Nuclear models in FLUKA: a review

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Abstract

Abstract – The foundations of the models for hadronic nuclear interactions as implemented in the FLUKA code are presented together with a few practical examples. The description of the relevant physics is schematically split into the major steps required for the full understanding of nuclear reactions at intermediate and high energies. Due to the complexity of the models, only a few semi-qualitative arguments are developed in this paper, the reader being referred to the existing literature for further details. Recent developments and exotic applications, neutrino interactions and nucleon decay, are covered in somewhat more details. Examples of FLUKA performances are presented throughout the paper in order to validate the theoretical description.

1 Introduction

FLUKA [1, 2, 3] is a transport and interaction Monte Carlo code, capable of handling hadronic and electromagnetic showers from thermal neutrons up to very high energies (100 TeV). Being based, as far as possible, on well tested microscopic models, it ensures a high level of accuracy and versatility, it preserves correlations within interactions and among the shower components, and it provides predictions where no experimental data is directly available. When needed, powerful biasing techniques are available to reduce computing time. Descriptions of FLUKA models and extensive benchmarking can be found in the literature (see the web page, www.fluka.org).

The approach to hadronic interaction modelling behaviour adopted in FLUKA is similar to the one adopted by most state-of-the-art codes. In this "microscopic" approach, each step has sound physical basis. Performances are optimized comparing with particle production data at single interaction level. No tuning whatsoever on "integral" data, like calorimeter resolutions, thick target yields etc, is performed. Therefore, final predictions are obtained with minimal free parameters, fixed for all energies and target/projectile combinations. Results in complex cases as well as scaling laws and properties come out naturally from the underlying physical models and the basic conservation laws are fulfilled "a priori".

Hadron-nucleus (h-A) interactions as modelled in FLUKA can be schematically described as a sequence of the following steps:

- Glauber-Gribov cascade and high energy collisions
- (Generalized)-IntraNuclear cascade
- Preequilibrium emission
- Evaporation/Fragmentation/Fission and final deexcitations

Some of the steps can be missing depending on the projectile energy and identity.

In the following, we will give a very short summary of the FLUKA hadron-nucleus interaction models, with more details on a few selected topics. More space will be given to the latest development, nucleus-nucleus interactions, and to the application to neutrino physics.

2 Hadron-nucleon interaction models

A comprehensive understanding of hadron-nucleon interactions over a large energy range is of course a basic ingredient for a sound description of hadron-nucleus ones. Elastic, charge exchange and strangeness exchange reactions are described as far as possible by phase-shift analysis and/or fits of experimental differential data. Standard eikonal approximations are used at high energies.

As soon as particle production (inelastic hadron-nucleon interactions) are concerned, the description becomes immediately more complex. Two families of models are adopted, depending on the projectile energy, the former is based on individual resonance production and decays [4, 5, 6], and covers the energy range up to 3–5 GeV, while the latter is based on the Dual Parton Model [7] (DPM), a particular quark/parton string model, and provides reliable results up to several tens of TeV. Further details can be found in the original DPM references [7] or in [8]. In DPM,

