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HEPWEB — **WEB**-PORTAL FOR MONTE CARLO SIMULATIONS IN HIGH-ENERGY PHYSICS

Александров Е. И. и др. E10-2011-126
HEPWEB — WEB-портал генераторов Монте-Карло
в физике высоких энергий

Создана WEB-страница, позволяющая производить наиболее популярные расчеты в физике высоких энергий — расчеты сечений адрон-адронных, адрон-ядерных и ядро-ядерных взаимодействий и расчеты характеристик вторичных частиц в указанных взаимодействиях с использованием программ-генераторов. Список программ-генераторов включает модель внутриядерного каскада (CASCADE), модель FRITIOF, модель ультрарелятивистской квантовой молекулярной динамики (UrQMD), модель HIJING и модель AMPT.

Задание характеристик сталкивающихся частиц (энергии соударения, массовых чисел и зарядов ядер, прицельного параметра взаимодействий, числа необходимых соударений и некоторых параметров моделей) осуществляется с использованием WEB-интерфейса. Запрос обрабатывается на сервере, и результаты работы представляются пользователю в виде WEB-страницы.

Работа выполнена в Лаборатории информационных технологий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 2011

Alexandrov E. I. et al. E10-2011-126
HEPWEB — WEB-Portal for Monte Carlo Simulations
in High-Energy Physics

A WEB-portal HepWeb allows users to perform the most popular calculations in high-energy physics — calculations of hadron–hadron, hadron–nucleus, and nucleus–nucleus interaction cross sections as well as calculations of secondary-particle characteristics in the interactions using Monte Carlo event generators. The list of the generators includes Dubna version of the intranuclear cascade model (CASCADE), FRITIOF model, ultrarelativistic quantum molecular dynamics model (UrQMD), HIJING model, and AMPT model.

Setting up the colliding particles/nucleus properties (collision energy, mass numbers and charges of nuclei, impact parameters of interactions, and number of generated events) is realized by a WEB-interface. A query is processed by a server, and results are presented to the user as a WEB-page.

Short descriptions of the installed generators, the WEB-interface implementation and the server operation are given.

The investigation has been performed at the Laboratory of Information Technologies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2011

INTRODUCTION

There are some servers for on-line calculations in particle physics and nuclear physics. The most advanced one is an NRV server (Nuclear Reactions Video) [1] at the Joint Institute for Nuclear Research (JINR, Dubna, Russia). The NRV is a system of management and graphical representation of nuclear data and computer simulations of low-energy nuclear dynamics. It consists of a complete and renewed nuclear database and well-known theoretical models of low-energy nuclear reactions altogether forming the "low-energy nuclear knowledge base". The NRV solves two main problems: fast search for and visualization of experimental data on nuclear structure and nuclear reactions, and on-line application of commonly used models of nuclear dynamics. The JavaScript technology is used for forming and managing the nuclear database, and running some nuclear models. Thus results are directly accessible through the net with any computer having a WEB-browser supported Java codes.

JetWeb server (a WWW interface and database for Monte Carlo tuning and validation) was created in 2002 [2]. The aim of the project was "to allow rapid and reproducible comparisons to be made between detailed measurements at high-energy physics colliders and general physics simulation packages". The "general" purpose Monte-Carlo simulation programs were PYTHIA [3] and HERWIG [4]. Only HERA, LEP, and Tevatron experimental data were included.

At the centre of JetWeb there was a Java object model containing the properties and interactions of Models, Papers, Plots, and Fits. The data underlying this model were stored in the JetWeb database — a MySQL database. A "Model" completely specified a unique generator, version and set of parameters. A "Paper" encapsulated the measured data from a single publication and was associated with measured cross sections. A "Fit" contained the results of a comparison between real data and predictions of a specific model. The data and MC results were processed with the help of HZTOOL package [5], and output histograms in the form of XML files in the Java Analysis Studio (JAS) [6] plotML DTD format [7] were written. The plotML data were converted into the Java object model, and written to the JetWeb database via JDBC [8]. The user accessed JetWeb via the WEB-interface, which consisted of Java servlets run on a Tomcat [9] server, delivering HTML pages written using the JetWeb HTMLWriter

facility (ucl.hep.jetweb.html package). The servlets accessed the JetWeb database via the JDBC calls encapsulated within the Java object model.

If a fit requested by the user were done before, the static webpages should be searched for and sent to the user. If there were no results stored for the user's specified set of parameters, a new job request with the required parameters should be generated.

Now JetWeb does not operate. It seems to us that the matter is that the HZTOOL library of the experimental data and corresponding FORTRAN routines has not been update for a long time. As the data set was restricted, all calculations were performed quite fast, and there was no need and possibilities to make new ones.

We think that the main idea of the JetWeb server was quite interesting, and we use it at the creation of our server — the HepWeb server.

The other interesting server is "Q_T resummation portal at Michigan State University (http://hep.pa.msu.edu/wwwlegacy/) created in 2003 [10]. It allows one to plot transverse momentum distributions for cross sections of several particle reactions. The following processes are implemented there:

- Massive vector boson production — $pp \to W^{\pm}X$, $pp \to Z^0X$;
- Photon pair production — $pp \to \gamma\gamma X$;
- Z-boson pair production — $pp \to Z^0Z^0X$;
- SM Higgs boson production — $pp \to H^0X$.

The output figure shows distributions $d\sigma/dQ^2dydq_T$ for the production of on-shell particles (or pairs of on-shell particles in the case of the $\gamma\gamma$ and ZZ production) with specified invariant mass Q, rapidity y, and transverse momentum q_T in the lab frame (the center-of-mass frame of the hadron beams). A user can obtain resummed, fixed-order and asymptotic cross sections. Details of the program implementation are unknown for us.

In Sec. 1 below we consider tasks of on-line calculations and formulate the aim of our project. A description of how to use our server for Monte Carlo calculations in CASCADE, FRITIOF, UrQMD, and HIJING models is given in Sec. 2. Technical details of the portal implementation are considered in Sec. 3. Appendices present short descriptions of the installed generators.

1. TASK OF ON-LINE CALCULATIONS

Monte Carlo event generators play a very important role in high-energy physics. One can mark the following areas of their application:

1. Pragmatic or practical tasks — development of new or upgrade of old experimental setups to study some processes/interactions, design of detectors, Monte Carlo simulation of the detector responses, and so on. Event generators applied at these should have fast operation speed, stability of work, and a rough

reproduction of previous experimental results. As an example, let us mention applications of the UrQMD model [11, 12] for the development of detectors for research on nucleus–nucleus interactions (CBM Collaboration [13]), and detectors for investigation of antiproton–proton annihilations (PANDA Collaboration [14]) at future GSI accelerators. The RQMD [15] and HIJING [16, 17] models have been used for analogous purposes for RHIC experiments. The well-known Geant4 package [18] is widely used to simulate various installations.

2. Analysis of new experimental data and planning of new investigations — they include comparison of new data with previous data and model predictions. As a rule, the new data do not agree with model predictions, so some questions arise in this regard: whether all special features of the setup have been taken into account; whether they are free of methodical errors; whether the theoretical models are used correctly; whether the model parameters set is right; whether the discrepancy between the experimental data and model predictions is of systematical character; whether the discrepancy was observed in previous experiments; whether the discrepancy was considered as an evidence of a new physical effect, and so on. They are solved differently, and often it is quite difficult to use event generators too often. The generators should have a flexibility in parameters variation and physical scenario, as well as a sufficient physical meaning of the parameters.

Another situation takes place at new research planning. The first question asked by experimentalists is related to the load of the setup by ordinary background processes. The second deals with the radiation condition of the experiment. The third question asks about the admixture of the background processes in the phenomenon under study, and how it can be damped, and so on. Clearly, experimentalists prefer to use well-approbated and well-recommended models for their estimations. Here one cannot avoid a study of model application experience. As a rule, there is no time enough to do it. Thus, experimental collaborations attract the authors of the models or use authors variants of model code to solve the questions. As an example, let us point out on the estimations of secondary particles multiplicity in central gold–gold interactions obtained by CBM Collaboration [19], and the estimations of background processes intensities by the PANDA Collaboration [20].

3. Scientific or cognition aims only — search for new effects or phenomena on the base of analysis of a discrepancy between experimental data and model predictions. One uses the fact that Monte Carlo models are a synthesis of existing notions about process mechanics. Thus, the discovered discrepancy can be considered as an evidence of our insufficient understanding or else as an evidence of new effects. For example, the discrepancy between experimental data and intranuclear cascade model calculations growing with the collision energy rising led in its time to appearing of a very important conception for high-energy physics — ”formation time of secondary particle”.

The final aim of all the efforts is creation of a theory of processes that could predict effects with any predetermined exactness. As there are only few such theories, the aim is reformulated — creation of a theory or a model predicting observable effects with specified exactness. Determination of the exactness is a special additional task.

The philosophical aspect of the scientific research — the «cognition of Good wisdom», is out of the scope of our consideration.

The aim of this work is to create a WEB-portal which allows one to perform calculations in the second stream.

Though the variety of tasks of the second stream is quite bright, one can select out some common tasks. We think, a user can be interested first of all in global properties of interactions such as interaction cross sections, charged-particle multiplicity distributions, momentum, angular and energy distributions of particles. There is a quite defined need in theoretical calculations of impact parameter distributions, multiplicity distributions of intranuclear collisions, and multiplicities of wounded nucleons. It is desirable for checking of a model quality to know whether energy, momentum, baryon number, lepton number and so on are saved in the model or not.

At high energies, total, inelastic and diffraction cross sections are usually calculated in the Glauber approach. The reggeon theory can be used also for the same aim. All of the possibilities are offered by our server. There is a possibility in the Glauber approximation of calculating impact parameter distributions, multiplicity distributions of intranuclear collisions, and multiplicities of wounded nucleons.

The most easiest way to calculate the inclusive and global properties of interactions is utilization of event generator programs. There are a lot of event generators especially at low and intermediate energies which are of great practical interests. Most of them are not accessible. It is impossible to review the left part of them. At high energies a set of the generators is not so large. A list of most actual ones is quite restricted. At energies below 10 GeV/nucleon various variants of intranuclear cascade model are very popular. We have installed at out server the variant of CASCADE code [21] quite well known in JINR. At high energies the FRITIOF model [22] was applied quite well in the past. At present time the ultrarelativistic quantum molecular dynamics model (UrQMD [11, 12]) is applied very often. At superhigh energies, the HIJING model [16, 17], PYTHIA [3], and HERWIG [4] models are utilized. The PYTHIA and HERWIG can be applied only for simulation of elementary-particles interactions. In order to simulate nucleus–nucleus interactions most actual now, we have installed at our server the FRITIOF, UrQMD, and HIJING models. The other models will be included in future whether according to user wishes, or mastering of new codes.

The models selected by us are quite well documented for experienced user as a rule. Though we think that most of the potential users use the model episo-

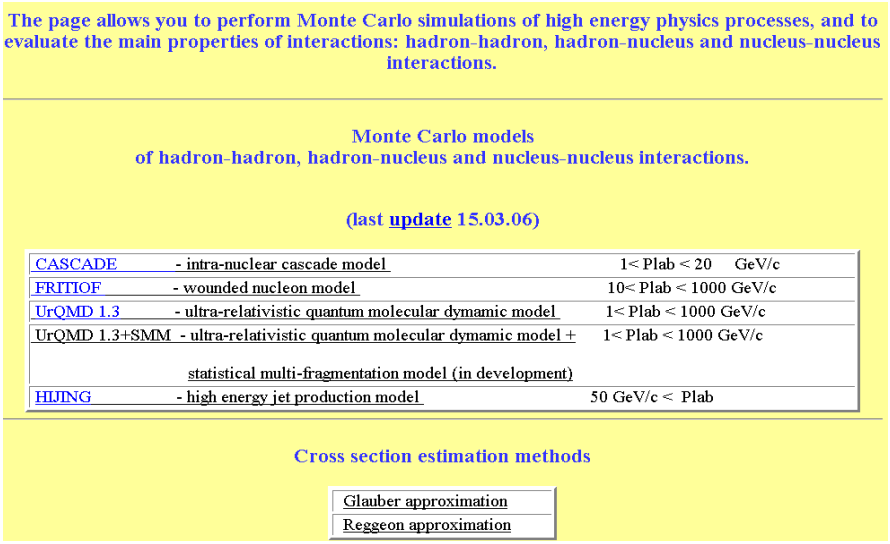

Fig. 1. View of the main page

dically. For them we have created a simplified access to the generators using WEB-based interface.

