DE LA RECHERCHE À L'INDUSTRIE

CALCULATION OF GAMMA-RAY RESPONSES FOR HPGe DETECTORS WITH TRIPOLI-4 MONTE CARLO CODE

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OUTLINE

- **/. Introduction**
- **/. TRIPOLI-4 code – application fields**
  verification & validation
- **/. Gamma-ray responses for HPGe detectors**
  - **-. Large crystal - ICRM 2008, 2018 cases**
  - **-. Small crystal - QUADOS 2003 case**
- **/. Calculation results**
- **/. Conclusions**

INTRODUCTION

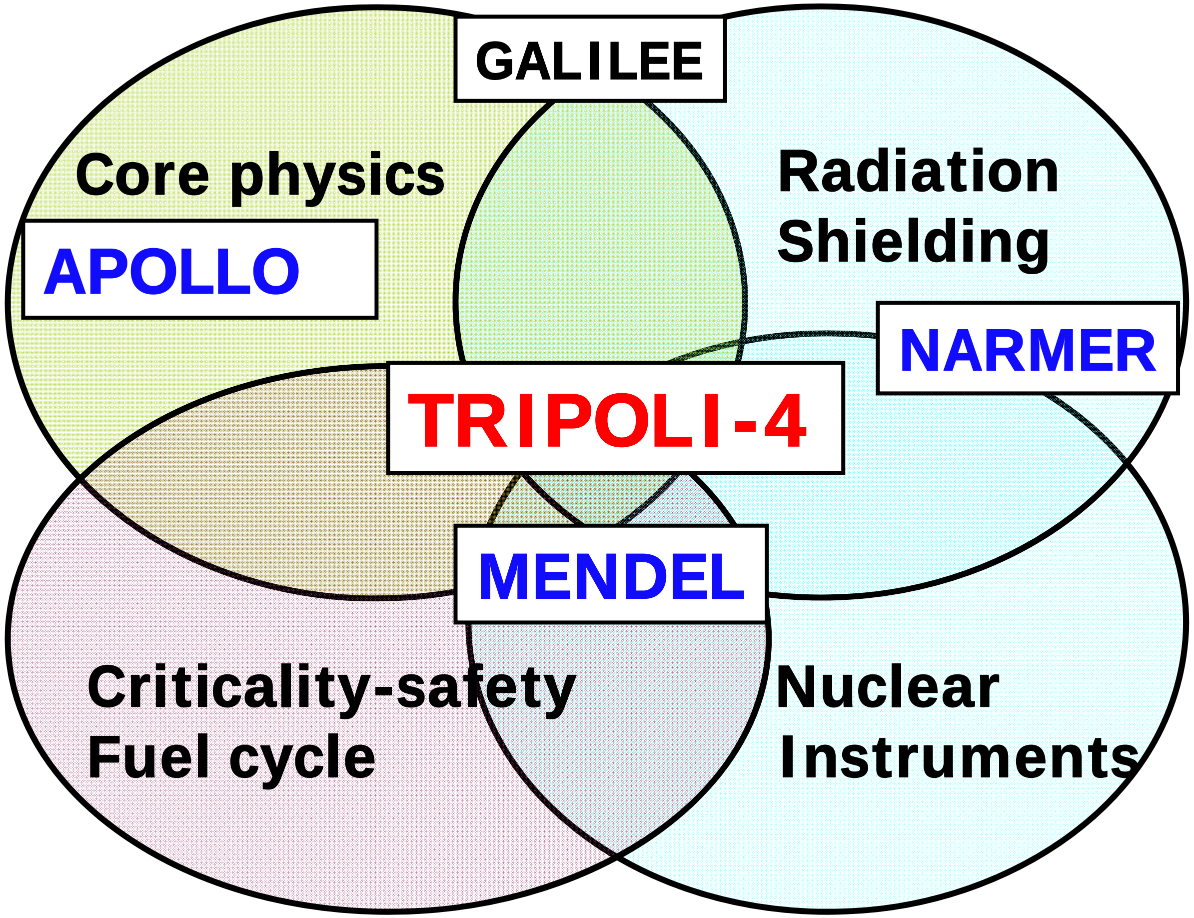
- **TRIPOLI-4 is a general purpose radiation transport code. It uses the continuous-energy Monte Carlo method to simulate neutron, photon, electron and positron transport in 3D geometry.**

- **TRIPOLI-4 application fields include radiation shielding, criticality safety, fission reactor physics, fusion reactor design, and nuclear instrumentation.**

- **To support the TRIPOLI-4 application on gamma-ray spectrometry, in this study, HPGe detector responses were calculated and benchmarked with PENELOPE and other Monte Carlo codes.**

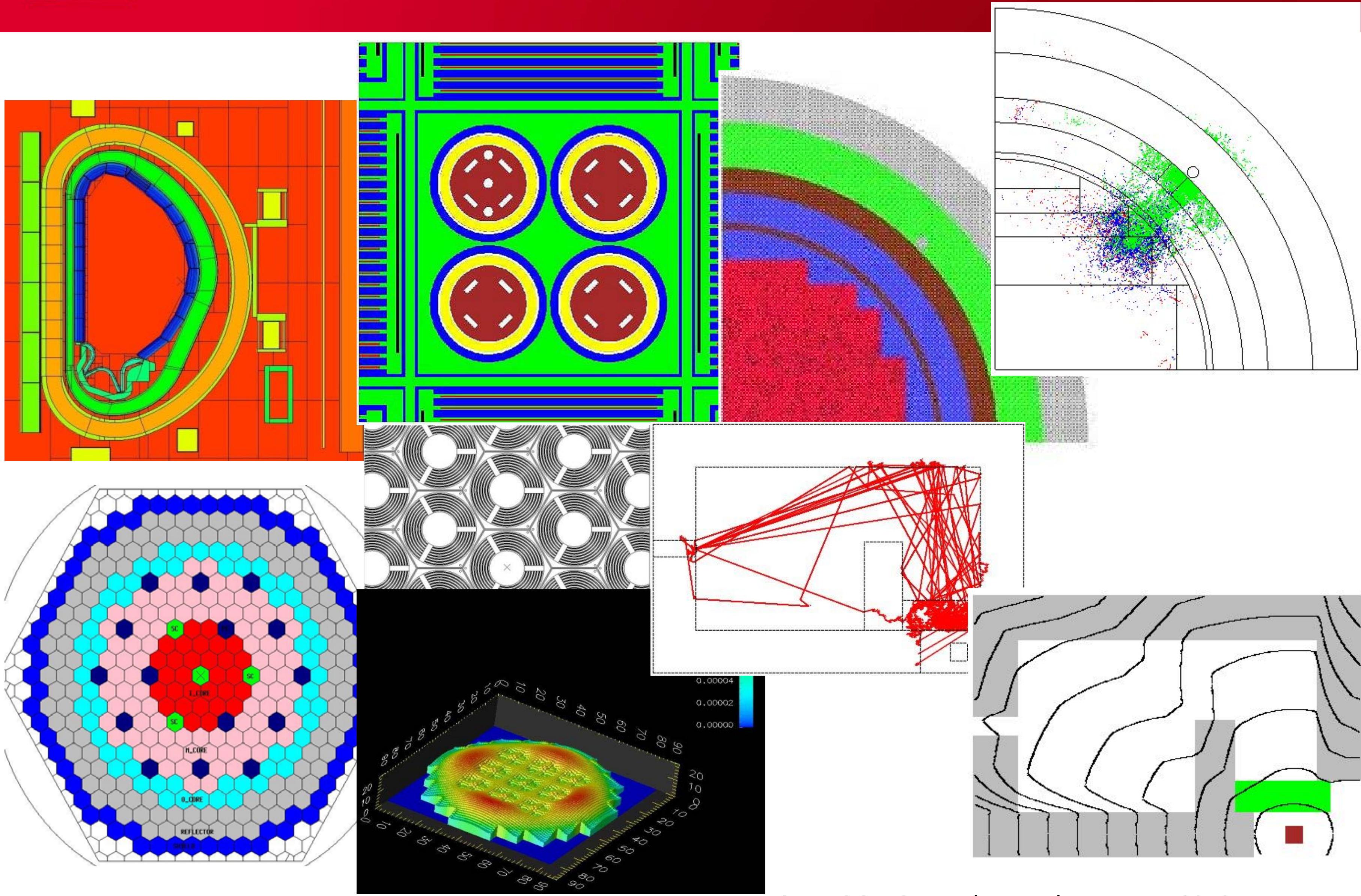
- **Using the new photon-electron cascades option of TRIPOLI-4, the detector efficiency curves and the pulse height distributions were established for HPGe detectors. The coincidence-summing correction factors of Co-60 were calculated.**

TRIPOLI-4 MONTE CARLO CODE & NUCLEAR ENGINEERING CALCULATIONS



- **GALILEE**
  JEFF, ENDF/B, ENDL
- **APOLLO2 / 3**
  DETERMINISTIC NEUTRONICS CODE
- **MENDEL**
  BATEMAN EQUATIONS SOLVER
- **NARMER**
  POINT KERNEL CODE

TRIPOLI-4 APPLICATION FIELDS



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TRIPOLI-4 CODE - VERIFICATION & VALIDATION

/. More than 1,000 benchmark cases from OECD/NEA are available in the TRIPOLI-4 validation database.
- SINBAD database for fission & fusion shielding
- ICSBEP handbook for criticality safety & shielding
- IRPhE database for reactor physics applications.

