A systematic study of the $\pi^-/\pi^+$ ratio in heavy-ion collisions with the same neutron/proton ratio but different masses

Ming Zhang,¹ Zhi-Gang Xiao,¹ Bao-An Li,² Lie-Wen Chen,³ Gao-Chan Yong,²,⁴ and Sheng-Jiang Zhu¹

¹Department of Physics, Tsinghua University, Beijing 100084, China
²Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA
³Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China
⁴Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China

(Dated: September 20, 2009)

A systematic study of the $\pi^-/\pi^+$ ratio in heavy-ion collisions with the same neutron/proton ratio but different masses can help single out effects of the nuclear mean field on pion production. Based on simulations using the IBUU04 transport model, it is found that the $\pi^-/\pi^+$ ratio in head-on collisions of $^{48}\text{Ca}+^{48}\text{Ca}$, $^{124}\text{Sn}+^{124}\text{Sn}$ and $^{197}\text{Au}+^{197}\text{Au}$ at beam energies from 0.25 to 0.6 GeV/nucleon increases with increasing the system size or decreasing the beam energies. A comprehensive analysis of the dynamical isospin fractionation and the $\pi^-/\pi^+$ ratio as well as their time evolution and spatial distributions demonstrates clearly that the $\pi^-/\pi^+$ ratio is an effective probe of the high-density behavior of the nuclear symmetry energy.

PACS numbers: 25.70.-z, 25.60.-t, 25.80.Ls, 24.10.Lx

The high-density (HD) behavior of the nuclear symmetry energy $E_{\text{sym}}(\rho)$ has long been regarded as among the most uncertain properties of dense neutron-rich nuclear matter [1, 2, 3, 4]. It is very essential for understanding not only fundamental astrophysical phenomena [2, 3, 4, 5] but also novel features of high energy heavy ion reactions especially those induced by rare isotopes [4, 6, 7, 8, 9, 10, 11]. The $\pi^-/\pi^+$ ratio in heavy-ion collisions has been a particularly sensitive probe of the HD behavior of the $E_{\text{sym}}(\rho)$ [2]. Based on the simulations using the IBUU04 transport model [12], analysis of the $\pi^-/\pi^+$ ratio in heavy-ion collisions with the same neutron/proton ratio in head-on collisions of $^{48}\text{Ca}+^{48}\text{Ca}$, $^{124}\text{Sn}+^{124}\text{Sn}$ and $^{197}\text{Au}+^{197}\text{Au}$ at beam energies from 0.25 to 0.6 GeV/nucleon increases with increasing the system size or decreasing the beam energies. A comprehensive analysis of the dynamical isospin fractionation and the $\pi^-/\pi^+$ ratio as well as their time evolution and spatial distributions demonstrates clearly that the $\pi^-/\pi^+$ ratio is an effective probe of the high-density behavior of the nuclear symmetry energy.

The values of the parameters are $\sigma = 4/3$, $B = 106.35$ MeV, $C_{\tau,\tau} = -11.70$ MeV, $C_{\tau,-\tau} = -103.40$ MeV and $A = p_f^0$ which is the Fermi momentum of nuclear matter at the saturation density $\rho_0$ [16]. For asymmetric nuclear matter at zero temperature, the MDI symmetry energy can be written as [15]

$$E_{\text{sym}}(\rho) = \frac{1}{2} \left( \frac{\partial^2 E}{\partial \rho^2} \right)_{\delta=0}$$

$$= \frac{8\pi}{9m\hbar^3} p_f^2 + \frac{\rho}{4\rho_0} (A_1(x) - A_2(x)) - \frac{Bx}{\sigma + 1} \left( \frac{\rho}{\rho_0} \right)^\sigma$$

$$+ \frac{C_1}{9\rho_0^4} \left( \frac{4\pi}{\hbar^3} \right)^2 \Lambda^2 \left[ 4p_f^2 - \Lambda^2 \right]$$

$$+ \frac{C_2}{9\rho_0^4} \left( \frac{4\pi}{\hbar^3} \right)^2 \Lambda^2 \left[ 4p_f^2 - p_f^2 (4p_f^2 + \Lambda^2) \right]$$