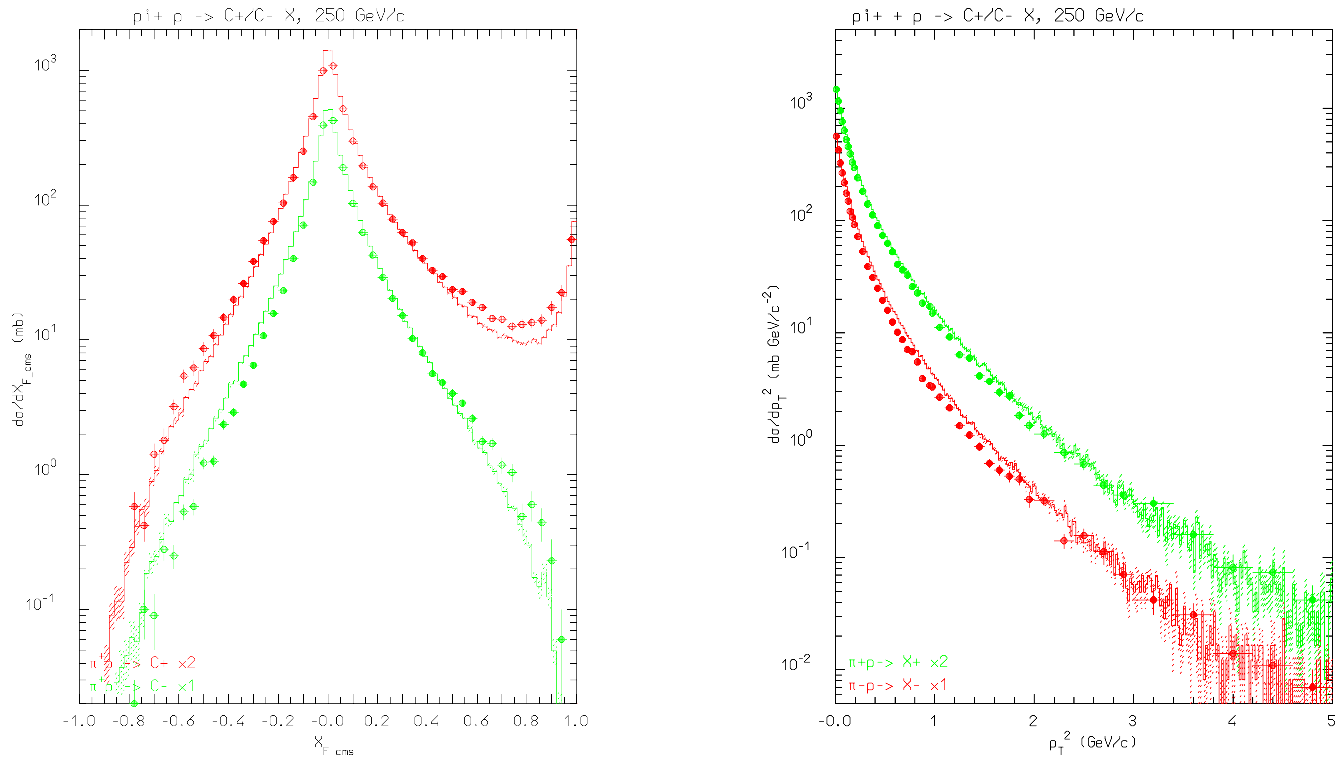

Figure 1: Feynman x_F^* (left) and transverse momenta (right) spectra of positive and negative particles (left) from (π^+,p) at 250 GeV/c . Experimental data (symbols) from [9].

hadron-hadron interactions result in the creation of two or more hadronic chains, from which hadrons have to be generated. The FLUKA chain hadronization model [11] (an improved version of [10]) is based on the *chain universality* assumption. The examples in fig. 1 show the ability of the FLUKA, DPM based, model to reproduce the features of particle production; further examples can be found in [1, 8].

3 Main steps of h-A interactions modelling in FLUKA

At energies high enough to consider coherent effects as corrections, a hadron-nucleus (hA) reaction can be described as a cascade of two-body interactions, concerning the projectile and the reaction products. This is the mechanism called IntraNuclearCascade (INC). Modern INC models had to incorporate many more ideas and effects in order to describe in a reasonable way reactions at higher and lower energies. Despite particle trajectories are described classically, many quantistic effects have to be incorporated in these (Generalized)INC models [1, 8]. The basic assumptions are:

1. Primary and secondary particles moving in the nuclear medium
2. Interaction probability from σ_{free} + Fermi motion $\times$ $\rho(r)$ + exceptions (ex. π)
3. Glauber cascade at high energies
4. Classical trajectories (+) nuclear mean potential (resonant for π's!!)
5. Curvature from nuclear potential $\rightarrow$ refraction and reflection.
6. Interactions are incoherent and uncorrelated
7. Interactions in projectile–target nucleon CMS $\rightarrow$ Lorentz boosts

8. Multibody absorption for π, μ^-, K^-
9. Quantum effects (Pauli, formation zone, correlations...)
10. Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil

All these items are accurately implemented in the low-intermediate energy model of FLUKA, called PEANUT (PreEquilibrium-Approach-to-NUclear-Thermalization). The INC goes on in PEANUT until all nucleons are below a smooth threshold around 50 MeV, *and* all particles but nucleons (typically pions) have been emitted or absorbed. The nuclear configuration at this point is used as starting condition for the preequilibrium stage, that follows the exciton formalism of M. Blann and coworkers [12, 13, 14, 15], with some modifications [8].

For projectile energies higher than 3-5 GeV, the first inelastic interaction is described according to the Glauber-Gribov [16, 17, 18] model, which represents the diagram interpretation of the Glauber cascade [19, 20]. The nuclear effects on the secondaries are taken into account by a simplified (G)INC.

At the end of the reaction chain, the nucleus is a thermally equilibrated system, characterized by its excitation energy. This system can "evaporate" nucleons, or fragments, or γ rays, or even fission, to dissipate the residual excitation. Evaporation and fission in FLUKA are based on statistical approaches [2, 21]. For light residual nuclei, where the excitation energy may overwhelm the total binding energy, a statistical fragmentation (Fermi Break-up) model is more appropriate (see [1, 8, 22] for the FLUKA implementation).

3.1 Formation zone and coherence length

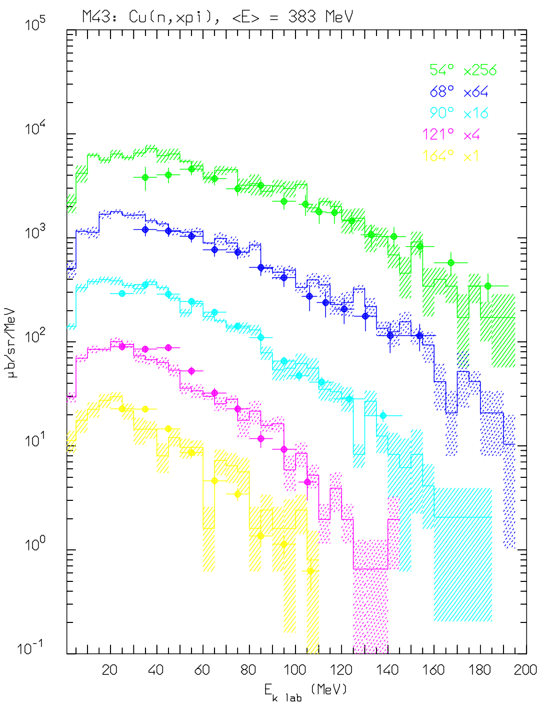

Figure 2: Simulated (histo) charged pion double differential distributions by neutrons of $< E_n >=$ 383 on Cu. Exp. data from [25].

