ELECTROMAGNETIC PHYSICS

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ELECTROMAGNETIC (EM) PHYSICS OVERVIEW
Geant4 Electromagnetic Physics

- Released with the 1st version of Geant4 with EM physics based on Geant3 experience (1998)
- Significant permanent development in many aspects of EM processes simulation since the beginning of Geant4 up to now
- Many years is used for large HEP experiments
  - BaBar, SLAC (since 2000)
  - LHC experiments: ATLAS, CMS and LHCb (since 2004)
- Many common requirements for HEP, space, medical and other applications
- A unique reference web page on Geant4 EM Physics
  - http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml
  - Includes a Web interface to validation repository
Geant4 simulation of **ATLAS** experiment at LHC, CERN
Gamma and electron transport

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

- **Electron and positron processes**
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - *Nuclear interaction in hadronic sub-package CHIPS*
  - Positron annihilation

- Suitable for **HEP & many other Geant4 applications** with electron and gamma beams

HEP calorimeter

Medical linac
Geant4 EM packages

- **Standard**
  - gammas, e+- up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV

- **Low-energy**
  - Livermore library g, e- from 250 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOE code rewrite, g, e-, e+ from 250 eV up to 1 GeV (2001 version & 2008 version as beta)
  - hadrons and ions up to 1 GeV
  - microdosimetry models for radiobiology (Geant4-DNA project) from 4 eV to 10 MeV
  - atomic de-excitation (fluorescence + Auger)

- **Adjoint**
  - New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation

- **Optical**
  - optical photon interactions

- **X-rays**
  - X-ray and optical photon production processes

- **High-energy**
  - processes at high energy (E>10GeV)
  - physics for exotic particles

- **Polarisation**
  - simulation of polarised beams

- **Utils**
  - general EM interfaces

- **Muons**
  - up to 1 PeV
  - energy loss propagator

Located in $G4INSTALL/sources/processes/electromagnetic$
Software design

Since Geant4 9.3beta (June, 2009) the design is uniform for all EM packages
- Allowing a coherent approach for high-energy and low-energy applications

A physical interaction or process is described by a process class
- Naming scheme : « G4ProcessName »
- For example: G4Compton for photon Compton scattering
- Assigned to Geant4 particle types
- Inherit from G4VEmProcess base class

A physical process can be simulated according to several models, each model being described by a model class
- Naming scheme : « G4ModelNameProcessNameModel »
- For example: G4LivermoreComptonModel
- Models can be assigned to certain energy ranges and G4Regions
- Inherit from G4VEmModel base class

Model classes provide the computation of
- Cross section and stopping power
- Sample selection of atom in compound
- Final state (kinematics, production of secondaries...)
Example: muon energy loss

- Continuous energy loss from processes
  - Ionisation
  - Production of e+e-
  - Bremsstrahlung

- Ionisation and delta-electron production
  - G4BetheBlochModel

- Below 200 keV – ICRU’49 parameterization of dE/dx
  - G4BraggIonModel

- Radiative corrections to ionization at E > 1 GeV
  - G4MuBetheBlochModel

Muon stopping power precision ~2%
Multiple Coulomb Scattering (MSC)

- Charged particles traversing a finite thickness of matter suffer elastic Coulomb scattering.

- The cumulative effect of these small angle scatterings is a net deflection from the original particle direction.
## MSC Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Particle type</th>
<th>Energy limit</th>
<th>Specifics and applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban (Urban 2006)</td>
<td>Any</td>
<td>-</td>
<td>Default model, (Lewis 1950) approach, tuned to data, used for LHC production.</td>
</tr>
<tr>
<td>Screened Nuclear Recoil</td>
<td>p, ions</td>
<td>&lt; 100 MeV/A</td>
<td>Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space app.</td>
</tr>
<tr>
<td>Goudsmit-Saunderson (Kadri 2009)</td>
<td>e^+, e^-</td>
<td>&lt; 1 GeV</td>
<td>Theory based cross sections (Goudsmit and Saunderson 1950). EPSEPA code developed by Penelope group, final state using EGSnrc method (Kawrakov et al. 1998), precise electron transport</td>
</tr>
<tr>
<td>Coulomb scattering (2008)</td>
<td>any</td>
<td>-</td>
<td>Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons</td>
</tr>
<tr>
<td>WentzelVI (2009)</td>
<td>any</td>
<td>-</td>
<td>MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons.</td>
</tr>
</tbody>
</table>
MSC algorithm

