Symmetry energy at subsaturation densities and the neutron skin thickness of $^{208}$Pb

FAN XiaoHua$^{1,2}$, DONG JianMin$^1$* & ZUO Wei$^1$†

1Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China; 2University of Chinese Academy of Sciences, Beijing, 100049, China;

Received Month date, Year; accepted Month date, Year

The mass-dependent symmetry energy coefficients $a_{sym}(A)$ has been extracted by analysing the heavy nuclear mass differences reducing the uncertainties as far as possible in our previous work. Taking advantage of the obtained symmetry energy coefficient $a_{sym}(A)$ and the density profiles obtained by switching off the Coulomb interaction in $^{208}$Pb, we calculated the slope parameter $L_{0.11}$ of the symmetry energy at the density of $0.11$ fm$^{-3}$. The calculated $L_{0.11}$ ranges from 40.5 MeV to 60.3 MeV. The slope parameter $L_{0.11}$ of the symmetry energy at the density of $0.11$ fm$^{-3}$ is also calculated directly with Skyrme interactions for nuclear matter and is found to have a fine linear relation with the neutron skin thickness of $^{208}$Pb, which is the difference of the neutron and proton rms radii of the nucleus. With the linear relation the neutron skin thickness $\Delta R_{np}$ of $^{208}$Pb is predicted to be 0.15 - 0.21 fm.

nuclear matter, symmetry energy, neutron skin

PACS number(s): 21.65.Ef, 21.10.Dr, 21.60.Jz

1 Introduction

Symmetry energy is one of the basic features of the equation of state (EOS) of nuclear matter. It represents the energy cost in translating all the protons to neutrons in symmetric nuclear matter for per nucleon approximately. The density-dependent symmetry energy $S(\rho)$ has attracted great attention in nuclear physics and astrophysics such as heavy ion reaction [1-14], the stability of superheavy nuclei [15], nuclear structure [16, 17], the structures, composition and cooling of neutron stars [18-21] and even some new physics beyond the standard model [22, 23]. Consequently, the slope and curvature parameters which describe the density-dependence are of much importance to understand a variety of issues in the mentioned areas. The slope parameter $L$ is vital particularly, which mostly decides its density-dependence. At the saturation density, the slope parameter $L$ probed by plenty of methods can vary largely [24]. Fortunately, recent available constraints on $L$ from terrestrial laboratory measurements and astrophysical observations are in agreement with $L = 55 \pm 25$ MeV, which is summarized by Chen recently [25]. But further efforts are still needed in the determination of the density-dependence of the symmetry energy, in particular, the high density behaviors. Although the nuclear properties given by various effective interactions are very different, the finite nuclei structure characters provided by them are approximately unanimous. For this reason, it is a significant way that we explore the nuclear matter with the help of properties of finite nuclei. In our work, we utilize the properties of finite nuclei to probe the density-dependence of symmetry energy around the subsaturation density of $0.11$ fm$^{-3}$.

In recent years, it has been established that the neutron skin

*Corresponding author (email: djm4008@126.com)
†Corresponding author (email: zuowei@impcas.ac.cn)
thickness $\Delta R_{np}$ of $^{208}\text{Pb}$ is linearly correlated with the density dependence of the nuclear symmetry energy around saturation [26-31]. In the present work, we also observe that there is a strong linear relation between the neutron skin thickness $\Delta R_{np}$ of $^{208}\text{Pb}$ and the slope parameter $L_{0.11}$ of the symmetry energy at the density of 0.11fm$^{-3}$. According to this, we can obtain a strong constraint on the density dependence of $S(\rho)$ with a measurement of $\Delta R_{np}$ with a high accuracy. Correspondingly, the neutron skin $\Delta R_{np}$ can be predicted by the slope parameter $I_{0.11}^{(6)}$. As smaller neutron skins in heavy nuclei tend to yield smaller neutron star radii [32] given by Horowitz and Piekarewicz and the value of neutron skin play a key role in deciding whether the 1.4$M_\odot$ neutron stars can have a direct Urca process [2], there is a great necessity for an accurate measurement of the neutron skin.

