Electromagnetic interactions of particles with matter

Slac, 18.02.02

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 implementation 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 (≈ keV →)
   - Coulomb scattering from nuclei (≈ keV →)
   - Cerenkov effect
   - Scintillation
   - transition radiation

2. Muons
   - (e+,e-) pair production (≈ 100GeV →)
   - bremsstrahlung (≈ 100GeV →)
   - nuclear interaction (≈ 1TeV →)

3. Electrons and positrons
   - bremsstrahlung (≈ 10MeV →)
   - e+ annihilation
4. Photons

- gamma conversion \( (\sim 10\text{MeV} \rightarrow) \)
- incoherent scattering \( (\sim 100\text{keV} \rightarrow 100\text{MeV}) \)
- photo electric effect \( (\sim 100\text{keV}) \)
- coherent scattering \( (\sim 100\text{keV}) \)

5. Optical photons

- reflection and refraction
- absorption
- Rayleigh scattering

Total: \( \sim 15 \) processes \( \rightarrow \sim 40 \) classes

+ \( \sim 10 \) classes for the materials category
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 2 or 4 of the following methods:

<table>
<thead>
<tr>
<th>GetPhysicalInteractionLength()</th>
<th>PostStep</th>
<th>AlongStep</th>
<th>AtRest</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoIt()</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **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

```cpp
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.
Electromagnetic interactions of particles with matter

\[ \sigma \] cross section per atom. \((cm^2/atom)\)

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

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

\[ \Phi = n_{at} \sigma \] number of interactions per unit of length. \((1/cm)\)

\[ \Sigma : \text{macroscopic cross section} \]

\[ \mu : \text{absorption, attenuation coefficients .etc..} \]

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

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

\[ \Phi / \rho \] nb of interactions per (mass/surface). \((1/(g/cm^2))\)

\[ \mu / \rho : \text{mass attenuation coefficient .etc..} \]

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

\[ dE/dt \] energy loss per (mass/surface) \((MeV/(g/cm^2))\)