The main page of the portal looks like it is presented in Fig. 1. The address in INTERNET is: http://hepweb.jinr.ru/

2. USER GUIDE

2.1. Cascade Evaporation Model (CASCADE). The page presented in Fig. 2 gives a user a possibility to calculate properties of interactions using well-known cascade-evaporation model [23–28]. A short description of the model is provided by the page also. The user should set up mass numbers and charges of colliding nuclei, an interval for the impact parameter sampling, a momentum of a projectile nucleus per nucleon in the target nucleus rest frame, a number of generated events, and run the calculation process pushing "Get Results" button. All of these are prompted by an interface presented in Fig. 2.

If the user is going to study hadron–nucleus interactions, he/she has to choose in the "Projectile" list a needed item. The user should obligatory set up a mass number and a charge of the hadron. The mass number is treated in the case as a number of particles in a projectile. Thus it must be equal to one.

If the user is going to study minimal bias interactions, he/she can use the following consideration for a choosing of the impact parameter interval. The radius of a nucleus with mass number A is near to the value $R_A \sim 1.2\ A^{1/3}$ (fm). Thus for interactions of nuclei with mass numbers P and T, the maximum impact

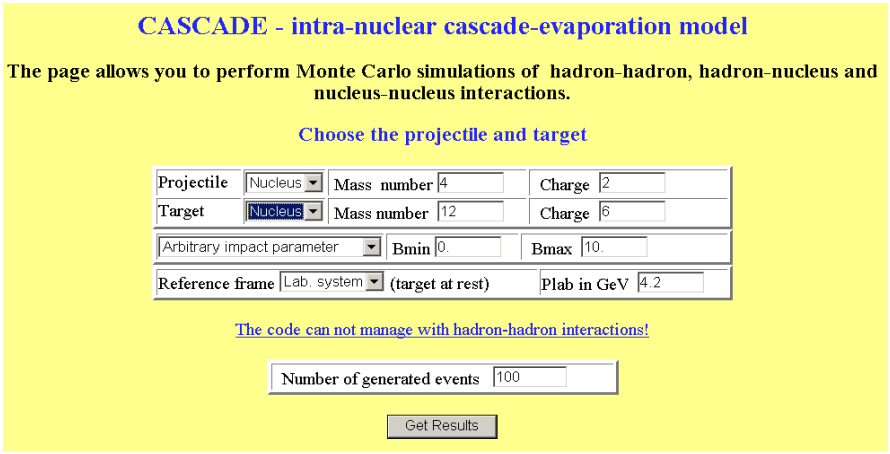

Fig. 2. View of the CASCADE page

parameter can be estimated as $R_P + R_T + 2$ (fm), «2» represents a double radius of NN interactions. The minimal value of the impact parameter is obviously equal in this case to 0.

For a projectile hadron the user can set up R_P to 1 (fm) (nucleon radius).

If you know experimental cross section of the interactions, you can estimate the maximum value of the impact parameter as $\sqrt{\sigma_{\rm exp}/\pi}$ (fm).

In other cases you should undertake additional consideration. A Glauber cross section calculations can be useful for you at this (see below).

If you set up a small number of events and are interested in light nuclei interactions, the results can be obtained quite fast. They will be presented on the page described below.

If your calculations require a lot of time, the view of the page does not change immediately. This means that your task is put in a queue for execution, or is executing now. In the following you have two possibilities: to be at the page refreshing it periodically until the results will be ready, or left the page and turn to your busy.

The results of your task execution will be stored in a database. To reach an access to them in a new connection you should set up one more just the same parameters of the task (mass numbers and charges of nuclei, impact parameter interval, momentum of the projectile, number of events), and should run process as it was described before. The server looks first of all through the database. If the corresponding results are in the database, they will be presented on a new page*.

*Unlike the other portals we do not undertake any efforts to identify users and their tasks. We are thinking that all calculations are unique ones, and their results are important.

Fig. 3. View of the Results page

The calculation results are presented on a page, a view of which is given in Fig. 3. In the upper part of the page, interaction parameters given by a user are presented. After that, a list of calculated interaction characteristics follows. At clicking on an item of the list, an additional window will be opened with a graphical representation of a characteristic. The page gives you a possibility to download the results as a ROOT files.

The version of the cascade-evaporation model developed by Zh.Zh. Musulmanbekov [21] is used at the calculations. A short description of the model extracted from [29] can be found at the CASCADE page.

2.2. FRITIOF Model. A page presented in Fig. 4 gives you a possibility to calculate properties of interactions using the famous FRITIOF model [22]. The code of the model was essentially modified by V. V. Uzhinsky [30]: calculations of cross sections and a sampling of interacting nucleons within the Glauber approximation were added; a unit for a simulation of the nuclear destruction at the fast stage of interactions (the reggeon nuclear destruction model [31]) was added also; the evaporation of nuclear residues was taken into account and so on. Most of the changes are described in [29]. An extraction from the paper [29] related to the model is presented on the page.

To run the simulation process you should set up:

• Mass numbers and charges of colliding nuclei, or choose a projectile particle from a pop-up menu (in the case arbitrary mass and charge are needed also);

• If you are interested in the minimal bias interactions, miss the next line. In other case, choose from a pop-up menu the item — "Impact parameter in

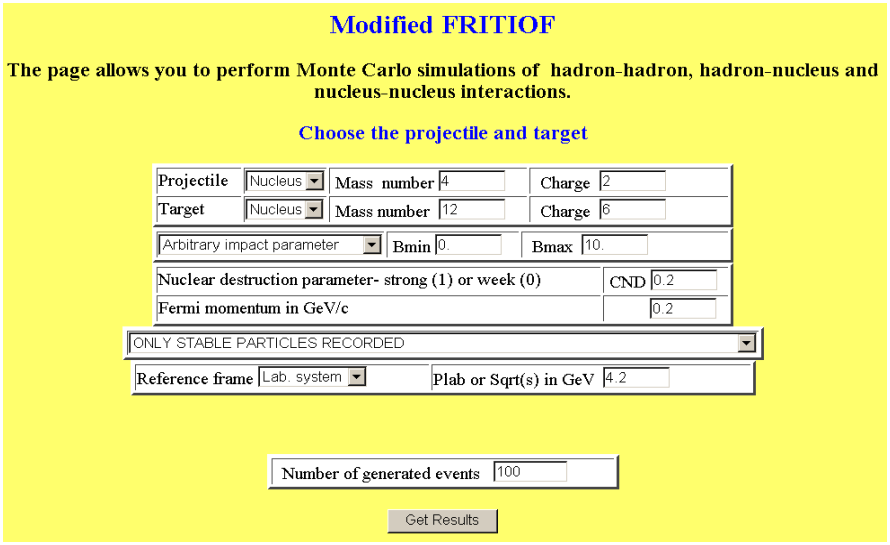

Fig. 4. View of the FRITIOF page

the range", and set up minimal and maximal values of the interaction impact parameter. They must be meaningful, see the previous section.

• We do not recommend to change the item — "Nuclear destruction parameter", without a special need. It allows one to variate the nuclear destruction power at the fast stage of interactions. The prompted value is determined at an analysis of heavy nuclei interactions. For light nuclei interactions it can be changed to 1.

• The item — "Fermi momentum", allows you to fit the Fermi momentum for a description, for example, of the spectator fragment spectra.

• The following pop-up menu gives you a possibility to order what to do with unstable particles at the end of the simulation of the fast stage of interactions.

• Particle characteristics can be calculated in the laboratory system, or in the centre-of-mass system. Depending on your choice, set up a momentum per nucleon of the projectile nucleus, or the corresponding energy of the NN interactions.

• It is natural that you should set up a number of the generated events.

• At the end of your typing, click on the button — "Get Results".

Calculated characteristics will be presented as it was described before.

2.3. The Ultrarelativistic Quantum Molecular Dynamics Model (UrQMD). The page presented in Fig. 5 gives you an opportunity to calculate the interaction characteristics using UrQMD model [11, 12]. Changes, made in the original code of the model, are described in detail in [32].

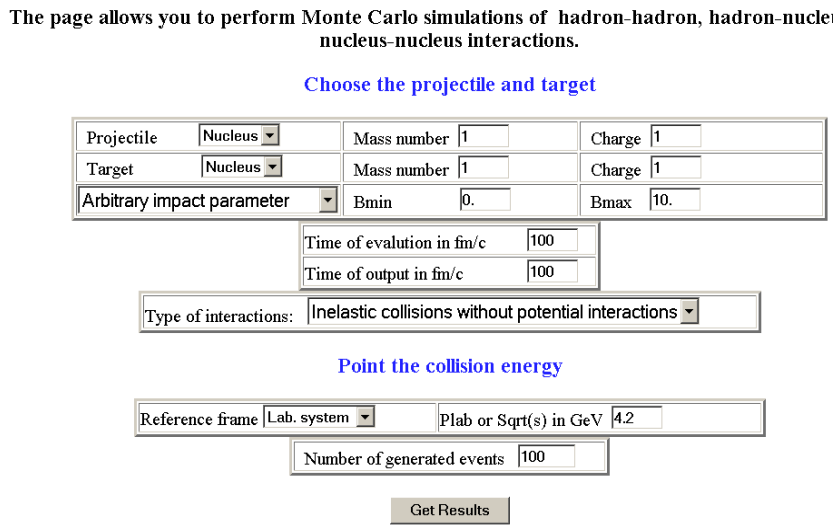

Fig. 5. View of the UrQMD page

To run the simulation process you should set up:

• Mass numbers and charges of colliding nuclei, or choose a projectile particle from a pop-up menu (in the case arbitrary mass and charge are needed also);

• If you are interested in the minimal bias interactions, miss the next line. In other case, choose from a pop-up menu the item — "Impact parameter in the range", and set up minimal and maximal values of the interaction impact parameter. They must be meaningful, see the previous section.

• We do not recommend to change the items — "Time of evolution in fm/c" and "Time of output in fm/c" without defined need. They determine a time of interactions and a frequency of an intermediate results output. It is obvious that the time of evolution must not be lower than the time of a particle penetration through a target nucleus. At low and intermediate energies, the change of the parameter has an influence on properties of the pre-equilibrium particles and residual nuclei. Giving a small time of the evolution, you will obtain a "hot" residual nucleus with a large mass because the pre-equilibrium particles will be captured by the residual. At large evolution time the nucleus will be more "cold", and the multiplicity of the pre-equilibrium particles will be larger.

• The item — "Type of interactions", allows you to order to perform calculations with or without potential interactions. The corresponding submenu items are "Inelastic collisions + potential interactions" and "Inelastic collisions without potential interactions". At energies larger then 4 GeV/nucleon, all calculations are performed without the potential interactions.

• Particle characteristics can be calculated in the laboratory system, or in the centre-of-mass system. Depending on your choice, set up a momentum per nucleon of the projectile nucleus, or the corresponding energy of the NN interactions.

• It is natural that you should set up a number of the generated events.

• At the end of your typing, click on the button — ”Get Results”.

Calculated characteristics will be presented as it was described before.

Below the menu there is a reference on the UrQMD model validation WEB-page which collects materials on a comparison of the UrQMD model calculations and experimental data [33].

2.4. HIJING Model. The page presented in Fig. 6, gives you an opportunity to calculate properties of hadron–hadron, hadron–nucleus, and nucleus–nucleus interactions at high and superhigh energies using the HIJING model [17]. We use a variant of the code disposed at the code depository of the LCG project [34] and described in [35].

To run the simulation process you should set up:

• Mass numbers and charges of colliding nuclei, or choose a projectile particle from a pop-up menu (in the case arbitrary mass and charge are needed also);

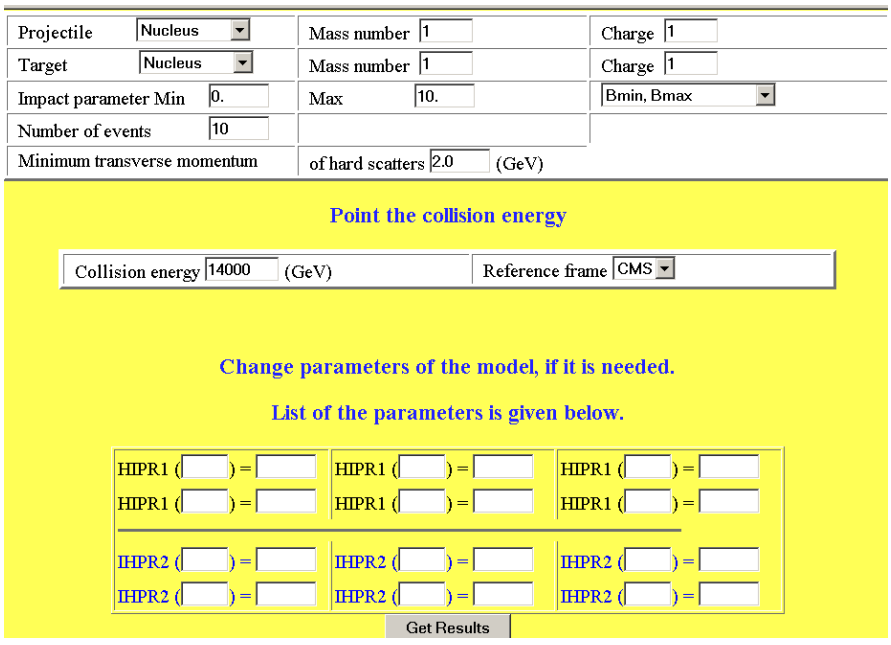

Fig. 6. View of the HIJING page

• If you are interested in the minimal bias interactions, miss the next line. In other case, choose from a pop-up menu the item — "Impact parameter in the range", and set up minimal and maximal values of the interaction impact parameter. They must be meaningful, see the previous section.

