Realistic simulations for Doppler shift lifetime measurements with complex level schemes

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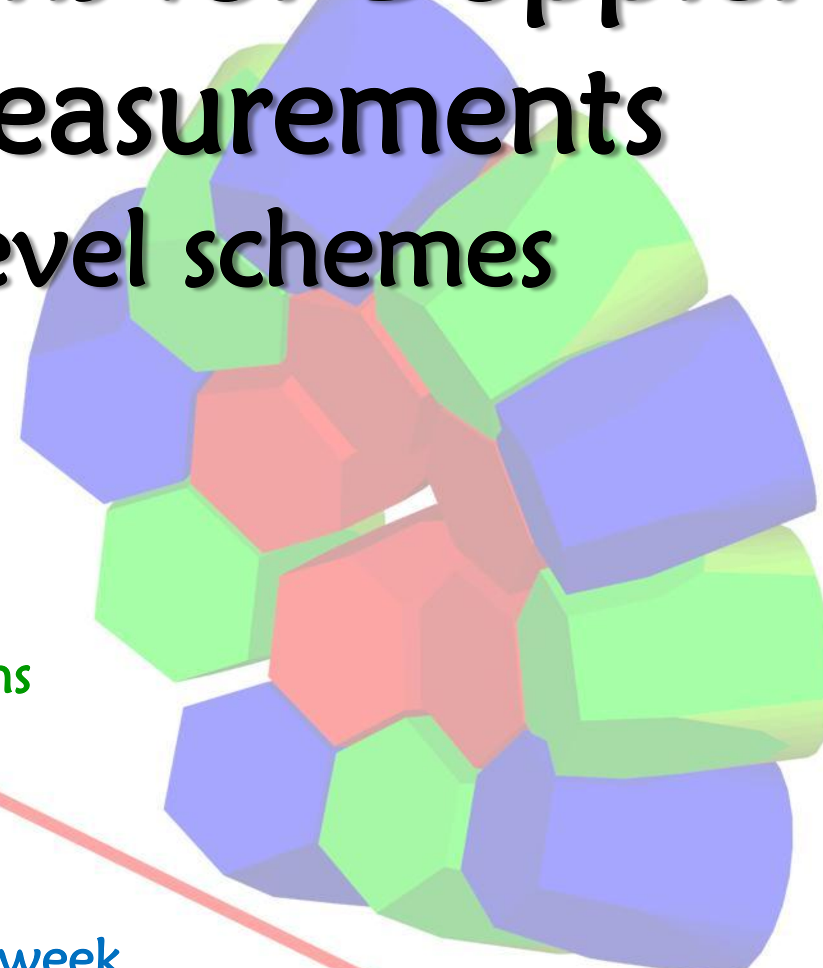
and the AGATA and PRISMA collaborations

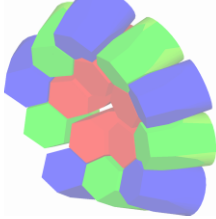
INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

AGATA ADVANCED GAMMA TRACKING ARRAY

Università degli Studi di Padova



10th AGATA week
IPN Lyon
22nd-26th November



my next 20 min goal…

…is to explain:

- ✓ what can be simulated (Geant4)
- ✓ to what extent it is reliable
- ✓ why do we need such a tool … !!!

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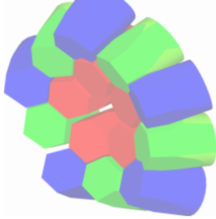
What I am going to outline is a work that is in progress

Hope to find volunteers for "beta testing"…!!!



Outline

1. Doppler shift lifetime measurements
   i. reminder of the basics of the principle
   ii. main techniques
   iii. why do we need Monte Carlo simulations
2. The simulation code
   i. reminder on the Geant4 philosophy
   ii. the code cornerstones
   iii. what can be simulated
   iv. some comparisons with "real" spectra
3. To-do list
4. Conclusions

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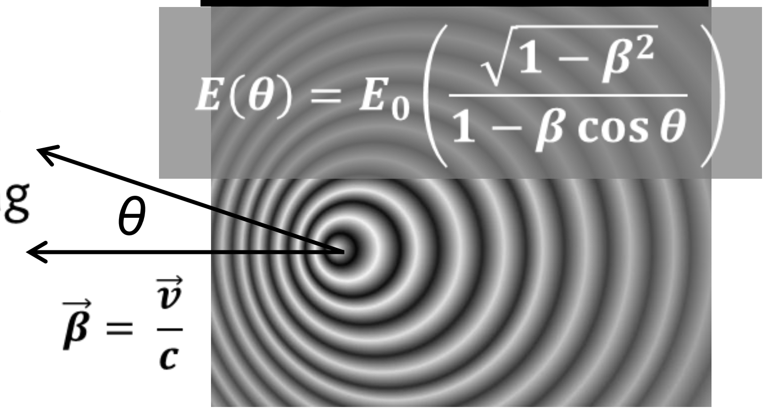
Lifetime measurements with Doppler shift techniques (1)

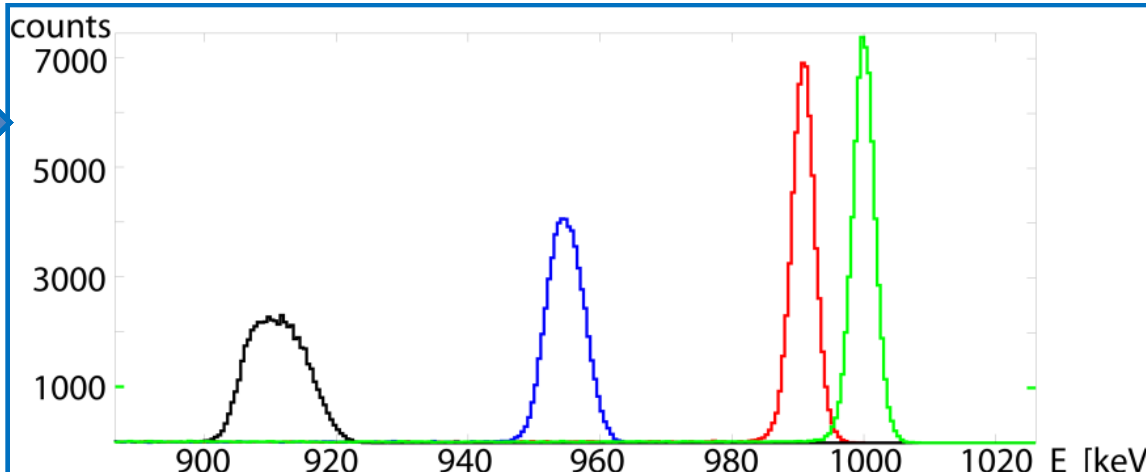
Lifetimes of excited nuclear levels in the $\approx 10^{-2} - 10^{2}$ ps range can be measured exploiting the Doppler shift of the energy (E_0) of the gamma de-exciting the level of interest while the emitting nucleus is moving with $\vec{\beta} = \frac{\vec{v}}{c}$

Doppler relation

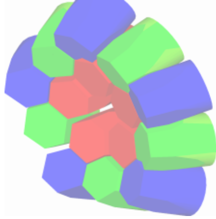
$$E(\theta) = E_0 \left(\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \right)$$



E_0=1MeV
β=0, 0.01, 0.05, 0.10
(fixed direction)
$\theta = 158\ deg$

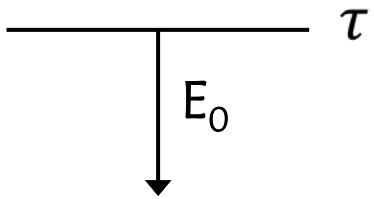


$\vec{\beta}$ is a key info.



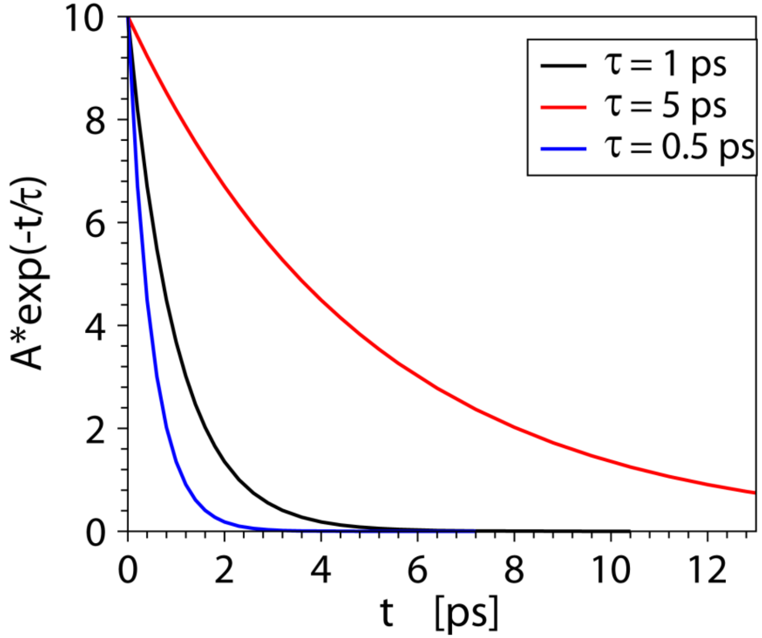
Lifetime measurements with Doppler shift techniques (2)

a "simple" case: N_0 nuclei populated at $t_0=0$ in an isolated level with lifetime τ



$$N(t) = \frac{N_0}{\tau}\, e^{-t/\tau}$$

$$I(t) = \int_0^t \frac{N_0}{\tau}\, e^{-t/\tau}$$



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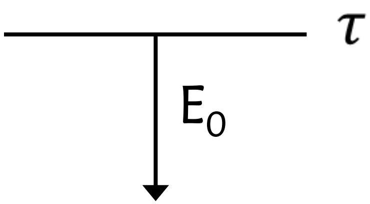

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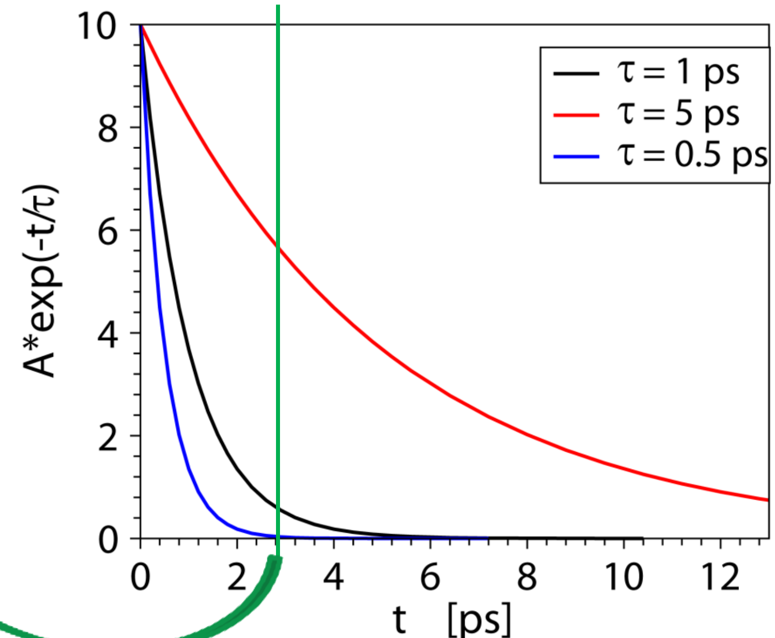
The intensity "observed" at the time t is sensitive to the lifetime of the de-exciting level



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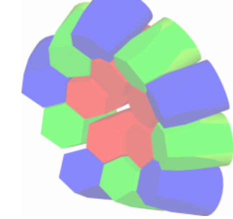

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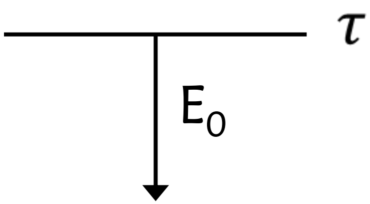

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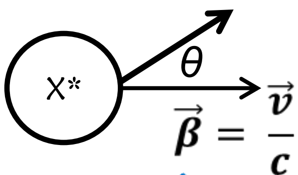

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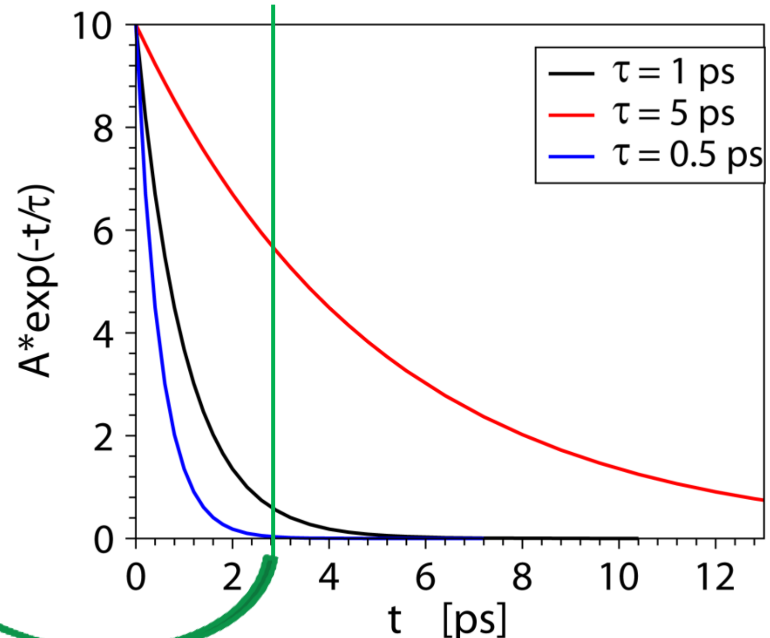
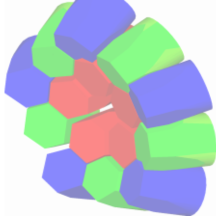


t = d/v can be taken as a reference time

("easy" in case of constant v...)



