Pion Production in Heavy-ion Collisions in the 1 A GeV region *

FENG Zhao-Qing[1,2]†, JIN Gen-Ming[1,2]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

[2] *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China*

Abstract

Within the framework of the improved isospin dependent quantum molecular dynamics (ImIQMD) model, the pion emission in heavy-ion collisions in the region 1 A GeV is investigated systematically, in which the pion is considered to be mainly produced by the decay of resonances △(1232) and N*(1440). The in-medium dependence and Coulomb effects of the pion production are included in the calculation. Total pion multiplicity and π^-/π^+ yields are calculated for the reaction ^{197}Au+^{197}Au in central collisions for selected Skyrme parameters SkP, SLy6, Ska, SIII and compared them with the measured data by the FOPI collaboration.

PACS: 25.75.-q, 13.75.Gx, 25.80.Ls

Heavy-ion collisions at intermediate energies play a significant role to extract the information of the nuclear equation of state (EoS) under extreme conditions, i.e., at high densities and high temperature. Besides nucleonic observables such as rapidity distribution and flow, also mesons emitted from the reaction zone can be probes of the hot and dense nuclear matter, that are also the interest physics at the Cooling Storage Ring (CSR) energies in Lanzhou.[1] The emission of pion in heavy-ion collisions in the region 1 A GeV is especially sensitive as probes of isospin asymmetric EoS at supra-saturation densities.[2] Spectra of the pion emission in heavy-ion collisions have

*Supported by the National Natural Science Foundation of China under Grant No. 10805061, the special foundation of the president fellowship, the west doctoral project of Chinese Academy of Sciences, and major state basic research development program 2007CB815000.

†Tel: 0931-4969215, 13893620698; Email: fengzhq@impcas.ac.cn

been measured by the Kaos and FOPI collaborations and analyzed systematically by the present theoretical transport models.[3, 4] A comparison of the various transport approaches was made in Ref. [5]. The present theoretical models overpredict the total pion multiplicity if using free nucleon-nucleon (NN) cross sections below 2 A GeV region compared with experimental data. Further investigations of the pion emissions in the 1 A GeV region are still necessary by improving transport models or developing some new approaches. The improved isospin-dependent quantum molecular dynamics model has been successfully applied to treat fusion dynamics and reaction mechanism of two colliding nuclei near Coulomb barrier.[6, 7, 8] To investigate the pion emission, we further include the inelastic channels in nucleon-nucleon collisions in the ImIQMD model.

In the ImIQMD model, the time evolutions of the baryons and pions in the system under the self-consistently generated mean-field are governed by Hamilton's equations of motion, which read as

$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}, \quad \dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}. \tag{1}$$

Here we omit the shell correction part in the Hamiltonian H as described in Ref. [7]. The Hamiltonian of baryons consists of the relativistic energy, the effective interaction potential and the momentum dependent part as follows:

$$H_B = \sum_i \sqrt{\mathbf{p}_i^2 + m_i^2} + U_{int} + U_{mom}. \tag{2}$$

Here the $\mathbf{p}_i$ and m_i represent the momentum and the mass of the baryons.

The effective interaction potential is composed of the Coulomb interaction and the local interaction

$$U_{int} = U_{Coul} + U_{loc}. \tag{3}$$

The Coulomb interaction potential is written as

$$U_{Coul} = \frac{1}{2} \sum_{i,j,j\neq i} \frac{e_i e_j}{r_{ij}} erf(r_{ij}/\sqrt{4L}) \tag{4}$$

where the e_j is the charged number including protons and charged resonances. The $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ is the relative distance of two charged particles. The local interaction potential is derived directly from the Skyrme energy-density functional and expressed as

$$U_{loc} = \int V_{loc}(\rho(\mathbf{r}))d\mathbf{r}. \tag{5}$$

The local potential energy-density functional reads [7]

