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RESEARCH ARTICLE

Particles Multiplicities in Proton-Proton, Nucleus–Nucleus Collisions and Relativistic Quantum Molecular Dynamics Model

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Abstract

Secondary particle multiplicities produced from hadron-hadron collisions such as proton-proton and heavy nuclei Pb+Pb and Au+Au, were analyzed in terms of the predictions of the dynamical postulates suggested by ultra-relativistic quantum molecular model UrQMD with recent version UrQMD-2.3. The proposed quark de-confinement and formation of strings and string-string interactions are used well to describe the experimental results of particle multiplicities for some hadrons. For strange baryons, the model will need to be modified due to high mass resonances and the adjustments of the strangeness suppression factors. The experimental mean multiplicity of each secondary hadron produced for p-p interactions at 200 A GeV is well agreement with the corresponding prediction suggested by UrQMD.

1. Introduction

Nuclear collisions between hadron-hadron and nucleus-nucleus at relativistic energies give good chance to study the properties of nuclear matter in terms of partonic processes. Now many of experimental data are available with a wide range of energies starting from center of mass (c.m.) energy $\sqrt{s}$ = 0.9 TeV, via 2.36 TeV, to the current maximum energy of 7 TeV [1–5]. In addition to the projectile energies, the mass number of interacting heavy nuclei such as Pb+Pb and Au+Au, increases the possibility for the number of interacting nucleons therefore, the average collision number per baryon increases. This gives suitable conditions of high energy density where the process becomes more difficult and confirms creation of non-equilibrium states of excited nuclear matter. During these conditions, a part of longitudinal momenta is converted into transverse momentum, which is responsible for production of secondary particles.

The quark model of hadrons and the development of quantum chromodynamics QCD, naturally led to new concepts consider the strongly interacting matter exists in different phases and study the nature of the transitions between these phases. In particular, it is commonly believed that a gas of hadrons will undergo a transition to a state of quasi-free quarks and gluons, the Quark Gluon Plasma (QGP) [6], when its temperature exceeds a critical value [7]. These postulates have motivated a broad experimental program of nucleus-nucleus collisions to study the properties of strongly interacting matter at extreme densities and temperatures. The multiplicities of secondaries are strong depending on the energy of the interacting system in center of mass coordinates. Many theoretical models are partly able to give new concepts on nuclear materials under these conditions and special formulations for treatments of the assumed processes that are responsible for the creations and production of secondary particles, which are observed experimentally. One of the important of these models is the quantum molecular dynamic model QMD and it ultra-relativistic implementation Ur-QMD. This model is a microscopic many body approach to pp, pA, and AA interactions at relativistic energies. It can be applied for studying hadron-hadron, hadron-nucleus and heavy ion reactions from E_{lab} = 100 A MeV to $\sqrt{s_{NN}}$ = 200 GeV. Its microscopic transport approach is based on the covariant propagation of color strings, constituent quarks and di-quarks (as string ends) accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of ingoing and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. At higher energies, the treatment of sub-hadronic degrees of freedom is of major importance. In the present model, these degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [8-10]. The major aspects of the formulation of Ur-QMD will now discuss briefly in section 2. For more detailed description in ref. [11,12]. The comparison and discussions with the recent results of secondary particle multiplicities for pp and for Pb-Pb collisions at relativistic energies and results suggested by Ur-QMD-2.3 model will be in section 3.

