Article ID: 1007-4627(2015) 02-0154-07

Constraining the Symmetry Energy Using Elliptic Flow and Yield Ratios of Light Particles

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Abstract: Based on the newly updated version of the Ultra-relativistic quantum molecular dynamics (UrQMD) model, the transverse-momentum dependent elliptic flow ratio of free neutrons vs hydrogen isotopes and the yield ratio of ^{3}H vs ^{3}He clusters emitted from ^{197}Au+^{197}Au collisions at the incident energy 400 MeV/nucleon are studied. It is found that the elliptic flow ratio $v_2^{\rm n}/v_2^{\rm H}$ is sensitive to the symmetry energy at supra-saturation densities, while the yield ratio ^{3}H/^{3}He is sensitive to the nuclear symmetry energy at sub-saturation densities. By comparing the data from FOPI/LAND and FOPI Collaborations with model calculations using various Skyrme interactions (all exhibiting similar values of isoscalar incompressibility but very different density dependences of the symmetry energy), we find that results using Skyrme interactions which parameterize a moderately soft to linear symmetry energy can reproduce both data quite well.

Key words: symmetry energy; elliptic flow; transport model

CLC number: O571.42 **Document code:** A **DOI:** 10.11804/NuclPhysRev.32.02.154

1 Introduction

It is well known that, the nuclear symmetry energy is important for investigating not only the properties of exotic nuclei, the dynamics process of heavy-ion collisions (HICs) with radioactive beams, but also many critical issues in astrophysics[1–5]. The nuclear symmetry energy can be written as

$$e_{\rm sym}(\rho)\equiv\frac{1}{2}\left(\frac{\partial^2 e(\rho,\delta)}{\partial\delta^2}\right)_{\delta=0}\approx e(\rho,\delta=1)-e(\rho,\delta=0), \tag{1}$$

where $\delta=(\rho_{\rm n}-\rho_{\rm p})/(\rho_{\rm n}+\rho_{\rm p})$ is the isospin asymmetry defined through the neutron ($\rho_{\rm n}$) and proton ($\rho_{\rm p}$) densities. $e(\rho,\delta=1)$ and $e(\rho,\delta=0)$ are the energy per nucleon of pure neutron matter and of isospin symmetric nuclear matter, respectively. Usually, the symmetry energy coefficient $S_0=e_{\rm sym}(\rho_0)$, the slope parameter $L=3\rho_0\left[\partial e_{\rm sym}(\rho)/\partial\rho\right]\big|_{\rho=\rho_0}$, and the curvature parameter $K_{\rm sym}=9\rho_0^2\left[\partial^2 e_{\rm sym}(\rho)/\partial\rho^2\right]\big|_{\rho=\rho_0}$ are used to describe the density dependence of the nuclear symmetry energy, where ρ_0 is the saturation density of nuclear matter. Although a large number of attempts have been made to identify the density dependence of the nuclear symmetry energy or the values of S_0, L, and $K_{\rm sym}$, at present there still exist some discrepancies, especially at supra-saturation densities[2–3, 6–8].

Measuring properties of nuclei, such as the thickness of the neutron skin[9–13], pygmy and giant dipole resonances[11, 14–15], nuclear isobaric analog-state energies[16], and nuclei masses[17–21], α- and β-decay energies[22], nuclear charge radii[23], we can get the information of the nuclear symmetry energy at saturation density and/or sub-saturation densities. To probe the high-density behavior of the nuclear symmetry energy in terrestrial laboratories, we need the aid of HICs. HICs offer a unique opportunity to investigate the nuclear symmetry energy from sub-saturation to supra-saturation densities. Furthermore, several observables have been found or proposed to be sensitive to the nuclear symmetry energy. These are isospin diffusions, isoscaling, yield and flow ratios of emitted nucleons and/or light clusters, π^-/π^+ and K^0/K^+ meson production ratios, the Σ^-/Σ^+ ratio, and the balance energy of directed flow[24–41]. So far, such as,

Received date: 14 Oct. 2014; **Revised date:** 8 Jun. 2015
Foundation item: National Natural Science Foundation of China (11375062, 11405054)
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the isoscaling, isospin diffusions and double neutron-proton ratio experimental data[25] are used to constrain the nuclear symmetry energy at subnormal densities, while the elliptic flow ratio of free neutrons vs protons (hydrogen isotopes)[29] and π^-/π^+[42] are used to obtain the nuclear symmetry energy at supra-saturation densities. Using the large-acceptance apparatus FOPI at the Schwerionen-Synchrotron (SIS) at GSI, the FOPI Collaboration has recently proposed a large amount of yield and collective flow data for light charged particles (proton, ^{2}H, ^{3}H, ^{3}He, and ^{4}He) from intermediate energy HICs[43–44]. These data offer new opportunities for optimizing transport model and, particularly, for the first time, provides the yield ratio of ^{3}H vs ^{3}He data over wide ranges of both beam energy and system size, for the extraction of the nuclear symmetry energy.

