EM interactions

Beginners’ FLUKA Course
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| **Ionization energy losses** |
| - Continuous |
| - Delta-ray production |

| **Transport** |
| - Multiple scattering |
| - Single scattering |

*These are common to all charged particles, although traditionally associated with EM*
E-M FLUKA (EMF) at a glance

Energy range for $e^+$, $e^-$, $\gamma$: 1 keV (100 eV for $\gamma$) - 1000 TeV
Full coupling in both directions with hadrons and low-energy neutrons
Energy conservation within computer precision
Up-to-date $\gamma$ cross section tabulations from EPDL97 database

EMF is activated by default....and with most DEFAULTS options, except: EET-TRAN, NEUTRONS, SHIELDING

To de-activate EMF:

With EMF-OFF, E.M. energy is deposited on the spot
Consider also the DISCARD command

Production and transport of optical photons (Cherenkov, scintillation) is implemented. Since it needs user coding, it is not treated in this beginners course
Transport thresholds

EM particles are transported until their energy falls below a preset threshold. In FLUKA, this energy threshold can be set \textit{REGION BY REGION}.

\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{EMFCUT} & \textbf{e}^\pm \textbf{Thresh} & \textbf{\gamma} \textbf{Thresh} & 0.0 & \textbf{Reg1} & \textbf{Reg2} \\
\hline
\end{tabular}

**HOW to choose?**

It depends on the “granularity” of the geometry and/or of the scoring mesh and on the “interest” in a given region. Energy/range tables are very useful (see for instance \url{http://physics.nist.gov})

**Warning 1:** to reproduce correctly electronic equilibrium, neighboring regions should have the same electron energy (NOT range) threshold. To be kept in mind for sampling calorimeters

**Warning 2:** Photon thresholds should be lower than electron thresholds (photons travel more)

**Warning 3:** \textit{low thresholds are CPU eaters}
Production Thresholds

Let’s introduce a concept that is treated again in the discussion of ionization energy losses: the separation between **CONTINUOUS** and **DISCRETE** energy deposition:

The simulation of all atomic interaction processes is not possible in all-purposes MCs, because

- the modeling of very low energy transfer would need detailed atomic/molecular physics
- the CPU time would diverge

→ 1) **ONLY** interactions resulting in a “substantial” energy transfer are simulated explicitly
→ 2) All other interactions are “condensed” in a continuous energy loss along the particle step

Condition 1) is implemented by setting a threshold for the energy of the produced secondary particles (“delta rays“):  
$$SDUM = PROD - CUT$$

The production threshold is also used as lowest energy limit to prepare cross section tabulations at initialization stage.
Production Thresholds -II

For electromagnetic interactions: **BY MATERIAL**!

<table>
<thead>
<tr>
<th>EMFCUT</th>
<th>e±Thresh</th>
<th>γThresh</th>
<th>Fudgem</th>
<th>Mat1</th>
<th>Mat2</th>
<th>Step</th>
<th>PROD-CUT</th>
</tr>
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</table>

**EMFCUT**
- Type: PROD-CUT
- Fudgem: 

Fudgem is related to multiple scattering. = 0 below ≈ 10 keV, = 1 above
MUST be set, if the field is empty ➞ 0

**Warning 1:** production and transport thresholds are set by default, depending on the DEFAULTS card. **DO NOT RELY** on them, choose those best suited for your problem.

**Warning 2:** if prod-cut < transport cut, CPU is wasted in producing/dumping particles on spot. Sometimes it could be convenient to define several “equal” materials with different production thresholds (and different names).

**Warning 3:** if prod-cut > transport cut, the program automatically increases the transport threshold, because it cannot transport a particle that it is not supposed to handle.
Photon interactions
## Photoelectric effect

<table>
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<th>Detailed treatment of</th>
<th>Fluorescence</th>
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<td>Photoelectron</td>
<td>Angular distribution</td>
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<tr>
<td>Approximate</td>
<td>Auger effect</td>
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<tr>
<td>Effect of photon</td>
<td>Polarization</td>
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Fluorescence after photoelectric is activated only with a subset of DEFAULTS.

**CPU time vs. precision in small granularity**

To activate/deactivate it:

EMFFLUO Flag  Mat1  Mat2  Step

Flag > 0: Activate  Flag < 0: De-activate

**Warning**: check consistency with production/transport thresholds
Compton and Rayleigh

- **Account for atomic bonds using inelastic Hartree-Fock form factors** (very important at low E in high Z materials)

- **NEW**: Compton with atomic bonds and orbital motion (as better alternative to form factors)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence

- **Account for effect of photon polarization**

  Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS.
  To activate/deactivate:

  | EMFRAY | Flag | Reg1 | Reg2 | Step |

  **Look in the manual for further details**
Compton profile examples

**green** = free electron  
**blue** = binding with form factors  
**red** = binding with shells and orbital motion

Larger effect at very low energies, where, however, the dominant process is photoelectric.  
Visible: shell structure near $E' = E$, smearing from motion at low $E'$
Polarization