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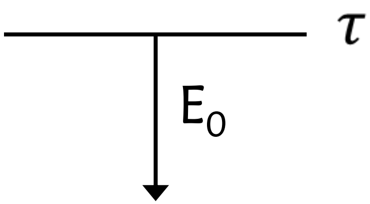

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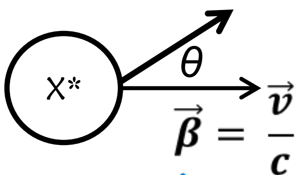

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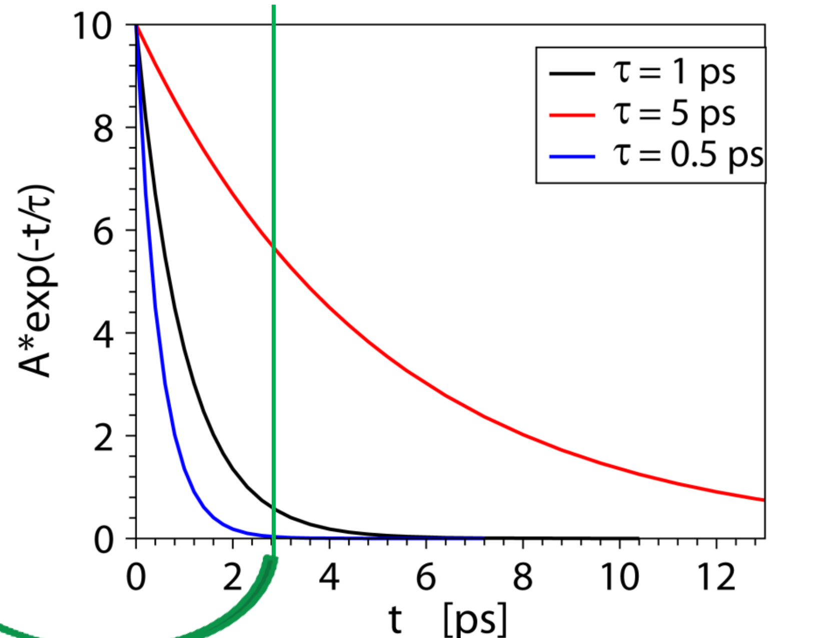

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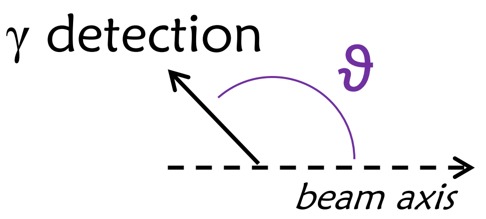
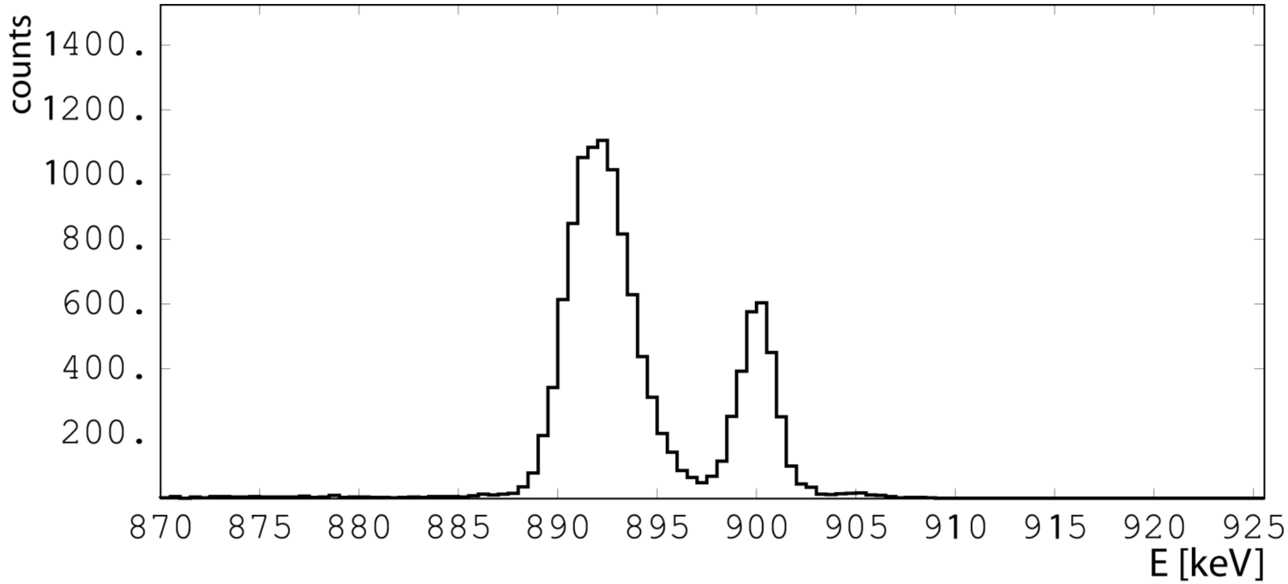
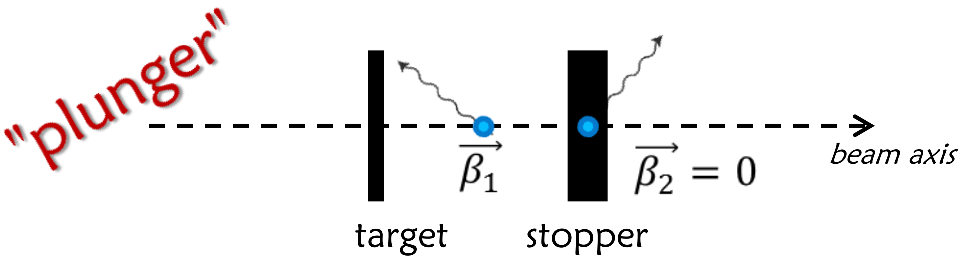
different lifetimes and experimental conditions led to different variants…

Lifetime measurements with Doppler shift techniques (3)

Recoil Distance Doppler shift (RDDS) methods







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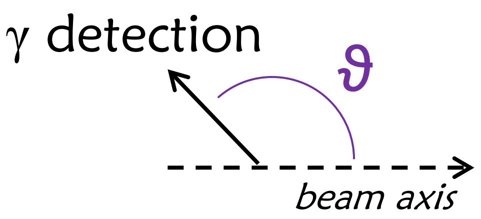

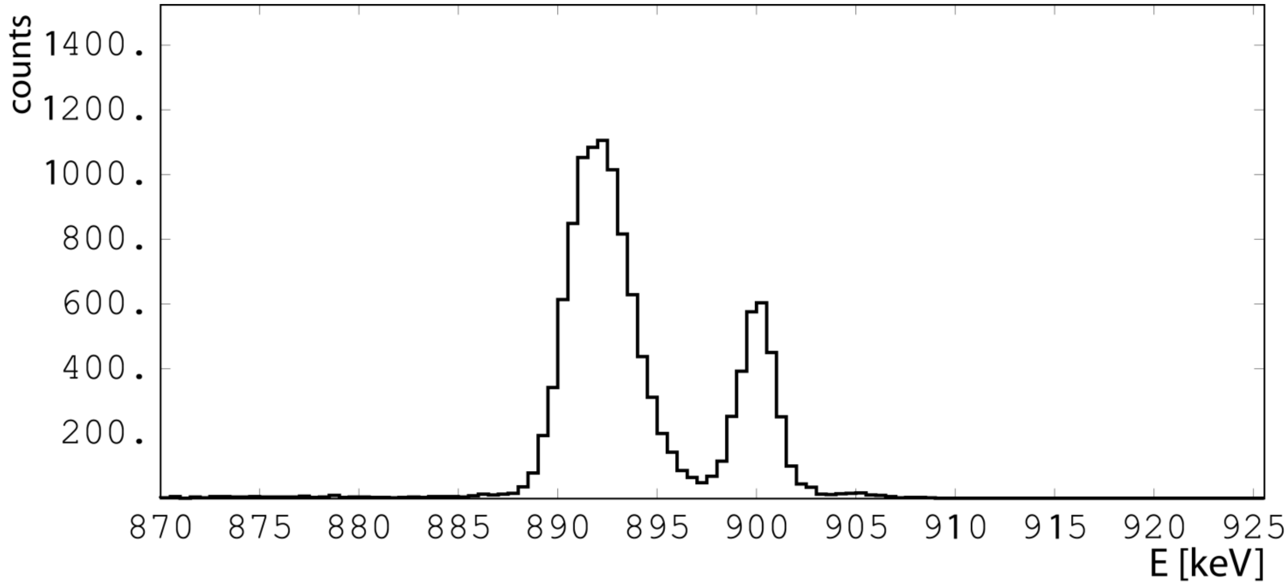

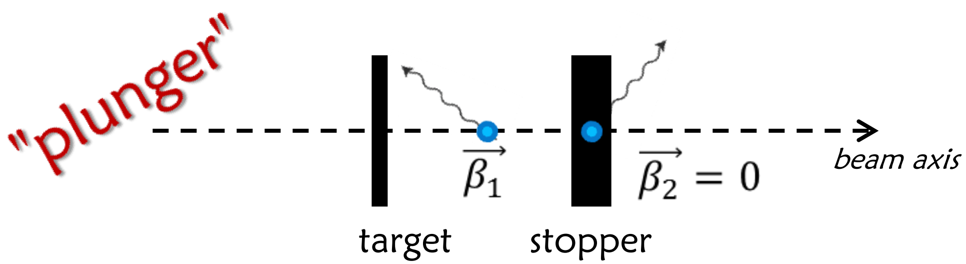

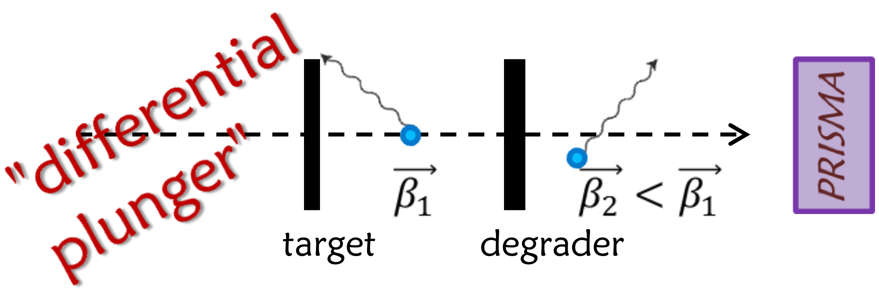

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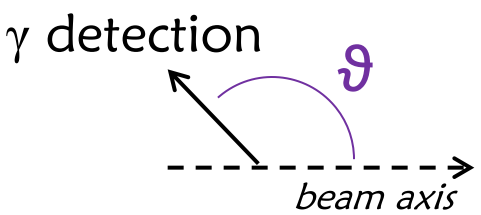
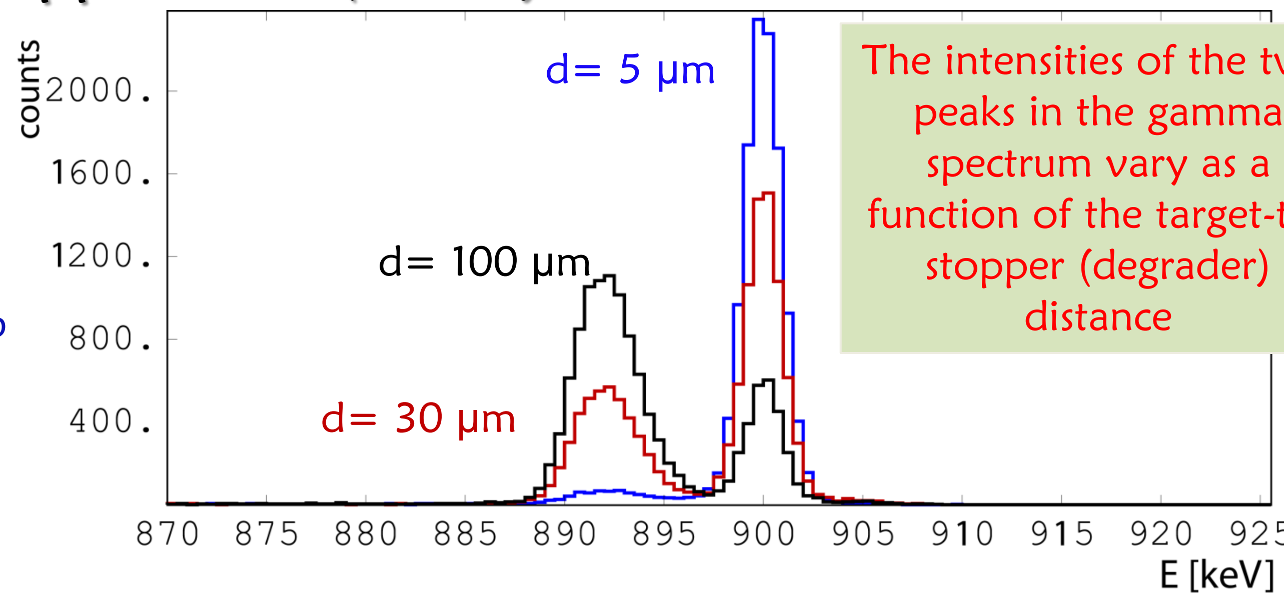
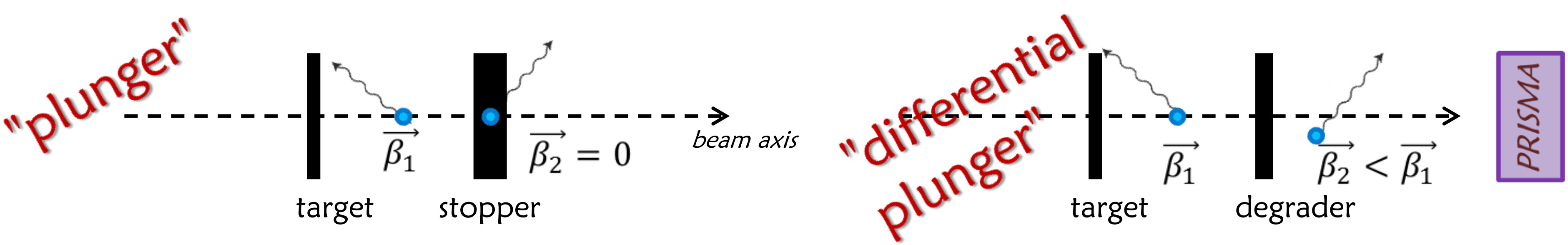


$t_{1/2}$ = 10 ps $\beta_1 \sim 1\%$

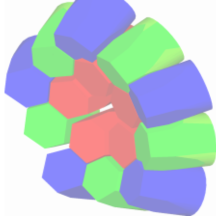
E_g = 900 keV $\beta_2 = 0$



The intensities of the two peaks in the gamma spectrum vary as a function of the target-to-stopper (degrader) distance

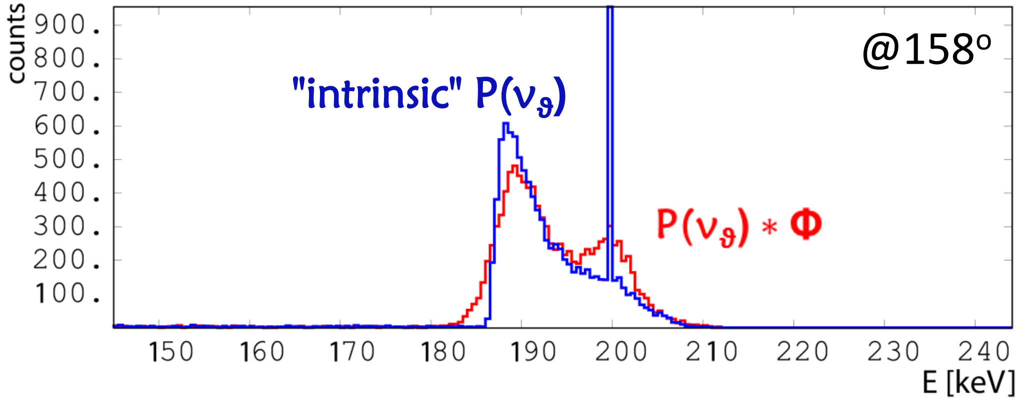


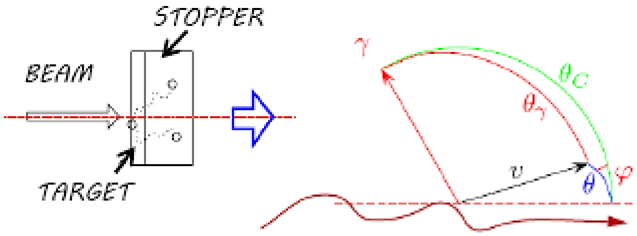
Lifetime measurements with Doppler shift techniques (4)



Doppler Shift attenuation Method (DSAM)

when the lifetime is ≈ slowing down time of the emitting ion in the substrate material a continuous energy distribution is observed in the gamma spectrum, from the “nominal” energy to the one corresponding to the max. Doppler shift





$$P(\nu_\vartheta)=\int_0^\infty dt\, S(t,v_\theta)\,\frac{n(t)}{\tau}$$

n(t) = decay function
(exp(-t/τ) in "our simple case")
$S(t,\nu_\vartheta)$ = slowing down matrix
Φ = detector response function

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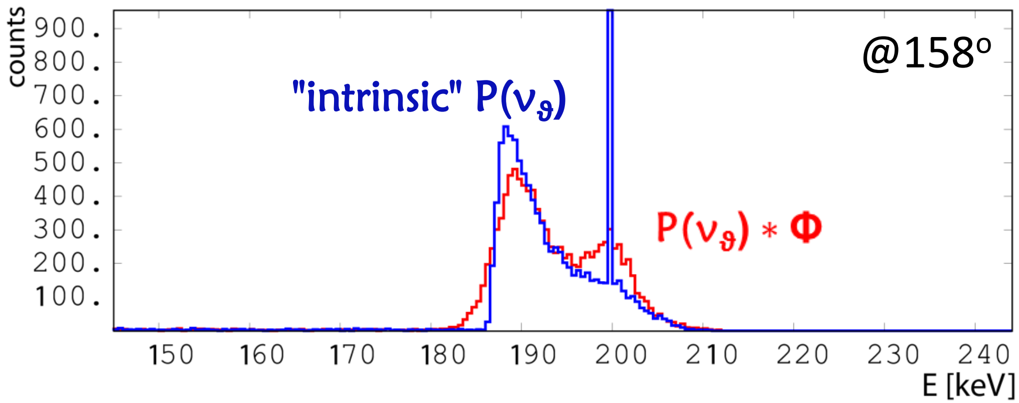

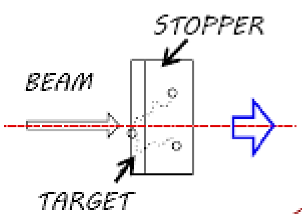

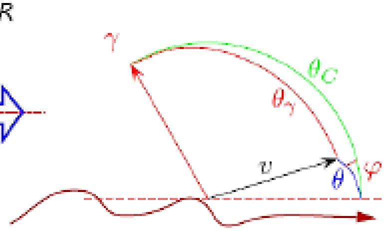

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Monte Carlo simulations of the stopping process allow for the determination of the lifetime from a *line-shape analysis* *(W.M.Currie, NIM 73 (1969) 173)*

RDDS & DSAM: some remarks

Main systematic errors on the determination of τ:

- multiple (side) feeding → "true" lifetime ≠ effective lifetime
- nuclear de-orientation (plunger) → variation of the intensities for different distances travelled by the emitting ion not related to the lifetime (S.Harissopulos *et al.*, NP A467 (1987) 528 and ref. therein)
- uncertainties on the (nuclear) stopping powers (DSAM→10-15%)
- in "special cases" a lineshape analysis is advantageous also for RDDS data (P.Petkov *et al.*, NIM A431 (1999) 208)

Analysis of coincidence data: RDDS → A.Dewald *et al.*, Z.Phys. A344 (1989) 163
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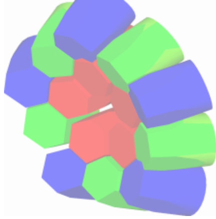
RDDS & DSAM: some remarks



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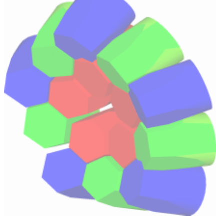
↓

This is not the case when the statistics is sufficient only for singles gamma spectra analysis!!!

