

Characterization and Monte Carlo simulations for a CLYC detector

A. Borella¹, E. Boogers¹, R. Rossa¹, P. Schillebeeckx²

¹aborella@sckcen.be

¹SCK•CEN, Belgian Nuclear Research Centre

²JRC-Geel, Joint Research Centre



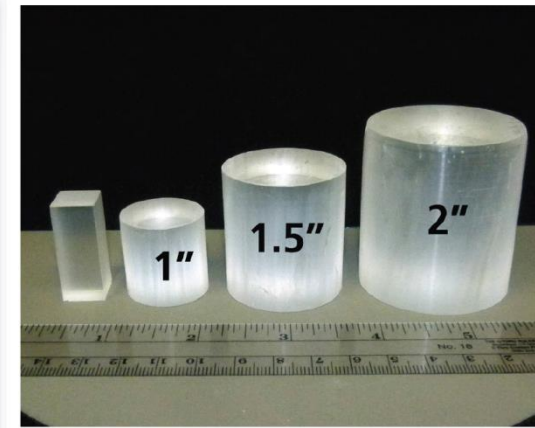
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work



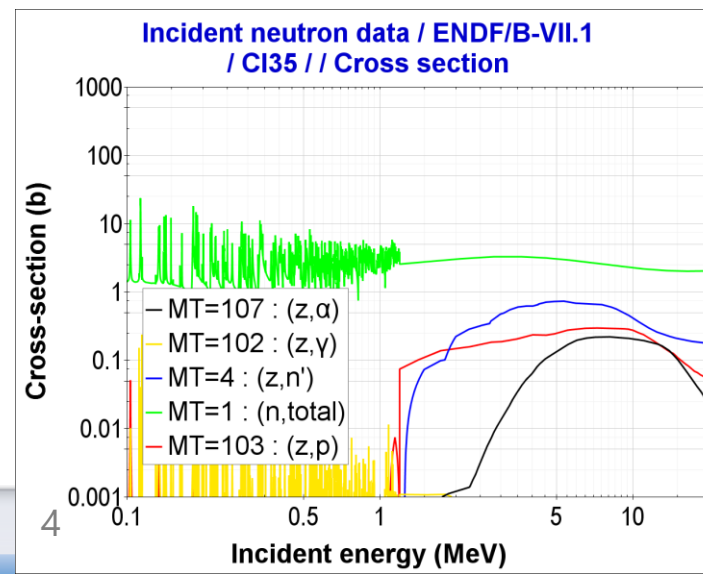
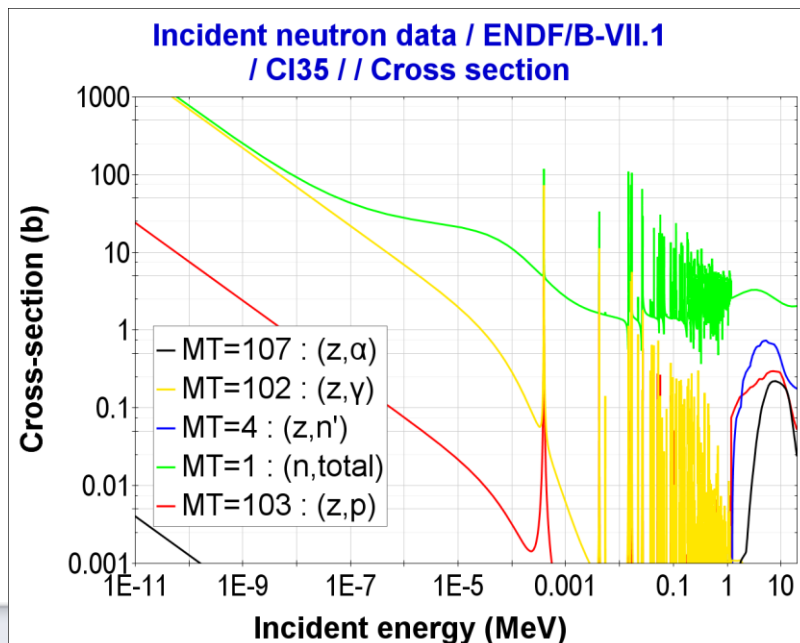
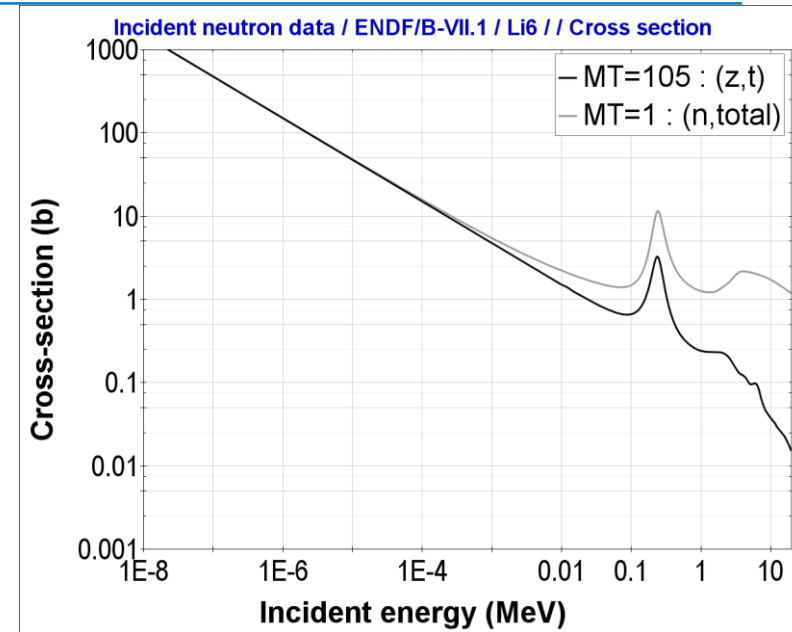
CLYC features