$$V_{loc}(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{1+\gamma}\frac{\rho^{1+\gamma}}{\rho_0^{\gamma}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur}^{iso}}{2\rho_0}[\nabla(\rho_n - \rho_p)]^2 + \frac{C_{sym}}{2\rho_0}\rho^2\delta^2 + g_\tau \rho^{8/3}/\rho_0^{5/3}, \tag{6}$$

where the ρ is the baryon density and the $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry with the proton density ρ_p and the neutron density ρ_n. The momentum dependent part in the Hamiltonian is expressed as

$$U_{mom} = \frac{\delta}{2} \sum_{i,j,j \neq i} \frac{\rho_{ij}}{\rho_0} [\ln(\epsilon(\mathbf{p}_i - \mathbf{p}_j)^2 + 1)]^2, \tag{7}$$

with

$$\rho_{ij} = \frac{1}{(4\pi L)^{3/2}} \exp\left[-\frac{(\mathbf{r}_i - \mathbf{r}_j)^2}{4L}\right]. \tag{8}$$

Here the L denotes the square of the pocket-wave width, which is dependent on the size of the nucleus.

In Table 1 we list the ImIQMD parameters related to several typical Skyrme forces after including the momentum dependent interaction. The parameters α, β, γ, g_τ, g_{sur}, g_{sur}^{iso}, δ and ϵ are related to the Skyrme parameters t_0, t_1, t_2, t_3 and x_0, x_1, x_2, x_3, and determined in order to reproduce the binding energy (E_B=-16 MeV) of symmetric nuclear matter at saturation density for a given incompressibility as well as the correct momentum dependence of the real part of the proton-nucleus optical potential. In the following calculation we take the Skyrme parameter SLy6, which can give the good properties from finite nucleus to neutron star [9].

Analogously to baryons, the Hamiltonian of pions is represented as

$$H_\pi = \sum_{i=1}^{N_\pi} \left(\sqrt{\mathbf{p}_i^2 + m_\pi^2} + V_i^{Coul} \right), \tag{9}$$

where the $\mathbf{p}_i$ and m_π represent the momentum and the mass of the pions. The Coulomb interaction is given by

$$V_i^{Coul} = \sum_{j=1}^{N_B} \frac{e_i e_j}{r_{ij}}, \tag{10}$$

where the N_π and N_B is the total number of pions and baryons including charged resonances. Thus, the pion propagation in the whole stage is guided essentially by the Coulomb effect. The in-medium pion potential in the mean field is not considered in the model. However, the inclusion of the pion optical potential based on the perturbation expansion of the Δ-hole model gives negligible influence on the transverse momentum distribution.[10]

The pion is created by the decay of the resonances $\triangle(1232)$ and N*(1440) which are produced in inelastic NN scattering. The direct pion production cross section is very small in the considered energies and not included in the model.[11] The reaction channels are given as follows:

$$\begin{aligned} &NN \leftrightarrow N\triangle, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \triangle\triangle, \\ &\Delta \leftrightarrow N\pi, \quad N^* \leftrightarrow N\pi. \end{aligned} \tag{11}$$

The cross section of each channel to produce resonances are taken the values calculated with the one-boson exchange model.[13] Transport models overpredicted the total pion production with the free cross section. In the ImIQMD model, we use the free elastic cross section and the in-medium inelastic cross section which is given by $\sigma_{medium}^{inelastic} = (\frac{\mu_{BB}^*}{\mu_{BB}})^2 \sigma_{free}^{inelastic}$ with the free baryon-baryon (BB) inelastic cross section $\sigma_{free}^{inelastic}$ and the reduced effective mass μ_{BB}^* (free mass μ_{BB}). The experimental data of total elastic and inelastic cross sections[12] are parameterized in the ImIQMD model as shown in Fig.1.