/. TRIPOLI-4 – Benchmark activities (CEA, IAEA, ANS, …)

C/T, C/E, C/C, Vn/Vn+1 => PENELOPE, MCNP ..
Component & Integral results
Code (options) => Photon & Electron
Data lib. (element, interaction) => ENDL-97
Modeling => HPGe & dead layer
User
Energy deposition,
e^- cutoff energy

TRIPOLI-4 BENCHMARK STUDY & REFERENCES

/. **ICRM (Int. Committee on Radionuclide Metrology) 2008 & 2018**

-. T. Vidmar et al., "An **Inter-comparison of Monte Carlo Codes** Used in **Gamma-ray Spectrometry**," ***Applied Radiation and Isotopes, 66 (2008) 764-768.***

-. **O. Sima**, "Simple Exercise on **Self-consistency** of the Methods Applied for the Evaluation of **Coincidence-summing Corrections** in the Case of Volume Sources," ***(2018)***

/. **QUADOS (Euratom FP6) 2003**

-. S. Ménard, "Peak Efficiencies and Pulse Height Distributions of a Photon Ge Spectrometer in the Energy Range Below 1 MeV," **Inter-comparison of the Usage of Computational Codes** in **Radiation Dosimetry**, Bologna, Italy, July 14-16, 2003.

Why is it important to repeat these benchmarks for TRIPOLI-4?

➔ 1) The electron-photon cascade showers option has been improved.

➔ 2) The coincidence summing corrections option is being introduced.

HPGE DETECTORS & GAMMA SOURCES MODELING

/. ICRM large Ge detector (Ge: D= 6 cm & H= 6cm)

-. **Model I : Bare cylinder Ge crystal & point source**

-. **Model II : HPGe detector & point source**

-. **Model III : HPGe detector & cylinder extended source**

-. **Model 2018 : HPGe detector & 3 cylinder extended sources**

-. HPGe detector: Ge crystal, **(dead layer),** central hole and Al housing
-. Extended source: high density water solution (2008) & **Vacuum (2018)**

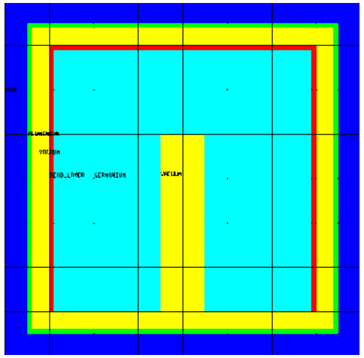
/. QUADOS small Ge detector (Ge: D= 4 cm & H= 1,5 cm) for low energy photon applications

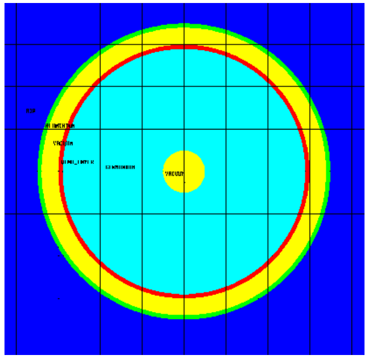
-. **Model IV : HPGe detector with Be window & disc source**

-. Detector: Ge crystal, dead layer, Al holder and housing

/. Mode I: Ge crystal only

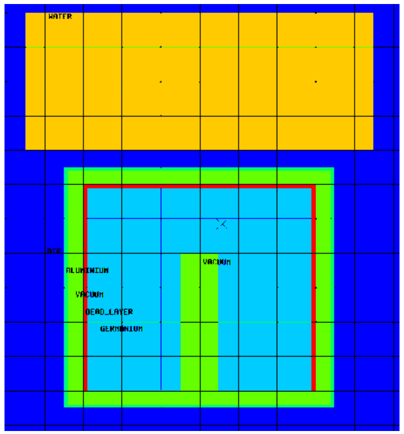
Point source

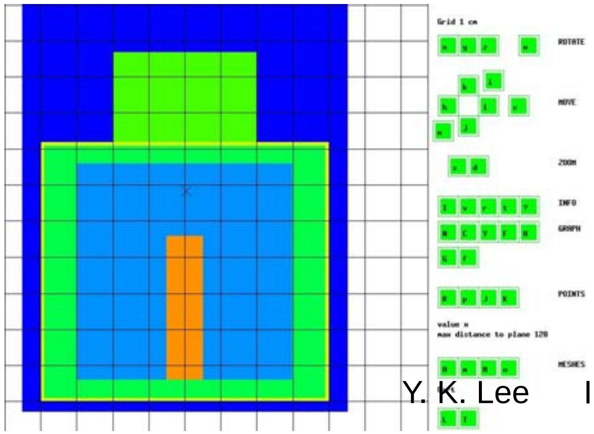




/. Model II: HPGe detector

Point source

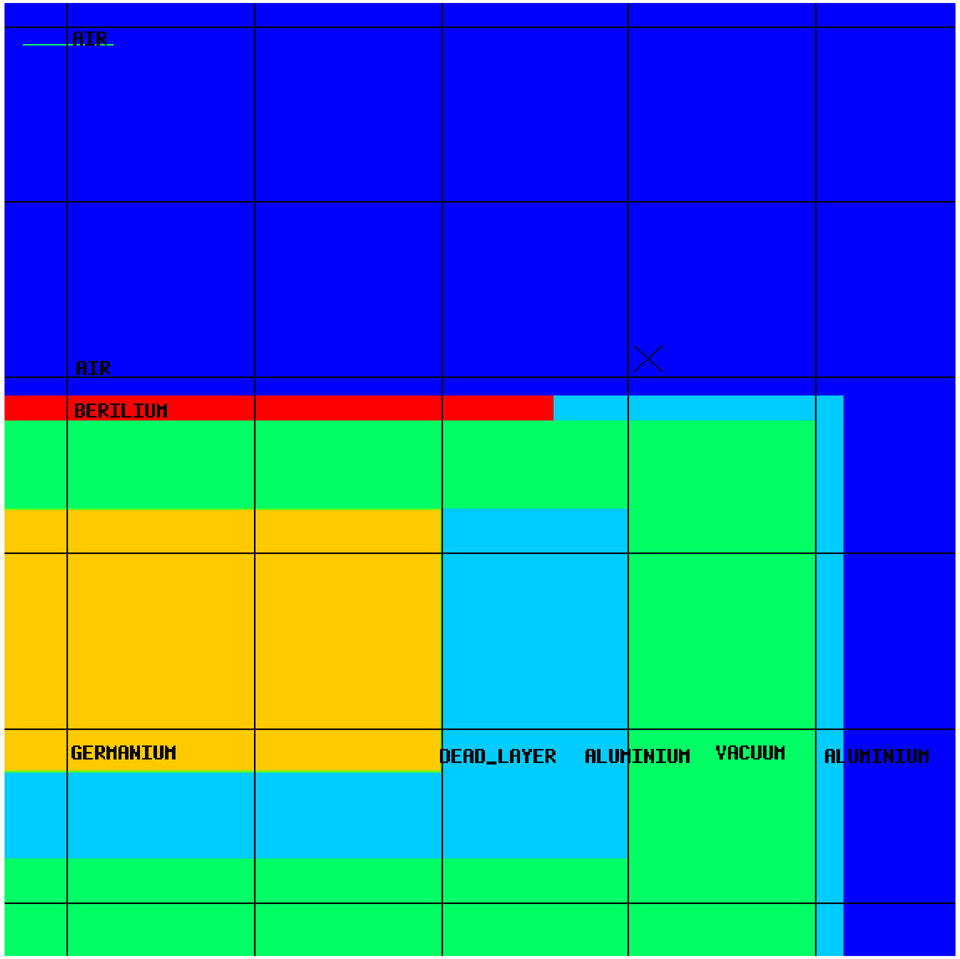




/. Model III & Model 2018a:

HPGe detector

& **Cylinder source**



Grid: 1 cm

/. Disc source

/. Al housing & Be window

/. Ge crystal

Ge dead layer 0.01 cm &

Al holder detector

TRIPOLI-4 – PARTICLE TALLY OPTIONS

/. Particle **flux** tallies can not be applied in this study

-. **Point** detector flux tally

-. **Volume** cell flux tally

-. **Surface** flux tally

-. **Mesh** flux tally

/. Two **energy deposition** **tallies** in TRIPOLI-4

-. **Deposited_Energy** tally (gamma-ray dose in a detector)

-. **Deposited_Spectrum** tally (HPGe detector efficiency)

TRIPOLI-4 – GAMMA SPECTROMETRY & SOURCE OPTIONS

/. **Deposited_Spectrum** tally (HPGe detector efficiency)

-. **FEP** Full energy peak efficiency

-. **TE** Total efficiency

-. **FC** Coincidence-summing correction factor

/. Source option and FC: 1.33 & 1.17 MeV γ from Co-60 (By courtesy of D. Mancusi)

-. Single: a traditional TRIPOLI-4 source, with overall NORM = 2

-. Single-ext.: an external source with NORM = 2 that randomly selects the photon energy with equal probability

