The solar composition problem

Recent re-evaluation of the photospheric abundances with **3D** models of the solar atmosphere

(Asplund, Grevesse, Sauval 2005):

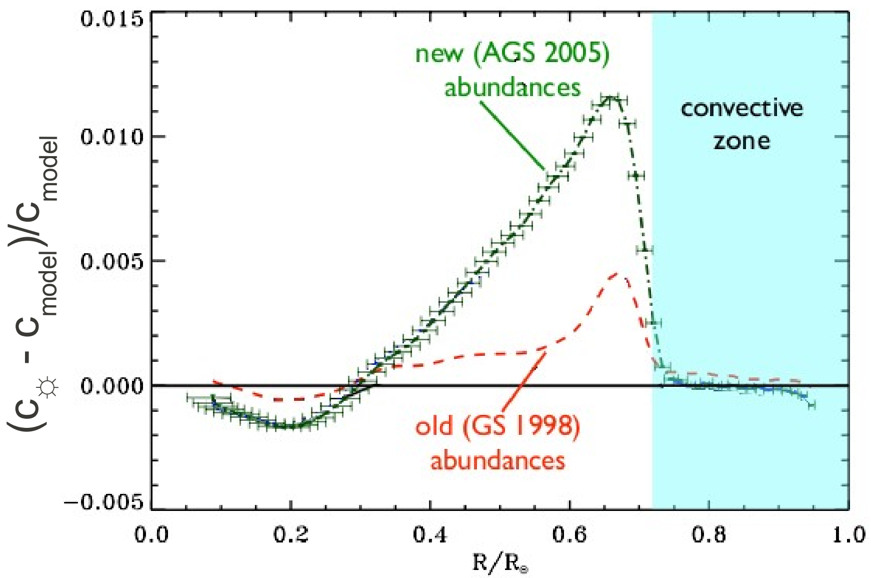


~30% decrease in metallicity

(Z_{1D} = 0.0170 → Z_{3D} = 0.0122)

N. Grevesse et al. Space Sci. Rev. (2007) 130

Measured VS modeled sound speed profile



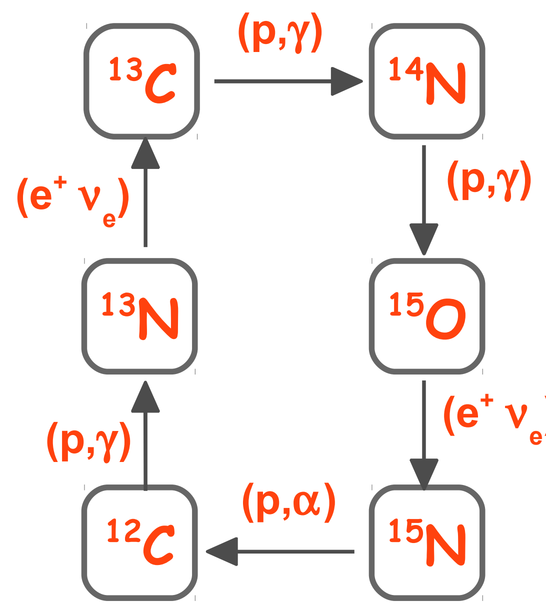
J.N. Bahcall et al. APJ, 621 (2005)

Solar Standard Model predictions on solar structure are in disagreement with helioseismic inferences!

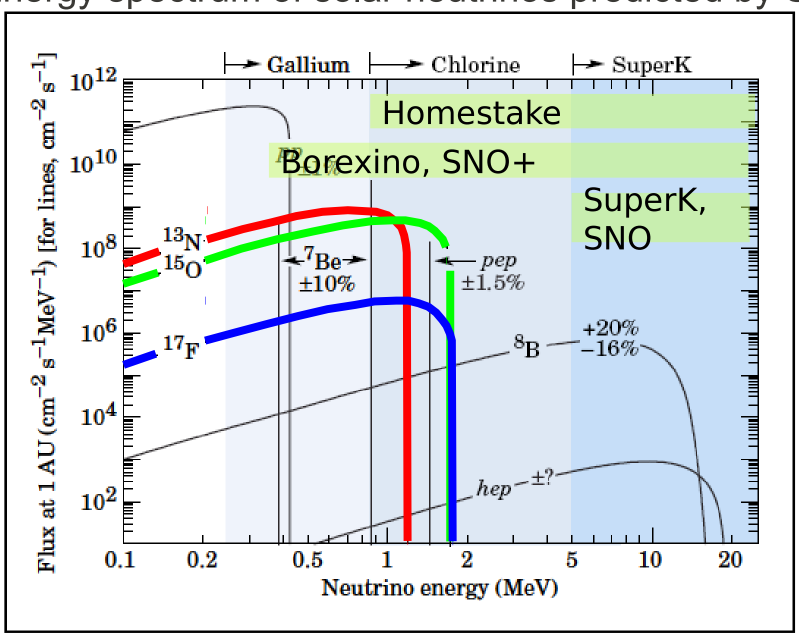
CNO neutrinos

C-N neutrinos can provide an independent measure of the solar core metallicity

W. Haxton and A. Serenelli ApJ 687 (2008) 678



Energy spectrum of solar neutrinos predicted by SSM



Measurable (SNO+, Borexino)

Calibrated using ^8B ν flux

$$\Phi_\nu^{CNO} = f(S_{nuc}, T, CN)$$

Main source of uncertainty

CNO neutrinos

C-N neutrinos can provide an independent measure of the solar core metallicity
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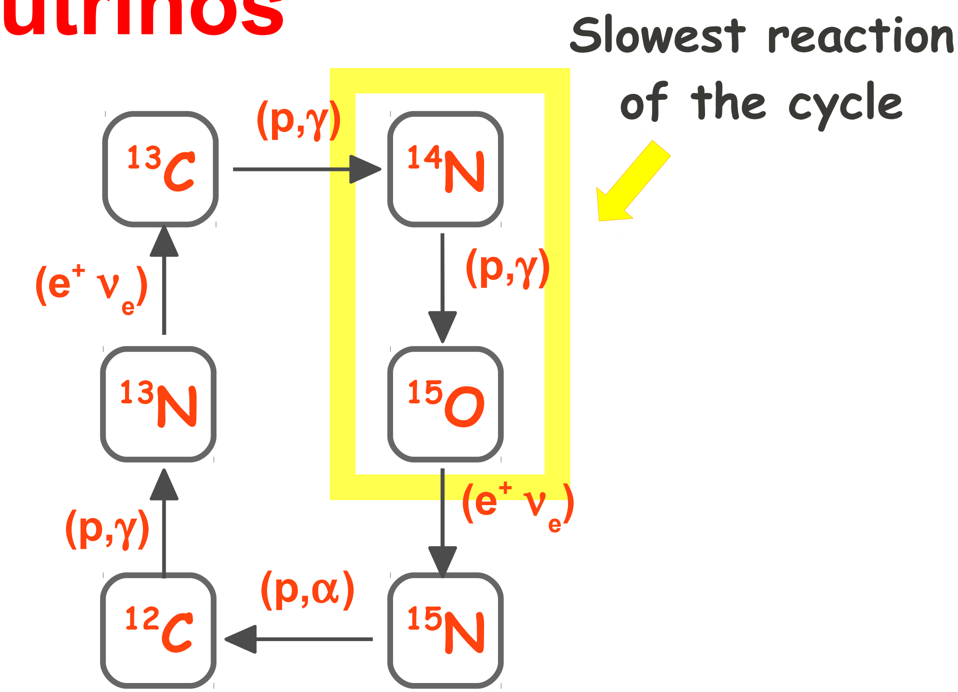

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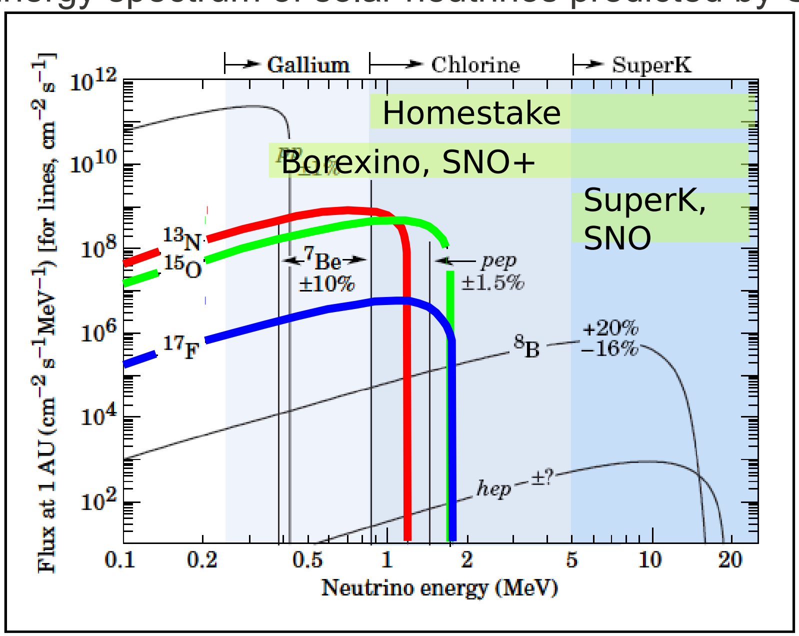

Measurable (SNO+, Borexino)

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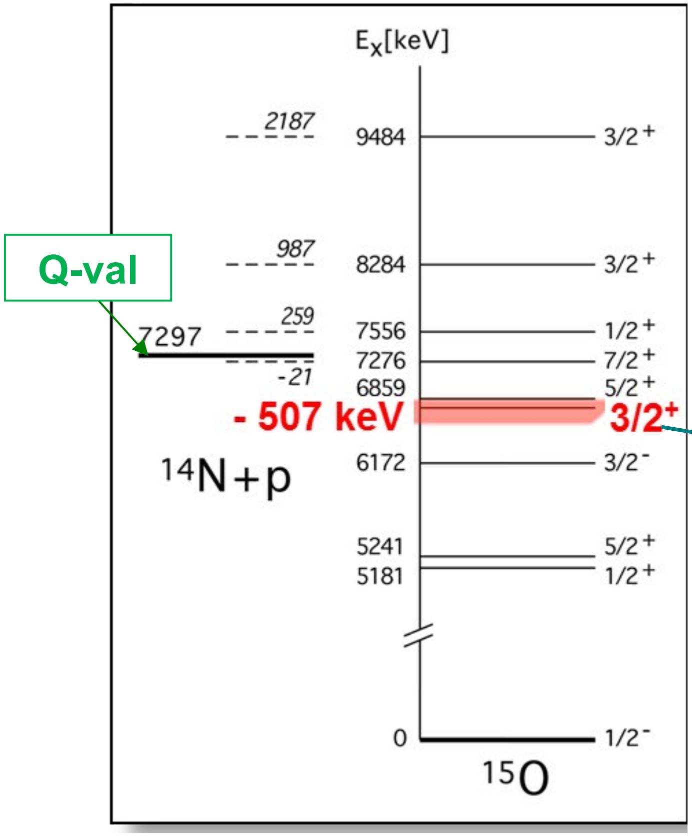
Main source of uncertainty

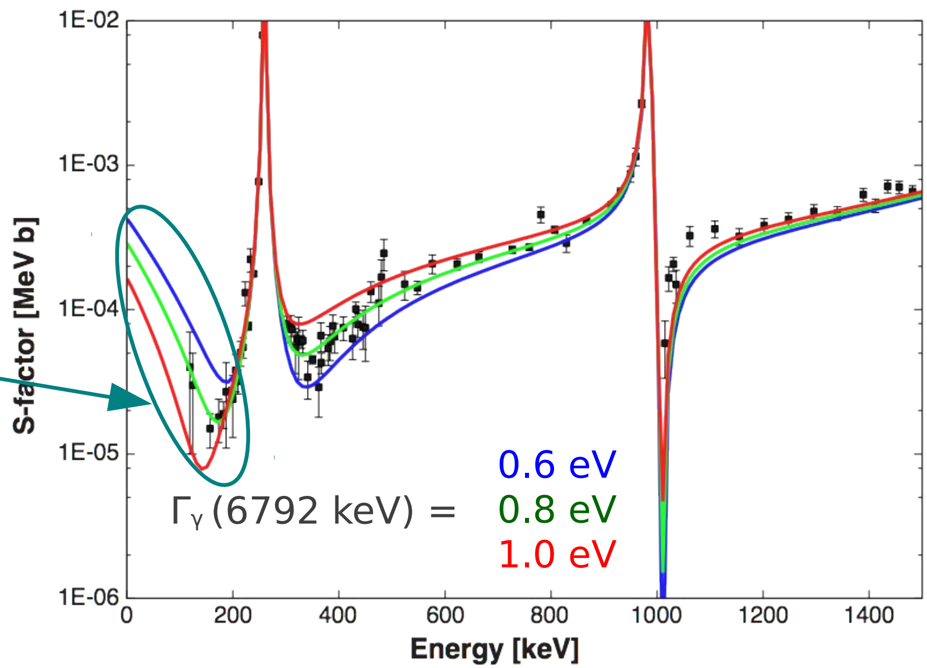
$^{14}N(p,\gamma)^{15}O$ cross section

Direct cross section measurements exist down to 70 keV
(D. Bemmerer NPA 779(2006) 297-317)

→ Extrapolation in the Gamow window (~30 keV) is needed!

