GEANT4 TOOLS
FOR THE DESIGN AND ANALYSIS OF PHOTO-FISSION EXPERIMENTS AT ELI-NP

Speaker: Dragos Nichita

ENSAR2 Workshop: GEANT4 in nuclear physics – April 24-26, 2019

Overview

Overview

1. ELI-NP facility

Overview

1. ELI-NP facility

2. Experimental setup optimization using GEANT4

Overview

1. ELI-NP facility

2. Experimental setup optimization using GEANT4

3. GEANT4 tool for determining the detector response function

Overview

1. ELI-NP facility
2. Experimental setup optimization using GEANT4
3. GEANT4 tool for determining the detector response function
4. Conclusions & feedback in using GEANT4

1. Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

User facility for nuclear physics experiments

Developed in Romania (near Bucharest)

Co-financed by the Romanian Government
and the European Union

Operational phase starting 2020

1. Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

High Power Laser System (HPLS)

– 2 arms, 6 outputs
– 2 x 0.1 PW, 10 Hz
– 2 x 1 PW, 1 Hz
– 2 x 10 PW, 0.1 Hz (world record!)

1. Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

High Power Laser System (HPLS)

- – 2 arms, 6 outputs
- – 2 x 0.1 PW, 10 Hz
- – 2 x 1 PW, 1 Hz
- – 2 x 10 PW, 0.1 Hz (world record!)

Gamma Beam System (GBS)

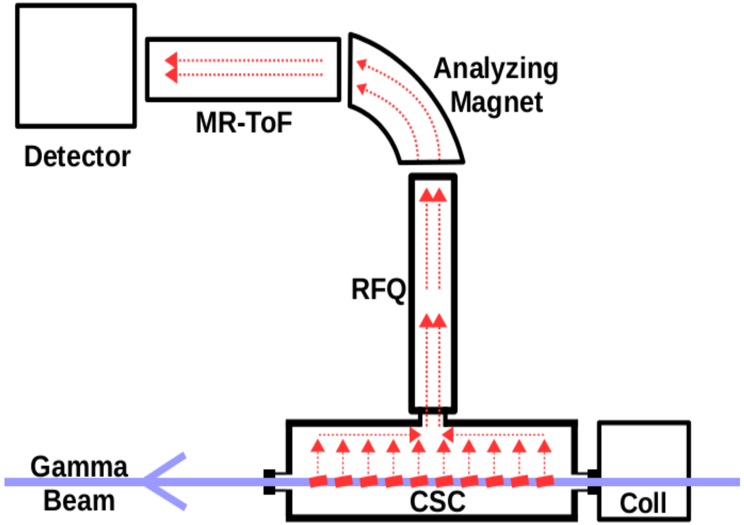
- – spectral density 0.8-4·10^4 γ/(s·eV)
- – narrow bandwidth 0.3-0.5%
- – energy range 0.2-19.5 MeV
- – linear polarization >99%

2. IGISOL beamline using the GBS at ELI-NP

2. IGISOL beamline using the GBS at ELI-NP

Goal: Production and study of exotic **neutron-rich** nuclei

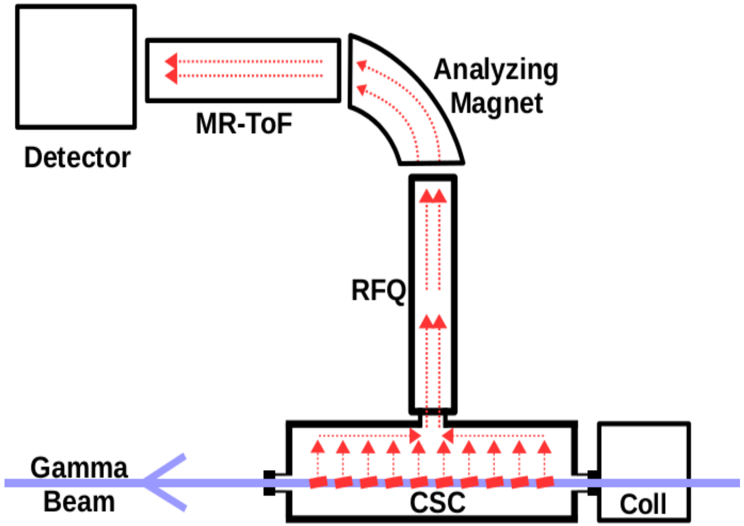
Production method: **Photo-fission** of actinides targets



2. IGISOL beamline using the GBS at ELI-NP

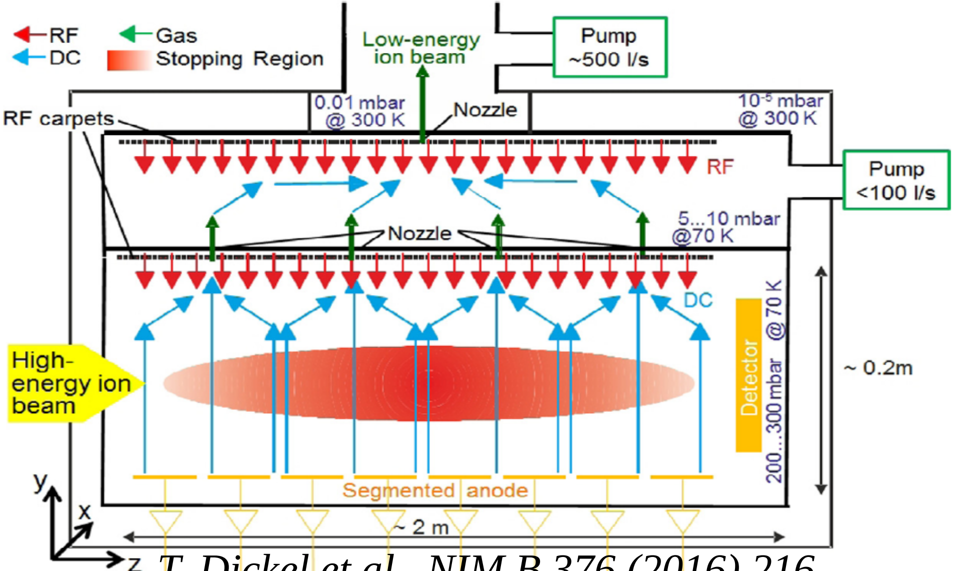
Goal: Production and study of exotic **neutron-rich** nuclei

Production method: **Photo-fission** of actinides targets



Targets:

- **thick** because σ(γ,f) small
- **sliced** in many thin foils: refractory, fast extraction
- **tilted:** (1) avoid hitting neighboring foils
  (2) increase γ pathlength

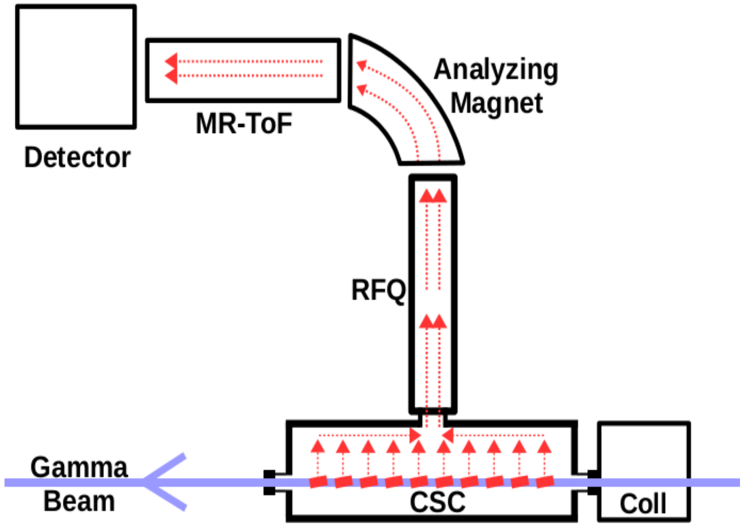


T. Dickel et al., NIM B 376 (2016) 216

2. IGISOL beamline using the GBS at ELI-NP

Goal: Production and study of exotic **neutron-rich** nuclei

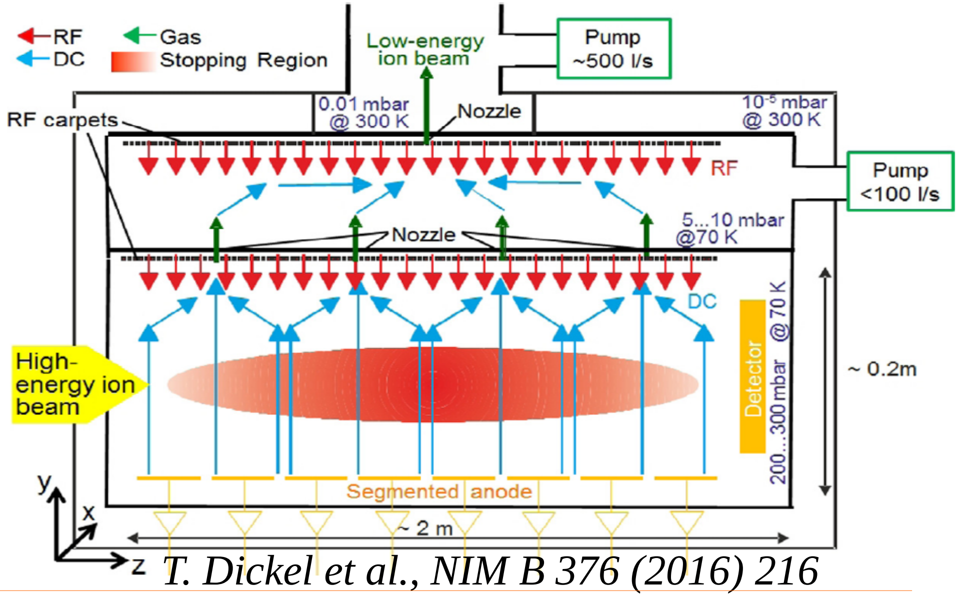
Production method: **Photo-fission** of actinides targets