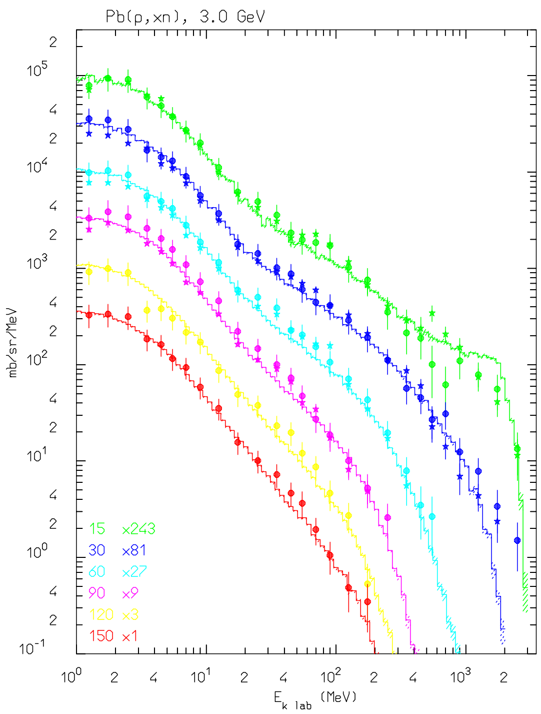

Figure 3: Simulated (histo) neutron double differential distributions by 3 GeV protons on Pb. Exp. data from [26].

The Formation Zone concept is essential to understand the observed reduction of the re-interaction probability with respect of the naive free cross section assumption. It can be understood as a "materialization" time. A qualitative estimate can be given as follows: in the frame where $p_{\|} = 0$, the time necessary for materialization $\bar{t}$ is

$$\bar{t} \quad = \quad \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

Going to lab system

$$t_{lab} \quad = \quad \frac{E_{lab}}{E_T}\bar{t} = \frac{\hbar E_{lab}}{p_T^2 + M^2}$$

The condition for possible re-interaction inside a nucleus is:

$$v \cdot t_{lab} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

At high energies, the "fast" (from the emulsion language) particles produced in the Glauber cascade have a high probability to materialize already outside the nucleus without triggering a secondary cascade. Only a small fraction of the projectile energy is thus left available for the INC and the evaporation.

Another critical issue is the "coherence" length after elastic, or quasi-elastic reactions. In analogy with the formation zone concept, such interactions cannot be localized better than the position uncertainty connected with the four-momentum transfer of the collision. Reinteractions occurring at distances shorter than the coherence length would undergo interference and cannot be treated as independent interactions on other nucleons. The coherence length concept has been applied to the secondaries in elastic, quasielastic or more generally quasi-two-body interactions.

3.2 Intermediate energy pions in nuclei

An accurate description of pion production and interactions is essential in many problems involving hadronic showers. The modelling of π nucleus interactions in PEANUT [8, 23] follows the theoretical approach of Oset and collaborators [24], taking into account:

- The resonant nature of the $\pi - N$ interaction, mostly dominated by the $\Delta(1232)$.
- The effect of the nuclear medium on the $\pi - N$ interaction
- The possibility of absorption (both s-wave and p-wave) on two or more nucleons
- The resonant nature of the pion-nucleus potential, which is rapidly varying with the pion energy

Two examples of neutron and charged pion production (and possibly reinteraction) are shown in figs. 2,3, compared with available experimental data.

