Electromagnetic Physics in Geant4

Luciano Pandola
INFN-LNGS

Partially based on presentations by A. Lechner, M.G. Pia, V. Ivanchenko, S. Incerti, M. Maire and A. Howard
Part I: EM physics models available in Geant4
Models and processes for the description of the EM interactions in Geant4 have been grouped in several packages:

<table>
<thead>
<tr>
<th>Package</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>$\gamma$-rays, $e^\pm$ up to 100 TeV, Hadrons, ions up to 100 TeV</td>
</tr>
<tr>
<td>Muons</td>
<td>Muons up to 1 PeV</td>
</tr>
<tr>
<td>X-rays</td>
<td>X-rays and optical photon production</td>
</tr>
<tr>
<td>Optical</td>
<td>Optical photons interactions</td>
</tr>
<tr>
<td>High-Energy</td>
<td>Processes at high energy (&gt; 10 GeV). Physics for exotic particles</td>
</tr>
<tr>
<td>Low-Energy</td>
<td>Specialized processes for low-energy (down to 250 eV), including atomic effects</td>
</tr>
<tr>
<td>Polarization</td>
<td>Simulation of polarized beams</td>
</tr>
</tbody>
</table>
The same physics processes (e.g. Compton scattering) can be described by different models, that can be alternative or complementary in a given energy range.

For instance: Compton scattering can be described by

- G4KleinNishinaCompton
- G4LivermoreComptonModel (specialized low-energy, based on the Livermore database)
- G4PenelopeComptonModel (specialized low-energy, based on the Penelope analytical model)
- G4LivermorePolarizedComptonModel (specialized low-energy, Livermore database with polarization)
- G4PolarizedComptonModel (Klein-Nishina with polarization)

Different models can be combined, so that the appropriate one is used in each given energy range (→ performance optimization)
EM concept - 2

- A physical interaction or process is described by a **process class**
  - Naming scheme: « G4ProcessName »
  - Eg.: « G4Compton » for photon Compton scattering

- A physical process can be simulated according to **several models**, each model being described by a **model class**
  - The usual naming scheme is: « G4ModelNameProcessNameModel »
  - Eg.: « G4LivermoreComptonModel » for the Livermore Compton model
  - Models can be alternative and/or complementary on certain energy ranges
  - Refer to the Geant4 manual for the full list of available models
EM processes for $\gamma$-rays, $e^{\pm}$

<table>
<thead>
<tr>
<th>Particle</th>
<th>Process</th>
<th>G4Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>Gamma Conversion in $e^{\pm}$</td>
<td>G4GammaConversion</td>
</tr>
<tr>
<td></td>
<td>Compton scattering</td>
<td>G4ComptonScattering</td>
</tr>
<tr>
<td></td>
<td>Photoelectric effect</td>
<td>G4PhotoElectricEffect</td>
</tr>
<tr>
<td></td>
<td>Rayleigh scattering</td>
<td>G4RayleighScattering</td>
</tr>
<tr>
<td>$e^{\pm}$</td>
<td>Ionisation</td>
<td>G4eIonisation</td>
</tr>
<tr>
<td></td>
<td>Bremsstrahlung</td>
<td>G4eBremsstrahlung</td>
</tr>
<tr>
<td></td>
<td>Multiple scattering</td>
<td>G4eMultipleScattering</td>
</tr>
<tr>
<td>$e^+$</td>
<td>Annihilation</td>
<td>G4eplusAnnihilation</td>
</tr>
</tbody>
</table>
### EM processes muons

<table>
<thead>
<tr>
<th>Particle</th>
<th>Process</th>
<th>G4Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>Ionisation</td>
<td>G4MuIonisation</td>
</tr>
<tr>
<td></td>
<td>Bremsstrahlung</td>
<td>G4MuBremsstrahlung</td>
</tr>
<tr>
<td></td>
<td>Multiple scattering</td>
<td>G4MuMultipleScattering</td>
</tr>
<tr>
<td></td>
<td>$e^\pm$ pair production</td>
<td>G4MuPairProduction</td>
</tr>
</tbody>
</table>

Only **one model available** for these processes (but in principle users may write their own processes, if needed)
Part II: A short overview of the models. Standard and High Energy
“Standard” EM physics

