INTERMEDIATE AND HIGH ENERGY MODELS IN FLUKA: IMPROVEMENTS, BENCHMARKS AND APPLICATIONS

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Abstract

The most recent improvements to the physical models of the FLUKA code are briefly described. They regard mainly the intermediate energy model for hadron interactions, where the inclusion of a variety of new effects led to better predictions about residual nuclei, double differential yields and fission cross sections. New generators have been implemented for specific applications. The high energy model has also been improved.

The increased accuracy and predictive power of FLUKA are shown by examples where model data are compared with experimental results.

1 The intermediate energy hadronic model PEANUT

The intermediate energy model of FLUKA, called PEANUT (PrEquilibrium Approach to NUclear Thermalization), was originally developed in 1991, as a substantial improvement in the description of nucleon induced reactions below the pion threshold.

During the years the model has been extended to other projectiles and to higher energies. Presently, PEANUT handles interactions of nucleons, pions, kaons and γ rays with nuclei from about 3 GeV down to reaction threshold (or 20 MeV for neutrons). The model also handles nucleon decay and neutrino-nucleus interactions, fully (for quasi-elastic interactions), or through coupling with external neutrino-nucleon generators. It is also able to describe negative muon absorption at rest.

The reaction mechanism is modelled in PEANUT by explicit intranuclear cascade smoothly joined to statistical (exciton) preequilibrium emission [1] and followed by evaporation (or fission or Fermi break-up) and gamma deexcitation.

In both stages, INC and exciton, the nucleus is modelled as a sphere with density given by a symmetrized Woods-Saxon [2] shape with parameters according to the droplet model [3] for A>16, and by a harmonic oscillator shell model for light isotopes (see [4]). The effects of the nuclear and Coulomb potentials outside the nuclear boundary are included. Proton and neutron densities are generally different.

Binding Energies are obtained from mass tables. Relativistic kinematics is applied at all stages, with accurate conservation of energy and momentum including those of the residual nucleus.

Care has been taken to avoid any inconsistency and discontinuity at the border between INC stage and preequilibrium stage. This internal consistency is documented for instance in the example of fig. 1, where the spectra obtained with the full algorithm and without the INC stage are practically identical.

More details about PEANUT can be found elsewhere [5]. Only a short description of the main steps of our approach is given in the following paragraphs.