In this work, using the newly updated version of the Ultra-relativistic quantum molecular dynamics (UrQMD) model, the nuclear symmetry energy is probed via the transverse-momentum dependent elliptic flow ratio of free neurons vs hydrogen isotopes and the yield ratio of ^{3}H vs ^{3}He clusters emitted from ^{197}Au+^{197}Au collisions at the incident energy 400 MeV/nucleon.

The paper is arranged as follows. In the next section, the UrQMD model and its new updates are introduced briefly, and some key parametrizations related closely to this work are presented. In Sec. 3, results for the elliptic flow ratio and the yield ratio of light clusters are shown and discussed. Finally, a summary is given in Sec. 4.

2 The UrQMD model

The UrQMD model is a microscopic many-body transport approach which can be used to simulate nuclear reactions of p+p, p+A and A+A systems within a large range of beam energies[45–48]. At lower energies, the mean field part of the UrQMD model is analogous to the quantum molecular dynamics (QMD) model. Nucleons are represented by Gaussian wavepackets in phase space, and the nucleons move according to Hamiltonian equations of motion: $\dot{r}_i = \partial H/\partial \boldsymbol{p}_i$ and $\dot{p}_i = -\partial H/\partial \boldsymbol{r}_i$. $\boldsymbol{r}_i$ and $\boldsymbol{p}_i$ represent the centroids of a nucleon i in the coordinate and momentum spaces, respectively. In the present version, the nuclear effective interaction potential energy U of the total H=T+U+U$_{\rm Coul}$ can be written as $U=\int u_{\rho,md}\mathrm{d}^3\boldsymbol{r}$, and u_ρ reads as

$$u_\rho = \frac{\alpha}{2}\frac{\rho^2}{\rho_0}+\frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}}+\frac{g_{\rm sur}}{2\rho_0}(\nabla\rho)^2+ \frac{g_{\rm sur,iso}}{2\rho_0}\left[\nabla(\rho_n-\rho_{\rm p})\right]^2+\left(A\rho^2+B\rho^{\eta+1}+ C\rho^{8/3}\right)\delta^2+g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}}\ , \tag{2}$$

where α, β, η, $g_{\rm sur}$, $g_{\rm sur,iso}$, A, B, C, and $g_{\rho\tau}$ are parameters which can be directly calculated by using Skyrme parameters (see, *e.g.*, Refs. [49–50]). The momentum dependent term $u_{\rm md}$ and the Coulomb term $U_{\rm Coul}$ are treated as the same as the QMD model[51].

In this work, we choose 21 Skyrme interactions Skz4, BSk8, Skz2, BSk5, SkT6, SV-kap00, SV-mas08, SLy230a, SLy5, SV-mas07, SV-sym32, MSL0, SkO', SkA, Sefm081, SV-sym34, Rs, Sefm074, Ska35s25, SkI5, and SkI1[52] which give similar values of incompressibility K_0 (within about 230±10 MeV) but different L values (spread from 5 MeV to 161 MeV) to investigate the elliptic flow ratio. Similarly, the 13 Skyrme interactions Skz4, Skz2, SV-mas08, SLy4, MSL0, SkO', SV-sym34, Rs, Gs, Ska35s25, SkI2, SkI5, and SkI1 are selected to investigate the yield ratio of ^{3}H vs ^{3}He clusters. Fig. 1 shows the density dependence of the symmetry energy as calculated with Skz4, MSL0, SkO', SV-sym34, Ska35s25, and SkI1. For comparison, some recent constraints extracted from nuclei properties such as, the binding energy, neutron skin thickness, isovector giant quadrupole resonance and isobaric analog states[11–13, 16, 21], are also presented. It can be seen that different forms of symmetry energies favored

