Introduction and Applications of FLUKA

Alfredo.Ferrari@cern.ch
CERN, Geneva, Switzerland
for the FLUKA collaboration

PSI, Oct. 3rd 2006
Outline

- What is FLUKA (short)
  - History
  - Collaboration
  - General structure

- Hadronic Physics in FLUKA (short)
  - Hadron-Nucleon
  - Hadron-Nucleus
  - (Nucleus-Nucleus)
  - (Real and Virtual Photonuclear interactions)

- Low energy neutron transport (short)
  - Main Features

- Hadronic (neutronic) applications
  - Examples

Info: [http://www.fluka.org](http://www.fluka.org)

Special attention on recent developments

Examples of “thin target” benchmarks, essential to test and develop models

Examples of “complex” benchmarks, to illustrate the code capabilities and performances
FLUKA

Main Authors: A. Fasso\textsuperscript{1}, A. Ferrari\textsuperscript{2}, J. Ranft\textsuperscript{3}, P. R. Sala\textsuperscript{4}
\textsuperscript{1} SLAC Stanford, \textsuperscript{2} CERN, \textsuperscript{3} Siegen University, \textsuperscript{4} INFN Milan

Contributing authors: G. Battistoni, F. Cerutti, A. Empl, M. V. Garzelli, V. Patera, S. Roesler, V. Vlachoudis

Interaction and Transport Monte Carlo code

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{6 GeV proton in Liquid Argon}
\end{figure}

Web site: http://www.fluka.org
FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications.
- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Electromagnetic and $\mu$ interactions 1 keV – 10000 TeV
  - Nucleus-nucleus interactions 0-10000 TeV/n
  - Charged particle transport – ionization energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - $\nu$ interactions
  - Transport in magnetic field
  - Combinatorial (boolean) and Voxel geometry
  - **Double capability to run either fully analogue and/or biased calculations**

- Maintained and developed under INFN-CERN agreement and copyright 1989-2006 (funding from NASA as well)
- More than 1000 users all over the world

http://www.fluka.org
Fluka Applications

- cosmic ray physics
- accelerator design (→ LHC systems)
- particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, … )
- neutrino physics (CNGS, … )
- shielding design
- dosimetry and radioprotection (standard tool at CERN and SLAC)
- space radiation (space related studies partially funded by NASA)
- hadron therapy
- neutronics
- ADS systems (→ “Energy amplifier”)
hN and hA inelastic interactions:

- **hN intermediate Energies**
  - \( N_1 + N_2 \to N_1' + N_2' + \pi \) threshold around 290 MeV important above 700 MeV
  - \( \pi + N \to \pi' + \pi'' + N' \) opens at 170 MeV
  (Dominance of the \( \Delta(1232) \) and of the N* resonances \( \to \) reactions treated in the framework of the isobar model \( \to \) all reactions proceed through an intermediate state containing at least one resonance)

- **hN high Energies: Dual Parton Model**
  - Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
  - each of the two hadrons splits into 2 colored partons \( \to \) combination into 2 colourless chains \( \to \) 2 back-to-back jets
  - each jet is then hadronized into physical hadrons

- **hA: Glauber(-Gribov) cascade**
  - Quantum mechanical method to compute Elastic, Quasi-elastic and Absorption hA cross sections
  - Field theory formulation of Glauber model
  - Multiple collisions \( \leftrightarrow \) Feynman diagrams \( \leftrightarrow \) Pomeron(s) exchange

- **hA: Formation zone** (=materialization time)
Inelastic hN interactions: examples

\[ \pi^+ + p \rightarrow \pi^+ + X (6 \& 22 \text{ GeV/c}) \]

\[ \pi^+ + p \rightarrow \text{Ch}^+/\text{Ch}^- + X (250 \text{ GeV/c}) \]

M.E. Law et al., LBL80 (1972)

Connected points: FLUKA
Symbols w. errors: DATA

Dots: Exp. Data
Histos: FLUKA

Positive hadrons X2
Negative hadrons

6 GeV
22 GeV
The Nuclear environment: PEANUT

Pre-Equilibrium Approach to Nuclear Thermalization

- PEANUT handles hadron-nucleus interactions from threshold (or 20 MeV neutrons) up to 5 GeV

Sophisticated Generalized IntraNuclear Cascade

Smooth transition (all non-nucleons emitted/absorbed/decayed + all secondaries below 30-50 MeV)

Pre-equilibrium stage

Standard Assumption on exciton number or excitation energy

Common FLUKA Evaporation/fission/fragmentation model

Peanut has proven to be a precise and reliable tool for intermediate energy hadron-nucleus reactions

Its “nuclear environment” is also used in the modelization of (real and virtual) photonuclear reactions, neutrino interactions, nucleon decays, muon captures, ...
Nonelastic hA interactions at high energies: examples

Recent results from the HARP experiment
12.9 GeV/c p on Al
π⁺ production at different angles

Double differential π⁺ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)
Low energy thin target example

Angle-integrated $^{90}\text{Zr}(p,xn)$ at 80.5 MeV

The various lines show the total, INC, preequilibrium and evaporation contributions

Thin target examples

\[ p + ^{80}\text{Zr} \rightarrow p + X \ (80 \text{ MeV}) \]

\[ p + \text{Al} \rightarrow \pi^- + X \ (4 \text{ GeV/c}) \]
Thick/Thin target examples: neutrons

$^9$Be(p,xn) @ 256 MeV, stopping target
Data: NSE110, 299 (1992)

Pb(p,xn) @ 3 GeV, thin target
Data: NST32, 827 (1995)
Equilibrium particle emission