The uncertainty on extrapolation is dominated by the width ($\Gamma = \hbar/\tau$) of the resonance corresponding to the 6.79 MeV level
E. G. Adelberger et al. Rev. Mod. Phys. 83, 195-245 (2011)





H.P. Trautvetter et al., JPG 35 (2008)

The lifetime of the 6.79 MeV level

Group	Method	$\tau_\gamma^{6.792}$ [fs]
Oxford 1968 W.Gill et al., Nucl. Phys. A 121. 209	**DSAM d(^{14}N, ^{15}O)n**	**< 28**
TUNL 2001 P.F. Bertone et al., Phys. Rev. Lett. 87, 152501	**DSAM ^{14}N(p,γ)^{15}O**	**1.6±0.7 (44%)**
RIKEN 2004 K. Yamada et al., Phys. Lett. B 579, 265	**CE ^{208}Pb(^{15}O, ^{15}O*)**	**0.69±0.43 (62%)**
LUNA 2004 A. Formicola et al., Phys. Lett. B 591, 61	Cross section + R-matrix fit	1.1±0.5 **(45%)**
TUNL 2005 R. Runkle et al., Phys. Rev. Let. 94, 082503	Cross section + R-matrix fit	0.3±0.1 **(33%)**
Bochum 2008 D. Schürmann et al., Phys. Rev. C 77, 055803	**DSAM ^{14}N(p,γ)^{15}O**	**< 0.77**
LUNA 2008 M. Marta et al., Phys. Rev. C 78, 022802(R)	Cross section + R-matrix fit	0.75±0.20 **(27%)**

Still high uncertainity!

New (direct) Doppler Shift Attenuation lifetime measurement exploiting the AGATA Demonstrator HPGe array capabilities

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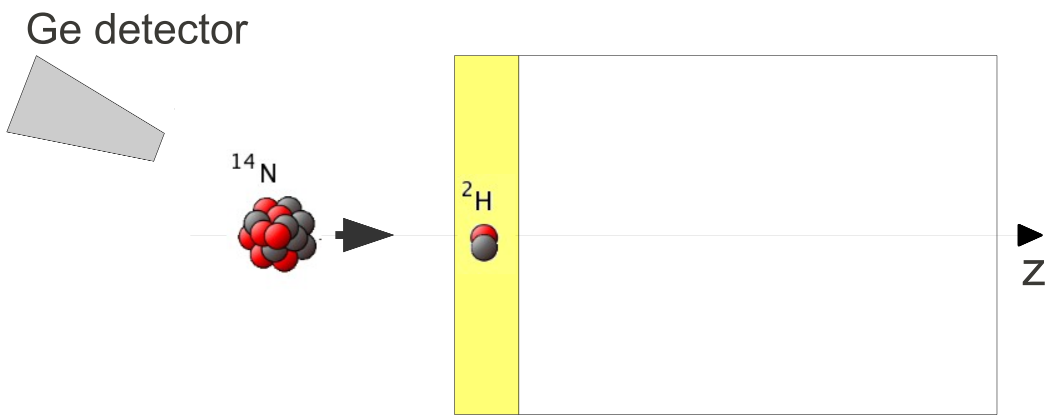
Data Analysis

- Data sorting
- Simulations of gamma ray emission and detection
- Reaction mechanism
- Lifetime evaluation: simulations VS experiment

The Doppler Shift Attenuation Method

Level lifetime compared with the characteristic slowing down time in a material ($10^{-15} < \tau < 10^{-11}$ s)



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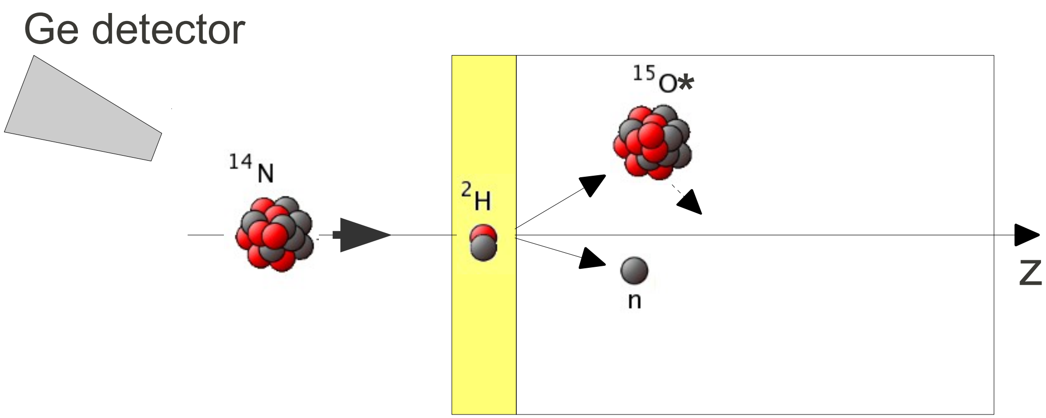

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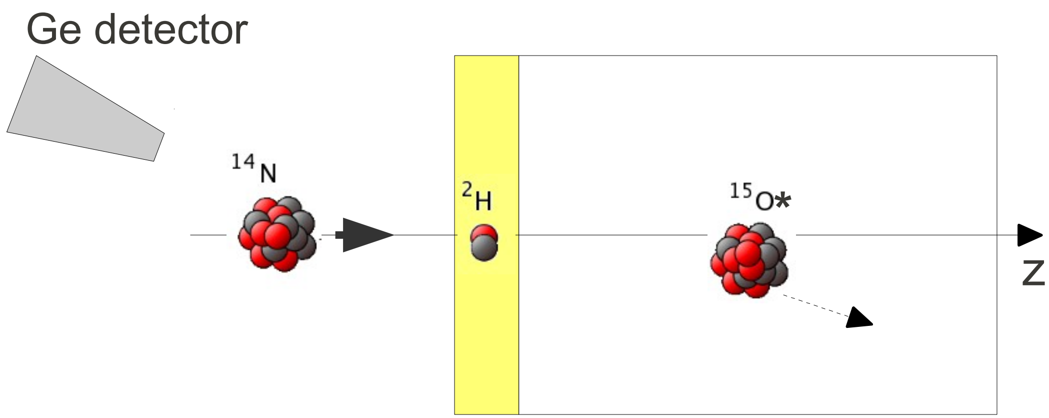

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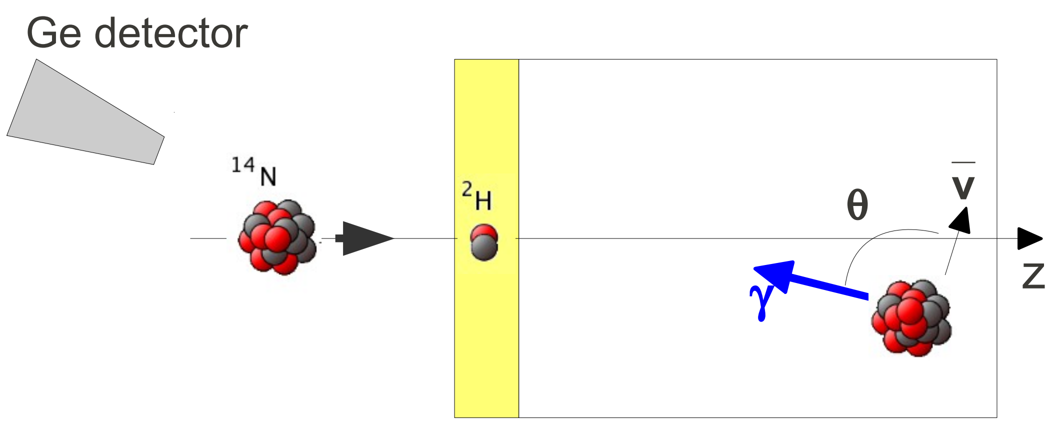
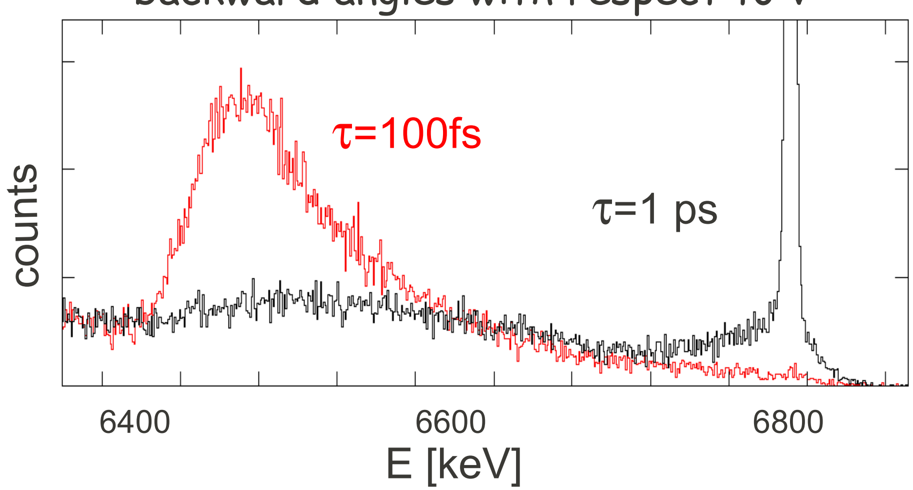


$$E(\vartheta) = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\vartheta}$$

Example: A 6.8 MeV γ-ray observed at backward angles with respect to $\bar{v}$

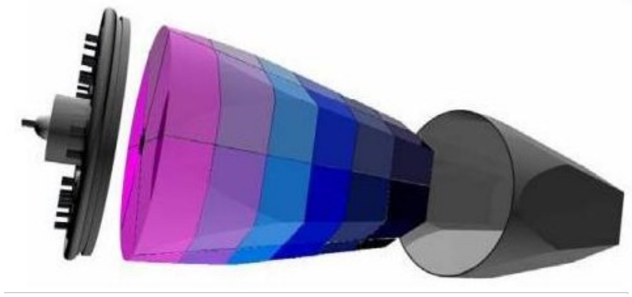


The decay occurs at different velocities depending on the distance covered inside the target (and hence on the lifetime)

The Advanced GAmma-ray Tracking Array

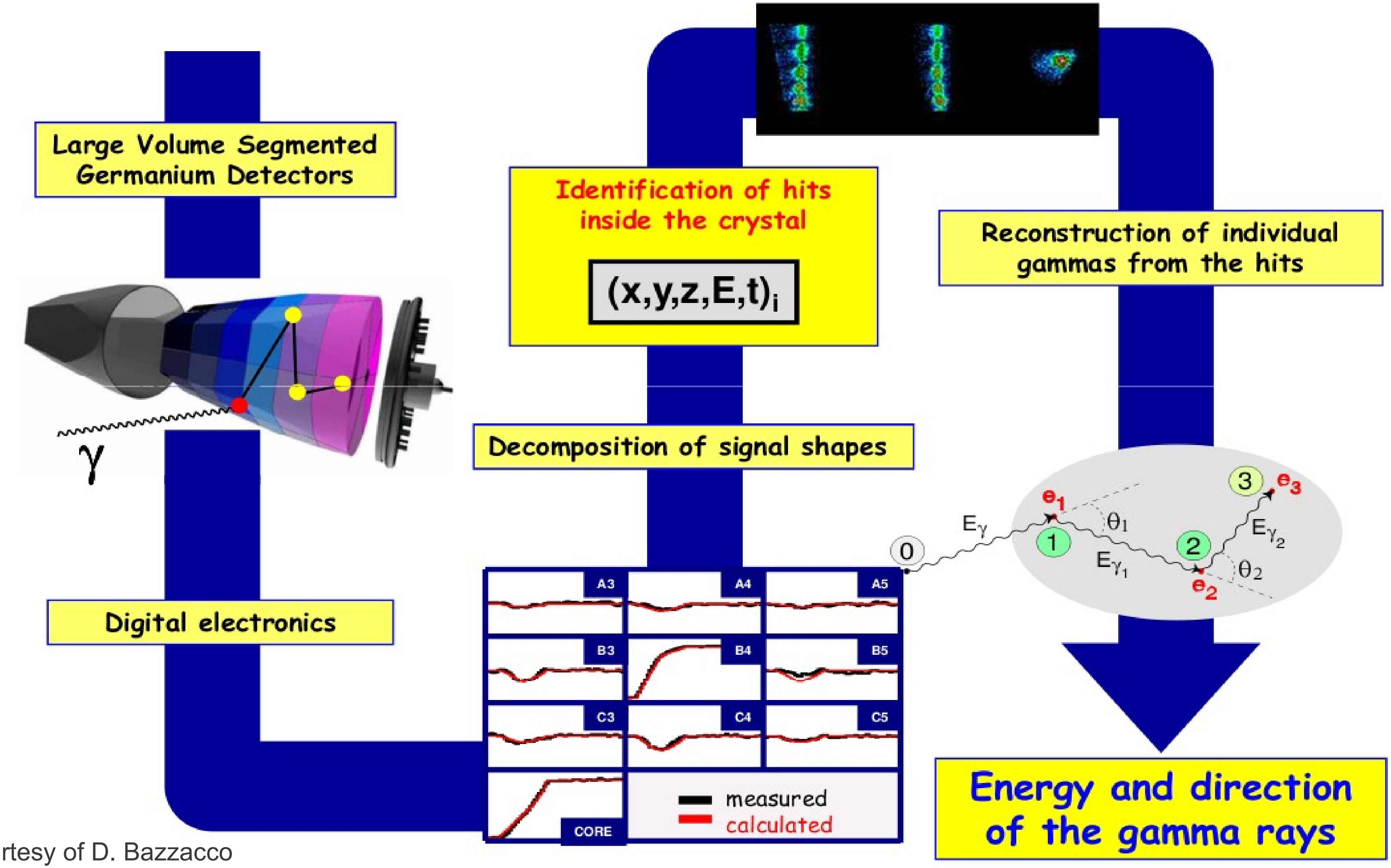
New generation array of position-sensitive HPGe detectors