GEANT4 as TOOL for MAX. RELEASED IONS

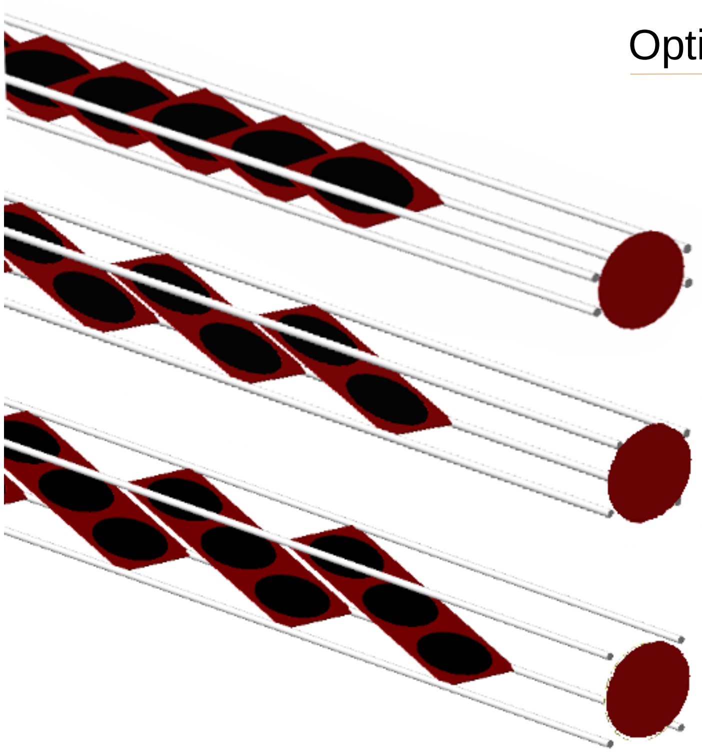
Targets:

- **thick** because σ(γ,f) small
- **sliced** in many thin foils: refractory, fast extraction
- **tilted:** (1) avoid hitting neighboring foils
  (2) increase γ pathlength



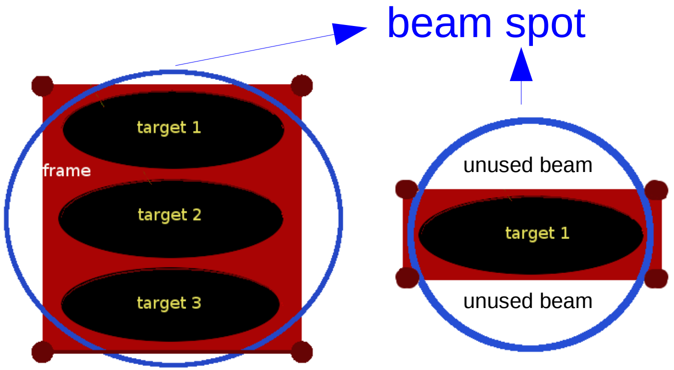
T. Dickel et al., NIM B 376 (2016) 216

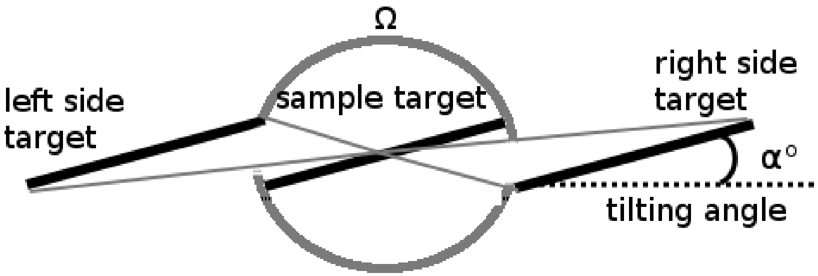
GEANT4 simulations for IGISOL ion release yield maximization



Optimization of correlated parameters:

- geometry of the targets
- tilting angle of the targets
- targets & backing thickness
- gamma beam energy window

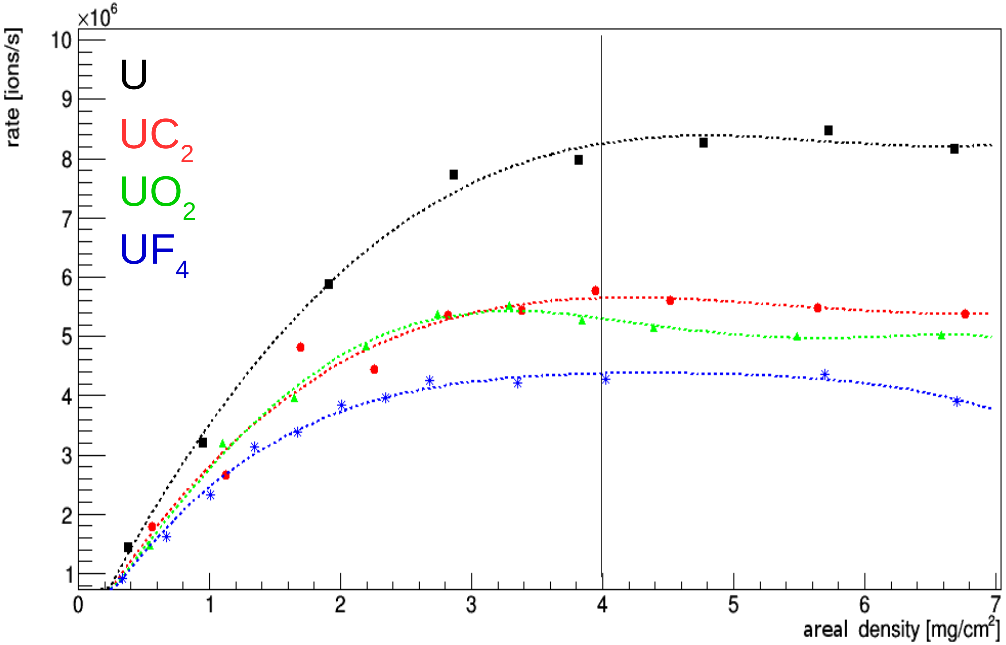




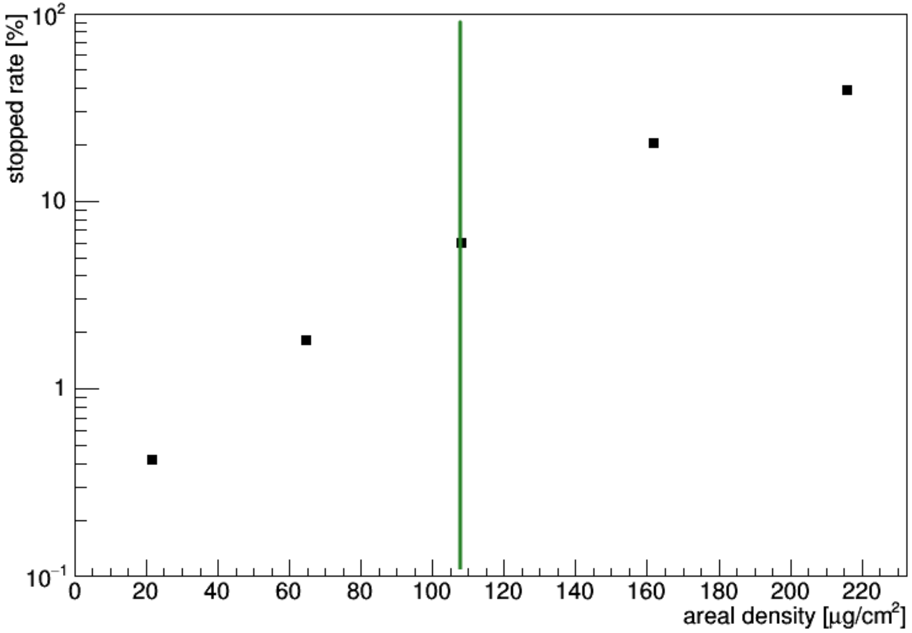
GEANT4 simulations for IGISOL ion release yield maximization

Optimization of correlated parameters:

- target released rate vs. target areal density



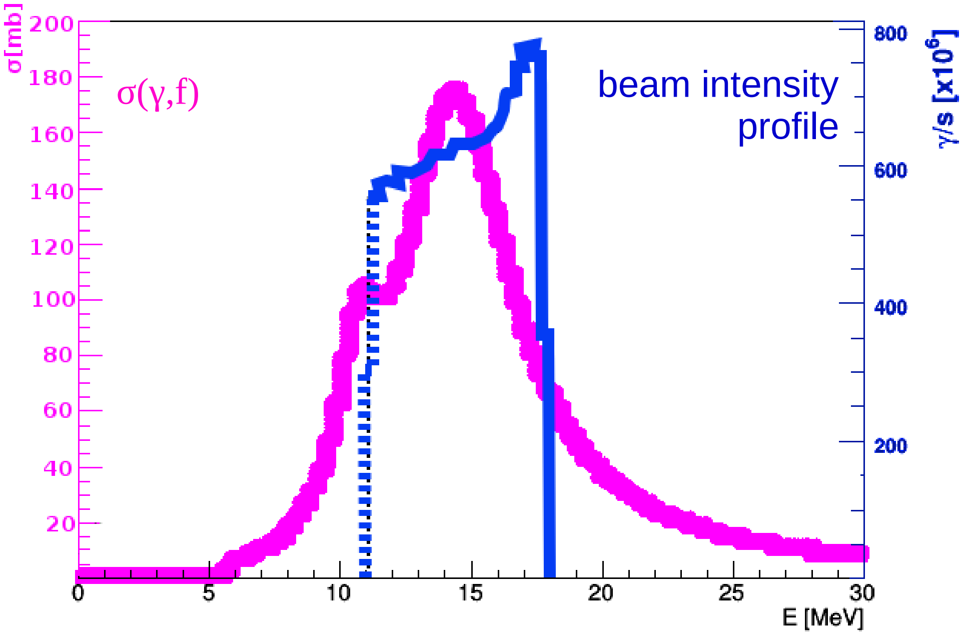
- stopped rate vs. backing areal density