**Evaporation**: Weisskopf-Ewing approach
- 600 possible emitted particles/states (A<25) with an extended evaporation/fragmentation formalism
- Full level density formula
- Inverse cross section with proper sub-barrier
- Analytic solution for the emission widths
- Emission energies from the width expression with no. approx.
  - New energy dependent self-consistent evaporation level densities (IAEA recommendations)
  - New pairing energies consistent with the above point
  - Extension of mass tables till A=330 using available offline calculations
  - New shell corrections coherent with the new masses

**Fission**:
- Actinide fission done on first principles
- New fission barrier calculations (following Myers & Swiatecki)
- Fission level density enhancement at saddle point washing out with excitation energy (following IAEA recommendations)
- Fission product widths and asymmetric versus symmetric probabilities better parameterized

**Fermi Break-up** for A<18 nuclei
- ~ 50000 combinations included with up to 6 ejectiles

**γ de-excitation**: statistical + rotational + tabulated levels
Example of fission/evaporation

- Quasi-elastic products
- Spallation products
- Deep spallation products
- Fission products
- Fragmentation products
- Evaporation products


Data
FLUKA
FLUKA only where exp data exist

σ (mb)

Mass number
Low-energy neutron transport in FLUKA

- Energy range up to 19.6 MeV divided in 72 energy groups (and 22 groups for secondary gamma generation)
- The library contains 140 different materials/temperatures
- Hydrogen cross sections available for different types of molecular binding (free, H₂O, CH₂)
- Pointwise, fully correlated, with explicit generation of all secondary recoils, cross sections available for reactions in H, ⁶Li, Ar and partially for ¹⁴N and ¹⁰B (⁴He, ¹²C and ¹⁶O in preparation)
- Gamma transport by the standard EM FLUKA modules
- For most materials, information on the residual nuclei produced by low-energy neutron interactions are available in the FLUKA library

The new library

- 260 n and 40 γ groups including 30 thermal groups at different temperatures and different self-shielding (publicly available at beginning of 2007)
Online evolution of activation and residual dose

NEW

- Decay $\beta$'s, $\gamma$'s produced and transported “on line”
  - Screening and Coulomb corrections accounted for $\beta^{+/-}$ spectra
  - Complete database for $\gamma$ lines and $\beta$ spectra covering down to 0.1% branching
- Time evolution of induced radioactivity calculated analytically
  - Fully coupled build-up and decay (Bateman equations)
  - Up to 4 different decay channels per isotope
- Results for activity, energy deposition, particle fluences etc, calculated for custom irradiation/cooling down profiles
CERN-EU High-Energy Reference Field (CERF) facility

Location of Samples:

Behind a 50 cm long, 7 cm diameter copper target, centred with the beam axis

Beam: 120 GeV, mixed hadrons from CERN SPS
Benchmark experiment - \textit{Results 1}

Dose rate as function of cooling time for different distances between sample and detector

# Activation: Stainless Steel

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$</th>
<th>Exp Bq/g ± %</th>
<th>OLD FLUKA/Exp ± %</th>
<th>FLUKA/Exp ± %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be 7</td>
<td>53.29d</td>
<td>0.205 24</td>
<td>0.096 34</td>
<td>1.070 30</td>
</tr>
<tr>
<td>Na 24</td>
<td>14.96h</td>
<td>0.513 4.3</td>
<td>0.278 8.6</td>
<td>0.406 13</td>
</tr>
<tr>
<td>K 43</td>
<td>22.30h</td>
<td>1.08 4.6</td>
<td>0.628 8.7</td>
<td>0.814 11</td>
</tr>
<tr>
<td>Ca 47</td>
<td>4.54d</td>
<td>0.098 25</td>
<td>0.424 44</td>
<td>(0.295 62)</td>
</tr>
<tr>
<td>Sc 44</td>
<td>3.93h</td>
<td>13.8 4.8</td>
<td>0.692 5.8</td>
<td>0.622 6.2</td>
</tr>
<tr>
<td>mSc 44</td>
<td>58.60h</td>
<td>6.51 7.1</td>
<td>1.372 8.1</td>
<td>1.233 8.6</td>
</tr>
<tr>
<td>Sc 46</td>
<td>83.79d</td>
<td>0.873 8.3</td>
<td>0.841 9.1</td>
<td>0.859 9.5</td>
</tr>
<tr>
<td>Sc 47</td>
<td>80.28h</td>
<td>6.57 8.2</td>
<td>0.970 9.7</td>
<td>1.050 13</td>
</tr>
<tr>
<td>Sc 48</td>
<td>43.67h</td>
<td>1.57 5.2</td>
<td>1.266 8.4</td>
<td>1.403 11</td>
</tr>
<tr>
<td>V 48</td>
<td>15.97d</td>
<td>8.97 3.1</td>
<td>1.464 3.8</td>
<td>1.354 4.8</td>
</tr>
<tr>
<td>Cr 48</td>
<td>21.56h</td>
<td>0.584 6.7</td>
<td>1.084 11</td>
<td>1.032 12</td>
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<tr>
<td>Cr 51</td>
<td>27.70d</td>
<td>15.1 12</td>
<td>1.261 13</td>
<td>1.231 13</td>
</tr>
<tr>
<td>Mn 54</td>
<td>312.12d</td>
<td>2.85 10</td>
<td>1.061 10</td>
<td>1.060 11</td>
</tr>
<tr>
<td>Co 55</td>
<td>17.53h</td>
<td>1.04 4.6</td>
<td>1.112 7.7</td>
<td>0.980 10</td>
</tr>
<tr>
<td>Co 56</td>
<td>77.27d</td>
<td>0.485 7.6</td>
<td>1.422 9.0</td>
<td>1.332 10</td>
</tr>
<tr>
<td>Co 57</td>
<td>271.79d</td>
<td>0.463 11</td>
<td>1.180 12</td>
<td>1.140 12</td>
</tr>
<tr>
<td>Co 58</td>
<td>70.82d</td>
<td>2.21 5.9</td>
<td>0.930 6.3</td>
<td>0.881 6.9</td>
</tr>
<tr>
<td>Ni 57</td>
<td>35.60h</td>
<td>3.52 4.5</td>
<td>1.477 6.5</td>
<td>1.412 8.2</td>
</tr>
</tbody>
</table>