where $p_f = (\frac{3\pi^2}{2} \hbar)^{1/3}$ is the Fermi momentum for symmetric nuclear matter at density $\rho$. We note here that since the $A_1(x) - A_2(x) = -24.59 + 4Bx/\sigma + 1$ according to Eq. (2), the $E_{\text{sym}}(\rho)$ depends linearly on the parameter $x$ at a given density except at $\rho_0$ where the $E_{\text{sym}}(\rho_0)$ is fixed at 30.54 MeV. Shown in the inset of Fig. 1 are examples of the $E_{\text{sym}}(\rho)$ with $x=1, 0$ and -2, respectively. The strengths of the corresponding isovector vector potential estimated from $(U_n - U_p)/2\hbar$ are shown for 3 typical densities in the main frame of Fig. 2. At the normal density $\rho_0$, by design, the symmetry potential is independent of $x$ and is consistent with the Lane potential extracted from the experimental data of nucleon-nucleus scatterings and the (p,n) charge exchange reactions [4]. It is necessary to emphasize that it is the symmetry potential, not the symmetry energy, that enters as a direct input in all transport model simulations. It is thus important to point out the key characteristics of the symmetry potentials. With $x=0$, the symmetry potential is weak but remains mostly posi-

*Electronic address: xiaozg@tsinghua.edu.cn
tive at all densities in the momentum range considered. With \(x=-2\) leading to the stiffer symmetry energy, the symmetry potential is positive at all densities. With \(x=1\) leading to the softer symmetry energy, however, the symmetry potential is negative at supra-saturation densities.

It was found that only the very soft \(E_{\text{sym}}(\rho)\) with \(x=1\) can well reproduce the FOPI data. The stiffer \(E_{\text{sym}}(\rho)\) with \(x=0\) (which resembles very well the APR prediction up to about 3.5\(\rho_0\)) under-predicts significantly the data as in earlier IQMD calculations using an \(E_{\text{sym}}(\rho)\) very similar to the APR prediction or the MDI \(E_{\text{sym}}(\rho)\) with \(x=0\). The interesting ramifications in both nuclear physics and astrophysics of this finding about the HD behavior of the \(E_{\text{sym}}(\rho)\) strongly calls for additional theoretical studies and experimental tests. Since pions always undergo strong final state interactions, the latter may distort the information carried by the \(\pi^-/\pi^+\) messenger about the HD behavior of the \(E_{\text{sym}}(\rho)\). In this work, based on the IBUU04 transport model simulations of heavy-ion collisions with the same neutron/proton ratio but different masses we further investigate how reliable the \(\pi^-/\pi^+\) ratio is in probing the HD behavior of the \(E_{\text{sym}}(\rho)\).

To understand the advantage of comparing systematically the \(\pi^-/\pi^+\) ratios in heavy-ion reactions with the same neutron/proton ratio but different masses, we start by recalling the first-chance nucleon-nucleon collision model for pion production and the dynamical isospin fractionation mechanism for enhancing the neutron/proton ratio of the HD region and thus the \(\pi^-/\pi^+\) ratio from there. Near the pion production threshold of about 300 MeV, it is reasonable to assume that only first chance inelastic nucleon-nucleon collisions produce pions. Since the \(\pi^-\) and \(\pi^+\) are mostly produced from \(nn \rightarrow np + \pi^-\) and \(pp \rightarrow np + \pi^+\), respectively, and the \(nn\) collisions contribute equally to the production of both \(\pi^-\) and \(\pi^+\), the primordial \(\pi^-/\pi^+\) ratio is expected to be proportional to the neutron/proton ratio squared, i.e., \((N/Z)^2_{\text{dense}}\) of the participant region. Indeed, more detailed estimate based on the \(\Delta(1232)\) isobar model predicts a primordial \(\pi^-/\pi^+\) ratio of \(R_{\text{iso}} = (\pi^-/\pi^+)_{\text{res}} \approx (5N^2 + N/Z)/(5Z^2 + N/Z) \approx (N/Z)^2_{\text{dense}}\). Due to the detailed balance, the reabsorption of \(\pi^-\) and \(\pi^+\) mainly through the \(\Delta\) resonances correlate proportionally to their production, they are thus not expected to change significantly the primordial \(\pi^-/\pi^+\) ratio in the absence of possible in-medium effects of the \(\Delta\) resonances (see, however, refs. [29] and [30]). The Coulomb force in the final state is expected to affect the differential \(\pi^-/\pi^+\) ratio as a function of pion momentum but not the integrated \(\pi^-/\pi^+\) ratio. The final \(\pi^-/\pi^+\) multiplicity ratio is thus a direct measure of the isospin asymmetry \((N/Z)^2_{\text{dense}}\) in the early stage of the reaction. While the latter is determined by the HD model through dynamical isospin fractionation phenomenon [21, 22, 23, 24, 25, 13], namely, the participant region is more neutron-rich (poor) if the value of the HD \(E_{\text{sym}}(\rho)\) there is lower (higher). In terms of the reaction dynamics for pion production within transport models, the \(\pi^-/\pi^+\) ratio depends on the \((N/Z)^2_{\text{dense}}\) which is determined by the isovector part of the nuclear mean-field. Effects of the latter depends on the density gradients reached and the duration of the reaction. The density range and reaction time can be varied by varying the masses of the reaction system and the beam energy. In doing so, to examine the effects of the HD \(E_{\text{sym}}(\rho)\), it is better to use reactions of the same neutron/proton ratio so that the initial isospin asymmetry of the reaction system remains and thus allows us to examine clearly effects of the isospin fractionation. The observed effects can then be essentially attributed to the variation of the dynamical isospin fractionation due to the changing density and reaction time. In the following, we compare head-on reactions of \(^{48}\text{Ca}+^{48}\text{Ca}, ^{124}\text{Sn}+^{124}\text{Sn}\) and \(^{197}\text{Au}+^{197}\text{Au}\) at beam energies from 0.25 to 0.6 GeV/nucleon. Their isospin asymmetries are approximately the same, more quantitatively, 1.40, 1.48 and 1.49, respectively.

