GEANT4 Simulation of Hadronic Interactions at 8 – 10 GeV/c: Response to the HARP-CDP Group

V.V. Uzhinsky[1], J. Apostolakis[2], G. Folger[2], V.N. Ivanchenko[3], M.V. Kossov[4], D.H. Wright[5]

[1]e-mail: uzhinsky@jinr.ru, Laboratory of Information Technologies, JINR, Dubna; [2]CERN, Geneva; [3]Ecoanalytica. MSU, Moscow; [4]ITEP, Moscow; [5]SLAC, NAL, Stanford, California

In 2008 the HARP-CDP group published simulation results on hadron interactions with beryllium nuclei at energies below 10 GeV [1]. These results were obtained with the help of the GEANT4 Monte Carlo event generators [2]. Problems were emphasized in two-dimensional plots of P_L vs. P_T of the produced low energy secondary particles. Significant irregularities, such as the peaks and valleys shown in Fig. 1a, were not seen in the experimental data[1]. Because the GEANT3 and GEANT4 toolkits are widely used by experimental collaborations for design and analysis of various detectors, these results require explanation, and programming errors, where found, in the GEANT4 code must be located and fixed. Below we show that these irregularities are connected with incomplete or un-optimized solutions of well-known problems.

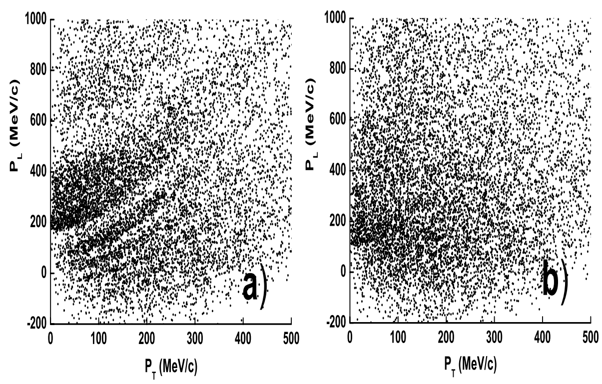

Figure 1: Two-dimensional distribution of π^+ mesons in the four-body final state generated by 8 GeV/c pp-interactions before (a) and after (b) the bug fix.

The HARP-CDP experimental group studied particle production in the interactions of π^+- and π^--mesons at a laboratory momentum of 8.0 GeV/c, and protons at a laboratory momentum of 8.9 GeV/c, with beryllium nuclei. They compared their experimental data to the results of simulations using GEANT4 version 9.1. The simulation results for the secondary mesons using the LHEP, QGSC and QGSP Physics Lists were described in Ref. [1] as unacceptable. All of these Physics Lists use the low energy parameterized model (LEP). Thus, the source of the problem is in the model.

[1]The dense regions in Fig. 1a correspond to the peaks, and the empty regions correspond to the valleys.

It is natural to assume that the observed peak-and-valley effect is caused by the nuclear environment of the multi-particle production process. In this case, it must be absent in hadron-nucleon interactions, and become more important as the target mass increases. Even though the beryllium nucleus is light, the hypothesis must be checked.

The calculations we present in Fig. 1a show that the structure is present in hadron-hadron interactions at projectile energies below 10 GeV when we choose the GEANT4 low energy parameterized model (LEP). It disappears at higher energies when the QGSP_BERT physics List is chosen, which is the preferred list of the major LHC experiments. Fig. 1a shows the two-dimensional distribution of π^+ mesons within four-particle states resulting from pp-interactions at 8 GeV/c. Some structure clearly appears here, as it does in the π^0 distribution. The corresponding distributions for protons and neutrons have no such structure. The other low energy models, the Bertini model and the binary cascade model, do not predict any structures.

The location of the ridges in the Fig. 1a allows to suggest that they are caused by the two-body kinematical decay of resonances with no smearing of the longitudinal and transverse momenta. However, this must be rejected because the old Gheisha [3] model, from which the GEANT4 model is translated, does not consider the production of mesonic and baryonic resonances. Only the production of π mesons and nucleons is taken into account. Thus we have to go deeper into the Gheisha model. Now it can be easily done because "the effect" is presented in hadron-hadron interactions.