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005
Applications - **CNGS**

![Diagram of CERN Neutrinos to Gran Sasso](image-url)
Cern Neutrino to Gran Sasso

Engineering and physics: target heating, shielding, activation, beam monitors, neutrino spectra

Energy dep. in CNGS target rods, GeV/cm³/pot

Muons in muon pit1: effect of focusing
Applications - CNGS

Example:
\[ t_{\text{cool}} = 1 \text{ day} \]

M. Lorenzo-Sentis, S. Roesler

Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 day cooling
8 \times 10^{12} \text{ protons/s}
Applications - ATLAS zoning

Example:

$$\sum_{i} \frac{A_i}{LE_i}$$

$\text{LE}_i = \text{Exemption limit for the } i_{th} \text{ radioisotope}$

$t_{irr} = 10 \text{ years}$
$t_{cool} = 10 \text{ days}$

SATIF06: V. Hedberg, M. Magistris, M. N. Morev, M. Silari, and Z. Zajacova,
Radioactive waste study of the ATLAS detector

Alfredo Ferrari, PSI
Example: instrumentation calibration (PTB)

Calibration of three different Bonner spheres (with \(^3\text{He} \) counters) with monoenergetic neutron beams at PTB (full symbols), compared with simulation (dashed histos and open symbols)
CERF: instrumentation calibration (PTB and PSI)

Calibration of the LINUS rem counter with monoenergetic neutron beams at PTB and with quasi-monoenergetic neutron beams at PSI (full symbols), compared with simulation (dashed histos and open symbols)

Alfredo Ferrari, PSI
CERF: neutron measurements

Top (left, one side removed) and side (right, roof removed) views of the CERF facility with the measuring positions
## CERF: results

<table>
<thead>
<tr>
<th></th>
<th>experimental cts/PIC</th>
<th>FLUKA cts/PIC</th>
<th>experimental %</th>
<th>FLUKA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINUS rem counter*</td>
<td>0.364</td>
<td>0.409</td>
<td>0.36</td>
<td>2.2</td>
</tr>
<tr>
<td>SNOOPY rem counter*</td>
<td>0.200</td>
<td>0.207</td>
<td>0.59</td>
<td>3.3</td>
</tr>
<tr>
<td>233 sphere</td>
<td>0.788</td>
<td>0.899</td>
<td>0.33</td>
<td>3.7</td>
</tr>
<tr>
<td>178 sphere</td>
<td>0.989</td>
<td>1.01</td>
<td>0.36</td>
<td>3.4</td>
</tr>
<tr>
<td>133 sphere</td>
<td>1.02</td>
<td>0.981</td>
<td>0.30</td>
<td>3.2</td>
</tr>
<tr>
<td>108 sphere</td>
<td>0.942</td>
<td>0.883</td>
<td>0.35</td>
<td>3.1</td>
</tr>
<tr>
<td>83 sphere</td>
<td>0.704</td>
<td>0.717</td>
<td>0.30</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN*. The percent statistical (%) uncertainty is indicated.

The TARC experiment at CERN:

- Beam hole \( \phi = 77.2 \text{ mm} \)
- Measuring holes \( \phi = 64 \text{ mm} \)

### Building Block

- Standard Block Weight = 613 kg

### Block Types

- **Block type 1:**
  - 390

- **Block type 2:**
  - 24x5

- **Block type 3:**
  - 14x5

### Dimensions

- Beam hole: \( \phi = 3.3 \text{ m} \)
- Hole distance to beam axis
- Hole number
- Hole distance to beam axis

### Notes

- Space for neutron absorbing blanket
- Alfredo Ferrari, PSI
The TARC experiment at CERN: neutron spectra

FLUKA + EA-MC (C. Rubbia et al.)

Neutron Energy (eV)

$E \times dF/dE$ (neutron/cm² for $10^9$ protons of 2.5 GeV/c)

$E \times dF/dE$ (neutron/cm² for $10^9$ protons of 3.5 GeV/c)

3.57 GeV/c

2.5 GeV/c

$^3$He Scintillation
$^3$He Ionization
$^6$Li/$^{233}$U Detectors
Monte Carlo

Alfredo Ferrari, PSI
The TARC experiment at CERN: spatial distribution.

![Graph showing spatial distribution with various energy levels and distance to the center of the lead volume.]

- $0.10 \text{ eV}$
- $1.46 \text{ eV (In)}$
- $5 \text{ eV (Au)}$
- $18 \text{ eV (W)}$
- $100 \text{ eV}$
- $480 \text{ eV}$
- $1 \text{ keV}$
- $10 \text{ keV}$
- $180 \text{ keV}$

**Legend:**
- $^3\text{He Ionization}$
- Activation Foils
- $^3\text{He Scintillation}$
- $^6\text{LiF, }^{238}\text{U Detectors}$
- Monte Carlo

**Units:**
- Dose rate: $dF/dE$ (n/cm$^2$/eV/10$^9$ protons)
- Distance: cm

Alfredo Ferrari, PSI
The n-tof facility at CERN: neutron beam with excellent energy resolution for cross section studies

Beam from PS:
20 GeV/c protons + Huge Lead target
Water moderator neutron beam line

Simulations: FLUKA + C. Rubbia's detailed low energy neutron transport
Assumption: 5 cm water moderator as in the design of the facility
Comparison with measured neutron spectrum shows up to 20% difference in the range 1-10^5 eV (published data)
Preparing for Lead target
dismount-
Discovery that the water layer is 6 cm thick instead of 5

FLUKA simulations with 6 cm water (black) compared with 5 cm (red)

PRELIMINARY, thanks to V. Vlachoudis-CERN
Simulation benchmark in mono-energetic neutron fields