In the 1 A GeV region, there are mostly Δ resonances which disintegrate into a π and a nucleon, however, the N^* yet gives considerable contribution to the high energetic pion yield. The energy and momentum dependent decay width is used in the ImIQMD model and expressed as

$$\Gamma(|\mathbf{p}|) = \frac{a_1|\mathbf{p}|^3}{(1+a_2|\mathbf{p}|^2)(a_3+|\mathbf{p}|^2)}\Gamma_0, \qquad (12)$$

which originates from the p-wave resonances. The $\mathbf{p}$ is the momentum of the created pion (in GeV/c) in the resonance rest frame. The values a_1 =22.48 (17.22), a_2 =39.69 and a_3 =0.04 (0.09) are used for the Δ (N^*) with bare decay width Γ_0 =0.12 GeV (0.2 GeV).[13] In Fig.2 we show a comparison of the time evolution of the π, Δ and N^* production in the reaction ^{197}Au+^{197}Au for head on collisions at 1 A GeV for two cases of the bare decay and energy dependent decay widths. Both methods almost give the same yield of the pion production. In the following calculation, we use the energy and momentum dependent decay width. In Fig.3 we give the multiplicity of produced pion as a function of the impact parameter for the same system at 1 A GeV energy. The numbers of produced π^-, $\pi^0$and π^+ are reduced with increasing the impact parameter because of the decrease of the participants of the 'fire ball' formed in the heavy-ion collisions.

The emission of the produced pion is sensitive to the incident energy owing to the size of the compressed nuclear matter. We calculated the transverse momentum distribution of π^-, $\pi^0$and π^+ in central ^{197}Au+^{197}Au collisions at different incident energies as shown in Fig.4. The larger and wider distributions were found at the higher incident energies due to the larger participant numbers of the collision nucleons. The high energy pions originate from the early phase and the decay of the N*(1440) resonance also plays a significant role.[14] In Fig.5 we compare the total pion number and the π^-/π^+ ratio with the FOPI data in central ^{197}Au+^{197}Au collisions[3] for the Skyrme parameters SkP, SLy6, Ska and SIII which correspond to the different incompressibility modulus as listed in table 1. The calculated value of the total pion number is related to the incompressibility modulus K_∞ and the effective mass in nuclear medium. Over the whole domain, the force SLy6 is nice and can reproduce the experimental data. But the parameter slight overpredicts the total pion multiplicity at lower incident energies and underestimates the value at higher incident energies if using the above in-medium inelastic cross section. The in-medium elastic and inelastic cross sections are still open problems in transport model calculations, which should be calculated by microscopic many-body models and then parameterized to add into transport models. The π^-/π^+ ratio is interest for extracting the high density behavior of the symmetry energy per nucleon.[2] Using the isobar model, one gets the ratio π^-/π^+=1.95 for pions from the Δ resonance, and π^-/π^+=1.7 from the N^* for the system ^{197}Au+^{197}Au.[15] These relations are globally valid, i.e. independent of the pion energy. The observed energy dependence of the π^-/π^+ ratio is due to the influence of the Coulomb force and the symmetry energy interaction. The π^-/π^+ ratio is sensitive to the stiffness of the symmetry energy at the lower incident energies. Recently, a soft nuclear symmetry energy at supra-saturation densities was pointed out by fitting the FOPI data with the IBUU04 model.[16] In the ImIQMD model, we only consider the linear dependence of the symmetry energy term on the baryon density as shown in Eq.(6). The inclusion of the density-dependent symmetry energy in the ImIQMD model is in progress.

In summary, the pion production in heavy-ion collisions in the region 1 A GeV for the reaction ^{197}Au+^{197} is investigated systematically by using the ImIQMD model. The distribution of the transverse momentum is calculated at different incident energies. The total number of produced pion and the π^-/π^+ ratio are calculated in central collisions for selected Skyrme parameters SkP, SLy6, Ska, SIII and compared them with the FOPI data. Deviations from the simple isobar model originate from the Coulomb and the symmetry interactions. The π^-/π^+ ratio is sensitive to the stiffness of the symmetry energy at the lower incident energies that may be further investigated at the CSR energies.

We would like to thank Prof. Lie-Wen Chen, Prof. Wei Zuo and Dr. Gao-Chan Yong for fruitful discussions.