-. Multi: a multi-particle source with NORM = 1, which produces a pair of **uncorrelated** decay photons (**SAME_HISTORY**)

-. Multi-ext: an external multi-particle source, producing two γ per history with **realistic angular correlations.** (Ref. E. L. Brady, Phys. Rev. 78(1950)558)

TRIPOLI-4 – ENERGY VARIABLE & PARALLEL COMPUTING

/. Models I, II, III, and IV (2008 & 2003)

4 detector models x 12 energy points x 2 particle options

-. **Limit to 4 input files for 4 models**

-. **Source energy: a variable "energy" instead of a value**

-. **Particle option: "photon" or "photon, electron, positron"**

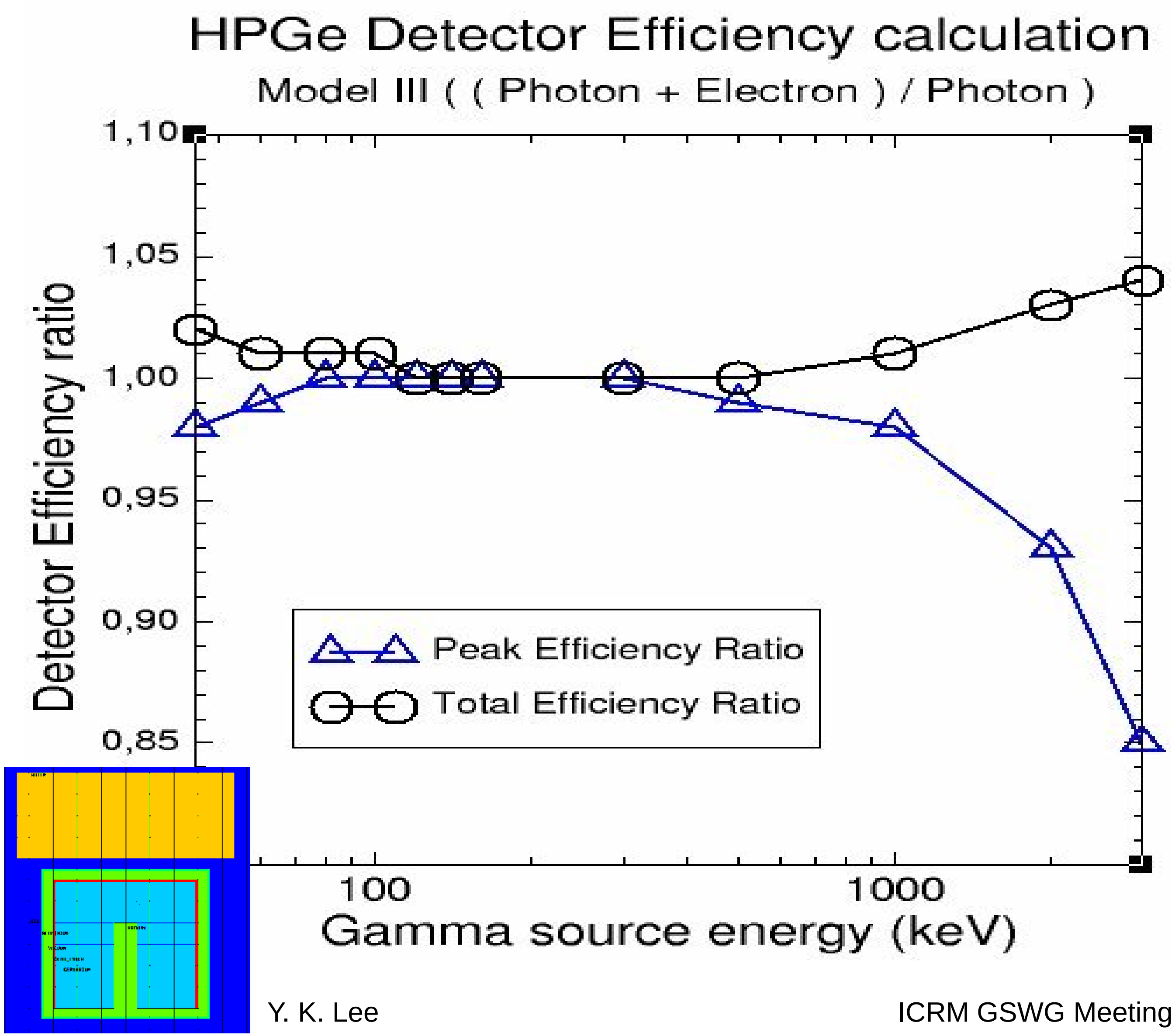
-. **for energy in 3, 2, 1, …..; do lpar –n 48 tripoli4.8.1 … done;**

/. TRIPOLI-4 parallel calculations for HPGe detector efficiency

-. **CPU runtime: (Deposited_Spectrum) >> (Flux)**

(Electron & Positron) >> (Photon)

CALCULATION RESULTS - 1 ((P + E) / P)