- Demonstration phase @ LNL → 5 triple clusters (4 available for the experiment)
  A. Gadea et al. NIM 654 (2011) 88-96
- Efficiency and FWHM @ 7 MeV : ~ 0.4% , 5 keV
- 36-fold electrically segmented HPGe crystals



- Digital signal processing and application of Pulse Shape Analysis and γ-ray Tracking techniques

γ-ray tracking concept

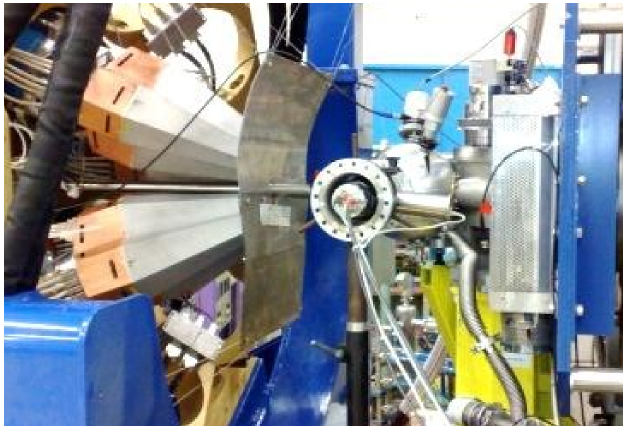


Courtesy of D. Bazzacco

Position of the first interaction point reconstructed with a 4mm uncertainty (E > 1MeV)

F. Recchia NIM 604 (2009) 555-562

Experimental setup



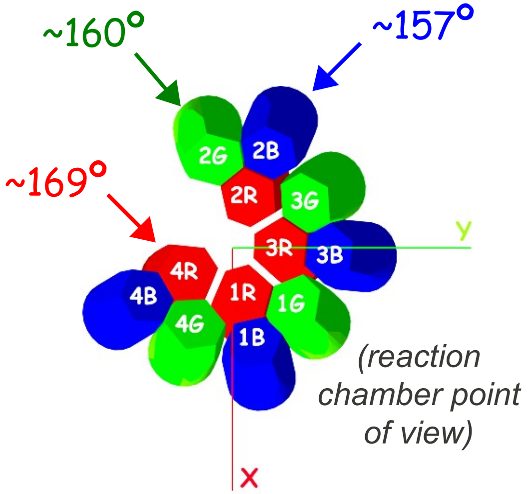
- **Reaction $^{2}H + {}^{14}N$ @ 32 MeV**

  Tandem XTU terminal voltage 8.95 MV

  $I({}^{14}N^{3+}) \sim 4 - 5$ pnA

  Main products → ^{15}N ; ^{15}O

- **^{2}H implanted in a 400nm surface layer of a 4mg/cm^{2} Au target**

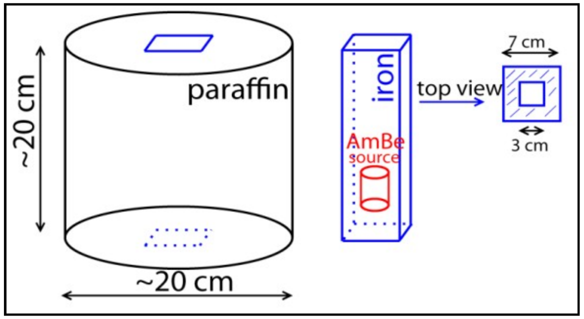


- **AGATA Demonstrator (4ATC's) at backward angles**

  $\beta({}^{15}O) \sim 6.5$ % ⟶ $E'_{\gamma} \sim 6400$ keV

- **AmBe(Fe) source during experiment to monitor gain stability**

  (~60 cm below the reaction chamber)



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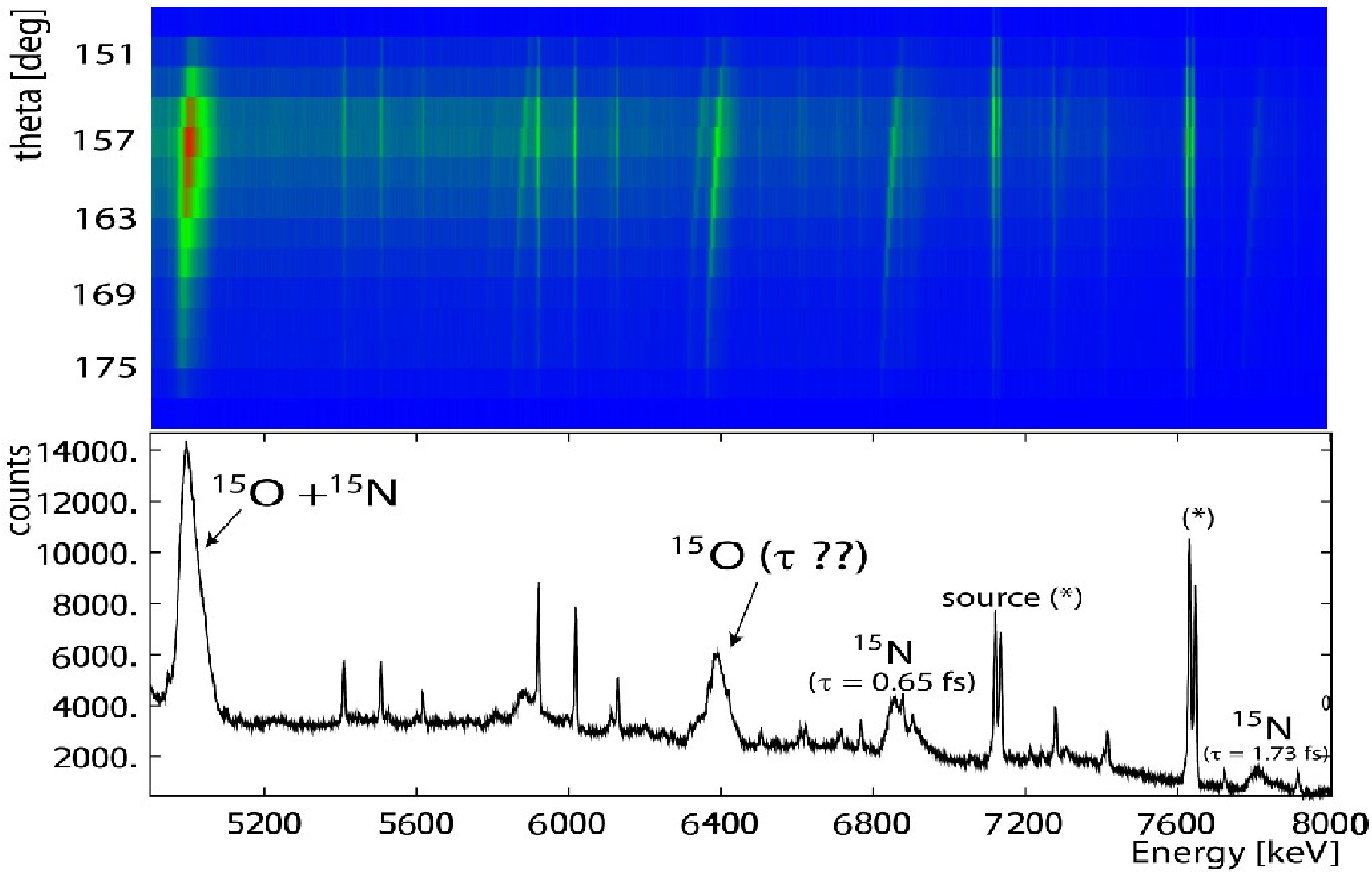
Lifetime evaluation: simulations VS experiment

Data analysis: events sorting

The angular range can be divided into 2° slices according to the angle of the first interaction point of each event



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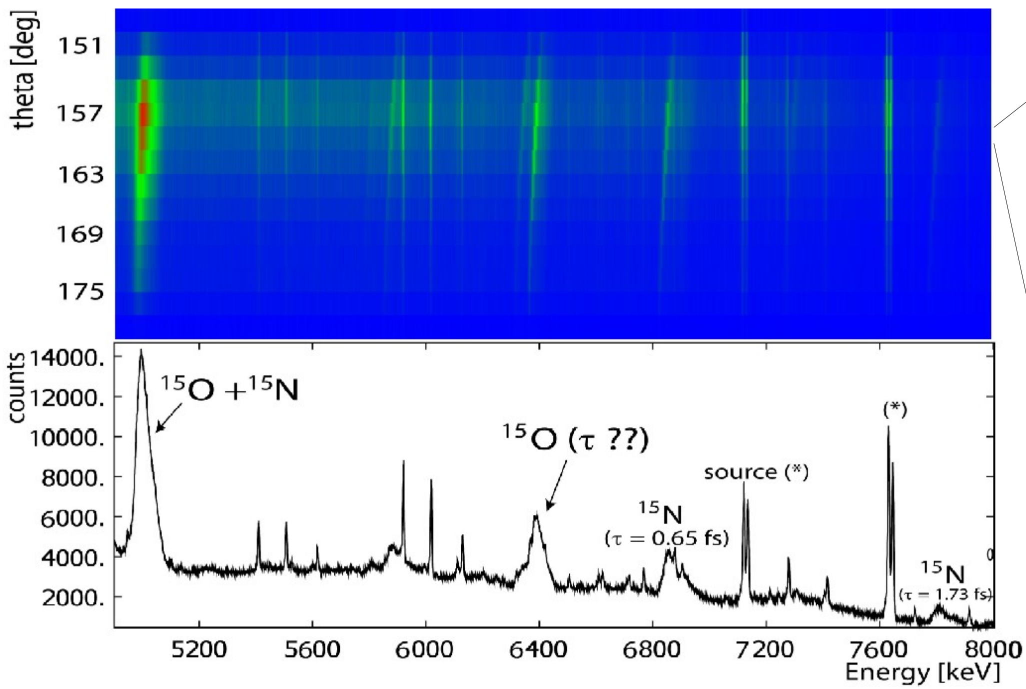
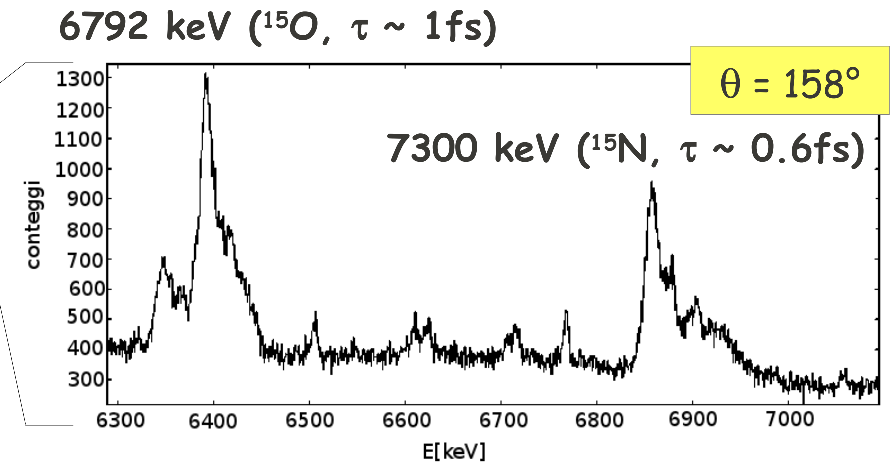
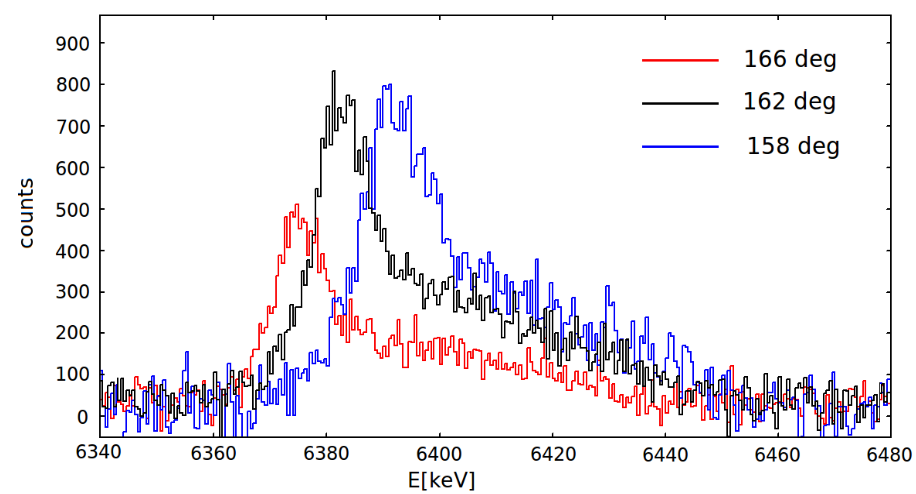




After subtraction of AmBe spectrum



Short lifetime

lineshape dominated by reaction kinematic

Data analysis: simulations

Lineshape analysis performed comparing experimental spectra with GEANT4 Simulations of the reaction and γ - ray emission and detection

E. Farnea et al. INFN-LNL Report 230 (2010) 57

INPUT :

- Projectile energy
- Target material and implantation profile (ERD and BS Analysis R.Depalo et al., INFN-LNL Rep. 234 (2011) 83)
- Reaction mechanism and angular distribution of emitting nuclei
- Excited levels energies, lifetimes and branching ratios
- Setup geometry (E. Farnea et al., NIM A 621 (2010) 331)

OUTPUT :

Interaction points of emitted gammas to be tracked with the same algorithm used for experimental data