- CLYC = $\text{Cs}_2\text{LiYCl}_6(\text{Ce})$
 - Elpasolite crystal
 - Hygroscopic
 - Scintillator
 - ~20,000 ph/MeV (e)
 - First work 1999 UDeft
 - Suppliers
 - RMD (natLi , enr^6Li , enr^7Li)
 - Scionix (95% ^6Li)
- Sensitive to both neutrons and gamma-rays

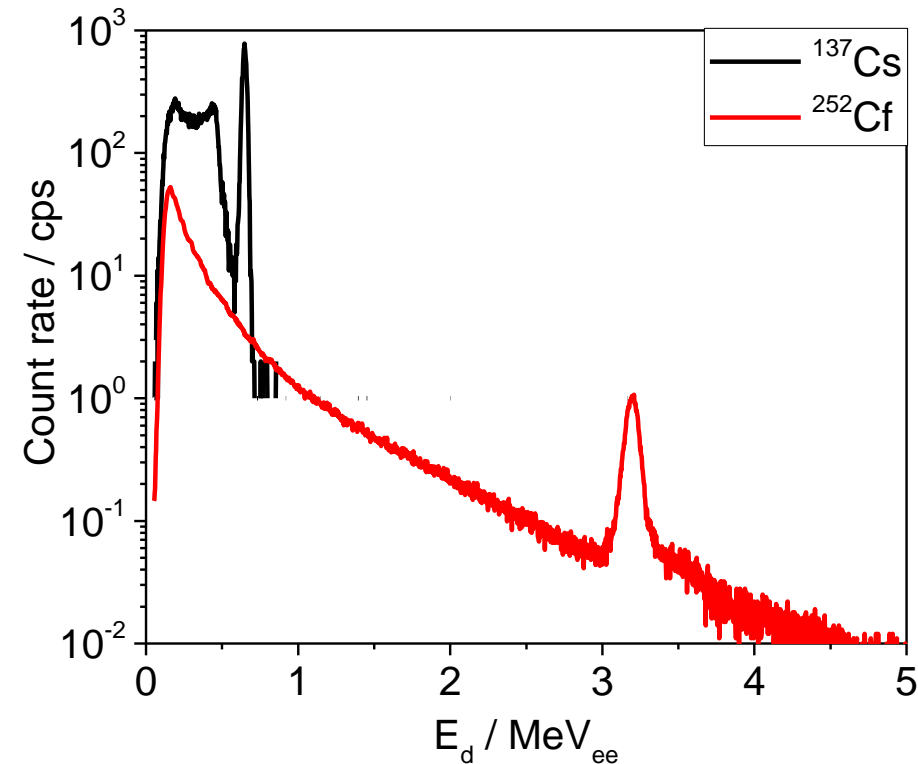


CLYC features - Reaction of interest for neutron detection

- ${}^6\text{Li}(n,\alpha)t$
 - $Q=4.78$ MeV
- ${}^{35}\text{Cl}(n,p){}^{35}\text{S}$
 - $Q=0.615$ MeV
 - Highest (n,p) reaction XS
 - Significant (n, γ)



- ${}^6\text{Li}(n,\alpha)t$
 - $Q=4.78\text{ MeV} \Rightarrow 3.2\text{ MeV}_{ee}$
 - Light output for α , t
- n,γ separation
 - Energy
 - Pulse Shape Discrimination
- CLYC without ${}^6\text{Li}$
 - ${}^{35}\text{Cl}(n,p){}^{35}\text{S}$
- Applications
 - Security, Safeguards
 - (Fast) neutron dosimetry
 - Space (<http://dx.doi.org/10.1016/j.nima.2015.08.080>)
 - Neutron radiography (Physics Procedia 69 (2015) 161 – 168)



- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work



- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work

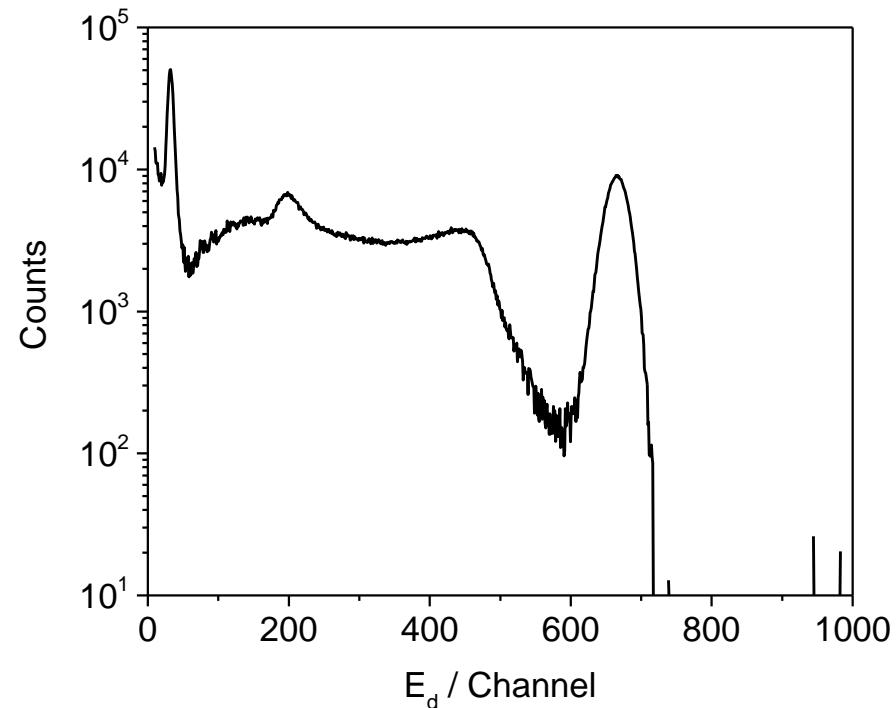


Detector response function

- Measured pulse height spectrum $N(E_d)$

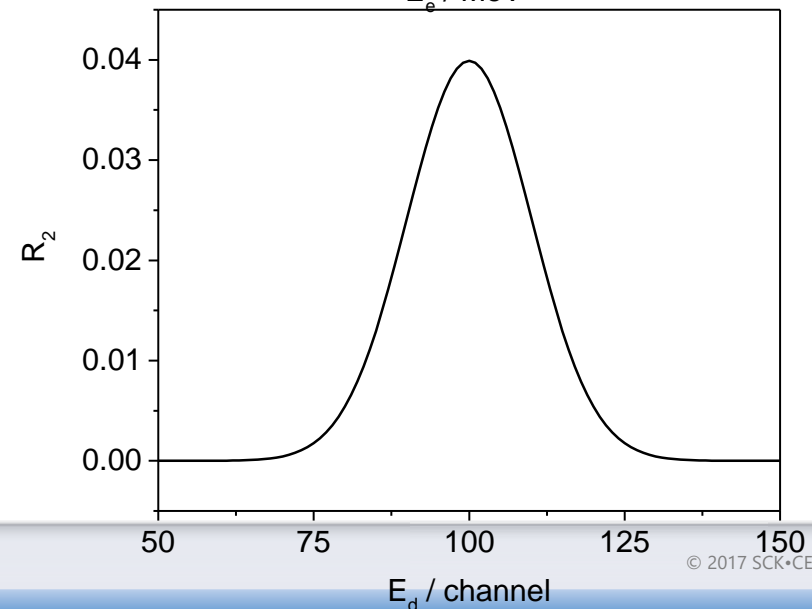
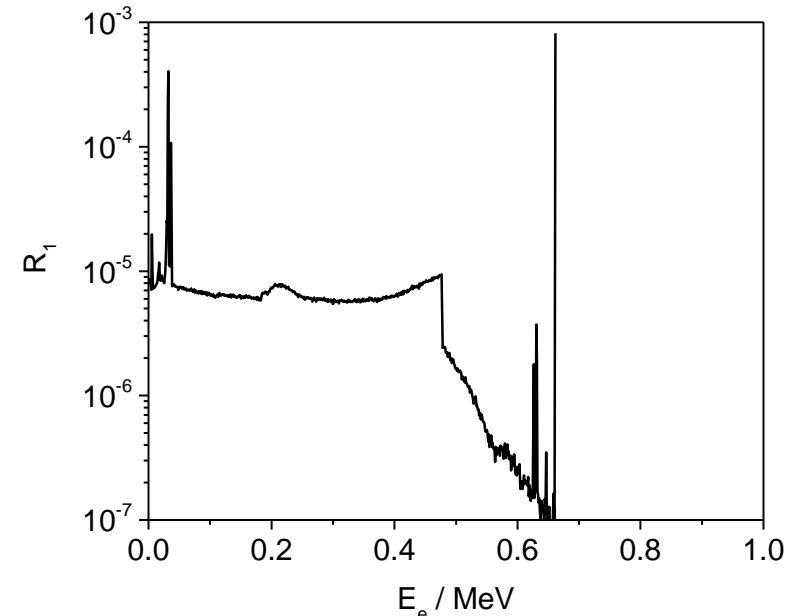
$$N(E_d) = \iint R_2(E_d, E_e) R_1(E_e, E_\gamma) \Phi_E(E_\gamma) dE_e dE_\gamma$$

- γ -ray fluence spectrum $\Phi_E(E_\gamma)$
- E_γ , γ -ray energy
- E_d , observed signal
- $R_1(E_e, E_\gamma)$ describes the transfer of E_γ in electron energy E_e
- $R_2(E_d, E_e)$ relates E_e to E_d .