Shown in Figure 2 are the excitation functions of the \(\pi^-/\pi^+\) ratio with the \(E_{\text{sym}}(\rho)\) of \(x=1\) and \(x=0\), respectively. The error bars presented in the plots are of only statistical origin. The \(\pi^-/\pi^+\) ratio increases with decreasing the beam energy and exceeds the isobar model prediction indicated by the dashed line in the plots. This trend is again consistent with the FOPI data in \(^{208}\text{Au}+^{208}\text{Au}\) reactions and other model calculations [13]. In the energy regime considered here, pions are mainly produced through the \(\Delta\) isobar. If we denote

\[ E = \frac{U_n - U_p}{2S} \]

\[ k(fm^{-1}) \]

FIG. 1: (Color online) The symmetry potential as a function of nucleon momentum. With \(\rho = \rho_0\), the curves are identical for \(x=-2, 0, 1\). The inset shows the density dependence of the symmetry energy with \(x=-2, 0, 1\), respectively.
FIG. 2: (Color online) Excitation function of the $\pi^-/\pi^+$ ratio using the MDI interaction with $x = 1$ (open square) and 0 (open triangle) for the head-on collisions of $^{40}$Ca+$^{48}$Ca, $^{124}$Sn and $^{158}$Au+$^{197}$Au, respectively.

$R_\pi \equiv \pi^-/\pi^+$, then its difference from the $\Delta$ isobar model prediction $R_{\text{isob}}$ can be used to measure effects of the isospin fractionation on pion production. To the first order of approximation, the $R_\pi - R_{\text{isob}}$ is due to the isovector nuclear mean-field. Effects of the latter are expected to depend on both the space-time volume and the density gradients reached in the reaction. Shown in the upper window of Fig. 3 is the mass $A_{\text{sym}}$ dependence of the $R_\pi - R_{\text{isob}}$ at beam energies of 0.25, 0.4 and 0.6 GeV/nucleon, respectively. The results are obtained using the $E_{\text{sym}}(\rho)$ with $x = 1$. The $R_\pi - R_{\text{isob}}$ exhibits a nearly linear dependence on the system mass or volume at a given beam energy. At lower beam energies, while the maximum density reached is lower the reaction time is longer. The net isospin fractionation effect of the isovector potential on the $\pi^-/\pi^+$ ratio is thus larger. On the other hand, at higher energies, the $R_\pi - R_{\text{isob}}$ increases with $A_{\text{sym}}$ much faster due to both the higher density gradients reached and the larger reaction volume available in these reactions. To quantify the sensitivity of the $\pi^-/\pi^+$ ratio to the variation of the $E_{\text{sym}}(\rho)$ and present its systematics compactly, we define the sensitivity as the double ratio of the $\pi^-/\pi^+$ obtained with the $E_{\text{sym}}(\rho)$ of $x = 1$ over that with $x = 0$. The sensitivity is shown in the lower panel of Fig. 3 as a function of the $R_\pi - R_{\text{isob}}$. It is interesting to see that at a given value of the $R_\pi - R_{\text{isob}}$, the sensitivity is independent of the reactions systems considered as they all have the same initial neutron/proton ratio $N/Z$. Moreover, the sensitivity increases with the $R_\pi - R_{\text{isob}}$ as one expects since effects of the isovector potential is approximately linearly proportional to the isospin asymmetry of the medium. Overall, all indications are that the $\pi^-/\pi^+$ ratio is probing the strength of the isovector potential and depends on the space-time volume of the reaction. More quantitatively, for the reactions considered, the sensitivity increases from about several percents to approximately twenty percents at the maximum isospin fractionation. It suggests that the $\pi^-/\pi^+$ ratio in heavy systems at relatively low beam energies is preferred for probing the HD behavior of the $E_{\text{sym}}(\rho)$.