• Set up a number of generated events.

• We do not recommend to change one of the most important parameters of the model — "Minimum transverse momentum of hard scatters", if you have not a special need.

• Particle characteristics can be calculated in the laboratory system, or in the centre-of-mass system. Depending on your choice, set up a momentum per nucleon of the projectile nucleus, or the corresponding energy of the NN interactions.

• We give in the menu an additional possibility to change the model parameters and options. A list of the parameters and options is given below. For example, to switch off the jet quenching effect it is needed to put IHPR2(5)=0. This means that you should enter the corresponding windows numbers "5" and "0".

• At the end of your typing, click on the button – "Get Results".

Calculated characteristics will be presented as it was described earlier.

Below the button — "Get Results", there is a reference on the HIJING model validation WEB-page [35] which collects materials on a comparison of the HIJING model calculations and experimental data.

2.5. Glauber Cross Section Calculation. A page presented in Fig. 7 gives you an opportunity to calculate hadron–nucleus and nucleus–nucleus interaction characteristics in the Glauber approximation such as the total cross section, the elastic cross section, the AB− >XB cross section, the AB− >AX cross section, the AB− >X cross section, the production cross section, the production cross section of interactions with composite materials, and various distributions of inelastic reactions. For this you should choose needed item and click a button — "Run".

All following pages for the Glauber calculations have nearly the same view presented in Fig. 8. To perform calculations you should set up:

• Mass numbers and charges of colliding nuclei. If you are going to study hadron–nucleus interactions, set up for the mass and charge of the projectile the values«1» and «1».

• After that you should set up NN-interaction properties — the total interaction cross section, the slope of differential elastic scattering cross section, and the ratio of real and imaginary parts of the elastic scattering amplitude at zero momentum transfer. All of the quantities can be found in the compilation [36]. The same quantities can be calculated assuming the gaussian parameterization of the elastic scattering amplitude and $\mathrm{Re}\, F/\mathrm{Im}\, F = 0$ if you know the total and elastic NN-interaction cross sections. For a determination of the NN cross sections one can use parameterizations proposed by the Particle Data Group (PDG [37]). We

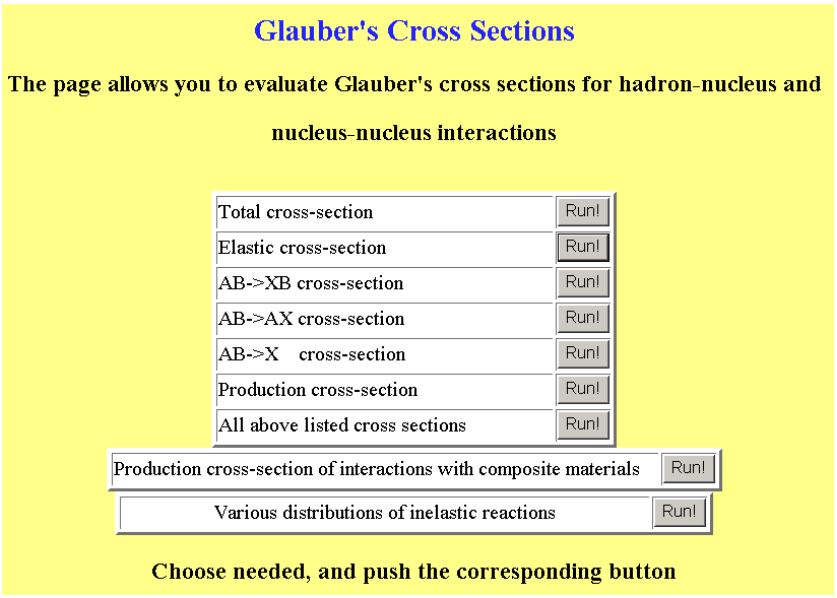

Fig. 7. View of the Glauber calculation page

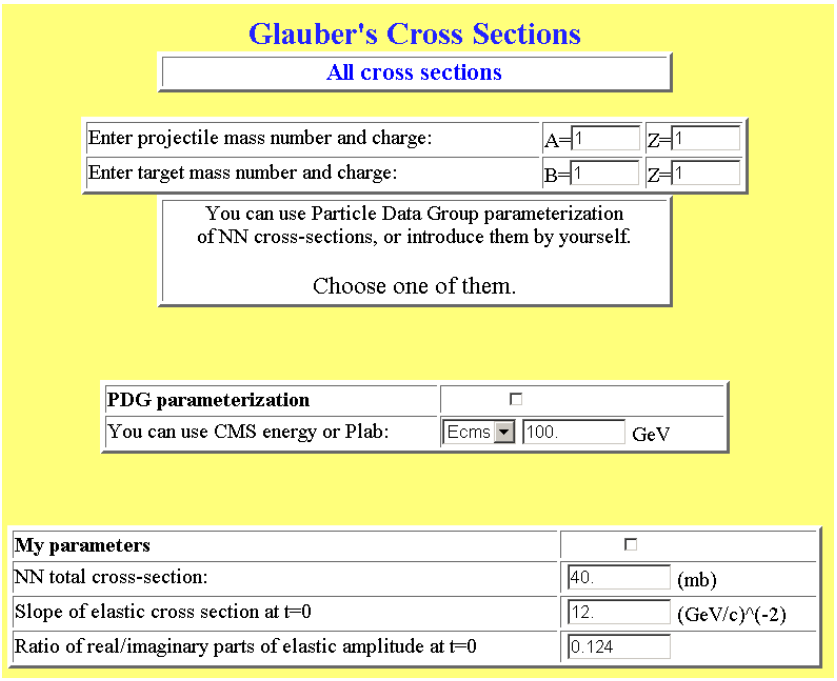

Fig. 8. View of the Glauber page

allow both of the possibilities. To choose one of the methods you should mark one of them in the corresponding check box.

If you choose a usage of the PDG parameterization, you should additionally set up a reference frame and a momentum per nucleon or an energy in the centre-of-mass system ($\sqrt{s}$).

You need to set up the required parameters by yourself if you are going to consider hadron–nucleus interactions ($\pi A, KA$).

• In the codes, the stochastic method of an evaluation of the multidimensional integrals is used. It is quite well described in [40–42]. Thus, you have to set a number of samples (statistic), it determines an accuracy of the calculation.

• At the end of your typing, click on the button — "Get Results".

2.6. Reggeon Cross-Section Calculation. The page presented in Fig. 9 gives you a possibility to calculate hadron–hadron, hadron–nucleus, and nucleus-nucleus interaction properties using the reggeon or pomeron approach.

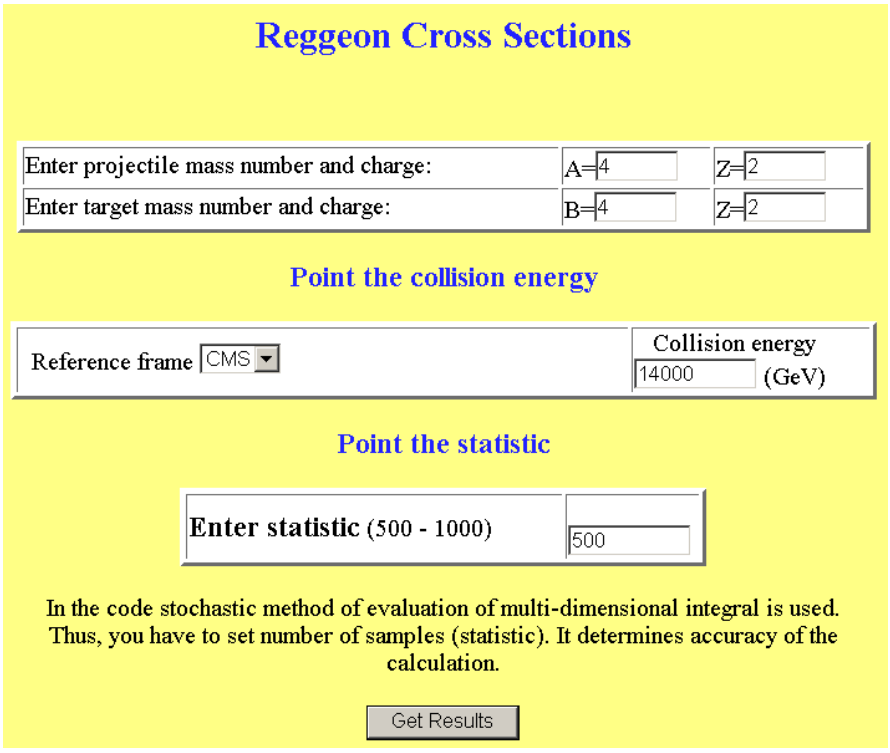

Fig. 9. View of the Reggeon page

To perform calculations you should set up:

• Mass numbers and charges of colliding nuclei. If you are going to study hadron–nucleus interactions, set up for the mass and charge of the projectile the values "1" and "1". If you are interesting in nucleon–nucleon collisions set up also for the target the values "1" and "1" (Proton is a nucleus of hydrogen atom.)

• You should set up a reference frame and a momentum per nucleon, or an energy of NN interactions in the centre-of-mass system. They are needed for a calculation of the reggeon parameters.

• Because in the code the stochastic method of an evaluation of the multi-dimensional integrals is used, you have to set a number of samples (statistic). It determines an accuracy of the calculation.

• At the end of your typing, click on the button — "Get Results".

A description of the calculating method will be published elsewhere.

3. STRUCTURE OF WEB-SERVICE HepWeb

Already existing servers described in the Introduction have been analyzed, and the following requirements to the HepWeb service have been formulated:

1. The HepWeb service should have a WEB-oriented architecture;

2. Requirements to a user's computer should be minimal one both on hardware and on software levels;

3. Generators should have standardized input and output streams;

4. Generators satisfying the point 3 should be easily installed and modified on the server, i.e., they should not have any special settings necessary only for the HepWeb;

5. Result of a generator work should be presented in standard graphic formats with possibility to create a root file or text fragments;

6. Result of the generator work should be saved because some calculations require a lot of a computational time, and it is inexpedient to repeat them.

The following structure was accepted and implemented in the accordance with given above requirements:

• The HepWeb service is based on the "client — server" architecture.

• The HepWEb service is implemented in Java, and uses the JavaServer Pages (JSP) technology. This allows one to result as XHTML- or XML-documents. User can apply any WEB-browser (IE, Mozilla, Opera, etc.) for their viewing.

• The output streams of all HepWeb generators are standardized.

An output data is written in a text file. Any number of histograms can be stored in the file. A histogram has a header where a name of the histogram and the names of the co-ordinate axes are given. Then a set of co-ordinates is followed. Additionally a ROOT-file of the histograms could be also created.

• The results are stored in the database.