GEANT4 simulations for IGISOL ion release yield maximization

Optimization of correlated parameters:

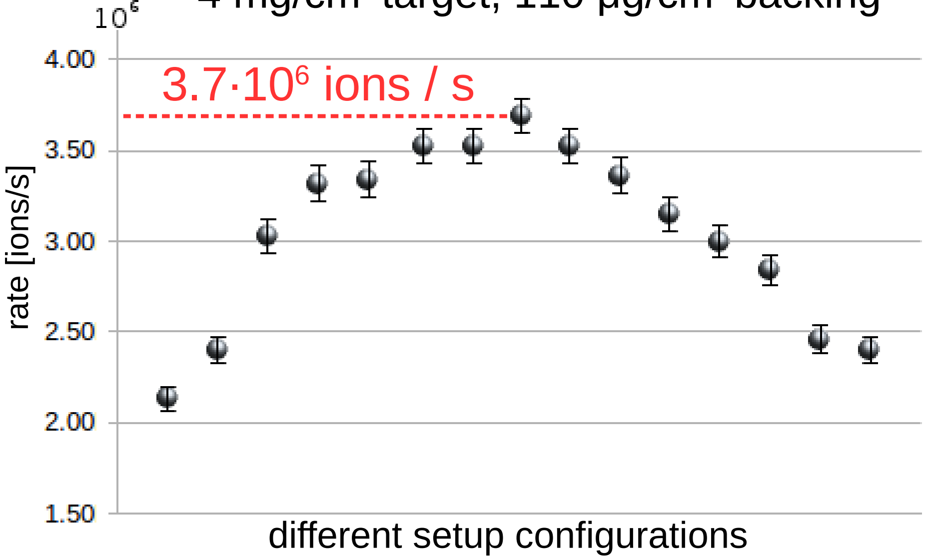
- gamma beam energy window optimization



- Maximum released rate for:

2 targets/set, 20° tilted, $E_{\gamma max}$ = 14.5 MeV

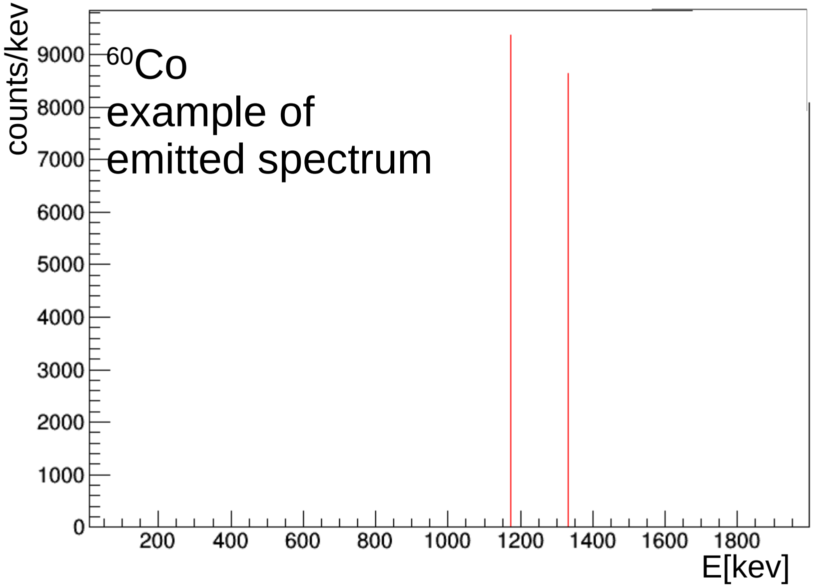
4 mg/cm² target, 110 μg/cm² backing

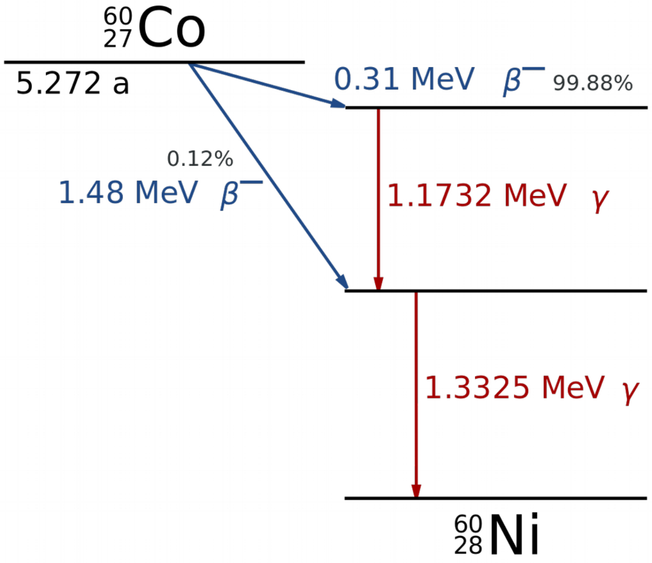


3. GEANT4 – tool for determining the detector response function

3. GEANT4 – tool for determining the detector response function

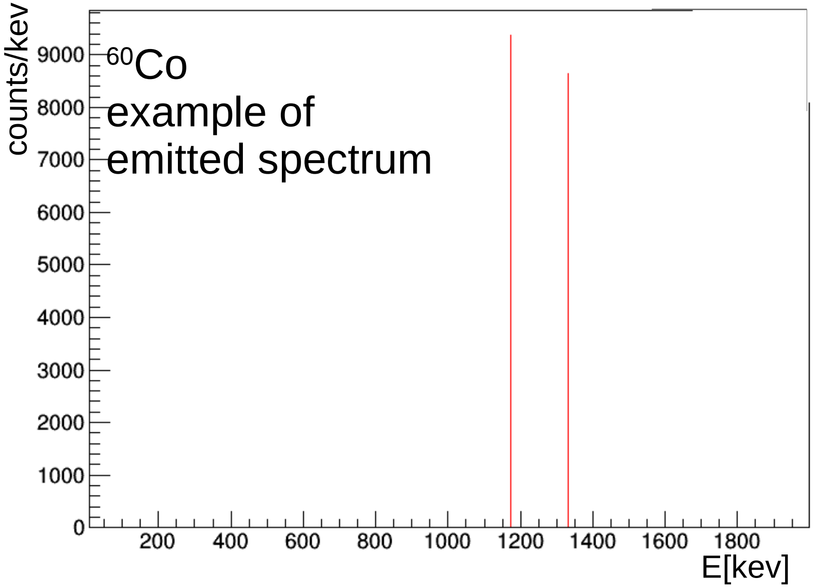
One of the important aspects of data analysis:
Unfolding the spectrum from the detector response function



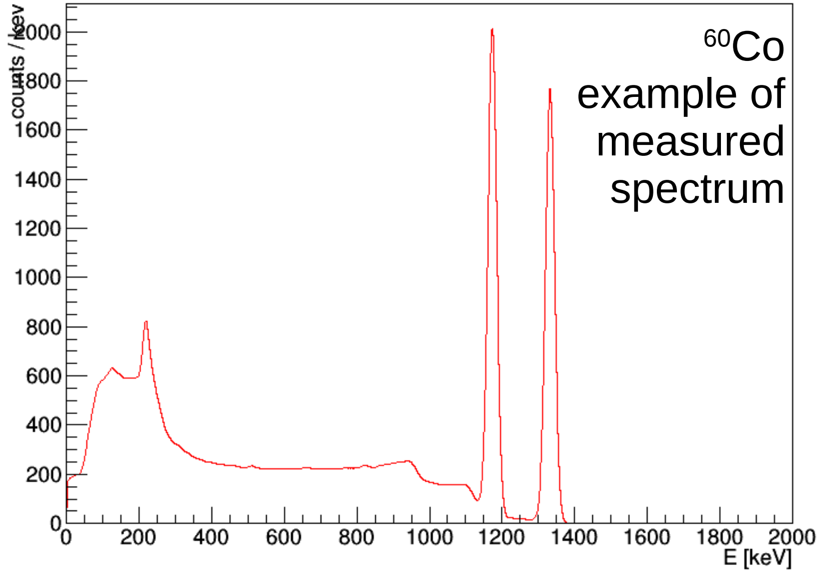


3. GEANT4 – tool for determining the detector response function

One of the important aspects of data analysis:
Unfolding the spectrum from the detector response function



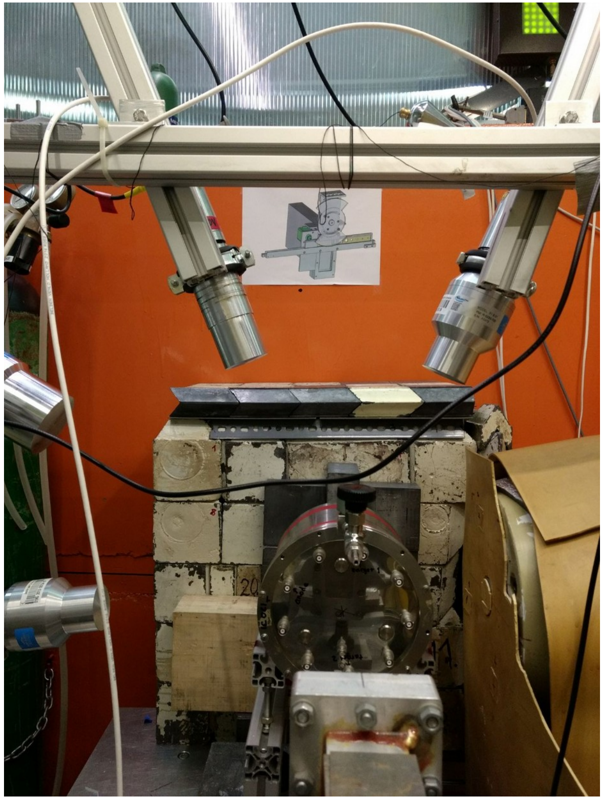
Detector response function
(LaBr$_3$)