References

[1] Zhan W L, Xia J W, Zhao H W et al (HIRFL-CSR Group) 2008 *Nucl. Phys. A* **805** 533c

[2] Li B A, Chen L W, Ko C M 2008 *Phys. Rep.* **464** 113

[3] Reisdorf W, Stockmeier M, Andronic A et al (FOPI collaboration) 2007 *Nucl. Phys. A* **781** 459

[4] C. Müntz et al (KaoS collaboration) 1995 *Z. Phys. A* **352** 175

[5] Kolomeitsev E E, Hartnack C, Barz H W et al 2005 *J. Phys. G* **31** S741

[6] Feng Z Q, Zhang F S, Jin G M, Huang X 2005 *Nucl. Phys. A* **750** 232

[7] Feng Z Q, Jin G M, Zhang F S 2008 *Nucl. Phys. A* **802** 91

[8] Wang N, Li Z X, Wu X Z et al 2004 *Phys. Rev. C* **69** 034608.

[9] Chabanat E, Bonche P, Haensel P et al 1997 *Nucl. Phys. A* **627** 710

[10] Fuchs C, Sehn L, Lehmann E et al 1997 *Phys. Rev. C* **55** 411.

[11] Li B A, Sustich A T, Zhang B, Ko C M 2001 *Int. J Mod. Phys. E* **10** 1

[12] Catherine L-L, François L 1993 *Rev. Mod. Phys.* **65** 47

[13] Huber S, Aichelin J 1994 *Nucl. Phys. A* **573** 587

[14] Maheswari V S, Fuchs C, Faessler A et al 1998 *Nucl. Phys. A* **628** 669

[15] Stock R 1986 *Phys. Rep.* **135** 259

[16] Xiao Z G, Li B A, Chen L W et al 2009 *Phys. Rev. Lett.* **102** 062502

Table 1: ImIQMD parameters and properties of symmetric nuclear matter for Skyrme effective interactions after the inclusion of the momentum dependent interaction with parameters δ=1.57 MeV and ϵ=500 c^2/GeV^2

Parameters	SkM*	Ska	SIII	SVI	SkP	RATP	SLy6
α (MeV)	-325.1	-179.3	-128.1	-123.0	-357.7	-250.3	-296.7
β (MeV)	238.3	71.9	42.2	51.6	286.3	149.6	199.3
γ	1.14	1.35	2.14	2.14	1.15	1.19	1.14
g_{sur}(MeV fm^2)	21.8	26.5	18.3	14.1	19.5	25.6	22.9
g_{sur}^{iso}(MeV fm^2)	-5.5	-7.9	-4.9	-3.0	-11.3	0.0	-2.7
g_τ (MeV)	5.9	13.9	6.4	1.1	0.0	11.0	9.9
C_{sym} (MeV)	30.1	33.0	28.2	27.0	30.9	29.3	32.0
ρ_∞ (fm^{-3})	0.16	0.155	0.145	0.144	0.162	0.16	0.16
m^*_∞/m	0.639	0.51	0.62	0.73	0.77	0.56	0.57
K_∞ (MeV)	215	262	353	366	200	239	230