2. Ultra Relativistic Quantum Molecular Dynamic (Ur-QMD)

In term, QCD, major theory for strong interactions, it depend on the small values of the coupling constant $\alpha_s(Q^2)$ at large values of Q^2, where Q, represents the momentum transfer. The perturbation theory is the dominant while at large values of coupling constant the non-perturbative effect is responsible for the confinement of hadrons. This large distance dynamics is very essential for understanding the processes with small momentum transfer, which gives a dominant contribution to the high-energy hadronic interaction. The Ur-QMD model [13] considers the hadrons as bubbles in QCD vacuum liquid with the chromodynamical fields of quarks which do not penetrate in the vacuum medium, then the interactions of such bubbles at high energies leads to the production of new objects color tubes, or strings. The interaction between such objects can take place with color transfer when quarks from different hadrons are interacting and without color transfer when hadrons are interacting only by exchange of the momenta. In both cases, it leads to increase of energy and at some momenta, it will be energetically favorable to break the color tube by producing $\overline{q}q$-pair from the vacuum. This process repeats until many white bubbles-hadrons will produced. According to the uncertainty principle, the time needed for production of a hadron with momentum p is $\tau \approx p/m^2$, so in the c.m. system the last will be produced the fastest hadrons containing the spectator quarks (inside-outside cascade). Each produced q and $\overline{q}$ has small relative moments in their rest frame or small rapidity distances. As a result, due to Lorentz invariance of the picture, finally produced hadrons at high energies will uniformly distributed in rapidity and will have limited transverse momenta.

At high-energy reactions, we use a similar picture corresponding to the case when two hadrons are interacting only by momentum transfer. In baryon-baryon (meson-meson) interaction strings between quark q_v and di-quark qq_v (anti-quark $\overline{q}_v$) from the same hadron are produced. The hadron-hadron interactions at high energies are simulated in three stages. According to the cross-sections, the type of interaction is defined: elastic, inelastic, anti-baryon-baryon annihilation. In the case of inelastic collision with string excitation the kinematical characteristics of strings are modeled in the following way: The hadron momentum transfer p_T is simulated according to a Gaussian distribution

$$f(p_T) \propto \frac{1}{\sqrt{\pi\sigma^2}} e^{\left(-\frac{p_T^2}{\sigma^2}\right)} \tag{1}$$

where σ =1.6 GeV/c. The other interacting hadron gets the same momentum transfer but in the opposite direction. The excited strings have the continuous mass distribution $f(M) \propto 1/M^2$ with the masses M, limited by the total collision energy $\sqrt{s}$: $M_1+M_2 \le \sqrt{s}$. The rest of the $\sqrt{s}$ is equally distributed between the longitudinal momenta of two produced strings: $p_{1\|} = p_{2\|}$. The energy of the *i*-th, string E_i is defined by the longitudinal momentum of the string $p_{i\|}$, momentum transfer p_T and the mass of the string M_i:

$$E_i^2 = p_{i\|}^2 + p_T^2 + M_i^2, \quad i = 1,2 \tag{2}$$

$$E_1 + E_2 = \sqrt{s} \tag{3}$$

The longitudinal momenta of the constituent quarks are chosen according to the structure functions of hadrons:

$$f(x_q) = f_0(x_q)^{\alpha-1}(1-x_q)^{\beta-1} \tag{4}$$

with α = 0.5 and β = 2.5 for valence quark in nucleons. The quantity x_q, represents the longitudinal momentum-fraction of the string which is transferred to the new hadron and it defined by Lorentz-invariant quantities:

$$x = \frac{p_{hadron}}{p_{total}} \qquad (0 \le x \le 1) \tag{5}$$

The transverse distribution of the constituent quarks was generated according to the same Gaussian distribution as for the momentum transfer Eq. (1). The di-quark transverse momentum is equal in magnitude, but of opposite direction.

The second stage of h-h interactions is connected with string fragmentation. Ur-QMD uses the Field-Feynman fragmentation procedure when the strings decay independently from both ends. It includes energy, momentum and quantum number conservation laws and the possibility of converting di-quarks into mesons via di-quark breaking. The excitation and fragmentation of a string follows an iterative scheme:

string⇒ hadron + new string ,

i.e. 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 a Breit-Wigner distribution. Finally, the energy-fraction of the string, which is assigned to the newly created hadron, must be 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 fragmentation function $f(x, m_t)$ represents the probability distribution for hadrons 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 [14]:

$$f(x, m_t) \sim \frac{1}{x}(1-x)^a \, e^{(-b \cdot m_t^2/x)} \tag{6}$$

In Ur-QMD, different fragmentation functions are used for leading nucleons and newly produced particles, respectively.