P + E

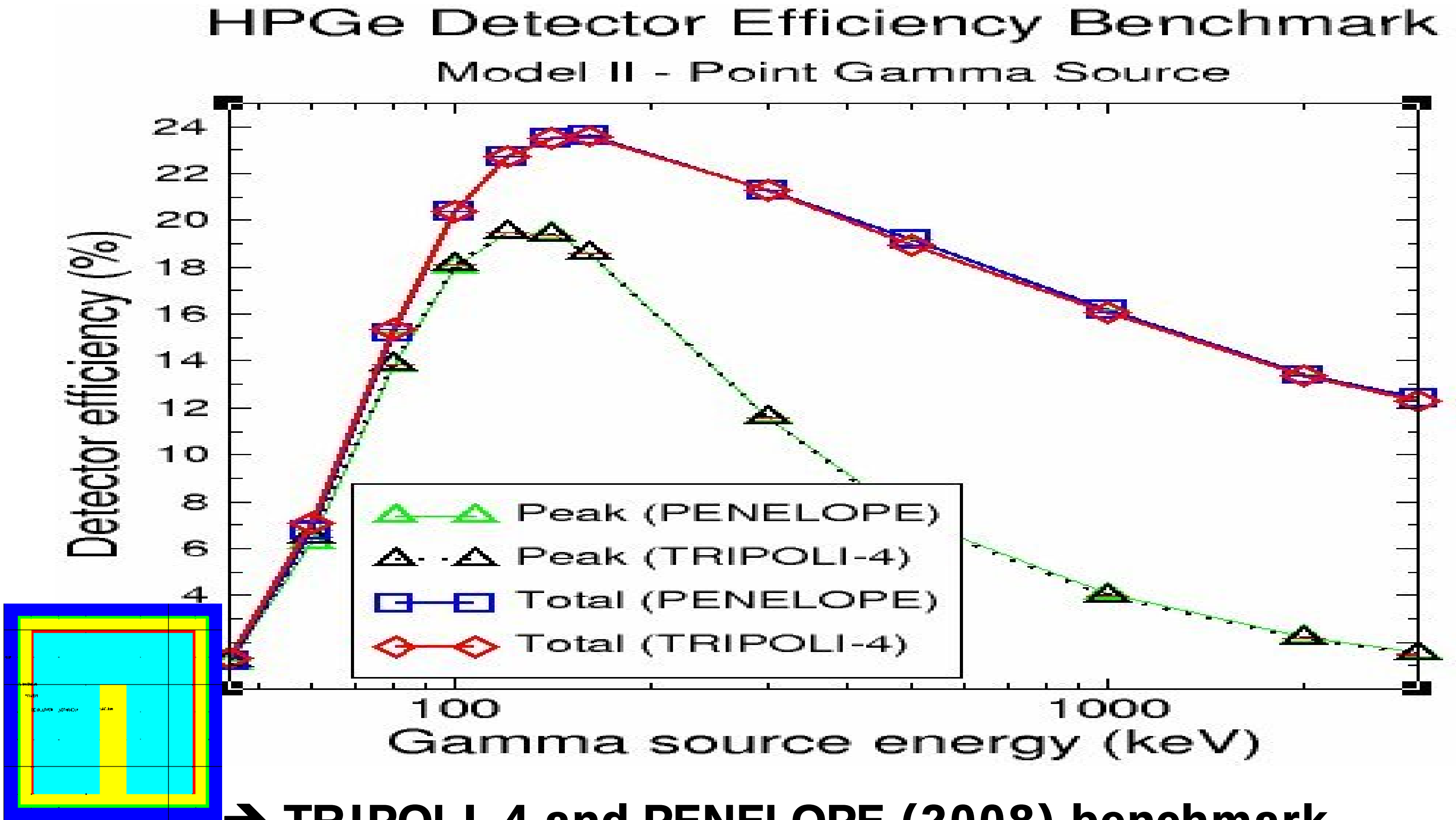
=> Photon + Electron + Positron

P

=> Photon transport only

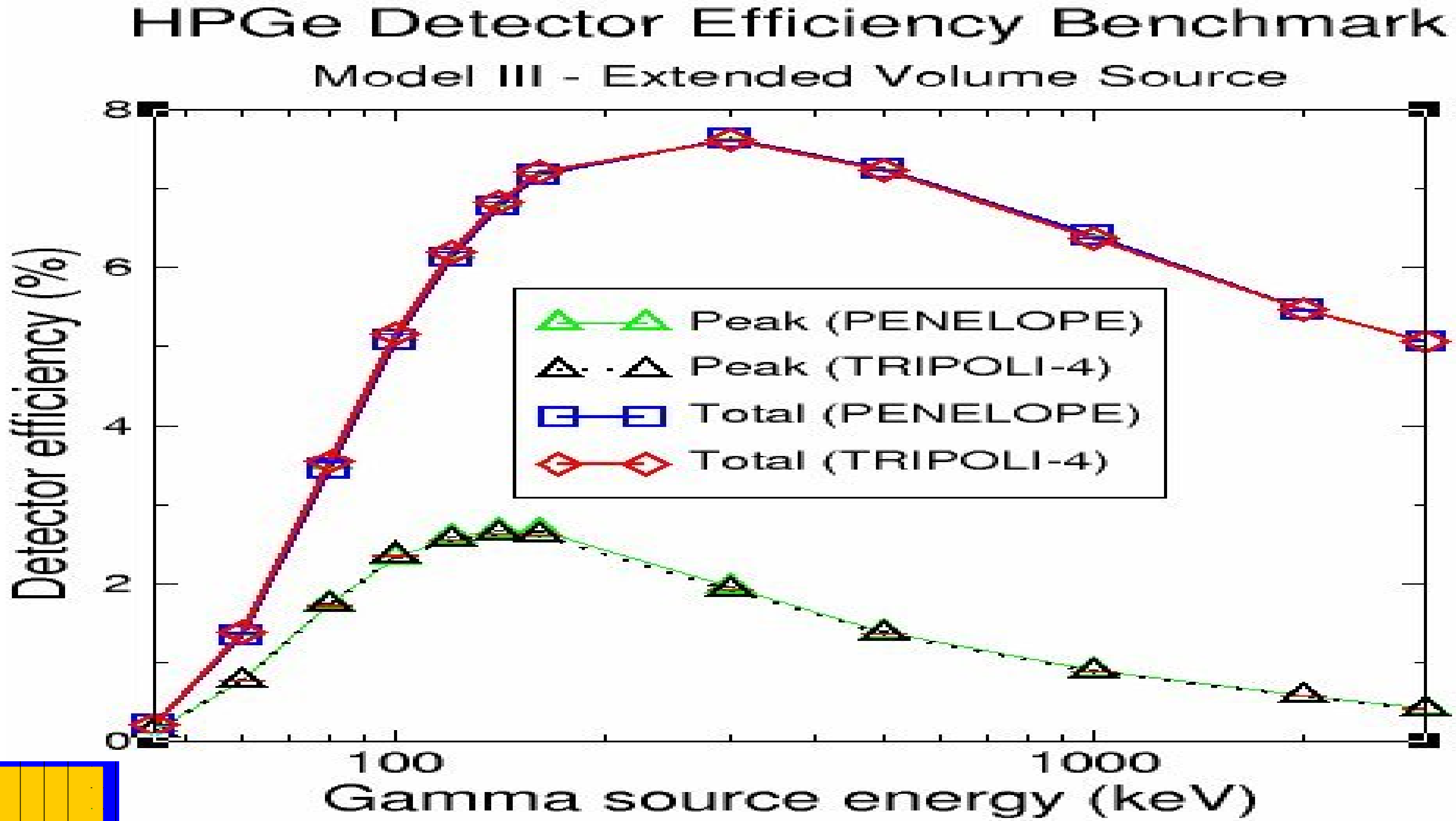
=> Over-estimate Detector Peak Efficiency