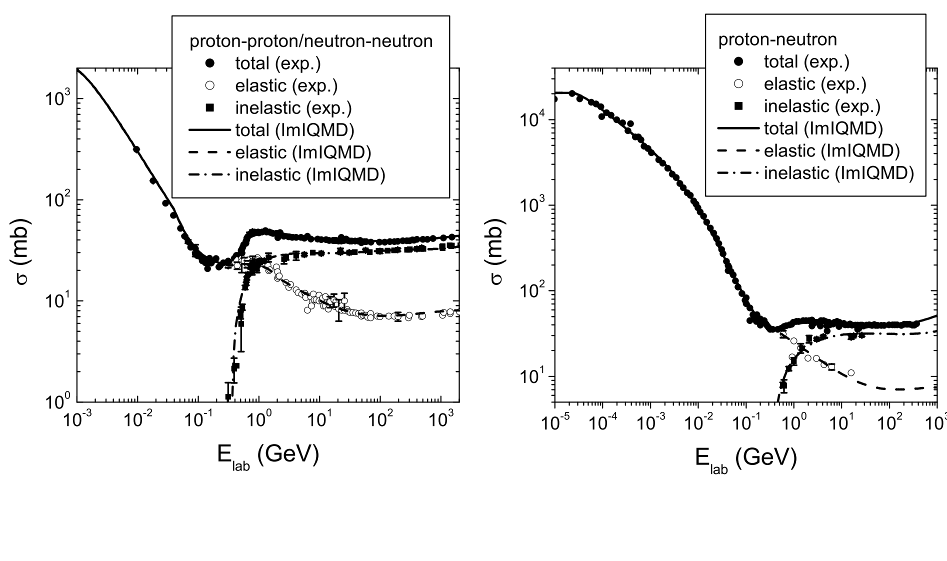

Figure 1: Comparison of nucleon-nucleon cross sections parameterized in ImIQMD and the experimental data.[12]

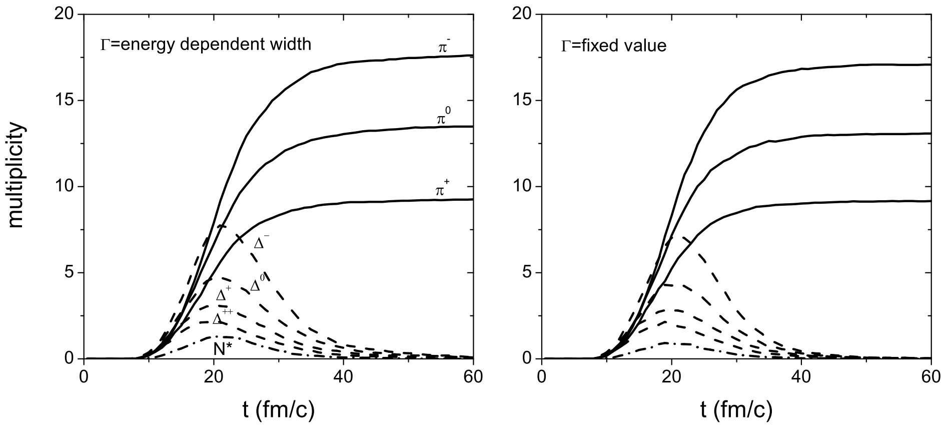

Figure 2: Production of pion, delta and N* for head-on collisions in the reaction ^{197}Au+^{197}Au at 1 A GeV as functions of evolution time with the energy dependent decay width (left panel) and fixed width (right panel).

