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SIMULATION OF NUCLEAR INTERACTIONS FOR BASIC RADIOBIOLOGY AND APPLICATIONS: THE FLUKA APPROACH

D. Alloni[a], F. Ballarini[a], G. Battistoni[b], M. Campanella[b], M. Carboni[c], F. Cerutti[b], A . Clivio[b], A. Empl[d], A. Fassò[e], A. Ferrari[f], E. Gadioli[b], E. Gadioli-Erba[b], M.V. Garzelli[b], E. Giroletti[a], A. Mairani[a], A. Mostacci[c], S. Muraro[b], A. Ottolenghi[a], V. Parini[b], M. Pelliccioni[c], L.S. Pinsky[d], J. Ranft[g], S . Roesler[f], P. R. Sala[b]*, D. Scannicchio[a], G. Smirnov[f], S. Trovati[a], R. Villari[c], V. Vlachoudis[f], T . Wilson[d], N. Zapp[d]
[a] University and INFN, Pavia Italy , [b] University and INFN, Milano, Italy [c] INFN Frascati, Italy,[d] University of Houston and NASA, [e] SLAC, [f] CERN, Switzerland,[g] Siegen University, Germany

The modeling of hadron and ion transport and interactions in matter is a subject of growing interest in dosimetry and radiobiology, mainly due to the strong development of applications related to hadrontherapy and space dosimetry. The nuclear reaction models embedded in the FLUKA code cover hadron-, ion- and photon-induced nuclear interactions from energies as low as few tens of MeV up to several tens of TeV. FLUKA deals also with transport and interactions of electromagnetic particles and low energy neutrons, allowing for fully integrated simulations of mixed field effects. On-line integration of results from event-by-event track structure simulations at the nm level allows for calculation of "biological doses" (e.g. DNA damage yields per cell in a given organ), in parallel with more standard LET-based evaluations. A short description of the FLUKA hadron and ion interaction models is given, as well as comparisons with experimental data. Examples of applications are also presented.

INTRODUCTION

FLUKA [1, 2] is a Monte Carlo code able to simulate interaction and transport of hadrons, heavy ions and electromagnetic particles from few keV (or thermal neutron) to cosmic ray energies in whichever material. It has proven capabilities in accelerator design and shielding, ADS studies and experiments, dosimetry and hadrontherapy, space radiation and cosmic ray shower studies in the atmosphere. The highest priority in the design and development of FLUKA has always been the implementation and improvement of sound and modern physical models. Microscopic models are adopted whenever possible, consistency among all the reaction steps and/or reaction types is ensured, basic conservation laws are enforced at each step, results are checked against experimental data at single interaction level. As a result, final predictions are obtained with a minimal set of free parameters fixed for all energy/target/projectile combinations. Therefore results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models, predictability is provided where no experimental data are directly available, and correlations within interactions and among shower components are preserved.

Since detailed descriptions of the FLUKA hadronic models and comparison with experimental data are available in the literature[3, 4], we give here only a short summary. The high energy range (>5 GeV) is treated in the Glauber-Gribov formalism, that couples Glauber multiple scattering approach to a Dual Parton Model description of hadron-nucleon interactions. Nuclear effects on reaction products are described by a Generalized IntraNuclear Cascade (GINC) where the formation zone concept plays a fundamental role.

At lower energies, the intermediate energy hadronic model of FLUKA, called PEANUT, is used. The reaction mechanism is modelled in PEANUT by explicit GINC smoothly joined to statistical (exciton) preequilibrium emission. GINC modelling in PEANUT is highly sophisticated. Different nuclear densities are adopted for neutrons and protons, Fermi motion is defined locally including wave packet-like uncertainty smearing, the curvature of particle trajectories due to the nuclear potential is taken into account, binding energies are obtained from mass tables and updated after each particle emission, energy-momentum conservation including the recoil of the residual nucleus is ensured. Quantum effects are explicitly included: Pauli blocking, formation zone, nucleon antisymmetrization, nucleon-nucleon hard-core correlations, coherence length. Independently from the original projectile energy, the equilibrium steps of the reaction include evaporation in competition with fission and gamma deexcitation.

