Article ID: 1007－4627(2009)Suppl.－0181－04

Probing Nuclear Symmetry Energy with Giant Dipole Resonances in Finite Nuclei*

CAO Li-gang[1,3], MA Zhong-yu[2,3]

(1 *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou* 730000, *China*;
2 *China Institute of Atomic Energy, Beijing* 102413, *China*;
3 *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Research Facility in Lanzhou, Lanzhou* 730000, *China*)

Abstract: The relationship between the centroid energies of the isovector giant dipole resonance of finite nuclei and the symmetry energy has been studied. It is found the excitation energies of the dipole resonance in finite nuclei are correlated linearly with the symmetry energy at and below the saturation density. This linear correlation leads to the symmetry energy at the saturation density at the interval 33.0 MeV $\leqslant S(\rho_0) \leqslant$ 37.0 MeV, and the symmetry energy at $\rho = 0.1\ \mathrm{fm}^{-3}$ at the interval 21.2—22.5 MeV. It is proposed that a precise measurement of the dipole mode in nuclei could set up an important constraint on the equation of state for nuclear matter.

Key words: symmetry energy; dipole resonance; Pygmy resonance

CLC number: O571.25$^+$1 **Document code**: A

1 Introduction

In recent years probing the symmetry energy, especially its density-dependence[1] has become the very hot issue in nuclear physics and astrophysics. The symmetry energy plays an important role in understanding the mechanisms of many exotic phenomena in nuclear physics and astrophysics. Unfortunately, the knowledge of the symmetry energy is rather poor, especially its density dependence. But the set up of new radioactive-beam facilities all over the world can provide more chances for probing the density dependence of symmetry energy. Most of the theoretical studies have been concentrated on the densities near saturation (~0.16 fm^{-3}) and above. Of course, this density interval is very important for the physics of neutron stars and heavy-ion collisions[2—6].

The symmetry energy at densities below the saturation density is also very important in describing the structure of neutron rich nuclei, predicting the position of neutron drip line and even for understanding the behaviour of neutron rich matter in nuclear astrophysics, e. g. the neutron star crust. The surface behaviour of finite nuclei, especially in nuclei far from β-stable line, is related to the property of asymmetric nuclear matter at the density much lower than the saturation density. Recently the study of neutron skin has been paid more attention and various experimental methods have been proposed[7—9]. It is found that the thickness of neutron skin is related to the EOS of asymmetric nuclear matter at the density below saturation point[10—14]. On the other hand, according to macroscopic hydrodynamics models[15] the restoring force of the isovector giant dipole resonance (IVGDR) is proportional to the symmetry energy

* **Received date**: 1 Sep. 2008; **Revised date**: 2 Sep. 2008

* **Foundation item**: National Natural Science Foundation of China(10875150, 10775183)

Biography: Cao Li-gang(1974－), male(Han Nationality), Xi'an, Shaanxi, China, Associated Professor, working on the properties of exotic nuclei using the energy density functional approach; E-mail: caolg@impcas.ac.cn

of nuclear matter. The property of IVGDR in finite nuclei are closely related to the symmetry energy at the saturation density based on various microscope approaches[16—18]. In this paper we investigate the relationship between the property of IVGDR in finite nuclei and the symmetry energy of nuclear matter, not only at the saturation density but also at the densities below the saturation point. The method used here is the relativistic mean field theory(RMF) plus the fully consistent relativistic random phase approximation (RRPA), more details can be found in recently papers[19—24]. In this paper the property of IVGDR in three stable nuclei ^{90}Zr, ^{144}Sm, ^{208}Pb are studied within six different RMF effective Lagrangian parameter sets: NLSH[25], NL3[26], NLBA[27], NLE, NLZ2[28], and NLVT[29]. Nuclear matter properties within different Lagrangian parameter sets is shown in Table 1.