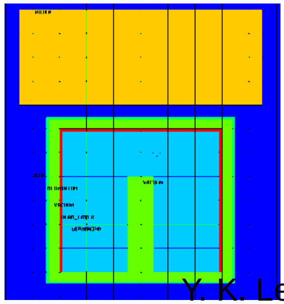
CALCULATION RESULTS - 2



➔ **TRIPOLI-4 and PENELOPE (2008) benchmark**

CALCULATION RESULTS - 3

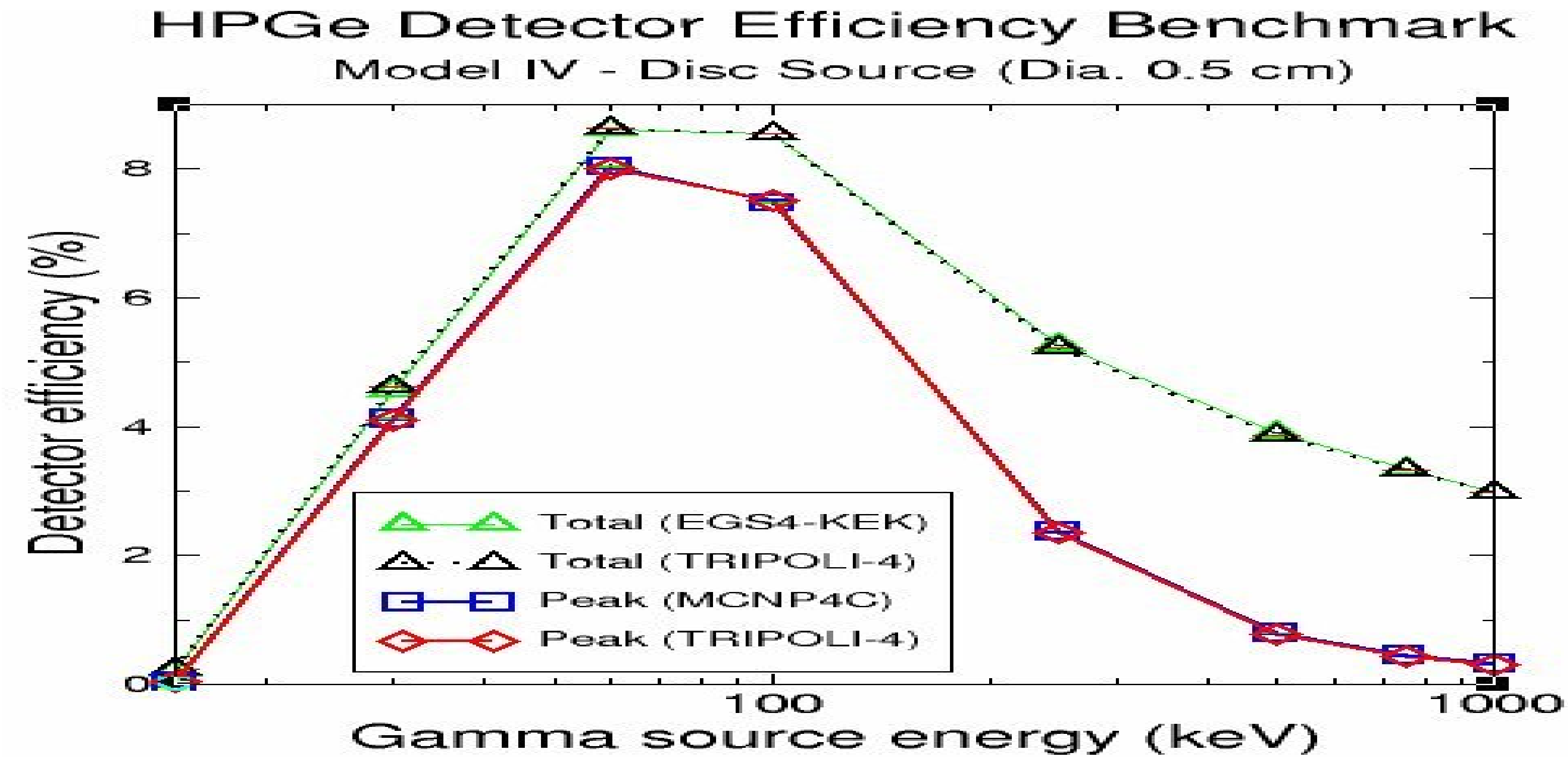




➔ TRIPOLI-4 and PENELOPE (2008) benchmark

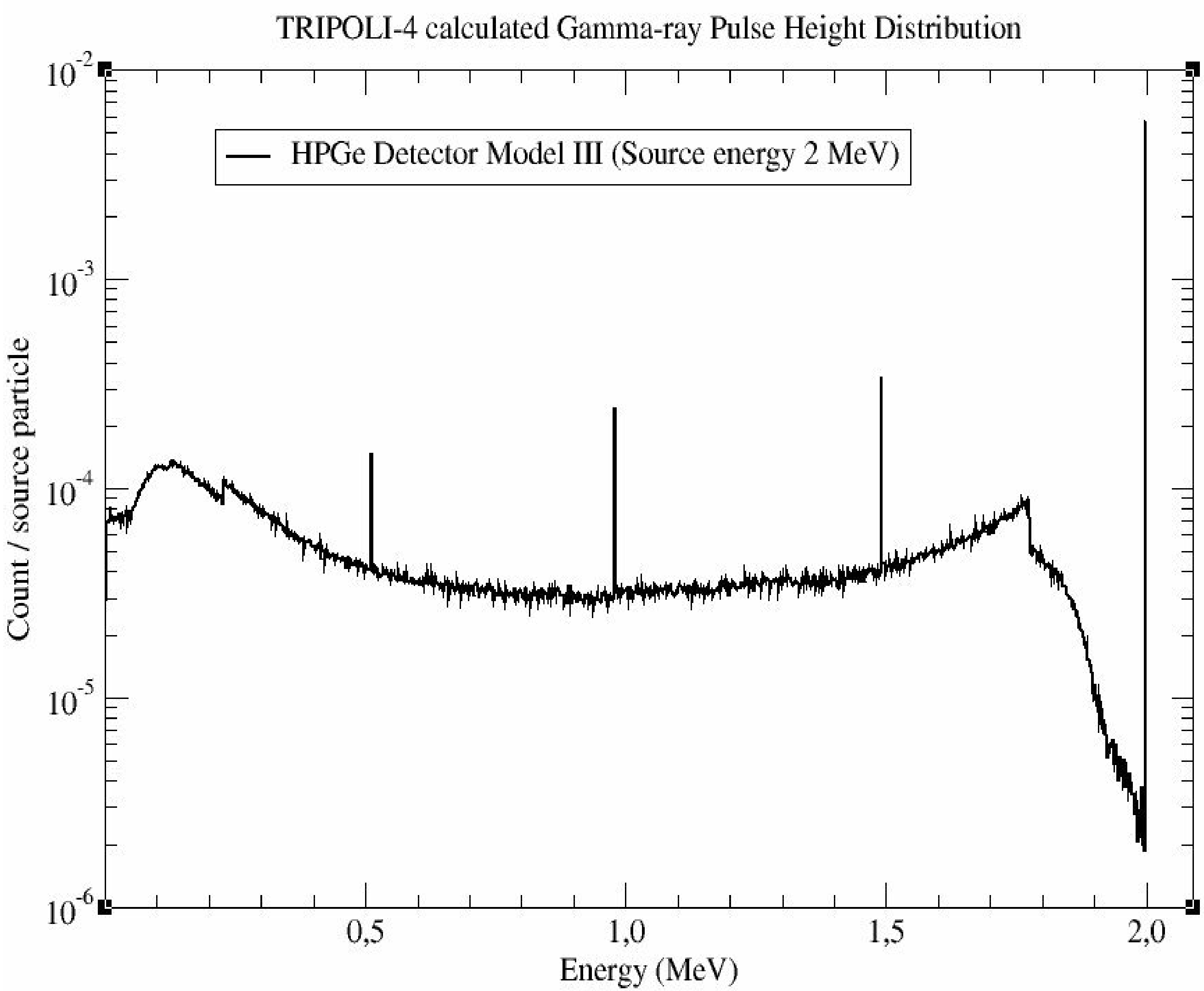
➔ Self-shielding effect in the extended source

CALCULATION RESULTS - 4



➔ **TRIPOLI-4, EGS4 and MCNP4C benchmark**
➔ **Low energy detector – Efficiency peak: 60 keV**