Having established that the $\pi^-/\pi^+$ ratio depends on the isovector mean-field through the isospin fractionation mechanism, we now examine more closely how the latter works and its dependence on the $E_{\text{sym}}(\rho)$. To quantify the isospin asymmetry of an excited system during heavy-ion reactions, we define $n_{\text{like}} \equiv n + \frac{2}{3} \Delta^0 + \frac{1}{3} \Delta^+ + \Delta^-$, $p_{\text{like}} \equiv p + \frac{2}{3} \Delta^+ + \frac{1}{3} \Delta^0 + \Delta^+$. As a typical example, the average ratio $< N/Z >= n_{\text{like}}/p_{\text{like}}$ at the instant of 8, 10 and 12 fm/c when the maximum compression is reached in the reaction of Ca+Ca, Sn+Sn and Au+Au at 0.4 GeV/nucleon, respectively, is shown as a function of the local density in Fig. 3. It is seen that the maximum density reached is the highest for the Au+Au reaction as one expects. To understand the results more easily, we recall that for two regions in thermal-chemical equilibrium at densities $\rho_1$ and $\rho_2$, and isospin asymmetries $\delta_1$ and $\delta_2$, one has approximately [22] $\delta_1 \cdot E_{\text{sym}}(\rho_1) = \delta_2 \cdot E_{\text{sym}}(\rho_2)$. While the reaction system may not be in complete thermal-chemical equilibrium, the above relation and the $E_{\text{sym}}(\rho)$ shown in Fig. 3 help us understand easily the observed correlation between the $< N/Z >$ and the local density. Comparing the $< N/Z >$ obtained with $x = 1$ and $x = 0$, it is seen that the supra-saturation density region is more neutron-rich with $x = 1$ as one expects based on the $E_{\text{sym}}(\rho)$ shown in figure 3. On the contrary, the subsaturation density region is more neutron-rich with $x = 0$. The effect from both the sub- and supra-saturation density behavior of $E_{\text{sym}}(\rho)$ will compete and contribute to the final observable. As shown in figure 2 the fact that the $\pi^-/\pi^+$ ratio is higher with $x = 1$ indicates that it indeed reflects the $< N/Z >$ of the supra-saturation density region, otherwise the final $\pi^-/\pi^+$ ratio would
be higher with $x = 0$ if it was mainly determined by the $E_{\text{sym}}(\rho)$ at subsaturation densities. On the other hand, it is seen in figure 2 that the $\pi^-/\pi^+$ ratios calculated with $x = 0$ are also above the predictions of the isobar model at low beam energies although the $\langle N/Z \rangle$ at supra-saturation densities is slightly below the N/Z value of the reaction system as shown in figure 4. This might indicate significant changes in the local N/Z ratios during the time evolution of the reaction since the results in figure 4 represent only the density dependence of the $\langle N/Z \rangle$ at the respective instants of the maximum compression, not for the entire duration of the reaction.

Since pions always subject to strong final state interactions the $\pi^-/\pi^+$ ratio may also be affected by the $E_{\text{sym}}(\rho)$ at sub-saturation densities. To quantitatively evaluate effects of the low density $E_{\text{sym}}(\rho)$, let’s define $x_L(x_H)$ as the $x$ parameter at sub (supra)-saturation densities. Effects of the $E_{\text{sym}}(\rho)$ at different densities can then be revealed by comparing calculations using different $x_L(x_H)$ parameters. As an illustration, shown in figure 3 is the $\pi^-/\pi^+$ ratio at the chemical freeze-out in the Au+Au collisions at 0.4 GeV/nucleon with different $x_L(x_H)$ combinations. Comparing the middle two panels, it is seen that the saturated value of the $\langle x \rangle/\langle y \rangle$ ratio increases by about 7% when the $x$ parameter is changed from $-2$ (stiff) to 1 (soft) at all densities. Interestingly, if we fix the $x_H$ either at $-2$ or 1 but vary the $x_L$ between 1 and $-2$, the $\pi^-/\pi^+$ ratio change by less than 2%. On the contrary, if the $x_L$ is fixed, the variation of the $x_H$ leads to about a 7% change similar to the effect observed when the $x$ parameter is varied at all densities also between $-2$ and 1. Thus, again, the $\pi^-/\pi^+$ ratio really reflects mainly the $E_{\text{sym}}(\rho)$ at supra-saturation densities with only very minor influences from the $E_{\text{sym}}(\rho)$ at sub-saturation densities.

