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GEANT4, MCNPX, AND SHIELD CODE COMPARISON CONCERNING RELATIVISTIC HEAVY-ION INTERACTION WITH MATTER

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The NICA complex design aims to provide collider experiments with 4.5×4.5 GeV/nucleon ions up to gold. To ensure proper radiation protection, the precise description of all radiation sources is needed — first, the double differential neutron yields from targets in the middle atomic mass region. For lack of reliable experimental data at such energies, a comparative evaluation of radiation transport codes with different physical models of nucleus–nucleus interaction has been performed. GEANT4, MCNPX, and SHIELD simulations for NICA design purposes are presented.

При проектировании ускорительного комплекса NICA, предназначенного для столкновений ядер золота с энергией $4{,}5 \times 4{,}5$ ГэВ/нукл., необходимо детальное описание всех радиационных источников. В первую очередь это касается двойных дифференциальных выходов вторичных нейтронов из мишеней со средним атомным весом. Надежные экспериментальные данные по взаимодействию с веществом таких ядер отсутствуют. Наиболее достоверная оценка применимости программ транспорта излучений в веществе с различными физическими моделями ядро-ядерных взаимодействий может быть получена путем сравнения между собой результатов расчета. В данной работе представлены результаты сравнения расчетов по программам GEANT4, MCNPX и SHIELD с точки зрения их пригодности при проектировании комплекса NICA.

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During the operation of NICA (the **N**uclotron-Based **I**on **C**ollider F**A**cility at JINR), secondary radiation will be generated along the collider rings, especially at the maximum beam loss locations. The ensuring of radiation protection measures at the collider requires solving a number of crucial problems: the estimation of the main source terms, prognostication of neutron fluence and the effective dose directly behind the shielding and in the environment around the facility, projection of the levels and evolution of induced radioactivity, assurance of all technological elements' radiation hardness, and so on. The reliable collider radiation forecast can be based on the simulation of different effects by Monte Carlo (MC) radiation transport codes, where the projectiles are heavy ions.

Many verifications of a few such multipurpose MC codes (FLUKA, GEATN4, MARS15, MCNPX, PHITS, and SHIELD) were carried out with benchmark experimental data on A–A and A–target interactions for light and intermediate atomic weight projectiles with energies of up to several hundred MeV. At the same time, experimental data on neutron production for primary very heavy ions with an energy of several GeV/nucleon are practically lacking. Therefore, the preliminary choice of a proper code was made by intercomparing FLUKA, GEANT4, and SHIELD simulations with unique experimental data on neutron production in a 1 GeV/nucleon ^{238}U beam interaction with a thick Fe target [1, 2]. As a result, the GEANT4 code was chosen to simulate NICA radiation conditions [3, 4]. Another verification of GEANT4 was performed to predict induced activity in a thick stainless steel and copper targets irradiated with 0.95 GeV/nucleon uranium ions [5].

For lack of experimental data on neutron production in high-energy ion collisions with matter, the mutual conformity of the simulations by the codes with different models of nucleus–nucleus interactions can be a relative criterion of calculation reliability. The main interest is in the comparison of the simulations of the heaviest ions with the energies as for the future NICA collider.

In the GEANT4 code, the Binary Cascade model (BIC) [6] is used to describe nucleus–nucleus collisions. BIC model is valid for ion energies up to 10 GeV/nucleon as opposed to the JQMD code [7] extending to about 3 GeV/nucleon. The SHIELD code combines the Dubna