- **Legend**
  - True path length: $t$
  - Longitudinal or geometrical displacement: $z$
  - Lateral displacement: $r$
  - Angular deflection: $(\theta, \phi)$

- The algorithm performs several steps for the simulation of MSC which are essentially the same for many « condensed » simulations
  - The physics processes and the geometry select the step length; MSC performs the $t \leftrightarrow z$ transformation only
  - The transport along the initial direction is not MSC’s business
  - Sampling of scattering angle $(\theta, \phi)$
  - Computing of lateral displacement and relocation of particle
The MSC model used in Geant4 is based on Lewis' MSC theory of transport of charged particles (1950).

It uses phenomenological functions to determine the angular and spatial distributions after a simulation step.

The functions have been chosen in such a way as to give the same moments of the angular and spatial distributions as the Lewis theory.
MSC classes

- Processes per particle type are available
  - G4eMultipleScattering for e+/e-
  - G4MuMultipleScattering for μ+/μ-
  - G4hMultipleScattering for hadrons and ions

- L. Urban models
  - G4UrbanMscModel93: used by default in G4eMultipleScattering
  - G4UrbanMscModel90: used for muons in G4MuMultipleScattering, and for hadrons & ions in G4hMultipleScattering

- Alternative single and multiple scattering models are available to users
  - see extended examples...
MSC in **Physics Lists from G4 9.4**

- **Situation is changed significantly**

<table>
<thead>
<tr>
<th>EM Reference Physics list</th>
<th>e- / e+ G4eMultipleScattering</th>
<th>mu+ / mu- G4MuMultipleScattering</th>
<th>Hadrons, ions G4hMultipleScattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4EmStandardPhysics</td>
<td>G4UrbanMscModel93</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
<tr>
<td>G4EmStandardPhysics_option1</td>
<td>G4UrbanMscModel93</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
<tr>
<td>G4EmStandardPhysics_option2</td>
<td>G4UrbanMscModel93</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4WentelVIModel for pions, kaons, protons</td>
</tr>
<tr>
<td>G4EmStandardPhysics_option3</td>
<td>G4UrbanMscModel93</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
<tr>
<td>G4EmLivermorePhysics</td>
<td>G4GoudsmithSaundersonMscModel</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
<tr>
<td>G4EmLivermorePolarizedPhysics</td>
<td>G4GoudsmithSaundersonMscModel</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
<tr>
<td>G4EmPenelopePhysics</td>
<td>G4GoudsmithSaundersonMscModel</td>
<td>G4WentelVIModel + G4CoulombScattering</td>
<td>G4UrbanMscModel90</td>
</tr>
</tbody>
</table>
Example of MSC validation
HOW TO INVOKE EM PHYSICS IN GEANT4?
Physics lists

- A Physics list is the mandatory user class making the general interface between the physics the user needs and the Geant4 kernel
  - It should include the list of particles
  - The G4ProcessManager of each particle maintains a list of processes

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

- Geant4 provides several configurations of EM physics lists called constructors (G4VPhysicsConstructor) in the physics_list library of Geant4

- These constructors can be included into a modular Physics list in a user application (G4VModularPhysicsList)
EM Physics constructors

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

Located in $G4INSTALL/source/physics_list/builders

Advantage of using these classes
- they are tested on a regular basis and are used for regular validation

