Program Complex for High Energy Hadron Transport Calculations to Solve Radiation Problems in Accelerators

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Abstract

A review of methods developed for solution of particle transport problem is made. These are the modifications of discrete-ordinates and Monte-Carlo methods: 1) ROZ-6H stationary one-dimensional discrete-ordinates transport code; 2) ROZ-W.2 time-dependent one-dimensional discrete-ordinates transport code; 3) MOSKIT Monte-Carlo three-dimensional code to solve particle transport in matter; 4) System of hADron COnstants (SADCO-2) to provide neutron, proton, pion, kaon and photon transport calculation. The program complex developed allows one to calculate transport of neutrons (with energy 0.01 eV<E<10 TeV), protons, pions, kaons (20MeV<E<10TeV) and photons (0.01MeV<E<20MeV) through matter with a high accuracy, and to solve many other radiation problems in accelerators.

1 INTRODUCTION

Calculational algorithms and program complexes are required for solution of various radiation problems in high-energy accelerators. The main ones are: predicting of dose power levels, designing of radiation shielding, background radiation estimating, etc.

Most of codes used for this purpose are based on analogue simulation of particle trajectories by the Monte-Carlo method (for example, HETC, GEANT, FLUKA87 [1-3]). Very important deficiency of this method is an exponential dependence of statistic error on thickness of matter. It does not allow one to solve the problem of particle penetration through the shielding with a thickness greater than 8÷10 optical lengths with a satisfactory statistic error.

In the general case, the problem of calculational investigation of radiation transport is reduced to solution of the linear Boltzmann equation for flux density of neutral and charged particles $\psi(\vec{r},\vec{\Omega},E)$:

$$\frac{1}{v}\frac{\partial\psi_i}{\partial t}+(\vec{\Omega}\vec{\nabla})\psi_i+Q_{v\,i}(\vec{r},\vec{\Omega},E)=I_{s\,i}+I_{el\,i} \qquad (1)$$

with boundary-value conditions

$$\psi_i(\vec{r},\vec{\Omega},E)\mid_{(\vec{\Omega}\vec{n})<0}=Q_{\Gamma i}(\vec{r},\vec{\Omega},E), \qquad (2)$$

where $I_{s\,i}$ is a nuclear scattering operator, $I_{el\,i}$ is an operator of electromagnetic losses of energy

$$I_{s\,i}\left(\vec{r},\vec{\Omega},E\right)=-\Sigma_{tot\,i}(\vec{r},E)\psi_i((\vec{r},\vec{\Omega},E)+$$

$$+\sum_j\int_{4\pi}d\vec{\Omega}'\int_0^\infty dE'\psi_j(\vec{r},\vec{\Omega},E)\Sigma_{s\ j\to i}\left(\begin{smallmatrix}E'\to E\\ \Omega'\to\Omega\end{smallmatrix}\right), \qquad (3)$$

$$I_{el\,i}(\vec{r},\vec{\Omega},E)=\frac{\partial}{\partial E}\left(\beta(E)_i\psi_i(\vec{r},\vec{\Omega},E)\right)+$$
$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}\left(\xi_i(E)\psi_i(\vec{r},\vec{\Omega},E)\right) \qquad (4)$$

$\Sigma_{tot\,i}$ is the total interaction cross-section, $\Sigma_{s\ i\to j}\left(\begin{smallmatrix}E'\to E\\ \vec{\Omega}'\to\vec{\Omega}\end{smallmatrix}\right)$ is the scattering cross-section,

$$\Sigma_{s\ i\to j}\left(\begin{smallmatrix}E'\to E\\ \Omega'\to\Omega\end{smallmatrix}\right)=\frac{d^2\sigma}{dEd\Omega}^{h_iA\to h_jX}\left(E',E,(\vec{\Omega}'\vec{\Omega})\right)\rho \qquad (5)$$

$\beta(E)_i$ is stopping power, $\xi(E)_i$ is an average square of energy losses per unit of length, $\vec{\Omega},\vec{\Omega}'$ is particle direction, $Q_{V\,i}(\vec{r},\vec{\Omega},E)$ is density of inner source, $Q_{\Gamma i}$ is density of external sources, v is velocity, ρ is nuclear density, i,j is a particle sort indexes.