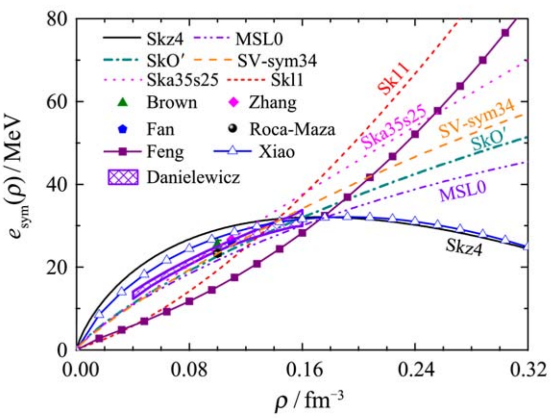

Fig. 1 (color online) Density dependence of the symmetry energy for Skz4, MSL0, SkO', SV-sym34, Ska35s25, and SkI1. The shaded region exhibits the result obtained by Danielewicz *et al.*[16]. Four different scattered symbols represent recent constraints on the symmetry energy at sub-saturation densities obtained by Roca-Maza *et al.*[11], Brown[13], Zhang *et al.*[12], and Fan *et al.*[21], respectively. Symmetry energies favored by IBUU04[27](line with open triangles) and LQMD[28] (line with solid squares) model calculations are also shown for comparison.

by theoretical groups can be covered by the selected Skyrme interactions. Moreover, we note that the symmetry energies predicted by MSL0, SkO', SV-sym34, and Ska35s25 are very close to each other at low densities (below 0.06 fm^{-3}) but well separated at high densities, and also cover the results obtained in Refs. [11–13, 16, 21].

3 Results and Discussions

The directed and elliptic flows are two of the most commonly used observables in HICs from the Fermi energy range (about 30 MeV/nucleon) up to energies available at the CERN Large Hadron Collider[53]. They can be characterized by the Fourier expansion of the azimuthal distribution of the considered emitted particles,

$$\frac{\mathrm{d}N}{u_t \mathrm{d}u_t \mathrm{d}y \mathrm{d}\phi} = v_0[1+2v_1\cos(\phi)+2v_2\cos(2\phi)] \ , \quad (3)$$

in which the directed and elliptic flow parameters v_1 and v_2 can be written as:

$$v_1 \equiv \langle\cos(\phi)\rangle = \langle\frac{p_x}{p_t}\rangle; v_2 \equiv \langle\cos(2\phi)\rangle = \langle\frac{p_x^2-p_y^2}{p_t^2}\rangle \ , \quad (4)$$

where ϕ is the azimuthal angle relative to the reaction plane, and $p_{\mathrm{t}}=\sqrt{p_{\mathrm{x}}^2+p_{\mathrm{y}}^2}$ is the transverse momentum of emitted particles. The angle brackets in Eq. 4 denote an average over all considered particles from all events. Usually the v_1 and v_2 relate to the reaction system, beam energy, impact parameter and species of the considered particles. They are also functions of u_{t} and rapidity $y=\frac{1}{2}\ln(E+p_{\mathrm{z}})/(E-p_{\mathrm{z}})$. Here $u_{\mathrm{t}}=\beta_{\mathrm{t}}\gamma$ is the transverse component of the four-velocity u=(γ, $\beta\gamma$). In this work the scaled units $u_{t0}\equiv u_{\mathrm{t}}/u_{1\mathrm{cm}}$ and $y_0\equiv y/y_{1\mathrm{cm}}$ are used as done in[44], and the subscript 1cm denotes the incident projectile in the center-of-mass system. The transverse momentum per nucleon p_{t}/A is also used in this work, here A is the mass number of the considered particles. At $E_{\mathrm{lab}}=400$ MeV/nucleon, $p_{\mathrm{t}}/A=u_{\mathrm{t}0}\cdot 0.431$ GeV/c.

As a first step, it is necessary to test the ability of our updated model to reproduce the existing elliptic flow data. Fig. 2 shows the $u_{\mathrm{t}0}$ and p_{t}/A dependence of the elliptic flow of protons and neutrons in semi-central [$0.25<b_0<0.45$ in Fig. 2(a) and $b<7.5$ fm in Fig. 2(b)] ^{197}Au+^{197}Au collisions at E_{lab} = 400 MeV/nucleon. The FOPI and FOPI/LAND experimental data are compared to the calculated results by using Skz4 and SkI1. Clearly, the two experimental data can be reproduced fairly well by both Skyrme parameter sets. Moreover, it can be seen that in both panels, the elliptic flow of protons or hydrogen isotopes (neutrons) is more evident than that of neutrons (protons or hydrogen isotopes) in the case of Skz4 (SkI1). As discussed in previous papers[29, 54], this phenomenon apparently reflects the high density behavior of the symmetry energy.

