EM interactions
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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 with most DEFAULTS options, except: EET-TRAN, NEUTRONS, SHIELDING

To de-activate EMF:

| EMF | EMF-OFF |

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 further in this beginners' course.
Photon interactions
Photon interactions modeled in FLUKA

- Rayleigh scattering

- Photoelectric absorption

- Compton scattering

- Pair production

+photo-nuclear processes

+Auger

+photo-muon production
Photon interactions modeled in FLUKA

- Rayleigh scattering
- Compton scattering
- Pair production

+photo-nuclear processes  
+photo-muon production

+Auger

Photoelectric absorption

Fluorescence

$E_e = E - U_i$
Photoelectric effect

Absorption of a photon by a target atom, electron ejected, inner-shell vacancy left behind.

Source: Evaluated Photon Data Library (Cullen et al., EPDL97).
Atomic de-excitation

Fluorescence vs Auger emission

Next: angular distribution of emitted electron and deexcitation via fluorescence / Auger emission.
Photoelectric effect

Detailed treatment of Fluorescence
Photoelectron Angular distribution
Approximate Auger effect
Effect of photon Polarization

Fluorescence (and Auger) after photoelectric is activated only with a subset of DEFAULTS: CALORIMETRY, EM-CASCA, ICARUS, PRECISION

CPU time vs. precision in small granularity
To activate/deactivate it:

<table>
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<th>EMFFLUO</th>
<th>Flag</th>
<th>Mat1</th>
<th>Mat2</th>
<th>Step</th>
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Flag > 0: Activate Flag < 0: De-activate

Warning: check consistency with production/transport thresholds

FLUKA Beginners' Course
The polarization of the incoming photon breaks the azimuthal symmetry in the angular distribution of the emitted electron.

E.g. for polarization along the x axis (\(\theta=90^\circ\), \(\phi=0^\circ\) or \(180^\circ\)) we have

Card POLARIZA discussed below
Compton and Rayleigh scattering

Rayleigh scattering

Photoelectric absorption

Compton scattering

Pair production

+photo-nuclear processes

+photo-muon production

+Auger

Fluorescence

FLUKA Beginners' Course
Compton and Rayleigh scattering

- Klein-Nishina cross section: free target electron at rest.
- 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 incoming 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 scattering

KN: free e\textsuperscript{−} at rest

Incoh. scatt. function: binding via form factor

FLUKA: accounting for atomic shell binding energies and e\textsuperscript{−} orbital motion

Ref: T. Boehlen et al., *J Instrum* 7 P07018 (2012)

Figure 4. Compton scattering cross sections differential in the energy of the scattered photon $E'$ at selected initial photon energies ($E = 20, 100, 1000$ keV) for carbon and lead. The cross sections are computed with the present Compton scattering model, using a fit to tabulations of the incoherent scattering function $S(q,Z)$ from EPDL97 [181], and using the KN cross section.
Effect of polarization on Compton scattering

50-keV photons impinging along Z on water cylinder

Unpolarized
Effect of polarization on Compton scattering

Azimuthal angle of outgoing photon preferentially along direction perpendicular to polarization.

50-keV photons impinging along Z on water cylinder

Incoming photon polarized along X

Compton photons preferentially emitted along Y (!)
Polarization

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

$$\text{POLARIZA Pcosx Pcosy Pcosz Flag1 Fraction Flag2}$$

Flag1 >= 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 in Water at 3 distances from beam axis as a function of penetration depth for 3 orientations wrt the polarization direction
e^-e^+ Pair Production

- Rayleigh scattering
- Photoelectric absorption
- Compton scattering
- Pair production

**Photo-nuclear processes**

**Photo-muon production**

FLUKA Beginners' Course
e⁻e⁺ Pair Production

- Kinematics: requires presence of target mass, threshold at ~2*511 keV.
- Dominant photon interaction mechanism at energies above ~100 MeV
- Angular and energy distribution of e⁺, e⁻ described correctly (no “fixed angle” theta=m/k or similar approximation)
- No approximations near threshold. Differences between emitted e⁺ and e⁻ at threshold accounted for
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect
Relative importance of processes (sub GeV)

Mass attenuation coefficient $\mu$

$\mu = N \sigma$ : inverse mean free path

Rho: density

$\mu/\rho$ is therefore a way to quote the integrated cross section in such a way that it is independent of aggregation state.

Coherent = Rayleigh
Incoherent = Compton
Pair product. = $e^-e^+$ pair prod.
Photomuon production

Muon mass $\sim 105 \text{ MeV/c}^2$. For photon energies above $\sim 2*105 \text{ MeV/c}^2$ we can expect muon-+ pair production near target mass.