The information about the neutron skin thickness of $^{208}\text{Pb}$ $\Delta R_{np} = 0.156^{+0.025}_{-0.025}$ fm from proton inelastic scattering [33], $\Delta R_{np} = 0.17 \pm 0.03$ fm from chiral effective field theory [34] and $\Delta R_{np} = 0.191 \pm 0.032$ fm from $\alpha$-decay energies [35] shows a big challenge of a precise constraint about the neutron skin thickness.

## 2 Method

For heavy nuclei, such as $^{208}\text{Pb}$, the nuclear surface region where nucleon density is much less than the saturation density, contributes dominantly to symmetry energy [35]. So it is better to describe the density-dependent symmetry energy by expanding around the density that is below the saturation density. Around the nuclear matter subsaturation density $\rho = 0.11$fm$^{-3}$, the symmetry energy $S(\rho)$ is expanded to second order in term of density $\rho$ as

$$S(\rho) = S_{0.11} + \frac{L_{0.11}}{3} (\frac{\rho - 0.11}{0.11}) + \frac{K_{\text{sym}}}{18} (\frac{\rho - 0.11}{0.11})^2. \quad (1)$$

There is an available connection that the $a_{\text{sym}}(A)$ of finite nuclei is approximately equal to $S(\rho_A)$ of the nuclear matter at a reference density $\rho_A$, which is proposed by Centelles, et al [36]. It makes the symmetry energy of the nuclear matter in contact with the one of finite nuclei, and thus allows one to explore the density dependence of the symmetry energy $S(\rho)$. We have extracted the mass-dependent symmetry energy coefficients $a_{\text{sym}}(A)$ in our previous work and found that $a_{\text{sym}}(A) \approx 22.4$ MeV for $^{208}\text{Pb}$ [36]. The reference density $\rho_A$ for $^{208}\text{Pb}$ is figured out to be 0.55$\rho_0 = 0.088$ fm$^{-3}$ with $\rho_0 = 0.16$ fm$^{-3}$. Substituting the $\rho_A$ in Eq.[1], we obtain

$$22.4 \text{ MeV} = S_{0.11} - \frac{0.6L_{0.11}}{9} - 0.02K_{\text{sym}}. \quad (2)$$

There are several shapes of symmetry energy as a function of density [37]. It is found that the expression $S(\rho) = S_0(\rho/\rho_0)^\gamma$ or $S(\rho) = 12.5(\rho/\rho_0)^{2/3} + C_\rho(\rho/\rho_0)^{\gamma}$ is not universal. But the shape from the density-dependent M3Y interaction [38] is much better. With it, we can describe the symmetry energy $S(\rho)$ in nuclear matter as the following formulism

$$S(\rho) = C_K \left(\frac{\rho}{0.11}\right)^2 + C_1 \left(\frac{\rho}{0.11}\right) + C_2 \left(\frac{\rho}{0.11}\right)^3, \quad (3)$$

where $C_K = \frac{\hbar^2K_{\text{sym}}^2}{m^2} \approx 9.6$ MeV, $C_1$ and $C_2$ are two parameters that are required to be determined. $L_{0.11} = 3\rho_0\frac{\partial S}{\partial \rho}|_{\rho=0.11}$ and $K_{\text{sym}} = 9\rho_0^2\frac{\partial^2 S}{\partial \rho^2}|_{\rho=0.11}$ are slope and curvature parameters at the density of 0.11fm$^{-3}$ respectively. There is an useful connection among the symmetry energy at the density of 0.11fm$^{-3}$ $S_{0.11}$, $L_{0.11}$ and $K_{\text{sym}}$

$$K_{\text{sym}} = 5L_{0.11} - 15S_{0.11} + 28.8, \quad (4)$$

which is sufficient to estimate the small contribution of $K_{\text{sym}}$ in Eq.[1]. As a consequence, Eq.[1] can be rewritten as

$$S(\rho) = \frac{195.24 - 0.52L_{0.11}}{9} + \frac{L_{0.11}}{3} \left(\frac{\rho - 0.11}{0.11}\right) + \frac{4.14L_{0.11} - 317.79}{18} \left(\frac{\rho - 0.11}{0.11}\right)^2. \quad (5)$$