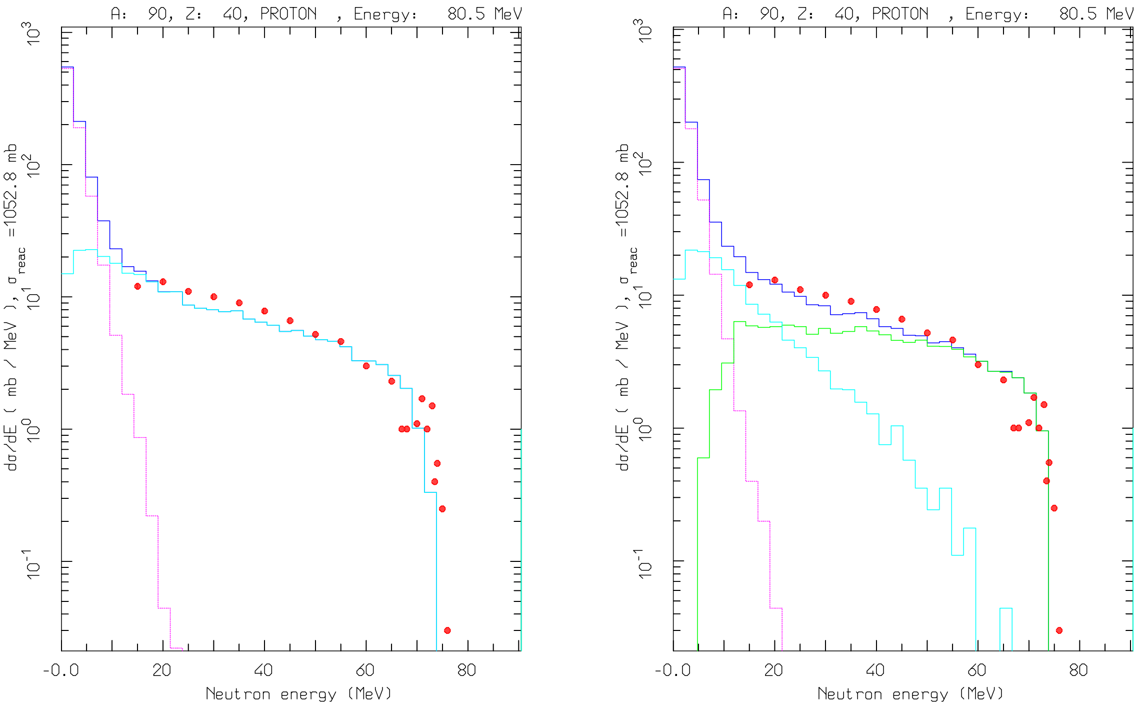


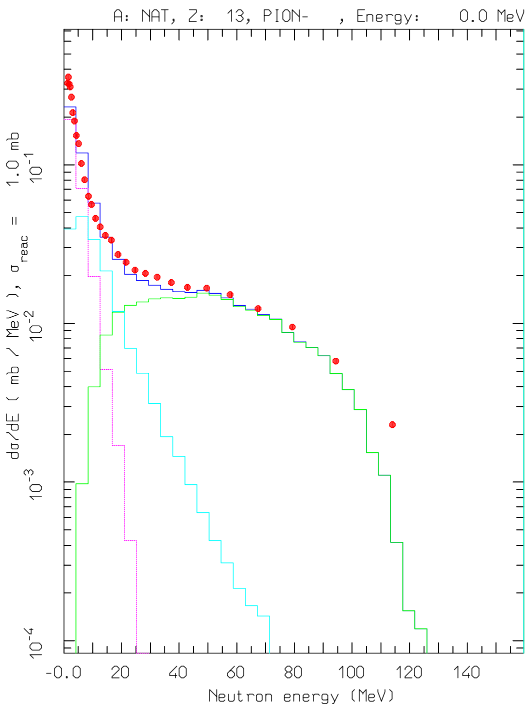
Figure 1: Example of angle integrated ^{90}Zr(p,xn) at 80.5 MeV calculations with the full algorithm (right), and without the INC stage (left). The various lines show the total, INC, preeq. and evaporation contributions, the exp. data have been taken from [6]

1.1 Nucleon Fermi motion

A standard Fermi momentum distribution in the local density approximation is implemented in PEANUT . On top of the mean field obtained in this way, a gaussian smearing of the momentum distribution of bound nucleons is applied according to uncertainty considerations, with parameters similar to those used in QMD models [7, 8]. Work is in progress to implement high momentum tails in the nucleon momentum distribution [9, 10].

1.2 Quantistic effects

Several quantistic effects are included in the INC and in the preequilibrium stages. They are essential in reducing hadron reinteraction rates with respect to naive expectations based on hadron-nucleon cross sections. Together with refraction/reflection at the nuclear surface, which are described in PEANUT in a semiclassical way propagating hadrons in the nuclear mean field, these effects are fundamental for an accurate description of reactions at the lowest and highest energies. A thourough discussion and an example of their effectiveness can be found in [5].



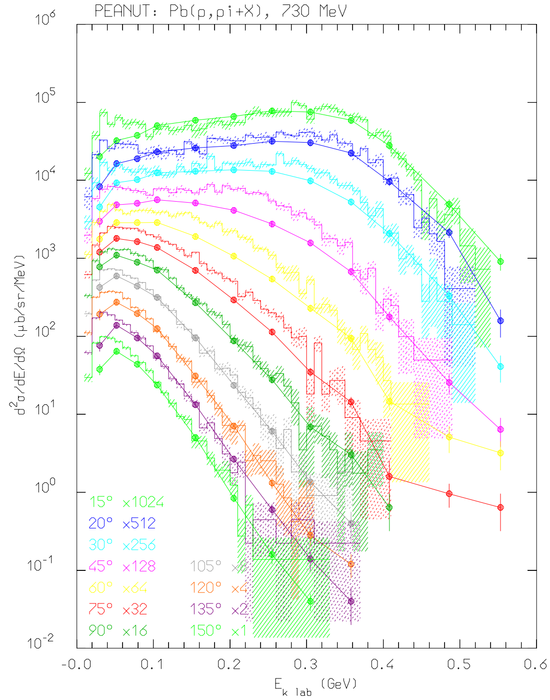


Figure 2: Angle integrated Al(π^-,xn) spectrum for stopping π^-: experimental data from [17]

Figure 3: Double differential cross section for Pb(p,xπ^+) at 730 MeV. Experimental data (symbols) from [18], computed data (histos) by PEANUT

1. Pauli blocking for all hadron-nucleon interactions
2. Nucleon antisymmetrization and hard core correlations
3. Formation time for inelastic interactions
4. Coherence length for (quasi)-elastic and charge exchange interactions

The former two effects are well known and will not be described.