TRIPOLI-4 RESULTS - PULSE HEIGHT DISTRIBUTION 1

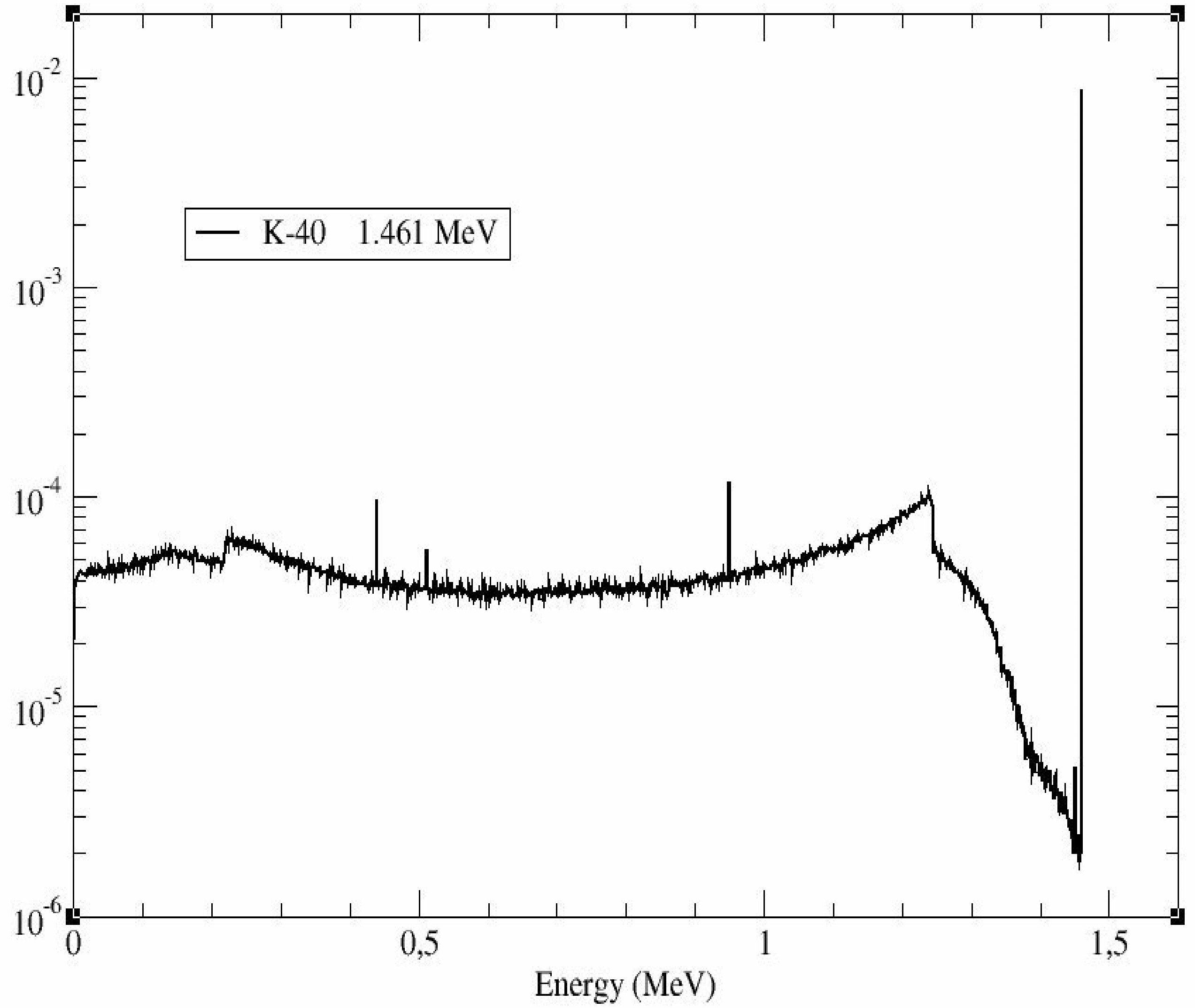


Source Energy: 2 MeV

=> Compton edge

=> SEP, DEP, 0.511 MeV peaks

TRIPOLI-4 RESULTS - PULSE HEIGHT DISTRIBUTION 2

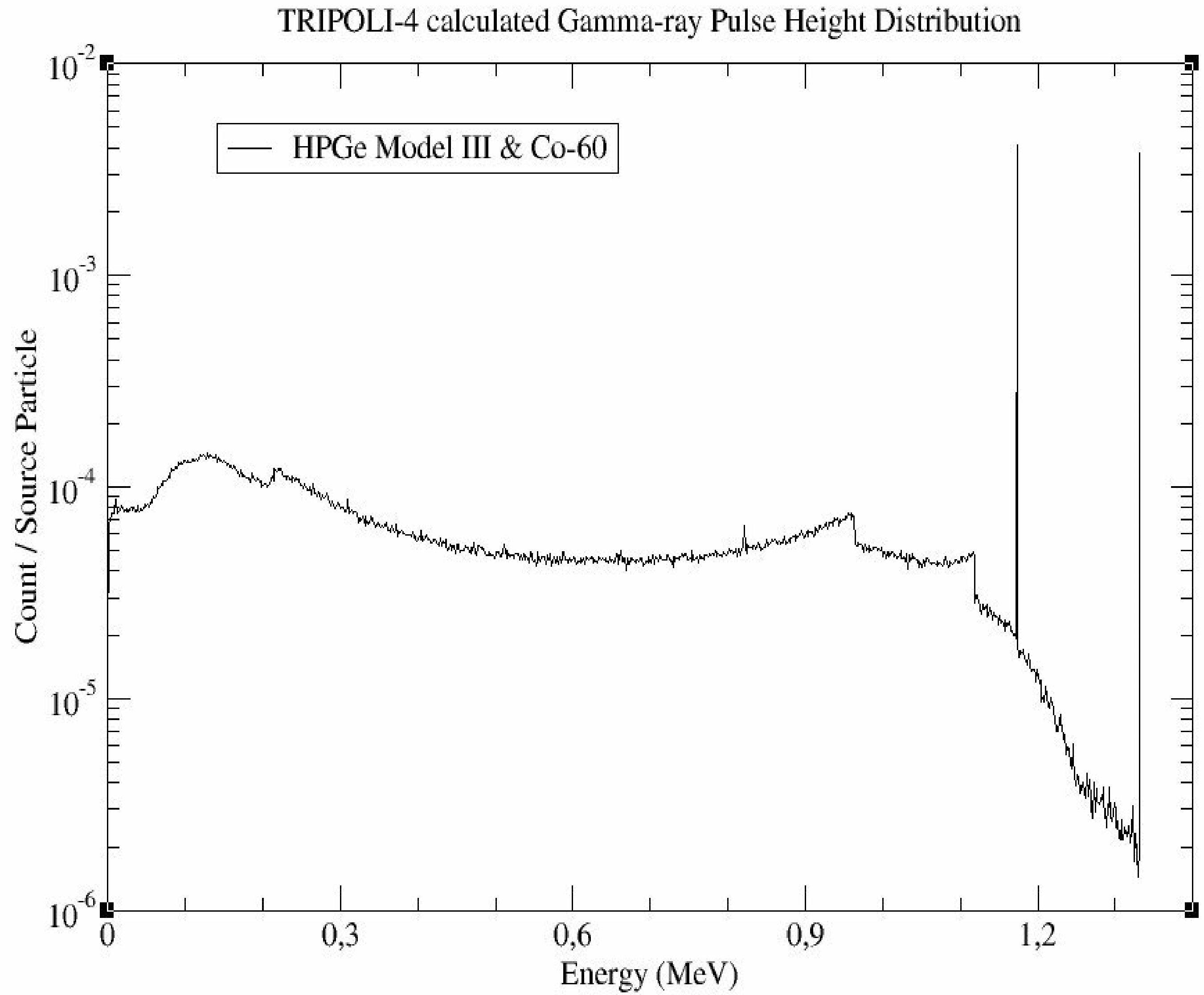


Source:
K40

=> Compton edge

=> SEP, 0.511 MeV, DEP peaks

TRIPOLI-4 RESULTS - PULSE HEIGHT DISTRIBUTION 3

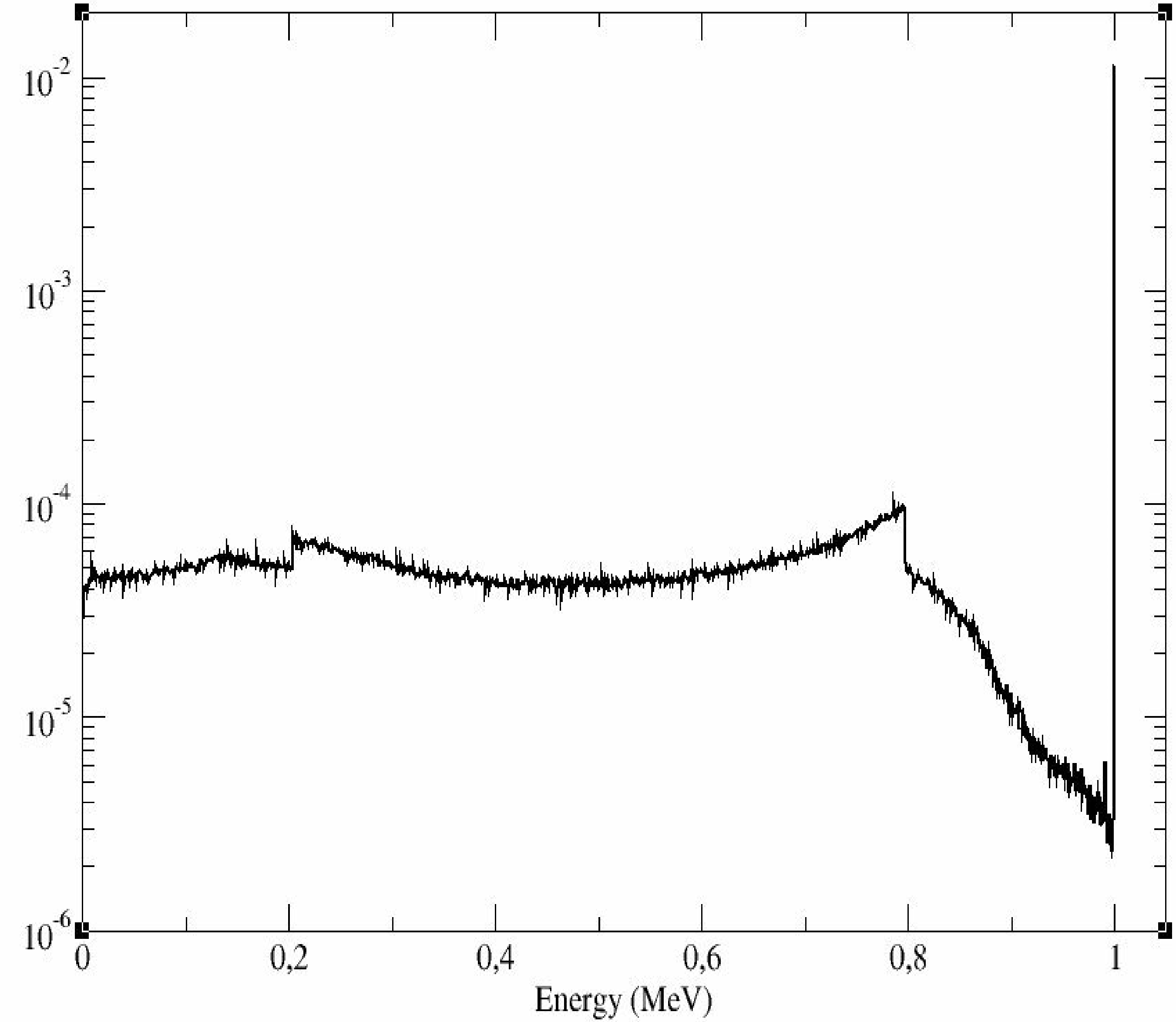


Source: Co60

=> 1.33, 1.17 MeV peaks

=> Compton edges

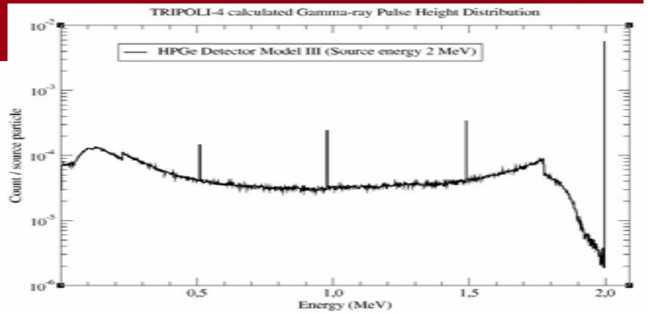
TRIPOLI-4 RESULTS - PULSE HEIGHT DISTRIBUTION 4