- Release with the 1st version of Geant4, mainly based on the Geant3 experience
- Significant permanent development in many aspects of EM processes simulation since then...
- Used for many years in production in HEP experiments
  - BaBar, SLAC (since 2000)
  - LHC experiments ATLAS, CMS and LHCb (since 2004)
- Many common requirements for HEP, space, medical and other applications
ATLAS (CERN), Geant4 simulation
Standard EM packages

- **Standard**
  - $\gamma$, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- **Muons**
  - up to 1 PeV
  - Energy loss propagator
- **Xrays**
  - X-ray and optical photons
- **Optical**
  - Optical photon interactions
- **High-energy**
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- **Polarisation**
  - New package for simulation of polarized beams

- Validation, two configurations:
  - 5 mm Pb/5 mm Scintillator
  - 10 mm Pb/2.5 mm Scintillator
- Data from NIM A262 (1987) 229; NIM A274 (1989) 134

![Graph](image)

- e$^- 10$ GeV in Pb/Scin Sampling Calorimeters

- Resolution (%)

- cut (mm)
Gamma and Electron Transport

- **Photon processes:**
  - $\gamma$ conversion into $e^+e^-$ pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering in LowE package
  - Gamma-nuclear interaction in hadronic sub-package CHIPS

- **$e^\pm$ processes:**
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - Nuclear interaction in hadronic sub-package CHIPS

- Positron annihilation

- Many Geant4 applications with e- and gamma beams
Multiple Coulomb scattering (MSC)

Charged particles traversing a finite thickness of matter suffer repeated elastic Coulomb scattering. The cumulative effect of these small angle scatterings is a net deflection from the original particle direction.

- longitudinal displacement $z$ (or geometrical path length)
- lateral displacement $r$, $\Phi$
- true (or corrected) path length $t$
- angular deflection $\theta$, $\phi$
Angular distribution of 2 MeV proton after 5 mic. Au

Gaussian
\[ C_1 \times \exp\left(-0.5 \times \left(\frac{\theta}{5.2}\right)^2\right) \]

Rutherford tail
\[ C_2 / \sin(\theta/2)^4 \]
Geant4 Urban MSC model

- **Starting point**: Lewis theory on transport equation of charged particles
- The Urban MSC model uses phenomenological functions to sample angular and spatial distributions after the simulation step
- The functions parameters are chosen to provide the **same value** of moments of the distribution as in Lewis theory
Simulation of x-rays and optical photons

- Optical photons are created by
  - Cherenkov effect (G4Cherenkov)
  - Transition radiation (G4TransitionRadiation)
  - Scintillation (G4Scintillation)

- Optical photons are hence managed by
  - Reflection and reflection at boundary (G4OpBoundaryProcess)
  - Absorption (G4OpAbsorption)
  - Rayleigh scattering (G4OpRayleigh)
  - Wavelength shifting (G4OpWLS)
Muon EM Physics Simulation

- **Main processes:**
  - Ionization and bremsstrahlung
  - $\mu^+\mu^-$ pair production
  - Muon-nuclear interactions in hadronic packages

---

**Total muon energy loss**

![Graph showing total muon energy loss](image)

- Iron
- Water

- **Muon stopping power**
  - Precision about 2%

---

![Graph showing stopping power](image)
Hadron and ion EM physics

- **Coulomb scattering**
- **Ionization**

Bethe-Bloch formula with corrections used for $E > 2$ MeV

$$-\frac{dE}{dx} = 4\pi N_e r_0^2 \frac{z^2}{\beta^2} \left( \ln \frac{2mc^2 \beta^2 \gamma^2}{I} - \frac{\beta^2}{2} \left( 1 - \frac{T_c}{T_{\text{max}}} \right) \frac{C}{Z} + \frac{G - \delta - F}{2} + zL_1 + z^2L_2 \right)$$

- C – shell correction
- G – Mott correction
- $\delta$ – density correction
- F – finite size correction
- L$_1$- Barkas correction
- L$_2$- Bloch correction
- Nuclear stopping
- Ion effective charge

- **Bragg peak parameterizations for $E < 2$ MeV**
  - ICRU’49 and NIST databases
Part III: A short overview of the models. Low Energy
Livermore Models

**Full set of models** in Geant4 for electrons, $\gamma$-rays and ions based on the **Livermore data libraries** (cross sections and final states)

Energy range down to **250 eV**. They include atomic effects, like fluorescence, Auger emission, etc.