Detector response function

- $R_1(E_e, E_\gamma)$
 - Transfer of E_γ into E_e
 - determined by γ -ray transport in detector material
 - can be calculated by Monte Carlo simulations
- $R_2(E_d, E_e)$
 - Transfer of E_e into E_d
 - depends on processes such as
 - ionization
 - scintillation
 - photo-multiplication
 - signal processing
 - phenomenological



Detector response function

$$R_2(E_d, \mu(E_e)) = \frac{1}{\sqrt{2\pi}\sigma_\mu} \exp\left(-\frac{(E_d - \mu(E_e))^2}{2\sigma_\mu^2}\right) \left\{ \begin{array}{l} \mu = \alpha E_e \\ \sigma_\mu^2 = \beta \mu \end{array} \right.$$

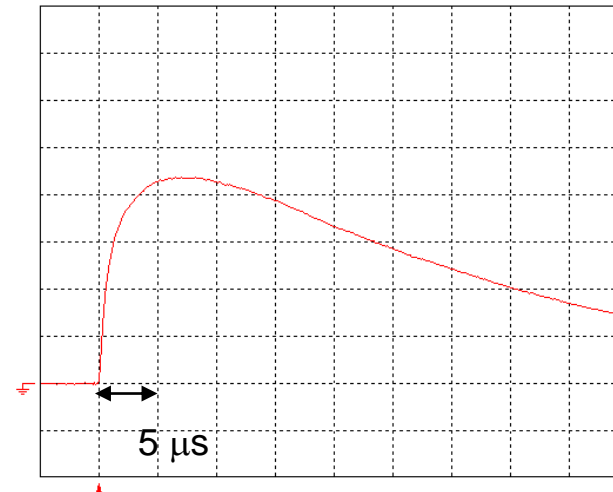
- R_2 includes
 - Energy calibration,
 - $\mu(E_e)$ conversion of E_e into observed signal E_d
 - Resolution broadening $\sigma_\mu = f(\mu(E_e))$
- Ideally, $\mu(E_e)$ and σ_μ^2 are directly proportional to E_e
- Phenomenological determination

- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work



Experiments - equipment

- 1" x 1" cylindrical CLYC detector, ${}^6\text{Li}$ 96%
- Hamamatsu R13089-100 PMT
- HV -1200 V
- Ortec 113 preamplifier with 200 pF input capacitance
- MCA527 unit from GBS-Elektronik
 - trigger filter (+1,0,-2,0,+1)
 - shaping time 0.5 μs
 - Flat Top time to 5 μs

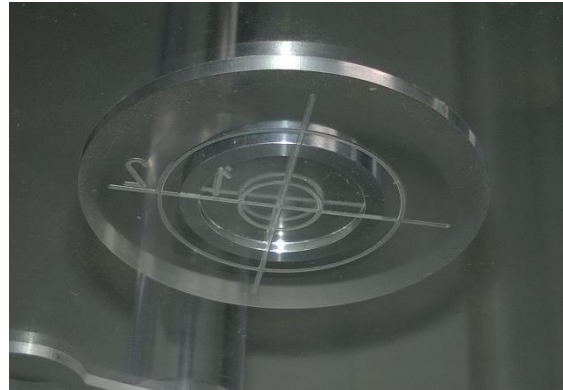


Experiments - sources



Main E _γ keV	Radionuclide	A kBq	Unc 1 sigma kBq	Reference date YYYY/MM/DD HH:MM CET
59.54	²⁴¹ Am	41.00	±0.72	2009-09-11 13:00
88.03	¹⁰⁹ Cd	37.74	±0.38	2016-02-15 21:00
122.06	⁵⁷ Co	27.47	±0.14	2016-01-01 00:00
165.87	¹³⁹ Ce	40.29	±0.40	2016-02-15 21:00
391.70	¹¹³ Sn	34.86	±0.35	2016-02-15 21:00
514.00	⁸⁵ Sr	79.10	±0.40	2016-02-01 00:00
661.66	¹³⁷ Cs	39.10	±0.39	2009-09-11 13:00
834.84	⁵⁴ Mn	38.40	±0.20	2016-01-01 00:00
1115.54	⁶⁵ Zn	38.04	±0.39	2016-02-15 21:00
1274.54	²² Na	42.00	±0.42	2009-09-11 13:00
1332.49 1173.23	⁶⁰ Co	38.68	±0.29	2009-09-11 13:00

- Aluminium structure
- Plexiglas holder
 - concentric circles
 - three distances between detector surface and source 0.67, 4.73 and 10.75 cm
- Repetitive measurements with a ^{137}Cs at 4.73 cm distance
 - impact of the source positioning vs uncertainty due to counting statistics