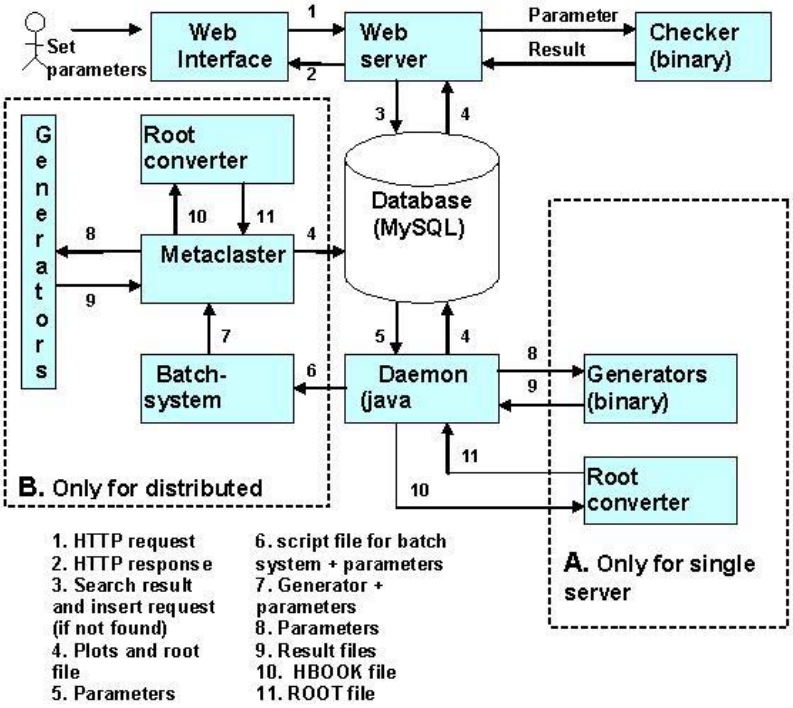

Fig. 10. Structure of the HepWeb-server

All generators are presented on the server as executable modules (the source files of the codes are unavailable for users). The modules can be also started independently of the HEPWEB. This allows one to upgrade generators without reboot of the server and add new generators specifying only the ways to the corresponding executable modules in a configuration file.

The standardized output stream is analyzed by a special method created by us in order to extract the histograms. The histograms are converted into graphic files (png-files) using the standard Java-technology.

The MySQL database was chosen to store the results because it is free, and its bandwidth of the read/write data is enough for the HepWeb service.

An interaction scheme between the components of the HepWeb service is presented in Fig. 10.

A client generates a request to the server using a form which is built in a static HTML page. Each generator uses its own HTML page with an according form. An answer on the query is generated by the server with the help of the

JSP technology. The server checks correctness of the parameters of the query. For example, it is checked that the energy of NN collision in the centre-of-mass system $\sqrt{s}$ is larger than the sum of nucleon masses, or that the range of the impact parameter does not extend to negative values, etc. All correct requests are stored in the database. The server checks for each request if a request is already stored in database or not. If the request is stored, then the server generates the result page and sends it to the user. If the results for the request are not presented, an empty page is sent to the client with a line — "Please wait a few minutes then refresh this page". In the case the requested generator with corresponding parameters is started on the server, the HepWeb service has two possibilities for executing the generator:

1. Use only one computer for the server;
2. Use distributed computing system for the server.

3.1. The Single-Computer Based HepWeb Service Structure. For the structure, all calculations are performed by one computer. A request to run a generator follows to the consecutive list. Thus, all queries of a generator will be executed in consecutive order. The given structure is efficient for a small number of the requests. If the number of queries increases, the astronomical time of their execution will increase, too. The structure is marked by letter "A" in Fig. 10.

3.2. Structure of the HepWeb Service Based on a Distributed Computer System. The structure is developed for starting tasks on several computers. It allows one to perform several queries simultaneously. In the presence of a sufficient quantity of computers in the system, the performance time of a new query is nearly equal to the performance time of this task on one computer. This structure is marked by letter "B" in Fig. 10.

The HepWeb service was tested in 2006 on distributed metaclaster of the Dubna-Grid project ([38, 39]). An interaction of the service in batch-mode of access to resources of the metaclaster has been successfully proved.

SUMMARY

A WEB-portal is designed which allows a user to perform the most popular calculations in high-energy physics — calculations of hadron–hadron, hadron–nucleus, and nucleus–nucleus interaction cross sections and calculations of secondary particles characteristics in the interactions using Monte Carlo event generators. The list of the generators includes the intranuclear cascade model (CASCADE), the FRITIOF model, the ultrarelativistic quantum molecular dynamic model (UrQMD), and HIJING model.

Setting up of colliding particles properties (collision energy, mass numbers and charges of nuclei, impact parameters of interactions, and a number of generated events) is realized by a WEB-interface. A query is processed by server, and results are presented to the user as a WEB-page.

APPENDIX: THE CASCADE-EVAPORATION MODEL (CEM)

The cascade-evaporation model (see [23–28]) was one of the first models of hadron–nucleus interactions at high energies ($E > 1$ GeV) very important for practical applications. It saves its position at present time, too. The model assumes that due to an inelastic interaction of a projectile hadron with one of target nucleons a new particle is produced. The participating target nucleon accepts momentum and begins moving in the nucleus. All moving (cascade) particles can interact with other nuclear nucleons to produce new particles or suffer an elastic rescattering. Therefore, a cascade reproduction of moving particles is assumed. The interactions between the cascade particles are usually omitted. The process continues until all moving particles either leave the nucleus or are absorbed.

In the case of nucleus–nucleus collisions, it is assumed that the cascade particles can interact with projectile and target nucleons. To choose the nucleons which can participate in elementary interactions, all of the nucleons of the colliding nuclei with mass numbers A and B are identified by the coordinates $(x_i, y_i, z_i,\ 1 \leqslant i \leqslant A)$ and $(x'_j, y'_j, z'_j,\ 1 \leqslant j \leqslant B)$ in the initial state in the corresponding reference frames. At the sampling of the nucleon coordinates for a nucleus with A (B) ≤ 10 the oscillator density is used. The Woods-Saxon density with the parameters $R_A = 1.07 \cdot A^{1/3}$ fm and $c = 0.545$ fm is applied for more heavy nuclei. The nucleon core is taken into account at sampling the nucleon coordinates according to the densities ρ_A and ρ_B (two nucleons cannot be closer than R_c, $R_c = 0.4$ fm).

Taking into account the Lorentz contraction of the projectile (A) in the rest frame of the target nucleus, the corresponding coordinates are redefined as $z_i \to z_i/\gamma - R_A/\gamma - R_B$. Here γ is the Lorentz factor of the projectile nucleus, R_A and R_B are radii of the nuclei. If the coordinates of the ith nucleon of the nucleus A and the jth nucleon of the nucleus B satisfy the condition

$$(b_x + x_i - x'_j)^2 + (b_y + y_i - y'_j)^2 \leqslant (R_{\rm int} + \lambda_D)^2,$$

then the two nucleons are considered as possible participants in the elementary interactions. Here (b_x, b_y) are components of the impact parameter, $R_{\rm int}$ is the strong interaction radius (1.3 fm) and λ_D is the de Broglie wavelength of the projectile nucleon. The possible participant can fly without interaction, or suffer an elastic scattering, or an inelastic interaction. The corresponding probabilities are

$$W_{\rm tot}(\pi \cdot (R_{\rm int} + \lambda_D)^2 - \sigma^{\rm tot})/(\pi \cdot (R_{\rm int} + \lambda_D)^2),$$
$$W_{\rm el} = \sigma^{\rm el}/(\pi \cdot (R_{\rm int} + \lambda_D)^2),$$
$$W_{\rm in} = \sigma^{\rm in}/(\pi \cdot (R_{\rm int} + \lambda_D)^2),$$

where $\sigma^{\rm tot}$, $\sigma^{\rm el}$ and $\sigma^{\rm in}$ are the total, elastic and inelastic nucleon–nucleon (NN) interaction cross sections. The time of possible interactions in the frame of the

target nucleus is determined as $t_{ij} = (z'_j - z_i)/v$, where v is the velocity of the projectile nucleus.

A minimal time interaction will be caused first. The nucleons taking part in the interaction are ascribed to a Fermi momentum in the corresponding reference frame, and the momentum of the projectile nucleon is transferred to the target nucleus rest frame. It is assumed that the Fermi momentum distribution has the form

$$W(p)dp = 3p^2/P_F^3(r)dp, \quad 0 \leqslant p \leqslant P_F(r), \tag{1}$$

where $P_F(r)$ depends on the local density of the nucleus $\rho(r)$,

$$P_F = \hbar(3\pi^2\rho(r))^{1/3}; \tag{2}$$

$\vec{r}$ is the radius-vector of the interacting nucleon in the corresponding nucleus. In the following the Fermi momenta are ascribed only to new involved nucleons.

An elementary interaction (elastic scattering or inelastic collisions) will be rejected, if at least one of the two colliding nucleons, after the interaction, falls into the region of occupied states of nucleus A or B (has an energy lower than the Fermi energy of $P_F^2/2m$). In this case the next possible interaction in the time is considered. This repeats until an interaction occurs.

The simulation procedure of elastic and inelastic nucleon–nucleon and meson–nucleon interactions is described in detail in [23]. It allows one to reproduce the experimental observations up to energies $\sim$ 10–15 GeV, and especially the particle momentum distributions.

After the first real interaction, the time is increased by t_{ij}. The coordinates of the moving particles are changed as $z_k \rightarrow z_k + vt_{ij}$. The coordinates of newly produced particles (π mesons) in the interaction with equal probabilities are identified by the coordinates of the target or projectile nucleons ($\vec{r}_i$ or $\vec{r}'_j$). Then all possible interactions of the produced and moving particles with the projectile or target nucleons are considered. Each cascade particle can interact with nucleons in a tube with radius $R_{\rm int}+\lambda_D$ along its trajectory. The time for possible interactions is determined as $t_{ik} = (\vec{v}_k(\vec{r}_i - \vec{r}''_k))/ \mid \vec{v}_k \mid$ or $t_{jk} = (\vec{v}_k(\vec{r}'_j - \vec{r}''_k)/ \mid \vec{v}_k \mid$, where v_k is the velocity of the cascade particle k, and $\vec{r}''_k$ is its radius vector.

Among all possible interactions the one with the minimum time is chosen. The processes continue until all possible interactions have been considered.

As mentioned above, the nucleon taking part in an interaction is considered as a cascade particle. Due to this, the local density of the nucleus gets lower. This is the so-called trailing effect.

At the end of the fast cascade stage of the process, the number and charges of spectator nucleons as well as the charges of the absorbed mesons determine the nuclear residual mass number and charge.

The excitation energy of the nuclear residual is the sum of the energies of absorbed particles and the holes counted from the Fermi energy. It is assumed

that due to an interaction of a cascade particle or a projectile nucleon with a target nucleon having the energy $p^2/2m_N$, where p is determined according to the distribution (1), a hole with an energy $E_h = P_F^2/2mN - p^2/2m_N$ is created in the target nucleus. (P_F is given by equation (2)). If an energy of the target nucleon after the interaction, T, is larger than the Fermi energy ($P_F^2/2m_N$) but lower than $P_F^2/2m_N + E_b$ ($E_b = 7$ MeV), it is assumed that the target nucleon will not leave the nucleus. It is considered to be an absorbed nucleon. In this case its yield to the excitation energy of the nucleus is determined as $E_n = T - P_F^2/2m_N$. A meson having an energy lower than 25 MeV counted from the bottom of the potential well is considered as to be an absorbed one, too. Its yield to the excitation energy of the nucleus is determined as $T_\pi + m_\pi$. (It is assumed that the elementary interaction is caused in the potential well with a depth $P_F^2/2m_N + E_b$. This value is added to the kinetic energy of the incoming cascade particle or the projectile nucleon and is subtracted from the kinetic energy of each outgoing particle.)

The total excitation energy of the target nucleus is a sum of the energies of the holes, the energies of absorbed nucleons and mesons. The analogous procedure can be applied to determine the excitation energy of the projectile nucleus. It is obvious that the excitation energy of the target nucleus will be proportional to the number of ejected nucleons if one neglects the absorption of the nucleons and mesons.

Let us note that according to the above prescription in the limit case, when all nucleons of the target nucleus are ejected, one can obtain a nucleus without any nucleons, but with a defined excitation energy.

The excitation energy governs the nuclear residual relaxation. So the method of the excitation energy calculation links the fast and slow stages of the interaction.

The nuclear residual relaxes before thermodynamic equilibrium and can emit the so-called pre-equilibrium particles. This process takes place if the number of quasiparticles — $N_q = N_h + N_n$, is larger than the equilibrium value $N_{q\,(\mathrm{eq.})} = 2\sqrt{6aE^*/\pi^2}$. Here N_h is the number of holes (the number of participating nucleons), N_n is the number of absorbed cascade nucleons, E^* is the excitation energy of the nucleus, and a is the level density parameter, taken as $= A/10$ MeV^{-1}. The pre-equilibrium decay of the nucleus is simulated in the framework of the exciton model [43]. The decay of a thermalized nucleus is described by the usual evaporation approach [44, 45].

Additional details of the model can be found in [28]. We have installed at the HepWeb server a code described in [21].

From the view point of modern approaches, the realization of CEM simulation is regarded as being too simple. It fails to take into account many important effects: a variation of the average nuclear field during the collision, a production of meson and baryon resonances, a finite formation time of a particle, a

coalescence of nucleons, a multifragmentation of nuclei and so on. Though, the analogous implementation of the model [46] was recognized as the best model code used in the physics of the intermediate energies.