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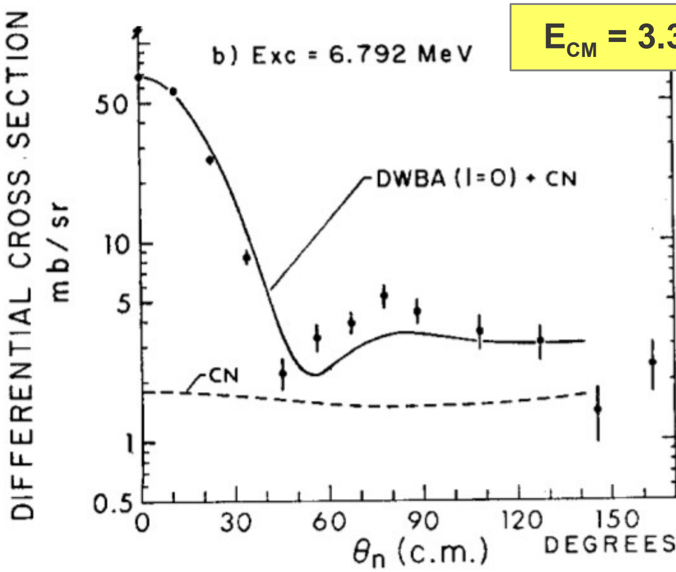
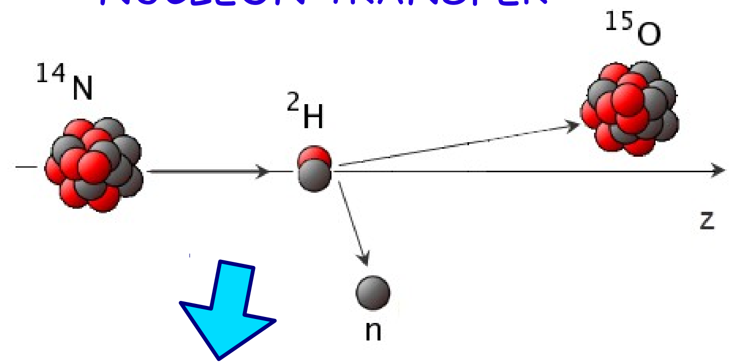
Reaction mechanism and kinematics

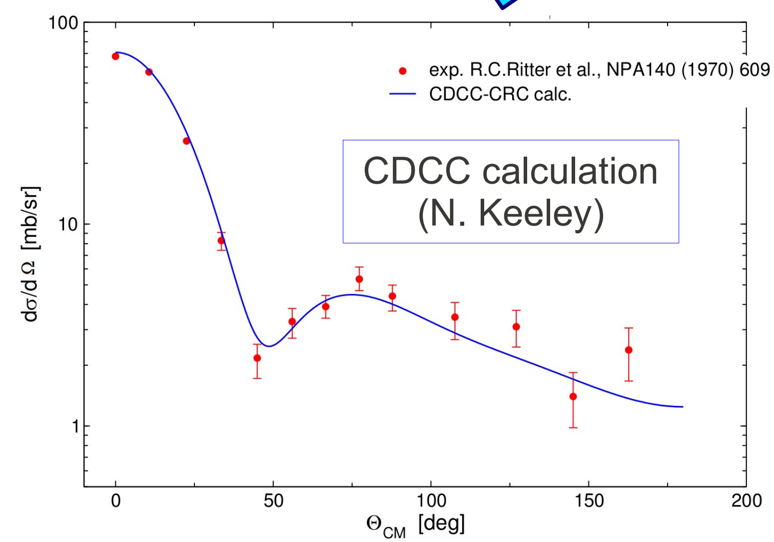


E_{CM} = 3.3 MeV

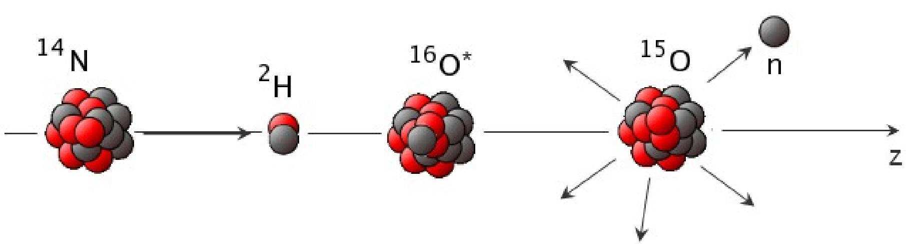
Ritter et al. NPA 140 (1970) 609-624

NUCLEON TRANSFER





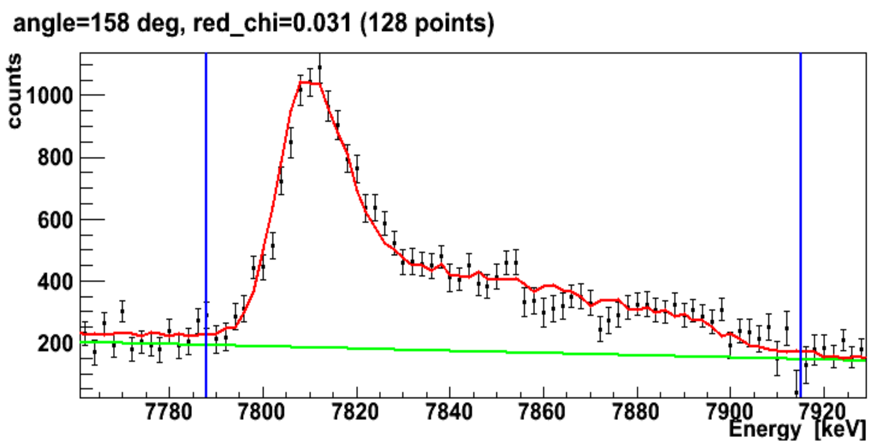
FUSION - EVAPORATION

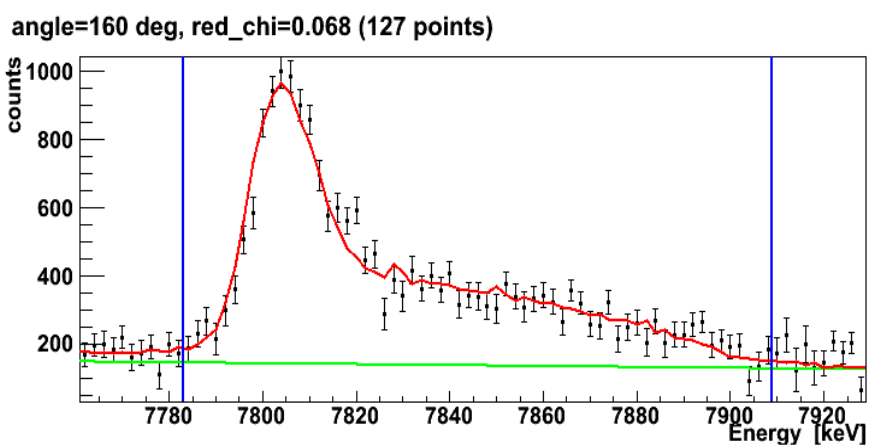


Neutrons energy distribution:
Maxwell – Boltzmann with kT = 4MeV

$$\frac{\sigma\ (\text{TRANSFER})}{\sigma\ (\text{FUS-EVAP})}$$ Not found in literature!

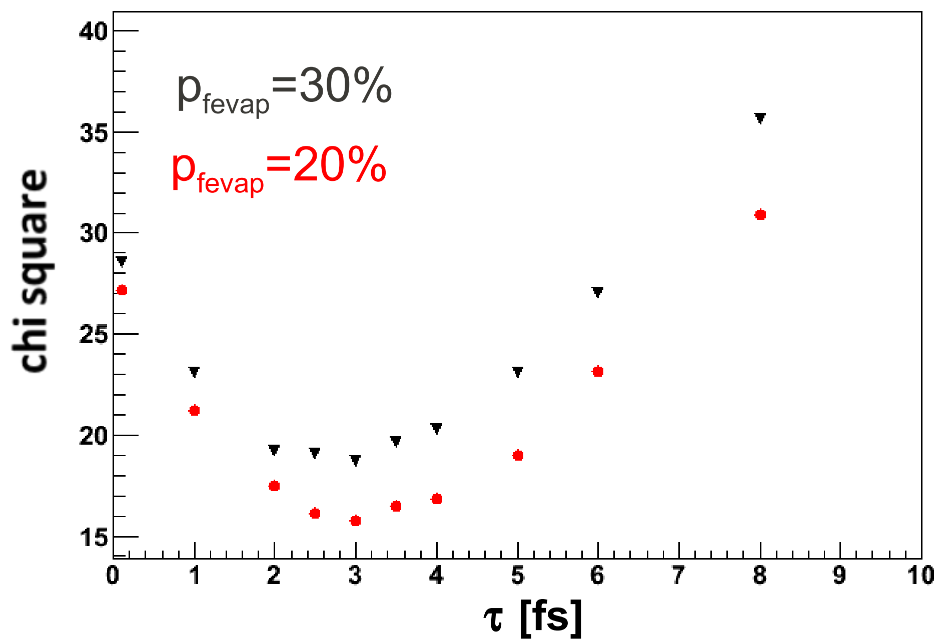
Data analysis: the 8.31 MeV level in ^{15}N



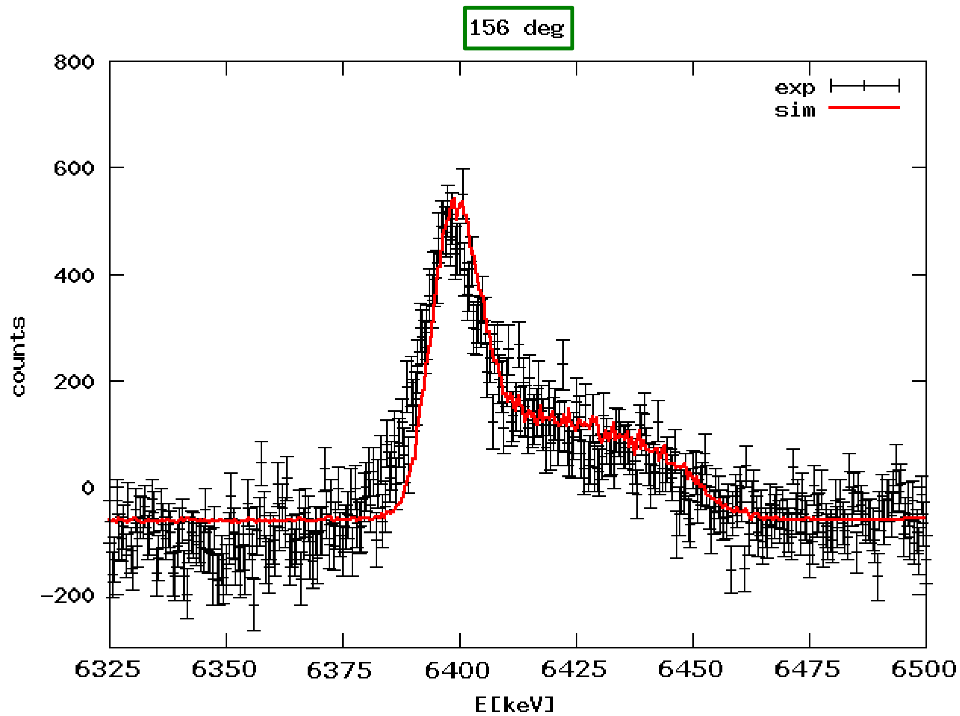


$\tau = 1.7 \pm 1.1$ fs

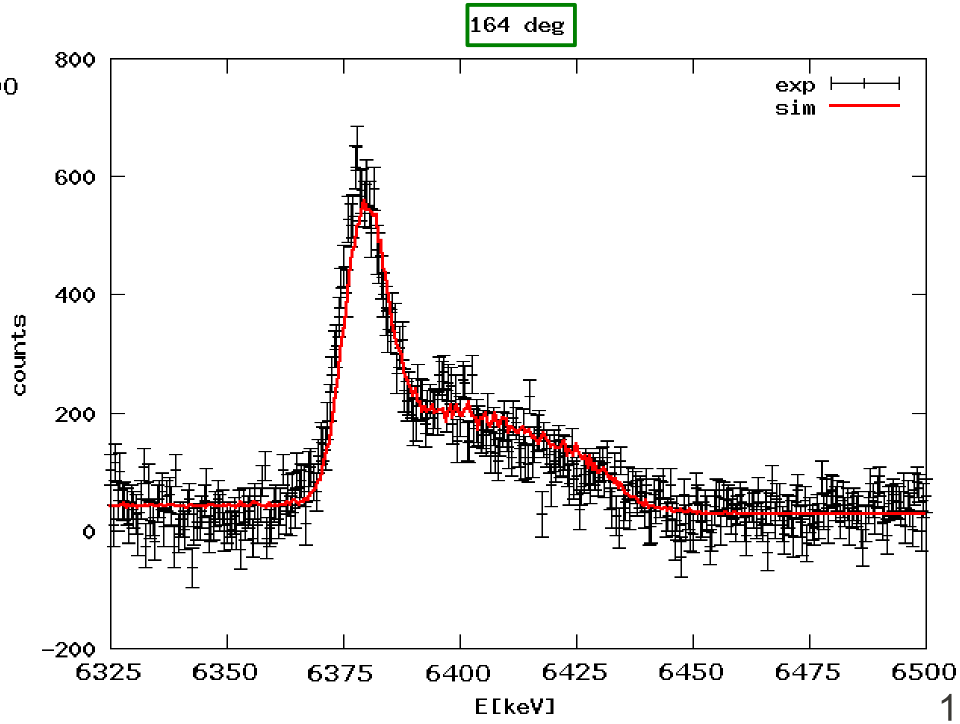
F. Ajzenberg-Selove NPA 523,1(1991)