To further investigate the reliability of the $\pi^-/\pi^+$ ratio in probing the HD $E_{\text{sym}}(\rho)$, we now turn to the
density profile and time evolution of the produced ∆ resonances through both $N + N \rightarrow N + ∆$ and $π + N \rightarrow ∆$ processes. Shown in Figure 5(a) is the total multiplicity $N_\Delta$ of primordial ∆ resonances of all charge states as a function of the local baryon density at which the ∆ resonances are produced during the entire reaction of Au+Au at 400 MeV/nucleon with $x = 0$ (solid square) and $x = 1$ (open triangle). It is seen that the $N_\Delta$ has a major peak around $2\rho_0$ and a minor bump around $0.1\rho_0$. The latter has contributions from both final state $π + N \rightarrow ∆$ resonances and the first chance $N + N \rightarrow N + ∆$ collisions when the surfaces of the two colliding nuclei just start overlapping. Interestingly, the majority of ∆ resonances are produced in the high density region. Moreover, the $N_\Delta$ is appreciably higher with the soft $E_{sym}(ρ)$ ($x = 1$) than that with the harder $E_{sym}(ρ)$ ($x = 0$) in the high density region. This is consistent with the total pion multiplicity studied in ref. [15].

We explore next the dynamics of resonance production. As an example, figure 5(b) shows the $N_\Delta$ averaged over the entire reaction volume as a function of time for the Au+Au reaction at 400 MeV/nucleon with $x = 1$. Figure 5(c) depicts the time evolution of the mean local baryon density where the ∆ resonances are produced. As a reference the average baryon density in the most central cell of 1 fm$^3$ of the colliding system is also shown using the solid curve. By comparing the results shown in Fig. 5(b) and (c), one can see clearly that the density where the ∆s are produced correlates closely to the central baryon density in the colliding system. More quantitatively, the $N_\Delta$ reaches its maximum at about 20 fm/c when the colliding system is still in the compressed phase. Indeed, most of the ∆ resonances are produced in the supra-saturation density region. Thus, the final $π^-/π^+$ ratio is more sensitive to the suprasaturation density $E_{sym}(ρ)$ instead of the subsaturation one. All these demonstrate again that the $π^-/π^+$ ratio carries effectively useful information about the HD IBUU04 transport model. The $π^-/π^+$ ratio is more sensitive to the supra-saturation density $E_{sym}(ρ)$ instead of the subsaturation one. All these demonstrate again that the $π^-/π^+$ ratio carries effectively useful information about the HD IBUU04 transport model. The $π^-/π^+$ ratio is more sensitive to the supra-saturation density $E_{sym}(ρ)$ instead of the subsaturation one. All these demonstrate again that the $π^-/π^+$ ratio carries effectively useful information about the HD IBUU04 transport model. The $π^-/π^+$ ratio is more sensitive to the supra-saturation density $E_{sym}(ρ)$ instead of the subsaturation one. All these demonstrate again that the $π^-/π^+$ ratio carries effectively useful information about the HD IBUU04 transport model.

FIG. 5: (Color online) The $π^-/π^+$ ratio with varying $E_{sym}(ρ)$ at sub- ($x_L$) and supra-saturation ($x_H$) densities for the head-on collisions of Au+Au at 400 MeV/nucleon.

FIG. 6: (Color online) The distribution of $∆$s as a function of density (a) and time (b), (c) the mean local density of $∆$s as a function of time. The curve in (c) presents the baryon density in the central region as a function of time.