Monte Carlo simulations are needed both to plan and analyse this kind of experiments



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Monte Carlo codes mainly used up to now (for lineshape analysis):

DECHIST (J.C.Bacelar) + STOPO (W.T.Milner)
DESASTOP (G.Winter, NIM 214 (1983) 537)

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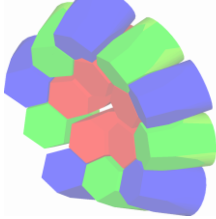
N_{hist} histories are generated starting from a random *seed* → each of them follows the ion from the production point and the vector velocity is stored at each user-defined *step* (slow.down matrix)



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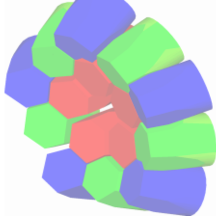
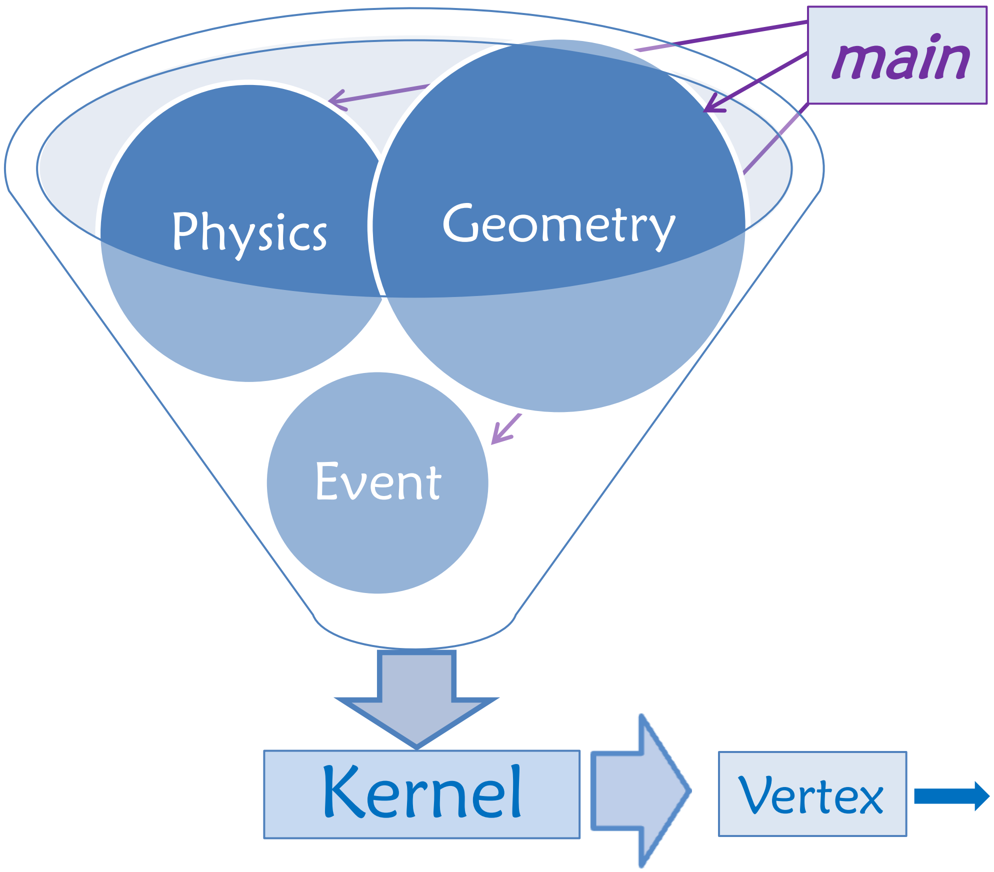
With the GEANT4 simulation package we aim to compact in a single program the simulation of the slowing down/reaction/γ-detection processes

Reminder of some Geant 4 basics





The user must provide the specific geometry of the setup, the kind of events to be processed and the processes that the involved particles undergo

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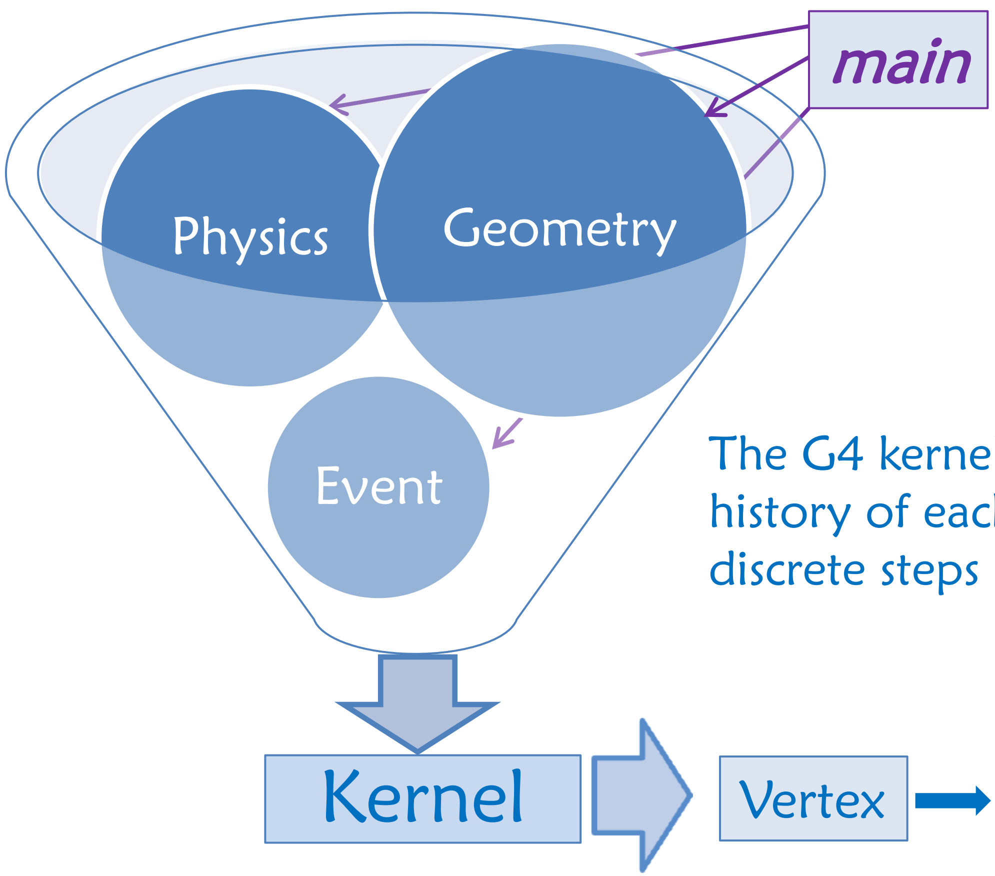

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The G4 kernel produce the history of each particle in discrete steps

The steps contain all the relevant informations, that are available for the user

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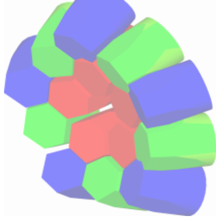

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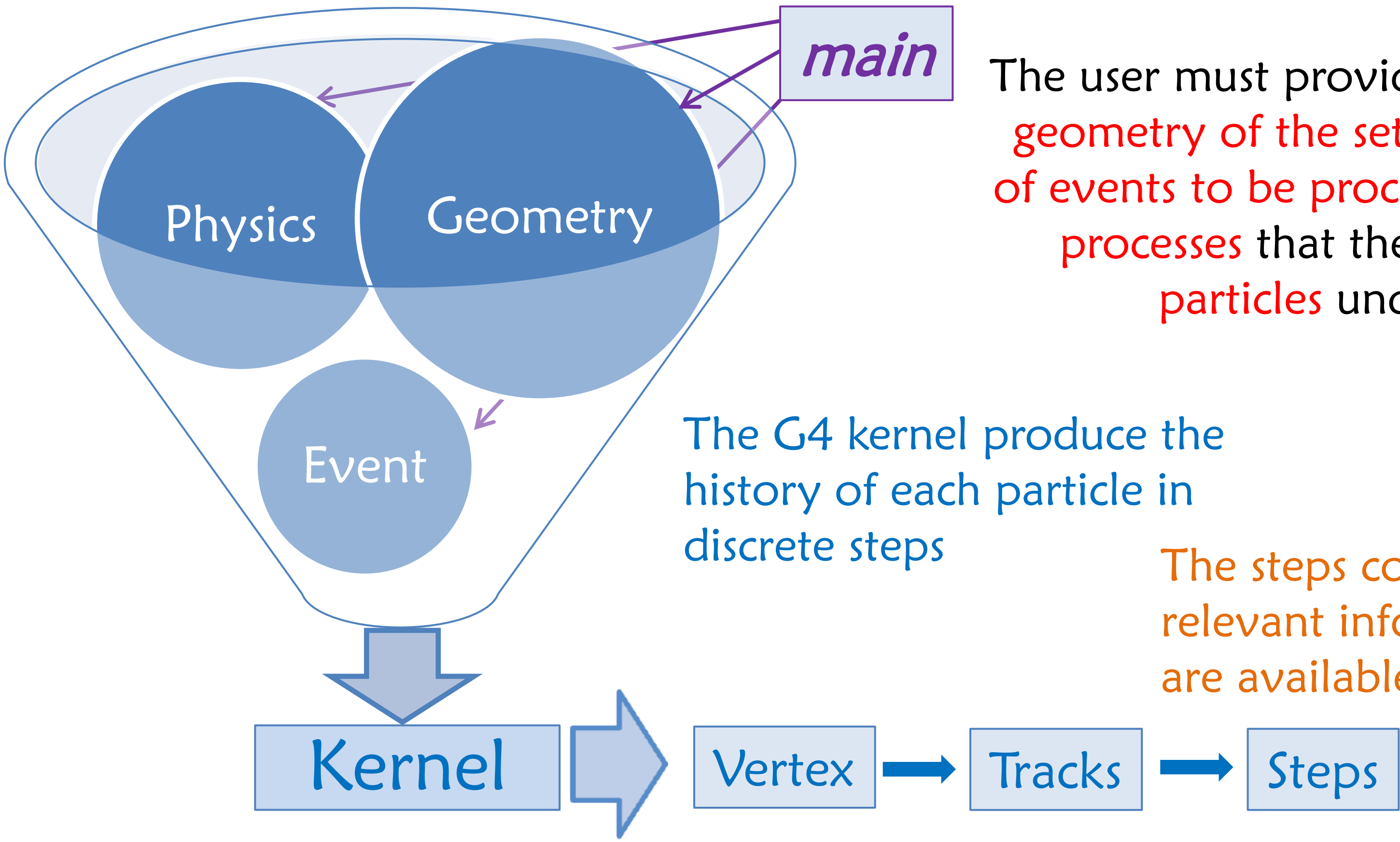

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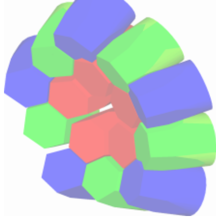
G4 was born as a HEP tool : careful check of the treatment of Nuclear physics problems is needed (and modification of the libraries…)!

The AGATA simulation code… …as ~ one year ago



The design and tracking capabilities of the Demonstrator were planned with a detailed G4 simulation code:

E. Farnea *et al.*, NIM A 621 (2010) 331

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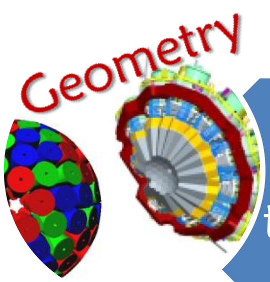
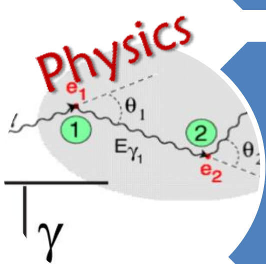
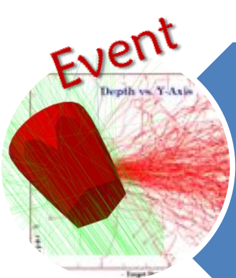


detector construction (shape of the crystals, geometry of the array, materials); ancillary devices



interaction of gammas and particles with matter



point or extended, at rest or moving source; no treatment of the interactions with target

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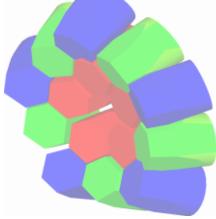

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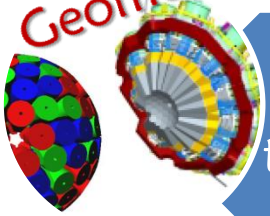
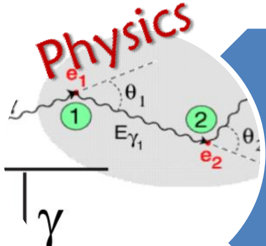
Geometry



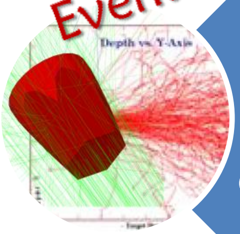
detector construction (shape of the crystals, geometry of the array, materials); ancillary devices

Physics



interaction of gammas and particles with matter

Event



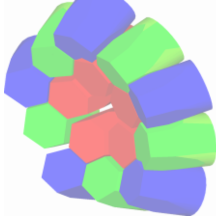
point or extended, at rest or moving source; no treatment of the interactions with target

Other classes:
Analysis
Management of I/O
….