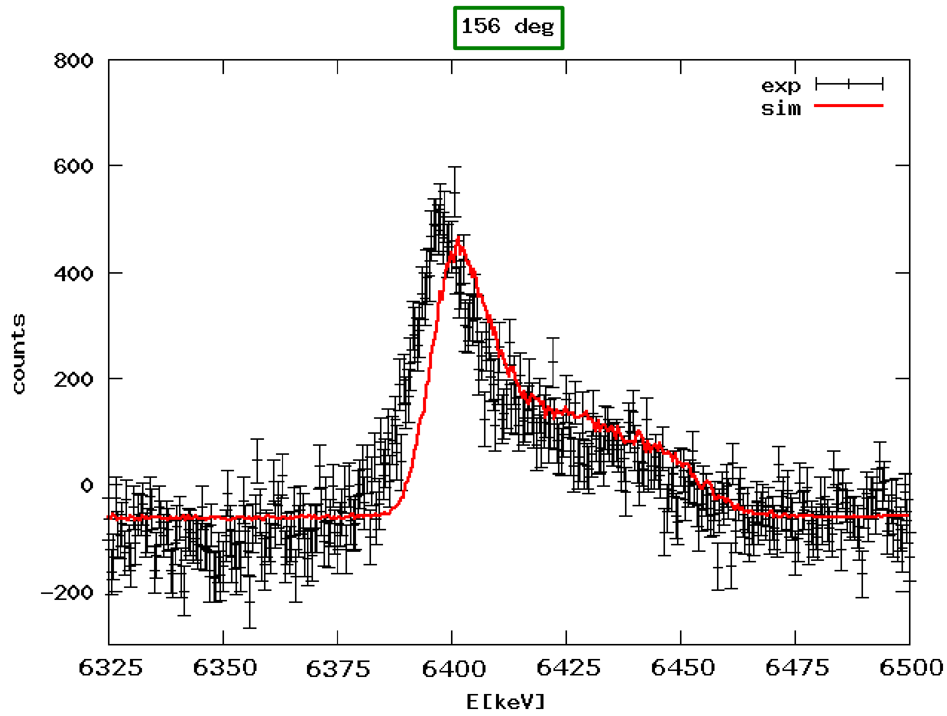
Data analysis: the 6.79 MeV level in ^{15}O



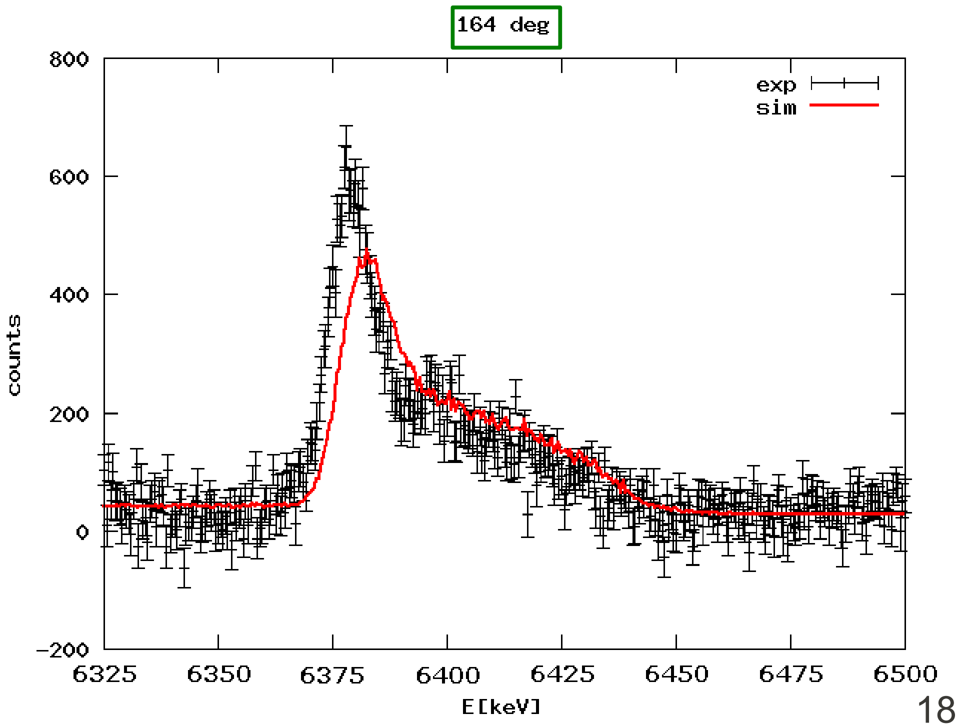
Experiment VS Simulation:
80% p transfer + 20% Fus. Evap.
τ = 1 fs



Data analysis: the 6.79 MeV level in ^{15}O



Experiment VS Simulation:
80% p transfer + 20% Fus. Evap.
τ = 5 fs



Summary

- The application of Advanced Gamma-ray Tracking technique allows DSAM studies over a “continuum” distribution of angles

- Line shape analysis on ^{15}N 8.31 MeV level in agreement with literature

- A qualitative estimation of the 6.79 MeV level in ^{15}O suggests a ~ 1fs lifetime (or shorter...)

- Insights in the reaction mechanism are needed to fully trust the results of Montecarlo simulations

EXTRAS

The solar composition problem

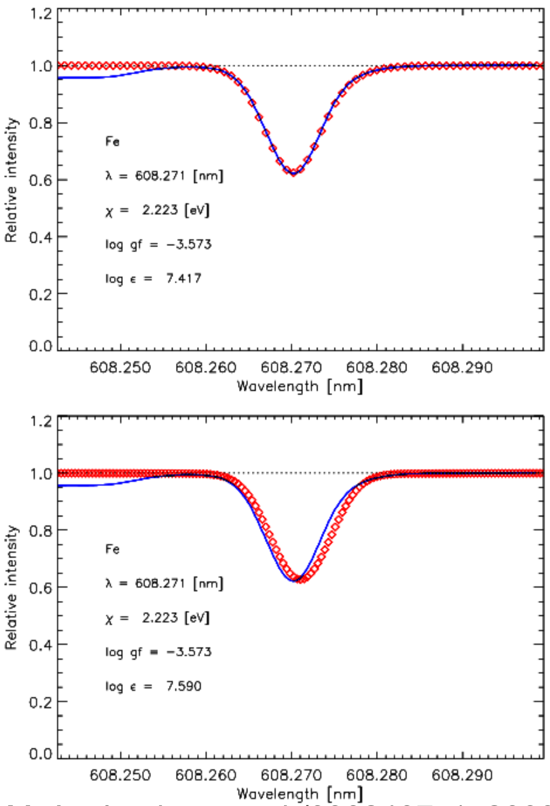
New 3D solar atmosphere models:

→ essentially parameters free

→ better fit of absorption lines

→ granulation

30% decrease in metallicity:

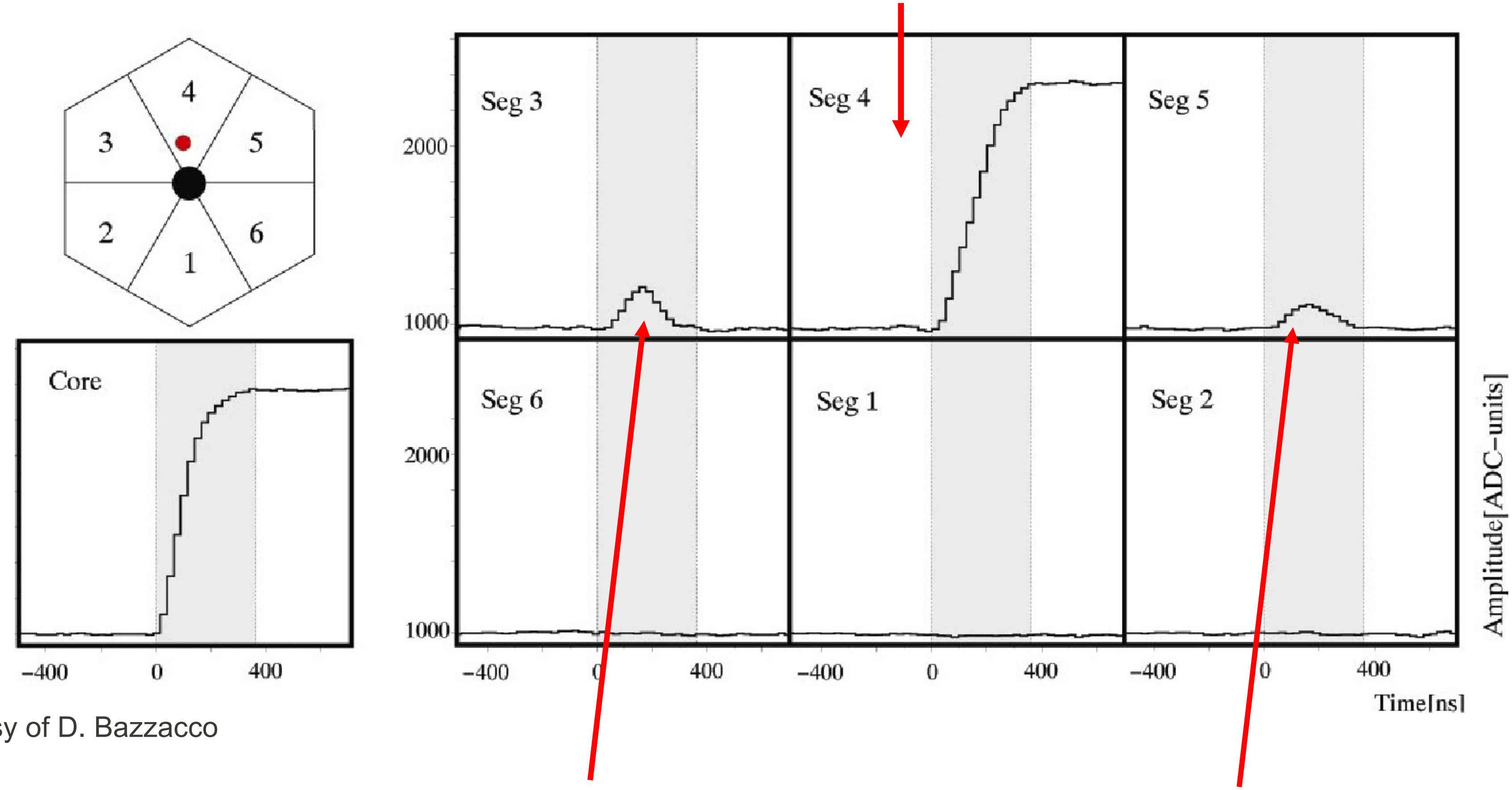


M. Asplund. astro-ph/0302407v1, 2003

- Smaller temperature gradient ⇨ $R_{CZ}/R_{\odot}$ from 0.713 to 0.728
- Age of globular clusters increased by 5 - 10%
- 40% decrease in CNO ν flux

Pulse Shape Analysis concept

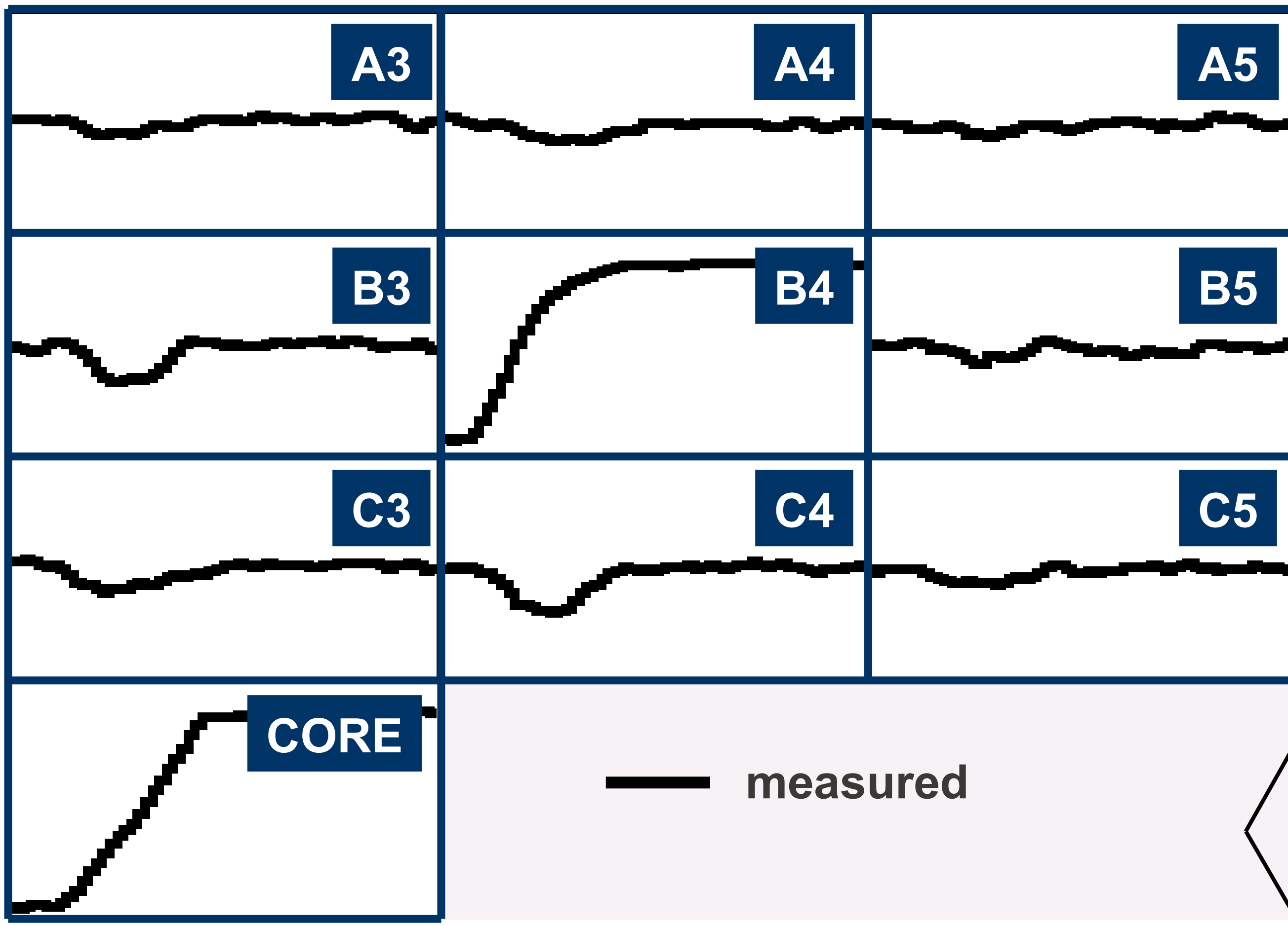
Interaction occurred in segment 4
(net charge signal)