3.3 Coalescence

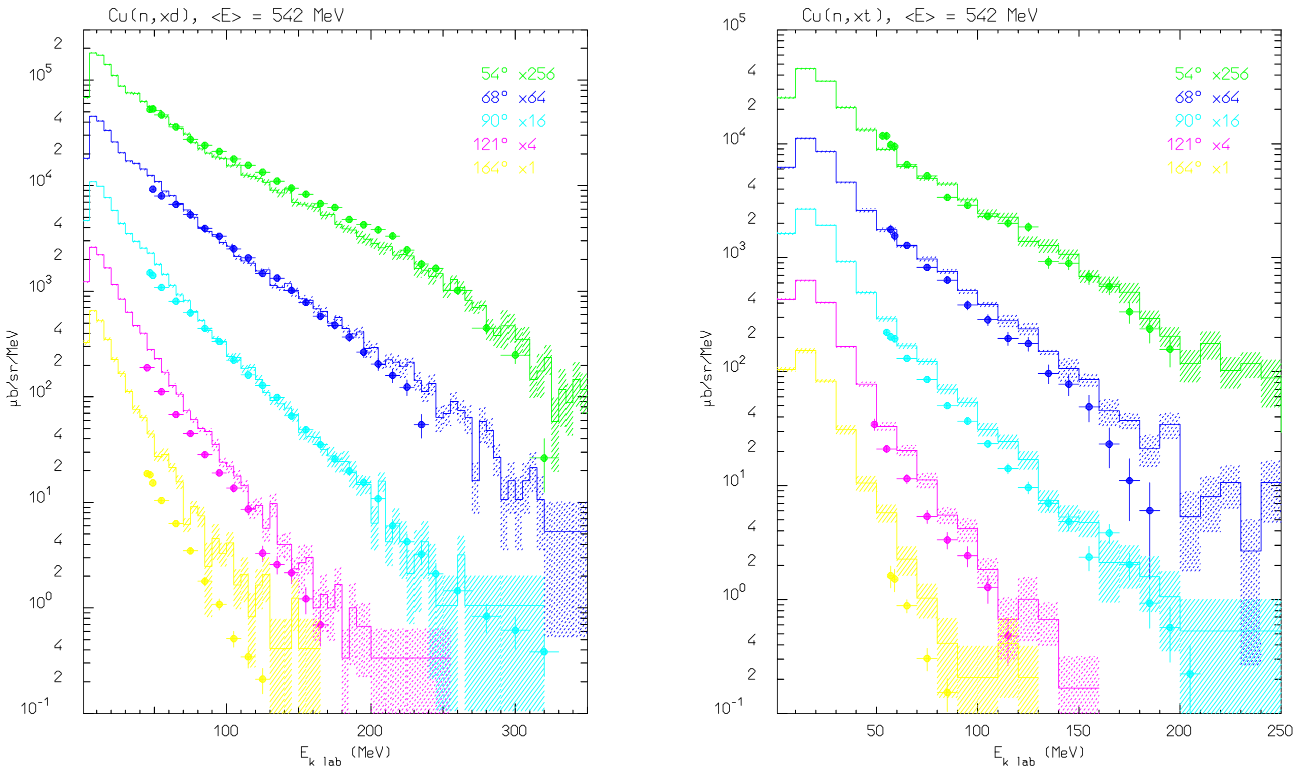

Figure 4: Deuteron (left) and triton (right) emission from 542 MeV neutrons on Cu. (exp data from [27])

Composite particles, ranging from deuterons to alphas and even larger fragments can obviously be emitted during the interaction "slow" stages (evaporation, fission, fragmentation). However, higher energy, lower intensity composite fragments can also be emitted through non-equilibrium processes. In particular mechanisms based on coalescence of energetic individual nucleons or light fragments into larger fragments when close in phase space have been proposed already many years ago as a natural explaination of high energy composite particle production [28]. These ions, even though relatively rare, can be of some importance and should not be neglected. An example of deuteron and triton production by means of the coalescence model embedded into FLUKA and available since 1997 is shown in fig. 4.

4 Nucleus-nucleus collisions

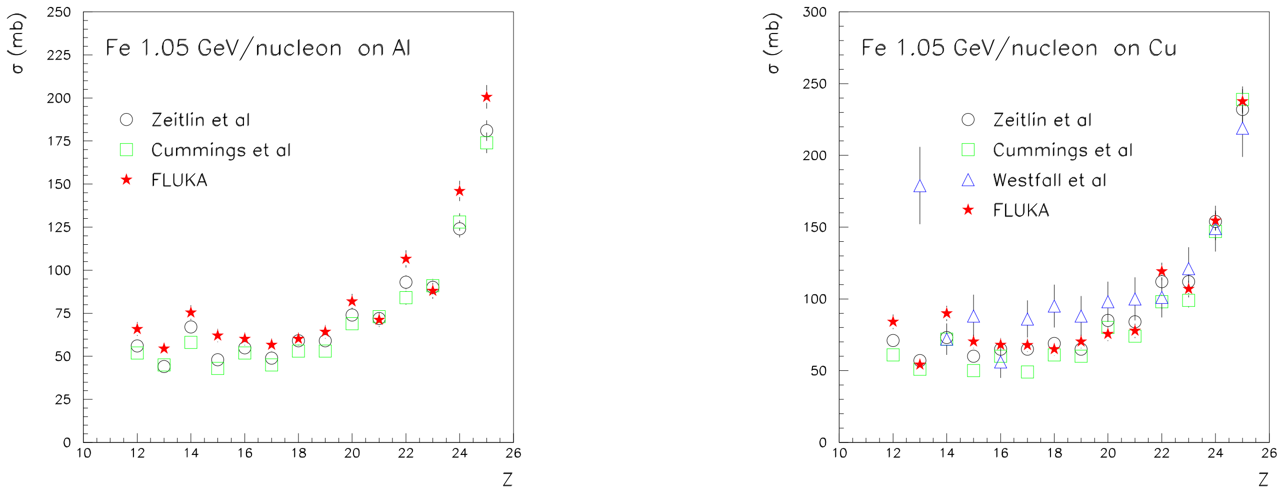

Figure 5: Fragment charge cross sections for 1.05 GeV/n Fe ions on Al (left) and Cu (right). Stars FLUKA, circles Zeitlin et al. [37], squares (1.5 GeV/n) Cummings et al. [38], triangles (1.88 GeV/n) Westfall et al. [39].

FLUKA has been successfully extended [29] to nucleus-nucleus collisions, using the DPMJET [30, 31] code at high (> 5 GeV/n) energies, and an extensively modified version of the RQMD-2.4 code [34, 35, 36].