In summary, we carried out simulations of the head-on collisions of 48Ca+48Ca, 124Sn+124Sn and 197Au+197Au at beam energies from 0.25 to 0.6 GeV/nucleon using the IBUU04 transport model. The $π^-/π^+$ ratio increases with increasing the system size or decreasing the beam energies, indicating the isovector mean-field is at work. A comprehensive analysis of the isospin fractionation in these reactions having approximately the same neutron/proton ratio but different masses, the time evolution and the spatial distributions of the $∆$s demonstrate
clearly that the $\pi^-/\pi^+$ is an effective probe of the HD behavior of the nuclear symmetry energy.

This work was supported in part by the National Natural Science Foundation of China under grants 10975097, 10675148, 10575071 and 10675082, MOE of China under project NCET-05-0392, Shanghai Rising-Star Program under Grant No. 06QA14024, the SRF for ROCS, SEM of China, and the National Basic Research Program of China (973 Program) under Contract No. 2007CB815004, the US National Science Foundation Awards PHY-0652548 and PHY-0757839, the Research Corporation under Award No. 7123 and the Texas Coordinating Board of Higher Education Award No. 003565-0004-2007.

[1] M. Kutschera, Phys. Lett. B 340 (1994) 1.
[2] B. A. Li, Phys. Rev. Lett. 88 (2002) 192701; Nucl. Phys. A708 (2002) 365.
[3] S. Kubis, M. Kutschera, Nucl. Phys. A 720 (2003) 189.
[4] B. A. Li, L. W. Chen, and C. M. Ko, Phys. Rep. 464 (2008) 113.
[5] K. Sumiyoshi and H. Toki, Astrophys. J. 422 (1994) 700.
[6] J. M. Lattimer, M. Prakash, Science 304 (2004) 536.
[7] A. W. Steiner et al., Phys. Rep. 411 (2005) 325.
[8] Isospin Physics in Heavy-Ion Collisions at Intermediate Energies, Eds B.A. Li, and W.UdoSchröder (Nova Science Publishers, Inc, New York, 2001).
[9] B. A. Li, C. M. Ko, and W. Bauer, Int. J. Mod. Phys. E 7 (1998) 147.
[10] P. Danielewicz, R. Lacey, and W. G. Lynch, Science 298 (2002) 1592.
[11] V. Baran, M. Colonna, V. Greco, M. Di Toro, Phys. Rep. 410 (2005) 335.
[12] B. A. Li, C. B. Das, Subal Das Gupta and C. Gale, Nucl. Phys. A 735 (2004) 563; B. A. Li, Phys. Rev. C 69 (2004) 064602.
[13] W. Reisdorf et al. for the FOPI Collaboration, Nucl. Phys. A 781 (2007) 459.
[14] A. Akmal, V. R. Pandharipande, D. G. Ravenhall, Phys. Rev. C 58 (1998) 1804.
[15] Z. G. Xiao, B. A. Li, L. W. Chen, G. C. Yong and M. Zhang, Phys. Rev. Lett. 102 (2009) 062502.
[16] C. B. Das, Subal Das Gupta, C. Gale and B. A. Li, Phys. Rev. C 67 (2003) 034611.
[17] L. W. Chen, C. M. Ko and B. A. Li, Phys. Rev. Lett. 94 (2005) 032701; B. A. Li and L. W. Chen, Phys. Rev. C 72 (2005) 064611.
[18] J. Xu, L. W. Chen, B. A. Li and H. R. Ma, Astrophys. J. 697, 1549 (2009) [arXiv:0901.2399].
[19] C. Hartnack et al., Euro. Phys. J., A1, 151 (1998).
[20] R. Stock, Phys. Rep. 135 (1986) 259.
[21] H. Muller, B. Serot, Phys. Rev. C 52 (1995) 2072.
[22] B. A. Li, C. M. Ko, Nucl. Phys. A 618 (1997) 498.
[23] V. Baran, M. Colonna, M. Di Toro, A. B. Larionov, Nucl. Phys. A 632 (1998) 287.
[24] B. A. Li, Phys. Rev. Lett. 85, 4221 (2000).
[25] H. S. Xu et al., Phys. Rev. Lett. 85 (2000) 716.
[26] L. Shi and P. Danielewicz, Europhys. Lett. 49 (2000) 34.
[27] B.A. Li, G.C. Yong and W. Zuo, Phys. Rev. C71:014608, (2005).
[28] A. B. Larionov, W. Cassing, S. Leupold, U. Mosel, Nucl. Phys. A 696 (2001) 747
[29] A. B. Larionov, U. Mosel, Nucl. Phys. A 728 (2003) 135
[30] Jun Xu, Che Ming Ko and Yongseok Oh, [arXiv:0906.1602]