APPENDIX: THE URQMD MODEL

A variation of the average nuclear mean field and its influence on the inclusive distributions at low and intermediate energies are commonly considered in the VUU/BUU approaches (Vlasov–Weling–Ulenbek or Bolzman–Weling–Ulenbek, see [48, 49]). At higher energies or at a strong breakup of nuclei the effects of the average field render weak. Here, the quantum molecular dynamical approach considering the explicit form of the two- and three-particle interactions is preferably applied. Its relativistic generalization combined with quark ideas of the multiparticle production is presented in the RQMD model [51–53] and UrQMD model [11, 12]). It allows one to describe numerous characteristics of produced particles in nucleus–nucleus (AA) collisions at high energies. The UrQMD model is well described in [11, 12]. Thus below we give only the main features of the model.

The UrQMD model describes hadronic interactions at low and intermediate energies ($\sqrt{s} < 5$ GeV, $P_{\rm lab} \leqslant 12$ GeV/c) in terms of interactions between known hadrons and their resonances. At higher energies, $\sqrt{s} > 5$ GeV, the excitation of color strings and their subsequent fragmentation into hadrons are taking into account.

The model is based on the covariant propagation of all hadrons considered on the (quasi-)particle level on classical trajectories in combination with stochastic binary scatterings, color string formation and resonance decay. It represents a Monte Carlo solution of a large set of coupled partial integro-differential equations for the time evolution of the various phase space densities of particle species $i = N, \Delta, \Lambda$, etc. The main components of the model are cross sections of binary reactions, potentials and decay widths of resonances.

The potential interaction is based on a nonrelativistic density-dependent Skyrme-type equation of state with additional Yukawa- and Coulomb potentials. Momentum-dependent potentials are not used. The Skyrme potential consists of a sum of two- and three-body interaction terms. The two-body term, which has a linear density-dependence, models the long range attractive component of the nucleon–nucleon interaction, whereas the three-body term with its quadratic density-dependence is responsible for the short range repulsive part of the interaction. The parameters of the components are connected with the nuclear equation of state. Only the hard equation of state has been implemented into the current UrQMD model.

The impact parameter of a collision is sampled according to the quadratic measure ($dW \sim bdb$). At the given impact parameter, the centers of projec-

tile and target are placed along the collision axis in such a manner that the distance between surfaces of the projectile and the target is equal to 3 fm. Momenta of nucleons are transformed in the system where the projectile and target have equal velocities directed in different directions of the axis. After that the time propagation starts. During the calculation each particle is checked at the beginning of each time step whether it will collide within that time step. A collision between two hadrons will occur if $d < \sqrt{\sigma^{\rm tot}/\pi}$, where d and $\sigma^{\rm tot}$ are the impact parameter of the hadrons and the total cross section of the two hadrons, respectively. After each binary collision or decay the outgoing particles are checked for further collisions within the respective time step.

In the UrQMD model the total cross section $\sigma^{\rm tot}$ depends on the isospins of colliding particles, their flavor and the c.m. energy. The total and elastic proton–proton and proton–neutron cross sections are well known [54]. Since their functional dependence on $\sqrt{s}$ shows a complicated shape at low energies, UrQMD uses a table-lookup for those cross sections. The neutron–neutron cross section is treated as equal to the proton–proton cross section (isospin–symmetry). In the high energy limit ($\sqrt{s} \geqslant 5$ GeV) the CERN/HERA parameterization for the proton–proton cross section is used [54].

Baryon resonances are produced in two different ways, namely

i) hard production: $N + N \rightarrow \Delta N,\ \Delta\Delta,\ N^*N$, etc.

ii) soft production: $\pi^- + p \rightarrow \Delta^0,\ K^- + p \rightarrow \Lambda^* \ldots$

The formation of s-channel resonances is fitted to measured data. Partial cross sections are used to calculate the relative weights for the different channels.

There are six channels of the excitation of nonstrange resonances in the UrQMD model, namely $NN \rightarrow N\Delta_{1232}$, NN^*, $N\Delta^*$, $\Delta_{1232}\Delta_{1232}$, $\Delta_{1232}N^*$, and $\Delta_{1232}\Delta^*$. The Δ_{1232} is explicitly listed, whereas higher excitations of the Δ resonance are denoted as Δ^*. For each of these 6 channels specific assumptions were made with respect to the form of the matrix element, and the free parameters were adjusted to the available experimental data.

Meson–baryon (MB) cross sections are dominated by the formation of s-channel resonances, i.e., the formation of a transient state of mass $m = \sqrt{s_{hh}}$, containing the total c.m. energy of the two incoming hadrons. On the quark level such a process implies that a quark from the baryon annihilates an antiquark from the incoming meson. Below 2.2 GeV c.m. energy, intermediate resonance states get excited. At higher energies the quark–antiquark annihilation processes become less important. There, t-channel excitations of the hadrons dominate, where the exchange of mesons and Pomeron exchange determines the total cross section of the MB interaction [55].

To describe the total meson–meson reaction cross sections, the additive quark model and the principle of detailed balance, which assumes the reversibility of the particle interactions, are used.

Resonance formation cross sections from the measured decay properties of the possible resonances up to c.m. energies of 2.25 GeV for baryon resonance and 1.7 GeV in the case of MM and MB reactions have been calculated based on the principle. Above these energies collisions are modeled by the formation of s-channel string or, at higher energies (beginning at $\sqrt{s} = 3$ GeV), by one/two t-channel strings. In the strangeness channel, elastic collisions are possible for those meson–baryon combinations which are not able to form a resonance, while the creation of t-channel strings is always possible at sufficiently large energies. At high collision energies both cross sections become equal due to quark counting rules.

A parameterization proposed by Koch and Dover [56] is used in UrQMD model for baryon–antibaryon annihilation cross section. It is assumed that the antiproton–neutron annihilation cross section is identical to the antiproton–proton annihilation cross section.

The hadron–hadron interactions at high energies are simulated in 3 stages. According to the cross sections, the type of interaction is defined: elastic, inelastic, antibaryon–baryon annihilation, etc. In the case of inelastic collision with string excitation the kinematical characteristics of strings are determined. The strings between quark and diquark (antiquark) from the same hadron are produced. The strings have the continuous mass distribution $f(M) \propto 1/M$ with the masses M, limited by the total collision energy $\sqrt{s}$: $M_1 + M_2 \leqslant \sqrt{s}$. The rest of the $\sqrt{s}$ is equally distributed between the longitudinal momenta of two produced strings.

The second stage of h-h interactions is connected with string fragmentation. The string break-up is treated iteratively: string $\rightarrow$ hadron + smaller string. A quark–antiquark (or a diquark–antidiquark) pair is created and placed between leading constituent quark–antiquark (or diquark–quark) pair. Then a hadron is formed randomly on one of the end-points of the string. The quark content of the hadron determines its species and charge. In case of resonances, the mass is determined according to the Breit–Wigner distribution. Finally, the energy-fraction of the string which is assigned to the newly created hadron is determined: After the hadron has been stochastically assigned, a transverse momentum, the fraction of longitudinal momentum transferred from the string to the hadron, is determined by the fragmentation function. The conservation laws are fulfilled. The diquark is permitted to convert into mesons via the breaking of the diquark link.

This iterative fragmentation process is repeated until the remaining energy of the string gets too small for a further fragmentation.

The fragmentation function $f(x, m_t)$ represents the probability distribution for a hadron with the transverse mass m_t to acquire the longitudinal momentum fraction x from the fragmenting string. One of the most common fragmentation functions is the one used in the LUND model [57]. In UrQMD, different frag-

mentation functions are used for leading nucleons and newly produced particles, respectively:

$$f(x)_{\rm nuc} = \exp\left(-\frac{(x-B)^2}{2\,A^2}\right) \quad \text{for leading nucleons} \tag{3}$$

$$f(x)_{\rm prod} = (1-x)^2 \quad \text{for produced particles} \tag{4}$$

with $A = 0.275$ and $B = 0.42$. The fragmentation function $f(x)_{\rm prod}$, used for newly produced particles, is the well-known Field–Feynman fragmentation function [58, 59].

The fragmentation scheme determines the formation time of created hadrons. Though there are various possibilities (for details see [11, 12]).

After the fragmentation, decay of the resonances proceeds according to the branching ratios compiled by the Particle Data Group [37, 54]. The resonance decay products have isotropical distributions in the rest frame of the resonance. If a resonance is among the outgoing particles, its mass must first be determined according to the Breit–Wigner mass-distribution. If the resonance decays into $N > 2$ particles, then the corresponding N-body phase space is used to calculate their N momenta stochastically.

The Pauli principle is applied to hadronic collisions or decays by blocking the final state if the outgoing phase space is occupied.

The UrQMD collision term contains 55 different baryon species (including nucleon, delta and hyperon resonances with masses up to 2.25 GeV) and 32 different meson species (including strange meson resonances), which are supplemented by their corresponding antiparticle and all isospin-projected states. The states can either be produced in string decays, s-channel collisions or resonance decays. For excitations with higher masses than 2 GeV, a string picture is used. Full baryon/antibaryon symmetry includes: The number of the implemented baryons therefore defines the number of antibaryons in the model and the antibaryon–antibaryon interaction is defined via the baryon–baryon interaction cross sections.

The elementary cross sections are fitted to available proton–proton or pion–proton data. Isospin symmetry is used when possible in order to reduce the number of individual cross sections which have to be parameterized or tabulated.

We have installed a bug fixed version of UrQMD 1.3 [32] at the HepWeb server.

APPENDIX: THE FRITIOF MODEL

The role of heavy resonances in hadron–hadron interactions becomes more and more essential with a growth of a collision energy. The resonances have wide mass distributions. The distributions overlap, and the mass spectra in the binary

reactions become practically continuous and smooth. This is taken into account in the FRITIOF model [22]. The model assumes that all hadron–hadron interactions at high energies are binary reactions: $a + b \longrightarrow a' + b'$, where a' and b' are excited states of initial hadrons a and b. The excited states are characterized by masses which are selected by the following procedure: in the center of mass of colliding hadrons the energy-momentum conservation low has the form:

$$\begin{aligned} E_a + E_b = E_{a'} + E_{b'} = \sqrt{s_{ab}}, \\ p_{az} + p_{bz} = p_{a'z} + p_{b'z} = 0, \\ 0 = \vec{p}_{a'\perp} + \vec{p}_{b'\perp}, \end{aligned} \tag{5}$$

where E_a and E_b $(E_{a'}, E_{b'})$ — energies of initial (final) hadrons a and $b\,(a', b')$; p_{az} and P_{bz} — longitudinal momentum components; $\vec{p}_{a'\perp}$ and $\vec{p}_{b'\perp}$ — transverse momentum components of hadrons a' and b'.

Adding and subtracting the first two equations from (5) leads to:

$$\begin{aligned} P_a^+ + P_b^+ = P_{a'}^+ + P_{b'}^+, \\ P_a^- + P_b^- = P_{a'}^- + P_{b'}^-, \\ 0 = \vec{p}_{a'\perp} + \vec{p}_{b'\perp}, \end{aligned} \tag{6}$$

where $P^+ = E + p_z$, $P^- = E - p_z$.

At high energies:

$$P_{a'}^- \simeq m_{a'}^2/2 \mid p_{a'z} \mid, \quad P_{b'}^+ \simeq m_{b'}^2/2 \mid p_{b'z} \mid . \tag{7}$$

Thus, the $P_{a'}^-$ and $P_{b'}^+$ distribution has the form:

$$\begin{aligned} dW \sim dP_{a'}^-/P_{a'}^- \simeq dm_{a'}^2/m_{a'}^2, \\ dW \sim dP_{b'}^+/P_{b'}^+ \simeq dm_{b'}^2/m_{b'}^2. \end{aligned} \tag{8}$$

The limits of $P_{a'}^-$ and $P_{b'}^+$ are defined as

$$[P_a^-, P_b^-], \quad [P_b^+, P_a^+]. \tag{9}$$

In case of hadron–nucleus interactions the kinematics governed by Eqs. (5)–(9) is applied for the first collision of the projectile hadron with one of the target nucleons ($a + N_1 \to a' + N_1'$). For the second collision ($a' + N_2 \to a'' + N_2'$), analogous relations are used but (9) is changed by

$$[P_{a'}^-, P_{N_2}^-], \quad [P_{N_2}^+, P_{a'}^+]. \tag{10}$$

As a result, the sequence of the collisions leads to a systematic increasing of the mass of the hadron a if transferred momenta are small.