3. GEANT4 – tool for determining the detector response function

^{233}U+n_{th} experiment

Location: Hungarian Academy of Sciences, Centre for Energy Research (MTA EK – Budapest) – Feb. 2018

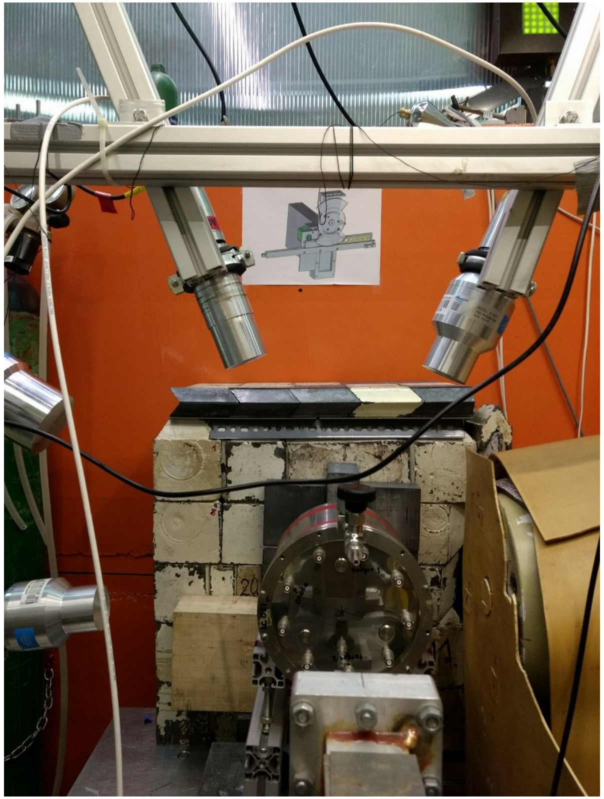


3. GEANT4 – tool for determining the detector response function

^{233}U+n$_{th}$ experiment

Location: Hungarian Academy of Sciences, Centre for Energy Research (MTA EK – Budapest) – Feb. 2018

Target: 2 samples of ^{233}U



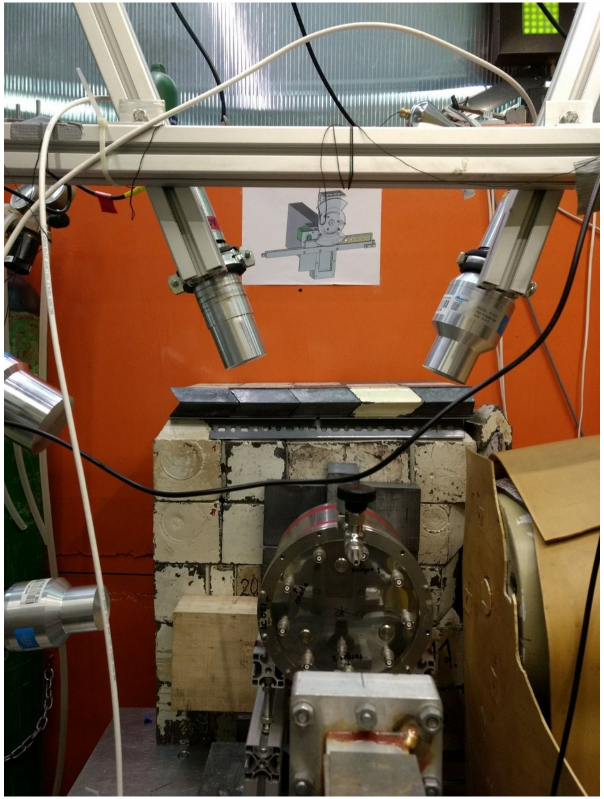
3. GEANT4 – tool for determining the detector response function

^{233}U+n$_{th}$ experiment

Location: Hungarian Academy of Sciences, Centre for Energy
Research (MTA EK – Budapest) – Feb. 2018

Target: 2 samples of ^{233}U

Detectors: 4 x LaBr$_3$:Ce scintillator detectors
(i.e. 3 x 2 in. x 2 in. and 1 x 3 in. x 3 in.),
1 x FGIC



3. GEANT4 – tool for determining the detector response function

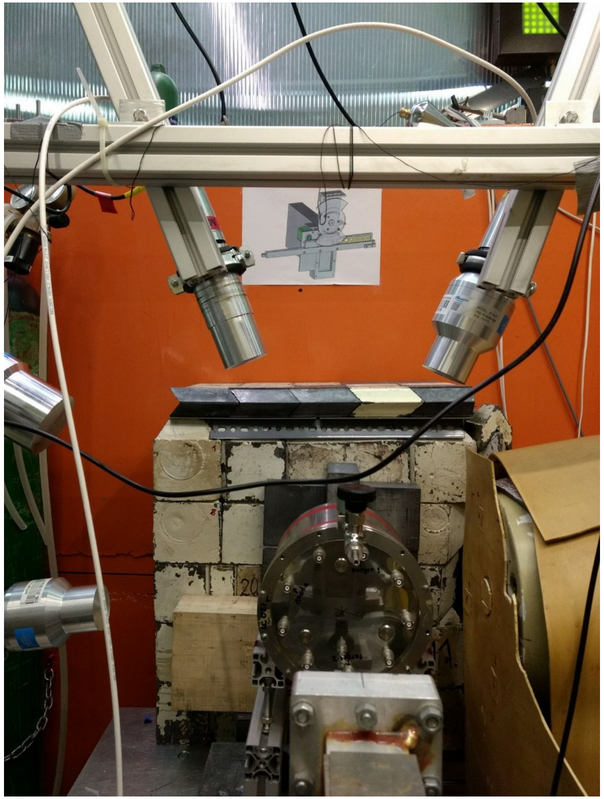
^{233}U+n$_{th}$ experiment

Location: Hungarian Academy of Sciences, Centre for Energy Research (MTA EK – Budapest) – Feb. 2018

Target: 2 samples of ^{233}U

Detectors: 4 x LaBr$_3$:Ce scintillator detectors
(i.e. 3 x 2 in. x 2 in. and 1 x 3 in. x 3 in.),
1 x FGIC

Goal: Measuring Prompt Fission Gamma Spectra (PFGS),
Determining average multiplicity per fission,
Mean energy per photon and total energy per fission



3. GEANT4 – tool for determining the detector response function

^{233}U+n_{th} experiment

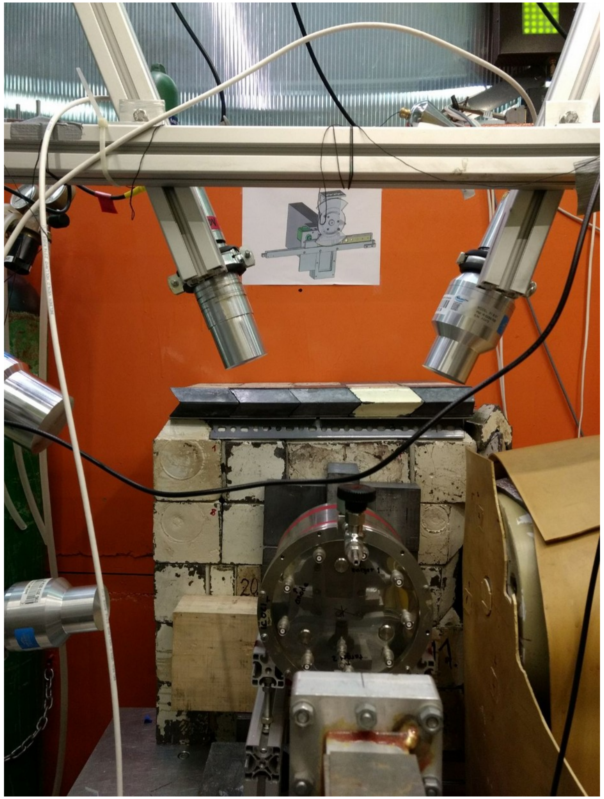
Location: Hungarian Academy of Sciences, Centre for Energy
Research (MTA EK – Budapest) – Feb. 2018

Target: 2 samples of ^{233}U

Detectors: 4 x $LaBr_3$:Ce scintillator detectors
(i.e. 3 x 2 in. x 2 in. and 1 x 3 in. x 3 in.),
1 x FGIC