Transport and interactions of electromagnetic particles are fully coupled to the hadronic sector, allowing for instance to follow in the same event secondary hadrons from photon nuclear interactions and γ rays from nuclear deexcitation.

NUCLEUS-NUCLEUS INTERACTIONS

Ion-Ion interaction are of great interest both for therapeutic beams, and for space radiation assessment. FLUKA implements DPMJET [5] as event generator to simulate nucleus-nucleus interactions for energies

*to whom correspondence should be addressed

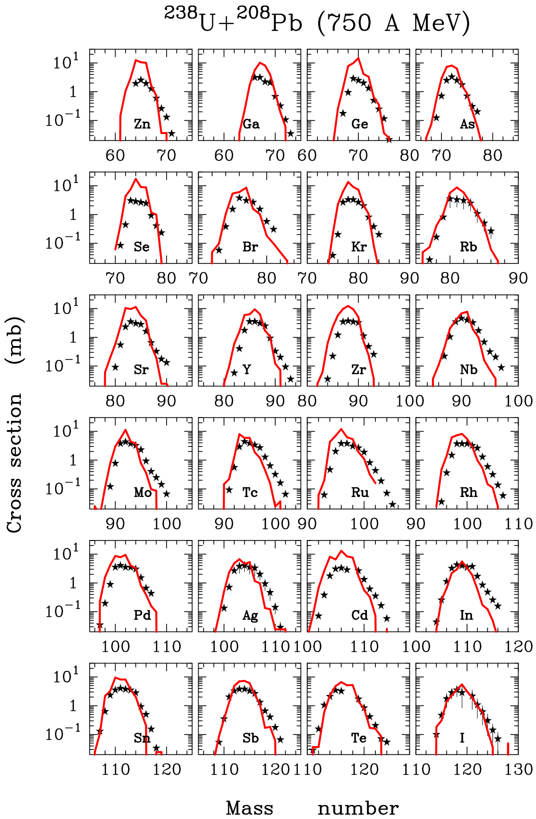

Figure 1. Computed projectile fragment cross sections for 750 MeV/n U ions on Pb. Data (stars) from [11]. Fission products have been excluded like in the experimental analysis.

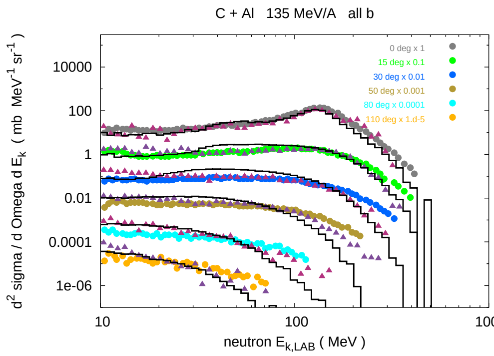

Figure 2. Emitted neutron spectra at various emission angles from 135 MeV/n Ne on Al. Circles are experimental data [13], lines are FLUKA-rQMD results, triangles are from the new FLUKA-QMD generator.

in excess of 5 GeV/n. The original interface to the DPMJET-II.53 version has recently been upgraded to use the DPMJET-III [6] version. DPMJET is based on the two component Dual Parton Model in connection with the Glauber formalism. An interface to a modified version of the RQMD-2.4 [7, 8] was developed to enable FLUKA to treat ion interactions from $\approx$ 100 MeV/n up to 5 GeV/nwhere DPMJET starts to be applicable[9, 10]. An example is shown in fig.1. The RQMD-2.4 is a relativistic QMD model which has been applied successfully to relativistic $A-A$ particle production over a wide energy range, from $\approx$ 0.1 GeV/n up to several hundreds of GeV/n. Several important modifications have been implemented in the RQMD code, in order to ensure energy-momentum conservation taking into account experimental binding energies, and to provide meaningful excitation energies for the residual fragments. A thorough discussion of the FLUKA implementation, as well as some results of this modified model can be found in [9].