A similar approach is also applied to simulate nucleus–nucleus interactions. Here the reactions $a' + b' \to a'' + b''$ are considered. The distributions on $P^-_{a''}$ and $P^+_{b''}$ are the same as those for $P^-_{a'}$ and $P^+_{b'}$, but the limits of $P^-_{a''}$ and $P^+_{b''}$ are redefined as

$$[P^-_{a'}, P^-_{b'}], \quad [P^+_{b'}, P^+_{a'}]. \tag{11}$$

Thus, the model considers the interactions of the cascade particles between themselves from the point of the view of the cascade-evaporation model. Probabilities of the multiple interactions are calculated in the Glauber approach.

The excited hadrons are treated as QCD-strings, and a corresponding algorithm is applied for a simulation of their fragmentation into observed hadrons. Due to the increasing of the masses, the multiplicities are increased too. Thus, the two factors – multiple interactions and the increasing of the masses, explain the increase of the produced particle multiplicity at a passage from hadron–nucleon interactions to the hadron–nucleus and nucleus–nucleus ones.

In the version of the model code installed at the HepWeb server, we take into account the elastic scattering of hadrons as well as the inelastic interactions (for details see [61]).

The cascading of the produced hadrons in nuclei was not considered in the model. As a results, a multiplicity of slow particles associated with a destruction of residual nuclei was not described sufficiently well. In order to overcome the drawback it was proposed in [29, 30] to enlarge the FRITIOF model by the reggeon theory inspired model of the nuclear destruction (RTIM) [31].

A simulation of the destruction consists of two stages. At the first stage a set of interacting nucleons (wounded nucleons) is determined with the help of the Glauber approximation. At the second stage noninteracting nuclear nucleons are considered. It is assumed that a noninteracting nucleon located at a relative impact parameter distance, r, from a wounded nucleon can be involved in the interactions with a probability

$$W = C_{\rm nd}\, e^{-r^2/r^2_{nd}},$$

where $C_{\rm nd}$ and $r_{\rm nd}$ are parameters. The involved nucleon can involve another spectator nucleon, and so on. It is assumed also that all wounded and involved nucleons leave the nucleus. Good results have been obtained for light nuclei at $C_{\rm nd} = 1$ and $r_{\rm nd} = 1.2$ fm. We recommend to use $C_{\rm nd} = 0.2$ and $r_{\rm nd} = 1$ fm for heavy nuclei.

To ascribe momenta of the escaped nucleon, we use the algorithm proposed in [29]. To explain its feature let us consider a reaction of a compound system, $(1, 2)$, with a hadron h: $(1, 2) + h \to 1 + 2 + h$. Neglecting transverse momenta, a final state of the reaction will be fully determined by a value of merely one independent kinematical variable. As the variable let us take

$$x^+_1 = (E_1 + p_1)/(E_1 + E_2 + p_1 + p_2).$$

It is obvious that an analogous variable for the second particle, x_2^+, will satisfy the condition — $x_1^+ + x_2^+ = 1$. All the other kinematical variables can be determined from the energy-momentum conservation law.

In the case of a dissociation of two compound systems, A and B, containing A and B constituents, respectively, the ith constituent of system A will be described by

$$x_i^+ = (E_{Ai} + p_{iz})/W_A^+ \quad \text{and} \quad \vec{p}_{i\perp},$$

and the jth constituent of system B — by

$$y_j^- = (E_{Bj} - q_{jz})/W_B^- \quad \text{and} \quad \vec{q}_{i\perp}.$$

Here, $E_{A_i}(E_{B_i})$ and $\vec{p}_i(\vec{q}_i)$ are energy and transverse momentum of ith constituent of $A(B)$.

$$W_A^+ = \sum_{i=1}^{A}(E_{Ai} + p_{iz}), \quad W_B^- = \sum_{i=1}^{B}(E_{Bi} - q_{iz}).$$

Using the variables, let us write the conservation law as

$$\begin{aligned}
&\frac{W_A^+}{2} + \frac{1}{2W_A^+}\sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+} + \frac{W_B^-}{2} + \frac{1}{2W_B^-}\sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-} = E_A^0 + E_B^0,\\
&\frac{W_A^+}{2} - \frac{1}{2W_A^+}\sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+} - \frac{W_B^-}{2} + \frac{1}{2W_B^-}\sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-} = P_A^0 + P_B^0, \qquad (12)\\
&\sum_{i=1}^{A}\vec{p}_{i\perp} + \sum_{i=1}^{B}\vec{q}_{i\perp} = 0,
\end{aligned}$$

where $m_{i\perp}^2 = m_i^2 + \vec{p}_{i\perp}^2$, $\mu_{i\perp}^2 = \mu_i^2 + \vec{q}_{i\perp}^2$, and $m_i(\mu_i)$ is a mass of the ith constituent of system $A(B)$.

The system (12) allows one to determine W_A^+, W_B^- and kinematic properties of all the particles in the finite sets $\{x_i^+, \vec{p}_{i\perp}\}$, $\{y_i^-, \vec{q}_{i\perp}\}$.

$$W_A^+ = (W_0^- W_0^+ + \alpha - \beta + \sqrt{\Delta})/2W_0^-; \qquad (13)$$

$$W_B^- = (W_0^- W_0^+ - \alpha + \beta + \sqrt{\Delta})/2W_0^+; \qquad (14)$$

$$W_0^+ = (E_A^0 + E_B^0) + (P_{Az}^0 + P_{Bz}^0);$$

$$W_0^- = (E_A^0 + E_B^0) - (P_{Az}^0 + P_{Bz}^0);$$

$$\alpha = \sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+}, \quad \beta = \sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-};$$

$$\Delta = (W_0^- W_0^+)^2 + \alpha^2 + \beta^2 - 2W_0^- W_0^+ \alpha - 2W_0^- W_0^+ \beta - 2\alpha\beta;$$
$$p_{iz} = (W_A^+ x_i^+ - \frac{m_{i\perp}^2}{x_i^+ W_A^+})/2; \quad q_{iz} = -(W_B^- y_i^- - \frac{\mu_{i\perp}^2}{y_i^- W_B^-})/2.$$

According to experimental observations [62], the average transverse momentum of a spectator fragment with mass number F obeys the parabolic law:

$$\langle P_\perp^2 \rangle = \frac{F(A-F)}{A} \langle p_\perp^2 \rangle, \quad \sqrt{\langle p_\perp^2 \rangle} = 0.05 \text{ GeV}/c.$$

To reproduce the result, the values of $\vec{p}_{i\perp}$ for the knocked-out nucleons were sampled according to the distribution:

$$dW \propto \exp\left(-\vec{p}_{i\perp}^2 / \langle p_\perp^2 \rangle\right) d^2 p_{i\perp}, \quad \sqrt{\langle p_\perp^2 \rangle} = 0.05. \tag{15}$$

The sum of the transverse momenta (with "minus" sign) was ascribed to the residual nucleus.

The choosing of x_i^+ is carried out by

$$dW \propto \exp\left[-(x_i^+ - 1/A)^2/(d_x/A)^2\right] dx_i^+, \quad d_x = 0.05. \tag{16}$$

The dispersion of the distribution was defined by fitting the average emission angle of b-particles; x^+ of the residual nucleus was included as $1 - \sum x_i^+$.

The knocked-out nucleons occurring in the zone of active action of nuclei were assumed to change again their characteristics. The new values of x_i^+ and $p_{i\perp}$ were simulated using the distributions (15) and (16) at $\langle p_\perp^2 \rangle = 0.3$ (GeV/c)^2 and $d_x = 0.21$. The results from [63–65] were used for a determination of the fitting parameters.

The calculation of the nuclear residual excitation energy is carried out according to [66]. The implemented method is described in detail in [29]. For a simulation of a relaxation of the excited nuclei the standard evaporation model is used [44].

A version of the model applied in [29, 67] underestimated negative charged particle multiplicities especially in the target fragmentation region. Thus, an attempt to take into account non-nucleon degree of freedom in nuclei has been considered.

It is no doubt that the nucleons in nuclei can have virtual transitions — $N \to N + \pi$ and $N + \pi \to N$. The virtual pairs can fall onto the mass-shell and become real ones due to an interaction with a projectile hadron. A calculation of cross sections and properties of the processes requires a solution of numerous questions of the nuclear theory, and cannot be done in a full volume in the present time. Additionally it is needed to consider a creation of the $N\pi$ pairs in the reggeon cascade. Thus, for a qualitative understanding of processes, we

have assumed that an involved or wounded nucleon can be the $N\pi$ pair with a probability of $\sim 20\%$. More concrete, we assume that a proton or a neutron participated in the interaction can be Δ^+- or Δ^0 isobar. It is the most simple solution from a programming point of view. It throws away a complicated question on kinematical properties of the pairs.

APPENDIX: HIJING AND AMPT MODELS

The quark–gluon degree of freedom manifests itself directly at superhigh energies in hadron–hadron interactions — jets of hadrons are produced which are interpreted as results of fragmentations of quarks and gluons suffered hard collisions with large transverse momenta. Inclusive properties of the jets are described by the quantum chromo-dynamics (QCD) with a high precision. The most popular Monte Carlo codes for a simalation of the processes are PYTHIA [3] and HERWIG [4]. Because the hadronization process — the fragmentation of quarks and gluons into hadrons, cannot be described in the frame of QCD, various phenomenological models are applied in the case. The total and elastic hadron–hadron cross sections are not described by QCD also. They are determined by the so-called soft interactions with low transverse momenta. Thus, for a complete interpretation of experimental data various models of a coupling of the hard and soft processes were proposed. One of the successful models is the HIJING code (Heavy Ion Jet Interaction Generator [16, 17]).

The model is a generalization of the FRITIOF model. It considers the hard jet production simulated with the help of the PYTHIA code. It is assumed in the model that the inelastic nucleon–nucleon interaction cross section has a form:

$$\sigma^{in} = \int d^2b[1 - e^{-(\sigma_{\rm soft}+\sigma_{\rm hard})T_N(\vec{b})}] =$$

$$= \int d^2b\Bigg([1 - e^{-\sigma_{\rm soft}T_N(\vec{b})}]\, e^{-\sigma_{\rm hard}T_N(\vec{b})} + \sum_{j=1} \frac{[\sigma_{\rm hard}\ T_N(\vec{b})]^j}{j!} e^{-\sigma_{\rm hard}\ T_N(\vec{b})} \Bigg), \quad (17)$$

where T_N is an overlap function of partons (quarks and gluons) from colliding hadrons at impact parameter $\vec{b}$. It is given by the Fourier transform of the dipole form factor of the proton:

$$T_N(\vec{b},s) = 2\frac{\chi_0(\xi)}{\sigma_{\rm soft}(s)}, \quad \chi_0(\xi) = \frac{\mu_0^2}{96}(\mu_0\xi)^3 K_3(\mu_0\xi), \quad \xi = |\vec{b}|/b_0(s),$$
$$\mu = 3.9, \quad \pi\ b_0^2 = \sigma_{\rm soft}(s)/2, \quad \sigma_{\rm soft}(s) = 57\ ({\rm mb}),$$

K_3 — Mac-Donald function, $\sigma_{\rm hard}$ — integrated inclusive jet production cross section given by QCD.

Equation (17) allows one to determine a number of the hard scatterings accompanied all time by the excitation of hadron residues. If the number is equal to zero, the soft interaction is simulated as in the FRITIOF model. For each hard interaction, the kinetic variables of the scattered partons (gluons) are determined by calling PYTHIA [3] subroutines. Since jet production is dominated by gluon scatterings, it is assumed that quark scatterings only involve valence quarks, and hard processes are restricted only by the gluon–gluon scatterings. Simplification is also made for the color flow in the case of multiple jet production. Produced gluons are ordered in their rapidities and then connected with their parent valence quarks or diquarks to form string systems. Finally, fragmentation subroutine of JETSET is called for hadronization.

Equation (17) is entering the Glauber formulae for hadron–nucleus and nucleus–nucleus cross sections in the corresponding routines of the HIJING code. Besides a change of the gluon distribution in nuclei (the nuclear shadowing) and interactions of the scattered gluons with spectators nucleons (the final state interactions, or jet quenching) are taken into account.

According to the Glauber approximation, it is assumed that a nucleus–nucleus collision can be decomposed into binary nucleon–nucleon collisions which generally involve the wounded nucleons. In a string picture, the wounded nucleons become strings excited along the beam direction. At high energy, the excited strings are assumed to interact again like the ordinary nucleon–nucleon collisions before they fragment. Unlike the FRITIOF model, it is allowed that an excited string can be de-excited within the kinematic limits in the subsequent collisions. The binary approximation can also be applied to rare hard scatterings which involve only independent pairs of partons. The probability for a given parton to suffer multiple high P_T scatterings is small and is not implemented in the current version of the program. A three-parameter Woods-Saxon nuclear density is used for a calculation of the number of binary collisions at a given impact parameter. After all binary collisions, the scattered partons are connected with the corresponding valence quarks and diquarks to form string systems. The strings are then fragmented into particles.