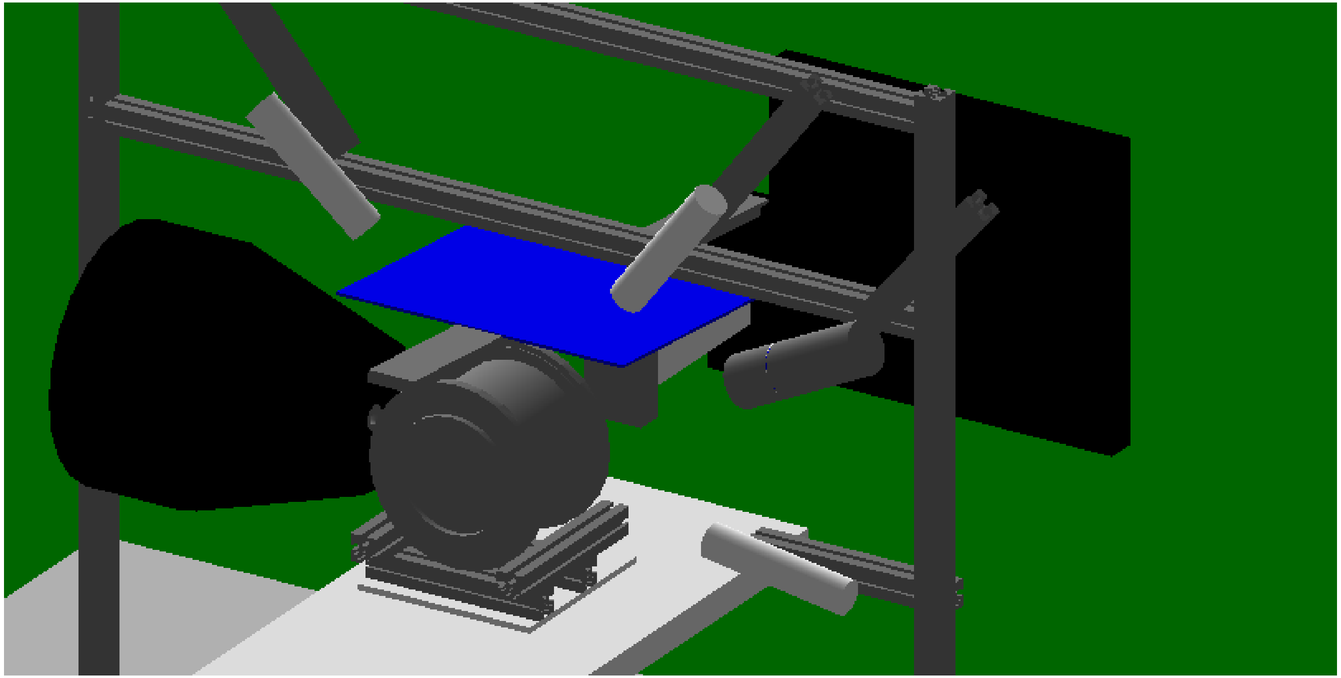
Goal: Measuring Prompt Fission Gamma Spectra (PFGS),
Determining average multiplicity per fission,
Mean energy per photon and total energy per fission

Motivation: Fission fragment deexcitation study, nuclear data, etc.



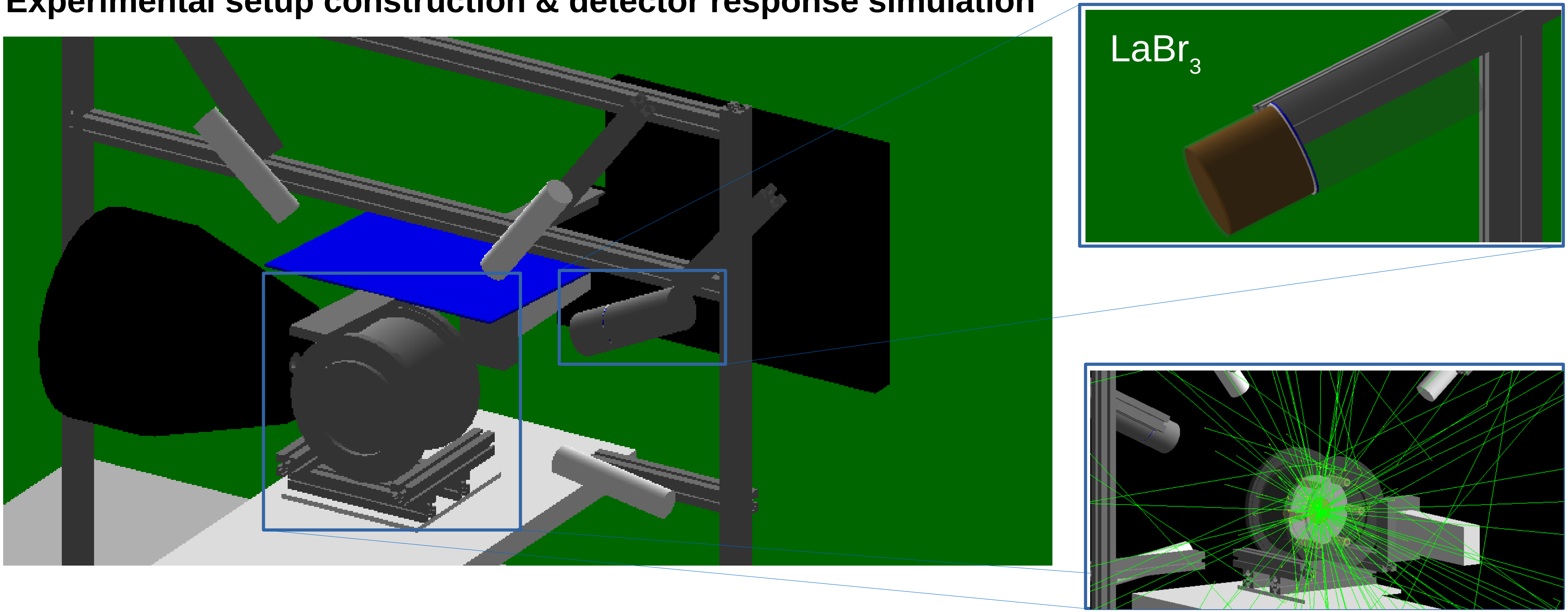
GEANT4 – simulation of the detector response

Experimental setup construction & detector response simulation



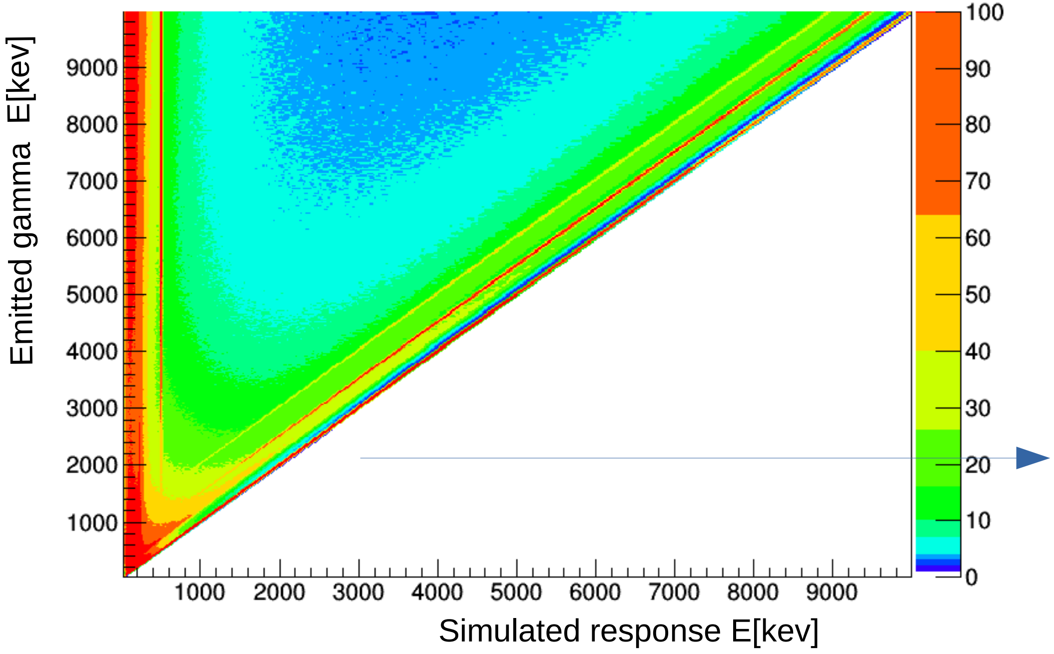
GEANT4 – simulation of the detector response

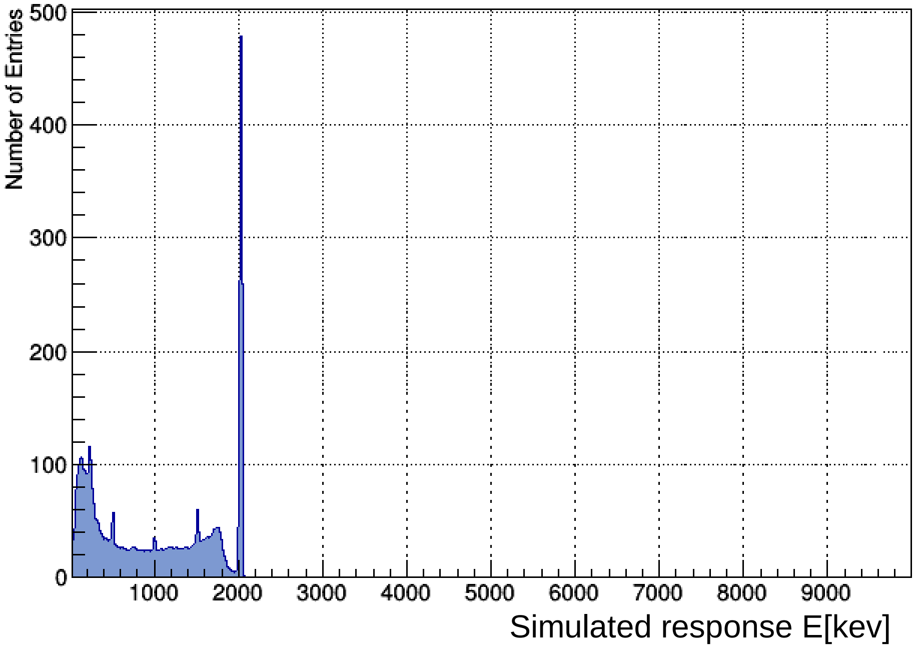
Experimental setup construction & detector response simulation