For both generators, de-excitation and evaporation of the excited residual nuclei is performed by calling the FLUKA evaporation/fission/fragmentation module.

Work is in progress to implement a Boltzmann Master Equation (BME) model[14, 15, 16, 17] for A-A interactions at very low energy[18] and to replace the RQMD interface with a new QMD model[9, 12] developed for FLUKA.

Quantum Molecular Dynamics (QMD) models are considered viable tools to simulate the initial hot stages of heavy-ion collisions and investigate the properties of the nuclear matter equation of state. A new QMD model has been developed by scratch during the last few years and recently coupled to the FLUKA fission/fragmentation/evaporation module. Reproduction of the experimental light particle (Z $<$3) yields is one of the most difficult challenges to be met by QMD models. An example of neutron production from the new QMD model, compared with the RQMD-FLUKA results and with experimental data, is shown in Figure 2. These results are quite satisfactory, thanks to the form of the potential terms involved in the nucleon-nucleon interaction and to many refinements applied in the fragment definition scheme, based on the potential which each particle experiences because of its neighbors. Nucleon isospin is taken into account all over the simulation, as well as the experimental binding energy constraints on nuclear states. This model is currently working at low energies, even if relativistic kinematics is applied, pion and heavy resonance production have not been implemented yet.

The BME model, as currently implemented in FLUKA, allows for light ion interaction on material of biological interest for energies ranging from the Coulomb barrier up to 100 MeV/n. The reaction mechanisms accounted for are:

- Complete fusion with a probability which depends on the energy and projectile-target combination under consideration. Ejectiles up to α s are then emitted with multiplicities, spectra and angular distributions computed according to the BME formalism
- Three body reactions, where the overlap region between the two nuclei, computed according to geometrical consideration combined with an impact parameter cross section profile, and the two remnants give rise to three excited objects subsequently de-excited by evaporation/fission/fragmentation.
- Inelastic excitation, where the nuclei are simply excited

The FLUKA implementation of the model is very new and it is undergoing extensive tests in order to crosscheck the results against experimental data and possibly fine tune its performances. The extension to heavier projectiles/targets is in progress, and the model will eventually cover all combinations up to 100 MeV/n.

EVAPORATION/FISSION/FRAGMENTATION AND SLOW FRAGMENTS

Evaporation, the latest stage of the nuclear reaction chain, is essential for the prediction of residual nuclei distribution. Therefore, it is a crucial ingredient in activation and residual dose rate simulations, but also in the exact determination of the fragment spectra following nucleus-nucleus interaction. The FLUKA evaporation model, which is based on the Weisskopf-Ewing approach, has been continuously updated along the years, with the inclusion, for instance, of sub-barrier emission, full level density formula, analytic solution of the emission widths. The latest upgrade is the extension to the evaporation of nuclear fragments up to $A \leq 24$, with impressive improvements in the low mass region of residual nuclei distributions. This, coupled to the exact energy and momentum balance in all reaction steps, allows to predict the mass and energy distribution of fragments, including very low energy, almost non-ionizing ones, whose biological effects are not precisely known. In Figures 3 and 4 the predicted energy-mass distribution of fragments for interaction of Carbon on Oxigen at two projectile energies are shown. In both cases, target-like and projectile-like with kinetic energies even smaller than 1 MeV/amu are present in non-negligible amounts.