In the near future, new intermediate energy nucleus-nucleus generators will be developed to replace the presently interfaced RQMD-2.4 code. In addition, the BME code developed at the University of Milan [41] will be interfaced to cover the lowest energy ion-ion interactions.

4.1 The FLUKA - DPMJET interface

DPMJET-II.53 [30], a Monte Carlo model for sampling hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at accelerator and cosmic ray energies (E_{lab} from 5-10 GeV/n up to 10^{11} GeV/n) was adapted and interfaced to the FLUKA program. FLUKA implements DPMJET-II.53 as an event generator to simulate nucleus-nucleus interactions exclusively. DPMJET is based on the two component Dual Parton Model in connection with the Glauber formalism. The implementation of DPMJET is also considered a possible, future option to extend the FLUKA energy limits for hadronic simulations in general.

Internally, DPMJET uses Glauber impact parameter distributions depending on projectile-target combination and collision energy. These are either computed during initialization of the program or can be processed and output in a dedicated run of DPMJET in advance. The computations are CPU intensive for colliding systems with heavier nuclei and it would not be practical to produce the required distributions repeatedly while processing full showers in FLUKA. Therefore, a procedure was devised to efficiently provide pre-computed impact parameter distributions for a complete matrix of projectile-target combinations up to a mass number of A=246 over the entire available energy range [33].

FLUKA requires AA reaction cross sections internally in order to select nucleus-nucleus interactions appropriately. Hence, a complete matrix of AA reaction cross sections was prepared along with the Glauber impact parameter distributions. Owing to the well established validity of the Glauber formalism, these cross sections can be safely applied down to a projectile kinetic energy ≈1 GeV/n.

DPMJET is called once per AA interaction. A list of final state particles as well as up to two excited residual nuclei with their relevant properties are returned by DPMJET for transport to FLUKA. De-excitation and evaporation of the excited residual nuclei is performed by calling the FLUKA evaporation module.

Work to interface DPMJET-III [32] is in progress.

4.2 The FLUKA - RQMD interface

Quantum-Molecular-Dynamics (QMD) approaches are a viable solution for nucleus-nucleus reactions. They represent an improvement over classical Intra Nuclear Cascade (INC) codes, thanks to their dynamic modeling of the nuclear field among nucleons during the reaction. The treatment of individual two-body scattering/interactions is usually based on similar approaches for INC and QMD codes.

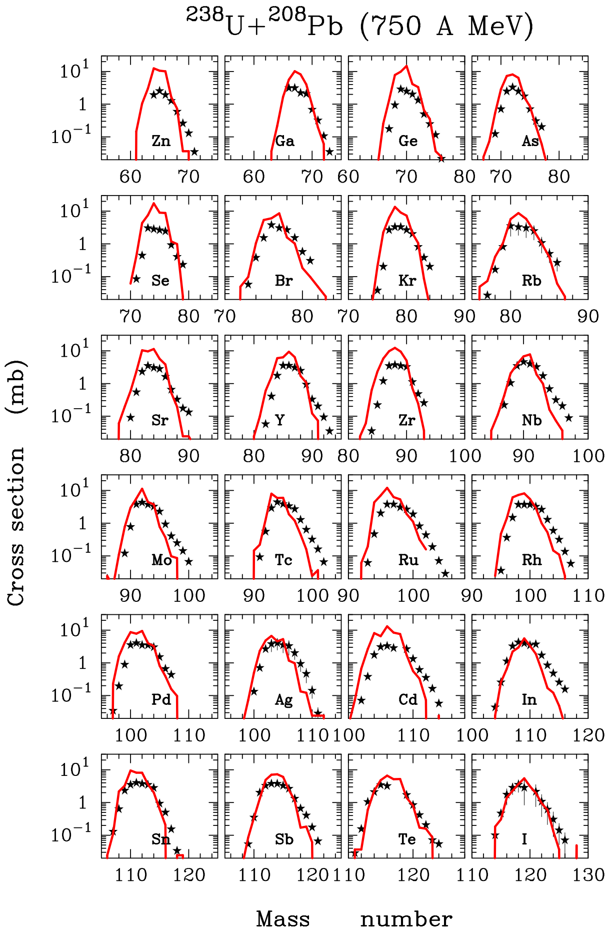

Figure 6: Computed projectile fragment cross sections for 750 MeV/n U ions on Pb. Data (stars) from [40]. Fission products have been excluded like in the experimental analysis.

The RQMD-2.4 [34, 36] is a relativistic QMD model which has been applied successfully to relativistic AA particle production over a wide energy range, from $\approx$ 0.1 GeV/n up to several hundreds of GeV/n. The high energy AA part in FLUKA is already successfully covered by DPMJET. For energies below a few GeV/n several models are under development, either new, or based on the extension of the present intermediate energy hadron-nucleus model of FLUKA. However, a RQMD-2.4 interface was developed meanwhile to enable FLUKA to treat ion interactions from $\approx$100 MeV/n up to 5 GeV/n where DPMJET starts to be applicable.

Several important issues had to be addressed. RQMD does not identify nuclei in the final state. Hence, no low energy de-excitation (evaporation, fragmentation…) is performed for both the excited projectile and target residuals. This is highly problematic, particularly for the projectile residual, since its de-excitation usually gives rise to the highest energy particle production in the laboratory frame. Serious energy non-conservation issues are also affecting the code, particularly when run in full QMD mode (RQMD can run both in full QMD mode or in the so called "fast cascade" mode where it behaves similar to an INC code). Therefore a meaningful calculation of residual excitation energies was impossible.