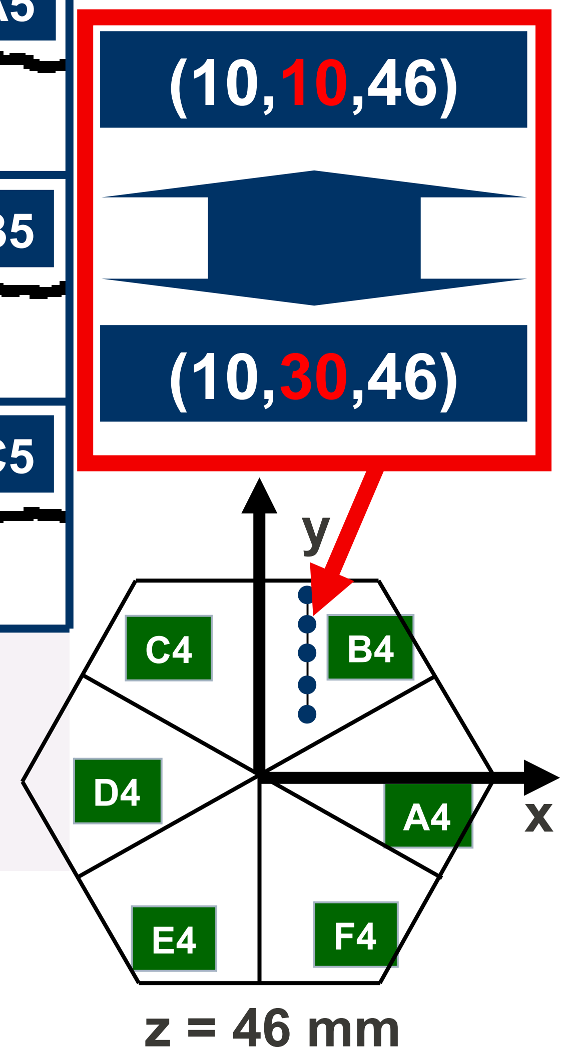


Courtesy of D. Bazzacco

Interaction is closer to segment 3 (larger amplitude than segment 5)

Pulse Shape Analysis concept

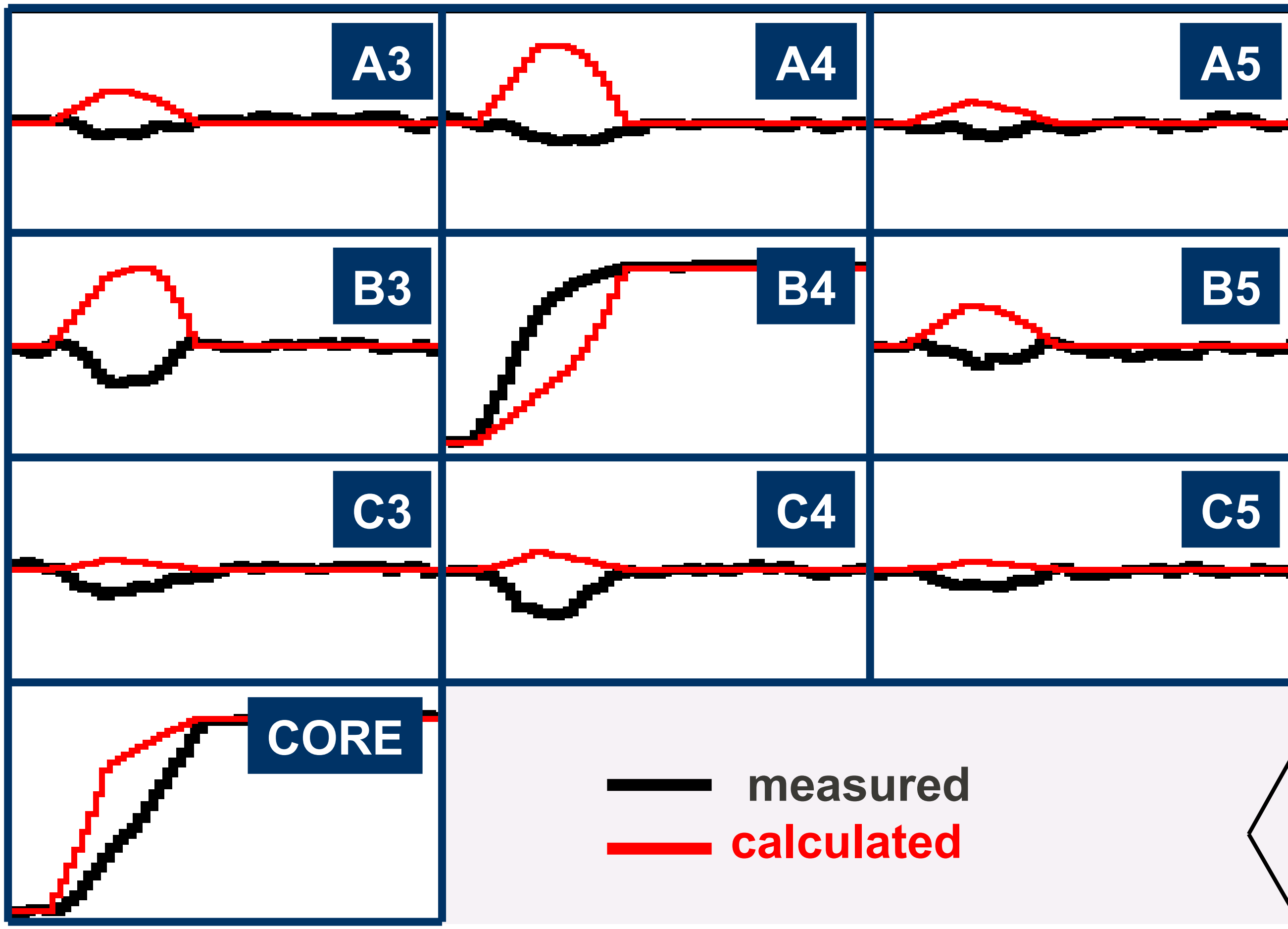




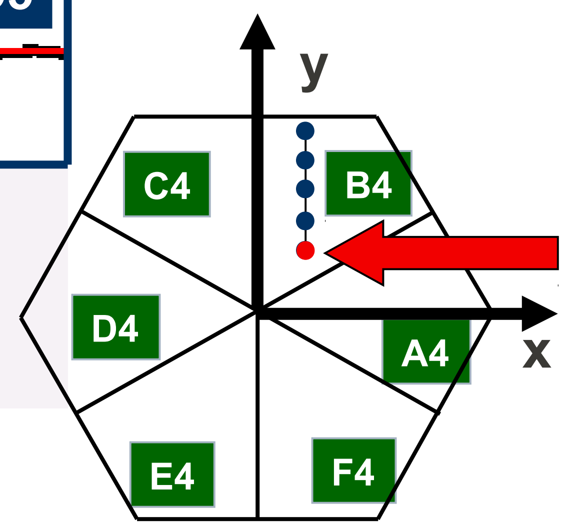
791 keV deposited in segment B4

Courtesy of D. Bazzacco

Pulse Shape Analysis concept



(10,10,46)

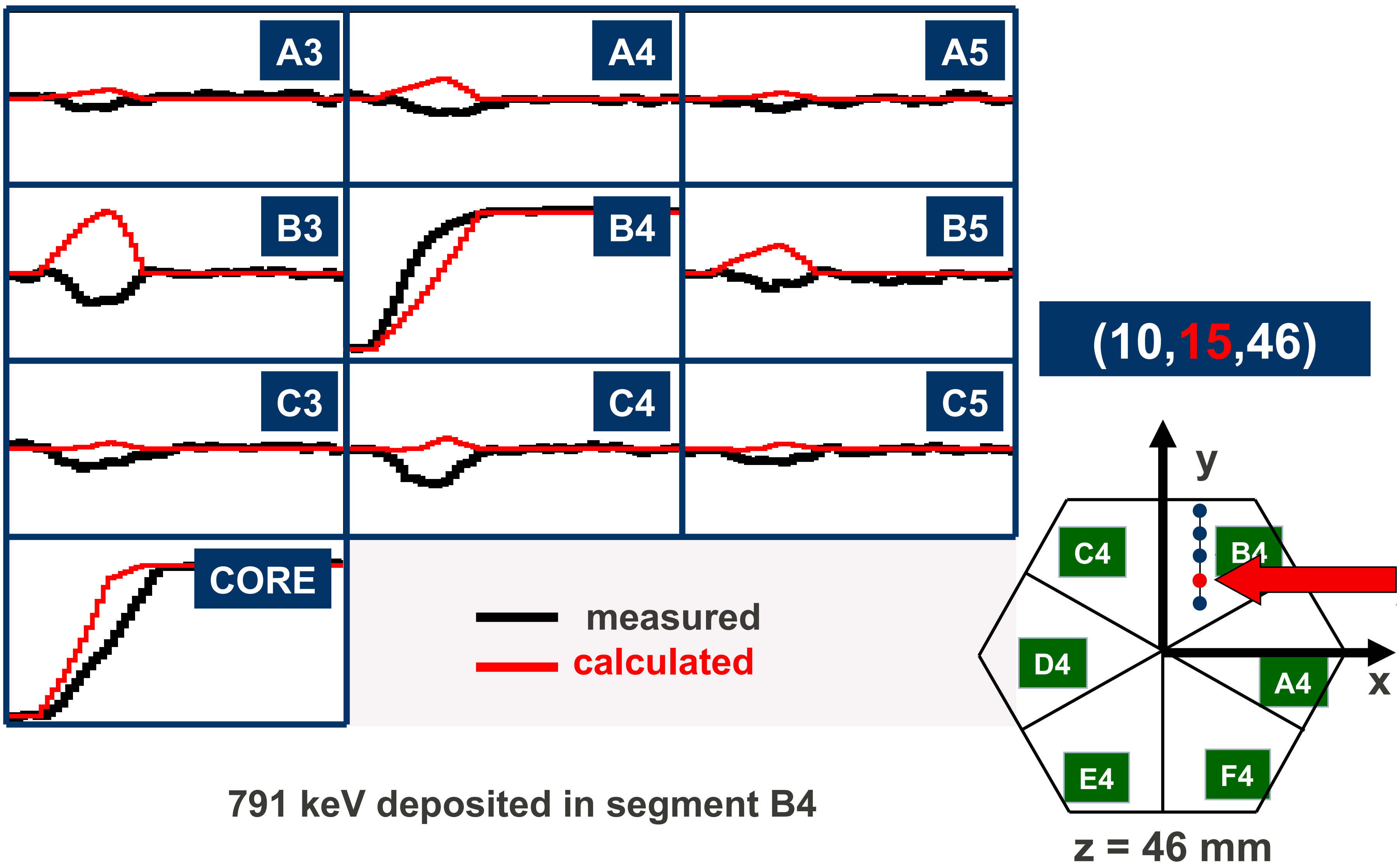


z = 46 mm

791 keV deposited in segment B4

Courtesy of D. Bazzacco

Pulse Shape Analysis concept



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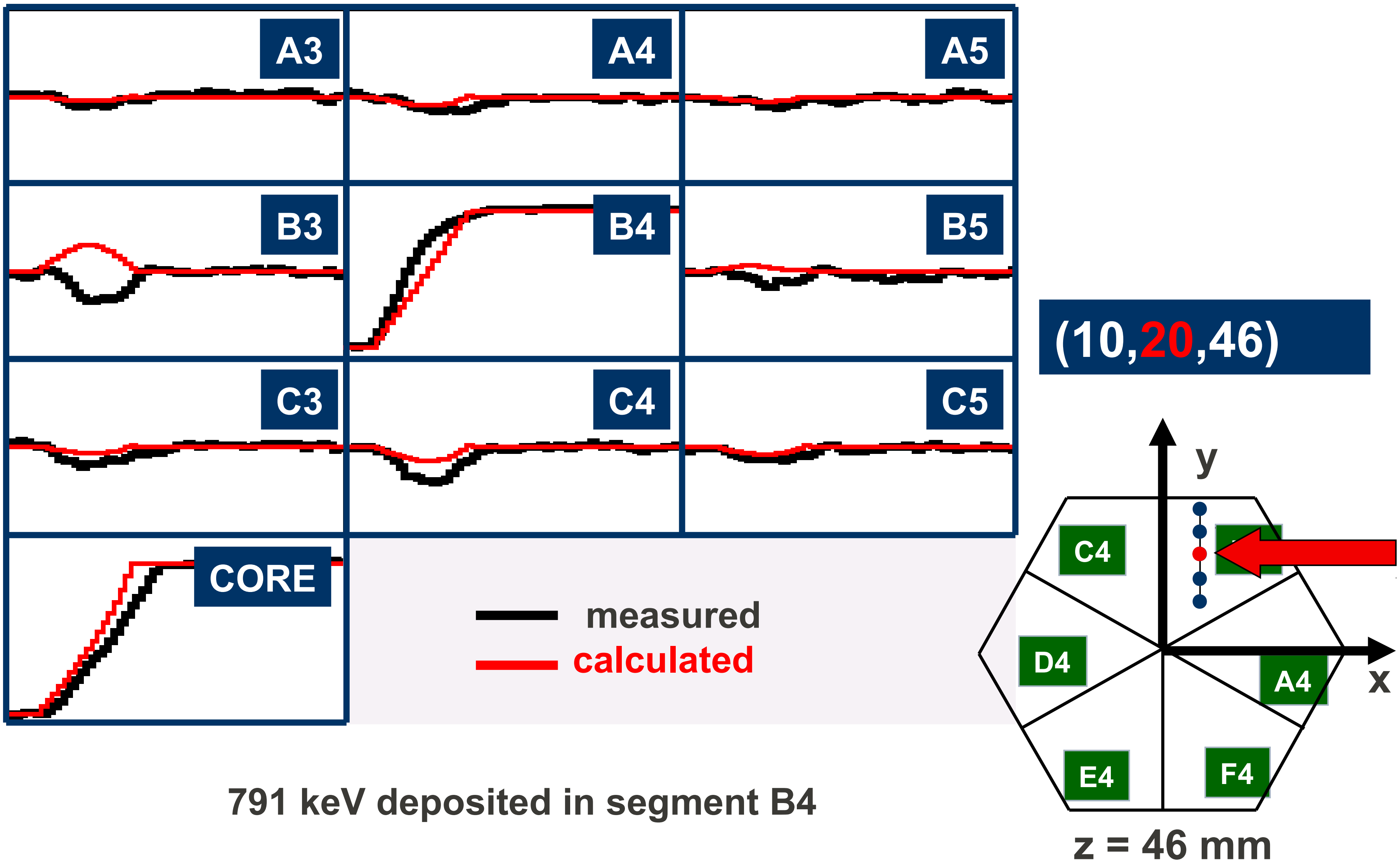