The AGATA simulation code… …present status

The code has been extended to accurately simulate Doppler shift lifetime experiments

‘source of inspiration’=P. Adrich *et al.*, NIM A598 (2009) 454 (differential plunger experiments @ MSU, courtesy of A. Dewald, W. Rother)



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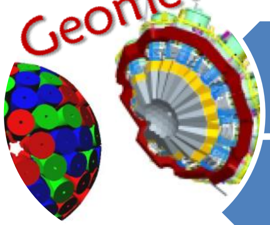
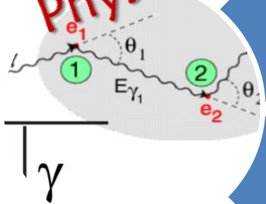
Geometry



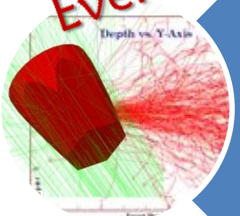
+ plunger/differential plunger

Physics



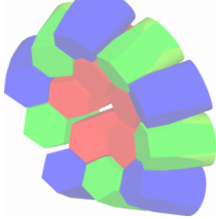
+ handling of gamma cascades with finite lifetimes and complex level schemes

Event



+ distribution in the target, reaction mechanisms

The AGATA simulation code…
…present status



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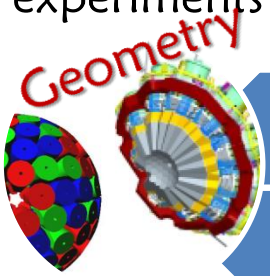

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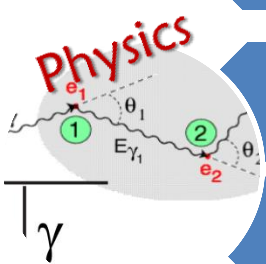

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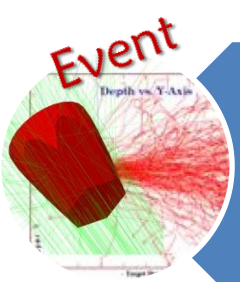


+ distribution in the target, reaction mechanisms

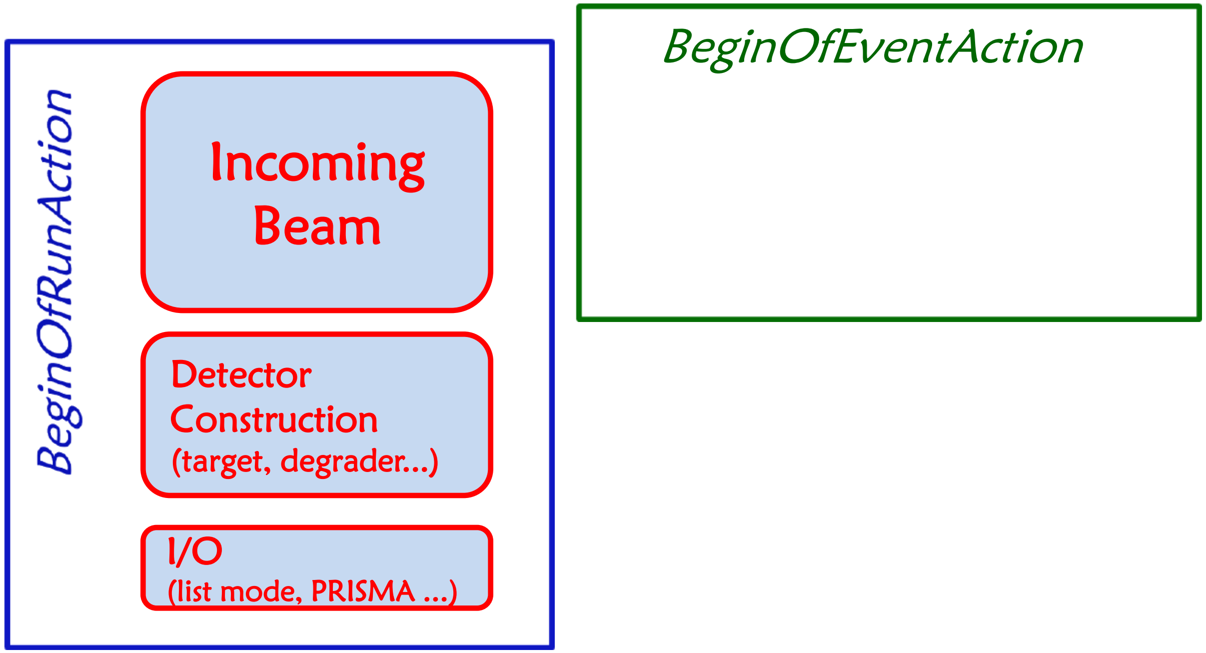
modified Stepping Action to extract info. on the residual nucleus
and
user-defined classes that handle the processes the nucleus of interest ("OutgoingBeam") undergoes

The structure of the code

BeginOfRunAction

BeginOfEventAction

The structure of the code



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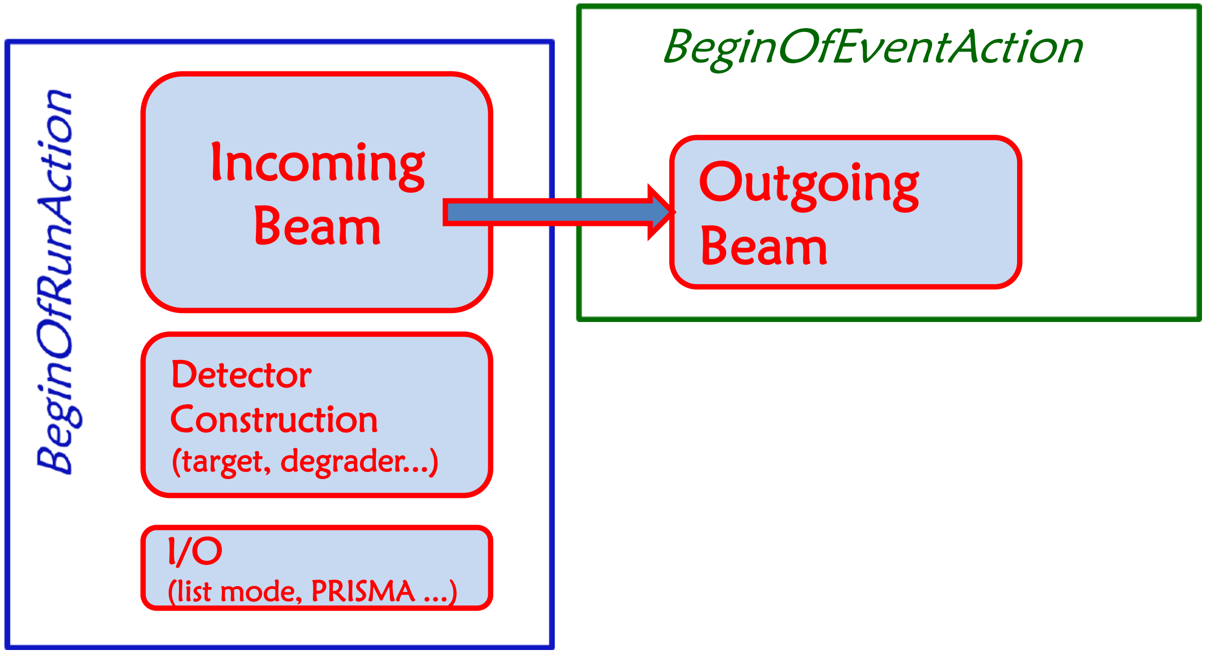

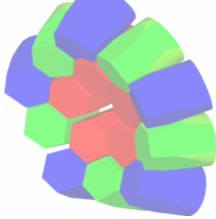

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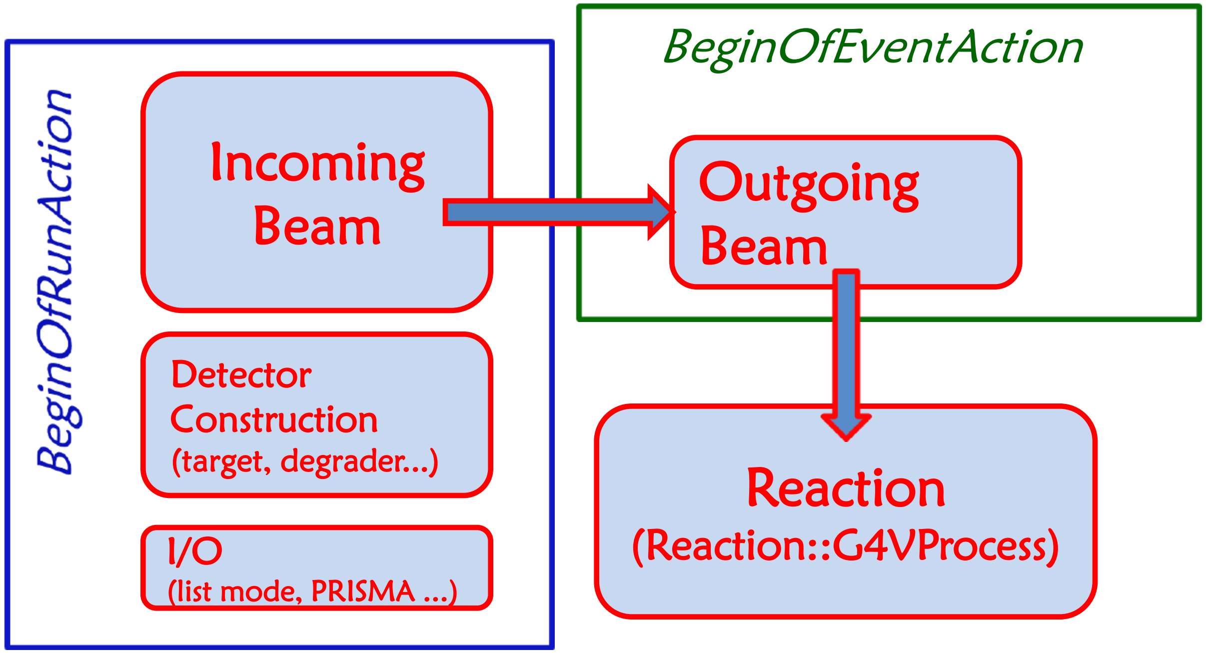

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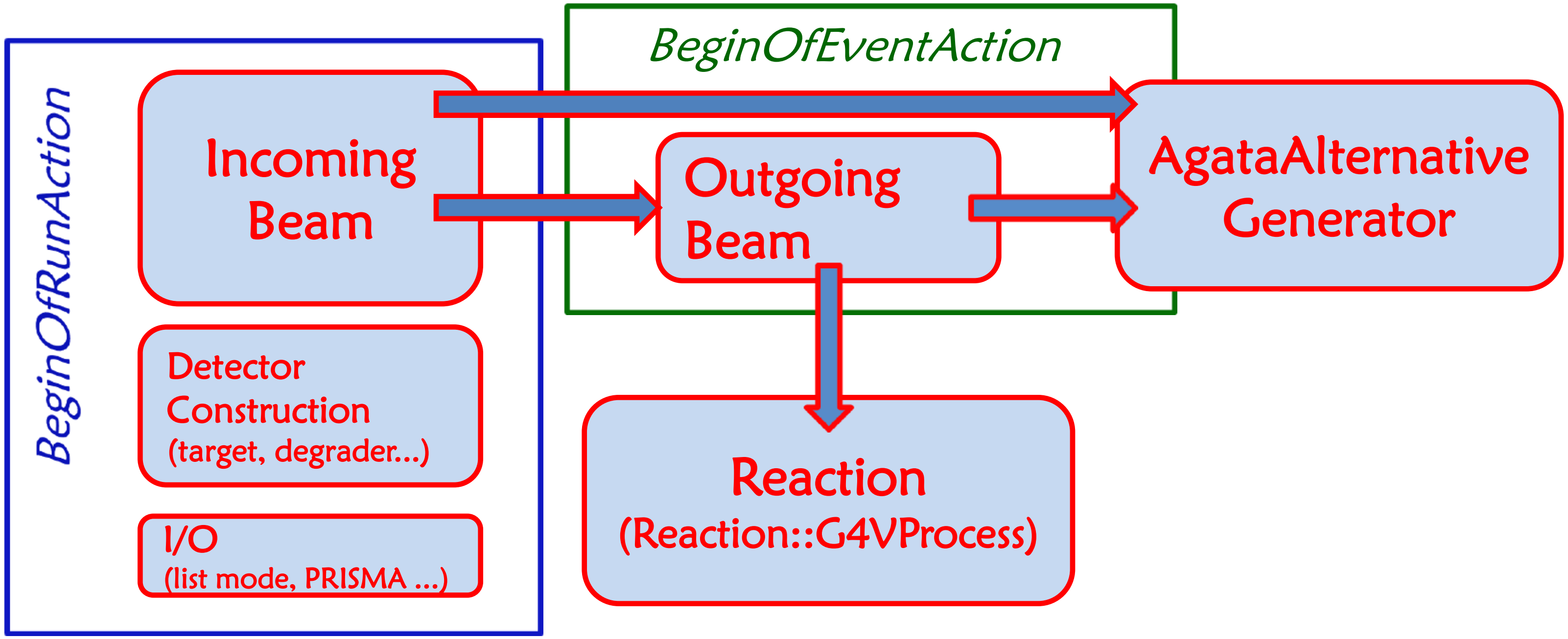

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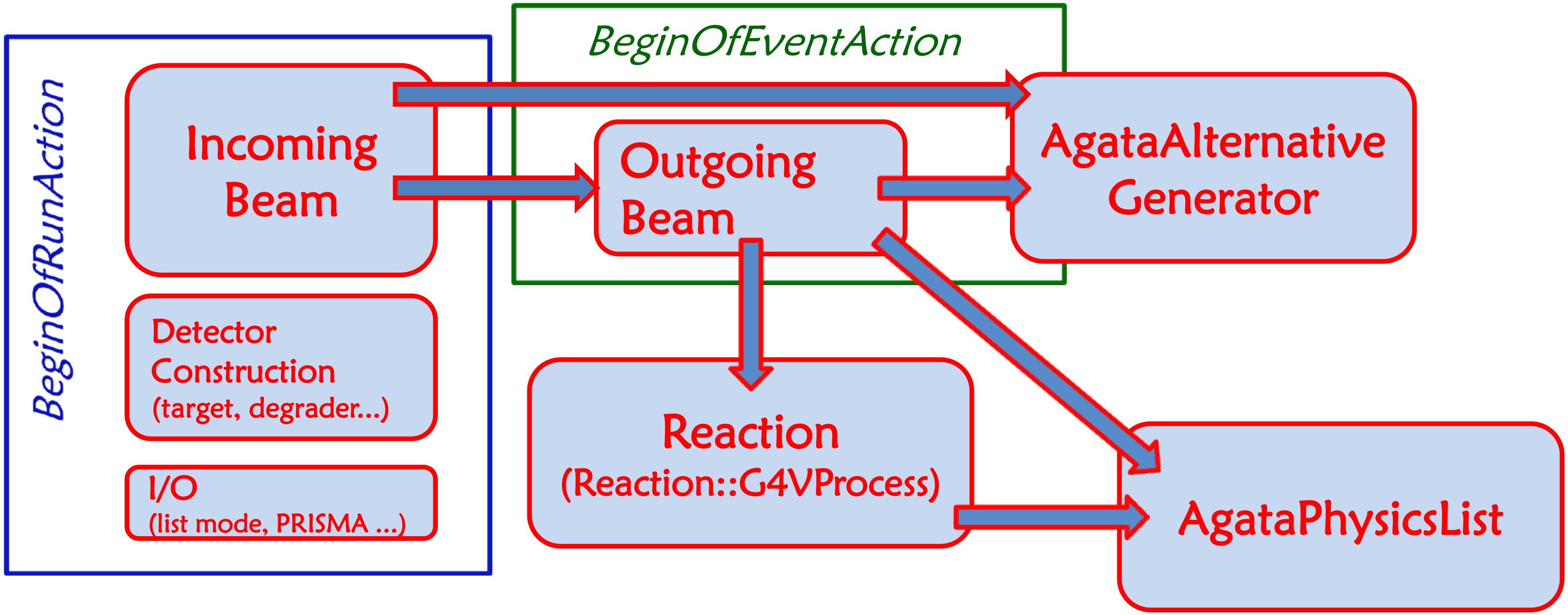