Response of hydrogen filled IG5 to neutrons

Centronic IG5-H20 ionization chamber
Active volume of 5.2l filled with hydrogen
Pressurized at 20 bars

Simulation benchmark in mixed fields at the CERF facility

Pos 1  Pos 2  Pos 3  Pos 4  Pos 5  Pos 6

Beam

PTW open-air ionization chamber, active volume of 3l at atmospheric pressure

<table>
<thead>
<tr>
<th>Location</th>
<th>Simulation/Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos 1</td>
<td>0.998 ± 0.10</td>
</tr>
<tr>
<td>Pos 2</td>
<td>1.031 ± 0.11</td>
</tr>
<tr>
<td>Pos 3</td>
<td>1.003 ± 0.10</td>
</tr>
<tr>
<td>Pos 4</td>
<td>1.080 ± 0.12</td>
</tr>
<tr>
<td>Pos 5</td>
<td>1.076 ± 0.12</td>
</tr>
<tr>
<td>Pos 6</td>
<td>0.936 ± 0.15</td>
</tr>
</tbody>
</table>

The TIARA neutron propagation experiment

- Source term: neutrons generated by 68 and 43 MeV protons on $^7$Li carefully measured with TOF techniques → quasi-energetic neutrons of 40 and 65 MeV
- Attenuation of the neutron beam at different depths in concrete and iron shields, both on-axis and off-axis (critical for elastic scattering!)
- Emerging neutron spectra measured with liquid scintillator detectors (the high energy component) and Bonner spheres (the low energy one)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different concrete thicknesses (from 25 to 150 cm), on axis. The neutrons are generated by $^7\text{Li}(p,n)$ at 43 (left) and 68 MeV (right).
Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 20 (left) and 40 cm thick iron shields. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right)
Heavy ion interaction models

- **DPMJET-III** for energies \( \geq 5 \text{ GeV/n} \)
  - DPMJET (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from \( 5-10 \text{ GeV/n} \) up to the highest Cosmic Ray energies \( (10^{18}-10^{20} \text{ eV}) \)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator

- **Modified and improved version of rQMD-2.4 for \( 0.1 < E < 5 \text{ GeV/n} \)**
  - rQMD-2.4 (H. Sorge et al.) Cascade-Relativistic QMD model
  - Energy range: from \( 0.1 \text{ GeV/n} \) up to several hundred \( \text{GeV/n} \)
  - Successfully applied to relativistic A-A particle production

**New developments:**
- New QMD for \( 0.05 < E < 0.5 \text{ GeV/n} \):
- BME (Boltzmann Master Equation) for \( E < 0.1 \text{ GeV/n} \)
  - FLUKA implementation of BME from E.Gadioli et al (Milan)
  - Now under test for \( A \leq 16 \)

**Common to all models:**
- Standard FLUKA evaporation/fission/fragmentation used in both Target/Projectile final de-excitation
- Electromagnetic dissociation
Full shower + biasing: cosmic rays in atmosphere

Particle production by cosmic rays showers in the atmosphere: check of hadron-nucleus and nucleus-nucleus models, particle transport, decay, biasing...

Negative muons at floating altitudes: CAPRICE94

Open symbols: CAPRICE data
Full symbols: FLUKA

primary spectrum normalization ~ AMS-BESS
Neutrons on the ER-2 plane at 21 km altitude

Measurements:
Goldhagen et al., NIM A476, 42 (2002)

Note one order of magnitude difference depending on latitude

FLUKA calculations:
Dosimetry Applications


Ambient dose equivalent from neutrons at solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg.

Solid lines: FLUKA simulation
Some recent achievements:

L3 Muons

(S. Muraro, PhD thesis Milano)

exp. data

Vertical

Kaon dominated

Horizontal

Kaon dominated

0.975 < \cos\theta < 1.

0.525 < \cos\theta < 0.600

FLUKA simulation
Many thanks for your attention!!

The Gran Sasso in FLUKA

Cosmic Rays in atmosphere
A weighted/biological dose

Radiation Protection: quality factors and weighting factors

ICRP 26: quality factors Q(L) depending on the radiation LET
ICRP 60: weighting factors depending on the radiation type

Radiobiology: Complex Lesions

\[ \geq 2 \text{ breaks on each strand within } 10 \text{ nm} \]

INTEGRATION OF RADIOBIOLOGICAL DATA AND CALCULATIONS INTO FLUKA

Radiobiological data and results of simulations (distributions) based on track structure codes (e.g. PARTRAC (GSF, Pavia)) and biophysical models (e.g. radiation induced CA models and codes)

Radiation field and irradiation geometry

extended FLUKA

Doses, Fluences...; effects at cellular, organ and organism levels

Alfredo Ferrari, MCNEG-06
The OPTIS therapeutic proton beam

Geometry of the OPTIS therapy unit

Complex Lesions as a function of LET and particle type

FLUKA CODE (EXTENDED)

Theor. predictions
Experim. data

Biaggi et al NIM-B, 1999, 159, 89-100
LHC Cleaning Insertions

Two warm LHC insertions are dedicated to beam cleaning.