Table 1 Nuclear matter properties calculated in the RMF with different Lagrangian parameter sets

Parameter sets	E/A/MeV	ρ_0/fm^{-3}	K/MeV	m^*/m	a_4/MeV
NL-SH	16.346	0.146	355.36	0.597	36.1
NL3	16.24	0.148	271.76	0.60	37.4
NL-BA	16.194 9	0.150 3	248.0	0.595	37.7
NLE	16.138	0.150 1	222.0	0.578 8	38.6
NLZ2	16.07	0.151	172.0	0.583	39.0
NLVT	16.088	0.153 1	173.3	0.591 8	39.8

2 Results and Discussions

The centroid energy of the response function is calculated as the ratio of the first and zeroth order moments,

$$E=\frac{\int_0^{\omega_{\max}} R(\omega)\omega\,\mathrm{d}\omega}{\int_0^{\omega_{\max}} R(\omega)\mathrm{d}\omega}. \tag{1}$$

The centroid energies of IVGDR as functions of the symmetry energy at the saturation density given by various parameter sets are plotted in Fig. 1. Symbols are the RRPA results and solid line is the least fitting. It is found that the excited energies of IVGDR decrease linearly with the increasing of the symmetry energy. The short- dashed lines represent the experimental values of IVGDR in corresponding nuclei, which are taken from Refs. [30—32]. From the comparison of the experimental data and the theoretical results, we can approximately constrain the symmetry energy at the saturation density at the interval 33.0 MeV $\leqslant S(\rho_0)\leqslant$ 37.0 MeV.

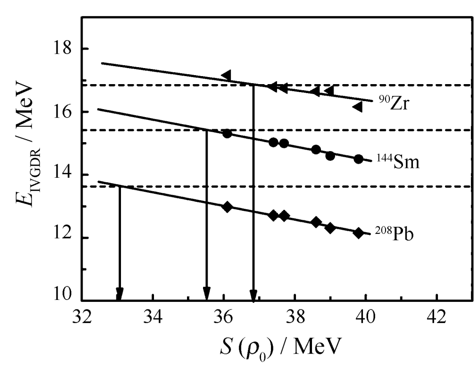

Fig. 1 The centroid energies of IVGDR for stable nuclei ^{90}Zr, ^{144}Sm, and ^{208}Pb calculated with various effective Lagrangian parameter sets vs the value of symmetry energy at saturation density.

Our result is consistent with that obtained in Ref. [17], where the authors adopted an effective Lagrangian with density-dependent meson-nucleon vertex functions. In order to investigate possible correlations between volume asymmetry and nuclear matter compression modulus, they have constructed three sets of effective interactions with K_{nm} = 230, 250, and 270 MeV, and for each value of K_{nm} they have adjusted five interactions with

$S(\rho_0)=30$, 32, 34, 36, and 38 MeV, respectively. They found that the IVGDR constrains the volume asymmetry at the interval 34.0 MeV $\leqslant S(\rho_0)\leqslant$ 36.0 MeV.

We further pay more attention to the relationship between the soft dipole mode in weakly bound nuclei and symmetry energy of nuclear matter at lower densities. It is well known that a genuine feature of weakly bound nuclei is the appearance of soft electric dipole modes, which are the so-called Pygmy Dipole Resonances (PDR). The appearance of the soft dipole modes in neutron rich nuclei is of particular interest because they are expected to reflect the motion of neutrons at nuclear surface against the core formed with equal number of neutrons and protons. In addition they could provide important information on isospin and density-dependent part of the effective interaction in many-body theory.

Recently, the dipole strength distribution above the one-neutron separation energy has been measured in the unstable ^{130}Sn and the double-magic ^{132}Sn isotopes with the LAND-FRS facility at GSI, Darmstadt[33]. In addition to the general giant dipole resonance at higher energy region, they also observed a resonance-like structure-pygmy resonance at the excitation energy around 9.8 MeV just above the neutron separation energy, which exhausts a few percents of the isovector E1 energy-weighted sum rule in ^{132}Sn.