Therefore, once the $L_{0.11}$ is determined, the symmetry energy $S(\rho)$ at subsaturation density is obtained. Thus, the centre goal of this work is to determine $L_{0.11}$. In the local density approximation, the symmetry energy coefficient $a_{\text{sym}}(A)$ can be calculated [39] as

$$a_{\text{sym}}(A) = \frac{1}{AX_0} \int d^3r\rho(r)S[\rho(r)]\delta(r)^2, \quad (6)$$

where $X_0 = (N - Z)/A$ is the whole nuclear isospin asymmetry, $\delta(r) = (\rho_0(r) - \rho_p(r))/\rho(r)$ the isospin asymmetry profile, $\rho(r)$ the whole nucleon density and $a_{\text{sym}} = 22.4$ MeV for $^{208}\text{Pb}$. $\rho_0(r)$ and $\rho_p(r)$ are the density profile of neutron and proton respectively in nucleus that can be given by the mean field models such as Skyrme-Hartree-Fock. Here, we calculated $\rho(r)$, $\delta(r)$ and the neutron skin thickness $\Delta R_{np}$ with the Skyrme interactions [40]: SIII, SLy4, SLy5, SkI2, SkI4, SkP, SkM*, SGII, T4, T6, BSk8, LNS1, LNS5, HFB17, KDO9, KDE, SKZ2, SKZ4, SV, MSK1, MSK6, v09D, SK255, SK272, SIV, SkMP, MSL0, SKA, SKSC15 and SKSC40. Substituting Eq.[5] in Eq.[6], the slope parameter $L_{0.11}$ is determined and the obtained $L_{0.11}$ with this method is labeled $I_{0.11}^{(6)}$. Indeed, in order to extract the nuclear symmetry energy that relates solely to the nuclear force, the effect due to the fact that the Coulomb interaction effectively polarizes the neutron and proton densities should be subtracted. So we calculate the neutron density $\rho_0(r)$ and proton density $\rho_p(r)$ by switching off the Coulomb interaction. On the contrary, the Coulomb interaction is necessary to work out the neutron skin thickness $\Delta R_{np}$ on account of that the protons and neutrons move slightly away from the core as a result of the Coulomb repulsion between charged protons.
3 Results

Known that \(a_{\text{sym}}(A) \approx 22.4\) of heavy spherical nucleus \(^{208}\text{Pb}\) above, we can obtain \(L_{0,11}\) with various Skyrme interactions. The results given by some typical Skyrme interactions mentioned above are shown in Table 1. \(L_{0,11}^{(6)}\) and \(S_{0,11}^{(6)}\) are the slope parameter and the symmetry energy at the density of 0.11fm\(^{-3}\) calculated with the properties of finite nuclei while \(L_{0,11}\) and \(S_{0,11}\) are those calculated with the Skyrme interactions for nuclear matter directly. \(L_{0,11}\) obtained by the Skyrme procedure for nuclear matter directly has a large scope but the \(L_{0,11}^{(6)}\) computed with Eq.[6] ranges narrowly. And it is the same for the comparison between both symmetry energy, namely \(S_{0,11}^{(6)}\) and \(S_{0,11}\) gained in the two ways. It thus appears that the method of calculating the features of nuclear matter by using the structure properties of the finite nuclei is feasible and effective.