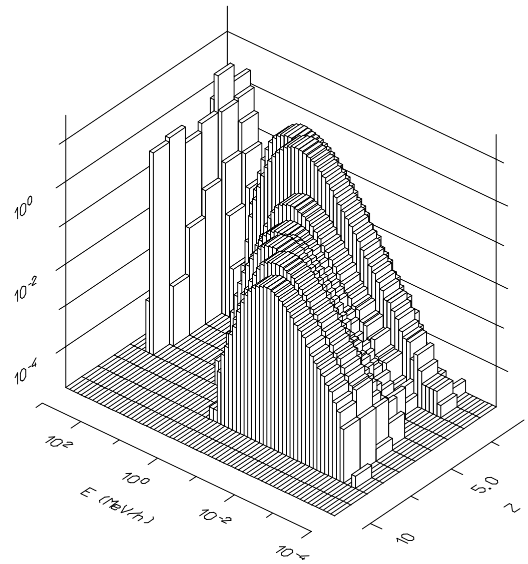

Figure 3. Fragment yield as a function of kinetic energy per nucleon and fragment charge, following C-O interactions at 300 MeV/n

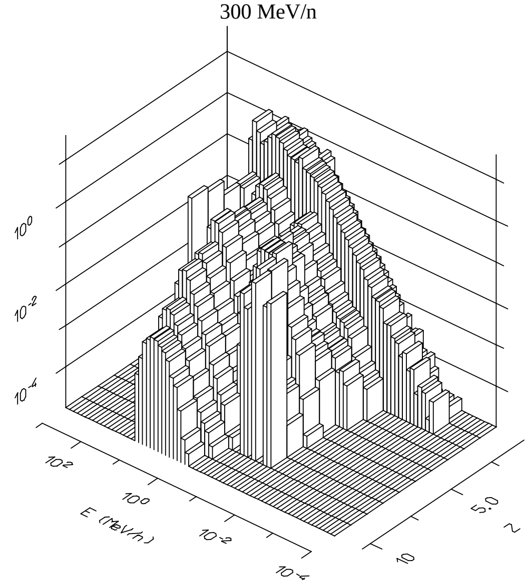

Figure 4. as in fig.3 at 30 MeV/n

EXAMPLE OF FRAGMENT PROPAGATION

The different particles species produced in hadron-nucleus or nucleus-nucleus interactions all contribute to the radiation field, each of them with different properties and effects. An accurate simulation of all differential quantities at each interaction, such as energy, emission angle, particle type etc, are essential to reproduce the macroscopic and microscopic effects of beam interaction with matter. As an example, the spatial distribution of energy deposition due to the different particle species is shown in Figure 5, for the case of an 1 GeV/n Fe beam hitting a PMMA cylinder surrounded by air. The heavy particles from projectile fragmentation are

