Nuclear Symmetry Energy for $A=48$ Isobars in Relativistic Mean Field Theory*

BAN Shu-Fang [1,2] MENG Jie [1,3,4;1)] Ramon. A. Wyss [2]

1 (School of Physics, Peking University, Beijing 100871, China)
2 (Royal Institute of Technology, AlbaNova University Center, 10691 Stockholm, Sweden)
3 (Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China)
4 (Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China)

Abstract Recently it was found that the nuclear symmetry energy can be directly associated with the mean level density and an iso-vector potential. In this paper, the nuclear symmetry energy is studied within the relativistic mean field (RMF) theory. The potential of the RMF theory can be separated into an isovector and isoscalar components. The nuclear binding energies in $A = 48$ isobaric chain calculated from RMF theory with or without the isovector terms for effective interactions PK1, NLSH, NL3, and TM1 have been used to analyze the nuclear symmetry energy in detail, i.e., mean level spacing ε and the effective isovector potential strength κ.

Key words nuclear symmetry energy, relativistic mean field, iso-cranking, mean level density, isovector potential

1 Introduction

According to standard textbooks[1], the nuclear symmetry energy originates from the kinetic energy and the interaction itself. Recently it was found that the nuclear symmetry energy can be directly associated with the mean level density and an isovector potential by Satula and Wyss, as demonstrated in Shyrme-Hartree-Fock (SHF) calculations[2,3]. The relativistic mean field (RMF) theory has been used successfully not only for describing the properties of nuclei near the valley of stability, but also for predicting the properties of exotic nuclei with large neutron or proton excess[4—7]. Here in this paper, we use the RMF theory to study the origin of the symmetry energy with different effective interactions NLSH, NL3, TM1 and the new developed PK1[5]. The potential of the RMF theory can be separated into isovector and isoscalar components. Then the nuclear binding energies in a given isobaric chain calculated from RMF with or without the isovector terms is used to analyze the nuclear symmetry energy in detail. In Section 2, the theoretical formalism is presented briefly. The results and discussions are given in the third section. At last, a brief summary is given.

2 Theoretical formalism

From standard text book[1], we know that the semi-empirical mass formula contains a term called the nuclear symmetry energy:

$$E_{\rm sym} = \frac{1}{2} b_{\rm sym} \frac{(N-Z)^2}{A} = \frac{1}{2} a_{\rm sym} T^2 \qquad (1)$$

with $T=(N-Z)/2$, which is said to originate from the kinetic energy and the interaction itself: $a_{\rm sym} = a_{\rm kin} + a_{\rm int}$. Recently, Satula and Wyss presented an alternative decomposition based on the iso-cranking

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1) E-mail: mengj@pku.edu.cn

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model[2] for nuclear symmetry energy:

$$\hat{H}^w = \hat{H}_{sp} - \omega_\tau \hat{T}, \quad E_T = \varepsilon T^2/2, \tag{2}$$

where ε is the mean level spacing for an equidistant level model. When an iso-vector potential $\frac{1}{2}\kappa\hat{T}\cdot\hat{T}$ is taken into account, the energy will be:

$$E_T = \frac{1}{2}\varepsilon T^2 + \frac{1}{2}\kappa T(T+1), \tag{3}$$

where κ is the average effective strength of the isovector potential and the linear part T originates from the Fock exchange term. Hence, the nuclear symmetry energy can be directly associated with the mean level spacing and an isovector potential, as shown in Ref. [3].

The details of RMF theory can be found in a number of reviews[4—7] and the references therein. The potential of RMF theory is described by the mesons, including an isoscalar scalar sigma (σ), isoscalar vector omega (ω) and an isovecor vector rho (ρ). Then the potential can be separated into an isovector and isoscalar components: $V_{\rm isov} = g_\rho\gamma^\mu \boldsymbol{\tau}\Box\boldsymbol{\rho}_\mu$, $V_{\rm isos} = g_\sigma\sigma + g_\omega\gamma^\mu\omega_\mu$. For the present study we neglect the Coulomb interaction. By removing the isovector part of the RMF potential, the mean level spacing ε can be obtained from the binding energies of the isobaric chain:

$$\tilde{E}_T - \tilde{E}_{T=0} \approx \varepsilon T^2/2. \tag{4}$$

Then the effective isovector potential strength κ can be obtained from the binding energy difference between those with and without the isovector terms in the RMF calculations for the same nucleus:

$$E_T - \tilde{E}_T \approx \kappa T^2/2 \quad \text{or} \quad \kappa T(T+1)/2. \tag{5}$$

3 Results and discussions

With effective interactions NL3, NLSH, TM1, and PK1, the binding energies of nuclei in $A=48$ isobaric chain, from $T=0$ to $T=14$, are calculated within the RMF theory. The calculations are not restricted to spherical symmetry. The behaviors of the mean level spacing ε and effective isovecor potential strength κ along isobaric chain are investigated.