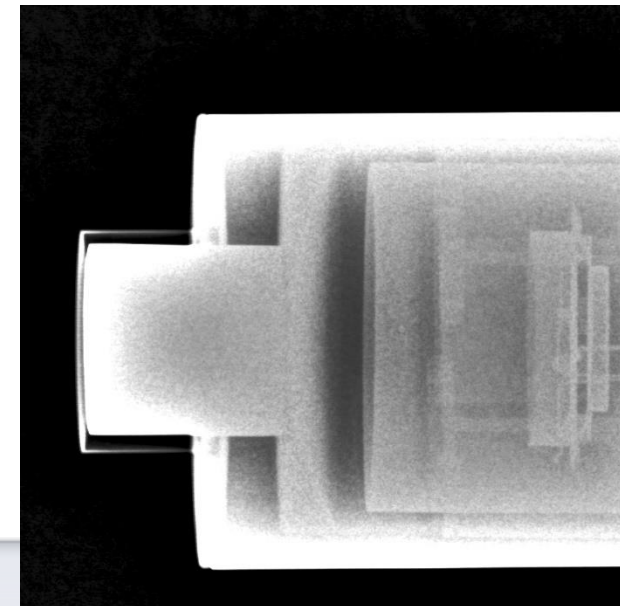
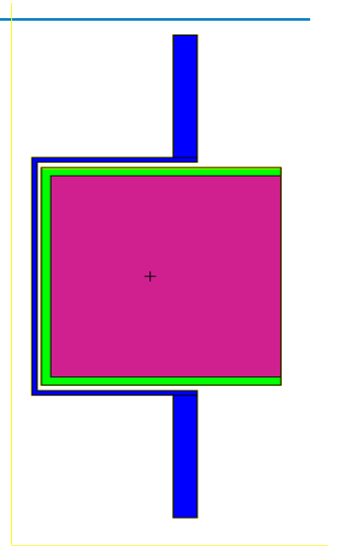


- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work



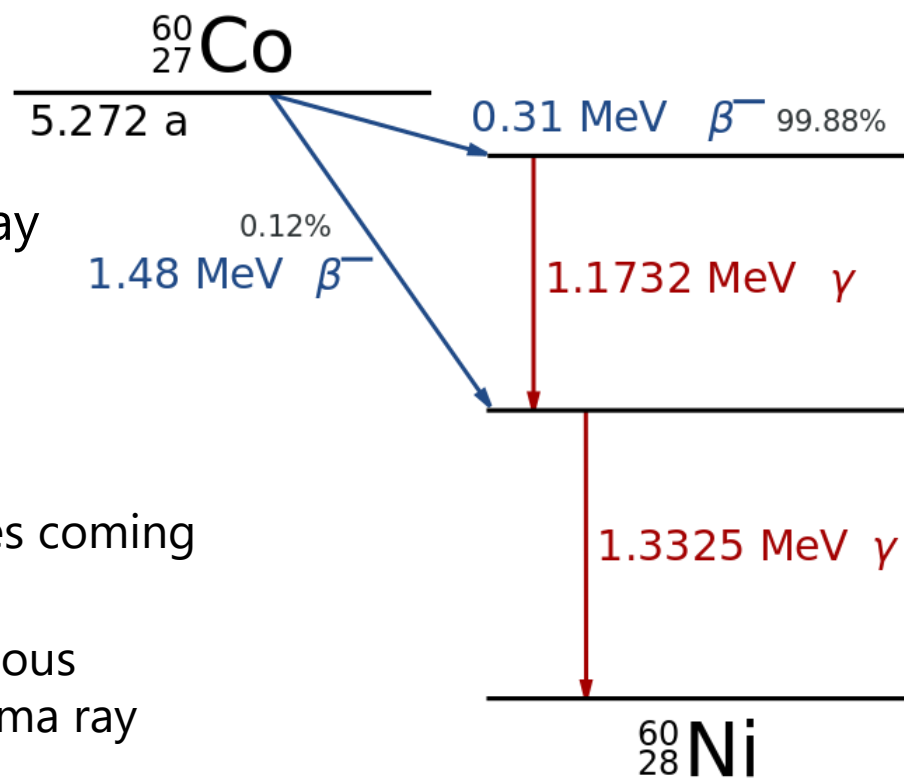
Modelling – Monte Carlo simulations

- Monte Carlo model of the measurement setup
 - modelled detector and materials around
 - Crystal
 - covered with PTFE reflector
 - surrounded by Aluminum casing
 - μ -metal shield covers the PM
- Design information verified by X-ray radiographies
 - crystal length 2.44 cm
 - diameter 2.46 cm



Modelling – Monte Carlo simulations

- F8 tally (R_1)
- MCNP6
 - Response to monoenergetic γ -ray
 - Tally, per simulated γ -ray
- MCNP-CP (patch of MCNP 4c)
 - Response to decay
 - statistical simulation of processes coming with the radioactive decay
 - i.e. accounts for quasi-simultaneous emission of more than one gamma ray following radioactive decay
 - All emitted nuclear particles tracked within the same history
 - Tally, per simulated decay
 - Same input, no VR, different source definition