One of the most important nuclear effects in relativistic heavy-ion collisions is the nuclear modification of parton structure functions. It has been observed [68] that the effective number of quarks and antiquarks in a nucleus is depleted in the low region of x. This is called in the code as the nuclear shadowing, and is implemented.

Another important nuclear effect on the jet production in heavy ion collisions is the final state integration. In high-energy heavy-ion collisions, a dense hadronic or partonic matter must be produced in the central region. Because this matter can extend over a transverse dimension of at least R_A, jets with large P_T from hard

scatterings have to traverse this hot environment. Thus, it is very important to simulate the interaction of jets with the matter and the energy loss they suffer. It is estimated [69] that the gluon bremsstrahlung induced by soft interaction dominates the energy loss mechanism. The induced radiation in HIGING is modeled via a simple collinear gluon splitting scheme with given energy loss dE/dz. It is assumed also that the interaction only occurs with the locally comoving matter in the transverse direction. The interaction points are determined via a probability

$$dP = \frac{dl}{\lambda_s} e^{-l/\lambda_s},$$

with given mean free path λ_s, where l is the distance the jet has traveled after its last interaction. The induced radiation is simulated by transferring a part of the jet energy $\Delta E(l) = ldE/z$ as a gluon kink to the other string which the jet interacts with. The procedure is continued until the jet is out of the whole excited system or when the jet energy is smaller than a cutoff below which a jet cannot loss energy any more. The cutoff is the same as the cutoff P_0 for jet production. To determine how many and which excited strings could interact with the jet, it is assumed that excited strings within a cylinder of radius r_s along the jet direction could interact with the jet. λ_s and r_s are two parameters in the jet quenching effect.

The code of the HIJING model operates quite fast. Thus, it was widely used by RHIC and LHC experimental collaborations at designs of experimental setups.

The AMPT model (A MultiPhase Transport model) [70] is built on the HIJING code. It considers additionally to the HIJING subjects, the final state interactions between the partons. The interaction of the produced hadrons with nuclear matter is taken into account, too.

APPENDIX: CALCULATION OF NUCLEUS–NUCLEUS INTERACTION CROSS SECTIONS AT HIGH ENERGY IN THE GLAUBER APPROACH

The amplitude of scattering of a nucleus A on a nucleus B, when each of them transforms from the initial state $|i\rangle$ into the final states $|f\rangle$, is given in the Glauber approach [71, 72–75] by the expression

$$F_{A,B}(\vec{q}) = \frac{ip_A}{2\pi} \int d^2b\, e^{i\vec{q}\vec{b}} \langle f_A, f_B | 1 - \prod_{j=1}^{A} \prod_{k=1}^{B} (1 - \gamma(\vec{b} - \vec{s}_j + \vec{\tau}_k)) | i_B, i_A \rangle, \tag{18}$$

where p_A is the momentum of the projectile nucleus A, $\vec{q}$ is the transferred transverse momentum, $\vec{b}$ is the impact parameter, γ is an amplitude of elastic

NN scattering in the impact parameter representation; $\{\vec{s}_j\}$, $j = 1, 2, \ldots, A$ and $\{\vec{\tau}_k\}$, $k = 1, 2, \ldots, B$ are coordinates of nucleons within, respectively, A and B nuclei on the impact parameter plane. These coordinates are measured from the center of mass of each nucleus respectively, too.

Starting from Eq. (18), it is possible to find AB elastic scattering amplitude

$$F_{AB}^{el}(\vec{q}) = \frac{ip_A}{2\pi} \int d^2b\, e^{\imath \vec{q}\ \vec{b}} \left\{ 1 - \prod_{j=1}^{A} \prod_{k=1}^{B} (1 - \gamma(\vec{b} - \vec{s}_j + \vec{\tau}_k)) \right\}, \tag{19}$$
$$|\psi_A(\vec{r}_1, \ldots, \vec{r}_A)|^2 |\psi_B(\vec{t}_1, \ldots, \vec{t}_B)|^2 \prod_{j=1}^{A} d^3 r_j \prod_{k=1}^{B} d^3 t_k,$$

differential cross section

$$\frac{d\sigma^{el}}{d\Omega} = |F_{AB}^{el}|^2, \tag{20}$$

and total cross section

$$\sigma_{AB}^{\text{tot}} = \frac{4\pi}{p_A} \operatorname{Im} F_{AB}^{el}(0). \tag{21}$$

The cross section of the quasi-elastic scattering of the nucleus A when it is conserved, but other nucleus B undergoes all excitations including destruction too $(A + B \to A + X)$, is given by the expression

$$\sigma(A + B \to A + X) = \int d^2b \left\{ 1 - \prod_{i=1}^{A} \prod_{k=1}^{B} (1 - \gamma(\vec{b} - \vec{s}_i + \vec{\tau}_k)) \right\} \cdot \tag{22}$$
$$\left\{ 1 - \prod_{j=1}^{A} \prod_{k=1}^{B} (1 - \gamma^*(\vec{b} - \vec{s}'_i + \vec{\tau}_j)) \right\} \cdot$$
$$|\psi_A(\vec{r}_1, \ldots, \vec{r}_A)|^2 |\psi_A(\vec{r}'_1, \ldots \vec{r}'_A)|^2 |\psi_B(\vec{t}_1, \ldots, \vec{t}_B)|^2 \cdot$$
$$\prod_{i=1}^{A} d^3 r_i \prod_{i=1}^{A} d^3 r'_i \prod_{i=1}^{B} d^3 t_i - \sigma_{AB}^{el}.$$

Finally, the cross section of the production of new particles can be defined as

$$\sigma_{AB}^{\text{prod}} = \int d^2b \left\{ 1 - \prod_{i=1}^{A} \prod_{k=1}^{B} (1 - p(\vec{b} - \vec{s}_i + \vec{\tau}_k)) \right\}, \tag{23}$$
$$|\psi_A(\vec{r}_1, \ldots, \vec{r}_A)|^2 |\psi_B(\vec{t}_1, \ldots, \vec{t}_B)|^2 \prod_{i=1}^{A} d^3 r_i \prod_{i=1}^{B} d^3 t_i,$$
$$p(\vec{b}) = \gamma(\vec{b}) + \gamma^*(\vec{b}) - \gamma(\vec{b})\gamma^*(\vec{b}).$$

Equation (23) can be rewritten in the form where each of the terms would be interpreted as a probability of some process

$$\sigma_{AB}^{\rm prod} = \int d^2b \left\{ \sum_{i=1}^{A}\sum_{j=1}^{B} \frac{p(\vec{b}-\vec{s}_i+\vec{\tau}_j)}{1-p(\vec{b}-\vec{s}_i+\vec{\tau}_j)} \prod_{k=1}^{A}\prod_{l=1}^{B}(1-p(\vec{b}-\vec{s}_k+\vec{\tau}_l)) + \right.$$
$$+ \frac{1}{2} \sum_{\substack{i=1,j=1 \\ i\neq j}}^{A}\sum_{k=1}^{B} \frac{p(\vec{b}-\vec{s}_i+\vec{\tau}_k)}{1-p(\vec{b}-\vec{s}_i+\vec{\tau}_k)} \frac{p(\vec{b}-\vec{s}_j+\vec{\tau}_k)}{1-p(\vec{b}-\vec{s}_j+\vec{\tau}_k)} \times$$
$$\left. \times \prod_{l=1}^{A}\prod_{m=1}^{B}(1-p(\vec{b}-\vec{s}_l+\vec{\tau}_m)) + \ldots \right\} \times$$
$$\times |\psi_A(\vec{r}_1,\ldots,\vec{r}_A)|^2 |\psi_B(\vec{t}_1,\ldots,\vec{t}_B)|^2 \prod_{i=1}^{A} d^3r_i \prod_{i=1}^{B} d^3t_i. \quad (24)$$

Here the first term in the first braces is interpreted as a probability that the only one inelastic collision between ith nucleon from nucleus A and jth nucleon from nucleus B takes place when all nucleon coordinates are fixed. The second term describes a probability of inelastic collision of the kth nucleon from nucleus B with ith and jth nucleons in A nucleus, etc. Nucleons involved in the collisions are called as "wounded" ones, but the others are called as "spectators" ones.

To calculate all cross sections discussed above, it is necessary to have a function $\gamma(\vec{b})$ and the square of the modulus of the ground state wave function $|\psi|^2$ of A and B nuclei.

The approximation

$$\gamma(\vec{b}) = \sigma_{NN}^{\rm tot} \cdot \frac{1-i\alpha}{4\pi B} e^{-\vec{b}^2/2B} \quad (25)$$

is often used at $E > 1$ GeV/nucleon. Here σ_{NN} is the total cross section of NN interaction, α is the ratio of the real part to the imaginary part of the elastic scattering amplitude at zero momentum transfer, B is the slope parameter of the differential cross section of the elastic NN scattering. Expression (25) corresponds to the following parameterization of the elastic NN scattering amplitude in the momentum representation

$$f_{NN}(\vec{q}) = \frac{ip_A}{4\pi} \cdot \sigma_{NN}^{\rm tot}(1-i\alpha)\ e^{-B\vec{q}^2/2}.$$

Sets of values $\sigma_{NN}^{\rm tot}$, α, and B at various energies are presented in the compilations [36]. The Particle Data Group proposed the following parameterizations for the total and elastic NN cross sections at high energies [37]:

$$\sigma(p) = A + Bp^n + C\ln^2(p) + D\ln(p), \quad (26)$$

where p is the laboratory momentum in GeV/c. The parameters — A, B, C, and D are given in [37].

Function $|\psi_A|^2$ is often given as

$$|\psi_A|^2 = \prod_{i=1}^{A} \rho_A(\vec{r}_i), \tag{27}$$

where ρ represents the one-particle density of a nucleus. In this case the aggregate of the nucleon coordinates does not meet self-evident demands

$$\sum_{i=1}^{A} \vec{r}_i = 0. \tag{28}$$

Taking into account this condition is named "an account of center-of-mass correlation".

If projectile is a nucleon, it is necessary to set a density ρ_A as a delta-function $\rho_A(\vec{r}) = \delta(\vec{r})$ in this case.

The parameterization from [76] is used for deuteron

$$|\psi_d|^2 = \sum_{i=1}^{3} c_i e^{-\vec{r}^2/4\gamma_i}, \tag{29}$$

$$\begin{aligned}
&\gamma_1 = 225\ (\text{GeV}/c)^{-2}, && c_1 = 0.178/(4\pi\gamma_1)^{3/2},\\
&\gamma_2 = \ 45\ (\text{GeV}/c)^{-2}, && c_1 = 0.287/(4\pi\gamma_2)^{3/2},\\
&\gamma_3 = \ 25\ (\text{GeV}/c)^{-2}, && c_1 = 0.535/(4\pi\gamma_3)^{3/2}.
\end{aligned}$$

Here r is a distance between a proton and a neutron within a deuteron.

For ^{3}H, ^{3}He, and ^{4}He nuclei $|\psi_A|^2$ has been chosen as

$$|\psi_A|^2 = \delta\left(\frac{1}{A}\sum_{i=1}^{A}\vec{r}_i\right)\prod_{i=1}^{A}\frac{1}{\left(\pi R_A^2\right)^{3/2}}e^{-r_i^2/R_A^2}, \tag{30}$$

where $R_{^3\text{H}} = R_{^3\text{He}} = 1.81$ fm, $R_{^4\text{He}} = 1.37$ fm. For all other nuclei ($A \geq 6$) a one-particle density has been defined as

$$\rho_A(r) = \text{const}/(1 + e^{\frac{r-R_A}{c}}), \tag{31}$$

with $R_A = 1.07 \cdot A^{1/3}$ fm, $c = 0.545$ fm. The center-of-mass correlation has been taken as in paper [77].