To describe the experimental data we calculated the soft dipole resonance of ^{132}Sn in the RRPA with the six parameter sets. The symmetry energies at $\rho=0.1$ fm^{-3} are 24.3, 24.95, 25.1, 25.43, 25.6, and 25.82 MeV for NLSH, NL3, NLBA, NLE, NLZ2, and NLVT, respectively. It is found that the soft dipole response strengths in neutron rich nuclei are very fragmented. The smaller symmetry energy and the higher energies of dipole strengths are predicted. The soft electric dipole modes are expected to describe the nucleon surface motion, which would be sensitive to the symmetry energy at the nuclear surface. It has been pointed out that some average between the symmetry energy at saturation density and the surface symmetry energy is constrained by the binding energy of nuclei[34]. Adding non-liner interactions between isoscalar and isovector mesons by unchanging the symmetric energy at $\rho=0.1$ fm^{-3} in the effective Lagrangian could modify the density dependence of symmetry energy without changing the agreement with existing ground state information. Therefore the symmetry energy at $\rho=0.1$ fm^{-3} is an important piece of information in describing the nuclear properties. In Fig. 2 we plot the peak energies of soft dipole mode in ^{132}Sn given by

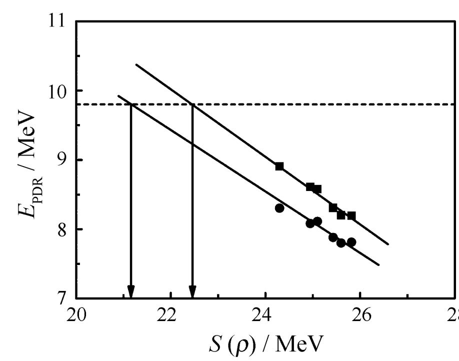

Fig. 2 The peak energies of soft dipole excitation in ^{132}Sn vs the values of symmetry energy at $\rho=0.1$ fm^{-3}.

RRPA approach as a function of the symmetry energy at $\rho=0.1$ fm^{-3} for six non-linear parameter sets. The circles and the squares are the results obtained by including and excluding the strengths under one neutron separation energy. It is shown that the calculated peak energies of soft dipole mode in ^{132}Sn are also linearly correlated to the value of symmetry energy at $\rho=0.1$ fm^{-3}. From the comparison to the present experimental data in PDR excited energy, we may approximately give an constraint to the symmetry energy at the interval 21.2 to 22.5 MeV at $\rho=0.1$ fm^{-3}. This result is consistent with recently findings[35, 36], where the authors analyzed the experimental reaction data and tried to extract information on the density dependence of symmetry energy with different microscopic approaches. They obtained that the symmetry energy at $\rho=0.1$ fm^{-3} is around 22.0 MeV.

3 Summary

In summary, we have investigated the relationship between the properties of IVGDR of finite nuclei and the symmetry energy at and below the saturation density based on the microscopic RMF plus fully consistent RRPA approach. Six different non-linear effective Lagrangian parameter sets (NLSH, NL3, NLBA, NLE, NLZ2, and NLVT), which scan a large range of possible values of the symmetry energy at nuclear matter saturation density, are adopted in our investigation. A strong linear correlation of the IVGDR centroid energies in stable nuclei ^{90}Zr, ^{144}Sm, ^{208}Pb and the symmetry energy at the saturation density is found. Comparison to the experimental data in IVGDR excited energy leads to value of the symmetry energy at saturation density in the range $33.0\ \mathrm{MeV} \leqslant S(\rho_0) \leqslant 37.0\ \mathrm{MeV}$. This result is similar to that obtained by using density-dependent parameter sets. The excitation energy of soft dipole mode in neutron rich nucleus ^{132}Sn and its relationship to the symmetry energy at low density is also studied. An approximately linear correlation is found. The comparison to the recent experimental data in the PDR excited energy could bring the symmetry energy to the interval 21.2 − 22.5 MeV at $\rho=0.1\ \mathrm{fm}^{-3}$. It is also stressed that the further measurement of the soft dipole mode in many neutron rich nuclei could provide an important constraint on the EOS for asymmetric nuclear matter.

