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L. Beskrovnaia, B. Florko, M. Paraipan,
N. Sobolevsky[1], G. Timoshenko*

VERIFICATION OF MONTE-CARLO TRANSPORT CODES FLUKA, GEANT4 AND SHIELD FOR RADIATION PROTECTION PURPOSES AT RELATIVISTIC HEAVY-ION ACCELERATORS

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[1]Institute for Nuclear Research RAS, Moscow, Russia
*E-mail: tim@jinr.ru

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Верификация Монте-Карло программ транспорта излучений
в веществе FLUKA, GEANT4 и SHIELD для целей радиационной
безопасности на ускорителях релятивистских тяжелых ядер

Острой проблемой при конструировании радиационных защит на ускорителях тяжелых ядер на энергии частиц до нескольких ГэВ/н является проблема корректного описания источника излучения. Экспериментальные данные по двойным дифференциальным выходам нейтронов из толстой мишени, облучаемой высокоэнергетичными ядрами урана, практически отсутствуют. В настоящее время существует несколько универсальных Монте-Карло транспортных программ, которые могут моделировать взаимодействия с веществом ядер урана. Эти программы используют различные физические модели для расчета ядро-ядерных соударений. По этой причине проверка корректности расчетов по данным программам представляется весьма важной для выбора программы, наиболее пригодной для решения практических задач. В настоящей работе приводятся результаты сравнения расчетов по программам FLUKA, GEANT4 и SHIELD с экспериментальными данными по генерации нейтронов при взаимодействии пучка ядер ^{238}U с энергией 1 ГэВ/н с толстой железной мишенью.

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Verification of Monte-Carlo Transport Codes FLUKA, GEANT4
and SHIELD for Radiation Protection Purposes at Relativistic
Heavy-Ion Accelerators

The crucial problem for radiation shielding design at heavy-ion accelerator facilities with beam energies to several GeV/n is the source term problem. Experimental data on double differential neutron yields from thick target irradiated with high-energy uranium nuclei are lacking. At present, there are not many Monte-Carlo multipurpose codes that can work with primary high-energy uranium nuclei. These codes use different physical models for simulation nucleus–nucleus reactions. Therefore, verification of the codes with available experimental data is very important for selection of the most reliable code for practical tasks. This paper presents comparisons of the FLUKA, GEANT4 and SHIELD codes simulations with the experimental data on neutron production at 1 GeV/n ^{238}U beam interaction with thick Fe target.

The investigation has been performed at the Laboratory of Radiation Biology, JINR.

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An essential condition of the NICA (Nuclotron-based Ion Collider facility) project implementation is to design an appropriate radiation shielding, primarily the upper shielding of the Nuclotron tunnel. The shielding design needs exact knowledge of the source term that is determined in the nucleus–nucleus interaction of the ^{238}U beam (3.5 GeV/u) with the Nuclotron chamber, cooling and magnetic equipment. In the shielding calculation all this equipment is usually modeled by a thick target (local or lengthy) with a certain thickness and material. The crucial radiation component determining the shielding thickness is high-energy secondary neutrons.

Unfortunately, there is a lack of experimental data about neutron emission from the interaction of relativistic uranium nuclei with thick metal target with average atomic weight. Only one experiment is known at GSI where the neutron spectra from thick iron target irradiated with 1 GeV/n ^{238}U nuclei were measured by a time-of-flight technique with different neutron detectors [1, 2]. Double differential neutron yields in the angular range $0-90^{\circ}$ with respect to the ion beam were measured by a BaF_2 detector; at the small angles $0-15^{\circ}$ a large area neutron detector (LAND) was also employed. It is significant that both techniques gave serious differences in the forward direction. Moreover, the experimental data with the BaF_2 detector and ^{238}U may raise some doubts owing to serious discrepancy with other experiment using a BaF_2 detector and a 400 MeV/n carbon beam in the data of experiment in [3]. The BaF_2 data for a GSI 400 MeV/n carbon beam hitting a graphite target indicate at 90° a high-energy neutron yield up to one decade of magnitude larger at the end of the spectrum in comparison with [3]. Therefore, we are aware of the fact that the GSI experiment with 1 GeV/n uranium beam is not a benchmark, but is rather a first measurement.

At present, not many Monte-Carlo universal transport codes can be used for heavy-ion accelerator shielding calculation (FLUKA [4, 5], GEANT4 [6], PHITS [7], SHIELD [8], MARS [9]). Recently, the first verification of the FLUKA and PHITS codes with aforementioned experiment has been done [1]. Comparison of the measured neutron spectra with FLUKA code calculations has shown the considerable underestimation of the simulation at large emission angles. Since this angular range is very important for the design of the upper shielding of the Nuclotron tunnel, another comparison of the experiment with neutron yields simulated by the GEANT4 code with the FRITIOF/RQMD models [6] has been carried out. Neutron yields simulations by the FLUKA code with RQMD [10] and DPMJET [11] models and by SHIELD with DCM, QGSM, SMM models [12–14] have also been performed.