At a given interaction energy, the Gheisha model first determines the multiplicity of secondary particles. After that, each particle is assigned a transverse momentum, P_T. It is assumed that the distribution of the momenta has the form $dW \sim P_T exp(-BP_T^2)\ dP_T$. In the following, the longitudinal momenta are sampled in the center-of-mass system of the colliding particles. It is clear from Fig. 1a, that the particles' P_T-distribution has no special features, and obeys the exponential law. The longitudinal momentum (P_L) distribution and the corresponding Feynman x (x_F) distribution have irregularities at a fixed P_T. In the model (see subroutine *genxpt.f* in the Gheisha code) the values of x_F are sampled discretely rather than continuously. There are 20 such discrete values, leading to the irregular structure in the two-dimensional distributions.

The method is used in the toolkits for simulations of the hadron-nucleus interactions at low energies. Thus the structure exists for the collisions of hadrons with heavy nuclei as well as light nuclei. The average multiplicities of the produced hadrons are reproduced quite well, though the P_L-P_T spectra have the layer structure which is strongly distorted for interactions within a substance. We believe that this drawback is not reflected in most practical applications where thick targets are used.

The low energy model, LEP, was applied in most of the Physics Lists used by the group for projectile mesons with momentum 8.0 GeV/c. The high energy FTF model was used in FTFC, FTFP and FTFP_BERT Physics Lists only. The Bertini cascade model was used in the QBBC and QGSP_BERT lists. The problems were observed for LHEP, LHEP_PRECO_HP, QGSC, QGS_BIC, QGSP and QGSP_BIC Physics Lists. All of them use the low energy parameterized model (LEP). Thus, the problems are connected with the same drawback of the LEP model.

The LEP model was recently improved by sampling x_F from a smooth distribution instead of a discrete one. It gives an acceptable result as shown in Fig. 1b. The other low energy models of Geant4 , the binary cascade model (BIC) and the Bertini model (BERT), do not predict any structure in the P_L-P_T spectra for the secondary mesons.

We have checked that the high energy quark-gluon string (QGS) and Fritiof (FTF) models by themselves do not predict structure in the P_L-P_T distributions of mesons. Such structure could only appear by considering the low energy secondaries of the initial interaction which cascade through the nucleus.

The low energy models of Geant4 (LEP, BERT, BIC) do not predict any structure for the proton spectra in the hadron-nucleus interactions. Unacceptable results, narrow peaks for secondary low energy protons near $\theta \sim 70^o$, were reported by the HARP-CDP group for the QBBC, FTFC, FTFP, and FTFP_BERT Physics Lists. The authors supposed that the results are connected with "the kinematics of elastic scattering of the incoming particle with a proton at rest". We check the hypothesis simulating p-Be interactions without a consideration of inelastic scatterings of the projectile in the nucleus, and without Fermi motion of the target nucleons. The corresponding distribution is presented in Fig. 2a. As seen, the figure shows a well-defined curve corresponding to the kinematics of two-body elastic scattering. The group of points near the origin is due to evaporated nucleons.

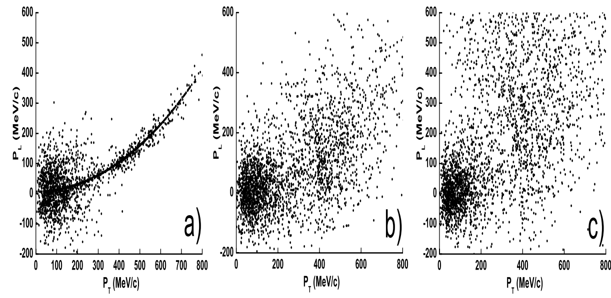

Figure 2: Proton distribution in the pBe-interactions at 8 GeV/c for the cases of: a) elastic scatterings only without Fermi motion; b) elastic scatterings with Fermi motion; c) elastic and inelastic scatterings with Fermi motion. The calculations were performed with the Geant4 FTFB Physics List.

In the second stage of our investigation, the Fermi motion was added (see Fig. 2b). It is natural that the curve seen in Fig. 2a should now be diffused. Usually the nuclear nucleons are assigned a Fermi momentum in a Monte Carlo calculation. Because the nucleons must be bound in the nucleus, they are not on the mass-shell. This means that the nucleons are given a mass $m^* = m_N - P_F^2/2m_N - 2\epsilon$, where m_N is the nucleon mass in the free state, and ϵ is the nuclear binding energy per nucleon. The nucleons return to the mass-shell during the subsequent interactions of the projectile. The projectile momentum is thus decreased by the quantity $\Delta P_L \simeq m_N - m^*$, and the target nucleon receives the corresponding fraction of the longitudinal momentum. This shift along the P_L-axis is small and not easily seen in Fig. 2b. Inelastic interactions are added in the third stage (see Fig. 2c). The smoothness of the plot depends, obviously, on the assumed elastic and inelastic cross sections, and also on the magnitude of the Fermi momentum. Once all of these effects are taken into account, there is practically no structure in the P_L-P_T spectra.