The adopted solution was to modify the code, reworking the nuclear final state out of the available information on spectators, correlating the excitation energy to the actual hole depth of hit nucleons. Finally, the remaining energy-momentum conservation issues were resolved taking into account experimental binding energies, as is the case for all other FLUKA models. After these improvements a meaningful excitation energy could be computed and the FLUKA evaporation model was used to produce the low energy (in their respective rest frames) particles emitted by the excited projectile and target residuals.

Examples of the performances of FLUKA compared with experimental data when running with the modified RQMD-2.4 model are presented in figs. 5 and 6, for charge fragment production by 1.05 GeV/n Fe ions on Al and Cu, and individual isotope production by 750 MeV/n U ions on Pb respectively. Despite these satisfactory results, the modified RQMD model is meant as a temporary solution for AA interactions below few GeV/n for FLUKA. Indeed the code is no longer developed or maintained and, given the shortcomings described before, in the long term we prefer to develop a new self-consistent QMD model where proper nuclear binding effects and excitation energy calculations are built in from the very beginning.

5 Neutrino Interactions

Neutrinos are not hadrons, however to describe their interaction nuclear effects are critical. The NUX-FLUKA event generator exploits all sophisticated nuclear physics of PEANUT. The quasielastic event generator is built-in. For Resonance and DIS the ν-nucleon interaction is described via the NUX [42] code of A. Rubbia, target nucleons and all secondaries are treated by PEANUT. The results agree very well with experimental observables as measured in the NOMAD [43] experiment. The Monte Carlo approach allows to disentangle the impact of the various Initial State and Final State effects on the reaction kinematics. This will be illustrated with several examples in the following, where kinematic quantities will be presented for:

- *Initial State*: particles as they are produced inside the nucleus by the primary ν-nucleon interaction
- *Final State* : particles emitted in the reaction, all nuclear effects included
- *No reinteractions*: particles emitted in the reaction, when reinteraction processes are inhibited. These differ from the Initial State configuration due to the effect of nuclear potentials.

The examples shown here refer mainly to ν_μ interactions in Oxygen and Iron, in the 0.5 to 10 GeV range. However, NUX-FLUKA is capable to handle interactions on any target material/compound, for energies up to 10 TeV and for all neutrino flavors.

5.1 Formation zone

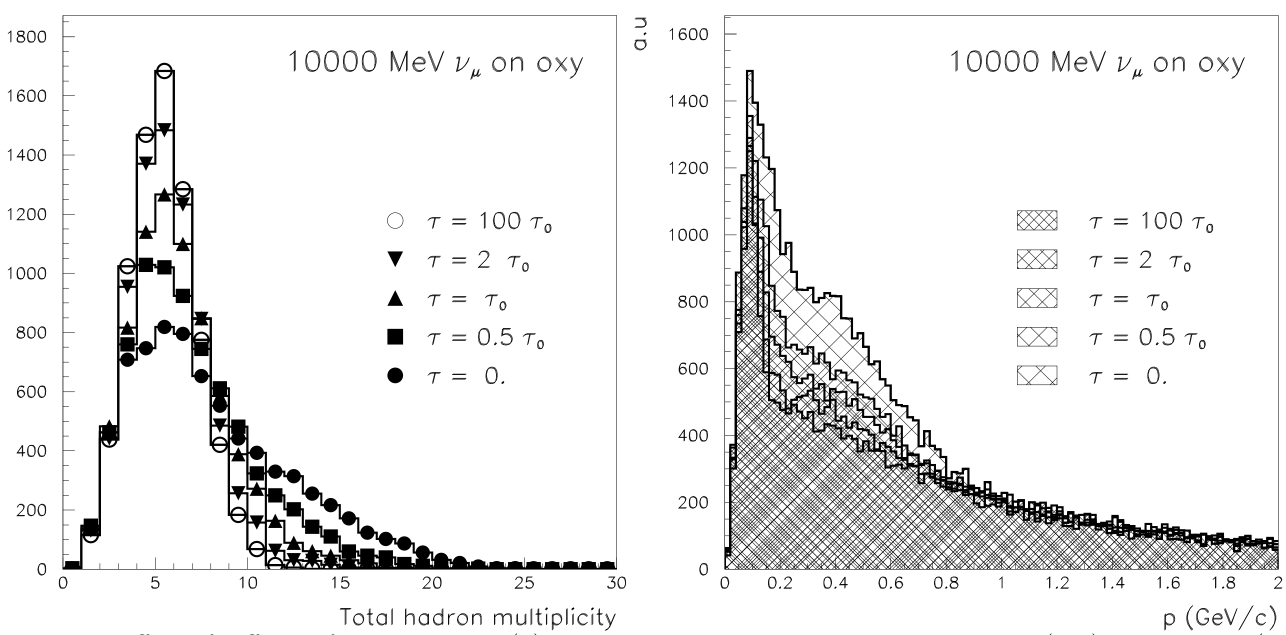

Figure 7: Effect of different formation time (τ) values on the charged hadron multiplicity (left) and spectra (right) in 10 GeV ν_μ CC interactions on Oxygen.