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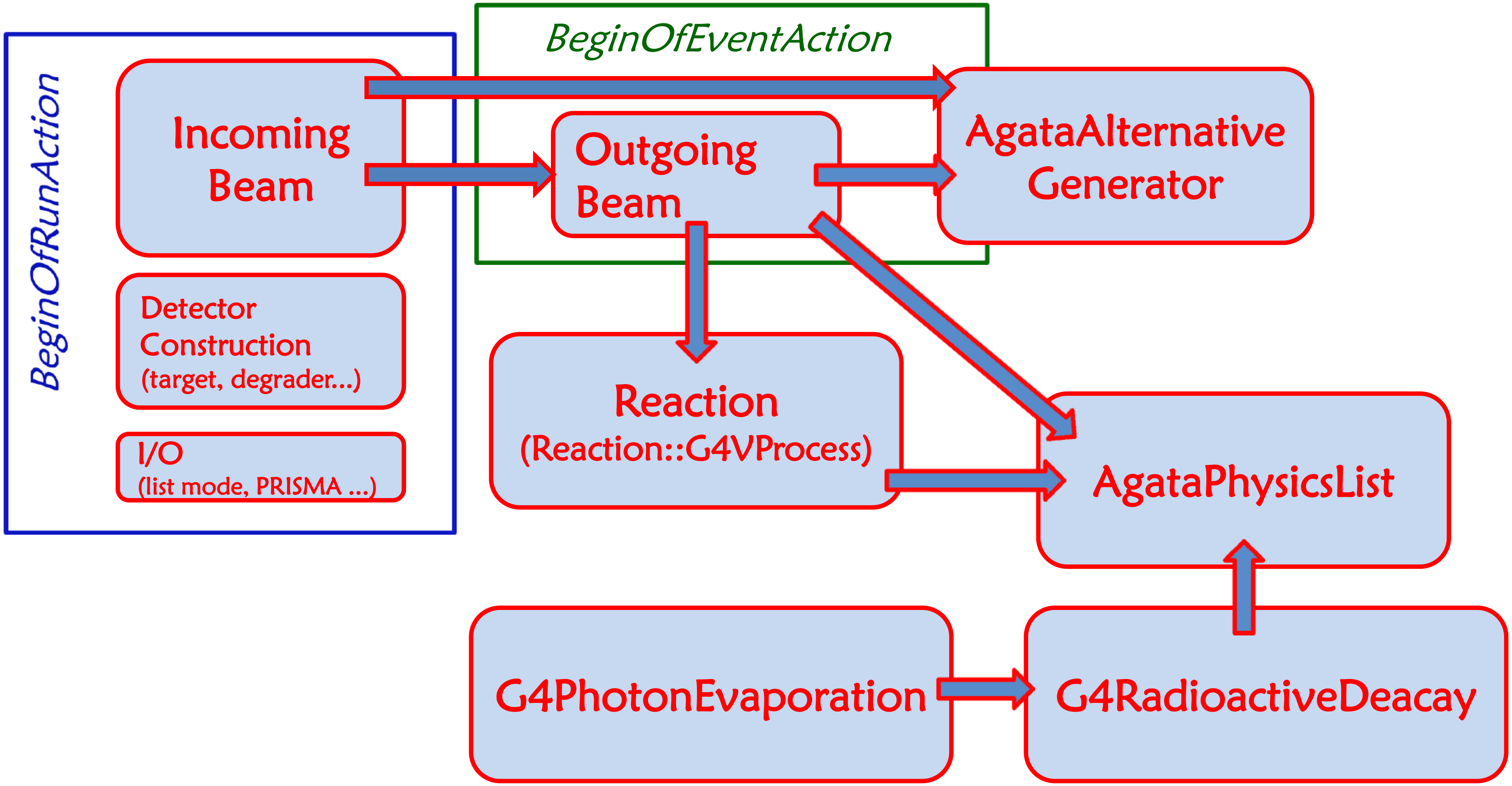

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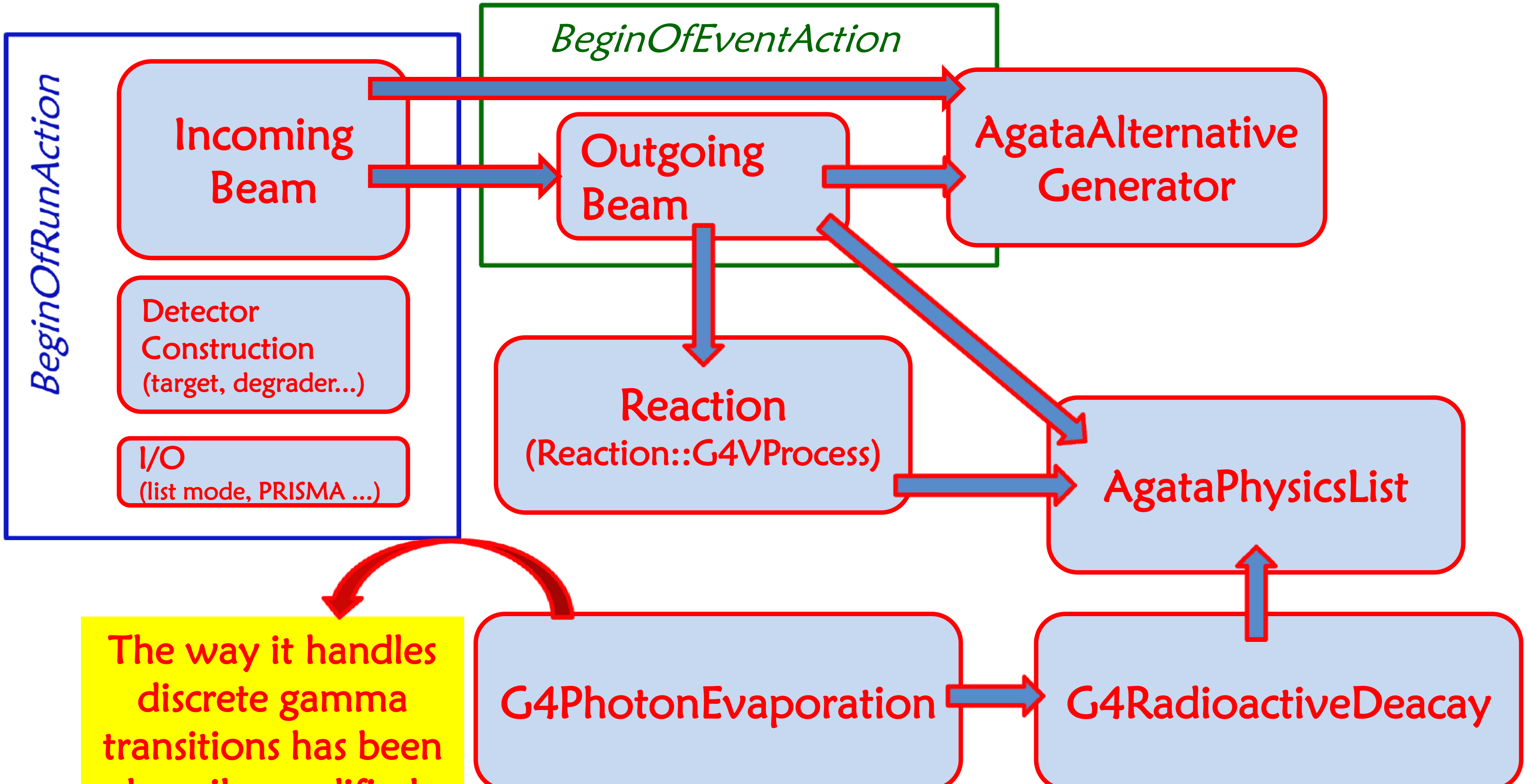
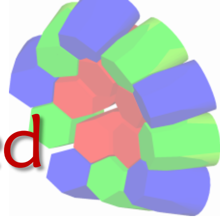


The way it handles discrete gamma transitions has been heavily modified

Different reaction processes can be considered
OutgoingBeam::GetOutgoingMomentum

(At least for the moment) only one kind of nucleus in the exit channel is considered. At each of the following reaction processes a finite probability is associated:

- ✓ fusion-evaporation (the spectrum of the energy of the evaporated particle(s) must be provided)
- ✓ (multi)nucleon transfer (differential cross-section as a function of ϑ_{LAB} and E_{LAB} must be provided)
- ❖ Coulex
- ❖ transfer-fission



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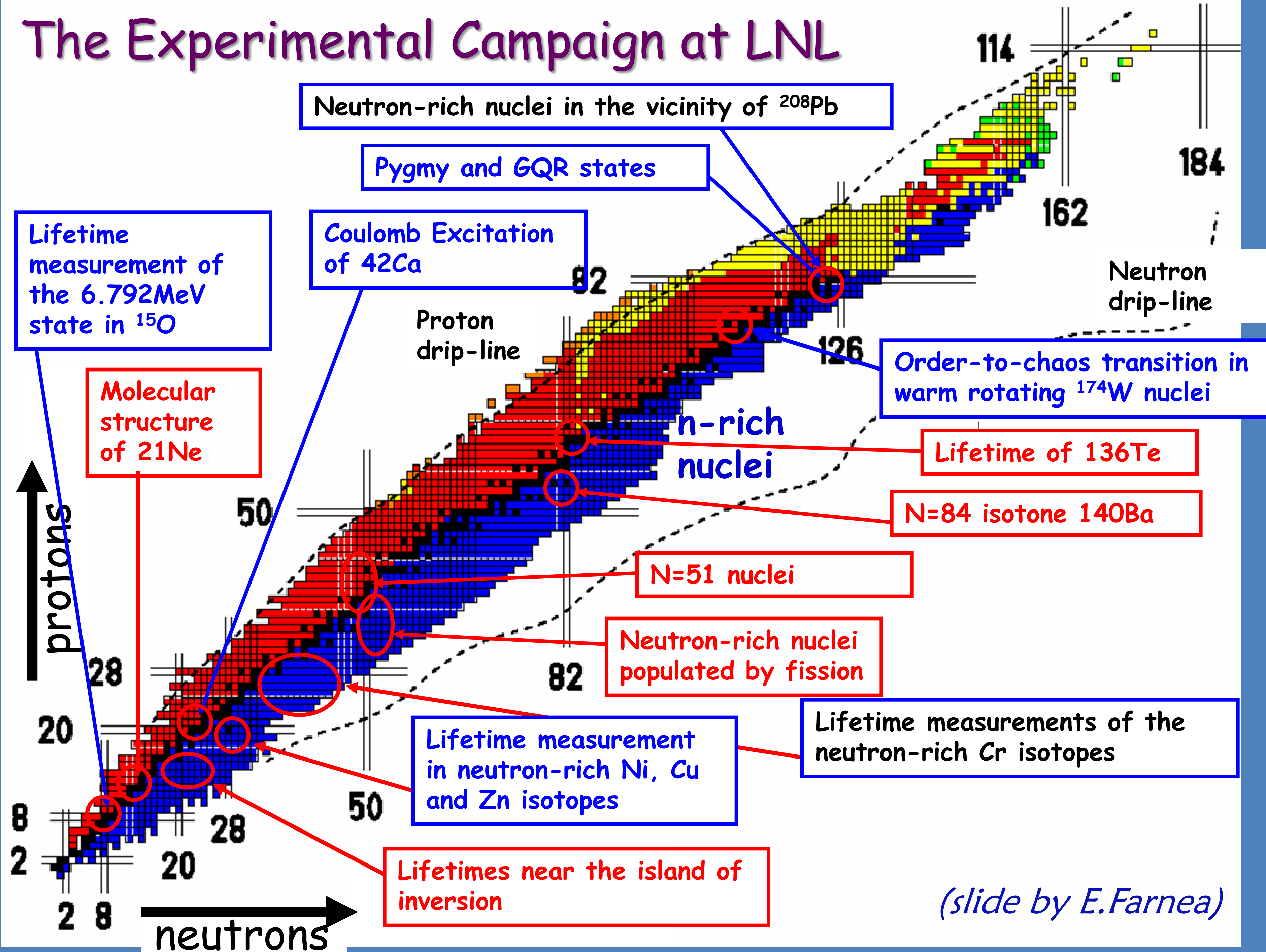
The Experimental Campaign at LNL

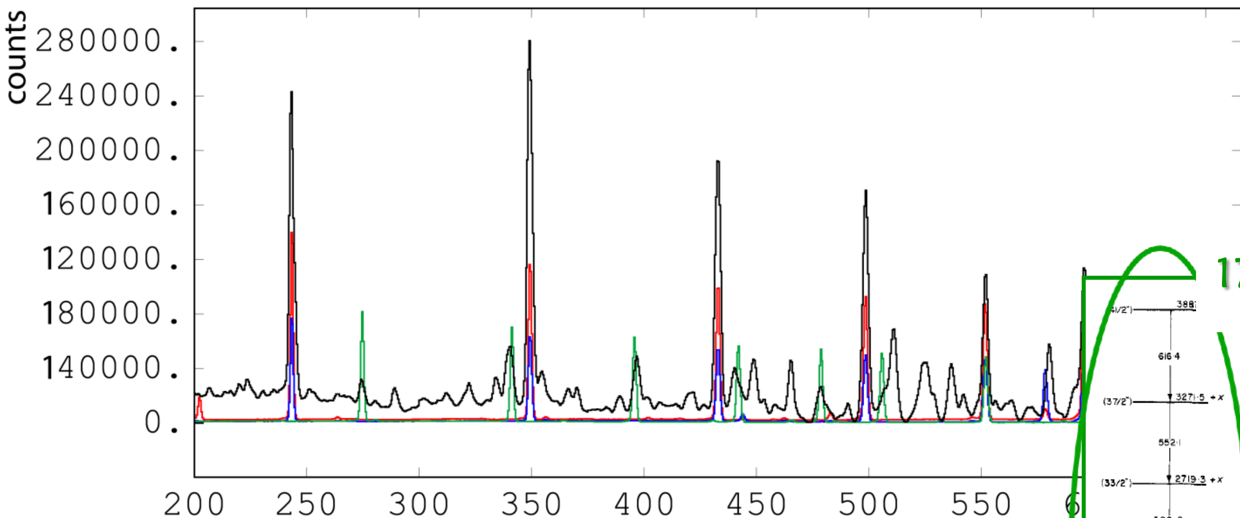


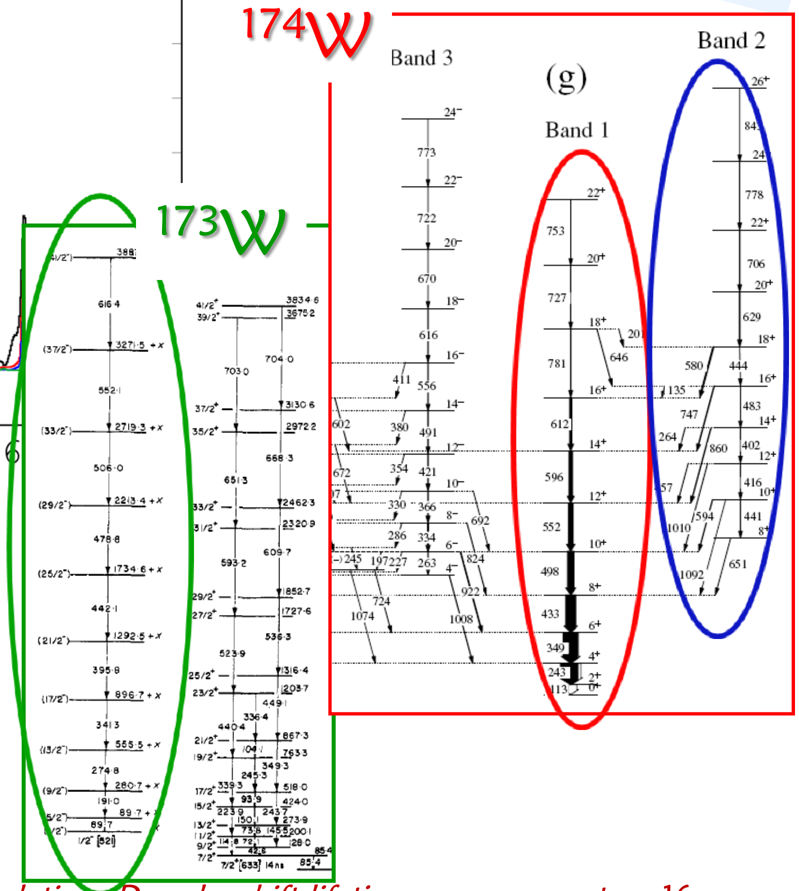
Handling of complex level schemes:
an example of fusion-evaporation spectrum

see talk by V. Vandone

experiment performed in week 28 2010

$^{128}Te(^{50}Ti, 4n)^{174}W$ & $^{128}Te(^{50}Ti, 5n)^{173}W$ @ 217 MeV





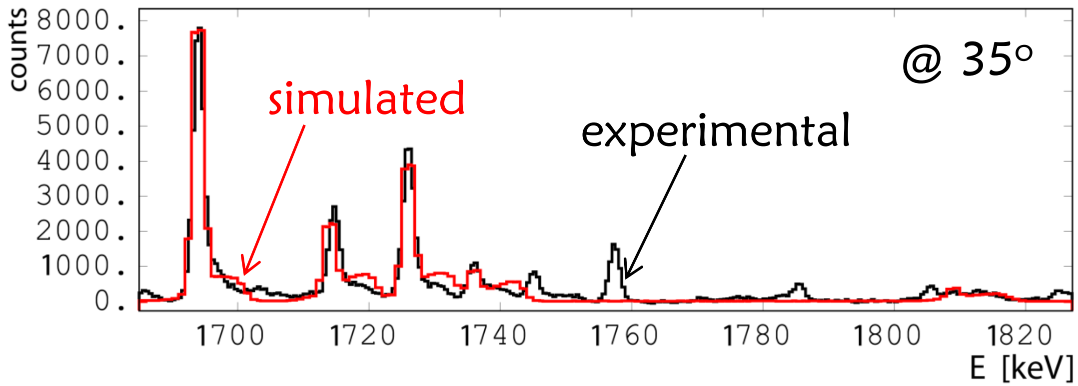
The handling of decay branching ratios (G4PhotonEvaporation) has been debugged