References:

[1] Steiner A W, Prakash M, Lattimer J M, *et al*. Phys Rep, 2005, 411: 325.

[2] Li B A, Champak B D, Gupta S D, *et al*. Nucl Phys, 2004, A735: 563.

[3] Baran V, Colonna M, Greco V, *et al*. Phys Rep, 2005, 410: 335.

[4] Gaitanos T, Colonna M, Greco V, *et al*. Nucl Phys, 2004, A732: 24.

[5] Shetty D V, Yennello S J, Botvina A S, *et al*. Phys Rev, 2004, C70: 011 601.

[6] Akira Ono, Danielewicz P, Friedman W A, *et al*. Phys Rev, 2004, C70: 041 604.

[7] Horowitz C J, Pollock S J, Souder P A, *et al*. Phys Rev, 2001, C63: 025 501.

[8] Suzuki T, Geissel H, Bochkarev O, *et al*. Phys Rev Lett, 1995, 75: 3 241.

[9] Krasznahorkay A, Fujiwara M, Aarle P van, *et al*. Phys Rev Lett, 1999, 82: 3 216.

[10] Brown B A. Phys Rev Lett, 2000, 85: 5 296.

[11] Typel S, Brown B A. Phys Rev, 2001, C64: 027 302.

[12] Furnstahl R J. Nucl Phys, 2002, A706: 85.

[13] Yoshida S, Sagawa H. Phys Rev, 2004, C69: 024 318.

[14] Baldo M, Maieron C, Schuck P, *et al*. Nucl Phys, 2004, A736: 241.

[15] Goldhaber M, Teller E. Phys Rev, 1948, 74: 1 046.

[16] Reinhard P G. Nucl Phys, 1999, A649: 305c.

[17] Vretenar D, Nikšic´ T, Ring P. Phys Rev, 2003, C68: 024 310.

[18] Piekarewicz J. Phys Rev, 2004, C69: 041 301.

[19] Ring P. Prog Part Nucl Phys, 2004, 37: 197.

[20] Ma Z Y, Giai N V, Wandelt A, *et al*. Nucl Phys, 2001, A686: 173; Ma Z Y, Wandelt A, Giai N V, *et al*. Nucl Phys, 2002, A703: 222.

[21] Cao L G, Ma Z Y. Phys Rev, 2002, C66: 024 311.

[22] Ring P, Ma Z Y, Giai N V, *et al*. Nucl Phys, 2001, A694: 249.

[23] Vretenar D, Wandelt A, Ring P. Phys Lett, 2000, B487: 334.

[24] Piekarewicz J. Phys Rev, 2001, C64: 024 307.

[25] Sharma M M, Nagarajan M A, Ring P. Phys Lett, 1993, B312: 377.

[26] Lalazissis G A, König J, Ring P. Phys Rev, 1997, C55: 540.

[27] Gmuca S. Proc 2nd Int Conf Fission and Properties of Neutron-rich Nuclei. Eds: Hamilton J H, Phillips W R, Carter H K. Singapore: World Scientific, 2000: 75.

[28] Rufa M, Reinhard P-G, Maruhn J A, *et al*. Phys Rev, 1988, C38: 390.

[29] Bender M, Rutz K, Reinhard P-G, *et al*. Phys Rev, 1999, C60: 034 304.

[30] Carlos P, Beil H, Bergere R, *et al*. Nucl Phys, 1974, A225: 171.

[31] Berman B L, Fultz S C. Rev Mod Phys, 1975, 47: 713.

[32] Ritman J, Berg F-D, Kühn W, *et al*. Phys Rev Lett, 1993, 70: 533.

[33] Adrich P, Klimkiewicz A, Fallot M, *et al*. Phys Rev Lett, 2005, 95: 132 501.

[34] Todd B G, Piekarewicz J. Phys Rev, 2003, C67: 044 317.

[35] Yennello S J, Shetty D V, Souliotis G A. arXiv: nucl-ex/0601006.

[36] Khoa D T, Than H S. Phys Rev, 2005, C71: 044 601.