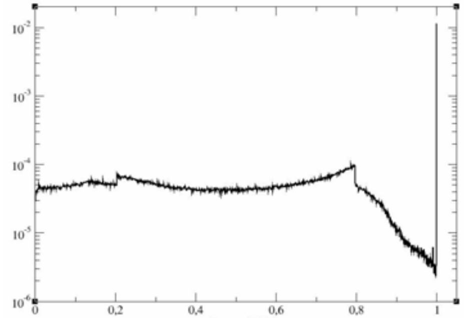
Source Energy: 1 MeV

=> Compton edge

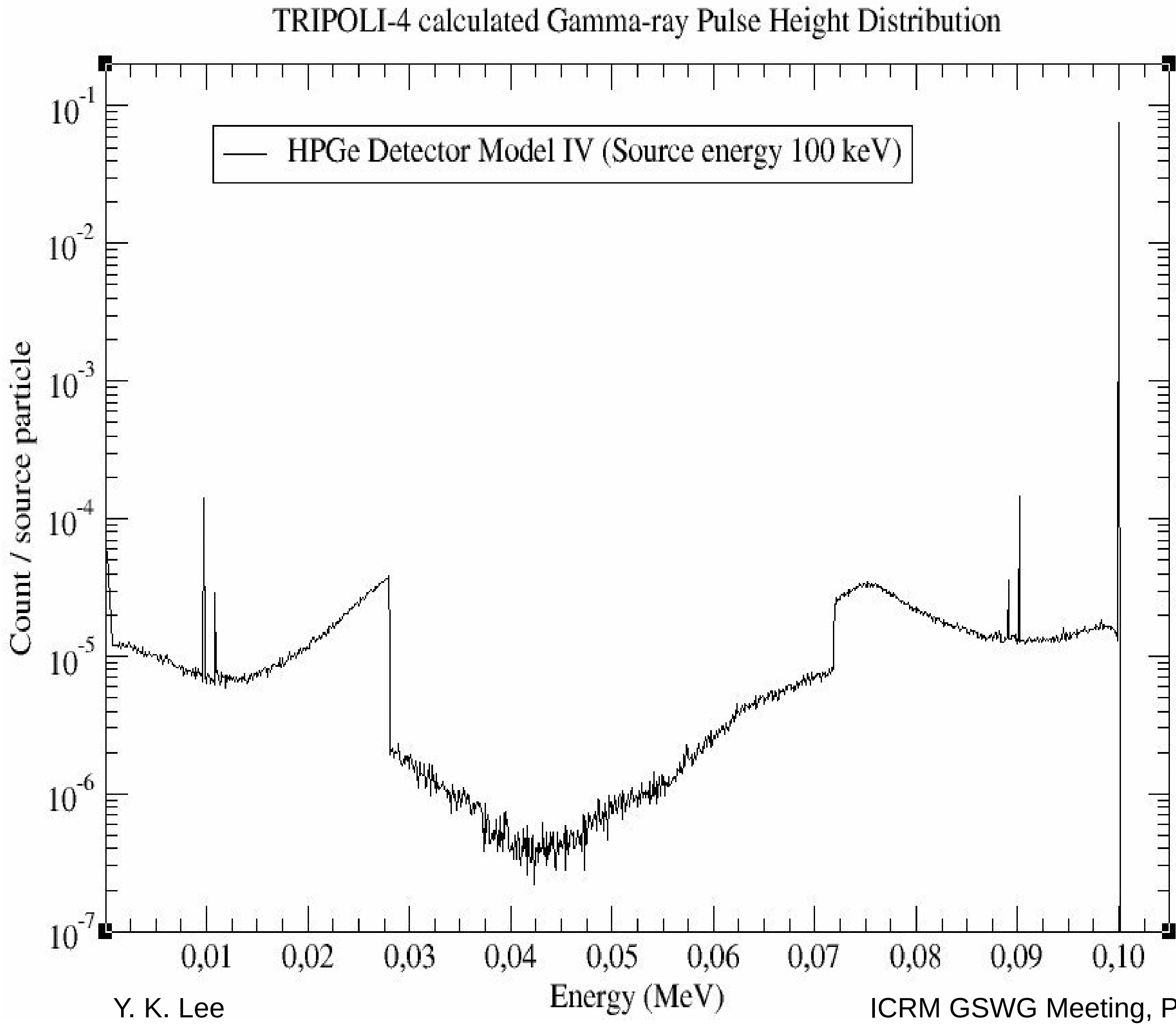
=> Backscatter peak



- Full-energy peak   E = E (source)
- Compton valley   Multiple Compton events
- Compton edge   E' = E – Ee⁻
  = E / (1 + 2 E / 0,511 MeV)
- Compton continuum   (SEP, DEP, 0,511 MeV peaks)
- Backscatter peak   E' < 0,25 MeV
- Low energy rise



TRIPOLI-4 RESULTS - Ge K-SHELL X-RAY ON PHD



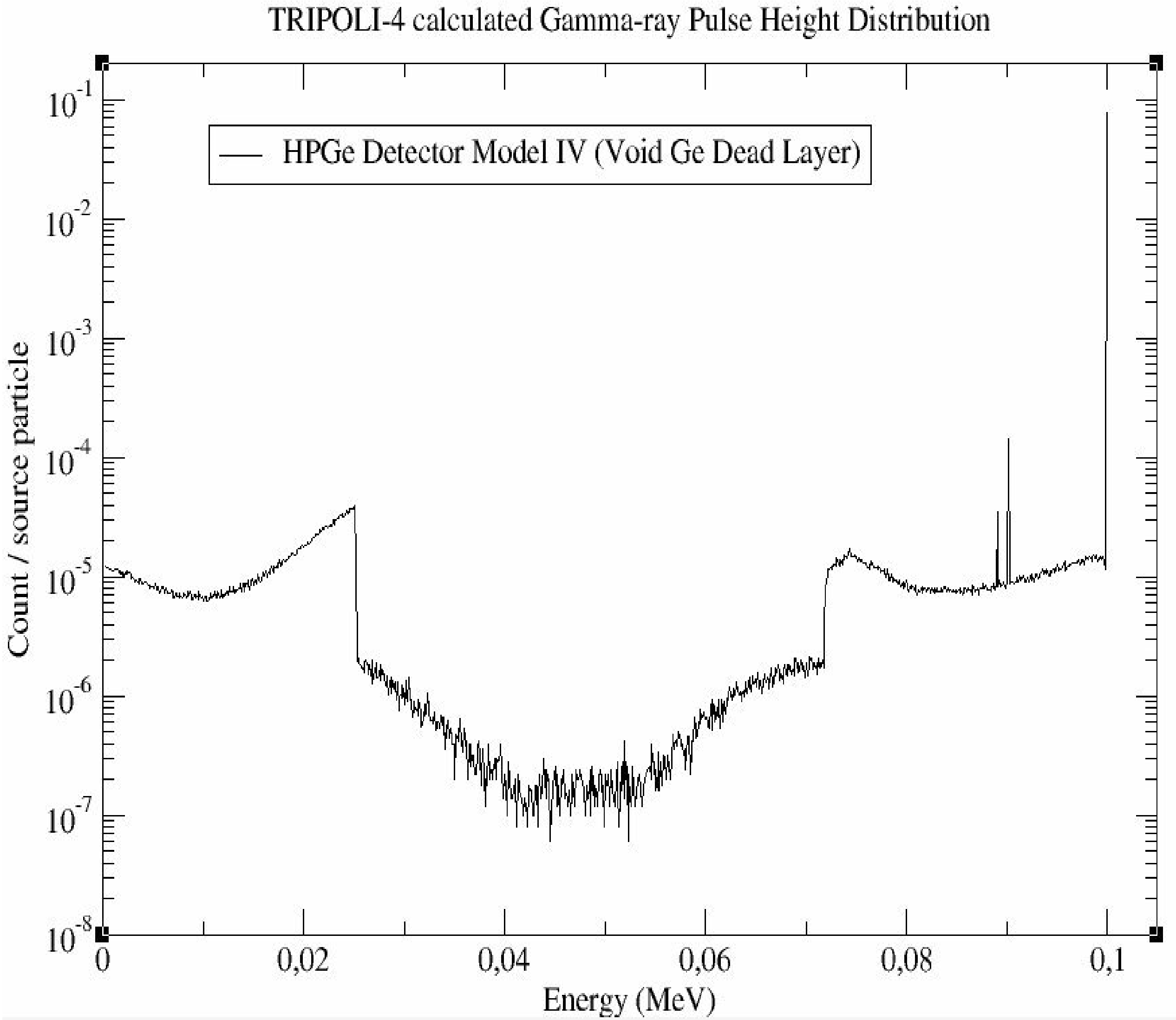
Source Energy: 100 keV

=> K-shell X-ray peaks

=> Compton edge

=> Backscatter peak

TRIPOLI-4 RESULTS - Ge Dead layer 100 μm



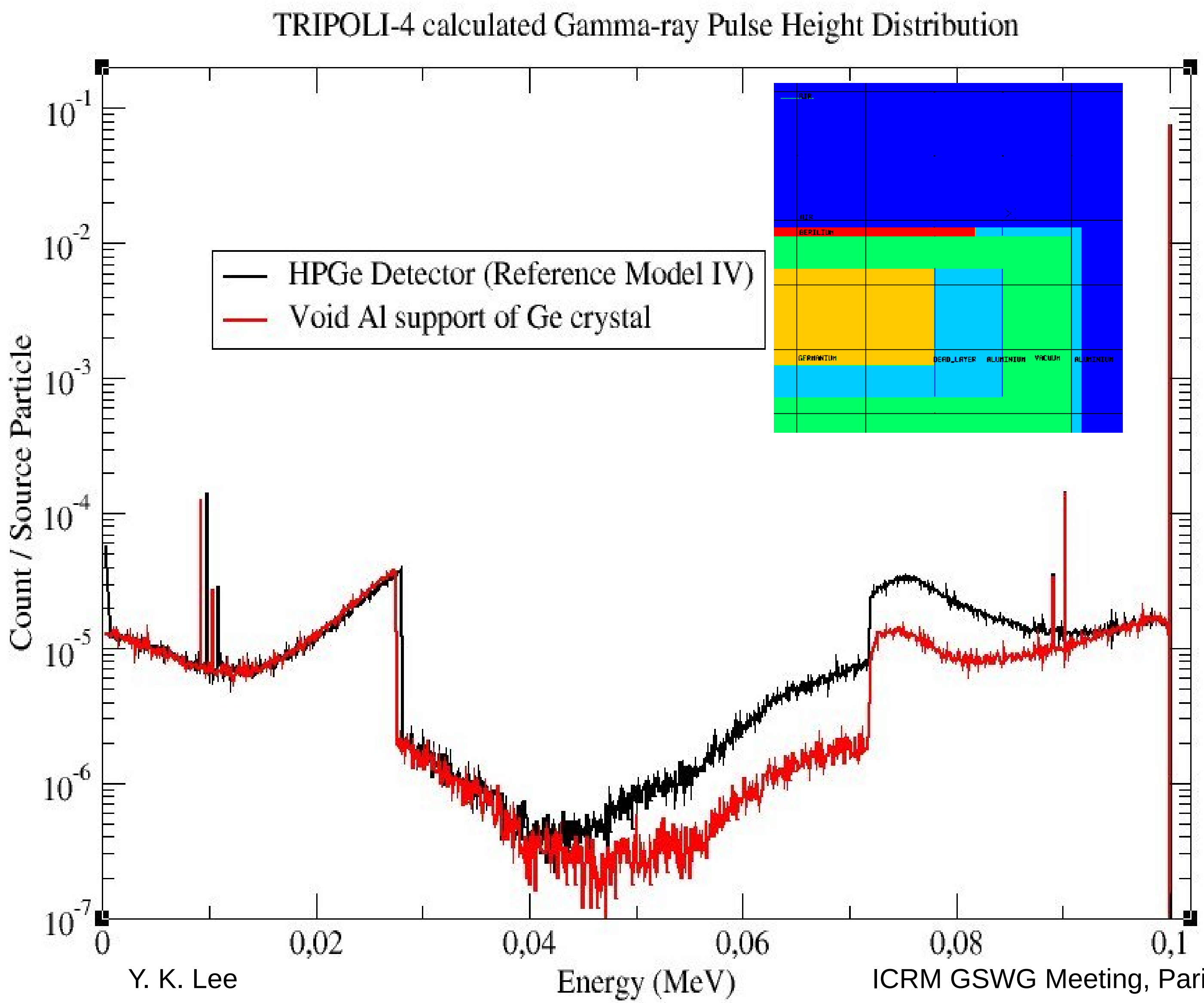
Void dead layer

=> Backscatter peak

=> Compton edge

=> K-shell X-ray peaks ?