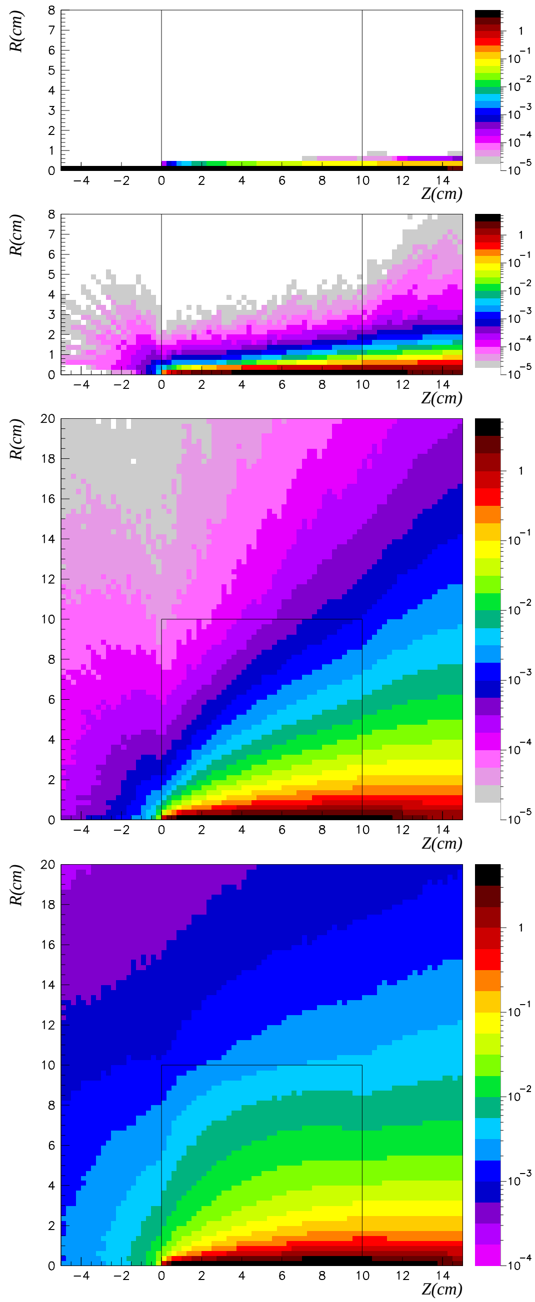

Figure 5. Energy deposition from a 1 GeV/n Fe beam in a 10 cm radius, 10 cm length PMMA cylinder. From top to bottom the contribution of fragments with $A \geq 10$, fragments with $A < 10$, protons, neutrons. Beam size is 2.5 mm, the beam is coming from the left and hitting the PMMA cylinder at R=0, Z=0. The topmost two plots are cut in the R coordinate.

confined in a narrow cone, while protons and especially neutrons spread over all the target and even in the backward region.

VOXEL GEOMETRY

The FLUKA geometrical modeler is based on the Combinatorial Geometry. Recently, the possibility to embed “voxel” regions in the CG has been added. This algorithm was originally developed to allow to use inside FLUKA human phantoms out of whole body CT scans. The first phantom, GOLEM, was modeled at GSI from the CT scan of an adult male person, and is descibed by more than 2x10^6 voxels, each one being a parallelepiped of 2x2x8 mm^3. This phantom is currently used in many FLUKA applications to dosimetry, for instance in the space dosimetry applications described below. Work is in progress to optimize algorithms to directly translate CT scans into voxels with the appropriate material assignments. The implementation of variable density materials in FLUKA is also in progress.

ON-LINE DOSE AND ACTIVITY EVOLUTION

The possibility to follow on-line the radiation from unstable residual nuclei has been implemented, together with an exact analytical calculation of activity evolution during irradiation and cooling down. As a consequence, results for production of residuals and their effects as a function of time can now be obtained in the same run.

COUPLING WITH TRACK STRUCTURE CODES

Absorbed dose and dose equivalent are are not sufficient to reproduce the radiation effects in biological targets. In fact they do not allow taking into account the effects of the radiation track structure at the nanometre scale, that is the order of magnitude of the DNA dimensions (2 nm diameter). In principle such effects can be well described with the so-called *event-by-event* codes, which simulate each single energy deposition down to the nanometre level. Event-by-event simulations can be successfully used at the cellular and subcellular level, that is at the scale between nanometres and microns[19, 20, 21]. However the ”event-by-event” approach cannot be applied to the case of tissues and organs, whose linear dimensions fall in the centimetre range, since unacceptable computing times would be required. An alternative approach can is the integration of calculation results from detailed event-by-event simulations and/or experimental data[22] in FLUKA.

With the main aim of characterising ion beams also from a biophysical point of view, the average number of *Complex Lesions* per cell was taken as a reference parameter to evaluate a quantity that we called *biological dose*. In a previous work[19], such lesions have been operationally defined as *at least two breaks on each of the two DNA strands within 30 base-pairs*. The yields