Combined Physics:
- Standard > 1 GeV
- Low Energy < 1 GeV
Example: G4EmStandard Physics

```cpp
G4ProcessManager* pmanager

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

- Numbers are process order
  - G4Transportation is the 1st (order = 0) for AlongStep and PostStep

- "-1" means that the process is not active
Example: Penelope Physics

- Process class **G4PhotoElectricEffect**
- The default model is **G4PEEffectModel**
- There are alternative Livermore and Penelope models
- Example of combined EM Physics Lists
  - Penelope photo-electric below 1 GeV

```cpp
G4double limit = 1.0*GeV;
If ( particleName == "gamma" )
{
    G4PhotoElectricEffect* pef = new G4PhotoElectricEffect();
    G4PenelopePhotoElectricModel* aModel = new G4PenelopePhotoElectricModel();
    aModel->SetHighEnergyLimit(limit);
    pef->AddEmModel(0, aModel);  // 1st parameter - order
    pmanager->AddDiscreteProcess(pef);
...
```
How to extract Physics?

- Possible to retrieve Physics quantities using a `G4EmCalculator` object

- Physics List should be initialized

- Example for retrieving the total cross section of a process with name `procName`, for particle and material `matName`

```c
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;

G4Material* material =
    G4NistManager::Instance()->FindOrBuildMaterial(matName);

G4double density = material->GetDensity();

G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
    (energy, particle, procName, material)/density;