Modelling – Monte Carlo simulations

Differences MCNP6 and MCNP-CP
vanish as distance increases

$$\Delta = 100 \times \left(\frac{\varepsilon_{MCNP6}}{(\varepsilon/P)_{MCNP-CP}} - 1 \right)$$

Main E _γ		0.67 cm		4.73 cm		10.75 cm	
keV		Δ	%	Δ	%	Δ	%
59.541	241Am	-0.1	±0.1	0.1	±0.1	0.2	±0.3
88.034	109Cd	0.1	±0.1	0.1	±0.1	-0.5	±0.3
122.061	57Co	0.3	±0.2	0.1	±0.2	-0.3	±0.2
165.857	139Ce	12.5	±0.2	0.9	±0.2	0.0	±0.4
391.698	113Sn	0.0	±0.2	0.4	±0.1	0.5	±0.2
514.007	85Sr	5.2	±0.2	5.1	±0.2	4.6	±0.2
661.657	137Cs	-0.1	±0.2	0.8	±0.2	0.7	±0.4
834.848	54Mn	0.8	±0.2	1.1	±0.2	1.1	±0.4
1115.539	65Zn	0.9	±0.2	1.6	±0.2	1.4	±0.3
1274.530	22Na	5.1	±0.2	2.2	±0.2	1.4	±0.4
1332.492	60Co	4.6	±0.2	2.3	±0.2	2.0	±0.3

ε full energy
peak efficiency
P emission probability

85Sr
Nuclear Decay Data
used by MCNP-CP ?

- The CLYC detector, general features
- Detector response to gamma-rays
 - Measurements
 - Modelling
 - Data analysis
 - Results
- Detector response to neutrons and future work



- Measured pulse height spectrum $N_{\text{exp}}(E_d)$

- Calculated $N_{\text{fit}}(E_d)$
$$N_{\text{fit}}(E_d) = C \iint R_2(E_d, E_e) R_1(E_e, E_\gamma) \Phi_E(E_\gamma) dE_e dE_\gamma$$

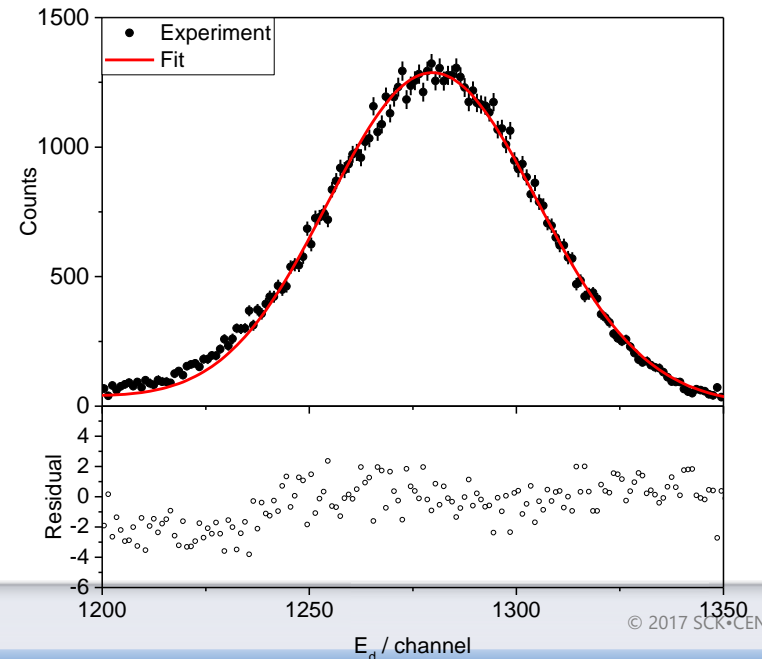
- $\Phi_E R_1$ from modelling

- $R_2(E_d, \mu(E_e)) = \frac{1}{\sqrt{2\pi}\sigma_\mu} \exp\left(-\frac{(E_d - \mu(E_e))^2}{2\sigma_\mu^2}\right)$
$$\left\{ \begin{array}{l} \mu = \alpha E_e \\ \sigma_\mu^2 = \beta \mu \end{array} \right.$$

- Least square minimization: C, α, β

$$\chi^2 = \sum_{i=1}^n \frac{(N_{\text{exp},i} - N_{\text{fit},i})^2}{S_{N,i}^2}$$

- C is # decayed nuclei, if R_1 expressed per decay, $N_{\text{exp}}(E_d)$ in counts



Results – repetitive measurements

- 9 repetitive measurements
 - ^{137}Cs source at 4.73 cm distance
 - source removed and repositioned every time
- C, α and σ for each case with uncertainty from fit (statistics)
- χ^2 analysis to determine uncertainty components not due to counting statistics

$$\chi^2 = \sum_{i=1}^n \frac{(\theta_i - \bar{\theta})^2}{s_{\theta,i}^2}$$

	C	α	σ
100 × $s_{\theta,i}/\theta_i$ (statistics)	0.5	0.01	1.3
χ^2 / ν	1.8	375	1.1
100 × $s_{\theta,i}/\theta_i$ (other)	0.4	0.15	0.5