Collimation systems:
- **IR3**: Momentum cleaning
- **IR7**: Betatron cleaning

Normal operation:
- 0.2 hours beam lifetime
- $4 \times 10^{11}$ p/s for 10 s
- Power = 448 kW
IR7: Overview

• Motivation
• Geometry and Simulation setup
• Studies:
  - Collimator robustness ⇒ Accident scenarios
  - Energy on the superconducting magnets ⇒ Active absorbers
  - Dose on warm magnets ⇒ Passive absorbers
  - Beam Loss Monitors ⇒ Signal in BLM’s as a function of the loss point

• Summary
IR7 layout

• IR7 Layout contains over 200 objects
• Warm section
• 2 Dispersion suppressors
• Collimators with variable positioning of the jaws

⇒ Challenging simulation work

• LHC optics files
• Top beam energy
• Primary collimators: 6 σ
• Secondary collimators: 7 σ
• Absorbers: 10 σ
IR7 Virtual Tour
Collimator robustness: C is the only viable choice

TT40 test beam: energy deposition (J/cm³) for 3 \(10^{13}\) 450 GeV protons on the collimator prototype
TEPC – Tissue Equivalent Proportional Counter

- Absorbed Dose \((\text{Gy}), Q(\text{LET})\),
- Dose Equivalent \((\text{Sv})\)
- \(0.3 \, \mu\text{m} - 10 \, \mu\text{m}\) tissue volume (1-2 \(\mu\text{m}\))
- Microdosimetric spectra \((\text{y}/\text{kev} \, \mu\text{m}^{-1})\)
- Measurements:
  - Photons: up to 7MeV
  - Neutrons: up to 200MeV
  - Mixed radiation field (CERF)
  - Heavy Ions
May 5th-6th 2003

**Rome:** (42N, 12E), Rc=7GV
Altitude: 12km, 10km; for 2 hours

**Aalborg:** (57N, 10E), Rc=2GV
Altitude: 12km, 10km; for 2 hours
Comparison: absolute absorbed dose

Simulation

Measurements

$y \cdot d(y)$ normalized to abs. dose

Aalborg FL320
Aalborg FL400
Rome FL320
Rome FL400

Simulation Measurements
Absolute dose equivalent

Simulation

Measurements

\( y\times h(y) \) normalized to dose equivalent

\( y\times h(y) \) simulated for:

- Aalborg FL320
- Aalborg FL400
- Rome FL320
- Rome FL400

\( y\times h(y) \) measured for:

- A400: \( y\times h(y) \)
- A320: \( y\times h(y) \)
- R400: \( y\times h(y) \)
- R320: \( y\times h(y) \)
Applications - CNGS
Real and Virtual Photonuclear Interactions

**Photonuclear reactions**
- Giant Dipole Resonance interaction (special database)
- Quasi-Deuteron effect
- Delta Resonance energy region
- Vector Meson Dominance in the high energy region
- INC, preequilibrium and evaporation via the PEANUT model
- Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability

**Virtual photon reactions**
- Muon photonuclear interactions
- Electromagnetic dissociation
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
Electromagnetic dissociation

Electromagnetic dissociation: $\sigma_{EM}$ increasingly large with (target) $Z$'s and energy. Already relevant for few GeV/n ions on heavy targets ($\sigma_{EM} \sim 1 \text{ b} \text{ vs } \sigma_{\text{nucl}} \sim 5 \text{ b}$ for 1 GeV/n Fe on Pb)

$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega) \sigma_{\gamma n_{A_1}}(\omega) \propto Z_1^2$$
Electromagnetic dissociation: example

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

Right: calculated total, $1nX$ and $2nX$ electromagnetic dissociation cross sections for 30 A GeV Pb ions on Al, Cu, Sn and Pb targets. Points – measured cross sections of forward $1n$ and $2n$ emissions as a function of target charge (M.B. Golubeva et al., in press)
158 GeV/n fragmentation

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. PRC, in press (red squares), histos are FLUKA (with DPMJET-III) predictions: the dashed histo is the electromagnetic dissociation contribution.
FLUKA with modified RQMD-2.4

Fragment charge cross section for 1.05 GeV/n Fe ions on Al (left) and Cu (right).

DPMJET-3 upgrade: chain fusion

Pseudorapidity distribution of charged particles in Au-Au and Cu-Cu collisions at $\sqrt{s_{NN}}=200$ GeV: with and without chain fusion, compared to PHOBOS results at RHIC.
Fragment charge cross section for 750 MeV/n U ions on Pb.


Fission products have been excluded like in the experimental analysis.
The new QMD model: (data PRC64 (2001) 034607)

Ar + C 95 MeV/A all b

- RQMD + FLUKA
- ▲ QMD + FLUKA
- ☢ EXP data
Bragg peaks vs exp. data: $^{20}$Ne @ 670 MeV/n

Dose vs depth distribution for 670 MeV/n $^{20}$Ne ions on a water phantom. The green line is the FLUKA prediction. The symbols are exp data from LBL and GSI.

Exp. Data

Fragmentation products
Bragg peaks vs exp. data: $^{12}\text{C} @ 270 \& 330 \text{MeV/n}$

Dose vs depth distribution for 270 and 330 MeV/n $^{12}\text{C}$ ions on a water phantom. The full green and dashed blue lines are the FLUKA predictions. The symbols are exp data from GSI.

Exp. Data
Calculated quantities
- Radioactive isotope production per primary particle
  - (Star density and particle energy spectra in the samples)
- Calculation of build-up and decay of radioactive isotopes for specific irradiation and cooling patterns including radioactive daughter products
Benchmark experiment – *Instrumentation 1*

M. Brugger, *et al.*, in Proceedings of the Int. Conf. on Accelerator Applications (AccApp’05), Venice, Italy, 2005

**Low-background coaxial High Precision Germanium detector (Canberra)**
- use of two different detectors (90 cm³ sensitive volume, 60% and 40% relative efficiency)

**Genie-2000 (Ver. 2.0/2.1) spectroscopy software by Canberra and PROcount-2000 counting procedure software**
- include a set of advanced spectrum analysis algorithms, *e.g.*, nuclide identification, interference correction, weighted mean activity, background subtraction and efficiency correction
- comprise well-developed methods for peak identification using standard or user-generated nuclide libraries. **HERE: use of user-generated nuclide libraries**, based on nuclides expected from the simulation and material composition

**Efficiency calibration with LABSOCS**
- allows the creation of a corrected efficiency calibration by modelling the sample taking into account **self-absorption inside the sample and the correct detector geometry**
# Details of Samples