The developed program complex is based on solutions of nonstationary and stationary kinetic equation (1) by the discrete-ordinates and Monte-Karlo methods. It allows one to calculate transport of n, p, π, K with energy up to 10 TeV and γ-rays with energy up to 20 MeV through a thick shielding with a high accuracy.

2 STRUCTURE OF THE PROGRAM COMPLEX

Structure of the program complex is presented in Fig.1. The developed program complex consist of:

- System of hADron COnstants (SADCO-2)[4] to support transport calculations of neutrons (0.01eV<E<10TeV), protons, pions, kaons (20MeV<E<10TeV) and photons (0.01MeV<E<20MeV).
- ROZ-6H stationary one-dimensional discrete-ordinates transport code [5].
- ROZ-W.2 time-dependent one-dimensional discrete-ordinates transport code [6].
- MOSKIT Monte-Carlo three-dimensional fast code for solving particle transport through the matter [7].

The radiation transport codes use the group method for description of cross-section energy dependencies. The extension of this method into the high-energy region requires

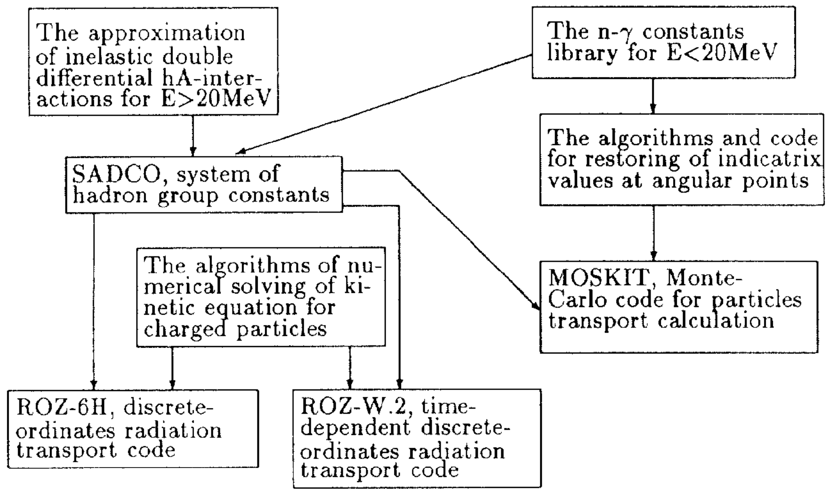

Figure 1: The program complex scheme

creation of system of constants for the neutral and charged radiation transport calculation, as well as new algorithms for solution of the kinetic equation which take into account the electromagnetic interactions of charged particles and high anisotropic scattering.

3 SYSTEM OF CONSTANTS

System of constants SADCO [4] prepares constants for neutrons with energies ranging from 0.01 eV to 10 TeV, protons, pions and kaons (20 MeV÷10 TeV) and photons (0.01 MeV÷20 MeV). This system is based on codes [8] that use approximations of both experimental and theoretical data on hA-interactions for energy E_0 <10 GeV by a parametrical formula:

$$\frac{d^2\sigma}{dEd\Omega} = \frac{1}{E_0}\exp\left[\sum_i\left(\sum_j \alpha_{i,j}\theta^{j-1}\right) ln^{i-1}\frac{E}{E_0}\right]. \qquad (6)$$