- Energy calibration

- 1.001 keV/ch \pm 0.7% over 2 months
- energy independent
- no offset
- 0.7 % - Long term stability of high voltage, PMT or electronics

$$\mu = \alpha E_e$$

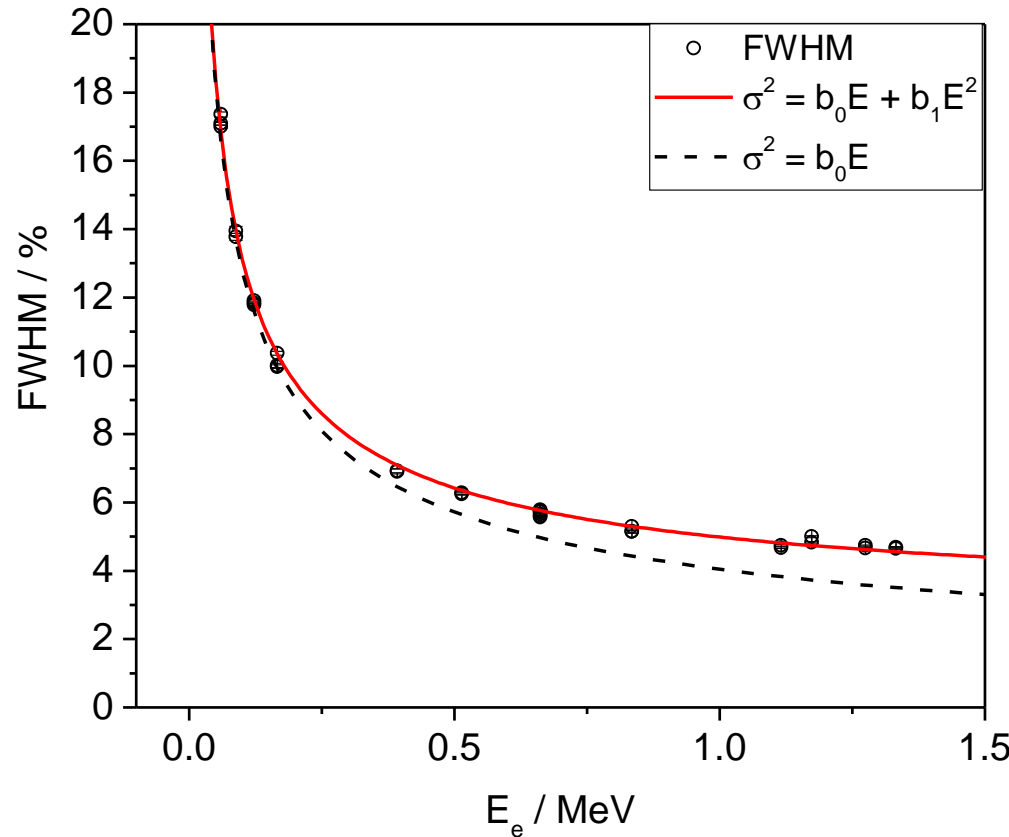
● Energy resolution

- $N_{\text{photons}} \propto E_e$
- $\sigma_{N_{\text{photons}}} \propto \sqrt{N_{\text{photons}}}$

$$FWHM_{\%} \propto \frac{\sigma_{\mu}}{\mu} \propto \frac{1}{\sqrt{E_e}}$$

● Deviation from $1/\sqrt{E_e}$

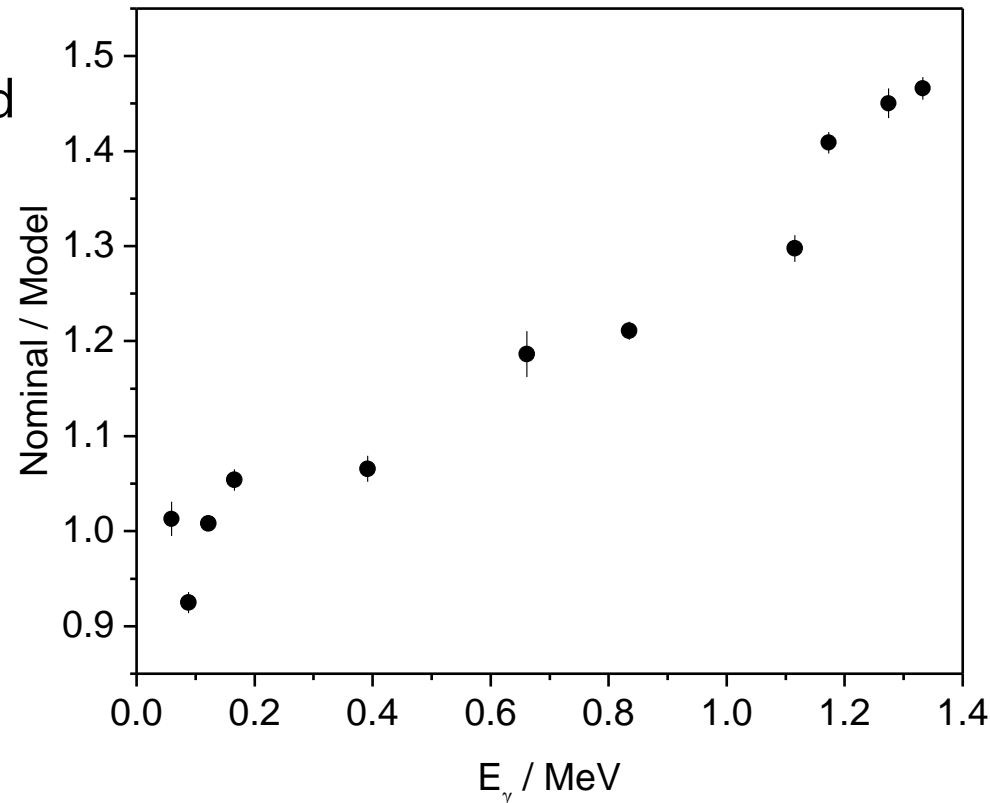
- Effects other than pure statistic
 - Crystal Intrinsic
 - PMT
 - Transfer variance (photon \Rightarrow electron)



