Physics 3: Cuts, Decay, and Optical Physics

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Slides courtesy of SLAC GEANT4 Team
Special thanks to Dennis Wright
Outline

- Production Thresholds
- Cuts per Region
- The Decay Process
  - applicability
  - available decay modes
- Optical Photons
  - available processes
Threshold for Secondary Production (1)

- Every simulation developer must answer the question: how low can you go?
  - at what energy do I stop tracking particles?

- This is a balancing act
  - need to go low enough to get the physics you're interested in
  - can't go too low because some processes have infrared divergence causing CPU time to skyrocket

- The traditional Monte Carlo solution is to impose an absolute cutoff in energy
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point
Threshold for Secondary Production (2)

• But, such a cut may cause imprecise stopping location and deposition of energy

• There is also a particle dependence
  ▪ range of 10 keV $\gamma$ in Si is a few cm
  ▪ range of 10 keV $\nu$ in Si is a few microns

• And a material dependence
  ▪ suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  ▪ if the cutoff is OK for Pb, it will likely be wrong for the scintillator which does the actual energy deposition measurement
Threshold for Secondary Production (3)

- Geant4 solution: impose a **production threshold**
  - this threshold is a **distance**, not an energy
  - default = 1 mm
  - the primary particle loses energy by producing secondary electrons or gammas
  - if primary no longer has enough energy to produce secondaries which travel at least 1mm, two things happen:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero energy using continuous energy loss
- Stopping location is therefore correct
- Only one value of production threshold distance is needed for all materials because it corresponds to different energies depending on material.

Slide from SLAC Geant4 tutorial course in '06
Production Threshold vs. Energy Cut

500 MeV p in LAr-Pb sampling calorimeter

Cut = 2 MeV

Cut = 450 keV

Production range = 1.5 mm
Threshold for Secondary Production (4)

- Geant4 recommends the default value of 1mm
  - user needs to decide the best value
  - this will depend on the size of sensitive elements within the simulated detector, and on available CPU

- This value is set in the SetCuts() method of your physics list.

- Instead of “secondary production threshold distance” it is more convenient to simply say “cuts”
  - but please remember that this does not mean that any particle is actually stopped before it runs out of energy
Exercise: Novice Example N03

I. In Novice Example N03, default production threshold of 1.0 mm is set in ExN03PhysicsList.cc\[defaultCutValue = 1.0*mm\]

Run the program to generate 3 events and see the track pattern (or see the picture posted on our “Hands-on 1” web page).

II. Change this threshold to 10 cm. Compile the code and run it to generate 3 events. Notice how the track pattern changes. Next, change it to 20cm and see what happens.

III. (After you are finished, it’s better to change it back to 1.0 mm and compile the code just in case...)
Cuts per Region (1)

- In a complex detector there may be many different types of sub-detectors involving
  - finely segmented volumes
  - very sensitive materials
  - large, undivided volumes
  - inert materials
- The same value of the secondary production threshold may not be appropriate for all of these
  - user must define regions of similar sensitivity and granularity and assign a different set of production thresholds (cuts) for each

- Warning: this feature is for users who are
  - simulating the most complex detectors
  - experienced at simulating EM showers in matter

Slide from SLAC Geant4 tutorial course in ‘06
Cuts per Region (2)

- A default region is created automatically for the world volume
  - it has the cuts which you set in SetCuts() in your physics list
  - these will be used everywhere except for user-defined regions

- To define a special region with different cuts, user must
  - create a G4ProductionCuts object
  - initialize it with the new cuts
  - assign it to a region which has already been created
The Decay Process

- Derived from G4VRestDiscreteProcess
  - decay can happen in-flight or at rest

- Should be applied to all unstable, long-lived particles

- Different from other physical processes:
  - mean free path for most processes: \( \lambda = N \rho \sigma / A \)
  - for decay in-flight: \( \lambda = \gamma \beta c \tau \)

- Same decay process for all eligible particles
  - decay process retrieves BR and decay modes from decay table stored in each particle type
Available Decay Modes

- Phase space:
  - 2-body e.g. \( \pi^0 \rightarrow \gamma \gamma, \Lambda \rightarrow p \pi^- \)
  - 3-body e.g. \( K^0_L \rightarrow \pi^0 \pi^+ \pi^- \)
  - many body

- Dalitz: \( P^0 \rightarrow \gamma l^+ l^- \)

- Muon decay
  - \( V - A, \) no radiative corrections, mono-energetic neutrinos

- Leptonic tau decay
  - like muon decay

- Semi-leptonic K decay: \( K \rightarrow \pi l \nu \)
Pre-assigned Decays

- Geant4 provides decay modes for long-lived particles
  - user can re-define decay channels if necessary

- But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4
  - user must “pre-assign” to particle:
    - proper lifetime
    - decay modes
    - decay products
  - decay process can invoke decay handler from the generator
    - must use G4VExtDecayer interface

- Take care that pre-assigned decays from generators do not overlap with those defined by Geant4
  - $K_S^0$, $\tau$
Optical Photons (1)

- Technically, should belong to electromagnetic category, but:
  - optical photon wavelength is >> atomic spacing
  - treated as waves -> no smooth transition between optical and gamma particle classes

- Optical photons are produced by the following Geant4 processes:
  - G4Cerenkov
  - G4Scintillation
  - G4TransitionRadiation

- Warning: these processes generate optical photons without energy conservation
Optical Photons (2)

- Optical photons undergo:
  - Rayleigh scattering
  - refraction and reflection at medium boundaries
  - bulk absorption
  - wavelength shifting

- Geant4 keeps track of polarization
  - but not overall phase -> no interference

- Optical properties can be specified in G4Material
  - reflectivity, transmission efficiency, dielectric constants, surface properties

- Photon spectrum properties also defined in G4Material
  - scintillation yield, time structure (fast, slow components)
Optical Photons (3)

- Geant4 demands particle-like behavior for tracking:
  - thus, no “splitting”
  - event with both refraction and reflection must be simulated by at least two events
Wavelength Shifting

- **Handled by G4OpWLS**
  - initial photon is killed, one with new wavelength is created
  - builds its own physics table for mean free path

- **User must supply:**
  - absorption length as function of photon energy
  - emission spectra parameters as function of energy
  - time delay between absorption and re-emission
Boundary Interactions

- **Handled by**
  - G4OpBoundaryProcess
    - refraction
    - reflection
- **User must supply surface properties using**
  - G4OpticalSurfaceModel

- **Boundary properties**
  - dielectric-dielectric
  - dielectric-metal
  - dielectric-black material

- **Surface properties:**
  - polished
  - ground
  - front- or back-painted, ...
Summary

- The precision of particle stopping and the production of secondary particles are determined by a **secondary production threshold**

- For complex detectors with different types of sensitive volumes, **different production thresholds** may be defined for **different regions** within the detector

- There is one **decay process** for all long-lived, unstable particles

- **Optical processes** handle the reflection, refraction, absorption, wavelength shifting and scattering of **long-wavelength photons**