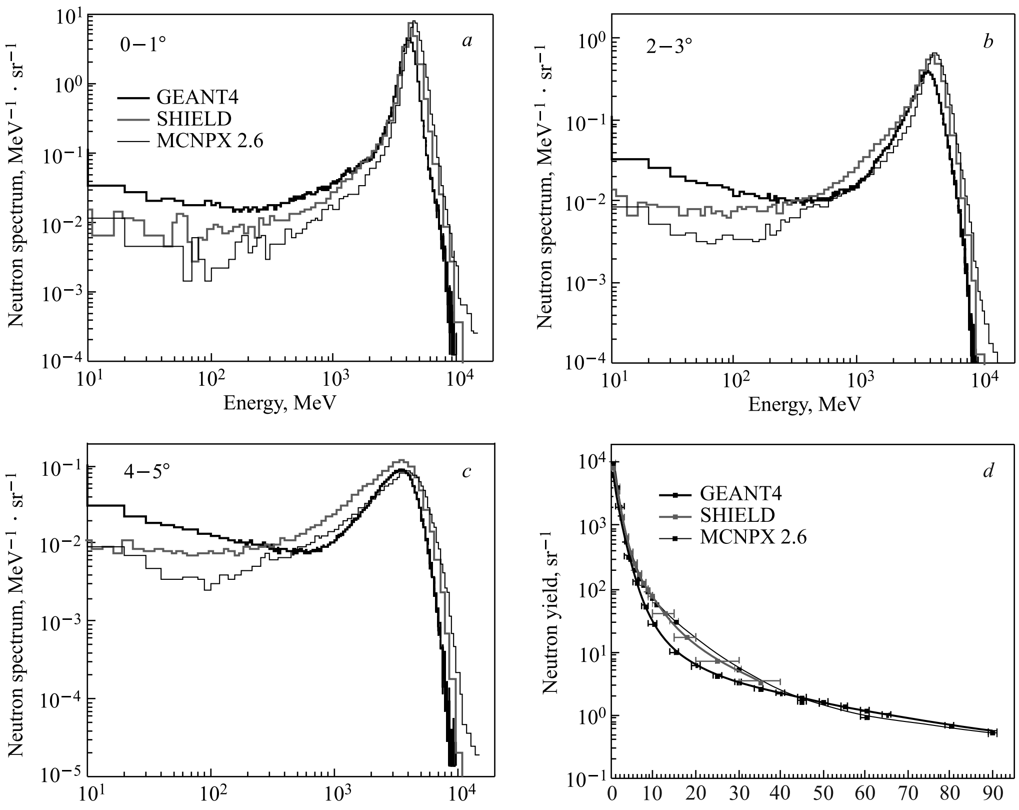

Fig. 1. *a–c*) A comparison of the secondary neutron spectra for the reactions ^{197}Au(4.5 GeV/nucleon) + $^{\rm nat}$Fe simulated by the GEANT4, SHIELD, and MCNPX 2.6 codes. *d*) A comparison of the angular distributions of neutrons for the reactions ^{197}Au(4.5 GeV/nucleon) + $^{\rm nat}$Fe

Cascade Model (DCM) [8] and the independent Quark–Gluon String Model (QGSM) [9, 10] in one MSDM generator. MCNPX 2.6 uses the LAQGSM03.01 [11] high-energy event generator that describes reactions induced by nuclei at incident energies above 1 GeV/nucleon with an improved version [12] of the intranuclear DCM.

The results of comparing double differential neutron and proton yields in the reaction $^{197}\mathrm{Au} + {}^{\mathrm{nat}}\mathrm{Fe}$ within narrow forward cones at a projectile energy of 4.5 GeV/nucleon simulated by GEANT4, SHIELD, and MCNPX 2.6 codes are presented in Fig. 1, *a–c* and in Fig. 2, *a–c*. The calculations were carried out for very thin target and normalized then to one nuclear interaction. There were no errors in the graphs, but the statistics at all calculations were about 1–2% for high-energy bins and about 20–30% in low-energy bins. The angular range is important in terms of the formation of secondary radiation fields within the NICA collider tunnel due to ion beam interaction with ring elements. A comparison of neutron angular distributions is shown in Fig. 1, *d*.