To illustrate the effect of the formation zone, the formation time and the coherence length have been multiplied by arbitary coefficients, ranging from 0 to 100, i.e. from no formation zone to almost no reinteractions.

- Reinteractions *increase* the hadron multiplicity with respect to the initial state kinematics, due to the buildup in the intranuclear cascade. An increase in the formation zone therefore corresponds to a suppression of the high mutiplicity tail, as shown in fig. 7.
- Reinteractions *populate* the hadron spectrum in the 100 MeV kinetic energy range, i.e. the *cascade* particles, and in the evaporation peak. This is well evident in fig 7. For 10 GeV ν_μ on ^{16}O, the introduction of the formation zone suppresses the cascade particles by about 40%; additional variations of a factor two have effects of the order of 15%.
- Reinteractions *depopulate* the hadron spectrum for $p >\approx 1 GeV/c$. In the same test case, the decrease is around 20%. The formation zone approximately halves this percentage.

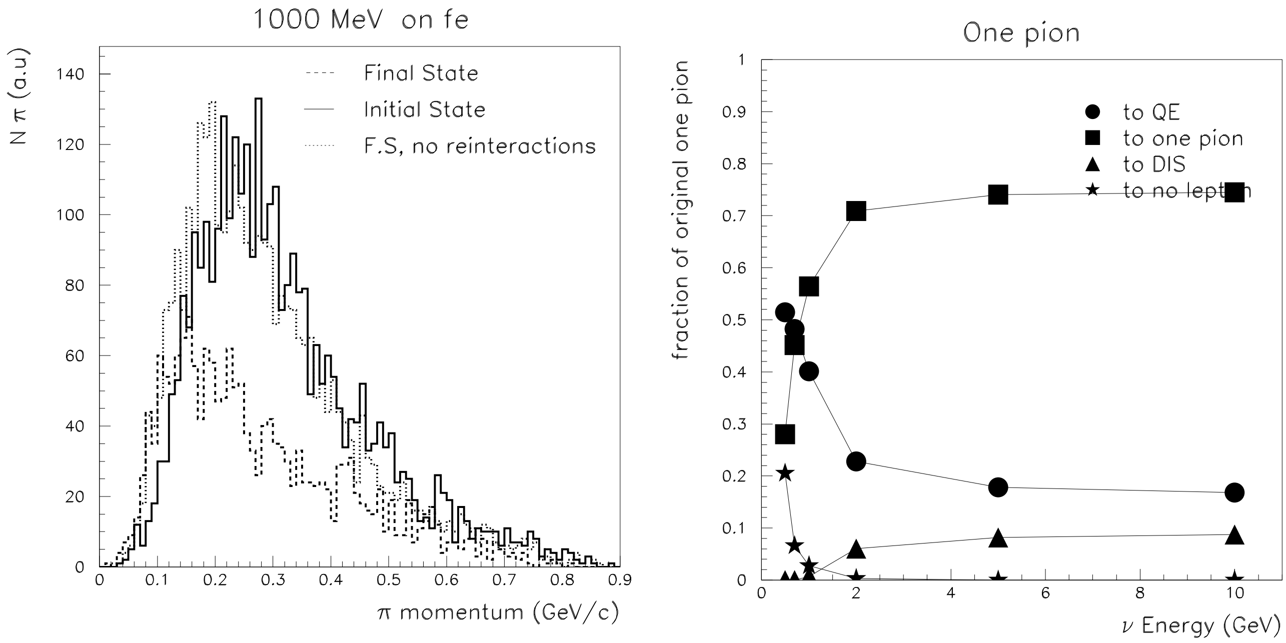

Figure 8: Charged pion spectra after 1 GeV ν_μ interaction on Iron (left). Fraction of generated ν_μ single pion CC events that is identified as QE, single pion or DIS in a water Cerenkov detector, as a function of the ν energy (right).