$$f(x)_{nuc} = e^{\left(-\frac{(x-B)^2}{2A^2}\right)} \quad \text{for leading nucleons} \tag{7}$$

$$f(x)_{prod} = (1-x)^2 \quad \text{for produced particles} \tag{8}$$

with A = 0.275 and B = 0.42. The fragmentation function $f(x)_{prod}$, used for newly produced particles, is the well-known Field-Feynman fragmentation function [15, 16]. At string break-up, $\bar{q}q$-pair have zero transverse momentum in the string frame, but the transverse momenta of a single quark, p_t, and the corresponding anti-quark, $-p_t$, is taken according to Eq. (1). The main criteria for the selection of the fragmentation functions and the fine-tuning of their parameters are that the particle multiplicities and momentum distributions in elementary proton-proton reactions must match the data.

3. Experimental comparisons

One of the most important tools for any theoretical model is comparison with experimental results for the same assumed criteria. The UrQMD transport model has been successfully used to predict and interpret experimental data at various energies and for a multitude of observables and reaction systems, e.g. hadron yields, transverse and longitudinal spectra [17- 19]. Now we make a comparison between experimental data, from NA49 Collaboration[20], for secondary particle multiplicities produce from inelastic 4π-space pp collisions from E_{lab} = 2 A GeV to $\sqrt{s_{NN}}$ = 200 GeV, with the corresponding predictions suggested by UrQMD with the recent version UrQMD-2.3.