## Elemental composition in percent by weight

<table>
<thead>
<tr>
<th>Steel $\rho = 7.25 \text{ g/cm}^3$</th>
<th>Copper $\rho = 8.89 \text{ g/cm}^3$</th>
<th>Aluminium $\rho = 2.72 \text{ g/cm}^3$</th>
<th>Concrete $\rho = 1.70 \text{ g/cm}^3$</th>
<th>Titanium $\rho = 4.42 \text{ g/cm}^3$</th>
<th>Resin $\rho = 1.24 \text{ g/cm}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 63.088</td>
<td>Cu 99.328</td>
<td>Al 96.4589</td>
<td>O 47.87</td>
<td>Ti 88.036</td>
<td>C 66.77</td>
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<tr>
<td>Cr 17.79</td>
<td>Al 0.4745</td>
<td>Si 1.08</td>
<td>Ca 35.4</td>
<td>Al 6.5</td>
<td>O 27.64</td>
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<tr>
<td>Mn 11.43</td>
<td>Si 0.13</td>
<td>Mg 0.83</td>
<td>C 9.24</td>
<td>V 5.28</td>
<td>H 5.59</td>
</tr>
<tr>
<td>Ni 6.5</td>
<td>Fe 0.0261</td>
<td>Mn 0.696</td>
<td>Si 4.0</td>
<td>Fe 0.093</td>
<td></td>
</tr>
<tr>
<td>Si 0.38</td>
<td>S 0.0137</td>
<td>Fe 0.5</td>
<td>Al 0.97</td>
<td>Cr 0.05</td>
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<tr>
<td>N 0.31</td>
<td>Cd 0.004</td>
<td>Cu 0.115</td>
<td>Fe 0.69</td>
<td>Ni 0.0116</td>
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</tr>
<tr>
<td>Co 0.11</td>
<td>Sb 0.004</td>
<td>Zn 0.1044</td>
<td>Mg 0.64</td>
<td>Cl 0.0102</td>
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<tr>
<td>P 0.019</td>
<td>Cr 0.0021</td>
<td>Cr 0.033</td>
<td>H 0.6</td>
<td>Mn 0.0071</td>
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<tr>
<td>C 0.095</td>
<td>Te 0.002</td>
<td>Ti 0.0302</td>
<td>K 0.26</td>
<td>Cu 0.0043</td>
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</tr>
<tr>
<td>Mo 0.09</td>
<td>Pb 0.002</td>
<td>Pb 0.0287</td>
<td>S 0.15</td>
<td>Zn 0.004</td>
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<td>Cu 0.085</td>
<td>Sn 0.002</td>
<td>Sn 0.0278</td>
<td>Ti 0.06</td>
<td>P 0.0038</td>
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<td>V 0.07</td>
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<td>Sr 0.05</td>
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<td></td>
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<td>Ti 0.01</td>
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<td>Bi 0.0161</td>
<td>P 0.03</td>
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<td>Nb 0.01</td>
<td>Zn 0.002</td>
<td>Ni 0.0128</td>
<td>Na 0.03</td>
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<tr>
<td>W 0.01</td>
<td>Mn 0.0016</td>
<td>P 0.0126</td>
<td>Mn 0.01</td>
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<td>O 0.002</td>
<td>Se 0.0011</td>
<td>Ga 0.0102</td>
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<td></td>
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<tr>
<td>S 0.001</td>
<td>Bi 0.001</td>
<td>Cl 0.0087</td>
<td></td>
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</tr>
<tr>
<td>Ni 0.001</td>
<td>S 0.0076</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P 0.0004</td>
<td>V 0.0041</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co 0.0002</td>
<td>Zr 0.0024</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Am 0.0014</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
Beam Conditions

- 120 GeV secondary SPS mixed hadron beam (p 34.8%, π 60.7% and K 4.5%)
- 16.8s spill cycle, 4s burst
- ~5x10^{10} (short) - 1x10^{12} (long) particles hit the target during irradiation

Beam Profile (approx. Gaussian): measured with multi-wire prop. Chamber, σ ~ 10 mm

Alfredo Ferrari, PSI
## Activation: Aluminum

**Table 2: Al, cooling times 1d 16h, 16d 08h , 51d 09h**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$</th>
<th>Exp Bq/g ± %</th>
<th>OLD FLUKA/Exp ± %</th>
<th>FLUKA/Exp ± %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be 7</td>
<td>53.29d</td>
<td>0.789 13</td>
<td>0.364 16</td>
<td>0.688 19</td>
</tr>
<tr>
<td>Na 22</td>
<td>2.60y</td>
<td>0.365 9.6</td>
<td>0.811 11</td>
<td>0.752 11</td>
</tr>
<tr>
<td>Na 24</td>
<td>14.96h</td>
<td>38.6 3.6</td>
<td>0.854 4.0</td>
<td>0.815 4.6</td>
</tr>
<tr>
<td>Sc 44</td>
<td>3.93h</td>
<td>0.229 24</td>
<td>2.219 27</td>
<td>0.820 36</td>
</tr>
<tr>
<td>Sc 46</td>
<td>83.79d</td>
<td>0.025 16</td>
<td>1.571 19</td>
<td>0.902 28</td>
</tr>
<tr>
<td>Sc 47</td>
<td>80.28h</td>
<td>0.163 12</td>
<td>0.986 27</td>
<td>(1.486 43)</td>
</tr>
<tr>
<td>V 48</td>
<td>15.97d</td>
<td>0.199 7.4</td>
<td>0.931 18</td>
<td>(0.938 29)</td>
</tr>
<tr>
<td>Cr 51</td>
<td>27.70d</td>
<td>0.257 17</td>
<td>0.873 23</td>
<td>0.942 28</td>
</tr>
<tr>
<td>Mn 52</td>
<td>5.59d</td>
<td>0.224 5.6</td>
<td>2.369 9.6</td>
<td>0.936 24</td>
</tr>
<tr>
<td>Mn 54</td>
<td>312.12d</td>
<td>0.081 11</td>
<td>0.972 15</td>
<td>0.917 19</td>
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<tr>
<td>Co 57</td>
<td>271.70d</td>
<td>0.00424 32</td>
<td>0.833 50</td>
<td>(0.760 67)</td>
</tr>
<tr>
<td>Co 58</td>
<td>70.82d</td>
<td>0.019 22</td>
<td>1.820 27</td>
<td>0.841 39</td>
</tr>
</tbody>
</table>
### Activation: Copper 1st part