Relative importance wrt e-e+ pair prod.: $(m_e/m_\mu)^2 \rightarrow \sim 1/40000$

Muon pair production by photons is NOT activated by any DEFAULT
To activate it use PHOTONUC with SDUM=MUMUPAIR:

```
PHOTONUC Flag Lambias 0.0 Mat1 Mat2 Step MUMUPAIR
```

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)

Ref: Y.S. Tsai, Rev. Mod. Phys. 46 4 815-851 (1974) + ERRATUM
Photonuclear interactions

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

- Giant Resonance interaction (~10-20 MeV)
- Quasi-Deuteron effect (~50-150 MeV)
- Delta Resonance production (~150-400 MeV)
- Vector Meson Dominance ($\gamma \equiv \rho, \Phi$ 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 (Tuesday lecture)

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

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

To activate them:

- **PHOTONUC Flag Mat1 Mat2 Step**

  *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).

- **LAM-BIAS 0.0 Factor Mat PHOTON**

Applications:
- electron accelerator shielding and activation
- neutron background by underground muons (together with muon photonuclear interactions (option **MUPHOTON**))
Photonuclear int.: example

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

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
Yield of neutrons per incident electron as a function of initial $e^-$ energy. Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))
Left: Pb, 1.01 $X_0$ (lower points) and 5.93 $X_0$ (upper)
Right: U, 1.14 and 3.46 $X_0$
Electron/Positron interactions
e+/e- interactions modelled in FLUKA

- Delta-ray production (-> EMFCUT)
  - Delta-ray production via Bhabha and Moeller scattering
- Bremsstrahlung production (-> EMFCUT)
  - Energy-differential cross sections based on the Seltzer and Berger database
  - Considers the LPM effect and the soft photon suppression (Ter-Mikaelyan) polarization effect
  - Detailed photon angular distribution fully correlated to energy
- Positron annihilation
  - At rest and in flight according to Heitler.
  - In annihilation at rest, account for mutual polarization of the two photons
- Muon capture
Figure 3.15: Radiative and collision stopping powers for electrons in aluminium, silver (×10) and gold (×100) as functions of the kinetic energy (solid and dashed curves, respectively). Dot-dashed lines represent the high-energy approximation given by Eq. (3.160). Diamonds indicate the critical energy $E_{\text{crit}}$ at which the radiative stopping power starts dominating for each material.
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)
Muon interactions
Muon interactions modelled in FLUKA

- Delta-ray production (\(\rightarrow\) DELTARAY card)
- Bremsstrahlung (\(\rightarrow\) PAIRBREM card)
  - Consideration of LPM effect
  - Detailed photon angular distribution fully correlated to energy
- Pair production (\(\rightarrow\) PAIRBREM card)
  - Consideration of LPM effect
  - Correlated angular and energy distribution
- Muon photo-nuclear reactions
  - See next slides
- Muon capture
  - See next slides
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 Vector Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models.
- Nuclear effects are the same as for hadron-nucleus interactions.

Schematic view of a $\mu$ hadronic interaction.

The interaction is mediated by a virtual photon.

The final state can be more complex.
Muon photonuclear reactions: options

Muon photonuclear interactions are **NOT activated** with any default.

To activate them:

```
MUPHOTON Flag 0.0 0.0 Mat1 Mat2 Step
```

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 $\mu$ 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 interactions

- Muon photonuclear is less likely than other processes.
- Bremsstrahlung dominates large energy losses.
- Pair production and ionization dominate small energy losses.


Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.
Muon capture

An exotic source of neutron background

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

Competes with:

$\mu^-$ at rest + atom = excited muonic atom $\rightarrow$ x rays $+$ g.s. muonic atom

Competition between $\mu$ decay $\Lambda_d$ and capture by nucleus $\Lambda_c$

In FLUKA: Goulard-Primakoff formula

$\Lambda_c / Z_{\text{eff}}^4$ Calculated $Z_{\text{eff}}$, Pauli blocking from data

$\frac{\Lambda_c}{\Lambda_d} = 9.2 \times 10^{-4}$ for H, 3.1 for Ar, 25.7 for Pb

Nuclear environment from PEANUT

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

Experimentally: high energy tails in n-spectra
Synchrotron radiation
Synchrotron radiation

A charged particle in a curved trajectory in a magnetic field may emit synchrotron radiation (SR), even in vacuum.

FLUKA can model the emission of SR by any charged particle traversing up to 2 circular arcs or helical paths, accounting for the emitted photon polarization, and sampling:

- SR photon energy
- SR photon angle

The emitting charged particle is NOT transported: SR photons are sampled directly.

Readily usable for bending magnets and wigglers (two steps so far).
Synchrotron radiation: cards

```
SPECSOURCE
  ELECTRON  3.0  -2.0  0.0000001  1.000  0.0  SYNC-RAS
SPECSOURCE
  150.0  0.0  -0.5  -1000.  0.0  -0.100
```

WHAT(1) = particle emitting the radiation
  Default: 3.0 (ELECTRON)
WHAT(2) > 0.0: emitting particle momentum (GeV/c)
  < 0.0: kinetic energy of the emitting particle (GeV)
WHAT(3) > 0.0: curvature radius of the emitting particle trajectory (cm)
  < 0.0: absolute value of the bending magnetic field (T)
WHAT(4) = lower limit of the photon energy spectrum (GeV)
  Default: 1.E-7 GeV
WHAT(5) = x-component of the magnetic field versor
WHAT(6) = y-component of the magnetic field versor