G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
```

- A good example: `$G4INSTALL/examples/extended/electromagnetic/TestEm14`.
  Look in particular at the `RunAction.cc` class
A web-based verification tool has been developed for easy comparison of EM physics results obtained with different Geant4 version, and with measurements.

http://www-zeuthen.desy.de/geant4/web/
To learn more:
$G4INSTALL/examples/extended/electromagnetic

<table>
<thead>
<tr>
<th>Check basic quantities</th>
<th>TestEm0, Em13, Em14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cross sections, mean free paths</td>
<td></td>
</tr>
<tr>
<td>Stopping power, particle range</td>
<td></td>
</tr>
<tr>
<td>Final state: energy spectra, angular distributions</td>
<td></td>
</tr>
<tr>
<td>Energy loss fluctuations, fluorescence</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multiple Coulomb scattering</th>
<th>Em15, Em5</th>
</tr>
</thead>
<tbody>
<tr>
<td>as an isolated mechanism</td>
<td></td>
</tr>
<tr>
<td>as a result of particle transport</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>More global verifications</th>
<th>Em5, Em7, Em11, Em12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single layer: transmission, absorption, reflexion</td>
<td></td>
</tr>
<tr>
<td>Bragg curve, tallies</td>
<td></td>
</tr>
<tr>
<td>Depth dose distribution</td>
<td></td>
</tr>
<tr>
<td>Shower shapes, Moliere radius</td>
<td></td>
</tr>
<tr>
<td>Sampling calorimeters, energy flow</td>
<td></td>
</tr>
<tr>
<td>Crystal calorimeters</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other specialized programs</th>
<th>Em17, Em6, Em16, Em8</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy muon physics</td>
<td></td>
</tr>
<tr>
<td>Other rare, high energy processes</td>
<td></td>
</tr>
<tr>
<td>Synchrotron radiation</td>
<td></td>
</tr>
<tr>
<td>Transition radiation</td>
<td></td>
</tr>
<tr>
<td>Photo-absorption-ionization model</td>
<td></td>
</tr>
</tbody>
</table>

Refer to section on extended examples in App. User Guide.
Suggestions

- The list of available EM processes and models is maintained by EM working groups in EM web pages
  - [http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml](http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml)

- Geant4 extended and advanced examples show how to use EM processes and models
  - In `$G4INSTALL/examples`

- User feedback is always welcome
Content

- Context
- Physics models
  - Livermore, including polarized photon models
  - Penelope
  - Ion ICRU’73 model
  - Geant4-DNA
  - Atomic de-excitation
- How to implement a Physics list?
- Documentation
Purpose

- Extend the coverage of Geant4 electromagnetic interactions with matter
  - for photons, electrons, hadrons and ions
  - down to very low energies (sub-keV scale)

- Possible domains of applications
  - space science
  - medical physics
  - microdosimetry for radiobiology
  - ...

- Choices of Physics models include
  - Livermore library: electrons and photons [250 eV – 1 GeV]
  - Penelope (Monte Carlo): electrons, positrons and photons [250 eV – 1 GeV]
  - Microdosimetry models (Geant4-DNA project): [eV – ~100 MeV]
Recent software design

- Identical to the one proposed by the Standard EM working group
  - Applicable to all low energy electromagnetic software classes
  - Allows a coherent approach to the modelling of all electromagnetic interactions
  - No more artificial separation between the 2 EM categories
  - Many bugs & flaws accumulated over past years have been solved
  - Please use Geant4 9.4 release and above!

- A physical interaction or process is described by a process class
  - Naming scheme: « G4ProcessName »
  - Eg.: « G4ComptonScattering » for photon Compton scattering

- A physical process can be simulated according to several models, each model being described by a model class
  - Naming scheme: « G4ModelNameProcessNameModel »
  - Eg.: « G4LivermoreComptonModel » for the Livermore Compton model
  - Models can be alternative and/or complementary in certain energy ranges

- According to the selected model, model classes provide the computation of
  - the process total cross section & the stopping power
  - the process final state (kinematics, production of secondaries...)

PHYSICS MODELS

Livermore models
Livermore models

- Full set of models for electrons and gammas
- Based on publicly available evaluated data tables from the Livemore data library
  - EADL: Evaluated Atomic Data Library
  - EEDL: Evaluated Electrons Data Library
  - EPDL97: Evaluated Photons Data Library
  - Mixture of experiments and theories
  - Binding energies: Scofield

- Data tables are interpolated by Livermore model classes to compute
  - Total cross sections: photoelectric, Compton, Rayleigh, pair production, Bremsstrahlung