<table>
<thead>
<tr>
<th>Particles</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sections (probability to</td>
<td>Evaluated Photon Data Library : EPDL97</td>
</tr>
<tr>
<td>interact)</td>
<td>Evaluated Electron Data Library : EEDL</td>
</tr>
<tr>
<td></td>
<td>Evaluated Atomic Data Library : EADL</td>
</tr>
<tr>
<td></td>
<td>International Commission on radiation Units : ICRU49</td>
</tr>
<tr>
<td></td>
<td>Binding energies : Scofield</td>
</tr>
</tbody>
</table>
Database
- Mixture: experiments and theories
- Extracted from public libraries: EEDL, EPDL ...

Implementation in Geant4
- Total cross sections: photo-electric effect, diffusions
- Compton and Rayleigh, pair production and Bremsstrahlung
- Sub-levels integrated cross sections: photo-electric and ionization
- Energy spectra: secondary processes in $e^-$
Livermore Models – cross sections, ranges
dosimetry with geant4-livermore

energy deposit in calorimeter

experimental data
G.J. Lockwood et al., SAND79-0414
Fluorescence

Experimental validation:

Test beam data, in collaboration with ESA

Spectrum from a Mars-simulant rock sample

Fe lines
GaAs lines
Scattered photons
Livermore Polarized Models

- Describe in detail the kinematics of polarized photon interactions
- Based on the Livermore database
- Applications of such developments include the design of new space mission for the detection of polarized photons
- Documentation on the MC methods could be found:
- Currently available: Compton and Rayleigh

G4LivemorePolarizedXXXXModel
Comparison between the theoretical rates of intensities with those obtained from GEANT4 for: 100 keV, 1 MeV and 10 MeV.

\[ p = \frac{d\sigma_{\perp}}{d\Omega} / \frac{d\sigma_{\parallel}}{d\Omega} \]
Penelope Models

- Geant4 includes the low-energy models for $e^\pm$ and $\gamma$-rays from the Monte Carlo code **PENELOPE** (PENetration and Energy LOss of Positrons and Electrons)

- The physics models have been specifically developed by the Barcelona group (F. Salvat *et al.*) and a great care was dedicated to the low-energy description (atomic effects, fluorescence, Doppler broadening, etc.)

- Mixed approach: analytical, parametrized & database-driven
  - applicability energy range: $250 \text{ eV} \rightarrow 1 \text{ GeV}$

- Includes also positrons (not described by Livermore models)
  G4PenelopeXXXXModel (e.g. G4PenelopeComptonModel)
Example: Doppler broadening in Compton scattering

**Compton scattering**: electrons bound and not at rest (as assumed for Klein-Nishina) → change of angular distribution, reduction of XS

Penelope model includes it (via **analytical** approach)

Livermore model also deals with Doppler broadening (**EGS database** approach)

**Good agreement Penelope-Livermore**

Standard model **includes cross section** suppression, but samples final state according to Klein-Nishina
Ion energy loss model

- Describes the energy loss of ions heavier than Helium due to interaction with the atomic shells of target atoms.

- The model computes:
  - Restricted stopping powers, which determine the continuous energy loss of ions as they slow down in an absorber (more details on next slides).
  - Cross sections for the production of δ-rays (Note: δ-rays are only produced above a given threshold), which inherently also govern the discrete energy loss of ions.

- Primarily of interest for:
  - Medical applications
  - Space applications
Using ICRU73 Tables

- ICRU 73 stopping powers are available for a range of elemental and compound materials:

  - In order that the ICRU 73 tables are used by the ion model, materials must have names of Geant4 NIST materials
  - Either Geant4 NIST materials are used, or user-specific materials are created having the same name as materials in Geant4 NIST data base.
  - Note: ICRU 73 stopping powers are not available for all NIST materials.
  - Available stopping powers can be looked up in the following classes of the Geant4 material sub-package ($G4INSTALL/source/materials):
    - G4SimpleMaterialStoppingICRU73 (ions up to Ar)
    - G4MaterialStoppingICRU73 (ions up to Ar)
    - G4IronStoppingICRU73 (Fe ions & ions scaled from Fe)
When/why to use Low Energy Models

