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

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OUTLINE

1. Introduction

2. TRIPOLI-4 code – application fields
   verification & validation

3. Gamma-ray responses for HPGe detectors
   - Large crystal - ICRM 2008, 2018 cases
   - Small crystal - QUADOS 2003 case

4. Calculation results

5. Conclusions
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.

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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
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

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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.
/. 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

/. 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
TRIPOLI-4 MODELING – QUADOS HPGe DETECTOR

Disc source

Al housing & Be window

Ge crystal

Ge dead layer 0.01 cm & Al holder detector

Grid: 1 cm
/ Particle flux tallies cannot 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 $\gamma$ 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 $\gamma$ per history with realistic angular correlations. (Ref. E. L. Brady, Phys. Rev. 78(1950)558)
  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**
  - \(\Rightarrow\) Photon + Electron + Positron

- **P**
  - \(\Rightarrow\) Photon transport only
  - \(\Rightarrow\) Over-estimate Detector Peak Efficiency
TRIPOLI -4 and PENELOPE (2008) benchmark

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TRI POLI -4 and PENELOPE (2008) benchmark
→ Self-shielding effect in the extended source

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TRI POLI -4, EGS4 and MCNP4C benchmark
Low energy detector - Efficiency peak: 60 keV
TRIPOLI-4 calculated Gamma-ray Pulse Height Distribution

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Source:
K40

=> Compton edge

=> SEP,
0.511 MeV,
DEP peaks
TRIPOLI-4 calculated Gamma-ray Pulse Height Distribution

Source:
Co60

=> 1.33,
1.17 MeV
peaks

=> Compton edges

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Source Energy: 1 MeV

=> Compton edge

=> Backscatter peak
/. Full-energy peak           \( E = E \) (source)

/. Compton valley           Multiple Compton events

/. Compton edge             \( E' = E - E_{e^-} \)

\[ = E / (1 + 2E / 0.511 \text{ MeV}) \]

/. Compton continuum        (SEP, DEP, 0.511 MeV peaks)

/. Backscatter peak          \( E' < 0.25 \text{ MeV} \)

/. Low energy rise

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

TRIPOLI-4 calculated Gamma-ray Pulse Height Distribution

Source Energy: 100 keV

- K-shell X-ray peaks
- Compton edge
- Backscatter peak

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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
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.
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