- Absolute model benchmark

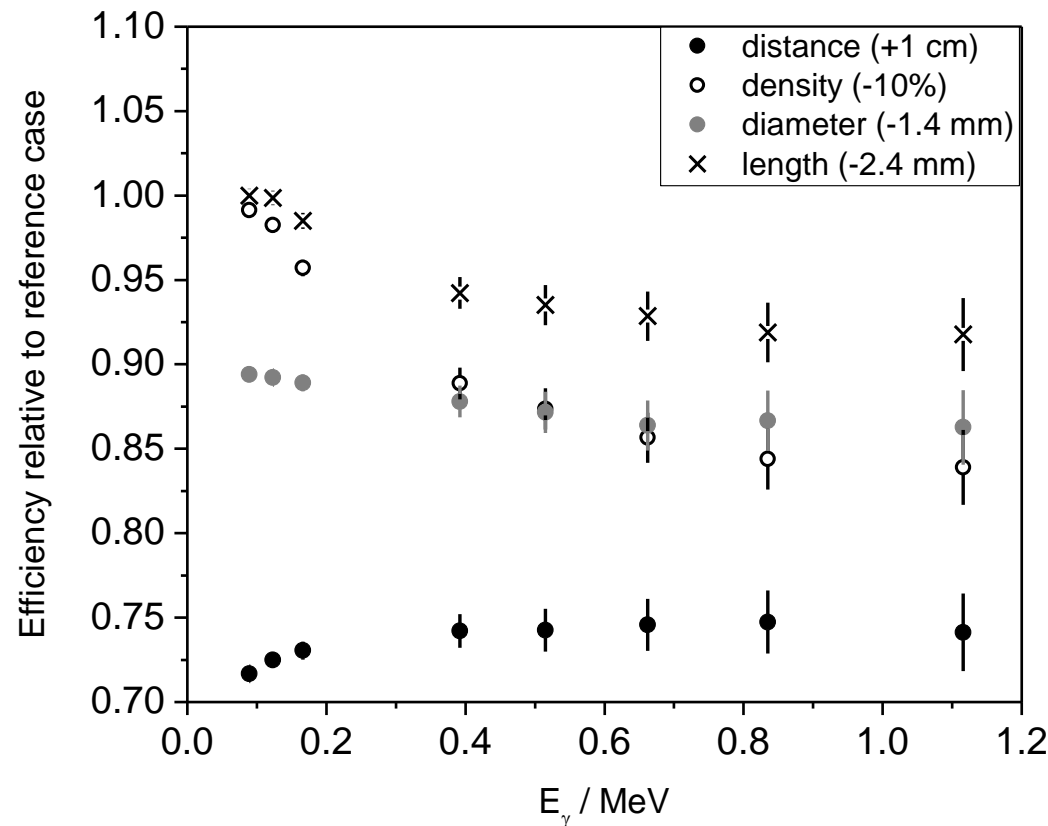
$$N_{fit}(E_d) = C \iint R_2(E_d, E_e) R_1(E_e, E_\gamma) \Phi_E(E_\gamma) dE_e dE_\gamma$$

- # of decayed nuclei
- Model response overestimated
- Trend with energy
- Same trend for all distances



Design variations

- Parameters affecting the efficiencies
 - Detector-Source distance
 - Crystal density
 - Crystal Diameter
 - Crystal Length
- Change in density consistent with observed trend



- Response of a CLYC detector to γ -rays
- Measurements with calibrated gamma point-sources in a well-given and reproducible geometry
- CLYC response modelled with MCNP-CP used to analyse the data
- Results
 - Linearity
 - Energy resolution
 - Presence on non statistical effect
 - Efficiency
 - Overestimated by model
 - Design variations

- Future work: testing the performance with neutron sources
- Data acquisition based on a CAEN 5730B digitizer
 - 2 ns sampling
 - Pulse Shape Discrimination on board