Table 3: Cu, cooling times 34m, 1h 07m, 48d 3h 21m

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$</th>
<th>Exp Bq/g ± %</th>
<th>OLD FLUKA/Exp ± %</th>
<th>FLUKA/Exp ± %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be 7</td>
<td>53.29d</td>
<td>1.29 13</td>
<td>0.045 17</td>
<td>1.472 14</td>
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<tr>
<td>Na 22</td>
<td>2.60y</td>
<td>0.029 14</td>
<td>0.655 17</td>
<td>0.677 20</td>
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<tr>
<td>Na 24</td>
<td>14.96h</td>
<td>14.8 8.5</td>
<td>0.266 10</td>
<td>0.515 12</td>
</tr>
<tr>
<td>K 42</td>
<td>12.36h</td>
<td>21.6 15</td>
<td>0.592 17</td>
<td>0.685 17</td>
</tr>
<tr>
<td>K 43</td>
<td>22.30h</td>
<td>6.38 11</td>
<td>0.656 14</td>
<td>0.844 16</td>
</tr>
<tr>
<td>Sc 43</td>
<td>3.89h</td>
<td>24.6 24</td>
<td>0.645 25</td>
<td>0.443 27</td>
</tr>
<tr>
<td>Sc 44</td>
<td>3.93h</td>
<td>45.4 9.5</td>
<td>1.160 10</td>
<td>0.863 10</td>
</tr>
<tr>
<td>Sc 46</td>
<td>83.79d</td>
<td>0.865 8.3</td>
<td>0.890 9.0</td>
<td>0.850 9.7</td>
</tr>
<tr>
<td>Sc 47</td>
<td>80.28h</td>
<td>11.0 14</td>
<td>0.927 16</td>
<td>0.959 17</td>
</tr>
<tr>
<td>Sc 48</td>
<td>43.67h</td>
<td>3.16 13</td>
<td>1.151 16</td>
<td>1.293 16</td>
</tr>
<tr>
<td>mSc 44</td>
<td>58.60h</td>
<td>18.4 13</td>
<td>1.280 14</td>
<td>0.952 14</td>
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<tr>
<td>V 48</td>
<td>15.97d</td>
<td>1.12 7.8</td>
<td>1.647 8.4</td>
<td>1.220 9.0</td>
</tr>
<tr>
<td>Cr 49</td>
<td>42.30m</td>
<td>15.0 25</td>
<td>1.357 26</td>
<td>0.909 27</td>
</tr>
<tr>
<td>Cr 51</td>
<td>27.70d</td>
<td>3.55 13</td>
<td>1.306 13</td>
<td>1.099 14</td>
</tr>
<tr>
<td>Mn 52</td>
<td>5.59d</td>
<td>18.3 5.5</td>
<td>0.790 6.3</td>
<td>0.651 6.9</td>
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<tr>
<td>mMn 52</td>
<td>21.10m</td>
<td>9.16 33</td>
<td>1.940 34</td>
<td>1.616 35</td>
</tr>
<tr>
<td>Mn 54</td>
<td>312.12d</td>
<td>1.13 10</td>
<td>1.177 11</td>
<td>1.171 11</td>
</tr>
<tr>
<td>Mn 56</td>
<td>2.58h</td>
<td>27.7 5.8</td>
<td>0.784 7.1</td>
<td>0.872 8.0</td>
</tr>
</tbody>
</table>

M. Brugger, et al., Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005
**Activation: Copper (2nd part)**

Table 4: Cu, cooling times 34m, 1h 07m, 48d 3h 21m

<table>
<thead>
<tr>
<th>Isotope</th>
<th>t½</th>
<th>Exp Bq/g ± %</th>
<th>OLD FLUKA/Exp ± %</th>
<th>FLUKA/Exp ± %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 59</td>
<td>44.50d</td>
<td>0.558 10</td>
<td>0.699 12</td>
<td>0.761 14</td>
</tr>
<tr>
<td>Co 55</td>
<td>17.53h</td>
<td>7.41 10</td>
<td>0.855 12</td>
<td>0.712 14</td>
</tr>
<tr>
<td>Co 56</td>
<td>77.27d</td>
<td>1.20 7.2</td>
<td>1.161 8.1</td>
<td>1.057 8.6</td>
</tr>
<tr>
<td>Co 57</td>
<td>271.79d</td>
<td>1.75 9.9</td>
<td>0.917 10</td>
<td>0.851 11</td>
</tr>
<tr>
<td>Co 58</td>
<td>70.82d</td>
<td>6.51 10</td>
<td>0.889 10</td>
<td>0.895 11</td>
</tr>
<tr>
<td>Co 60</td>
<td>5.27y</td>
<td>0.172 8.5</td>
<td>0.798 8.9</td>
<td>0.832 9.4</td>
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<tr>
<td>Co 61</td>
<td>99.00m</td>
<td>52.7 12</td>
<td>0.836 13</td>
<td>0.878 14</td>
</tr>
<tr>
<td>Ni 57</td>
<td>35.60h</td>
<td>4.78 12</td>
<td>0.864 15</td>
<td>0.789 16</td>
</tr>
<tr>
<td>Ni 65</td>
<td>2.52h</td>
<td>3.46 19</td>
<td>1.553 22</td>
<td>1.350 24</td>
</tr>
<tr>
<td>Cu 60</td>
<td>23.70m</td>
<td>16.4 8.7</td>
<td>0.847 9.9</td>
<td>0.787 11</td>
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<td>Cu 61</td>
<td>3.33h</td>
<td>165. 27</td>
<td>1.047 28</td>
<td>0.944 28</td>
</tr>
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<td>Cu 64</td>
<td>12.70h</td>
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<td>0.564 14</td>
<td>0.560 15</td>
</tr>
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<td>Zn 62</td>
<td>9.19h</td>
<td>5.66 20</td>
<td>1.213 22</td>
<td>1.117 24</td>
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<tr>
<td>Zn 65</td>
<td>244.26d</td>
<td>0.117 12</td>
<td>0.635 14</td>
<td>0.615 17</td>
</tr>
</tbody>
</table>