GEANT4 – simulation of the detector response

Detector response matrix construction





GEANT4 – simulation of the detector response

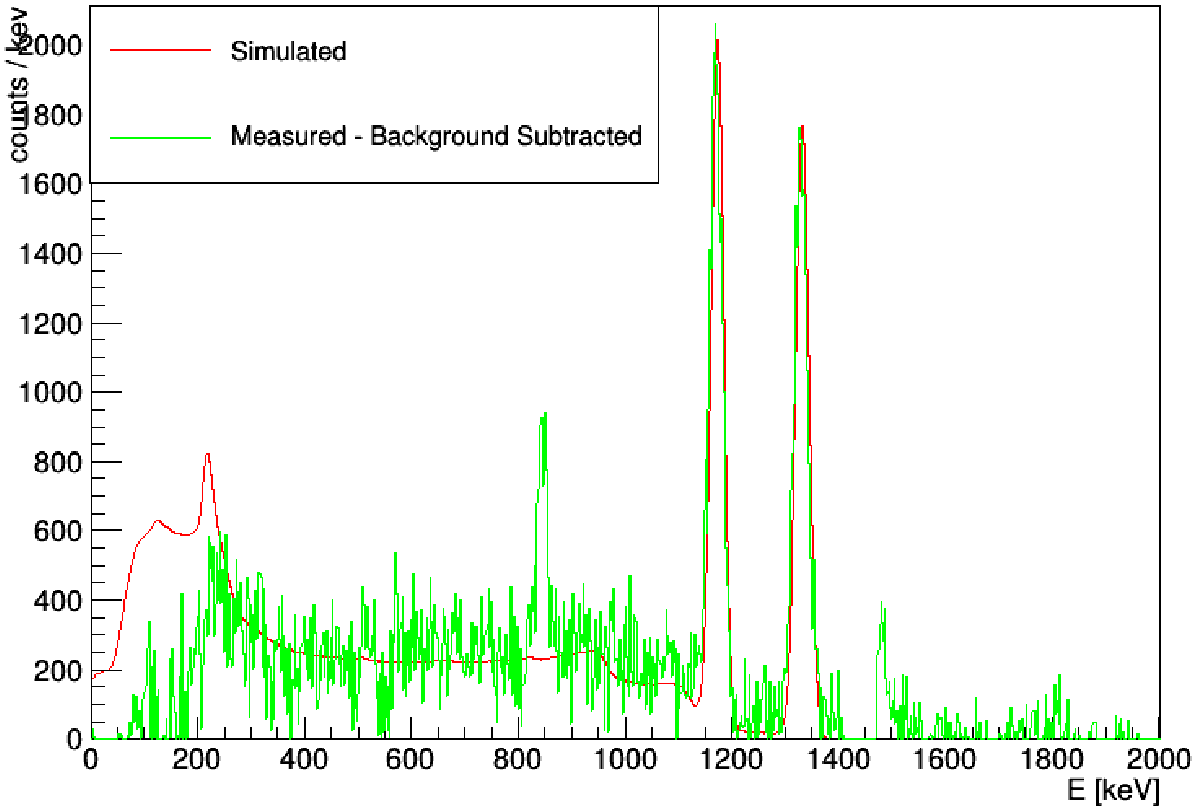
Detector response validation

- Simulation of ^{60}Co source
- Compare:

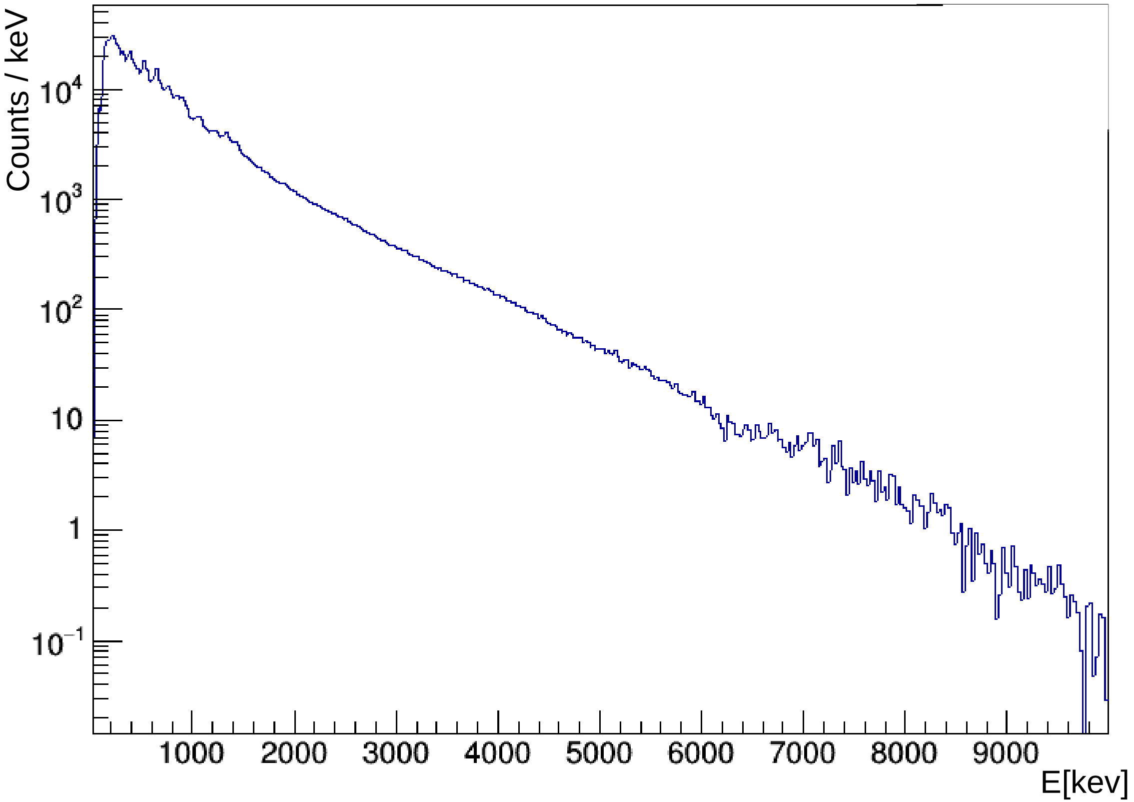
  Simulated detector response

  with

  Measured detector response



^{233}U+n$_{th}$ prompt fission gamma spectrum (PFGS) unfolding



Using matrix inversion method for unfolding

- GEANT4 simulations to determine the response function of the detector in the given setup
- Construct the response matrix
- Using the inverse response matrix to unfold the spectrum from the detector response function

GEANT4 – User feedback

GEANT4 is an important tool in nuclear physics
for simulation and design of experiments but also for data analysis.

Necessary additions to GEANT4 implemented by me:

- Photo-fission cross section and data model in 5-25 MeV range
(cross section function on energy and compute of secondaries);
P. Constantin et al., NIMB 372 (2016)
B. Mei et al., Phys. Rev. C 96 (2017)

- Schiwietz charge state parameterisation for energy loss (default Ziegler):
Schiwietz performs better than Ziegler for slow (E ~ 1 MeV/u) & heavy ions (M > 80 GeV)
P. Constantin et al., NIMB 372 (2016)
G. Schiwietz et al., Nucl. Instr. Meth. B 175–177 (2001)

- Personal wish: Have more realistic examples for constructing common detector types & simulating response functions taking into account effects as pile-up and dead time

Group acknowledgements & THANK YOU!

ELI-NP (Romania): D. Nichita, P. Constantin, A. Oberstedt, D. L. Balabanski, D. Choudhury, A. Spataru

IFIN-HH (Romania): A. Rotaru, T. Sava, A. State

GSI / Gießen (Germany): T. Dickel, W. R. Plaß

JRC Geel (Belgium): A. Gatera

IPN Orsay (France): L. Qi

EUROPEAN UNION

Competitiveness Operational Programme (COP)