1.2.1 Formation Time

It has been known for many years that a plain treatment of INC at energies exceeding a few GeV overestimates the measured particle yields. In particular, there is experimental evidence for some mechanism which limits the reinteractions of energetic (fast) particles. This physical mechanism is the so called "formation zone". On the contrary of common feelings, this concept has sound theoretical foundations [11, 12, 13] and retains a strong analogy with the LPM [14] effect which has been experimentally verified.

Naively, it can be understood considering that hadrons are composite objects and that the typical time of strong interactions is of the order of 1 fm. Thus, it requires some time to the hadrons emerging from an inelastic interaction to "materialize" and be able to undergo further interactions. A simple qualitative estimate [5], yields for the formation time in the laboratory system:

$$t_{for} \quad = \quad \frac{E_{lab}}{E_T}\bar{t}_{for} = \frac{E_{lab}}{M}\tau_{for} = \frac{\hbar E_{lab}}{p_T^2 + M^2} \qquad (1)$$

This poses a condition for possible reinteraction inside a nucleus:

$$v \cdot t_{for} \leq R_A \approx r_0 A^{\frac{1}{3}} \tag{2}$$

1.2.2 Coherence length

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, with the following recipe: given a two body interaction with four-momentum transfer $q = p_{1i} - p_{1f}$, between a particle $1i$ and a nucleon $2i$ with final particles (which could be resonances) $1f$ and $2f$ the energy transfer seen in a frame where the particle 2 is at rest is given by

$$\Delta E_2 = \nu_2 = \frac{q \cdot p_{2i}}{m_2} \tag{3}$$

From the uncertainty principle this ΔE corresponds to an indetermination in proper time given by $\Delta\tau \cdot \Delta E_2 = \hbar$, that boosted to the lab frame gives a coherence length

$$\Delta x_{lab} = \frac{p_{2lab}}{m_2} \cdot \Delta\tau = \frac{p_{2lab}}{m_2} \frac{\hbar}{\nu_2} \tag{4}$$

1.3 The PreEquilibrium stage

The INC step goes on until all nucleons are below a smooth threshold around 50 MeV, *and* all particles but nucleons (typically pions) have been emitted or absorbed. At the end of the INC stage a few particles may have been emitted and the input configuration for the preequilibrium stage is characterized by the total number of protons and neutrons, by the number of particle-like excitons (nucleons excited above the Fermi level), and of hole-like excitons (holes created in the Fermi sea by the INC interactions), by the "compound" nucleus excitation energy (actually the nucleus is not yet at all in a equilibrated state and the term "compound" is somewhat incorrect), and by the "compound" nucleus momentum. All the above quantities can be derived by proper counting of what occurred during the INC stage. The exciton formalism of PEANUT follows that of M. Blann and coworkers [15], with some modifications:

- Inverse cross sections from systematics
- Correlation/formation zone/hardcore effects on reinteractions: the escape probability for an exciton in the continuum is calculated as sum of the probabilities in three zones: the first is the largest between the hardcore and the formation ones, the second extends up to the correlation radius (here reinteractions are allowed only on the non-correlated nucleon specie), the third is the remaining nuclear volume.
- Constrained exciton state densities for the configurations 1p-1h, 2p-1h, 1p-2h, 2p-2h, 3p-1h and 3p-2h

- Energy dependent form for the single particle density g_x [16]
- Position dependent parameters = point like values :
  - first step : n_h holes generated in the INC step at positions $\vec{x}_i$:

$$\rho^{loc}_{n_h} = \frac{\sum_{i=1}^{n_h} \rho(\vec{x}_i)}{n_h} \quad ; \quad E^{loc}_{F\ n_h} = \frac{\sum_{i=1}^{n_h} E_F(\vec{x}_i)}{n_h} \tag{5}$$

  - When looking at reinteraction: consider neighborhood:

$$\rho^{nei}_{n_h} = \frac{n_h \rho^{loc}_{n_h} + \rho^{ave}}{n_h + 1} \quad ; \quad E^{nei}_{F\ n_h} = \frac{n_h E^{loc}_{F\ n_h} + E^{ave}_F}{n_h + 1} \tag{6}$$

  - Subsequent steps: go towards *ave*rage quantities

$$\rho^{loc}_{n_h+1} = \rho^{nei}_{n_h} \quad ; \quad E^{loc}_{F\ n_h+1} = E^{nei}_{F\ n_h} \tag{7}$$

- Angular distributions of emitted particles in the fast particle approximation

1.4 Pion interactions and pion production

Pion transport and interactions in nuclei are treated in the INC part of the code. Pions feel an energy and density dependent nuclear potential derived from the optical model. Two and three body interactions are included to describe pion absorption both at rest and in flight. Details and examples are given in [5]. Here only an example of stopping π^- absorption is shown in fig. 2.