3.1 The mean level spacing ε

The mean level spacing ε for $A=48$ isobaric chain calculated in RMF theory are shown in Fig. 1. We can see that all results given by the different effective interactions are very close to each other. ε is nearly a constant at large T and after scaled by $m*/m$, all curves are within the empirical limits, which are[2]:

$$\varepsilon \approx \frac{53}{A} : \frac{66}{A}\text{MeV} \approx 1.104 : 1.375\text{MeV}(A=48). \tag{6}$$

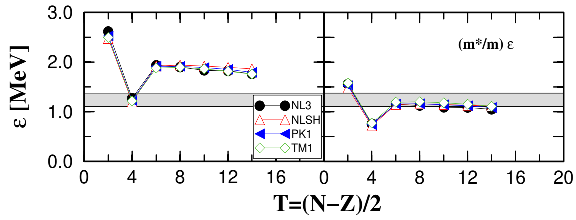

Fig. 1. The mean level spacing ε (left-hand side) for $A=48$ isobaric chain calculated in RMF theory with different effective interactions as marked in the figure. Right-hand side shows the results scaled by the effective mass m^*/m. The shadowed areas is corresponding the empirical values of ε in Eq. (6).

At small T, there are strong variations in ε, e. g., $T=4$, corresponding to the double magic nucleus ^{48}Ca, which is associated with different shell structure and hence a large level spacing. The results are also very similar to those of the SHF calculations in Ref. [3], except that ε toward the lower limit of the empirical value.

3.2 Effective isovector potential strength κ

In Fig. 2, the average strengths of the effective isovector potential κ for the $A=48$ isobaric chain calculated in RMF theory are shown. In the left-hand side, κ decreases with T obviously, while κ is nearly constant in the right panel, i.e., no T-dependence. Similar conclusion as SHF calculation can be obtained as: the complex isovector potential can be characterized by a single number, κ, along an isobaric chain. One should point out that κ still is somewhat decreasing in the right-hand panel. Then we can suppose the symmetry energy like:

$$E_{\rm sym} = \varepsilon T^2/2 + \kappa T(T+x)/2. \tag{7}$$

When $x>1$, the average strengths of the effective isovector potential κ will be more like a constant along an isobaric chain. Hence we obtain a nuclear symmetry energy,

$$E_{\rm sym} = (\varepsilon+\kappa)T(T+1)/2 = a_{\rm sym}T(T+1)/2 \tag{8}$$

with a $T(T+1)$ dependence, which may have good agreement with experiment data in Ref. [8]. It encourages us to calculate more isobaric chains to study the nuclear symmetry energy further.

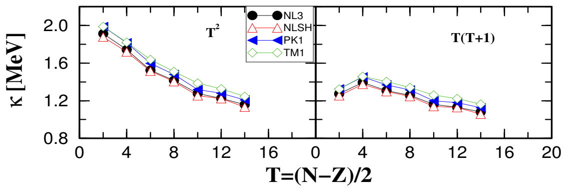

Fig. 2. The average strength of the effective isovector potential κ for $A=48$ isobaric chain. Left-hand side shows the values of κ estimated by assuming $E_{\rm sym}=(\varepsilon+\kappa)T^2/2$ and right-hand side shows those estimated by assuming $E_{\rm sym}=\varepsilon T^2/2+\kappa T(T+1)/2$, as given in Eqs. (4) and (5).

4 Summary

The nuclear symmetry energy has been studied in RMF theory with effective interactions NL3, NLSH, TM1, and PK1. The mean level spacing ε and the effective isovecor potential strength κ are calculated for the $A=48$ isobaric chain and its behavior along one isobaric chain is investigated.

The mean level spacing, ε, is nearly a constant at large T, while it can be affected by shell structure at small T. The effective isovector potential strength κ is almost constant with a $T(T+1)$ dependence in nuclear symmetry energy. We can say that the isovector potential can be characterized by a single number, κ, along an isobaric chain. The above conclusions are similar as those from the SHF calculation. There are also some differences: 1. the mean level spacing ε toward the lower limit of the empirical value after being scaled by the effective mass. 2. the nuclear symmetry energy has $T(T+x)$ dependence on κ with $x>1$, which can lead to the symmetry energy with $T(T+1)$ on ($\varepsilon+\kappa$), i.e., $E_{\rm sym}=a_{\rm sym}T(T+1)/2$.

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相对论平均场理论对 $A=48$ 同质量数链原子核对称能的研究*

班淑芳[1,2] 孟杰[1,3,4;1)] Ramon. A. Wyss[2]

1 (北京大学物理学院 北京 100871)
2 (瑞典皇家工学院 斯德哥尔摩 10691 瑞典)
3 (兰州重离子加速器国家实验室原子核理论中心 兰州 730000)
4 (中国科学院理论物理研究所 北京 100080)

摘要 最新研究发现原子核对称能与平均的能级密度和同位旋矢量势直接相关. 在相对论平均场理论中, 势场可以分为同位旋矢量和同位旋标量两部分. 采用PK1, NL3, NLSH和TM1相互作用参数, 对于 $A=48$ 同质量数链, 分别了计算势场中包含或不含同位旋矢量项时的原子核结合能, 研究了原子核的对称能, 即平均能级间距 ε 和同位旋矢量势的有效强度 κ.

关键词 原子核对称能 相对论平均场 同位旋推转 平均能级密度 同位旋矢量势

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1) E-mail: mengj@pku.edu.cn