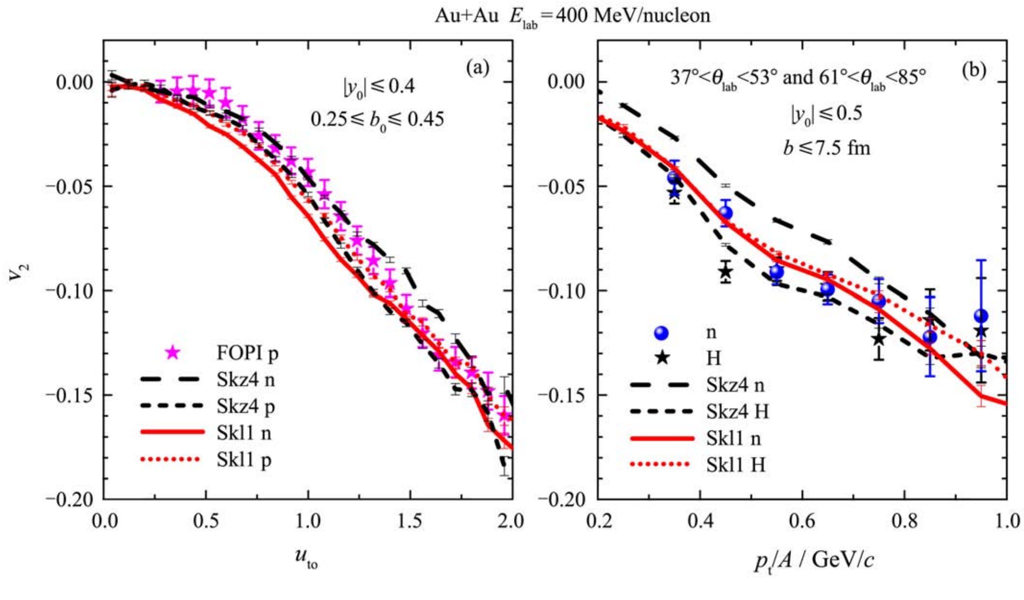

Fig. 2 (color online) Elliptic flow of free nucleons and hydrogen isotopes in ^{197}Au+^{197}Au collisions at the incident energy 400 MeV/nucleon as a function of transverse-velocity (a) and transverse-momentum per nucleon (b). Calculations with Skz4 and SkI are shown and compared with the corresponding FOPI experimental data reported in Ref. [44] and FOPI/LAND data reported in Ref. [29].

After describing the existing FOPI/LAND data, we show the comparison of the measured and the calculated ratios $v_2^{\rm n}/v_2^{\rm H}$ as a function of the $p_{\rm t}/A$ in Fig. 3(a). Calculated results with Skz4, Skz2, SV-mas08, MSL0, SV-sym34, SkA, SkI5, and SkI1 combined with the FP4 parameterization of the in-medium nucleon-nucleon elastic cross section (NNECS) (see Refs. [47, 49] for details) are shown by lines with solid symbols, and the result calculated with SV-mas08 and the FP2 parameterization of the NNECS is shown by a line. First, it can be seen that the $v_2^{\rm n}/v_2^{\rm H}$ ratio increases with increasing L, from Skz4 to SkI5, and its spreading steadily grows when moving to the low transverse momentum region. Second, results calculated with SV-sym34 and SkA, for which the difference in the value of L is only about 6 MeV and in K_0 is as large as 30 MeV, are almost overlapped. It illustrates the sensitivity of the elliptic flow ratio to the stiffness of the symmetry energy and not to the incompressibility of the nuclear EoS. Third, the results obtained with SV-mas08&FP2 and SV-mas08 (*i.e.* with FP4) track each other closely, confirming the weak effect of the in-medium NNECS on the elliptic flow ratio already observed in Ref. [29]. Therefore, we may conclude that the systematically increasing values of the elliptic flow ratio $v_2^{\rm n}/v_2^{\rm H}$ calculated with the selected forces are mainly due to the increase of the stiffness of the symmetry energy and not to other changes of isoscalar components of the dynamic transport.

In order to describe how well the calculations fit the experimental data, the total χ^2 values are shown in Fig. 3(b) as a function of the slope parameter L. Using a quadratic fit to the total χ^2, the slope parameter $L=(89\pm45)$ MeV within a 2-σ uncertainty is obtained. This result is rather close to the $L=(83\pm52)$ MeV (within 2-σ uncertainty) obtained previously[29] and also overlaps well with recent constraints for the symmetry energy (see, *e.g.*, Refs. [2–3, 6–7]).