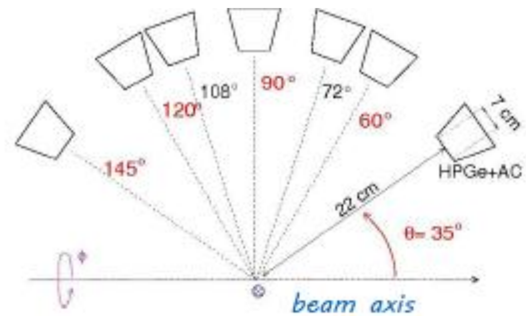
User-defined reaction entry-point still in progress…

Fusion evaporation + DSAM lifetimes: a GASP experiment

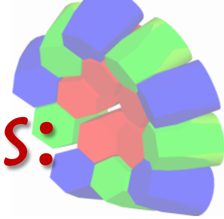
$^{108}Cd(^{16}O, 2n)^{122}Ba$ @ 64 MeV (thick-target)

lifetimes determined with DSAM technique (C.Michelagnoli *et al.*, to be published)





(C. Michelagnoli, Diploma Thesis, Univ. of Florence, Italy, April 2009)



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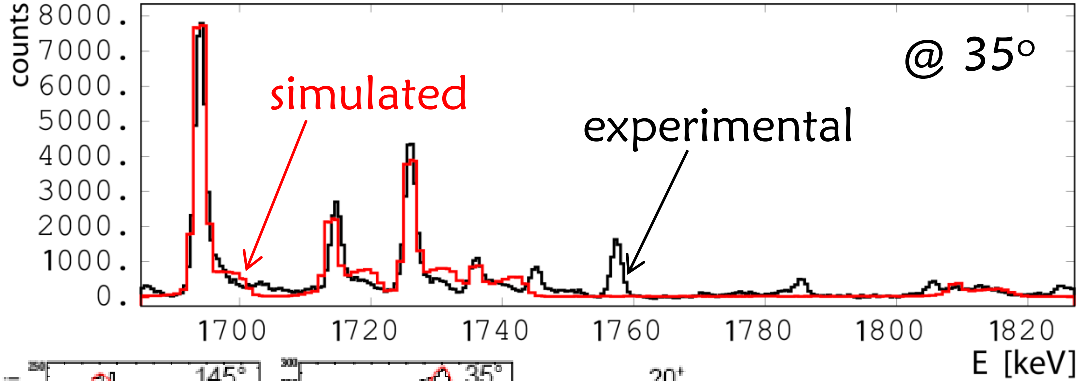

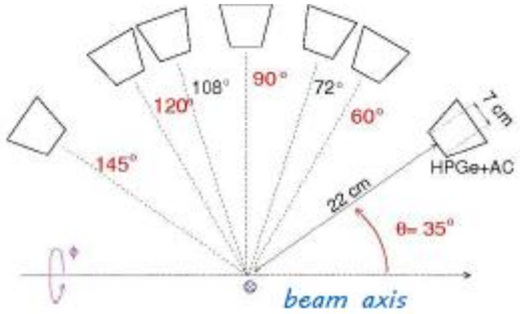

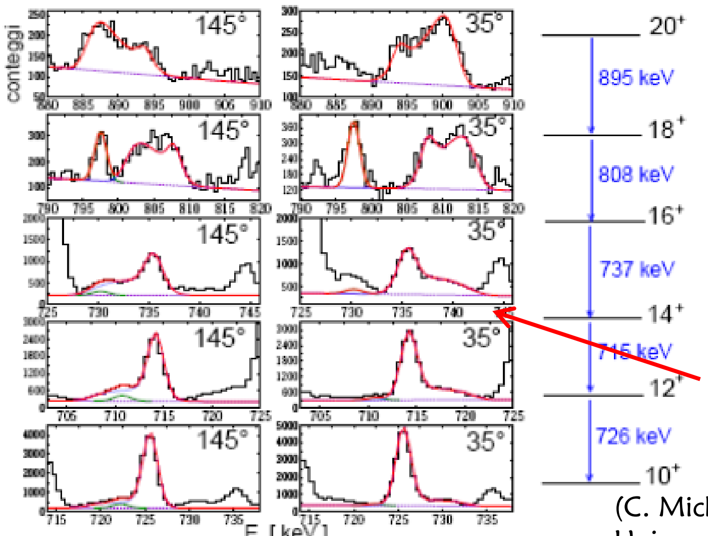

The discrepancies observed are likely to be due to the finite lifetimes of the side-feeding components at the moment not implemented!

This is our target ☺ !

(C. Michelagnoli, Diploma Thesis, Univ. of Florence, Italy, April 2009)

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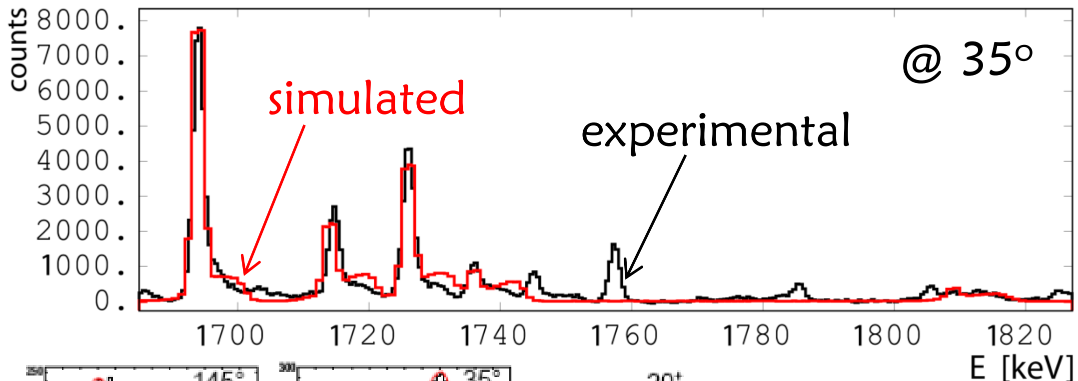

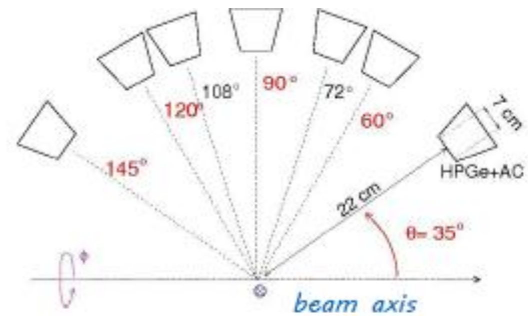

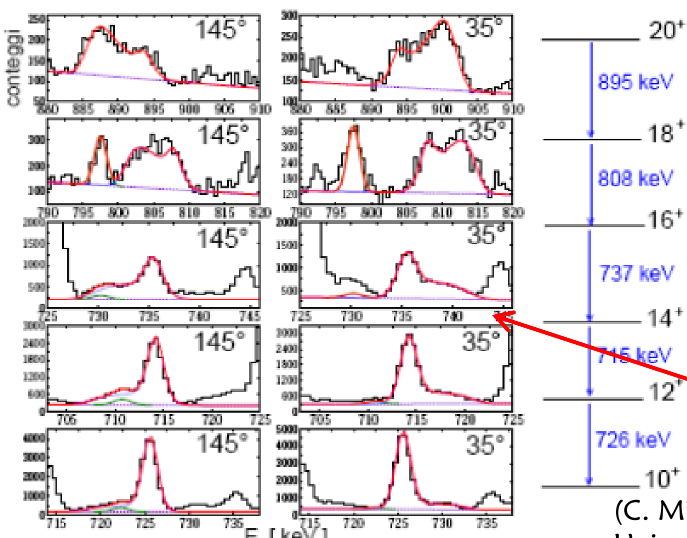

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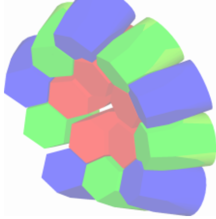
(C. Michelagnoli, Diploma Th
Univ. of Florence, Italy, April 2009)

Remark: the code (modified pieces of library) is versatile (different geometries can be implemented)



DSAM with the AD:

the special case of week 29 2010

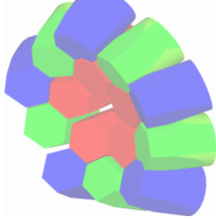
see talk by C.Michelagnoli

^{14}N @ 32 MeV + ^{2}H (^{197}Au)

4 ATC

beam axis

dominant exit channels: ^{15}O and ^{15}N



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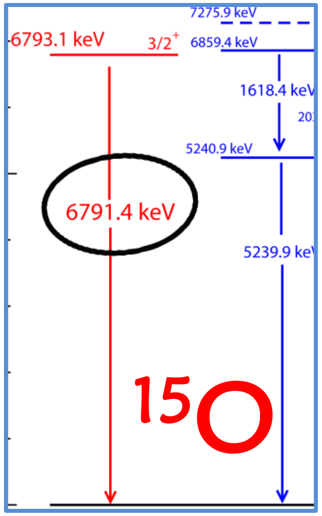
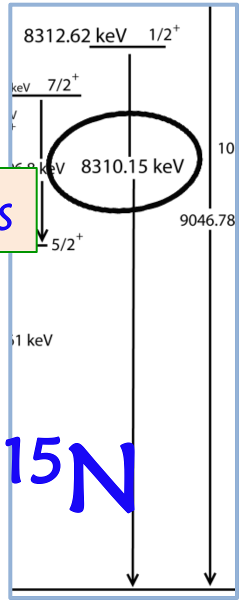


$\tau \sim$ fs (???)

excited nuclear states populated either by fusion-evaporation and nucleon-transfer

τ = 0.45 fs



DSAM with the AD:

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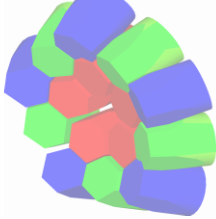

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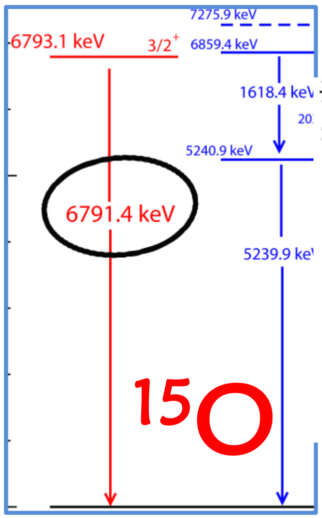
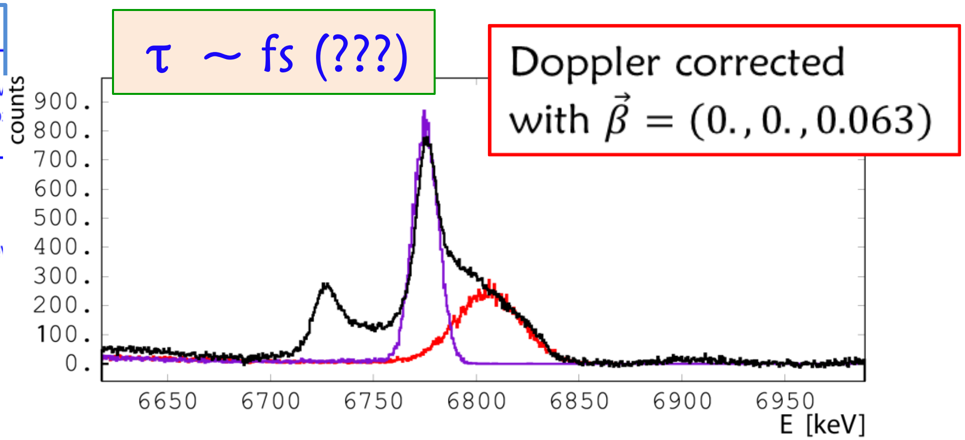
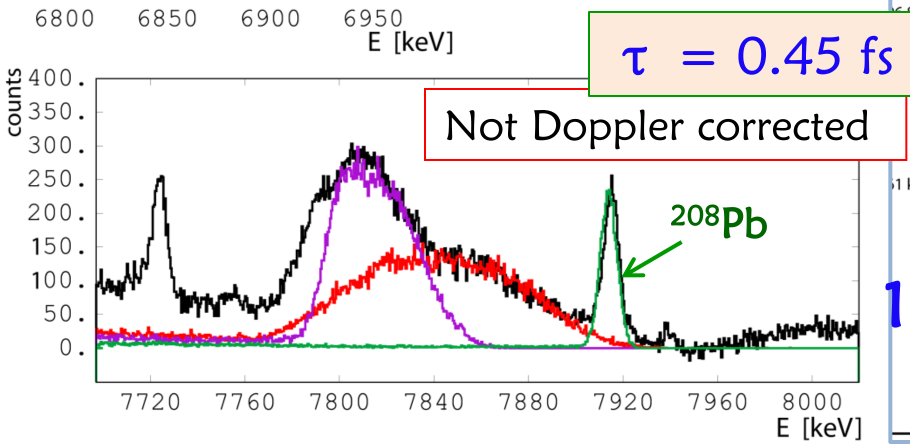
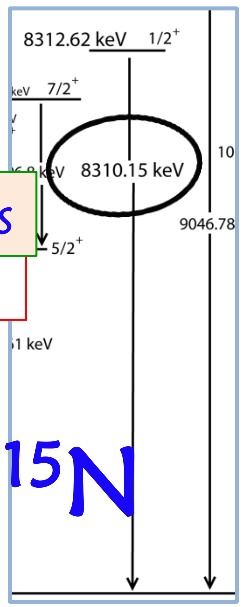






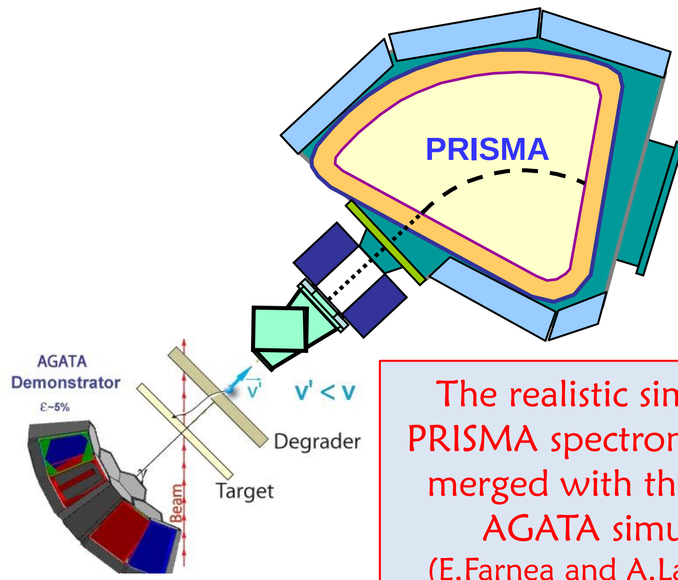


→experimental spectrum

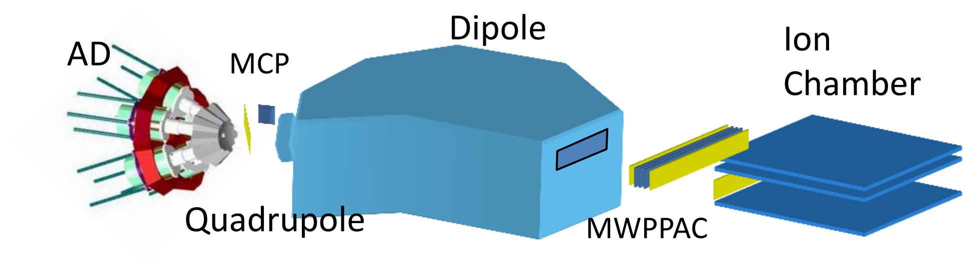
→simulated fusion-evap.