Table 1 Comparison between the values of the slope parameter and the symmetry energy at the density of 0.11fm\(^{-3}\) with the properties of finite nuclei namely, Eq.[6], and those calculated with Skyrme interactions directly.

| Force   | \(L_{0,11}^{(6)}\) (MeV) | \(S_{0,11}^{(6)}\) (MeV) | \(L_{0,11}\) (MeV) | \(S_{0,11}\) (MeV) |
|---------|--------------------------|--------------------------|---------------------|---------------------|
| SIII    | 50.71                    | 25.54                    | 32.02               | 26.06               |
| SLY4    | 48.03                    | 25.34                    | 42.09               | 26.49               |
| SLY5    | 47.29                    | 25.28                    | 43.52               | 26.22               |
| SKI2    | 60.30                    | 25.17                    | 68.17               | 23.23               |
| SKI4    | 49.74                    | 25.47                    | 46.09               | 22.9                |
| SKP     | 46.33                    | 25.21                    | 35.26               | 26.21               |
| SKM*    | 50.33                    | 25.51                    | 44.17               | 24.32               |
| SKMP    | 53.31                    | 25.74                    | 53.45               | 22.59               |
| SHI     | 45.26                    | 25.13                    | 37.95               | 22.18               |
| T4      | 59.63                    | 26.22                    | 67.33               | 25.63               |
| T6      | 52.77                    | 26.70                    | 38.58               | 25.43               |
| BSk8    | 50.85                    | 25.55                    | 28.82               | 25.18               |
| LNS1    | 44.54                    | 25.07                    | 38.54               | 25.31               |
| LNS5    | 45.17                    | 25.12                    | 44.91               | 23.14               |
| HFB17   | 49.00                    | 25.41                    | 40.08               | 25.25               |
| KDE0    | 46.42                    | 25.22                    | 43.89               | 27.30               |
| KDE     | 44.87                    | 25.10                    | 41.05               | 26.39               |
| SK22    | 43.53                    | 25.00                    | 33.36               | 28.69               |
| SKz4    | 43.15                    | 24.97                    | 25.59               | 29.90               |
| SV      | 42.81                    | 24.94                    | 66.72               | 23.62               |
| MSK1    | 49.15                    | 25.42                    | 39.69               | 25.49               |
| MSKA    | 50.07                    | 25.49                    | 50.90               | 24.31               |
| v@090   | 43.35                    | 25.06                    | 27.44               | 25.84               |
| SK255   | 58.60                    | 26.14                    | 71.00               | 27.56               |
| SK272   | 58.72                    | 26.15                    | 70.15               | 28.13               |
| SIV     | 52.04                    | 25.64                    | 55.59               | 24.91               |
| MSL0    | 52.29                    | 25.66                    | 49.38               | 23.15               |
| SKA     | 55.55                    | 25.91                    | 58.98               | 25.25               |
| SKSC15  | 43.15                    | 24.97                    | 27.99               | 25.58               |
| SKSC40  | 40.51                    | 24.77                    | 21.12               | 25.98               |

All the results about \(L_{0,11}\) from Eq.[6] (labeled \(L_{0,11}^{(6)}\)) are shown in the left panel of Fig.1 between the two dashed lines. The calculated \(L_{0,11}\) directly for the nuclear matter is shown in the horizontal axis and the the neutron skin thickness \(\Delta R_{np}\) is shown in the vertical axis. The linear relation is demonstrated obviously. By employing the least square fitting, we obtained the correlation between \(\Delta R_{np}\) in \(^{208}\text{Pb}\) and \(L_{0,11}\) as following

\[\Delta R_{np} = (0.0279 \pm 0.00338) + (0.00307 \pm 0.00007)L_{0,11}\]  (7)