The qualitative agreement between the secondary neutron spectra is satisfactory. In total, the difference between neutron yields per 1 sr for the given angular ranges does not exceed the factor of 1.8 at 0–1° bin even. At greater angles, the distinctions between the total neutron yields are decreased. The forward direction spectra simulated by MCNPX 2.6 are

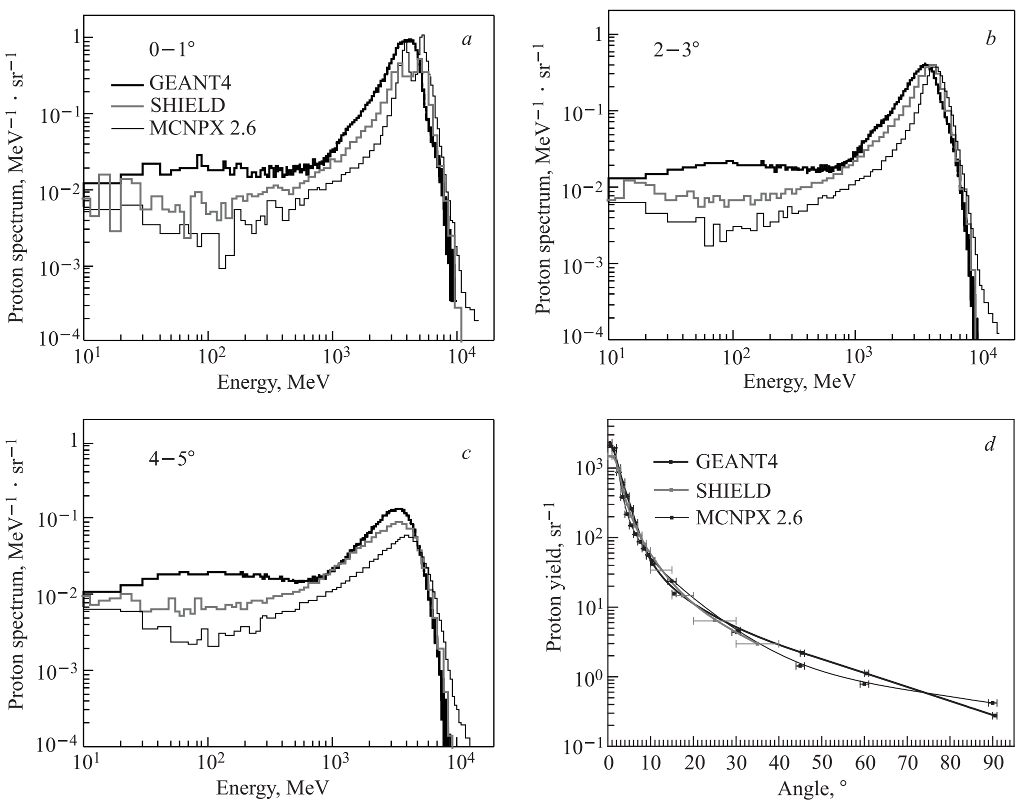

Fig. 2. *a–c*) A comparison of the secondary proton spectra for the reactions ^{197}Au(4.5 GeV/nucleon) + $^{\mathrm{nat}}$Fe simulated by the GEANT4, SHIELD, and MCNPX 2.6 codes. *d*) A comparison of the angular distributions of protons for the reactions ^{197}Au(4.5 GeV/nucleon) + $^{\mathrm{nat}}$Fe

the hardest at high energies and the softest at low and intermediate energies in comparison with simulations by other codes. The largest discrepancy between the angular neutron yield dependences occurs at 5–40°.

Similar spectral and angular distributions of the secondary protons from the reactions ^{197}Au (4.5 GeV/nucleon) $+ ^{\rm nat}$Fe are shown in Fig. 2. On the whole, the differences between the proton spectra are more evident than between the neutron spectra. Though, the difference between the proton yields per 1 sr in the forward angular range also does not exceed the factor of 2. The agreement between the proton yield angular distributions simulated by the codes in the forward hemisphere is quite good.

Summing up the comparison, it is possible to claim that the agreement between the simulations (at least near the forward direction) is quite acceptable for radiation protection purposes. It proves the choice of the GEANT4 code as a reasonable tool for the NICA radiation shielding calculation with the dose reserve factor of 2.

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