The yield ratio of ^{3}H and ^{3}He emitted from HICs is usually taken as a useful probe of the nuclear symmetry energy, because of the high detection efficiency for both ^{3}H and ^{3}He clusters. On the theoretical model side, the ratio was also found to be sensitive to the symmetry energy[55–59].

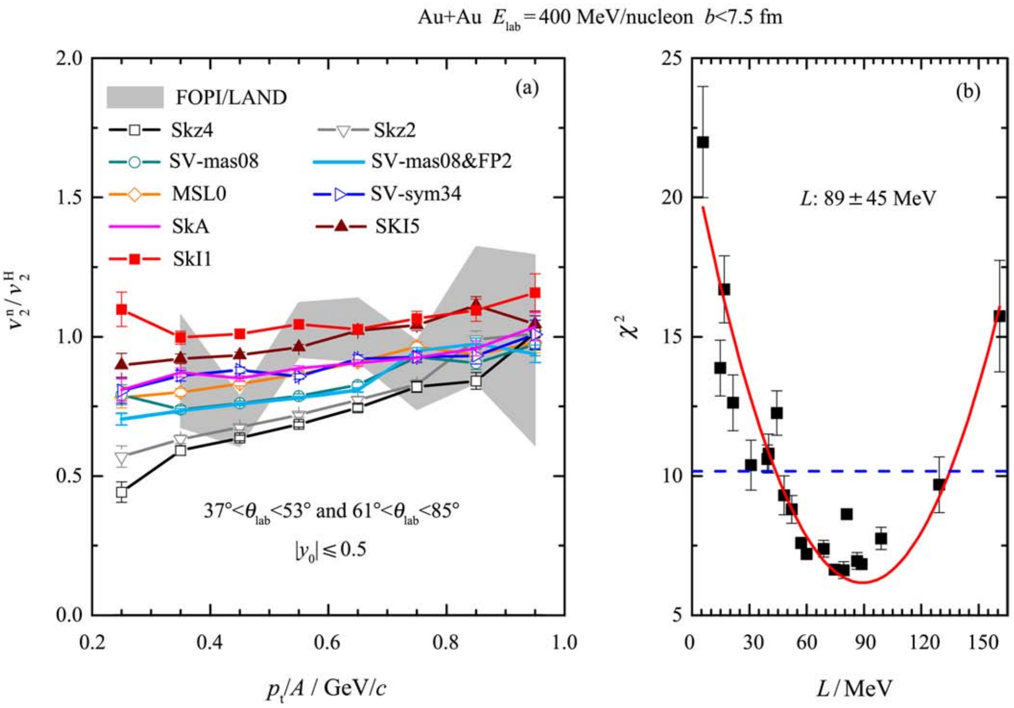

Fig. 3　(color online) (a) Elliptic flow ratio of free neutrons vs hydrogen isotopes as a function of the transverse momentum $p_{\rm t}/A$. The FOPI/LAND data (shaded area) reported in Ref. [29] are compared with calculations using the indicated 9 Skyrme interactions. (b) The total χ^2 identifying the goodness of fit between the FOPI/LAND data and simulations with the 21 studied Skyrme forces as a function of the slope parameter L. The symbols represent the total χ^2 as calculated with the 21 Skyrme interactions. The smooth curve represent a quadratic fit to the total χ^2, and the horizontal dashed line represent $\chi^2_{\rm min}$+4.

Fig. 4 show the yield ratio of ^{3}H vs ^{3}He clusters calculated with 13 selected Skyrme parametrizations as functions of the slope parameter L and the symmetry energy at density of $\rho = 0.03$ fm^{-3}. The ratio generally decreases with increasing L, indicating the ratio predominantly reflects the symmetry energy at sub-saturation densities. Very similar results can be found in both BUU-type and QMD-type model calculations[55–58]. It can be seen in Fig. 4(b) that, the linearity between the ^{3}H/^{3}He ratio and the symmetry energy at density of $\rho = 0.03$ fm^{-3} is quite good, which indicates again a strong correlation between them at low densities. Moreover, the ^{3}H/^{3}He ratios calculated with MSL0, SkO', SV-sym34, and Ska35s25 (which give almost the same value of the symmetry energy below 0.06 fm^{-3} and represent a moderately soft to linear symmetry energy) are close to each other and centered in the shaded band, while the results obtained with Skz4 and Skz2 lie outside the band. Obviously, although the large uncertainty of the experimental data prevents us from getting a tighter constraint on the density-dependent symmetry energy, good consistency among results obtained using both the ^{3}H/^{3}He yield ratio and the $v_2^{\rm n}/v_2^{\rm H}$ flow ratio is achieved.