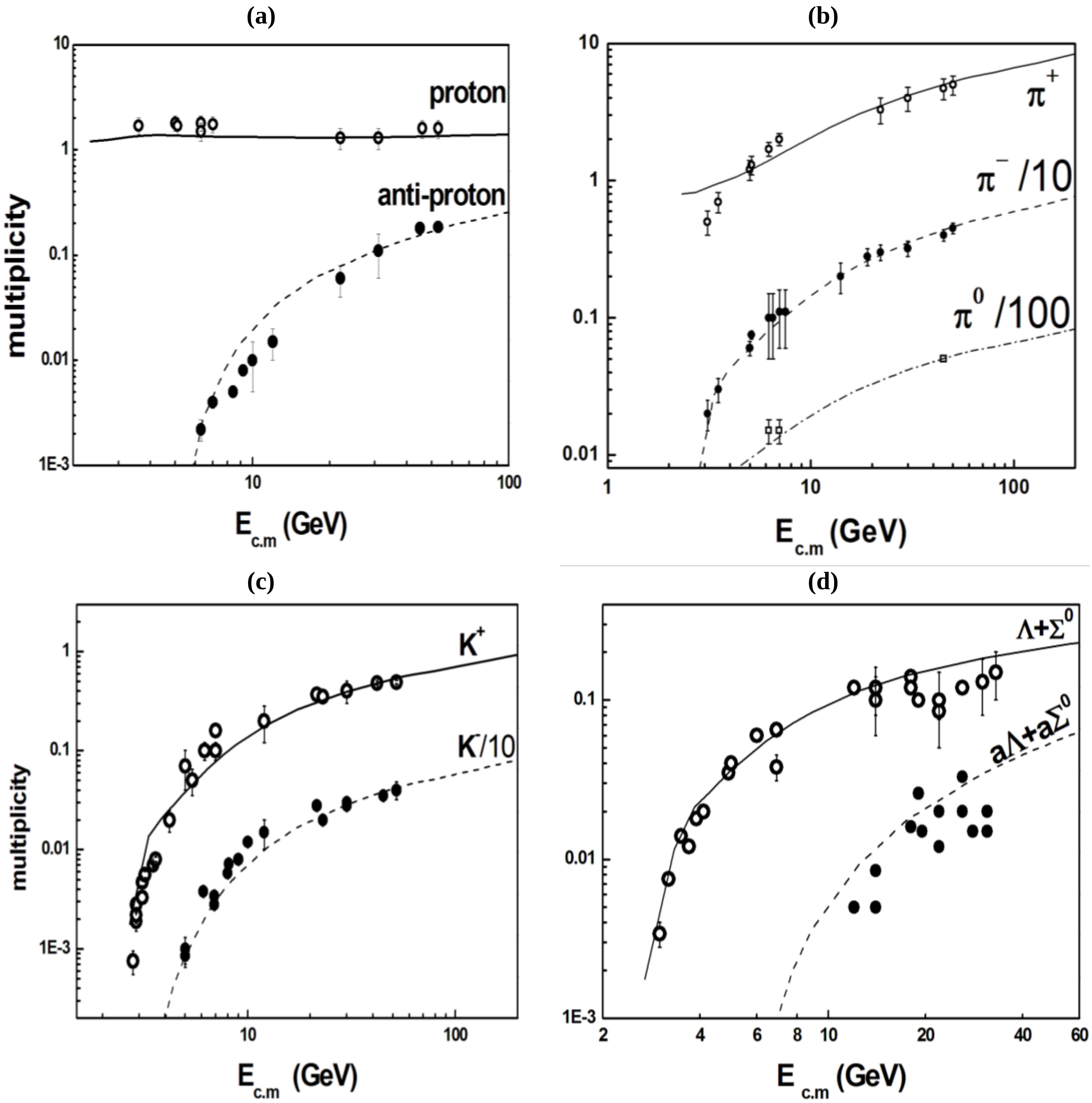

Figure 1 The dependence secondary charged multiplicities for pp collisions on center of mass energy for proton and anti-proton (a), π-mesons (b), charged k-meson (c) and $\Lambda + \Sigma^0$and respective antiparticle (d). the solid and dash lines are the corresponding prediction by UrQMD-2.3

Figure 1 gives the available experimental data for multiplicities of secondary proton, anti-proton (fig.1a) charged and neutral π-meson (fig.1b), charged k-meson (fig.1c) and $\Lambda + \Sigma^0$ and their respective antiparticle (fig.1d) produced from pp interactions and their dependence on the collision center of mass energies. The solid and dash lines represent the suggested data by the UrQMD-2.3 model. Within experimental errors, one can notice the multiplicities of proton, antiproton and possible secondary pions and k-mesons are well described by the model. The experimental data for anti $\Lambda + \Sigma^0$, is not completely described by the model. It may due to the experimental statistics and the model required additional treatments for double strange di-quark suppression factor. The experimental mean multiplicities of each hadron and the corresponding suggested by UrQMD recorded from p-p interactions at 200 A GeV is given in table 1. The model gives good agreement with the experimental data.

The experimental average transverse momentum $< P_T >$ for charged π-meson and k-meson at different collision energies for pp interactions is shown in figure 2. The model is success for giving the dynamical description of the pp-collisions and so the transverse momentum, which give an indication of the distribution function of the parton momentum and hence the energy density of the nuclear matter under consideration.

Table 1 the mean multiplicities of secondary particles compared to prediction of UrQMD for p-p reaction at 200 A GeV

Secondary particle	Mean multiplicity	Prediction by UrQMD
p	1.34±0.15	1.32
$\overline{p}$	0.05±0.02	0.05
π^-	2.62±0.06	2.47
π^+	3.22±0.12	3.07
π^0	3.34±0.24	3.01
k^-	0.18±0.05	0.13
k^+	0.28±0.06	0.23
k^0	0.17±0.01	0.18
$\Lambda + \Sigma^0$	0.096±0.01	0.17
$\overline{\Lambda} + \overline{\Sigma}^0$	0.013±0.004	0.03