The results of the FLUKA, GEANT4 and SHIELD verification are presented in Figs. 1–6. The angular bin in these simulations is 1°. The calculation statistics (not shown) are quite satisfactory for GEANT4 and SHIELD at all angles (more than 10^5 initial events), but are slightly worse for FLUKA. Our simulations by FLUKA are very close to analogous calculations from [1]. As regards to the small angles of the secondary neutron emission from the target, the FLUKA and SHIELD simulations are in better agreement with the LAND experimental data than the GEANT4 simulations. The other situation is at large emission angles. At 50° and 90° the FLUKA calculations greatly underestimate the high-energy

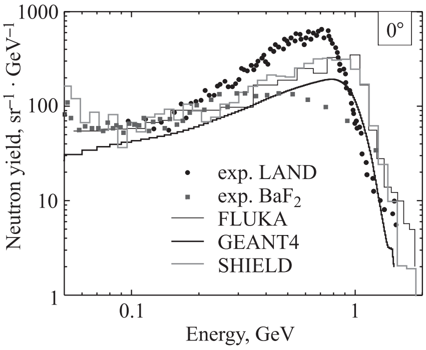

Fig. 1. Double differential neutron yield at 0° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

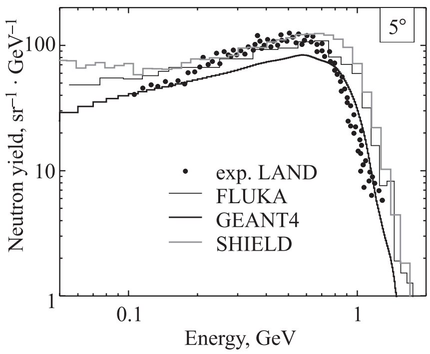

Fig. 2. Double differential neutron yield at 5° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

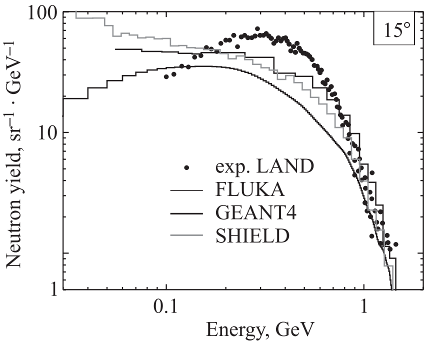

Fig. 3. Double differential neutron yield at 15° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

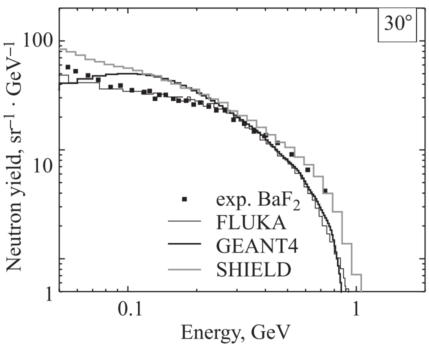

Fig. 4. Double differential neutron yield at 30° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

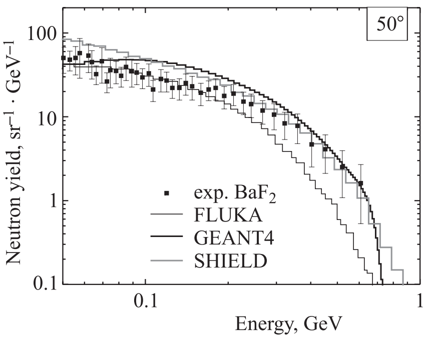

Fig. 5. Double differential neutron yield at 50° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

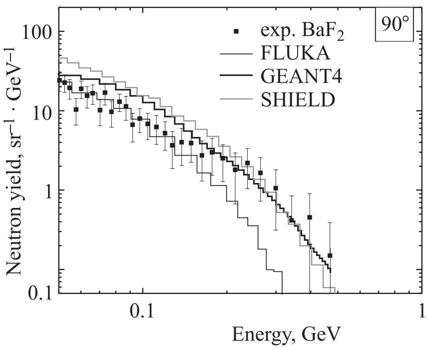

Fig. 6. Double differential neutron yield at 90° from a thick iron target induced by ^{238}U nucleus with energy 1 GeV/n

parts of the BaF_2 neutron spectra in spite of the large experimental errors. The GEANT4 and SHIELD simulations at these angles demonstrate better agreement with the experiment.

In view of the final objective of codes verification it is essential to follow the practical principle of radiation protection (overestimation is preferable to underestimation). For this reason we cannot now take into account the doubts concerning the only GSI experiment with BaF_2 detector even if its results are crude. On the other hand, we have no doubt that such a verification can not be the basis for preference of any code in other situations.

Thus, the Monte-Carlo calculation with FLUKA can be used for the NICA shielding design for estimation of the beam stopper thickness in the beam direction, whereas the GEANT4 code is better for design of the Nuclotron upper shielding, shielding of beam transport channel and transverse size of the beam stopper. The SHIELD code is good for both cases. Unfortunately, the SHIELD code is little-suited for calculation of hadrons transport through the thick shielding because of the long period of calculation. However, this code can be soon modernized to avoid this limitation.

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Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/