**Use** Low-Energy models (Livermore or Penlope), as an *alternative* to Standard models, when you:

- need **precise treatment** of EM showers and interactions at **low-energy** (keV scale)
- are interested in **atomic effects**, as fluorescence x-rays, Doppler broadening, etc.
- can afford a more **CPU-intensive** simulation
- want to **cross-check** an other simulation (e.g. with a different model)

**Do not use** when you are interested in EM physics > MeV

- same results as Standard EM models, **performance penalty**
Part IV: How to use the EM physics and to set-up the physics list
Physics Lists is the user class making general interface between physics and Geant4 kernel
- It should include the list of particles
- The G4ProcessManager of each particle maintains a list of processes

There are 3 ordered lists of processes per particle which are active at different stage of Geant4 tracking:
- AtRest (annihilation, ...)
- AlongStep (ionisation, bremsstrahlung, ...)
- PostStep (photo-electric, Compton, Cerenkov,...)

Geant4 provided a set of different configurations of EM physics (G4VPhysicsConstructor) with physics_list library

These constructors can be included into modular Physics List in user application (G4VModularPhysicsList)
Example: PhysicsList, $\gamma$-rays

```cpp
G4ProcessManager* pmanager
if (particleName == "gamma")
{
    pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
    pmanager->AddDiscreteProcess(new G4ComptonScattering);
    pmanager->AddDiscreteProcess(new G4GammaConversion);
    pmanager->AddDiscreteProcess(new G4RayleighScattering);
}
```

- Use `AddDiscreteProcess` because $\gamma$-rays processes have only PostStep actions

- For each process, the **default model** is used among all the available ones (e.g. `G4KleinNishinaCompton` for `G4ComptonScattering`) → see later for non-default
else if ( particleName == "e+" )
{
    pmanager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
    pmanager->AddProcess(new G4eIonisation, -1, 2, 2);
    pmanager->AddProcess(new G4eBremsstrahlung, -1, 3, 3);
    pmanager->AddProcess(new G4eplusAnnihilation, 0, -1, 4);
}

- Use **AddProcess()** to add a generic process
- Numbers are **process ordering:**
  - **G4Transportation** is the 1\textsuperscript{st} (order = 0) for AlongStep and PostStep
  - "-1" means that the process is not active
Example: change default model

- **Process** class `G4ComptonScattering`
- Default model in G4 9.3 is `G4KleinNishinaCompton` (EM Standard)
- There are alternative Livermore and Penelope models
  - Let’s try `G4PenelopeComptonModel`

```cpp
G4double limit = 1.0*GeV;
if ( particleName == "gamma" ) {
    G4ComptonScattering* cs = new G4ComptonScattering();
    G4PenelopeComptonModel* aModel = new G4PenelopeComptonModel();
    aModel->SetHighEnergyLimit(limit);
    cs->AddEmModel(0, aModel); // 1st parameter - order
    pmanager->AddDiscreteProcess(pef);
}
```
EM Physics Constructors for Geant4 9.3 - ready-for-the-use

- G4EmStandardPhysics – default
- G4EmStandardPhysics_option1 – HEP fast but not precise
- G4EmStandardPhysics_option2 – Experimental
- G4EmStandardPhysics_option3 – medical, space
- G4EmLivermorePhysics
- G4EmLivermorePolarizedPhysics
- G4EmPenelopePhysics
- G4EmDNAPhysics

- Combined Physics
  - Standard > 1 GeV
  - LowEnergy < 1 GeV

- $G4INSTALL/source/physics_list/builders
- Advantage of using these classes – they are tested on regular basis and are used for regular validation
How to extract Physics?

- Possible to retrieve physics quantities via \texttt{G4EmCalculator} or directly from the physics models.
  - Physics List should be initialized.

- Example for retrieving the \textbf{total cross section} (cm\(^{-1}\)) of a process with name \textit{procName}: for particle \textit{partName} and material \textit{matName}.

```cpp
G4EmCalculator emCalculator;
G4Material* material =
    G4NistManager::Instance()->FindOrBuildMaterial("matName");
G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
    (energy, particle, procName, material);
G4cout << G4BestUnit(massSigma, "Surface/Volume") << G4endl;
```

A good example:

\$G4INSTALL/examples/extended/electromagnetic/TestEm14