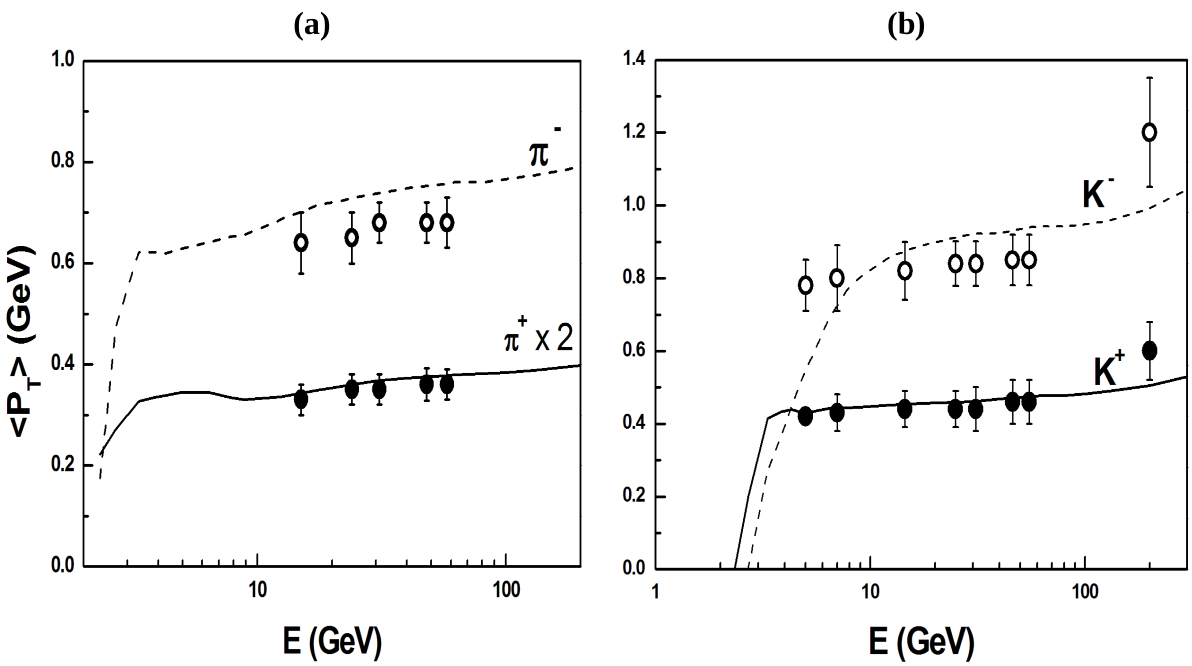

Figure 2 The dependence of the transverse momentum for charged π-meson (a) and k-meson (b) on interaction energy. The solid and dash lines are the corresponding prediction by UrQMD-2.3

In heavy-ion interactions, such as Pb+Pb and Au+Au collisions the energy dependence is more complicated and number of produced charged hadrons is much bigger than in pp collisions of the order of 20000 charged hadrons in a central Pb-Pb collision at to $\sqrt{s_{NN}}$ =2.76 TeV. It explains in terms of increasing the number of interacting nucleons and hence the multiplicities of secondary produced particles. The analyses of the energy dependence of hadron production properties in central Pb+Pb and Au+Au collisions within various theoretical approaches support the hypothesis that the onset of de-confinement is located at the low SPS energies.

For A+A collisions, UrQMD[13] treat the initial nucleon-nucleon interactions within a string-hadronic framework. In addition, these models include effects such as string-string interactions and hadronic re-scattering that are expected to be relevant in A+A collisions. The predictions of the excitation function of 4π multiplicities for different particle species using UrQMD-2.3 models are shown in fig. 3. All the calculations have been performed for central collisions (b < 3.4 fm). The model can give a suitable representation of particle multiplicity for pions and k-mesons but the yields of the (multi) strange baryons has changed because of the new treatment of high mass resonances and the adjustments of the strangeness suppression factors.