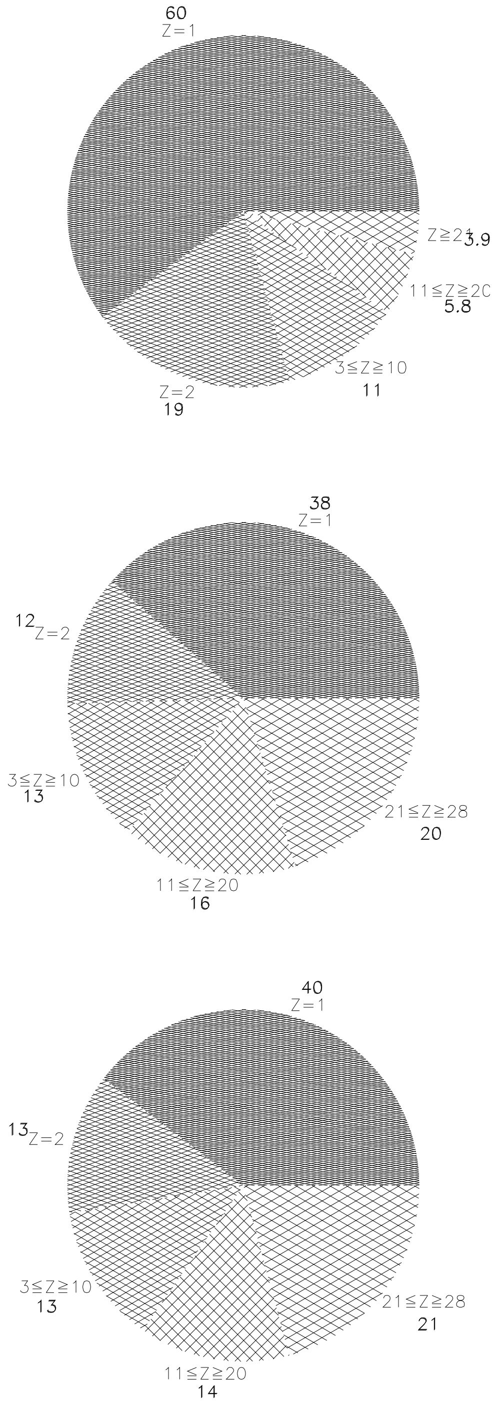

Figure 6. Dose due to galactic cosmic rays to RBM. From top to bottom: absorbed dose, dose equivalent, biological dose. The percentages due to the different field components are given.

of CL per unit dose and DNA mass induced by different radiation types as a function of the LET have been calculated by coupling an event-by-event track structure code to a DNA model[19]. The effectiveness at inducing CL has been found to increase with the radiation LET up to about 100 keV/micron. Furthermore, protons have shown a higher effectiveness with respect to alpha particles having the same LET. The following values were integrated in FLUKA: 0.6-5 CL/Gy/cell for protons with energy 0.3-5 MeV/n; 1.5-10.5 CL/Gy/cell for alpha particles of energy 0.3-5 MeV/n; 0.4 CL/Gy/cell for higher energy protons and alphas and for electrons; 10.5 CL/Gy/cell (the highest alpha-particle value) for slow heavy ions. A linear decrease down to 0 was assumed below 0.3 MeV/n. The integration method described above was applied to the characterisation of the 72 MeV proton beam used for the treatment of ocular tumours at the Paul Sherrer Institute (PSI) in Switzerland[23]. Ad hoc experiments for comparison were carried out at PSI. The depth-dose distribution calculated with FLUKA was found to be in excellent agreement with that measured at PSI. The contributions of the various beam components were calculated separately. Secondary hadrons (including ions) produced in nuclear interactions accounted for less than 4% of the total dose. In contrast with the physical dose, which was roughly constant with depth, the calculated profile of the "biological" dose (i.e. average number of CL/cell) showed a sharp increase at the Bragg peak, due to the presence of protons with low energy and thus high biological effectiveness. Nuclear reaction products were found to play a more relevant role for the biological dose. Excellent agreement was also found by comparing the calculated ratio between proton-induced CL and X-ray-induced CL to the measured ratio between proton-induced lethal lesions and X-ray-induced lethal lesions.

The same approach has been extensively used in calculating doses due to cosmic rays and solar flares. Figure 6 shows the contribution of the different field components to the absorbed dose, the equivalent dose and the biological dose in red bone mallow due to cosmic rays. All quantities have been calculated at solar minimum, behind a 1 g/cm^2 Aluminum shield. Details of the simulations and more results can be found in [24, 25].

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