By default, source photons are NOT polarized. Polarization can be set by 

\[ \text{POLARIZA Pcosx Pcosy Pcosz Flag1 Fraction Flag2} \]

Flag1 \(\geq 1\) \(\Rightarrow\) Pol. direction orthogonal to direction of motion,
Fraction + flag2 \(\Rightarrow\) fraction of polarized/unpolarized or polarized/orthogonally polarized photons
(see the manual for further details)

Effect of photon polarization
Deposited dose by 30 keV photons on Water at 3 distances from beam axis as a function of penetration depth for 3 orientations wrt the polarization direction
Pair Production

- Angular and energy distribution of $e^+, e^-$ described correctly (no “fixed angle” or similar approximation)
- No approximations near threshold
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect
- Differences between emitted $e^+$ and $e^-$ at threshold accounted for
Photonuclear interactions

Photon-nucleus interactions in FLUKA are simulated over the whole energy range, through different mechanisms:

- Giant Resonance interaction
- Quasi-Deuteron effect
- Delta Resonance production
- Vector Meson Dominance \((\gamma \equiv \rho, \Phi \text{ mesons})\) at high energies

Nuclear effects on the initial state (i.e. Fermi motion) and on the final state (reinteraction / emission of reaction products) are treated by the FLUKA hadronic interaction model (PEANUT) \(\Rightarrow\) INC + pre-equilibrium + evaporation/fission/breakup

The (small) photonuclear interaction probability can be enhanced through biasing (see command LAM-BIAS)
Photonuclear interactions: options

Photonuclear interactions are **NOT activated** with any default

To activate them:

<table>
<thead>
<tr>
<th>PHOTONUC Flag</th>
<th>Mat1</th>
<th>Mat2</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flag controls activation of interactions, with the possibility to select a subset of the photonuclear mechanisms

Since the photonuclear cross section is very small, PHOTONUC should be always accompanied by LAM-BIAS with SDUM = blank (see lecture on biasing)

<table>
<thead>
<tr>
<th>LAM-BIAS 0.0 Factor</th>
<th>Mat</th>
<th>PHOTON</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
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Applications:
- electron accelerator shielding and activation
- neutron background by underground muons (together with muon photonuclear interactions (option MUPHOTON))
Photonuclear Interactions: benchmark

Yield of neutrons per incident electron as a function of initial e\textsuperscript{-} energy.
Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))

Left: Pb, $1.01 \times X_0$ (lower points) and $5.93 \times X_0$ (upper)
Right: U, $1.14$ and $3.46 \times X_0$
Photonuclear int.: example

Reaction:
\(^{208}\text{Pb}(\gamma,x\,n)\)
\(20 \leq E_\gamma \leq 140\ \text{MeV}\)

Cross section for multiple neutron emission as a function of photon energy, Different colors refer to neutron multiplicity \(\geq n\), with \(2 \leq n \leq 8\)

Symbols: exp. data (NPA367, 237 (1981); NPA390, 221 (1982))

Lines: FLUKA
Photomuon production

Muon pair production by photons is NOT activated with any default

To activate it:

<table>
<thead>
<tr>
<th>PHOTONUC Flag</th>
<th>Lambias</th>
<th>Mat1</th>
<th>Mat2</th>
<th>Step</th>
<th>MUMUPAIR</th>
</tr>
</thead>
</table>

Flag controls activation of interactions, with the possibility to select a subset of the photomuon mechanisms (coherent, incoherent, inelastic...) Biasing of photomuon production can be done directly with this card, setting WHAT(2)
Electron/Positron interactions
Bremsstrahlung

- Energy-differential cross sections based on the Seltzer and Berger database, interpolated and extended to a finer energy mesh, tip, and larger energies
- Finite value at tip energy (tip == max energy of photon)
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect
- Soft photon suppression (Ter-Mikaelyan) polarization effect
- Special treatment of positron bremsstrahlung with ad hoc spectra at low energies
- Detailed photon angular distribution fully correlated to energy
Bremsstrahlung: benchmark

2 MeV electrons on Iron, Bremsstrahlung photon spectra measured (dots) and simulated (histos) at three different angles.
Bremsstrahlung: benchmark II

12 and 20.9 MeV electrons on a W-Au-Al target, bremsstrahlung photon spectra in the forward direction measured (dots) and simulated (histos)
Bremsstrahlung: benchmark III
Esposito et al., LNF 93-072

ADONE storage ring
1.5 GeV e⁻

Bremss. on the residual gas in the straight sections

Measured with TLD’s matrices at different distances from the straight Section

Here: dose vs. horizontal position at different vertical positions, d=218cm
Other $e^\pm$ interactions

Positron Annihilation

- At rest and in flight according to Heitler.
- In annihilation at rest, account for mutual polarization of the two photons
- Acolinearity of the photons at rest can be requested, with annihilation photon energies spread out