TRIPOLI-4 RESULTS - VOID Alu. SUPPORT OF Ge

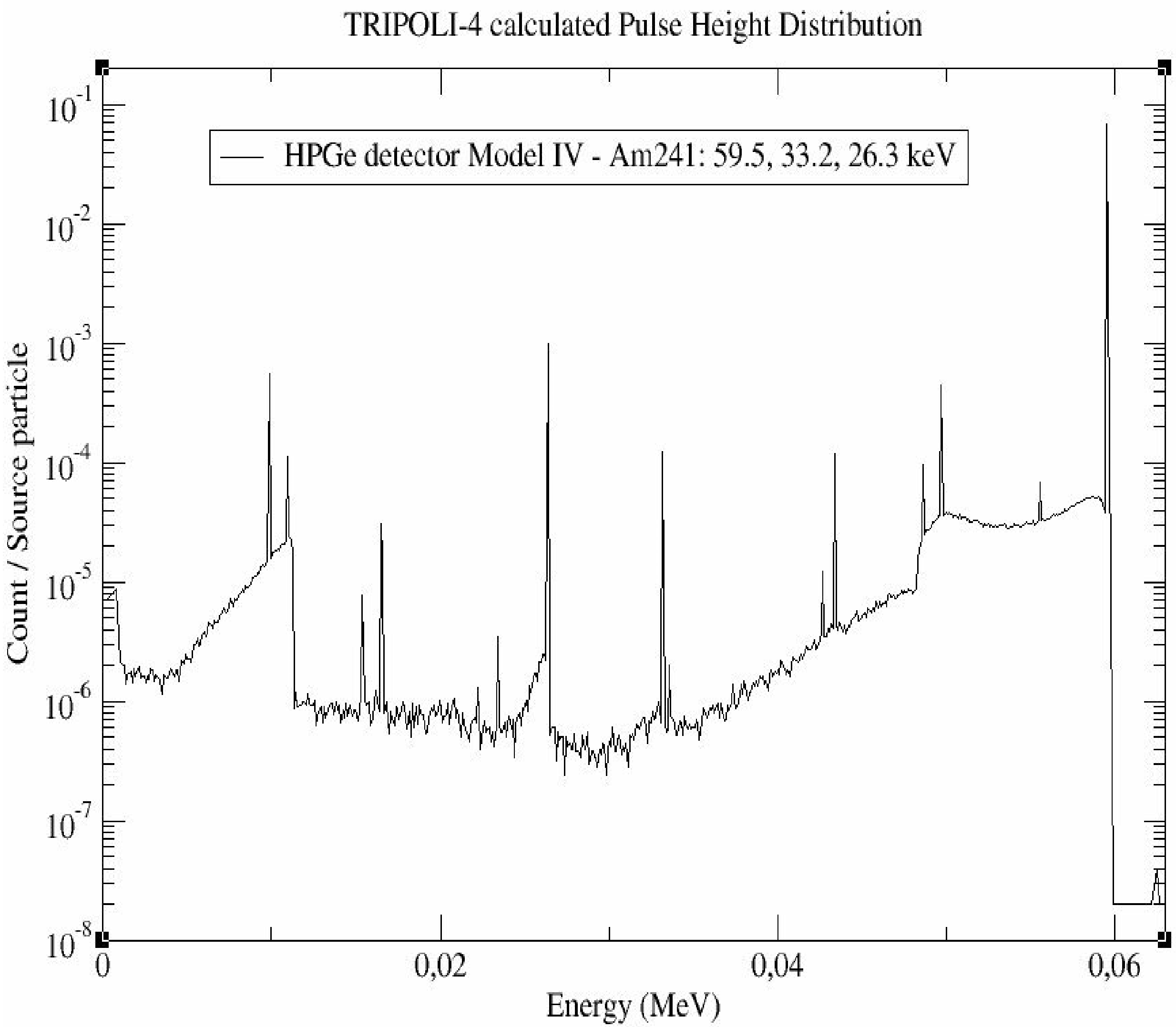


Void Alu.

=> Backscatter peak decreases

=> Compton edge & K-shell X-ray peaks

TRIPOLI-4 RESULTS - LOW ENERGY PHD



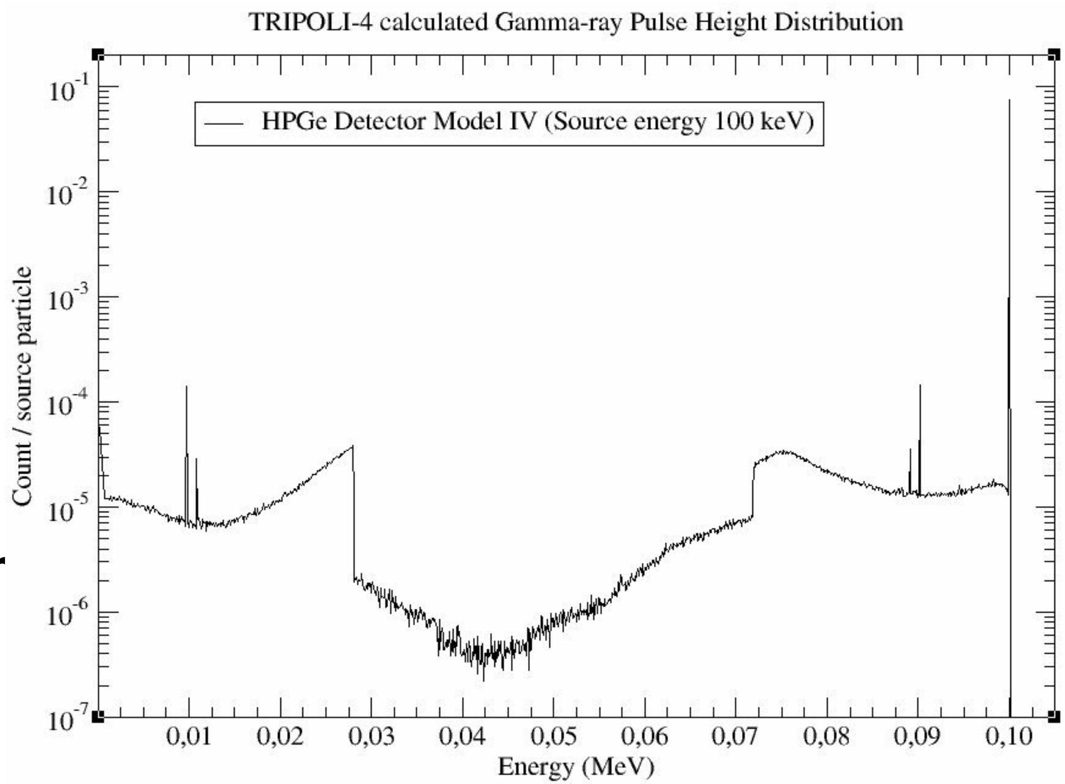
Source:
Am241

=> 59.5, 33.2, 26.3 keV peaks

=> Ge K-shell peaks

Low energy photon cases

- **Full-energy peak**
- **X-ray escape peaks**
- **Backscatter peak**
- **Compton continuum**
- **Compton edge**



- **X-ray peaks** **HPGe K-shell 11.1 keV**

Dead layer K-shell X-ray 9.83 & 10.93 keV

CONCLUSIONS - 1

/. The TRIPOLI-4 Monte Carlo transport code was successfully applied on the gamma-ray spectrometry.

/. TRIPOLI-4 calculated HPGe detector efficiencies were in good agreement with the PENELOPE and MCNP ones.

/. Neglecting the electron transport in calculation can under-estimate the leakage of gamma energy from the Ge crystal and over-estimate the detector efficiency.

/. Higher cut-off energy of electron reduces the cpu runtime but it increases the deposited energy in the detector and thus over-estimates the detector efficiency.

CONCLUSIONS - 2

/. Neglecting the characteristic X-ray escapes from Ge crystal in simulation can introduce error in the detector efficiency for low energy gamma-ray.

/. From the TRIPOLI-4 calculated deposited energy pulse height distributions, Compton edge, single and double escape peaks of pair production were identified.

/. The coincidence summing corrections option is being introduced into TRIPOLI-4 code. Preliminary tests for Co-60 were performed with Prof. Sima's Model 2018.

/. The calculation efficiency was improved with the current TRIPOLI-4.11 compared with the earlier versions.

Questions?

TRIPOLI-4.8.1 & TRIPOLI-4.9S are available from OECD/NEA databank

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