  - Sub-levels integrated cross sections: photo-electric, ionization
  - Energy spectra: secondary e- processes

- Validity range: 250 eV - 100 GeV
  - Processes can be used down to 100 eV, with a reduced accuracy
  - In principle, validity range down to ~10 eV

- Included elements from Z=1 to Z=100
  - Include atomic effects (fluorescence, Auger)
  - Atomic relaxation: Z > 5 (EADL transition data)

- Naming scheme: G4LivermoreXXXModel (eg. G4LivermoreComptonModel)
## Livermore models

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Process Class</th>
<th>Model Class</th>
<th>Low Energy Limit</th>
<th>High Energy Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gammas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compton</td>
<td>G4ComptonScattering</td>
<td>G4LivermoreComptonModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Polarized Compton</td>
<td>G4ComptonScattering</td>
<td>G4LivermorePolarizedComptonModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>G4RayleighScattering</td>
<td>G4LivermoreRayleighModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Polarized Rayleigh</td>
<td>G4RayleighScattering</td>
<td>G4LivermorePolarizedRayleighModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Conversion</td>
<td>G4GammaConversion</td>
<td>G4LivermoreGammaConversionModel</td>
<td>1.022 MeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Polarized Conversion</td>
<td>G4GammaConversion</td>
<td>G4LivermorePolarizedGammaConversionModel</td>
<td>1.022 MeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Photo-electric</td>
<td>G4PhotoElectricEffect</td>
<td>G4LivermorePhotoElectricModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Polarized Photo-electric</td>
<td>G4PhotoElectricEffect</td>
<td>G4LivermorePolarizedPhotoElectricModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionization</td>
<td>G4eIonisation</td>
<td>G4LivermoreIonisationModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>G4eBremsstrahlung</td>
<td>G4LivermoreBremsstrahlungModel</td>
<td>250 eV</td>
<td>100 GeV</td>
</tr>
</tbody>
</table>
Eg. of validation of Livermore models
Polarized Livermore processes

- Describe in detail the kinematics of polarized photon interactions
- Based on the Livermore database
- Possible applications of such developments
  - design of space missions for the detection of polarized photons
- Documentation
- Naming scheme: G4LivermorePolarizedXXXModel
  - eg. G4LivermorePolarizedComptonModel
PHYSICS MODELS

Penelope models
Penelope physics

- 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) version 2001 (and 2008 as beta)

- Physics models
  - Specifically developed by the Barcelona group (F. Salvat et al.)
  - 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 eV - 1 GeV

- Includes also positrons (not described by Livermore models)

- G4PenelopeXXXModel (e.g. G4PenelopeComptonModel)
## Penelope models

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Process Class</th>
<th>Model Class</th>
<th>Low Energy Limit</th>
<th>High Energy Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gammas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compton</td>
<td>G4ComptonScattering</td>
<td>G4PenelopeComptonModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>G4RayleighScattering</td>
<td>G4PenelopeRayleighModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
<tr>
<td>Conversion</td>
<td>G4GammaConversion</td>
<td>G4PenelopeGammaConversionModel</td>
<td>1.022 MeV</td>
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</tr>
<tr>
<td>Photo-electric</td>
<td>G4PhotoElectricEffect</td>
<td>G4PenelopePhotoElectricModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
<tr>
<td><strong>Electrons/Positrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionization</td>
<td>G4eIonisation</td>
<td>G4PenelopeIonisationModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>G4eBremsstrahlung</td>
<td>G4PenelopeBremsstrahlungModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
<tr>
<td><strong>Positrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annihilation</td>
<td>G4eplusAnnihilation</td>
<td>G4PenelopeAnnihilationModel</td>
<td>250 eV</td>
<td>1 GeV</td>
</tr>
</tbody>
</table>
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: continuous energy loss of ions as they slow down in an absorber.
  - Cross sections for the production of $\delta$-rays:
    - $\delta$-rays are only produced above a given threshold, which inherently also governs the discrete energy loss of ions.

- Primarily of interest for:
  - Medical applications
  - Space applications
Electronic stopping powers are an important ingredient to determine the mean energy loss of ions along simulation steps:
- Impacts the ion range (for example)