Scattering

- $e^+$: Bhabha
- $e^-$: Møller
Electron scattering:

Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm² thick Copper foil. Measured (dots) and simulated (histos) data.
The ATLAS EM “accordion” calo (standalone test beams)

Energy resolution 10-100 GeV:

\[
\text{Exp: } \frac{\sigma}{E} = \frac{9.8 \pm 0.4\%}{\sqrt{E}}
\]

\[
\text{Fluka: } \frac{\sigma}{E} = \frac{9.2 \pm 0.3\%}{\sqrt{E}}
\]
Muon interactions
Bremsstrahlung and pair production

- At high energies, bremsstrahlung and pair production are important also for muons and charged hadrons. For instance, in Lead the muon energy loss is dominated by these processes above 300 GeV.

For muons and all charged hadrons:
- **Bremsstrahlung**: implemented in FLUKA including the effect of nuclear form factors
- **Pair Production**: implemented

Activation of these processes and thresholds of EXPLICIT $\gamma$ and $e^{\pm}$ production depend on the DEFAULTS chosen. They are controlled by the card

```
PAIRBREM Flag  e+Thresh gammaThresh Mat1 Mat2 Step
```

Below threshold, energy loss is accounted for in a continuous approximation.
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

Ionization

Bremsstrahlung + Pair production

<table>
<thead>
<tr>
<th>ID</th>
<th>1050</th>
</tr>
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<tbody>
<tr>
<td>Entries</td>
<td>743729</td>
</tr>
<tr>
<td>Mean</td>
<td>5.293</td>
</tr>
<tr>
<td>RMS</td>
<td>11.89</td>
</tr>
</tbody>
</table>
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

![Graph showing muon energy distribution](image-url)
Muon Photonuclear Reactions

- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction
- Nuclear screening is taken into account
- Only Virtual Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models
- Nuclear effects are the same as for hadron-nucleus interactions
Muon photonuclear: options

μ photonuclear interactions are **NOT activated** with any default

To activate them:

<table>
<thead>
<tr>
<th>MUPHOTON Flag</th>
<th>0.0</th>
<th>0.0</th>
<th>Mat1</th>
<th>Mat2</th>
<th>Step</th>
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Flag controls activation of interactions, with the possibility to simulate the interaction without explicit production and transport of secondaries (this gives the correct muon energy loss/ straggling)

Since the μ photonuclear cross section is very small, MUPHOTON should be always accompanied by LAM-BIAS (see lecture on biasing)

| LAM-BIAS | 0.0 | Factor | Mat | MUON+ | MUON- |
Muon-induced neutron background in underground labs

Neutron production rate as a function of muon energy

Stars+line: FLUKA simulation with a fit to a power law.

Exp. points:
  - Abscissa: average μ energy at the experiment's depth:
    - A) 20 m.w.e.
    - B) 25 m.w.e.
    - C) 32 m.w.e. (Palo Verde)
    - D) 316 m.w.e.
    - E) 750 m.w.e.
    - F) 3650 m.w.e. (LVD)
    - G) 5200 m.w.e. (LSD)

m.w.e. = meter of water equivalent

PRD64 (2001) 013012
Muon Capture (1)

An exotic source of neutron background *(See background at nTOF)*

Basic weak process: \( \mu^- + p \rightarrow \nu_\mu + n \)

\( \mu^- \) at rest + atom → excited muonic atom → x-rays+g.s muonic atom

Competition between \( \mu^- \) decay and \( \mu^- \) capture by the nucleus.

In FLUKA: Goulard-Primakoff formula

\[ \Lambda_c \propto Z_{eff}^4, \] calculated \( Z_{eff} \), Pauli blocking from fit to data.

\[ \frac{\Lambda_c}{\Lambda_d} = 9.2 \cdot 10^{-4} \] for H, \[ 3.1 \] for Ar, \[ 25.7 \] for Pb

Nuclear environment (Fermi motion, reinteractions, deexcitation..) from the FLUKA intermediate-energy module PEANUT

Slow projectile, low energy transfer (neutron \( E=5 \text{ MeV} \) on free p)

Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption
Muon Capture (2)

capture on Calcium
histograms: FLUKA calculations
Emitted:
0.62 neutrons/capture
0.27 protons/capture
Electromagnetic dissociation

Note: Electromagnetic dissociation is already relevant for interactions of few GeV/n ions in heavy targets.
Electromagnetic dissociation cross sections (total, 1nX, 2nX) for 30GeV/n Pb ions on Al, Cu, Sn, and Pb targets.

FLUKA: lines (calculated cross section as a function of target charge)
Exp. data: M.B.Golubeva et al.
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), *yellow* histos are FLUKA (with DPMJET-III) predictions: *purple* histos are the electromagnetic dissociation contribution.
Spare slides
Electromagnetic dissociation: example

$^{28}\text{Si}(\gamma,\text{tot})$ as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.