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The FLUKA code: New developments and application to 1 GeV/n iron beams

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Abstract

The modeling of ion transport and interactions in matter is a subject of growing interest, driven by the continuous increase of possible application fields. These include hadron therapy, dosimetry, and space missions, but there are also several issues involving fundamental research, accelerator physics, and cosmic ray physics, where a reliable description of heavy ion induced cascades is important.

In the present work, the capabilities of the FLUKA code for ion beams will be briefly recalled and some recent developments presented. Applications of the code to the simulation of therapeutic carbon, nitrogen and oxygen ion beams, and of iron beams, which are of direct interest for space mission related experiments, will be also presented together with interesting consideration relative to the evaluation of dosimetric quantities. Both applications involve ion beams in the *A*GeV range.

Keywords: Monte Carlo simulations; Heavy ion interactions; Therapeutic beams; Space dosimetry

1. Introduction

One of the important concerns about long term missions of astronauts, especially in deep space (such as in the case of a possible mission to Mars), is the biological risk from radiation. The effective dose per day due to galactic cosmic rays is ≈1 mSv, the order of magnitude

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of the dose on the Earth in one year. Moreover, one must take into account the risk of solar particle events, which are very intensive and unpredictable fluxes of particles (mainly protons) lasting up to few days, that in absence of appropriate shielding may determine a dose of several Sieverts.

Estimating biological risk from GCR and planning countermeasures are difficult tasks for several reasons: (a) it is necessary to have a detailed description of the effects of the spacecraft (and possible shields and shelters) in modulating the radiation fields; (b) the spectrum of the GCR, peaked at an energy of ≈1 GeV/n, has a significant presence of HZE particles, which represent only 1% of the particle flux, but may provide up to 50% of the equivalent dose; (c) the biological effects of HZE particles are not yet known and experimental ground-based experiments are needed for several biological endpoints (Durante et al., 2001) (see for example the experiments carried on in Brookhaven with iron ions); (d) radiobiological models and simulations based on a mechanistic description of biological damage need further developments to reliably predict the effects of mixed fields. In all of these cases the contribution of Monte Carlo transport codes is crucial.

The best way to describe the radiation field is undoubtedly to use fluencies. This is particularly true when one wants to understand radiation damage mechanisms. It is well known that LET is a "weak" quantity for predicting radiation effects. Even α particles and protons of the same LET can have different radiobiological effectiveness, due to the different velocities that determine different ionization clustering properties (Ottolenghi et al., 1997, 2001). Things are even more complicated with heavy ions, for which the same particle type with the same LET may have different biological effectiveness, again depending on their velocity. Nevertheless the LET and its various types of average values (typically track- and dose-average LET) and distributions are still frequently used to provide a first-approximation synthetic description of the radiation quality. Moreover, the LET is still used as a reference quantity to determine the quality factors when weighting factors are not defined in radiation protection (ICRP, 1991). In any case the use of track-average LET (and its corresponding microdosimetric quantity Y_F) is of scarce usefulness since it gives an unreasonable emphasis to the role of the flux of low-LET particles, which are of minor importance both in terms of dose and in terms of biological effectiveness. Moreover, in this work we will also show the large uncertainty (and the large dependence on experimental conditions and assumptions) in the determination of its values. If one has to use an average value we suggest to use the dose-average LET (and its corresponding microdosimetric quantity Y_D) which has a more soundly based justification both in terms of its predictive ability and in terms of theoretical and experimental determinations.

In this context, benchmark studies on LET distributions and average values, involving both theoretical models (and simulation codes) and experimental measurements, have become crucial particularly for iron ions, extensively used in radiobiological experiments. In this paper, the application of the FLUKA simulation code to ion beam studies is presented and discussed.

FLUKA (Fassò et al., 2001a; Fassò et al., 2001b) is a transport and interaction Monte Carlo code, capable of handling hadronic and electromagnetic showers from thermal neutrons up to very high energies (10,000 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 (Fassò et al., 2001a; Fassò et al., 2001b; http://www.fluka.org).

In the recent years, FLUKA has been successfully extended (Andersen et al., 2004) to nucleus–nucleus collisions. The DPMJET (Ranft, 1995; Roesler et al., 2001) code has been interfaced to cover the high (>5 GeV/n) energy range, and an extensively modified version of the RQMD-2.4 code (Sorge et al., 1989a,b; Sorge, 1995) is used at lower energies.

2. Ion–ion interactions in FLUKA

DPMJET (Ranft, 1995), a Monte Carlo model for sampling hadron–hadron, hadron–nucleus and nucleus–nucleus collisions at accelerator and cosmic ray energies, was adapted and interfaced to the FLUKA program. The original interface to the DPMJET-II.53 version has recently been upgraded to comply with the DPMJET-III version. DPMJET is based on the two component Dual Parton Model in connection with the Glauber formalism. FLUKA implements DPMJET as event generator to simulate nucleus–nucleus interactions exclusively. De-excitation and evaporation of the excited residual nuclei is performed by calling the FLUKA evaporation module.

The RQMD-2.4 (Sorge et al., 1989a; Sorge, 1995) is a relativistic QMD model which has been applied successfully to relativistic *AA* particle production over a wide energy range, from ≈0.1 GeV/n up to several hundreds of GeV/n. A RQMD-2.4 interface was developed to enable FLUKA to treat ion interactions from ≈100 MeV/n up to 5 GeV/n where DPMJET starts to be applicable. Several important modifications have been implemented in the RQMD code, in order to ensure energy-momentum conservation taking into account experimental binding