Pion transport is a key ingredient to extend the range of the model above the pion threshold. The other ingredient is of course the modelling of pion production reactions. These are supposed to proceed via resonance production. Improvements in the resonance production angular distribution and an energy dependent width have been implemented for the Δ resonance, allowing to obtain the satisfactory results shown in fig. 3. These improvements will soon be extended to other resonant channels.

1.5 Residual nuclei production and scoring

The FLUKA ability in predicting residual nuclei has been substantially strengthened thanks to the major improvement in the evaporation model and to the introduction of the Fermi break-up. Examples of predicted excitation function for reactions Co(p,x) are reported in fig. 4. The evaporation part has been rewritten adopting a sampling scheme for the emitted particle spectra which no longer makes any maxwellian approximation and which includes sub-barrier effects. Gamma competition has been introduced too.

2 Applications

FLUKA is widely used in many different applications ranging from shielding, dosimetry and proton therapy, to high energy detector description and modelization, and cosmic ray shower simulations. Due to space constraint these items are not discussed here. A summary and some examples can be found in [20, 21, 22], together with an exhaustive bibliography.

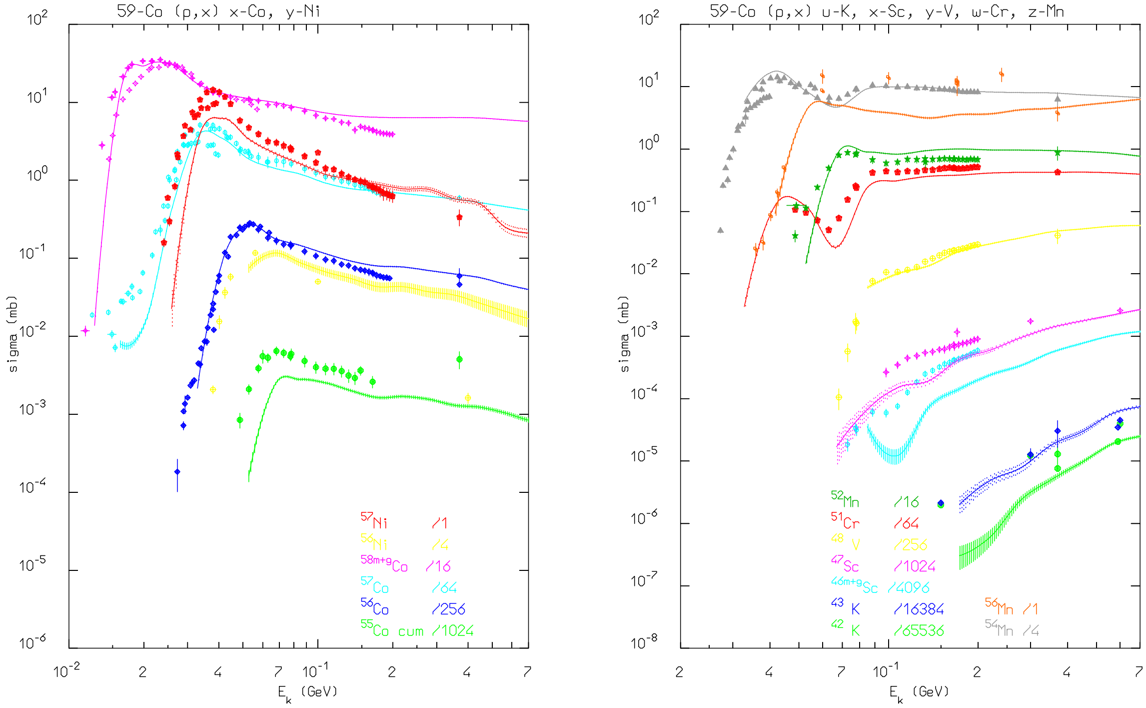


Figure 4: Comparison between computed and measured [19] isotope production by protons on natural Cobalt

3 Conclusions

The field of applications of FLUKA is becoming wider and wider, with a growing emphasis towards description and design of physics experiments. The capabilities of the code in the detailed description of hadronic processes from few tens of MeV up to atmospheric showers proved to be a key issue in many applications.

The code resulted to be useful also in the field of rare event detection [20, 22] (nucleon decay, neutrino induced events, etc.), where the very demanding constraints on physics description call for refined models.

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