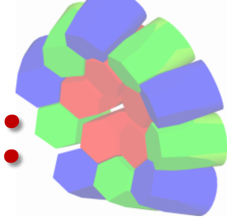
→simulated nucleon-transfer

Differential plunger experiments:
AGATA demonstrator + PRISMA



The realistic simulation of the PRISMA spectrometer response is merged with the output of the AGATA simulation code
(E.Farnea and A.Latina, LNL Annual Report 2007(2006) p.199)

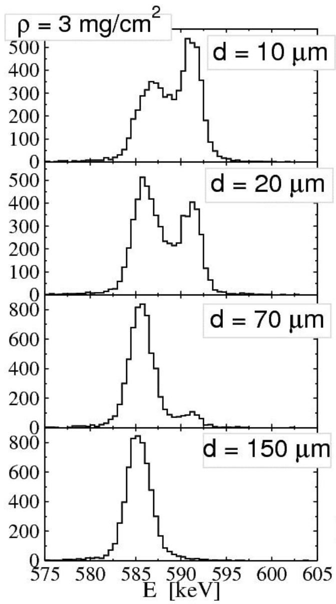


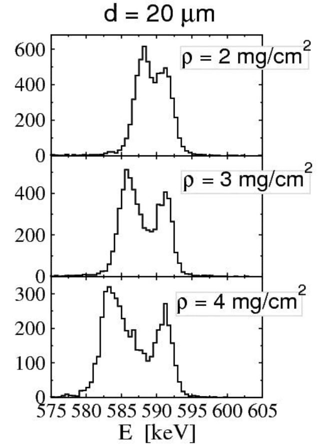


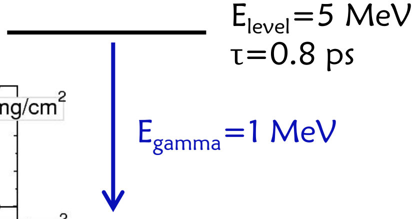
Differential plunger experiments:
AGATA demonstrator + PRISMA

E. Farnea *et al.*, LNL Annual Report 2010(2009) p.57

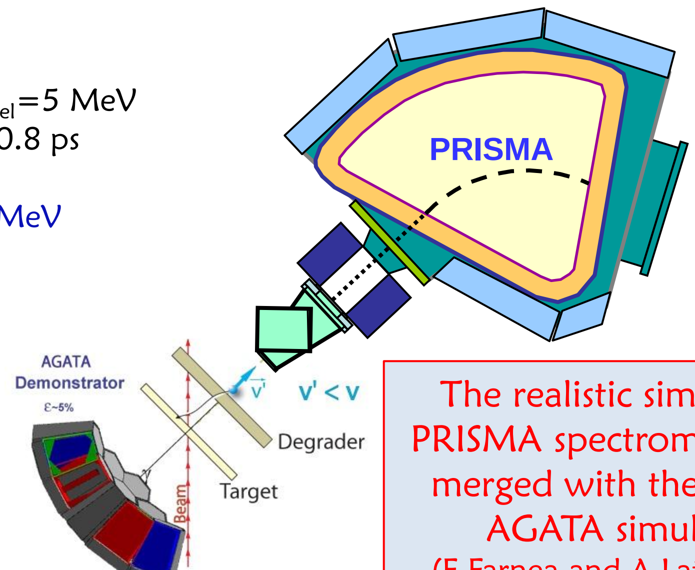
$^{36}S+^{208}Pb$ @ 215 MeV → ^{34}Si







[d = target-to-degrader distance]
[ρ = degrader thickness]



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calculation of the differential cross section for the
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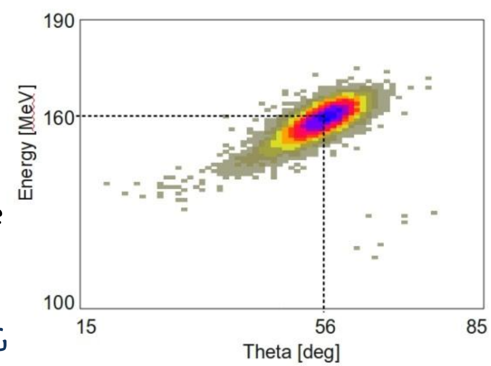
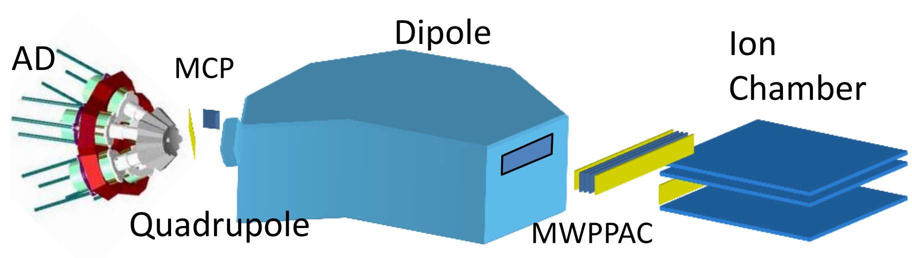
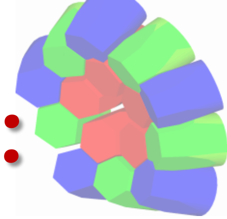
(A.Winter, program GRAZING,
http:/www.to.infn.it/nanni/grazing







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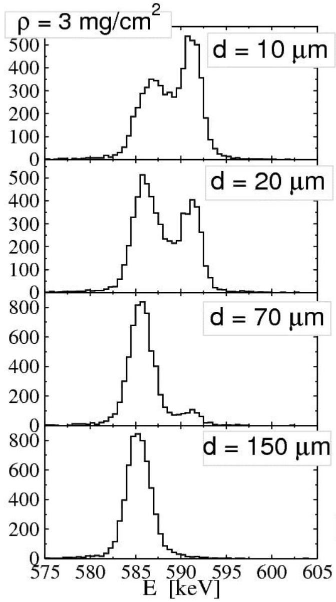

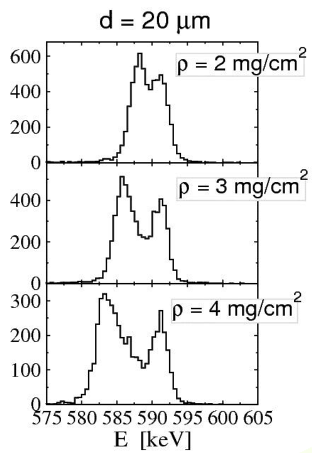

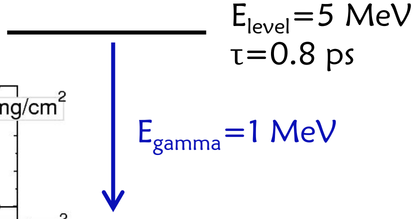

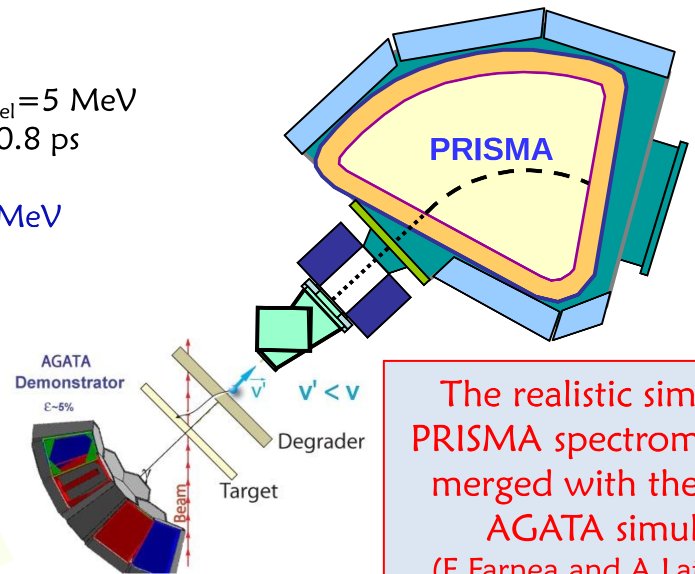

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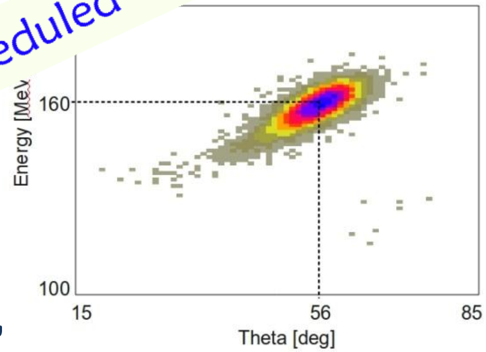
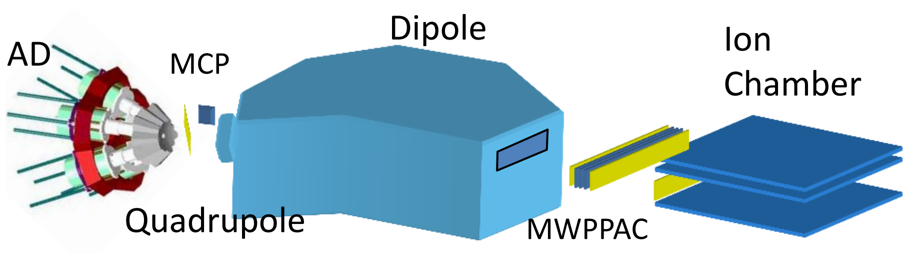
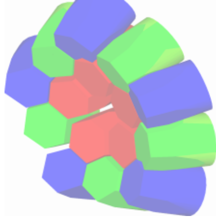
scheduled experiment ☺

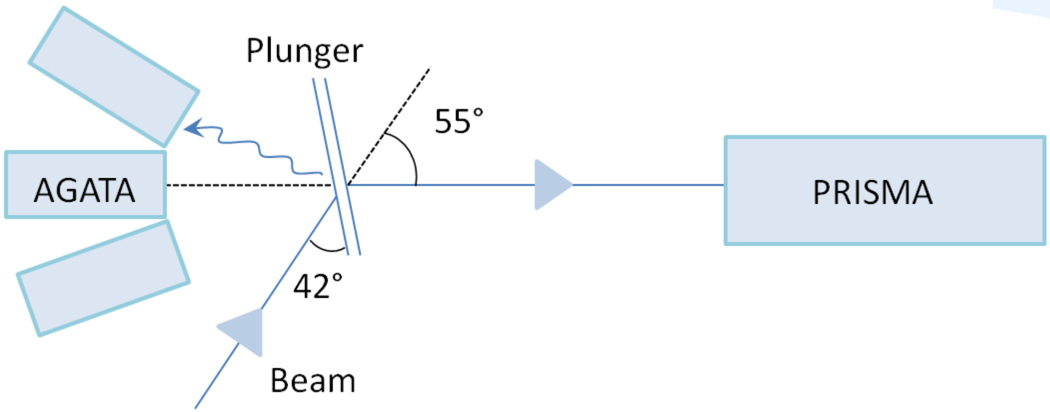




Köln differ. plunger+AD+PRISMA experiment performed in week 23 2010 (1)



see talk by C. Louchart

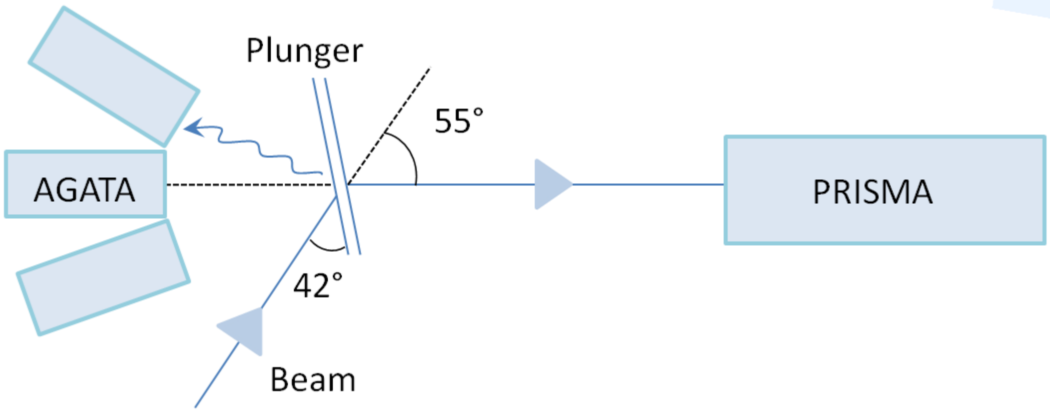


(courtesy of C.Louchart)

$^{76}Ge + ^{238}U$ @ 577 MeV
Nb degrader

Köln differ. plunger+AD+PRISMA experiment performed in week 23 2010 (1)

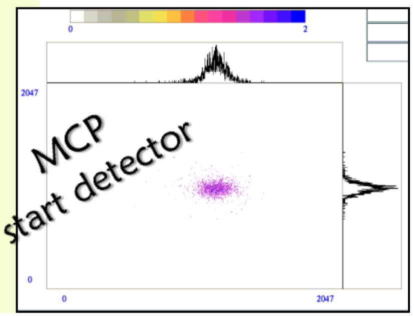
see talk by C. Louchart

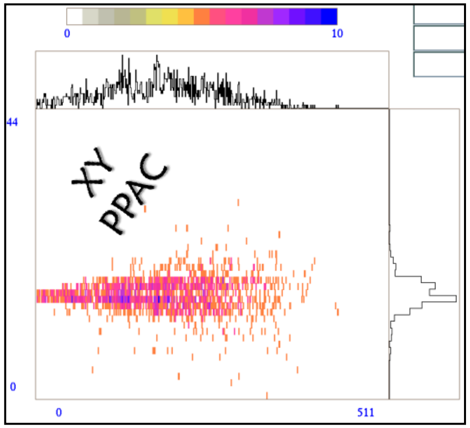


(courtesy of C.Louchart)

^{76}Ge + ^{238}U @ 577 MeV
Nb degrader

simulated PRISMA data:



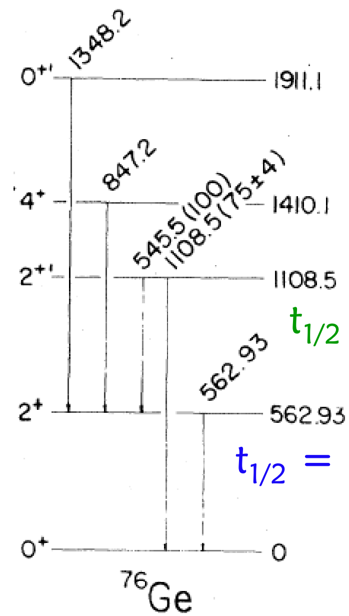


simulation of the ^{76}Ge channel

simplification : ^{76}Ge proj-like emitted at a fixed direction (grazing angle, 55°) monochromatic (417 MeV)

Köln differ. plunger+AD+PRISMA experiment performed in week 23 2010 (2)

see talk by C. Louchart



$t_{1/2}$ = 8 ps

$t_{1/2}$ = 18.2 ps

feeding:

~30%

~70%

Köln differ. plunger+AD+PRISMA experiment performed in week 23 2010 (2)

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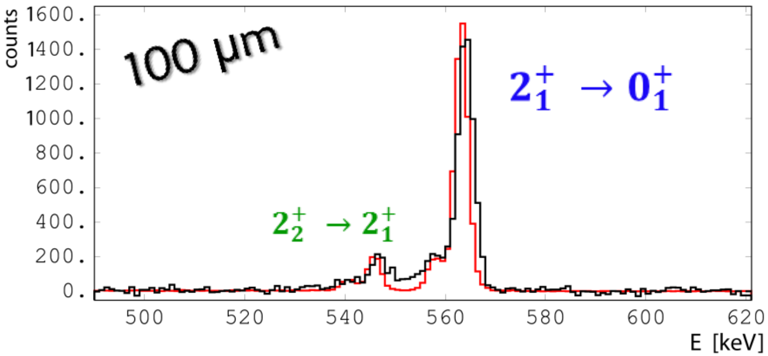

