Electromagnetic interactions of particles with matter

October 25, 2006

Abstract

This document is a brief review to the main mechanisms of electromagnetic interactions of charged particles and photons with matter, pertinent in Particle Physics, and their inplementation in GEANT4.

'Standard' em physics : the model

The projectile is assumed to have an energy $\geq$ 1 keV.

- The atomic electrons are quasi-free : their binding energy is neglected (except for photoelectric effect).
- The atomic nucleus is fixe : the recoil momentum is neglected.

The matter is described as homogeneous, isotropic, amorphous.

1. Common to all charged particles
   - ionization $(\sim keV \longrightarrow)$
   - Coulomb scattering from nuclei $(\sim keV \longrightarrow)$
   - Cerenkov effect
   - Scintillation
   - transition radiation
2. Muons
   - (e+,e-) pair production $(\sim 100GeV \longrightarrow)$
   - bremsstrahlung $(\sim 100GeV \longrightarrow)$
   - nuclear interaction $(\sim 1TeV \longrightarrow)$
3. Electrons and positrons
   - bremsstrahlung $(\sim 10MeV \longrightarrow)$
   - e+ annihilation

4. Photons
   - gamma conversion $(\sim 10MeV \longrightarrow)$
   - incoherent scattering $(\sim 100keV \longrightarrow \sim 10MeV)$
   - photo electric effect $(\longleftarrow \sim 100keV)$
   - coherent scattering $(\longleftarrow \sim 100keV)$
5. Optical photons
   - reflection and refraction
   - absorption
   - Rayleigh scattering

Total :$\sim$ 15 processes $\longrightarrow$ $\sim$ 40 classes

+ $\sim$ 10 classes for the materials category

Low Energy Extension

Additional electromagnetic physics processes for photons, electrons, hadrons and ions have been implemented in Geant4 in order to extend the validity range of particle interactions to lower energies (250 eV) : fluorescence of excited atoms is also considered.

The data used for the determination of cross-sections and are extracted from a set of publicly distributed evaluated data libraries:

- EPDL97 (Evaluated Photons Data Library);
- EEDL (Evaluated Electrons Data Library);
- EADL (Evaluated Atomic Data Library);
- ICRU49 (stopping power data);
- binding energy values based on data of Scofield.

These libraries provide the following data relevant for the simulation of Geant4 low energy processes:

- total cross-sections for photoelectric effect, Compton scattering, Rayleigh scattering, pair production and bremsstrahlung,
- subshell integrated cross sections for photo-electric effect and ionization,
- energy spectra of the secondaries for electron processes,
- scattering functions for the Compton effect,
- form factors for Rayleigh scattering,
- binding energies for electrons for all subshells,
- transition probabilities between subshells for fluorescence and the Auger effect, and
- stopping power tables.

A few words about the GEANT4 processes in general

A process may have three types of actions :

- well located in space : PostStep action
- not well located in space : AlongStep action
- well located in time : AtRest action

Each action is twofold :

- predicts where/when the interaction will occur : `GetPhysicalInteractionLength()`
- computes the final state of the interaction, where/when it occurs : `DoIt()`

A process has to fill 1, 2 or 3 couples of the following methods :

	AtRest	AlongStep	PostStep
GetPhysicalInteractionLength()			
DoIt()			

- DiscreteProcess is shortcut for a process which have **only** PostStep action.
- ContinuousProcess is shortcut for a process which have **only** AlongStep action.
- AtRestProcess is shortcut for a process which have **only** AtRest action.

examples

- discrete process : Compton scattering
  step determined by cross section, interaction at the end of the step (PostStepAction).
- continuous process : Cerenkov effect
  photons are created along the step, nb of photons (roughly) proportional to the step length (AlongStepAction).
- at rest process : no displacement, time is the relevant variable, e.g. positron annihilation at rest.

These are the 'pure' process types.

Some of the e.m. processes have combinations of actions :

- ionisation : continuous (energy loss) + discrete (Moller/Bhabha scattering, knock-on electron production)
- bremsstrahlung : continuous (energy loss due to soft photons) + discrete (hard photon emission)

in both cases the production threshold separates the continuous and discrete part of the process :

- if the (kinetic) energy of the secondary $\leq$ threshold energy, the secondary is not created , the effect of these soft interactions are treated as a continuous energy loss
- if the energy of the secondary is big enough, it is created at the end of the step (discrete part)

PhysicsList

For each type of particle the ProcessManager maintains a list of processes to be apply.

More precisely, there are 3 ordered lists of processes :

- AtRest action
- AlongStep action
- PostStep action

These lists are registered in the `UserPhysicsList` class.

example of PhysicsList

```
if (particleName == "e-") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4eIonisation,        -1, 2,2);
pmanager->AddProcess(new G4eBremsstrahlung,    -1,-1,3);
}

else if (particleName == "e+") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4eIonisation,        -1, 2,2);
pmanager->AddProcess(new G4eBremsstrahlung,    -1,-1,3);
pmanager->AddProcess(new G4eplusAnnihilation,   0,-1,4);
}
```

```
if (particleName == "mu+" || particleName == "mu-") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4MuIonisation,       -1, 2,2);
pmanager->AddProcess(new G4MuBremsstrahlung,   -1,-1,3);
pmanager->AddProcess(new G4MuPairProduction,   -1,-1,4);
}

if ((particle->GetPDGCharge() != 0.0) &&
(!particle->IsShortLived()) &&
(particle->GetParticleName() != "chargedgeantino")) {
pmanager->AddProcess(new G4MultipleScattering, -1,1,1);
pmanager->AddProcess(new G4hIonisation,        -1,2,2);
}
```

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

is a shortcut for :

```
pmanager->AddProcess(new G4PhotoElectricEffect, -1,-1,1);
pmanager->AddProcess(new G4ComptonScattering,   -1,-1,2);
pmanager->AddProcess(new G4GammaConversion,     -1,-1,3);
```

For processes which have only PostStepAction, the ordering is not important.

σ cross section per atom. $(cm^2/atom)$

$n_{at} = \mathcal{N}\rho/A$ number of atoms per unit of volume. $(atoms/cm^3)$

$$n_{at} = n_1 + n_2 + \cdots = \frac{\mathcal{N}\rho w_1}{A_1} + \frac{\mathcal{N}\rho w_2}{A_2} + \cdots$$

$\Sigma = n_{at}\,\sigma$ cross section per volume. (cm^2/cm^3)

Φ : number of interactions per unit of length. $(1/cm)$

μ : absorption, attenuation coefficients ..etc..

$\lambda = 1/\Phi$ mean free path, interaction length, etc .. (cm)

$t = x\rho$ mass-thickness, mass/surface .. (g/cm^2)

Φ/ρ cross section per mass. (cm^2/g)

μ/ρ : **mass** attenuation coefficient ..etc..

$X_0\rho$ radiation length, expressed in mass/surface (g/cm^2)

dE/dt energy loss per (mass/surface) $(MeV/(g/cm^2))$