M. Brugger, et al., Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005
LHC: Conclusions on activation study

- Good agreement was found between the measured and calculated values for most of the isotopes and samples.

- The large number of samples and variety of different materials offers a extensive possibility to study isotope production.

- Multifragmentation (NOW DEVELOPED AND PRESENTED AT INT. CONF. ON NUCLEAR DATA FOR SCIENCE AND TECHN. (Santa Fe 2004)) has significantly improved the agreement for intermediate and small mass isotopes.

- As a consequence, the calculation of remanent dose rates based on an explicit simulation of isotope production and transport of radiation from radioactive decay with FLUKA should also give reliable results → Part 2.
Part 2: Radioactivity Produced in LHC Materials: Residual Dose Rates

- Levels of residual dose rates are an important design criterion for any high energy facility.

- Residual dose rates for arbitrary locations and cooling times are so far predicted with a rather poor accuracy:
  - Typically based on the concept of so-called $\omega$-factors and comprising several severe restrictions.
  - Layouts and material composition of beam-line components and surrounding equipment are often very complex.

- A proper two-step approach based on the explicit generation and transport of gamma and beta radiation from radioactive decay should result in much more accurate results.
Benchmark experiment - Instrumentation 2


Portable spectrometer Microspec
- NaI detector, cylindrical shape, 5 x 5 cm
- folds spectrum with detector response ("calibrated" with $^{22}\text{Na}$ source)
- physical centre of detector determined with additional measurements with known sources ($^{60}\text{Co}$, $^{137}\text{Cs}$, $^{22}\text{Na}$) to be 2.4 cm

Thermo-Eberline dose-meter FHZ 672
- organic Scintillator and NaI detector, cylindrical shape, 9 x 9 cm
- assumes average detector response
- physical centre of detector determined as above to be 7.3 cm
Benchmark experiment - Results 2


Dose rate as function of cooling time for different distances between sample and detector

Alfredo Ferrari, PSI
Benchmark experiment - *Results 3*

Dose rate as function of cooling time
for different distances between sample and detector

Simulation benchmark in mixed fields at the CERF facility

Low-energy neutron transport in FLUKA performed by a multigroup algorithm:

- Widely used in low-energy neutron transport codes (not only Monte Carlo, but also Discrete Ordinate codes)
- Energy range of interest is divided in a given number of discrete intervals “energy groups”
- Elastic and inelastic reactions simulated not as exclusive process, but by group-to-group transfer probabilities (down-scattering matrix)
- The scattering transfer probability between different groups represented by a Legendre polynomial expansion truncated at the (N+1)\(^\text{th}\) term:

\[
\sigma_s(g \rightarrow g', \mu) = \sum_{i=0}^{N} \frac{2i + 1}{4\pi} P_i(\mu) \sigma_s^i(g \rightarrow g')
\]

\(\mu = \) scattering angle \hspace{1cm} \(N = \) chosen Legendre order of anisotropy
FLUKA Implementation

- Both fully biased and semi-analog approaches available
- Energy range up to 19.6 MeV divided in 72 energy groups of approximately equal logarithmic width, and one thermal
- Prepared using a specialized code (NJOY) and ad-hoc programs
- Continuously enriched and updated on the basis of the most recent evaluations (ENDF/B, JEF, JENDL, etc.)
- The library contains 140 different materials/temperatures
- Cross sections of some materials are available at 2 or 3 different temperatures (0, 87 and 293° K) + Doppler broadening
- Hydrogen cross sections available for different types of molecular binding (free, H₂O, CH₂)
- Neutron energy deposition calculated by means of kerma factors
- However, H recoil protons, protons from ¹⁴N(n,p) and (α, ³H) from neutron capture in ⁶Li and ¹⁰B can be produced and transported explicitly
- Pointwise cross sections available for reactions in H, ⁶Li , Ar

The new library

- A new library is in preparation, based on 260 n and 40 γ groups including 30 thermal groups at different temperatures and different self-shielding
Other features

**Gamma Generation**
- In general, gamma generation by low energy neutrons (but not gamma transport) is treated also in the frame of a multigroup scheme.
- A downscattering matrix provides the probability, for a neutron in a given energy group, to generate a photon in each of 22 gamma energy groups, covering the range from 10 keV to 20 MeV.
- The actual energy of the photon is sampled randomly in the energy interval corresponding to its gamma group. With the exception of a few important gamma lines, such as the 2.2 MeV transition of Deuterium and the 478 keV photon from $^{10}\text{B}(n,\gamma)$ reaction, all $^{40}\text{Ar}$ lines, and the capture lines for Cd and Xe.
- The gamma generation matrix apart from capture gammas, includes also gammas produced by other inelastic reactions such as $(n,n')$.

**Residual Nuclei**
- For many materials (not for all), group-dependent information on the residual nuclei produced by low-energy neutron interactions is available in the FLUKA library.
- This information can be used to score residual nuclei, but the user must check its availability before requesting scoring.