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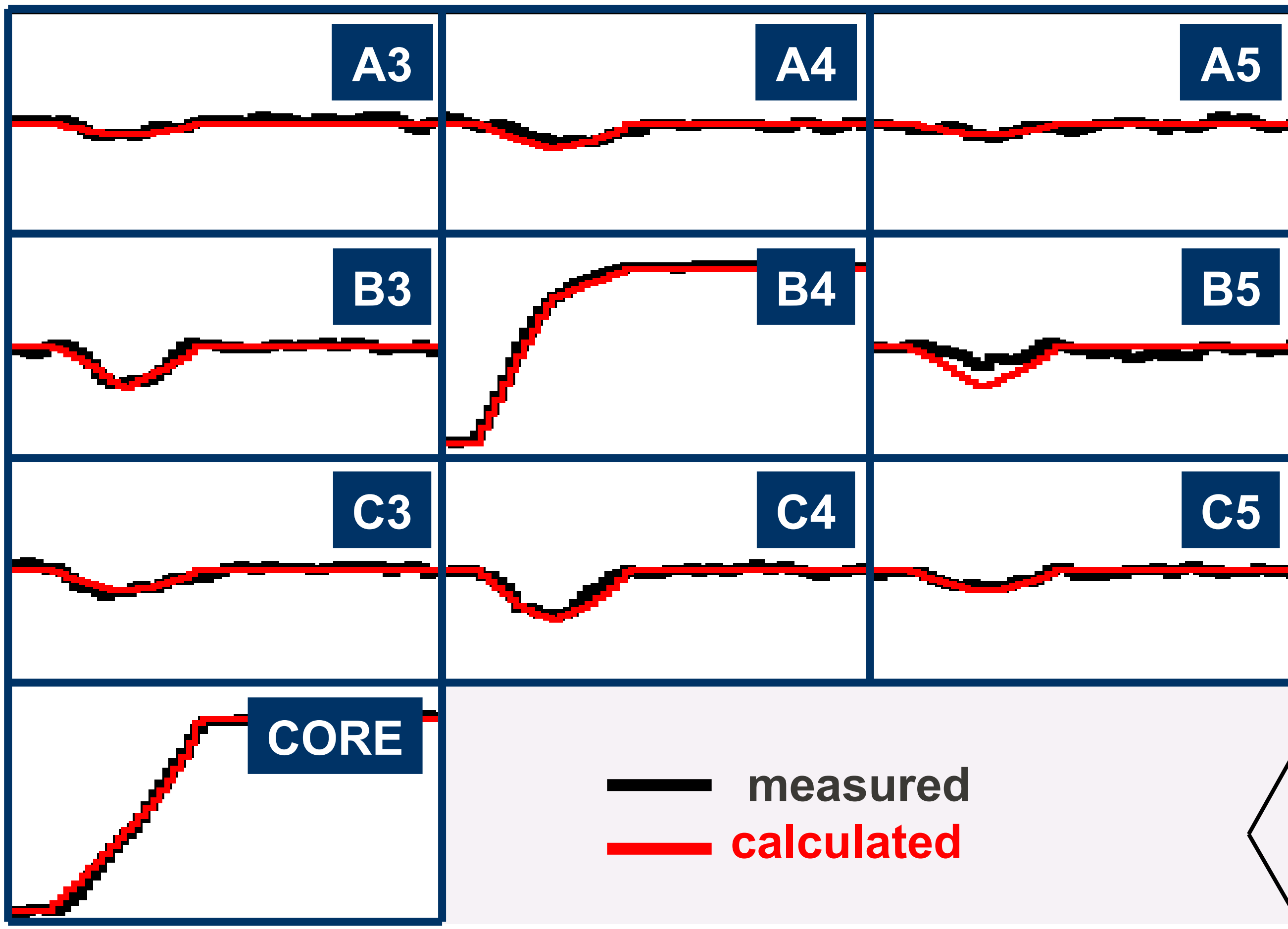

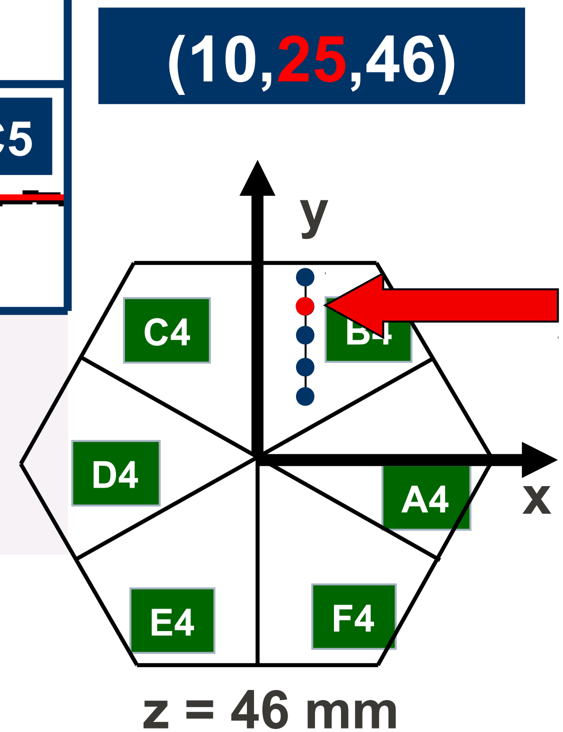

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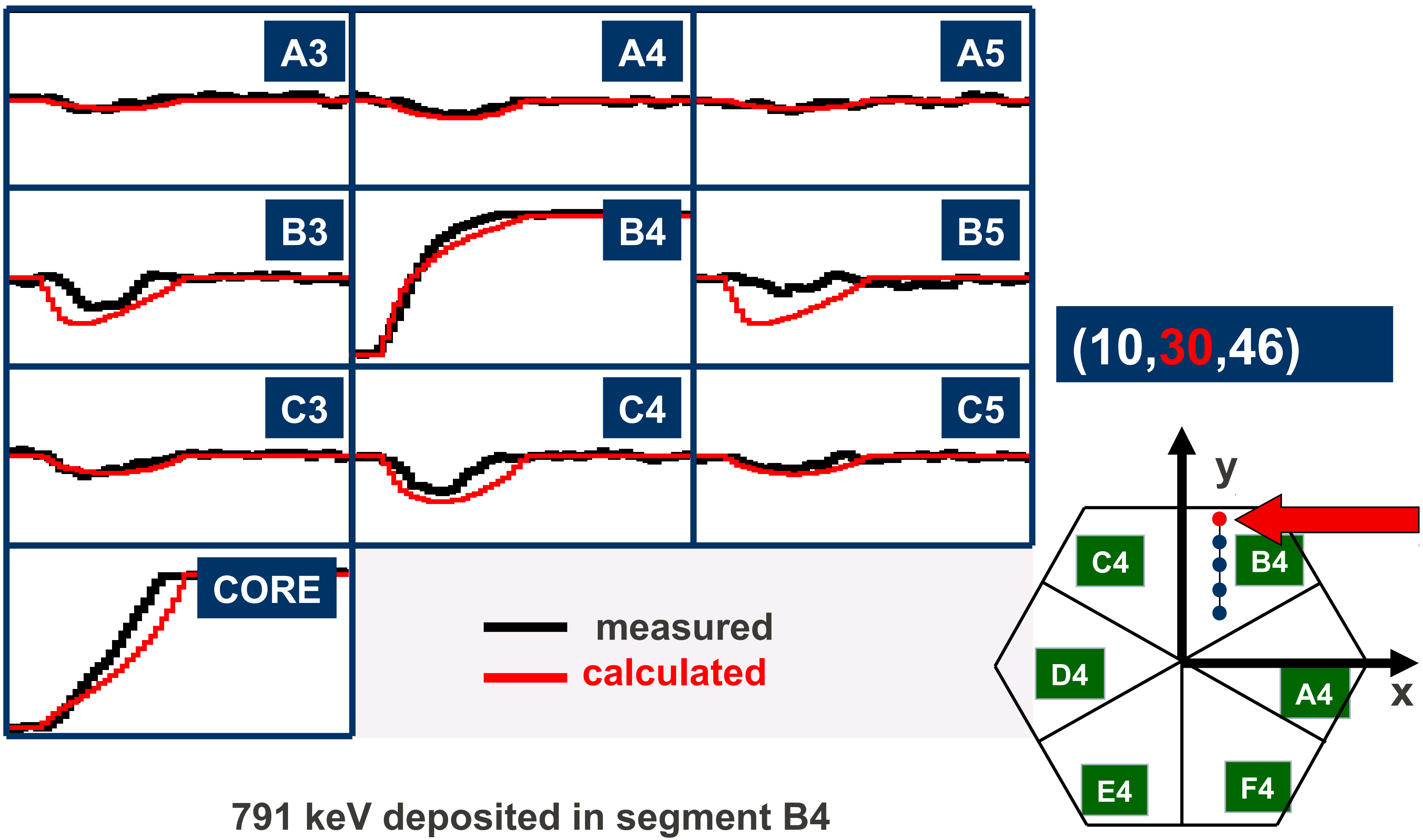

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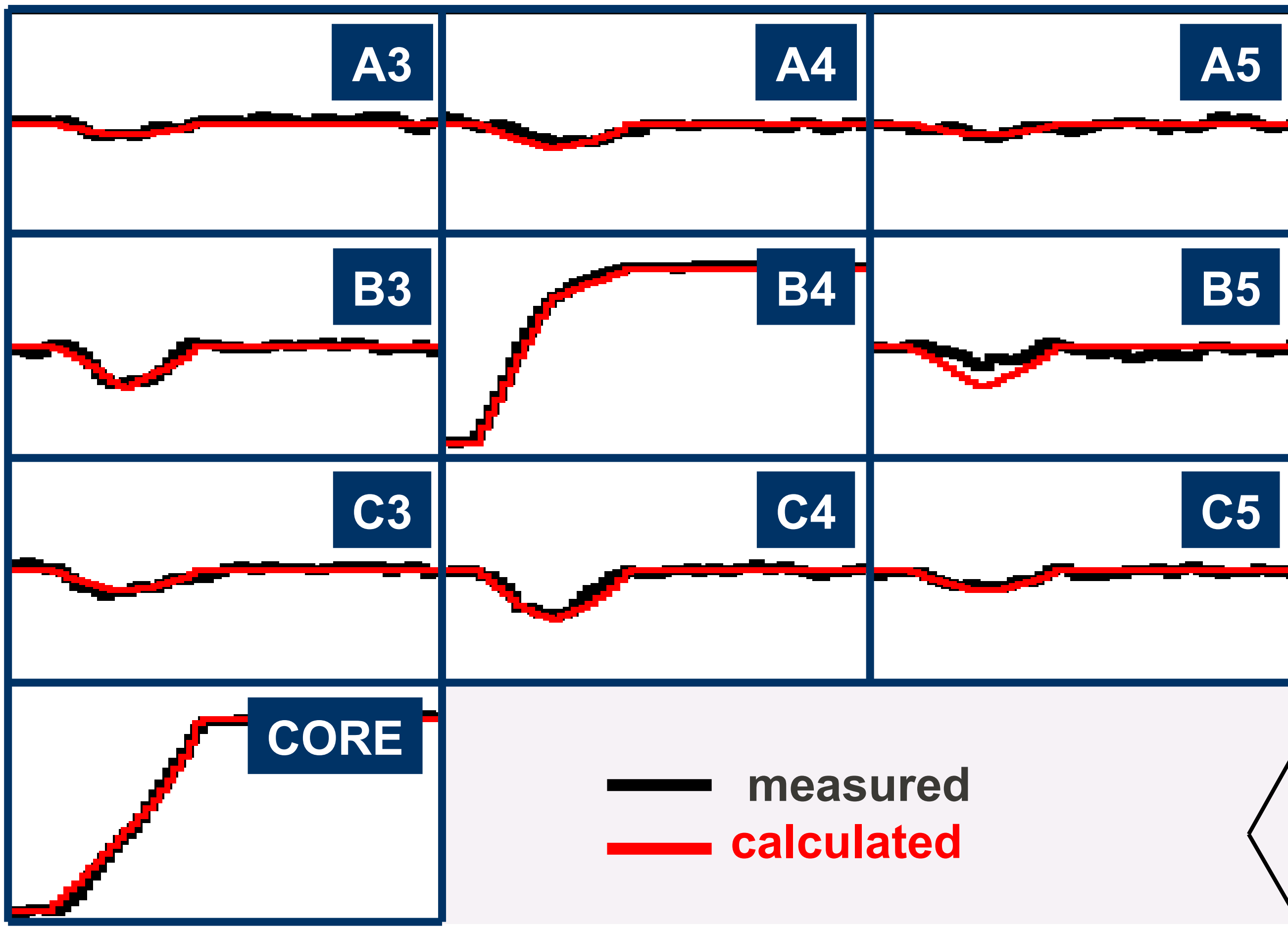
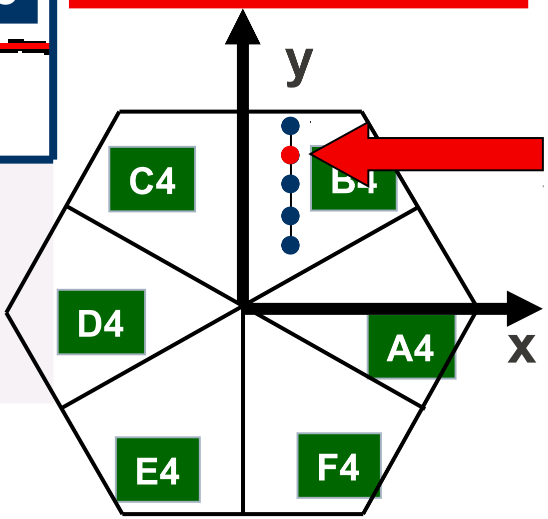