Restricted stopping powers: account for the fact that the continuous energy loss description is restricted to energies below $T_{\text{cut}}$ (where $T_{\text{cut}}$ denotes the lower production threshold of $\delta$-rays)

Restricted stopping powers are calculated according to ($T =$ kinetic energy per nucleon):
- $T < T_L$: Free electron gas model
- $T_L \leq T \leq T_H$: Interpolation of tables or parameterization approach
- $T > T_H$: Bethe formula (using an effect. charge) + high order corr.
Parameterization approach
- Model incorporates ICRU 73 stopping powers into Geant4

ICRU73 model
- Covers a large range of ion-material combinations: Li to Ar, and Fe
- Stopping powers: based on binary theory
- Special case: water
  - Revised ICRU 73 tables of P. Sigmund are used (since Geant4 9.3.b01)
  - Mean ionization potential of water of 78 eV
- Current model parameters (Geant4 9.3.b01):
  - $T_{\text{High}} = 10$ MeV/nucleon (except Fe ions: $T_{\text{H}} = 1$ GeV/nucleon)
  - $T_{\text{Low}} = 0.025$ MeV/nucleon (lower boundary of ICRU 73 tables)
- For ions heavier than Ar
  - Scaling of Fe ions based on effective charge approach
How to use the new model?

- **Model name:** G4IonParametrisedLossModel

- **Applicable from Z>2**

- **Already included in** G4EmStandardPhysics_option3, G4EmLivermorePhysics and G4EmPenelopePhysics physics builders

- Designed to be used with the **G4IonIonisation** process (in standard EM category)
  - Not activated by default when using G4IonIonisation
  - Users can employ this model by using the SetEmModel method of the G4IonIonisation process

- **Restricted to one Geant4 particle type:** G4GenericIon
  - the process G4IonIonisation is also applicable to alpha particles (G4Alpha) and He3 ions (G4He3), however the G4IonParametrisedLossModel model must not be activated for these light ions
  - Below Z<2, we use G4BraggModel, G4BraggIonModel, and G4BetheBlochModel with the G4IonIonisation process
Using ICRU 73 data tables

- The ion model
  - uses ICRU 73 stopping powers, if corresponding ion-material combinations are covered by the ICRU 73 report
  - otherwise applies a Bethe-Bloch based formalism

- For compounds, ICRU 73 stopping powers are used if the material name coincides with the name of Geant4 NIST materials
  - e.g. G4_WATER

- Elemental materials are matched to the corresponding ICRU 73 stopping powers by means of the atomic number of the material. The material name may be arbitrary in this case.

- For a list of applicable materials, the user is referred to the ICRU 73 report.

- All data files are in the G4LEDATA set of data.
PHYSICS MODELS

Geant4-DNA
Geant4 for microdosimetry

- **History**: initiated in 2001 by Petteri Nieminen (European Space Agency / ESTEC) in the framework of the « Geant4-DNA » project

- **Objective**: adapt the general purpose Geant4 Monte Carlo toolkit for the simulation of interactions of radiation with biological systems at the cellular and DNA level (« microdosimetry »)

- A full multidisciplinary activity of the Geant4 low energy electromagnetic Physics working group, involving physicists, theoreticians, biophysicists...

- **Applications**:
  - Radiobiology, radiotherapy and hadrontherapy (eg. early prediction of direct & non-direct DNA strand breaks from ionising radiation)
  - Radioprotection for human exploration of Solar system
  - Not limited to biological materials (ex. DNA bases)
Several models are available for the description of physical processes involving $e^-, p, H, He, He^+, He^{2+}, C^{6+}, N^{7+}, O^{8+}, Fe^{28+}$

- Include elastic scattering, excitation (electronic + vibrations), ionisation and charge change

- For now, these models are valid for liquid water medium only

- Models available in Geant4-DNA are published in the literature
  - may be purely analytical or use interpolated cross section data

- They are all discrete processes
  - See $G4INSTALL/examples/advanced/dnaphysics$

- Can be combined with other EM categories (Standard, LowE)
  - See $G4INSTALL/examples/advanced/microdosimetry$
Physics stage:
status of Physics models in Geant4 9.4

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>H</th>
<th>a, He+, He</th>
<th>C, O, Fe,...</th>
</tr>
</thead>
</table>
| Elastic scattering | > 9 eV – 1 MeV Screened Rutherford
>4 eV – 1 MeV Champion | -            | -            | -          | -            |
| Excitation       | 9 eV – 1 MeV
Born              | 10 eV – 500 keV Miller Green
500 keV – 100 MeV Born | 10 eV – 500 keV Miller Green | Effective charge scaling from same models as for proton
1 keV – 400 MeV |
| Charge Change    | -            | 100 eV – 10 MeV Dingfelder | 100 eV – 10 MeV Dingfelder | -          | -            |
| Ionisation       | 11 eV – 1 MeV
Born              | 100 eV – 500 keV Rudd
500 keV – 100 MeV Born | 100 eV – 100 MeV Rudd | Effective charge scaling