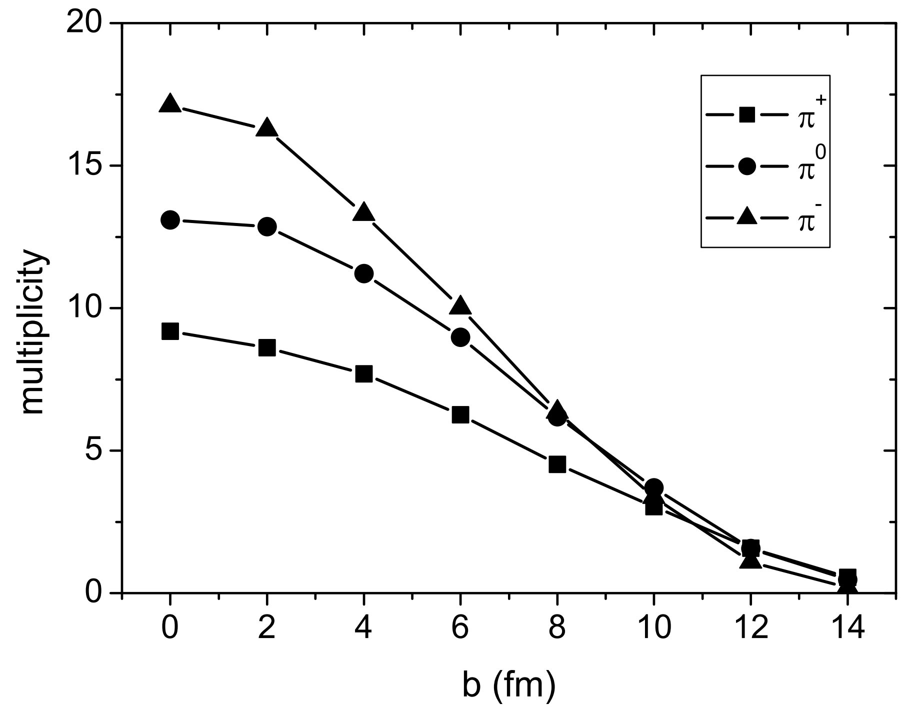

Figure 3: Final multiplicities of π^-, π^0 and π^+ as a function of impact parameter for head-on collisions in the reaction ^{197}Au+^{197}Au at 1 A GeV.

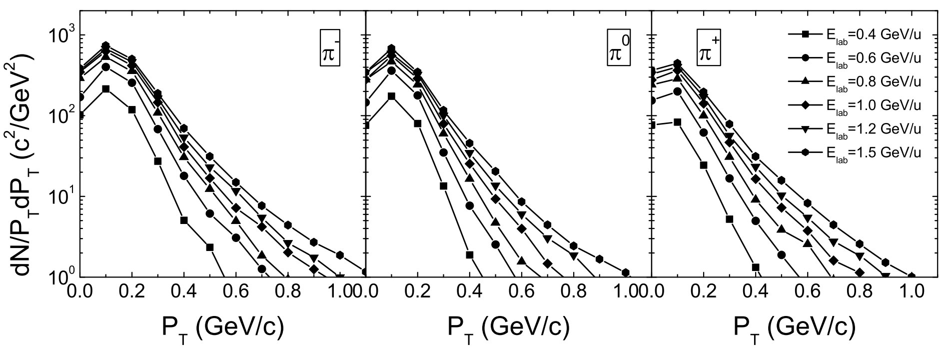

Figure 4: Final transverse momentum distribution in central ^{197}Au+^{197}Au collisions at different incident energies.

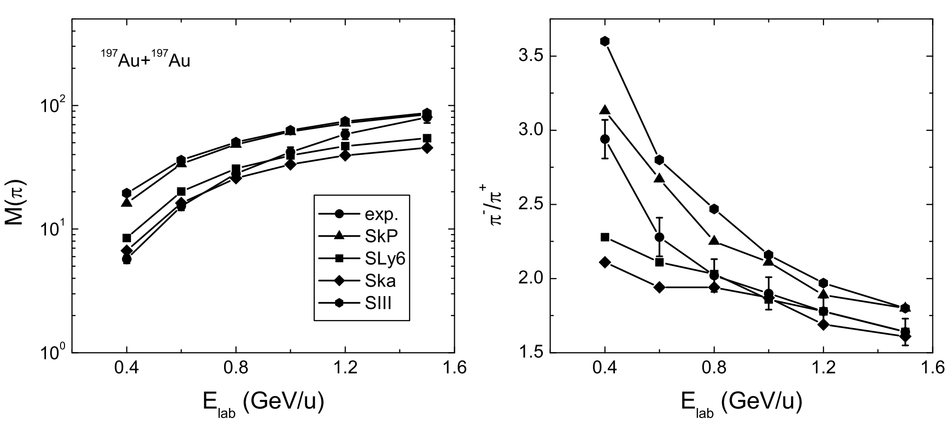

Figure 5: Calculated excitation functions of the total pion multiplicity (left panel) and the ratio π^-/π^+ (right panel) in central ^{197}Au+^{197}Au collisions and compared with the FOPI data.[3]