where \(\Delta R_{np}\) and \(L_{0,11}\) are in units of fm and MeV respectively. The gained linear fitting coloured red is fine with the correlation coefficient \(r\) up to 0.984. The slope parameter of symmetry energy at the density of 0.11fm\(^{-3}\) \(L_{0,11}^{(6)}\) given by our present work with the finite nuclear properties ranges from 40.5 MeV to 60.3 MeV within the 30 sets of Skyrme interaction. Consequently, the neutron skin thickness \(\Delta R_{np}\) of \(^{208}\text{Pb}\) can be predicted in terms of this correlation, which is constrained from 0.15 fm to 0.21 fm. If \(\Delta R_{np}\) of \(^{208}\text{Pb}\) is greater than 0.24 fm, the direct Urca process to cool down a 1.4\(M_{\odot}\) neutron star is allowed [18]. Our result is too small to make the direct Urca process in the 1.4\(M_{\odot}\) neutron star occur. There are some recent data about the neutron skin thickness \(\Delta R_{np}\) of \(^{208}\text{Pb}\), which are shown in Table 2, obtained from various approaches. It appears that our result consists well with 0.180 \pm 0.035 fm from the pygmy dipole resonances (PDR) [42] and 0.185 \pm 0.03 fm from mean field [47]. Recently, Dong et al employed a more practicable strategy than the current lead radius experiment (PREX) to probe the neutron skin thickness of \(^{208}\text{Pb}\) based on a high linear correlation between the \(\Delta R_{np}\) and \(J - a_{\text{sym}}\) [44], where \(J\) is the symmetry energy (coefficient) of nuclear matter at saturation density. The obtained \(\Delta R_{np}\) in \(^{208}\text{Pb}\) was 0.176 \pm 0.021 fm robustly, being consistent with the present result.

Table 2 The neutron skin thickness \(\Delta R_{np}\) of \(^{208}\text{Pb}\) probed in various independent studies.

| Reference | Method | \(\Delta R_{np}\) (fm) |
|-----------|--------|----------------------|
| [23]      | proton inelastic scattering | 0.156 \(\pm 0.025\)   |
| [42]      | proton elastic scattering | 0.211 \(\pm 0.063\)   |
| [32]      | chiral effective field theory | 0.17 \pm 0.03       |
| [34]      | alpha-decay energies | 0.191 \pm 0.032     |
| [37]      | mean field | 0.185 \pm 0.035    |
| [12]      | pygmy dipole resonance | 0.185 \pm 0.035   |
| [13]      | pygmy dipole resonance | 0.194 \pm 0.024   |
| Present    | Nuclear mass differences | 0.15-0.21       |

In addition, we also show the correlations of the neutron skin thickness \(\Delta R_{np}\) of \(^{208}\text{Pb}\) and the slope coefficient \(L_{0}\) of symmetry energy at the saturation density in the right panel of Fig.1 with a linear fitting. The linear relation is strong with the correlation coefficient \(r=0.964\) but is weaker than the one in the left panel. It can be concluded that the neutron skin
thickness of heavy nuclei is uniquely fixed by the symmetry energy density slope at a subsaturation density of 0.11 fm\(^{-3}\) rather than at the saturation density, which is in agreement with the conclusion in [45].

After we have got the slope coefficients \(L_{0,11}\) of symmetry energy at the density of 0.11 fm\(^{-3}\) by 30 sets of Skyrme parameters, with Eq.[2] and Eq.[4], the symmetry energy \(S_{0,11}\) and the curvature parameter \(K_{\text{sym}}\) at the density of 0.11 fm\(^{-3}\) can be measured. Then, the description Eq.[1] for the density-dependent symmetry energy around the subsaturation density of 0.11 fm\(^{-3}\) becomes clear. The behaviors of established symmetry energy \(S(\rho)\) are presented as a function of density \(\rho\) in Fig. 2.