Structural Instruments 2014-2020

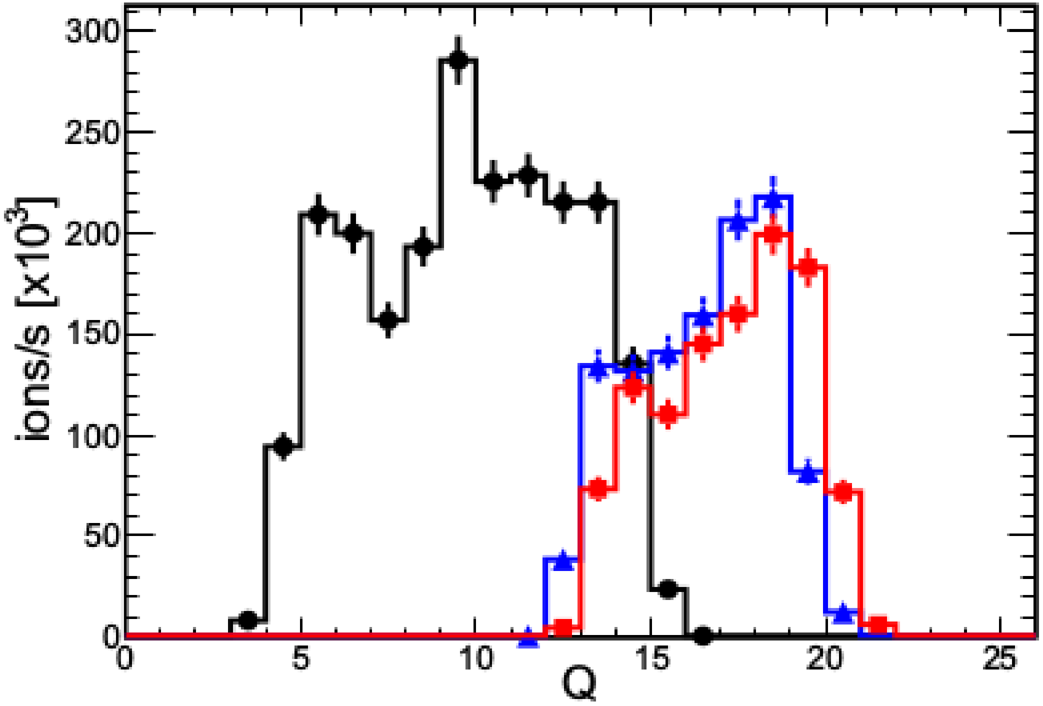
Group acknowledgements

ADDITIONAL

Group acknowledgements

Measurements with the LOHENGRIN spectrometer at ILL Grenoble of ionic charge state distributions in thermal neutron induced fission of ^{235}U [18] found $\langle Q\rangle = 20$–22 and $\sigma_Q = 2.0$–2.4. Similar values were measured in $^{239}\mathrm{Pu}(n_{th},f)$ [19], $^{241}\mathrm{Am}(2n_{th},f)$ [20] and $^{241}\mathrm{Pu}(n_{th},f)$ [21]. These values refer to the regular ionic charge state distributions, unaffected by the presence of nanosecond isomeric states. When such isomers are present, they decay by conversion with electrons from internal shells and the produced vacancies lead to Auger cascades and, consequently, to ionic charge states higher by $\Delta\langle Q\rangle \approx 3$ [18].

Fig. 6 shows the dependence of the ionic charge Q, at the moment of release from the target, on the ion velocity v for five values of the nuclear charge $Z = 36, 38, 40, 56, 58$. The lower set of five tightly bound curves, drawn with open circles, is produced with the Ziegler parameterization, while the upper set of five loosely bound curves, drawn with full squares, is produced with the Schiwietz parameterization. Apart from the overall higher Q values, the Schiwietz parameterization has also a more pronounced dependence on the nuclear charge Z than the Ziegler



GIF U238 implementation in GEANT4

Reimplemented two classes

GamaFissionCrossSection (for TCS) & **GammaFissionDataModel** (for A,Z)

The implemented algorithm is calculating the fission fragments yields in 3 steps:

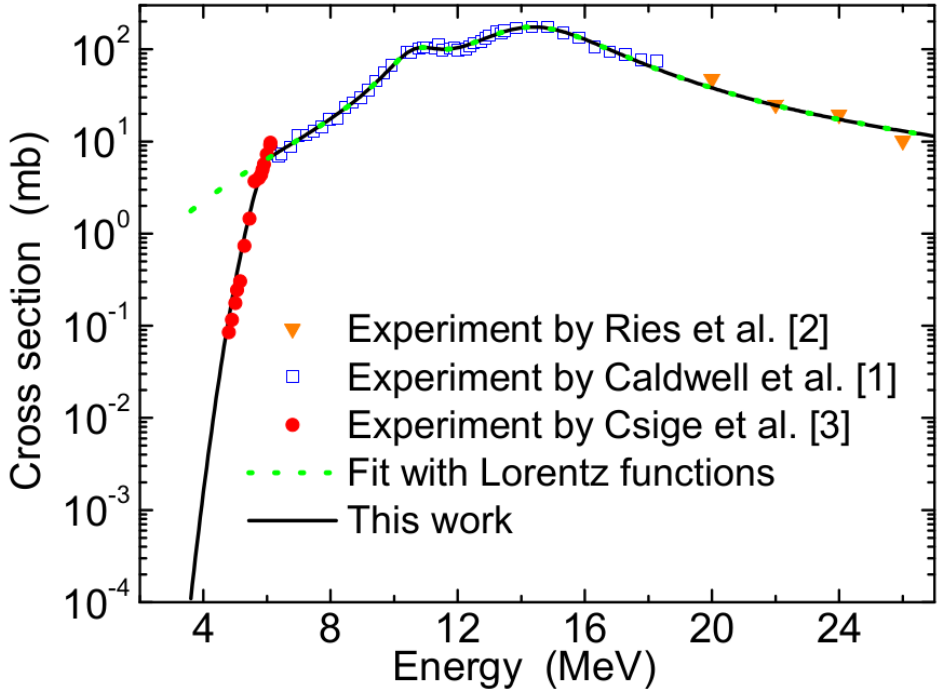
1. The calculation of the Total Cross Section of the Photo-Fission reaction (depending on the incident photon energy)

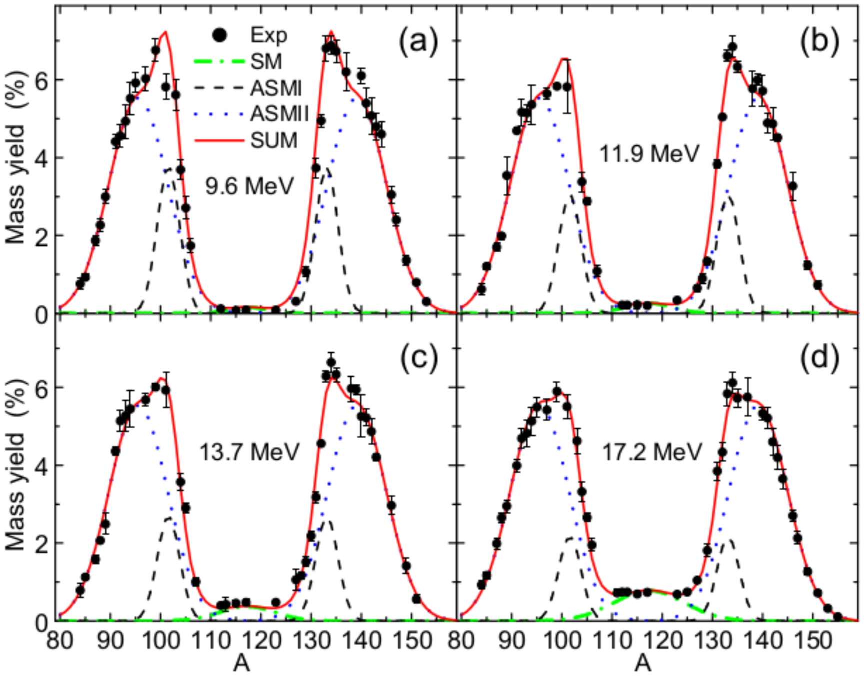
2. After the photo-fission reaction is decided to take place at the current event the mass (A) is calculated according to the mass distribution

3. For the current mass A decided at step 2, the charge (Z) number is being decided according with the charge distribution

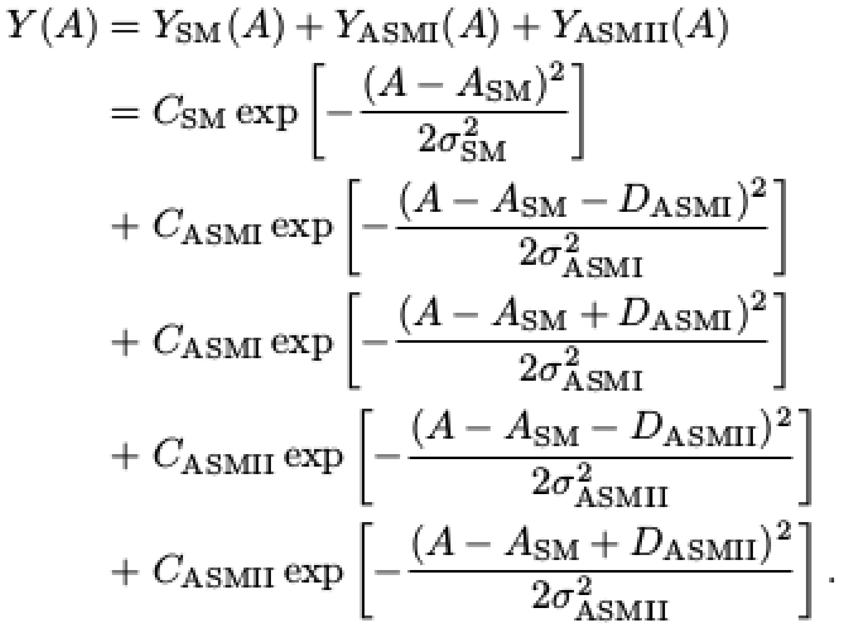
Group acknowledgements

$$\sigma_f\left(E_\gamma\right) = \sum_{i=1}^{2} \frac{\sigma_i}{1+[\frac{(E_\gamma^2-E_i^2)}{E_\gamma \Gamma_i}]^2}.$$