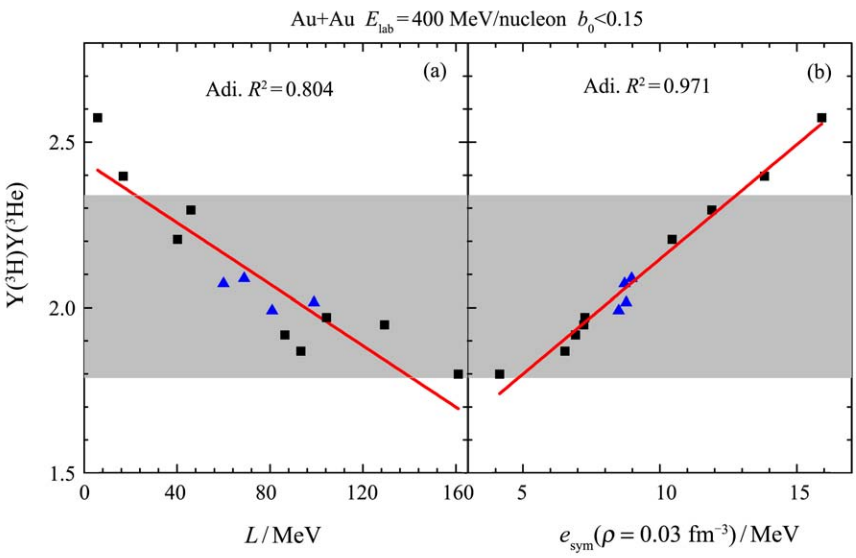

Fig. 4 (color online) Yield ratio of ^{3}H vs ^{3}He plotted as a function of the slope parameter L (a) and the symmetry energy at density of $\rho = 0.03$ fm^{-3} (b). Four triangle symbols denote calculations with MSL0, SkO', SV-sym34, and Ska35s25, and square symbols represent calculations with other 9 Skyrme interactions listed in the text. The lines represent linear fit of ^{3}H/^{3}He vs L, and ^{3}H/^{3}He vs $e_{\rm sym}(\rho = 0.03$ fm^{-3}), respectively. Correspondingly, the Adj. R^2 values are also shown. The shaded area indicates the FOPI data taken from Ref. [43].

4 Summary

In summary, the Skyrme energy density functional has been introduced into the UrQMD model. And, with the updated UrQMD model, the elliptic flow ratio of free neurons vs hydrogen isotopes and the yield ratio of ^{3}H vs ^{3}He clusters emitted from ^{197}Au+^{197}Au collisions at the incident energy 400 MeV/nucleon are studied. The elliptic flow ratio $v_2^{\rm n}/v_2^{\rm H}$ and the yield ratio ^{3}H/^{3}He are shown to be sensitive to the nuclear symmetry energy at supra-saturation and sub-saturation densities, respectively. By comparing calculations with the transverse-momentum dependent FOPI/LAND flow ratio $v_2^{\rm n}/v_2^{\rm H}$, the slope parameter of the symmetry energy is extracted to be $L = (89 \pm 45)$ MeV within a 2-σ confidence limit. And, we also find that calculations using several Skyrme interactions which parameterize a moderately soft to linear symmetry energy can reproduce semi-quantitatively the FOPI data of ^{3}H/^{3}He yield ratio, which is also consistent with the extraction from elliptic flow data.

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利用椭圆流和轻带电粒子产额比探测对称能

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摘要: 基于最近更新的极端相对论量子分子动力学模型，研究了^{197}Au+^{197}Au 产生的中子和氢同位素的横动量依赖的椭圆流和轻带电粒子的产额比。发现中子和氢同位素的椭圆流之比$v_2^{\mathrm{n}}/v_2^{\mathrm{H}}$敏感于对称能的高密行为，而^{3}H 和^{3}He 的产额比敏感于对称能的低密行为。通过比较 FOPI/LAND 和 FOPI 合作组的最新实验数据与模型模拟的结果，发现接近线性对称能的 Skyrme 参数给出的结果能与这两个实验值都符合。

关键词: 对称能；椭圆流；输运模型

收稿日期: 2014-10-14；　**修改日期:** 2015-06-08
基金项目: 国家自然科学基金资助项目(11375062, 11405054)
通信作者: 李庆峰，E-mail: liqf@hutc.zj.cn。