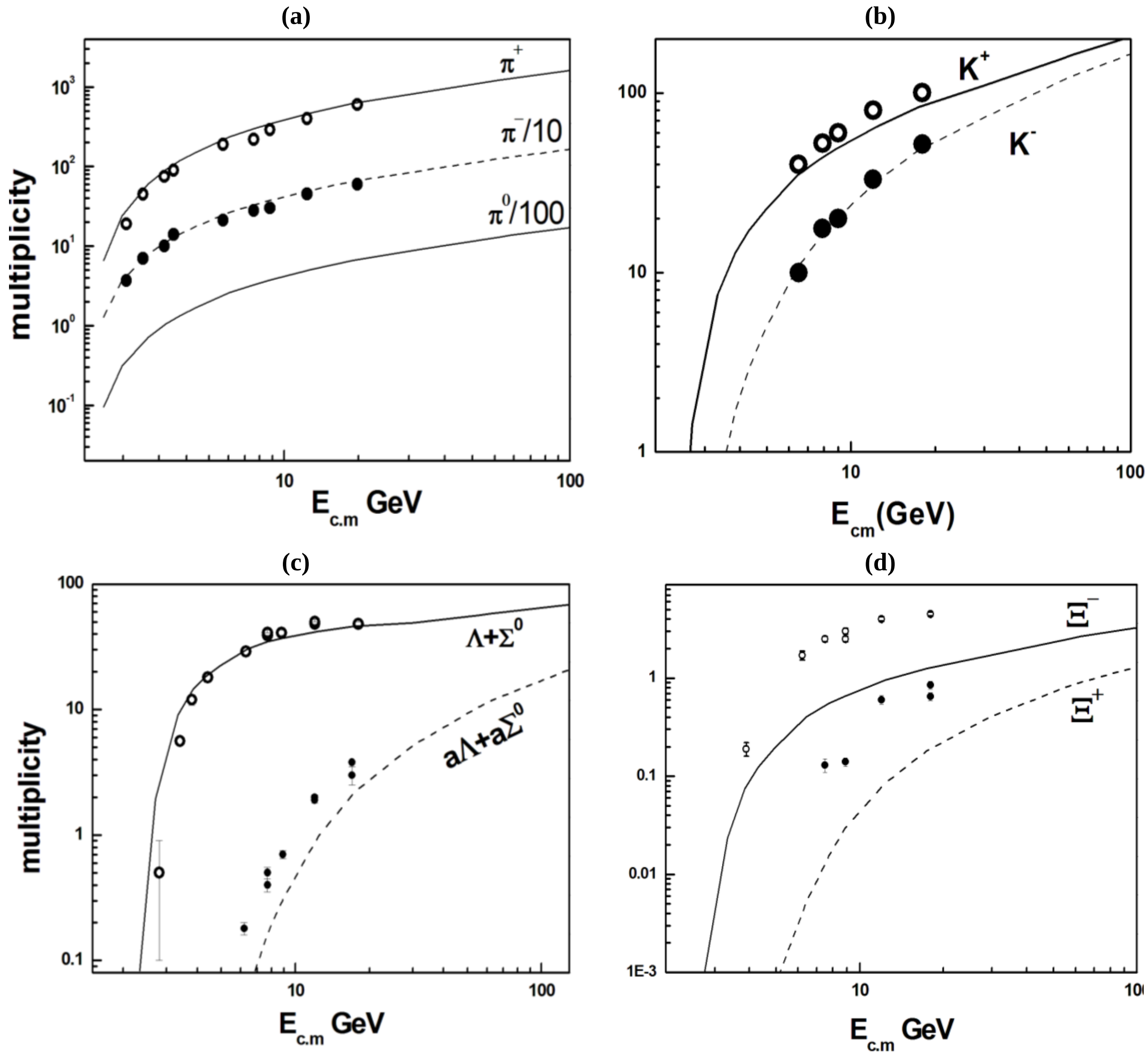

Figure 3 The dependence secondary charged multiplicities for Pb+Pb and Au+Au on center of mass energy for proton and anti-proton (a), π-mesons (b), charged k-meson (c) and $\Lambda + \Sigma^0$and charged Ξ particle (d). the solid and dash lines are the corresponding prediction by UrQMD-2.3

Conclusion

The dependence of the multiplicities for different secondary particles produced from proton- proton interaction on the center of mass energy are well represented by the predictions suggested by ultra-relativistic quantum molecular model using the recent version UrQMD-2.3. This agreement is extended to heavy ion collisions such as Pb-Pb and Au-Au. For heavy strange baryons, the model needs a new treatment of high mass resonances and the adjustments of the strangeness suppression factors.

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