The calculation of the cross sections is performed in accordance with the method discussed in [41], where the statement

$$|\psi_A|^2\ |\psi_B|^2 \prod_{i=1}^{A} d^3 r_i \prod_{j=1}^{B} d^3 t_j$$

is treated as a probability measure to find out different sets of nucleon coordinates in A or B nucleus. In this case, the cross sections are found as mean values over various sets of nucleon coordinates. Thus it can be written in the form

$$\sigma_{AB}^{\rm tot} = \frac{1}{N_{\rm stat}} \sum_{i=1}^{N_{\rm stat}} \int d^2b \, E_{AB}^{\rm tot}(\vec{b}, \{\vec{r_A}\}, \{\vec{t_B}\}), \tag{32}$$

where

$$E_{AB}^{\rm tot} = 1 - \prod_{i=1}^{A} \prod_{j=1}^{B} (1 - \gamma(\vec{b} - \vec{s_i} + \vec{\tau_j})),$$

and $N_{\rm stat}$ denotes a number of various sets of nucleon coordinates. Therefore, the accuracy of the calculation depends on the value of $N_{\rm stat}$. (The expressions analogous to (32) can be written for all other cross sections.)

The function E is called as a distribution over impact parameter for inelastic AB interactions:

$$P(\vec{b}) = \frac{1}{N_{\rm stat}} \cdot \sum_{i=1}^{N_{\rm stat}} E_{AB}^{\rm prod}(\vec{b}, \{\vec{r_A}\}, \{\vec{t_B}\}), \tag{33}$$

where

$$E_{AB}^{\rm prod} = 1 - \prod_{i=1}^{A} \prod_{j=1}^{B} (1 - p(\vec{b} - \vec{s_i} + \vec{\tau_j})).$$

In accordance with the expression (24), the algorithm for simulation of inelastic collisions consists of the following steps:

1. Calculation and tabulation of the function $P(\vec{b})$;

2. Generation of the impact parameter $\vec{b}$ in accordance with $P(\vec{b})$ distribution;

3. Sampling of the coordinates of the nucleons within nuclei according to $|\psi_A|^2$ and $|\psi_B|^2$ distribution functions;

4. Sampling and storing pairs of nucleons interacting inelastically. For this purposes $A \cdot B$ random numbers $\xi_{ij} (i = 1, \ldots, A, j = 1, \ldots, B)$, uniformly distributed in the $[0, 1]$ interval, are chosen. If $\xi_{ij} < p(\vec{b} - \vec{s_i} + \vec{\tau_j})$, then it is considered that an inelastic collision takes place between ith nucleon of A nucleus and jth nucleon of B nucleus.

The first step is performed only once with given nuclei A and B. The steps 2–4 are repeated as many times as it is necessary.

The method described above has been realized as a set of FORTRAN routines. These routines and their assignments are presented in the Table.

All of them can be called through the HepWeb server.

NN	Name	Routines' function	Subject
1	TOTAL	Calc. total cross sect.	$\sigma_{AB}^{\mathrm{tot}}$
2	ELASTIC	Calc. elastic cross sect.	σ_{el}
3	AB_TO_AX	Calc. cross sect. of reaction	$A+B \to A+X$
4	AB_TO_XB	Calc. cross sect. of reaction	$A+B \to X+B$
5	AB_TO_X	Calc. cross sect. of reaction without process of production of particles	$A+B \to X$
6	PRODUCT	Calc. cross sect. of multiparticle production	$\sigma_{AB}^{\mathrm{prod}}$
7	G_X_SECT	Calc. all above cross sect.	
8	GL_STAR	Simulates inelastic events	

REFERENCES

1. *V. Zagrebaev and A. Kozhin*, Nuclear Reactions Video (knowledge base on low-energy nuclear physics), JINR Report, E10-99-151, Dubna, 1999; http://nrv.jinr.ru
2. *J. M. Butterworth and S. Butterworth*, arXiv: hep-ph/0210404 (2002).
3. http://home.thep.lu.se/∼torbjorn/Pythia.html
4. http://hepwww.rl.ac.uk/theory/seymour/herwig/
5. *J. Bromley et al.*, Hamburg 1995/96, Future Physics at HERA, vol. 1, 611–612.
6. *A. S. Johnson*, CHEP 2000, Computing in High-Energy and Nuclear Physics, 741–745. http://jas.freehep.org/
7. http://www-sldnt.slac.stanford.edu/jas/Documentation/ howto/xml/default.shtml
8. *M. Matthews*, http://mmmysql.sourceforge.net/old-index.html; http://www.mysql.com/downloads/api-jdbc.html
9. Tomcat http://jakarta.apache.org/tomcat
10. *J. C. Collins, D. E. Soper and G. Sterman*, Nucl. Phys. **B250** (1985) 199; *F. Landry, R. Brock, Pavel M. Nadolsky, C. P. Yuan*, Phys. Rev. **D67** (2003) 073016, e-Print: hep-ph/0212159.
11. *S. A. Bass et al.*, Prog. Part. Nucl. Phys. **41** (1998) 225; nucl-th/9803035.
12. *M. Bleicher et al.*, J. Phys. **G25** (1999) 1859; hep-ph/9909407.
13. http://www.gsi.de/fair/experiments/CBM/index_e.html
14. http://www-panda.gsi.de/auto/_home.htm
15. *H. Sorge*, Phys. Rev. **C52** (1995) 3291.
16. *X. -N. Wang and M. Gyulassy*, Phys. Rev. **D44** (1991) 3501.
17. *M. Gyulassy and X. -N. Wang*, Comput. Phys. Commun. **83** (1994) 307; nucl-th/9502021.
18. http://geant4.web.cern.ch/geant4/
19. CBM Collaboration, Compressed Baryonic Matter Experiment — Technical Status Report, 2005.

20. *PANDA Collaboration*, Technical Progress Report for: PANDA (AntiProton Annihilations at Darmstadt) Strong Interaction Studies with Antiprotons, 2005.
21. *V. S. Barashenkov, F. G. Zheregy and Zh. Zh. Musulmanbekov*, JINR Preprint **P2-83-117**, Dubna, 1983.
22. *B. Andersson et al.*, Nucl. Phys. **B281** (1987) 289;
B. Nilsson-Almquist and E. Stenlund, Comp. Phys. Commun. **43** (1987) 387.
23. *V. S. Barashenkov and V. D. Toneev*, Interaction of High-Energy Particles and Atomic Nuclei with Nuclei, Moscow, Atomizadt, 1972.
24. *N. W. Bertini et al.*, Phys. Rev. **C9** (1974) 522.
25. *N. W. Bertini et al.*, Phys. Rev. **C14** (1976) 590.
26. *J. P. Bondorf et al.*, Phys. Lett. **65B** (1976) 217.
27. *J. P. Bondorf et al.*, Zeit. Phys. **A279** (1976) 385.
28. *V. D. Toneev and K. K. Gudima*, Nucl. Phys. **A400** (1983) 173.
29. *M. I. Adamovich et al.* (EMU-01/12 - Collab.), Zeit. Phys. **A 358** (1997) 337.
30. *V. V. Uzhinskii*, JINR Commun, E2-96-192, Dubna, 1996.
31. *Kh. El-Waged and V. V. Uzhinskii*, Phys. Atom. Nucl. **60** (1997) 828; Yad. Fiz. **60** (1997) 925.
32. *A. Galoyan, J. Ritman and V. Uzhinsky*, nucl-th/0605021 (2006).
33. *A. Galoyan, J. Ritman and V. Uzhinsky*, nucl-th/0605039 (2006).
34. http://lcgapp.cern.ch/project/simu/generator/
35. *V. V. Uzhinsky*, hep-ph/0312089 (2003).
36. *O. Benary, L. R. Price and G. Alexander.* NN and ND Interactions [above 0.5 GeV/c] — a Compilation, UCRL-20000NN, 1970;
V. Flaminio, W. G. Moorhead, D. R. O. Morrison and N. Rivoire, Compilation of Cross Sections: p and $\bar{p}$ Induced Reactions, CERN–HERA 84-01, 1984.
37. The Particle Data Group, Phys. Rev. **D54** (1996) 125.
38. LIT Scientific Report 2004-2005, 2005-179, JINR, Dubna 2005, pp. 25–28.
39. LIT Scientific Report 2004-2005, 2005-179, JINR, Dubna 2005, pp. 29–32.
40. *S. Yu. Shmakov, V. V. Uzhinskii and A. M. Zadorozhny*, Comp. Phys. Commun. **54** (1989) 125.
41. *S. Yu. Shmakov, V. V. Uzhinski, A. M. Zadorojny*, Comp. Phys. Commun. 54. (1989) 125.
42. *A. G. Galperin and V. V. Uzhinskii*, JINR Preprint, **E2-94-505**, Dubna, 1994.
43. *M. Blann*, Ann. Rev. Nucl. Sci. **17** (1966) 478.
44. *V. Weisskopf*, Phys. Rev. **52** (1937) 295.
45. *W. A. Friedman*, Phys. Rev. **C28** (1983) 16.
46. *S. G. Mashnik*, In "Proceedings of a Specialists Meeting - Intermediate Energy Nuclear Data: Models and Codes". Paris, 1994, P. 107.
47. *M. B. Blann, H. Gruppelaar, P. Nagel, J. Rodens*, Report "International Code Comparison for Intermediate Energy Nuclear Data", NEA, OECD, Paris, 1994.
48. *G. F. Bertch and S. Das Gupta*, Phys. Rep. **160** (1988) 189.

49. *W. Cassing, V. Metag, V. Mosel, K. Nuta*, Phys. Rep. **188** (1990) 363.
50. *J. Aichelin*, Phys. Rep. **202** (1991) 233.
51. *H. Sorge, H. Stoker, W. Greiner*, Ann. of Phys. (N.Y.) **192** (1989) 266; Nucl. Phys. **A498** (1989) 567c.
52. *H. Sorge et al.*, Zeit. für Phys. **C47** (1990) 629.
53. *H. Sorge et al.*, Zeit. für Phys. **C59** (1993) 85.
54. *K. Hikasa et al.*, Phys. Rev. **D45** (1992) III.83.
55. *A. Donnachie and P. V. Landshoff*, Phys. Lett. **B296** (1992) 227.
56. *P. Koch, B. Muller and J. Rafelski*, Phys. Rept. **142** (1986) 167.
57. *Bo Andersson, G. Gustafson and B. Soderberg*, Z. Phys. **C20** (1983) 317.
58. *R. D. Field and R. P. Feynman*, Phys. Rev. D15 (1977) 2590.
59. *R. D. Field and R. P.* Feynman, Nucl. Phys. **B136** (1978) 1.
60. *B. Ganhuyag and V. Uzhinsky*, JINR Commun. **1-97-315**, Dubna, 1997; JINR Commun. **2-97-397**, Dubna, 1997;
B. Ganhuyag, JINR Commun. **2-98-26**, Dubna, 1998.
61. *V. V. Uzhinsky and A. S. Pak*, Yad. Fiz. **59** (1996) 1109.
62. *A. I. Bondarenko, V. V. Rusakova, J. A. Salomov, G. M. Chernov*, Yad. Fiz. **55** (1992) 135 (Sov. J. Nucl. Phys. **55** (1992)).
63. *D. Armutlisky et al.*, Zeit. für Phys. **A328** (1987) 455.
64. *H. N. Agakishiev et al.*, Yad. Fiz. **56** (1993) 170 (Sov. J. Nucl. Phys. **56** (1993)).
65. *A. A. Baldin*, Yad. Fiz. **56** (1993) 174 (Sov. J. Nucl. Phys. **56** (1993)).
66. *A. Y. Abul-Magd, W. A. Friedman, J. Hufner*, Phys. Rev. **C34** (1986) 113.
67. *A. I. Bondarenko et al.*, Yad. Fiz. **65** (2002) 95.
68. *EM Collab., J. Ashman et al.*, Phys. Lett. **B202** (1988) 603;
EM ColIab., M. Arneodo et al., Phys. Left. **B211** (1988) 493.
69. *M. Gyuiassy et al.*, Nucl. Phys. **A538** (1992) 37 c;
M. Gyulassy and X-. N. Wang, Nuci. Phys. **B420** (1993) 583.
70. *Z. W. Lin et al.*, Phys. Rev. **C72** (2005) 064901; Phys. Rev. **C64** (2001) 011902;
B. Zhang et al., Phys. Rev. **C61** (2000) 067901.
71. *V. Franco*, Phys. Rev. **175** (1968) 1376.
72. *W. Czyz, L. C. Maximon*, Ann. of Phys. (N.Y.) **52** (1969) 59.
73. *O. Kofoed–Hansen*, Nuov. Cim. **60A** (1969) 621.
74. *D. R. Harrington and A. Pagnamenta*, Phys. Rev. **184** (1969) 1908.
75. *J. Formanek*, Nucl. Phys. **1312** (1969) 441.
76. *L. S. Azhgirey et al.*, JINR Preprint **E2-12683**, Dubna, 1979.
77. *V. V. Uzhinskii and S. Yu. Shmakov, S. J.* Nucl. Phys. **57** (1994) 1532.

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