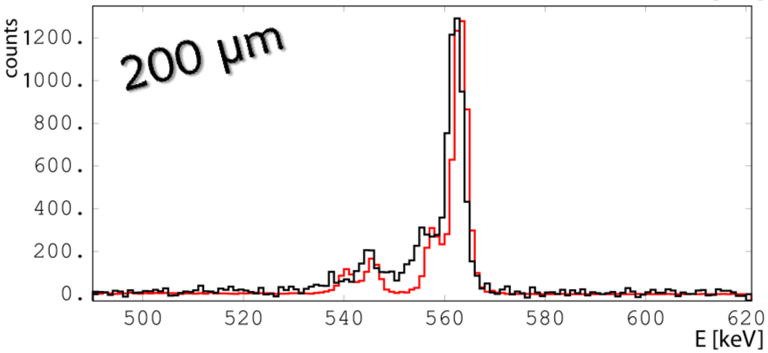

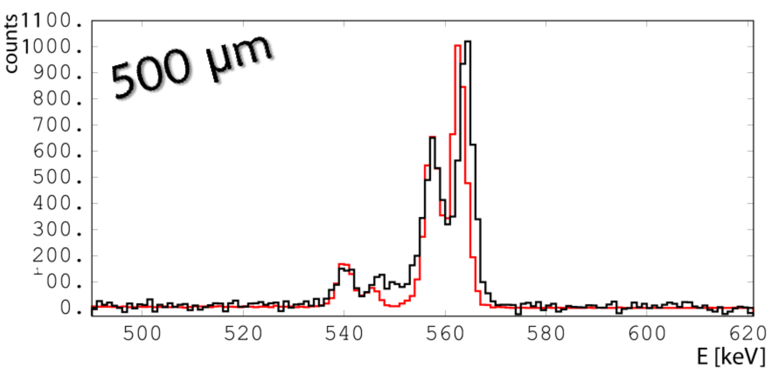

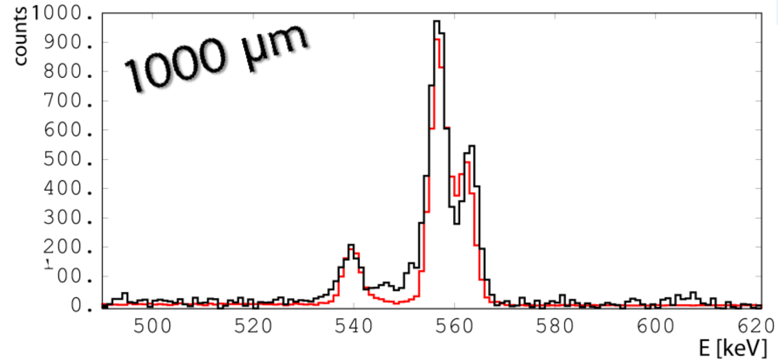

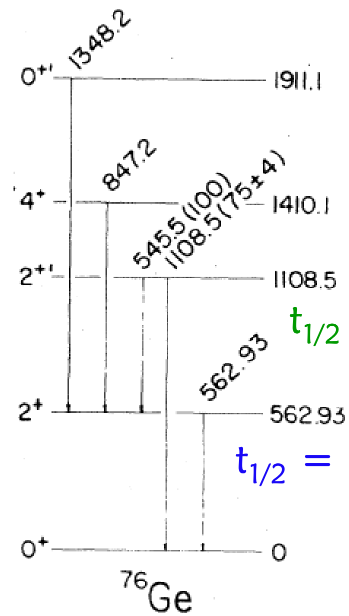

simulated

experim.

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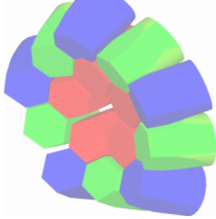
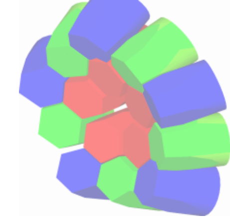


to-do list 

1. implementation of a "user-defined" entry-point of the reaction (fusion-evaporation) and side-feeding components (intensity, τ)
2. test of the G4 treatment of the stopping powers
3. if one wants to use the code as an analysis tool or "on-line check": independent generation of random seeds on different machines to reduce the computing time (*HEP Random* utility)
4. improvement of "user-friendship" (even a manual?!)

suggestions are welcome !!!



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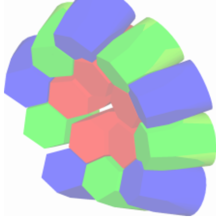

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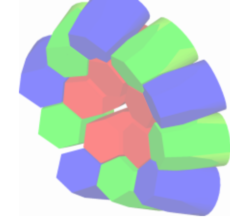

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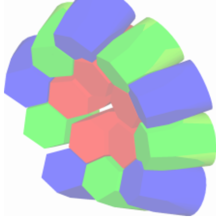

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Concluding remarks

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- In this scope, the needed G4 libraries have been extensively modified (and debugged) for complex level schemes to be handled with the proper intermediate lifetimes → classes and libraries can be easily integrated with different detection geometries!!!
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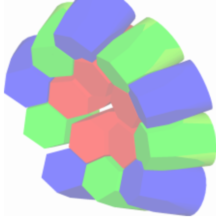

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Contacts

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(simulations "team leader")

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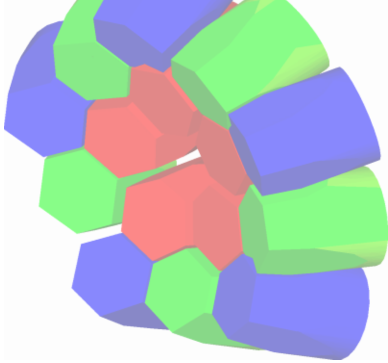
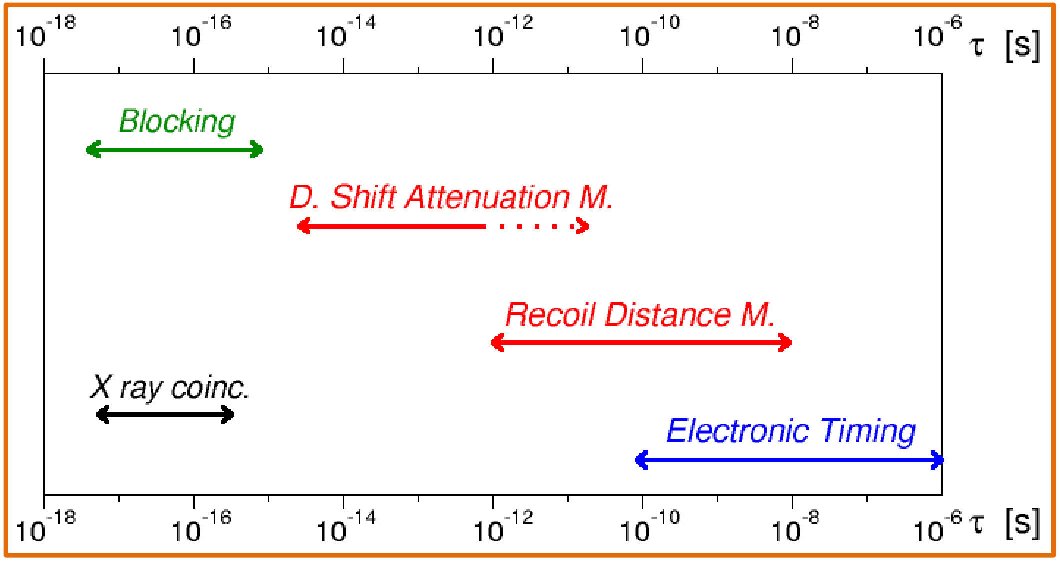
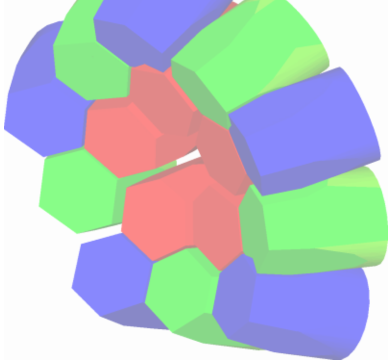
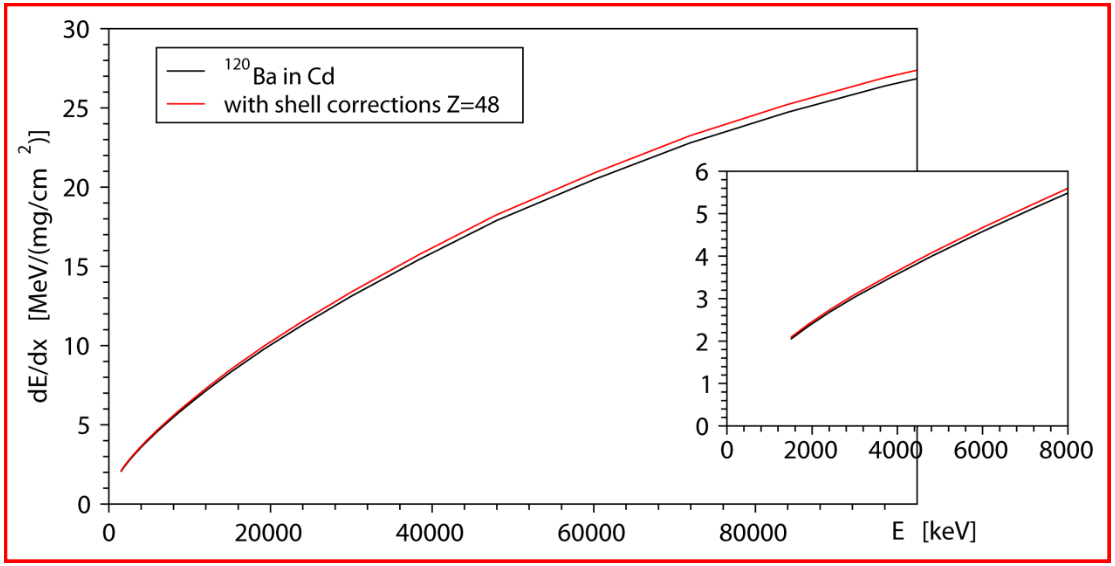


extra



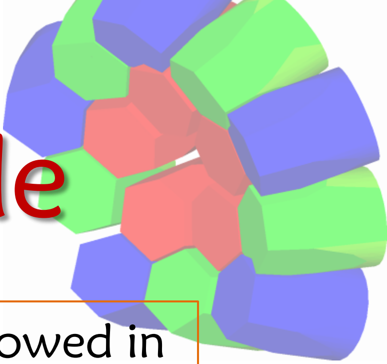
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} τ [s]
Blocking
D. Shift Attenuation M.
Recoil Distance M.
X ray coinc.
Electronic Timing





^{120}Ba in Cd
with shell corrections Z=48
dE/dx [MeV/(mg/cm^2)]
E [keV]
0
20000
40000
60000
80000
0
5
10
15
20
25
30
0
2000
4000
6000
8000
0
1
2
3
4
5
6

The structure of the code



Incoming Beam
("*SET*" methods)

(parameters given by the user)
- ❑ Z
- ❑ A
- ❑ kinetic energy
- ❑ beam charachteristics
- ❑ …

→ The projectile is followed in its slowing down in the target material until the reaction point is reached

Outgoing Beam

- ❑ default-Incoming-Ion
- ❑ scan-Initial-Conditions
- ❑ Z_{target} and A_{target}
- ❑ $\Delta Z = Z_{final}$-Z and ΔA
  (‘final’=nucleus of interest in the exit channel)
- ❑ set-Decay-Properties
- ❑ Reaction-Position
- ❑ Reaction-Product → (G4DynamicParticle*)
- ❑ Get-Outgoing-Momentum

set-Decay-Properties →

ion = G4ParticleTable::G4ParticleTable → GetIon(Z_{in}+DZ, A_{in}+DA, E_x) (G4ParticleDefinition*)

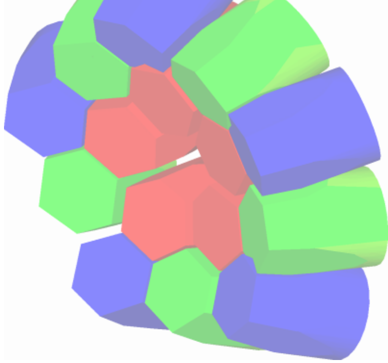
ion→ SetPDGStable(**false**)

DecTab = ion→ GetDecayTable()

Get-Outgoing-Momentum →

(reaction mechanism --kinematics)
- ➢ fusion-evaporation
- ➢ (multi)nucleon-transfer
- ➢ coulex
- ➢ (fusion-fission)

computing time



1 level (1 gamma) $5x10^6$ events

real 30m5.216s

user 30m4.431s

sys 0m0.193s

2 processors machine

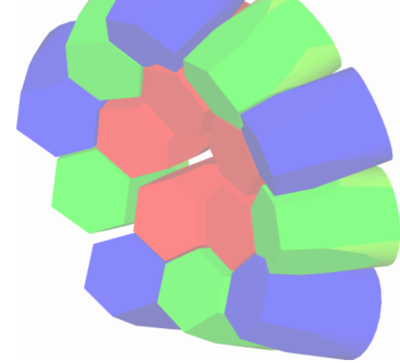
Xenon 5420 quad-core

12MB cache L2 and fast serial bus @ 1333 MHz

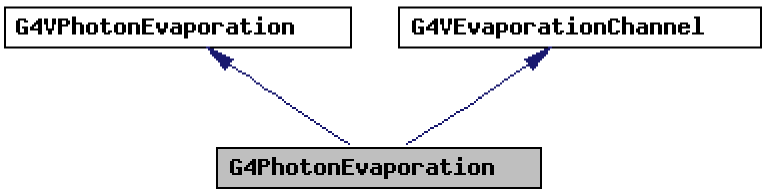
20GB RAM @ 667 MHz

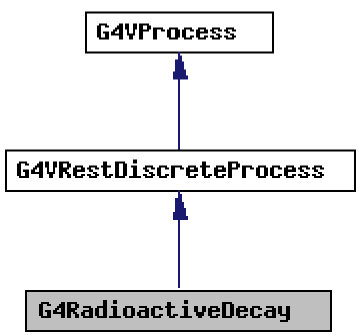
motherboard with system bus @ 1333 MHz

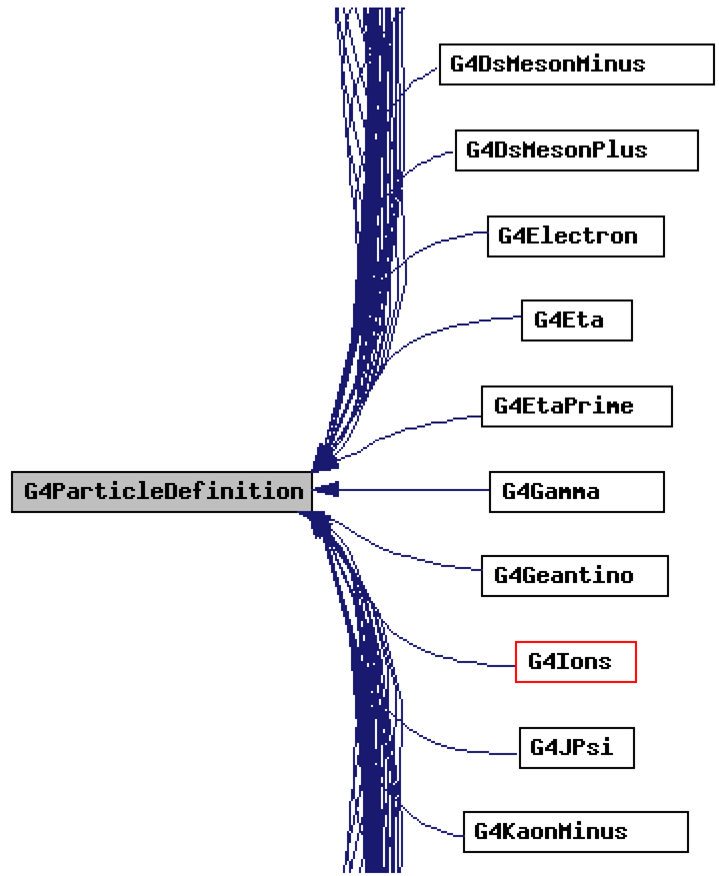
hard disk @ 7200 rpm



some inheritances…







light vs heavy ion (dsam)