791 keV deposited in segment B4

Result of *Grid Search* algorithm

(10,25,46)



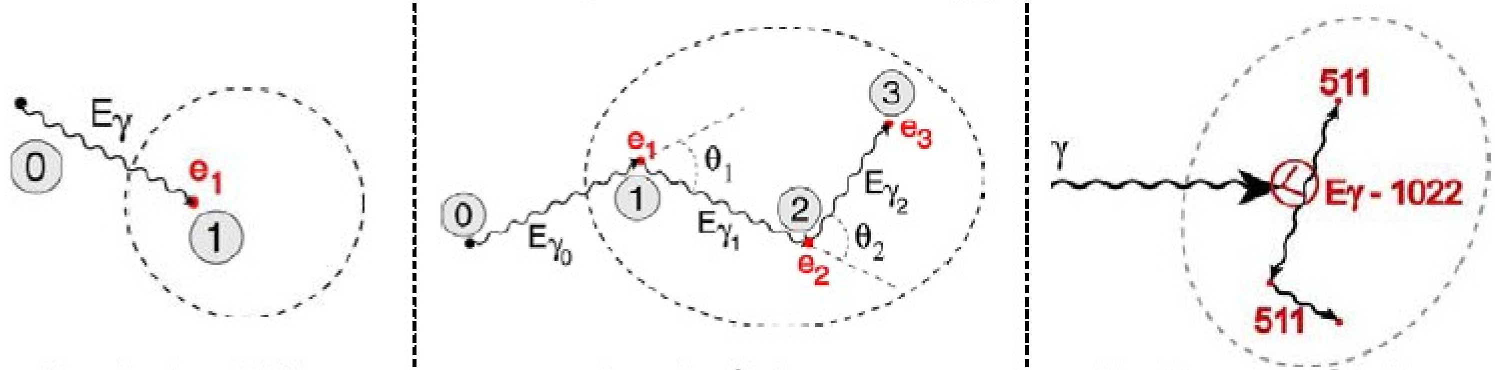
z = 46 mm

Courtesy of D. Bazzacco

γ-ray tracking concept

~ 100 keV | ~1 MeV | ~ 10 MeV | γ-ray energy

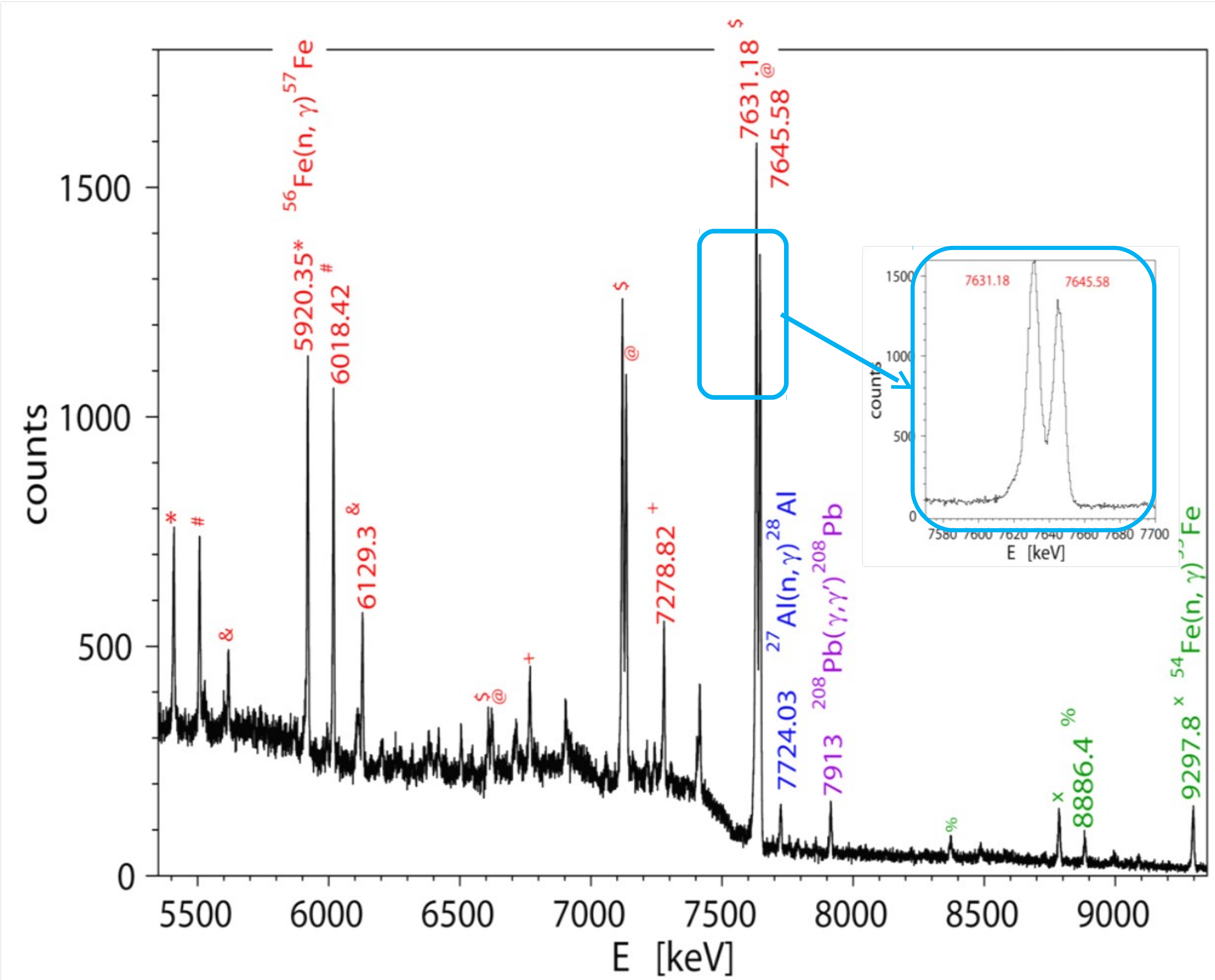
Photoelectric	Compton Scattering	Pair Production



Isolated hits	Angle/Energy	Pattern of hits
Probability of interaction depth	$E_{\gamma'} = \dfrac{E_\gamma}{1 + \dfrac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$	$E_{1st} = E_\gamma - 2\ mc^2$

Courtesy of D. Bazzacco

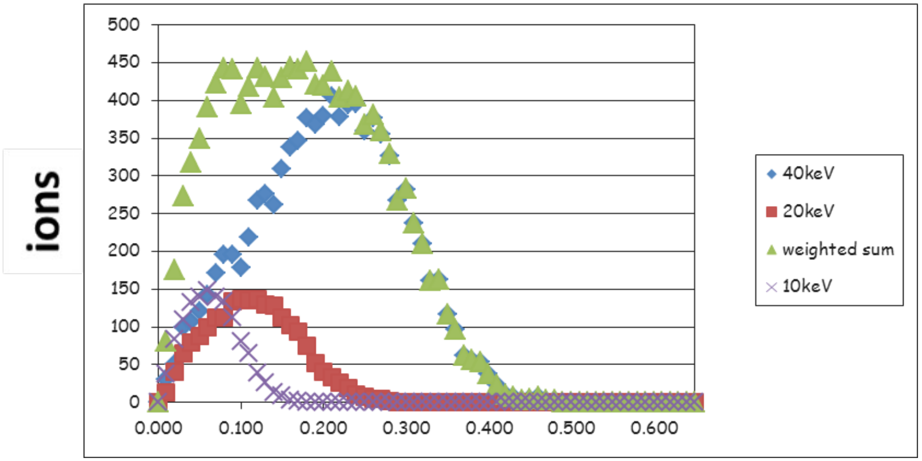
^{241}AmBe + Fe gamma spectrum



high-energy (≈5-8 MeV) γ source during beam-on-target to monitor electronic gain instabilities

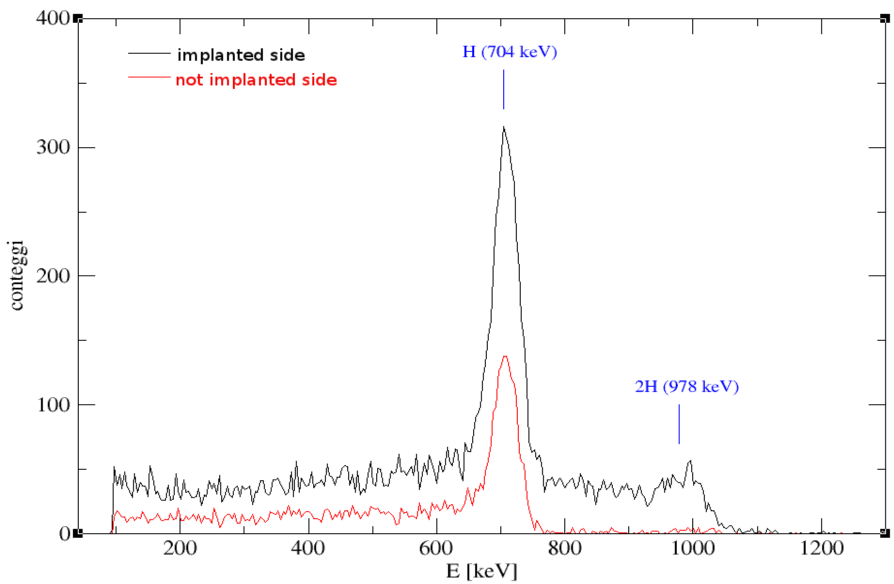
Target Analysis

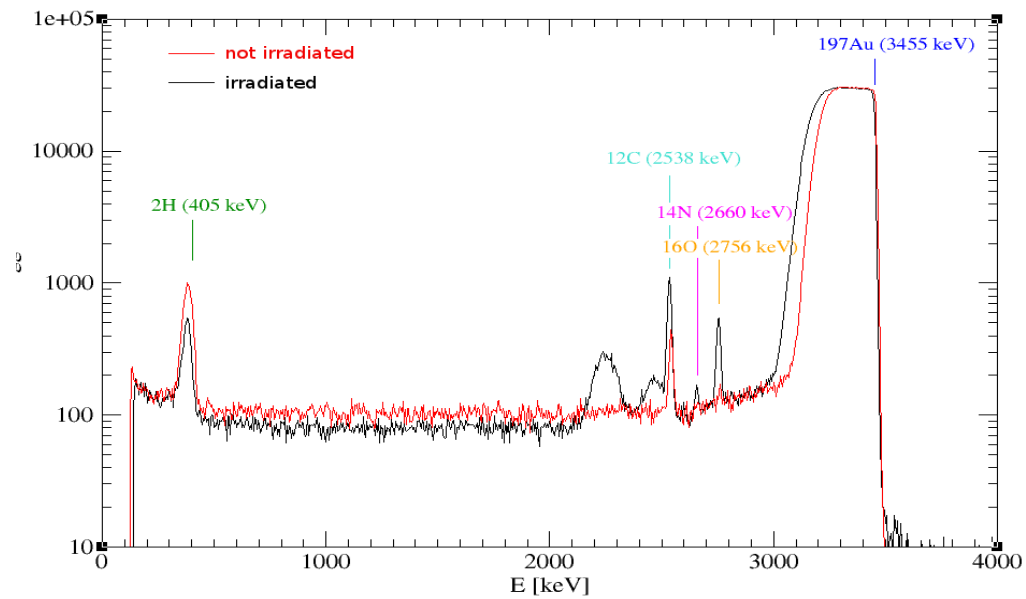
target = deuterium implanted in a Au backing (~3.8 mg/cm²)



following consecutive deuterium implantations at energies between 30 and 100 keV:

~1x10^{+18} atoms/cm² (Au: ^{2}H ~2.6:1)





R.Depalo et al., INFN-LNL Rep. 234 (2011) 83