Here parameters $\alpha_{i,j}$ were found by the least square fit, energetic balance being taken into account; E_0 is energy of a primary particle; E is that of a secondary particle; θ is a polar angle. For energies higher than 10 GeV factorization of of total and double differential cross-sections results in:

$$\frac{d^2\sigma}{dEd\Omega} = \frac{\sigma_{in}^{hA}}{\sigma_{in}^{hp}} R^{h_1A\rightarrow h_2X}(E_0,E,\theta)\frac{d^2\sigma^{h_1p\rightarrow h_2X}}{dEd\Omega} \qquad (7)$$

where σ_{in}^{hA} and σ_{in}^{hp} are the cross-sections of hA- and hp- inelastic interactions, R is the ratio of cross-section of hA- to hp-interaction. This method allows one to obtain the differential cross-sections with errors less than 50% in a short time. For neutron and gamma energies less than 20 MeV libraries of constants ENDF/B, [9] or GNDL, [10] are used for multi-group library forming. System SADCO consists of: 1) a bank of experimental data on cross-sections of hA-interactions with energies less than 100 GeV; 2) codes for estimation of experimental and theoretical data and their approximation; 3) codes for group files of constants to be created in ANISN and FMAC-M formats; 4) codes to merge files of constants for various sorts of particles and energy ranges.

4 ROZ-6H, DISCRETE-ORDINATES RADIATION TRANSPORT CODE

Program ROZ-6H[5] is developed for solution of multigroup kinetic equation of (n, p, π,γ) particle transport in a one-dimensional geometry by the discrete-ordinates method for a different sources, involving problems with fission and cascade processes. Angular distribution of scattering is represented either in P_L-approximation, or in points of scattering angle. To approximate spatial derivative, it uses one of the following schemes: 1) Adapted Weighted Diamond scheme; 2) method of characteristics. The energy derivative describing ionizing energy losses in a continuous slowing-down approach and diffusion dilution in energy are approximated with a second-order accuracy scheme. The angular dependence of Boltzmann's operator with a high anisotropic scattering is described in a Fokker-Planck, or in a δ-function approximation.

Systematic error of the numerical schemes, as realized in code ROZ-6H, is less than 1%. The total accuracy of calculations is determined by errors of constants from the multigroup system of constants SADCO, and amounts about 30%. Developed algorithm makes it possible to calculate different functionals of radiation field in deep-penetration problems with a high anisotropic scattering.

5 ROZ-W.2, TIME-DEPENDENT DISCRETE-ORDINATES TRANSPORT CODE

Program ROZ-W.2 [6] is to solve transport problem for neutrons, protons, pions, kaons, electrons and gamma, with time dependence of source, for plain, spherical and cylindrical geometries. This program allows one to calculate nonstationary fields of neutral and charged particles in heterogeneous medium including the possibility of fission material inclusions. Various spatial and temporal meshes are used for problems of pulsed source to restore the detailed form of radiation pulse at detection points. The second-order numerical scheme is used for approximation of time derivative. The architecture and algorithms of spatial and energetic operator approximations are identical to those of ROZ-6H.

6 MOSKIT, MONTE-CARLO PROGRAM FOR PARTICLE TRANSPORT IN THE MATTER

A new program MOSKIT, presented here, is developed for solution of n, p, π, K and γ transport equation in a complicated geometry by Monte-Carlo method. The peculiar feature of this code, as compared with analogous ones, is realization of particle trajectory simulation in a phase space of (X, Y, Z, E, θ, φ, i), where variables θ, E, i acquire discrete values only. For this purpose this code uses angular and energy meshes. The particle scattering in the matter is completely described by a transition matrix. The matrix elements are functions of particle type, and of nodes in angular and energy meshes. These determine the discrete distribution of probability density, and are employed to choose particle characteristics after scattering. This method provides effeciency and universality to the code. Energy range and particle sort to be processed by the code are given through the library of constants. The transition matrix for particles is prepared on the base of a group file of constants, produced by SADCO program complex. The code is equiped by a set service tools to simplify input of geometrical and physical data.

7 CONCLUSION

Program complex presented here allows one to calculate transport of neutrons (0.01eV<E<10TeV), protons, pions, kaons (20MeV<E<10TeV) and photons (0.01MeV<E<20MeV) in a one-dimensional geometry with a high accuracy (error less than 30%) by the discrete-ordinates method. It may be used to investigate stationary and nonstationary radiation fields formed behind a high energy accelerator shielding. For solution of complicated three-dimensional problems one can use the Monte-Carlo transport program that provides a satisfactory accuracy.

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