In summary, we have employed the symmetry energy coefficient \(\alpha_{\text{sym}}(A)\) extracted by experimental nuclear masses in our previous work and the density profiles of heavy nuclei to explore the behavior of the density-dependent symmetry energy around the subsaturation density of 0.11 fm\(^{-3}\). The estimated value of the slope parameter \(L_{0,11}\) of symmetry energy at the density of 0.11 fm\(^{-3}\) is 40.5-60.3 MeV. With the nice linear correlation of \(L_{0,11}\) and the neutron skin \(\Delta R_{np}\) of \(^{208}\text{Pb}\), \(\Delta R_{np}\) is predicted to be 0.15-0.21 fm, which is too small to allow the direct Urca process in the 1.4\(M_\odot\) neutron stars. It proves that the approach of probing the nuclear matter features by using the information about the nuclear structure is effective.
state of dense matter. science, 2002, 298: 1592-1596
2 Steiner A W, Prakash M, Lattimer J, et al. Isospin asymmetry in nuclei and neutron stars. Phys Rep, 2005, 411: 325-375
3 Baran V, Colonna M, Greco V, et al. Reaction dynamics with exotic nuclei. Phys Rep, 2005, 410: 335-466
4 Li B A, Chen L W, Ko C M. Recent progress and new challenges in isospin physics with heavy-ion reactions. Phys Rep, 2008, 464: 113-281
5 Zhang Y C, Danielewicz P, Famiano M, et al. The influence of cluster emission and the symmetry energy on neutron-proton spectral double ratios. Phys Lett B, 2008, 664: 145-148
6 Wu Q H, Zhang Y X, Xiao Z G, et al. Probing the density dependence of the symmetry energy via multifragmentation at subatmospheric densities. Phys Rev C, 2011, 84: 064620
7 Feng Z Q. Constraining the high-density behavior of the nuclear equation of state from strangeness production in heavy-ion collisions. Phys Rev C, 2011, 83: 067601
8 Ma W C, Wang F, Ma Y G, et al. Isobaric yield ratios in heavy-ion collisions with isotopes, isobars and isotones. Sci China-Phys Mech Astron, 2012, 55: 2407-2413
9 Zhang Y X, Danielewicz P, Famiano M, et al. The influence of cluster emission and the symmetry energy of neutron-rich nuclei at intermediate energies. Phys Rev C, 2013, 88: 014308
10 Guo C C, Wang Y J, Li Q F, et al. Influence of the symmetry energy on the balance energy of the directed flow. Sci China-Phys Mech Astron, 2012, 55: 252-259
11 Wang Y J, Guo C C, Li Q F, et al. The effect of symmetry potential on the balance energy of light particles emitted from mass symmetric heavy-ion collisions with isotopes, isobars and isobones. Sci China-Phys Mech Astron, 2012, 55: 2407-2413
12 Gao Y, Yong G C, Wang Y J, et al. Influence of the symmetry energy on the cone-azimuthal emission. Phys Rev C, 2013, 88: 057601
13 Wang Y J, Guo C C, Li Q F, et al. Constraining the high-density nuclear symmetry energy with the transverse-momentum dependent elliptic flow. Phys Rev C, 2014 89: 044603
14 Wu Q H, Zhang Y X, Xiao Z G, et al. Competition between Coulomb and symmetry potential in semi-peripheral heavy ion collisions. Phys Rev C, 2015, 91: 014617
15 Dong J, Zuo W, Scheid W. Correlation between α-decay energies of superheavy nuclei involving the effects of symmetry energy. Phys Rev Lett, 2011, 107: 012501
16 Liu Jian, Ren Zhongzhou, Xu Chang, et al. Systematic study of the symmetry energy under the local density approximation. Phys Rev C, 2013, 88: 024324
17 Xu Chang, Ren Zhongzhou, Liu Jian. Attempt to link the neutron skin thickness of 208Pb with the symmetry energy through cluster radioactivity. Phys Rev C, 2014, 90: 064310
18 Sharma B K, Pal S. Neutron star structure and the neutron radius of 208Pb. Phys Rev Lett, 2001, 86: 5647-5650
19 Sharma B K, Pal S. Neutron star structure and the neutron radius of 208Pb. Phys Rev Lett, 2009, 682: 23-26
20 Lattimer J M, Prakash M. Nuclear matter and its role in supernovae, neutron stars and compact object binary mergers. Phys Rep, 2004, 333: 121-146; The physics of neutron stars. Science, 2004, 304: 536-542