SDUM  = SYNC-RAD if the z-component of the magnetic field versor is > 0.0
SYNC-RDN if the z-component is < 0.0
SYNC-RAS if the z-component of the magnetic field versor is > 0.0
  and the magnetic field of the second arc (if present) has opposed
  sign to that of the first arc.
SYNC-RDS if the z-component is < 0.0 and the magnetic field of
  the second arc (if present) has opposed sign to that of the first
  arc.
Synchrotron radiation: cards (continuation card)

SPECSOUR | ELECTRON | 3.0 | -2.0 | 0.0000001 | 1.000 | 0.0SYNC-RAS
SPECSOUR | 150.0 | 0.0 | -0.5 | -1000. | 0.0 | -0.100&

Continuation card:

WHAT(1) = length of the emission arc or helical path (cm)
Default = 100.0 cm
WHAT(2) = x-coordinate of the starting point of a possible second path of
same length (see Note 1)
WHAT(3) = y-coordinate of the starting point of the second path (see Note 1)
WHAT(4) = z-coordinate of the starting point of the second path (see Note 1)
WHAT(5) = x-component of the emitting particle direction versor at the
beginning of the second path (see Notes 1 and 2)
WHAT(6) = y-component of the emitting particle direction versor at the
beginning of the second path (see Notes 1 and 2)
SDUM = "&" in any position in columns 71-78 (or in last field if free
format is used)
Synchrotron radiation: example

Synchrotron radiation photons from 3-GeV electrons on a 150 cm arc in B=2 T along X (into the screen)
Synchrotron radiation: 1-arc example

![Synchrotron radiation photon fluence diagram]

**BEAMPOS**
- 0.5  -1400.0  0.100

**SPECSOUR**
- ELECTRON  3.0  -2.0  0.0000001  1.000  0.0 SYNC-RAS
- 150.0
Synchrotron radiation: 2-arc example

Synchrotron radiation photon fluence

BEAMPOS
0.5  -1400.0  0.100

SPECSOUR ELECTRON 3.0  -2.0  0.0000001  1.000  0.0 SYNC-RAS
SPECSOUR 150.0  0.0  -0.5  -1000.  0.0  -0.100
A comment about the units

All simulation results for the synchrotron radiation SPECSOUR are quoted per simulated synchrotron radiation photon.

From the output file:

<<< Synchrotron radiation source n. 1 >>>

- Emitting particle: ELECTRON P: 3.000000 GeV/c
- Initial position: 0.0000000 0.50000000 1.40000000 cm
- Initial direction: 0.0000000 0.10000000 0.99498744

- Magnetic field: 2.0000000 0.0000000 0.0000000 T
- Nominal curvature radius: 500.34614 cm
- Nominal arc: 150.00000 cm
- Arc angle: 0.29979246 rad
- Actual curvature radius: 500.34614 cm
- Actual arc: 150.00000 cm
- Transverse p_t: 3.0000000 GeV/c and gamma: 5870.85237
- Critical energy: 0.0000119705 GeV

Photon emission threshold: 1.0000000E-07 GeV
Photons >1 eV/nominal unit length: 0.11693748 cm^-1
Photons/unit length 1 eV thres.: 2.38764527E-02 cm^-1
Photons/unit length above thres.: 9.30610323E-02 cm^-1

- Total energy/nominal unit length: 4.55537630E-07 GeV/cm
- Energy/unit length below thresh.: 7.5428751E-10 GeV/cm
- Energy/unit length above thresh.: 4.54783401E-07 GeV/cm

We would have to scale results by 150*.093061 so as to obtain results per primary emitting particle.
Synchrotron radiation: a higher-energy example

175-GeV electrons on a few cm in an arc with 9 km turning radius:

- Lead shielding
- Al layer
- Vacuum

175-GeV e-
R=9000 km
Synchrotron radiation: a higher-energy example

Flux $E^2 dI/dE$ (1/cm$^2$/SR photon)

175-GeV electron, 9 km turning radius

- Annihilation photons
- Pb K lines
- Al K lines
END
Spare slides
Compton profile examples

50 keV γ on Au

500 keV γ on Au

E: energy of incoming photon, E’: energy of the emitted photon

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 absorption.
Visible: shell structure near E’=E, smearing from motion at low E’
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.
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
The ATLAS EM “accordion” calo (standalone test beams)

Detail of the FLUKA geometry and response vs. electron impact position depositted energy

Energy resolution 10-100 GeV:

\[ \frac{\sigma}{E} = \frac{9.8 \pm 0.4}{\sqrt{E}} \]

\[ \text{Fluka: } \frac{\sigma}{E} = \frac{9.2 \pm 0.3}{\sqrt{E}} \]
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

Ionization

Bremsstrahlung + Pair production
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

Muon energy [GeV]
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
Muon Capture (2)

capture on Calcium

histograms: FLUKA calculations

Emitted:
0.62 neutrons/capture
0.27 protons/capture
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.
Electromagnetic dissociation: example

\( \gamma - ^{28}\text{Si} \) cross section

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