The elastic scatterings of a projectile on the nuclear nucleons (quasi-elastic scatterings) were introduced into the Geant4 high energy hadronic models in order to improve the agreement of simulated shower shapes with those measured in LHC test-beam experiments. This resulted in a significant improvement, although some questions remain. The first question has to do with the influence of the elastic scatterings on a projectile. This was considered many years ago by R.J. Glauber and G. Matthiae [4], and beautiful results were obtained for p-A interactions at 19.2 and 24 GeV/c [5], [6] by taking this into account. The spectra of nucleons ejected from the nucleus were not considered at that time. Thus it was a second question for us - how to simulate the spectra of low energy ejected nucleons?

The Fermi motion was neglected in Geant4 version 9.1 and this was reflected in the proton spectra observed by the HARP-CDP group. This omission was corrected in the last version of the Geant4 (release 9.2).

Accounting for the Fermi motion of the nucleon ejected in quasi-elastic scattering is not a simple one. According to the Glauber theory, one has to write exact wave functions of all the possible states of a nucleus. This can only be done for hadron-deuteron scattering because the deuteron has no bound excited states. For heavy nuclei, one has to use a phenomenological approach like that presented above.

In addition, we note that there is no unique method of accounting for the Fermi motion in inelastic hadron-nucleus interactions which is completely correct from a theoretical point of view. Such a method would be equivalent to a solution of the many-body problem of nuclear reactions. Thus all practical methods can be criticized.

In program implementation now we ascribe the Fermi momentum to the involved target nucleons, and allow them to take part in the following intranuclear cascading. The analogous method is applied in many other high energy Monte Carlo generators. We have also introduced Fermi motion in other Monte Carlo codes for the 9.2 release of Geant4 .

Looking carefully at Fig. 2c, one can see a depletion region restricted by the condition $100 \leq \sqrt{P_T^2 + P_L^2} \leq 400$ (MeV/c). The upper bound (400 MeV/c) corresponds to protons of 80 MeV kinetic energy. It is assumed in the Geant4 pre-compound model (PRECO) of the nuclear residual excitation energy calculation that nucleons with energies below 80 MeV are captured by the residual nucleus, thus removing nucleons from the plot. The lower bound of the region depends on the assumed excitation energy of the nuclear residual. Thus, the coupling of high- and low-energy particle cascades in nuclei can bring, in principle, some irregularities in the P_L-P_T spectra.

The HARP-CDP group has performed important and useful tests of several Geant4 models and identified obvious problems in secondary particle generation. We have shown that these problems are not due to faults in the physical models used in Geant4 , but are in fact caused by incorrect programming solutions to problems inherited from very early versions of the code. The defects have been repaired in recent versions of the Geant4 toolkit. We have checked that the identified defects have no effect on the simulation of calorimeter detectors, and we believe that most other practical applications will also not be affected. We point out some remaining theoretical problems, but none of these pertain to the present tests.

The authors thank the HARP-CDP group for bringing these problems to our attention. They are grateful to Alberto Ribon for calculations of calorimeter responses.

References

[1] HARP-CDP group (A. Bolshakova et al.), Eur. Phys. J. **C56** (2008) 323; hep-exp/0804.3013.

[2] S. Agostinelli et al. (Geant4 collaboration), NIM **A506** (2003) 250.

J. Allison et al. (Geant4 collaboration), IEEE Trans. Nucl. Sci. **53** (2006) 270.

[3] H. Fesefeld, *Simulation of Hadronic Showers, Physics and Applications*, Technical Report PITHA 85-02, 1985, Aachen, Germany,

[4] R.J. Glauber and G. Matthiae, Nucl. Phys. **B21** (1970) 135.

[5] O. Kofoed-Hansen, Nucl. Phys. **B54** (1973) 42.

[6] G.B. Alaverdian, A.S. Pak, A.V. Tarasov, Ch. Tseren, Yad. Fiz. **31** (1980) 776 (Sov. J. Nucl. Phys. **31** (1980) 402).