0.5 MeV*u – 10^6 MeV*u |
| Vibrational excitation | 2 – 100 eV Sanche |              |              |              |              |
| Attachment       | 4 – 13 eV Melton |              |              | -           |              |
PHYSICS MODELS

Atomic de-excitation
Atomic effects

- Atomic de-excitation initiated by other EM processes
  - Examples: photo-electric effect, ionisation by e- and ions (eg. PIXE)
  - Leave the atom in an excited state

- EADL data contain transition probabilities
  - radiative: fluorescence
  - non-radiative:
    - Auger e-: initial and final vacancies in different sub-shells
    - Coster-Kronig e-: identical sub-shells

- Atomic de-excitation simulation is now compatible with both Standard & LowE EM categories
Including atomic effects

- **How to use fluorescence in Livermore & Penelope Physics?**
  - Fluorescence is automatically activated for gamma photo electric effect and for electron ionisation.
  - If a user wants to deactivate fluorescence, he/she needs to apply the `SetUseAtomicDeexcitation(false)` method to the corresponding model.

- **How to include Auger emission in Livermore & Penelope Physics?**
  - The user must apply the method `ActivateAuger(true)` to the corresponding model.
  - For example, for gammas and electrons with Penelope:
    ```
    thePenelopePhotoElectricModel->ActivateAuger(true);
    thePenelopeIonisationModel->ActivateAuger(true);
    ```

- **How to include fluorescence, Auger emission in Standard EM (options 2 & 3)?**
  - Some UI commands are available (no more code edition necessary!)
    ```
    /run/initialize
    /process/em/fluo true
    /process/em/auger true
    /process/em/pixe true
    ```
  - The same approach will be proposed for Livermore & Penelope.

- **Example to start from**
  - See `$G4INSTALL/examples/extended/electromagnetic/TestEm18`
HOW TO IMPLEMENT A  
**EM PHYSICS LIST?**
Physics lists

- A user can
  - use reference Physics lists provided with Geant4 (QBCC, ....)
  - build his/her own Physics list in his/her application
  - or use already available EM constructors

1. If you choose to build your own Physics list
   - Refer to the Geant4 Low Energy EM working group website, look at the Processes and Physics lists sections
   - Also you may refer to Geant4 examples
     - $G4INSTALL/examples/extended/electromagnetic/TestEm14

2. More safe: if you prefer to use the available constructors, these are named as:
   - G4EmLivermorePhysics
   - G4EmLivermorePolarizedPhysics
   - G4EmPenelopePhysics
   - G4EmDNAPhysics
How to use the already available Physics lists constructors?

- These classes derive from the `G4VPhysicsConstructor` abstract base class; they are added to the reference Physics lists via the method `RegisterPhysics(G4VPhysicsConstructor*)`
  - see `$G4INSTALL/source/physics_lists/lists` subdirectory

- A good alternative implementation example of Physics list that uses EM physics constructors is available in `$G4INSTALL/examples/extended/electromagnetic/TestEm2`

- If some hadronic physics is needed additionally to EM Physics: `$G4INSTALL/examples/extended/electromagnetic/TestEm7`

- The source code for Physics list constructors is available in the following directory `$G4INSTALL/source/physics_list/builders`
DOCUMENTATION
A unique reference web page on Geant4 EM Physics

From there, links to:
- Geant4 Standard Electromagnetic Physics working group pages
- Geant4 Low Energy Electromagnetic Physics working group pages

Also from Geant4 web site:
- http://cern.ch/geant4
  - Who we are
    - Low energy Electromagnetic Physics
EM Physics CERN TWiki

https://twiki.cern.ch/twiki/bin/view/Geant4/ElectromagneticPhysics

Electromagnetic Physics

- Introduction
- Working Group pages
- Validation and verification
- Publications and presentations
- Examples
- Physical Lists
- Models and Processes
- Milestones
- Release notes
- Manuals
- Getting Help
- Related links

Introduction

The electromagnetic physics domain includes Geant4 sub-packages for simulation of electromagnetic interactions of charged particles, gammas and optical photons. This is central TWiki page for Geant4 EM physics maintained by common efforts of the EM Standard and EM Low-energy working groups.

Working Group pages

- Electromagnetic Physics Home
- Electromagnetic Standard working group page
- Electromagnetic Standard working group coordination TWiki
- Low Energy Electromagnetic working group page
- Low Energy Electromagnetic working group TWiki
Summary:
when/why to use Low Energy Models

- **Use** Low-Energy models (Livermore or Penelope), 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 another simulation (e.g. with a different model)

- **Do not use** when you are interested in EM physics > MeV
  - same results as Standard EM models, strong performance penalty
THANK YOU