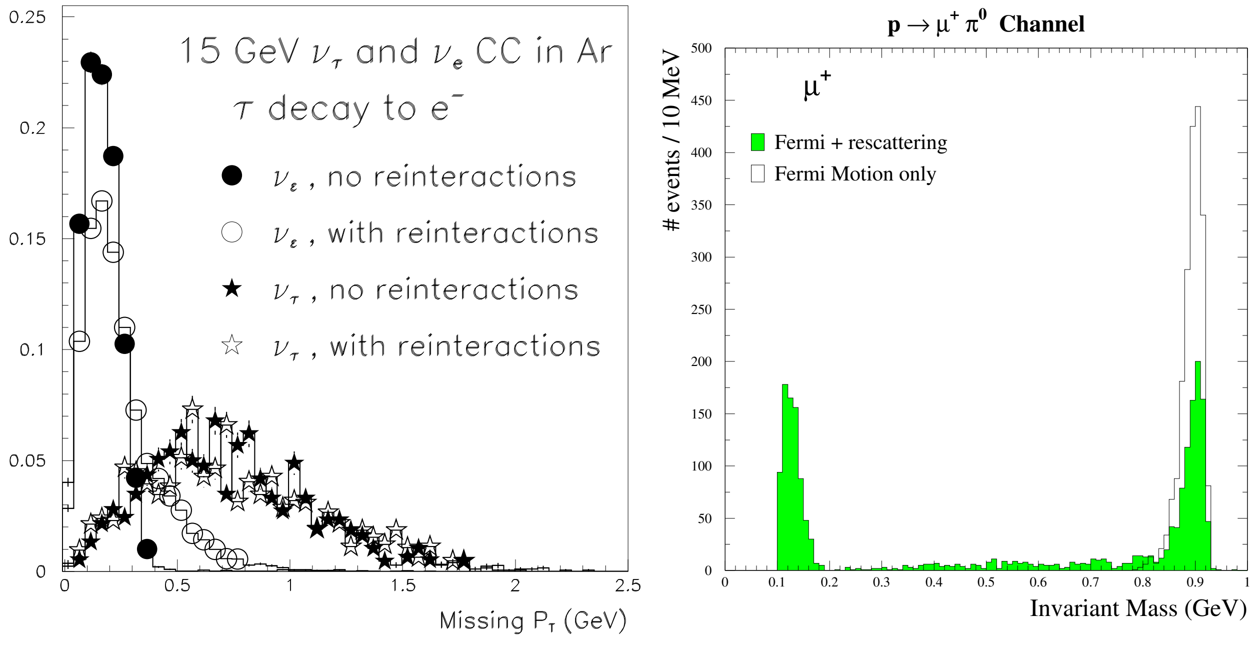

Figure 9: Transverse momentum distribution in CNGS-like events (left) and Reconstructed invariant mass in proton decay within an Argon nucleus (no recoils and low energy nucleons detected) (right)

- Reinteractions *increase* the average emission angle, even for the high energy part of the spectrum. The "standard" formation zone decreases the average hadron emission angle by 10% for $p > 0.2$ GeV/c, and by 4% for $p > 2$ GeV/c (both for 10 GeV ν_μ on ^{16}O).

5.2 Pion absorption

The large cross section for pion absorption in the Δ region can change dramatically the kinematics of ν interactions. As an example, charged pion spectra after ν_μ interaction on Iron are shown in fig. 8, with and without the effect of pion re-interaction. For 1 GeV ν_μ energy, only 55% of the produced π escape from a Fe nucleus, and 75% from an Oxygen nucleus.

The experimental separation among the different ν reaction channels is important both for the theoetical understanding and for the reconstruction of the ν kinematical variables. The "Golden" channel is the ν-nucleon Quasi Elastic scattering , thanks to its simple two-body final state. Reinteractions inside the nucleus, however, can change the multiplicity and particle identity in the final state, thus mixing different reaction channels. In a water Cerenkov detector (i.e. SuperKamiokande) Charged Current (CC) Quasi Elastic (QE) reactions are identified by the presence of one lepton ("single ring") events, and no other particles above the Cerenkov threshold. At low ν energies, an important contamination to the QE sample comes from the "single-pion" channel (i.e. $\nu_l + N \rightarrow l + N' + \pi$), when the pion is absorbed. Fig. 8 shows the repartition of original one-pion events in Oxigen as identified in an hypothetic Cerenkov detector. It can be seen that almost all the events lost in the one-pion channel populate the QE channel.

5.3 Momentum and energy smearing

In the search for ν_τ events in long baseline neutrino beam experiments (like ICARUS at CNGS), the cleanest signal comes from the τ decay in the electron channel. In this case, one of the kinematical variables used to discriminate from ν_e events is the transverse momentum (P_T) of the reaction products. In the chain $\nu_\tau + A \rightarrow \tau^- + X \rightarrow e^- + \bar{\nu}_e + \nu_\tau + X$ P_T is different fom zero due to the undetectable neutrinos, while in $\nu_e + A \rightarrow e^- + X$ P_T would be zero in absence of nuclear effects. As seen in fig. 9, the situation is different. Already the Fermi momentum of the target nucleon leads to a non-zero P_T in the ν_e induced reactions, and the reinteractons add tails to the P_T distribution. Of course, this does not mean that momentum is not conserved in the reaction, but that it is carried by reaction products that are not detected or not measured, like residual nuclei and heavy fragments.

Similar effects influence the experimental search for nucleon decay. As shown in fig. 9 for the $p \rightarrow e^+\pi^0$ decay, the experimentally reconstructed invariant mass is always smaller than the nucleon mass, due to the energy carried by undetected particles (in this case, ICARUS-like energy cuts have been applied). Pion scattering and absorption add a tail and a low energy peak to the initial smearing due to Fermi motion.

6 Conclusions

Hadron interaction modelling in FLUKA is enough advanced to provide reliable estimates of particle production and propagation under most circumstances. The basic features of nuclear interactions can be understood in terms of a general scheme where the fast, cascade, preequilibrium and equilibrium stages can be naturally concatenated, each one explaining for some of the experimental observables, and linked together in a coherent and self-consistent picture. This approach makes FLUKA a powerful tool in predicting interaction properties over a wide energy range and for a variety of applications, ranging from basic research to applied physics, not only for hadron induced reactions but also for more exotic applications like neutrino-nucleus interactions and nucleon decays.

The recent addition of nucleus-nucleus capabilities to the code has further widened its range of application.

Acknowledgements

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