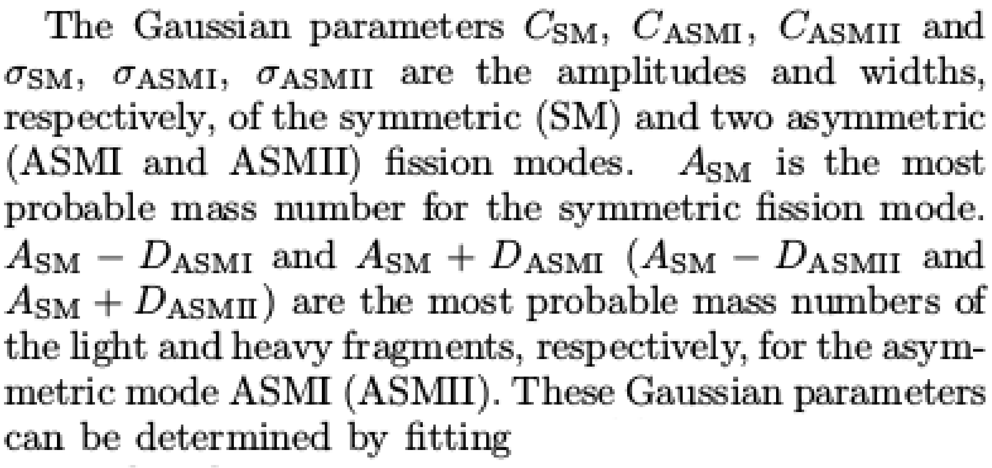




Group acknowledgements



$$
\begin{aligned}
Y(A) &= Y_{\mathrm{SM}}(A) + Y_{\mathrm{ASMI}}(A) + Y_{\mathrm{ASMII}}(A) \\
&= C_{\mathrm{SM}} \exp\left[-\frac{(A - A_{\mathrm{SM}})^2}{2\sigma_{\mathrm{SM}}^2}\right] \\
&+ C_{\mathrm{ASMI}} \exp\left[-\frac{(A - A_{\mathrm{SM}} - D_{\mathrm{ASMI}})^2}{2\sigma_{\mathrm{ASMI}}^2}\right] \\
&+ C_{\mathrm{ASMI}} \exp\left[-\frac{(A - A_{\mathrm{SM}} + D_{\mathrm{ASMI}})^2}{2\sigma_{\mathrm{ASMI}}^2}\right] \\
&+ C_{\mathrm{ASMII}} \exp\left[-\frac{(A - A_{\mathrm{SM}} - D_{\mathrm{ASMII}})^2}{2\sigma_{\mathrm{ASMII}}^2}\right] \\
&+ C_{\mathrm{ASMII}} \exp\left[-\frac{(A - A_{\mathrm{SM}} + D_{\mathrm{ASMII}})^2}{2\sigma_{\mathrm{ASMII}}^2}\right].
\end{aligned}
$$



The Gaussian parameters C_{SM}, C_{ASMI}, C_{ASMII} and σ_{SM}, σ_{ASMI}, σ_{ASMII} are the amplitudes and widths, respectively, of the symmetric (SM) and two asymmetric (ASMI and ASMII) fission modes. A_{SM} is the most probable mass number for the symmetric fission mode. $A_{\mathrm{SM}} - D_{\mathrm{ASMI}}$ and $A_{\mathrm{SM}} + D_{\mathrm{ASMI}}$ ($A_{\mathrm{SM}} - D_{\mathrm{ASMII}}$ and $A_{\mathrm{SM}} + D_{\mathrm{ASMII}}$) are the most probable mass numbers of the light and heavy fragments, respectively, for the asymmetric mode ASMI (ASMII). These Gaussian parameters can be determined by fitting

Group acknowledgements

$$Z_s = \frac{A + [(a_c A^{2/3})/(2x)]}{(4a_{\mathrm{sym}}/x) + [(a_c A^{2/3})/x]},$$

where $x = 2a_{\mathrm{sym}} + [(m_n - m_p)/2]$, and m_n and m_p are the masses of proton and neutron, respectively [27]. The constants $a_c = 0.71$ MeV and $a_{\mathrm{sym}} = 23.21$ MeV are the Coulomb and symmetry energy coefficients, respectively

$$Z_{\mathrm{prob}} = Z_s - 3.8 + \Delta_Z,$$

$$\Delta_Z = d_1 + d_2 A + d_3 A^2 + d_4 A^3,$$

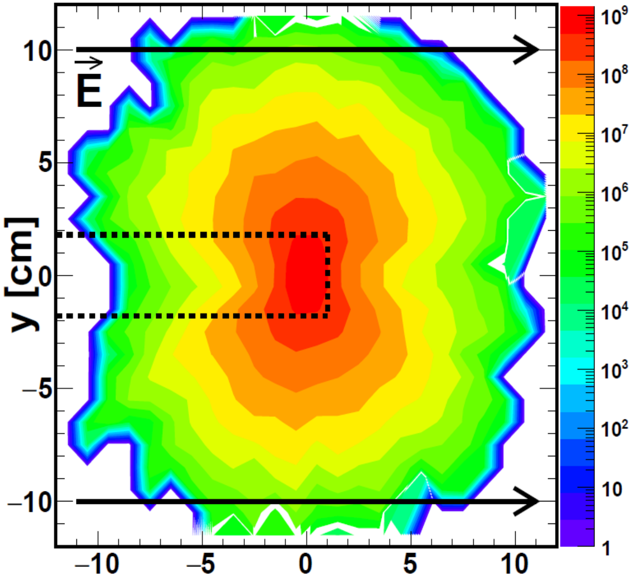
for light fragments with $A < 134$,

$$\Delta_Z = d_5 + d_6 \exp(A/d_7),$$

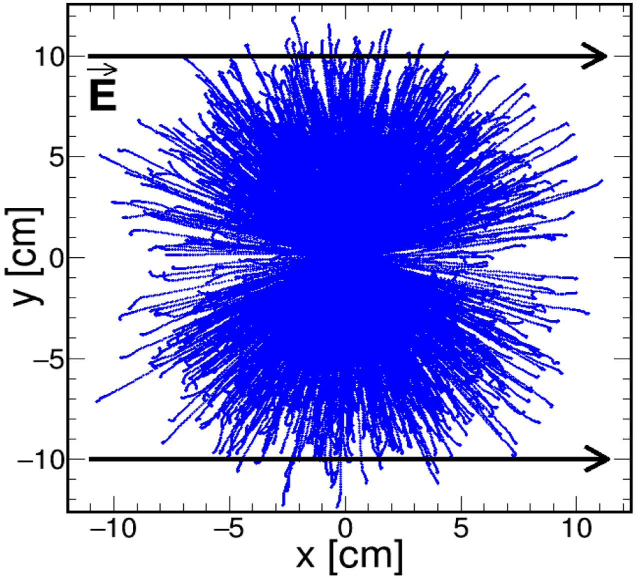
for heavy fragments with $A \geqslant 134$.

Group acknowledgements

Space charge = He$^+$ cloud created by fragment (>90%) and e$^+$/e$^-$ (<10%) induced ionization of He gas
Above a certain **charge density rate Q**: field saturation, strong e-ion recombination, weak plasma.

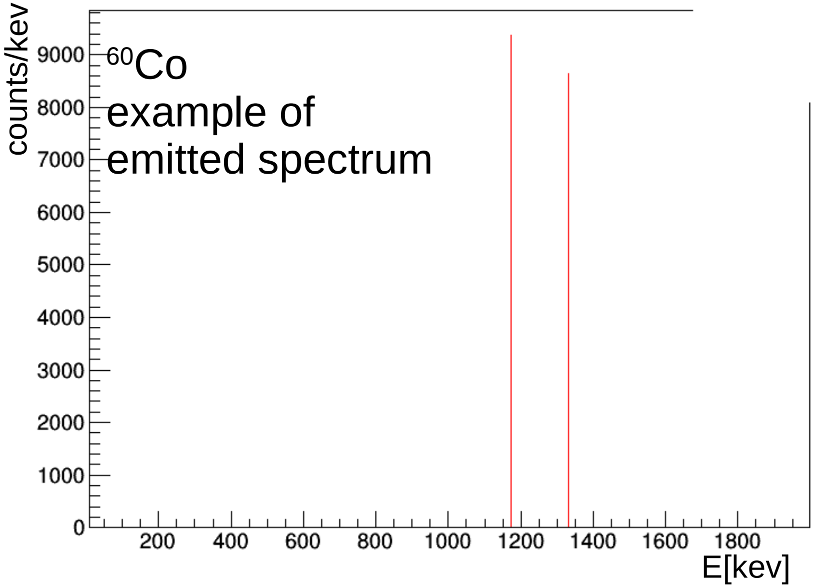


Geant4: He, T=70K, p=300mbar (ρ=0.206mg/cm^3)
>95% of fragments stop in 11.3cm → **width~24cm**

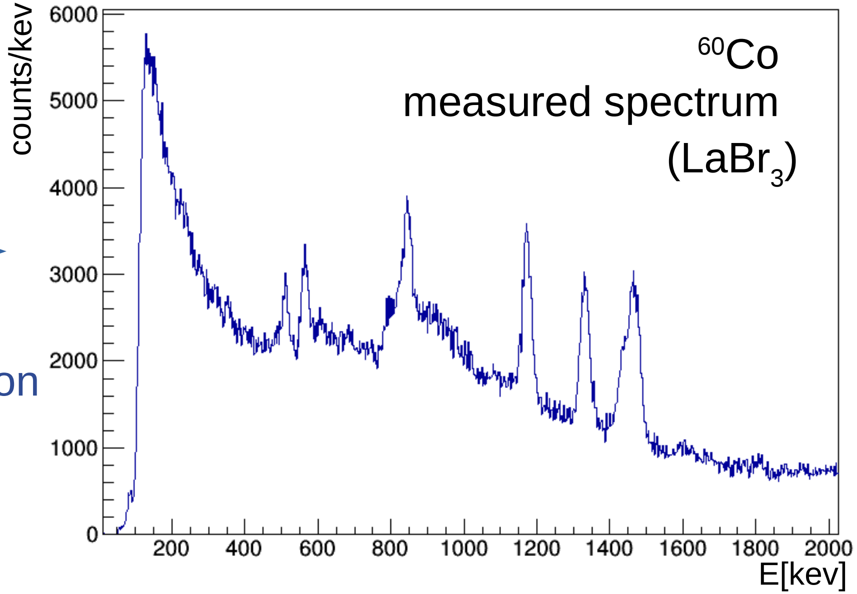


3. GEANT4 – tool for determining the detector response function

One of the important aspects of data analysis:
Unfolding the spectrum from the detector response function


^{60}Co
example of
emitted spectrum

Detector
response function
+background


^{60}Co
measured spectrum
($LaBr_3$)

Group acknowledgements

THANK YOU!