21 Todd-Rutel B G, Piekarewicz J. Neutron-rich nuclei and neutron stars: a new accurately calibrated interaction for the study of neutron-rich matter. Phys Rev Lett, 2005, 95: 122501
22 Horowitz C J, Pollock S J, Souder P A, et al. Parity violating measurements of neutron densities. Phys Rev, 2001, 63: 025501
23 Sil T, Centelles M, Vinas X, et al. Atomic parity nonconservation, neutron radii, and effective field theories of nuclei. Phys Rev C, 2005, 71: 045502
24 Dong J M, Zhang H F, Wang L J, et al. Density dependence of the symmetry energy probed by β-decay energies of odd-A nuclei. Phys Rev C, 2013, 88: 014302
25 Chen L W. Recent progress on the determination of the symmetry energy. Nucl Phys Rev, 2014, 31: 273-284
26 Alex Brown B. Neutron Radii in Nuclei and the Neutron Equation of State. Phys Rev Lett, 2000, 85: 5296-5299
27 Typel S, Alex Brown B. Neutron radii and the neutron equation of state in relativistic models. Phys Rev C, 2001, 64: 027302
28 Furnstahl R J. Neutron radii in mean-field models. Nucl Phys A, 2002, 706: 85-110
29 Steiner A W, Prakash M, Lattimer J M, et al. Isospin asymmetry in nuclei and neutron stars. Phys Rev C, 2005, 411: 325-375
30 Centelles M, Roca-Maza X, Vinas X, et al. Nuclear symmetry energy probed by neutron skin thickness of nuclei. Phys Rev Lett, 2009, 102: 122502
31 Warda M, Vinas X, Roca-Maza X, et al. Neutron skin thickness in the droplet model with surface width dependence: Indications of softness of the nuclear symmetry energy. Phys Rev C, 2009, 80: 024316
32 Horowitz C J, Piekarewicz J. Neutron Star Structure and the Neutron Radius of 208Pb. Phys Rev Lett, 2001, 86: 5647-5650
33 Tamii A, et al. Complete Electric Dipole Response and the Neutron Skin in 208Pb. Phys Rev Lett, 2011, 107: 062502
34 Hebeler K, Lattimer J M, Pethick C J, et al. Constraints on neutron star radii based on chiral effective field theory interactions. Phys Rev Lett, 2010, 105: 161102
35 Dong J M, Zuo W, Gu J Z. Origin of symmetry energy in finite nuclei and density dependence of nuclear matter symmetry energy from measured α– decay energies. Phys Rev C, 2013, 87: 014303
36 Fan X H, Dong J M, Zuo W. Density-dependent nuclear matter symmetry energy at sub saturation densities from nuclear mass differences. Phys Rev C, 2014, 89: 014305
37 Dong J M, Zuo W, Gu J Z, et al. Density dependence of the nuclear symmetry energy constrained by mean-field calculations. Phys Rev C, 2012, 85: 034308
38 Mukhopadhyay T, Basu D N. Nuclear symmetry energy from effective interaction and masses of isospin asymmetric nuclei. Nucl Phys A, 2007, 789: 201-208
39 Samadkar S K, De J N, Vilas X, et al. Excitation energy dependence of the symmetry energy of finite nuclei. Phys Rev C, 2007, 76: 041602(R)
40 Dutra M, Lourenço O, Sá Martins J S, et al. Skyrme interaction and nuclear matter constraints. Phys Rev C, 2012, 85: 035201
41 Zenrihiro J, Sakaguchi H, Murakami T, et al. Neutron density distributions of 204,206,208Pb deduced via proton elastic scattering at E p=295 MeV. Phys Rev C, 2010, 82: 044611
42 KLIMKIEWICZ A, PAAR N, ADRICH P, FALLOT M, et al. Nuclear symmetry energy and neutron skins derived from pygmy dipole resonances. Phys Rev C, 2007, 76: 051603(R)
43 Carbone A, Colo G, Bracco A, et al. Constraints on the symmetry energy and neutron skins from pygmy resonances in 68Ni and 132Sn. Phys Rev C 2010, 81: 041301(R)
44 Jianmin Dong, Wei Zuo, and Jianzhong Gu. Constraints on neutron skin thickness in 208Pb and density-dependent symmetry energy. Phys Rev C, 2015, 91: 034315
45 Zhang Z, Chen L W. Constraining the symmetry energy at subatmospheric densities using isotope binding energy difference and neutron skin thickness. Phys Lett B, 2013, 726: 234-238