Brazilian Journal of Physics
ISSN: 0103-9733
luizno.bjp@gmail.com
Sociedade Brasileira de Física
Brasil

Biswal, S. K.; Singh, S. K.; Bhuyan, M.; Patra, S. K.
The Effects of Self Interacting Isoscalar-Vector Meson on Finite Nuclei and Infinite Nuclear Matter
Brazilian Journal of Physics, vol. 45, núm. 3, junio, 2015, pp. 347-352
Sociedade Brasileira de Física
Sâo Paulo, Brasil

Braz J Phys (2015) 45:347–352
DOI 10.1007/s13538-015-0317-z

NUCLEAR PHYSICS

The Effects of Self Interacting Isoscalar-Vector Meson on Finite Nuclei and Infinite Nuclear Matter

S. K. Biswal[1] · S. K. Singh[1] · M. Bhuyan[1] · S. K. Patra[1]

Received: 30 January 2015 / Published online: 11 April 2015

Abstract In this work we perform a detailed study of the nucleon-nucleon (NN) interaction based on relativistic mean field theory in which the potential is explicitly expressed in terms of the masses and the coupling constants of the meson fields. A unified treatment for the self-couplings of isoscalar-scalar σ meson, isoscalar-vector ω mesons, and their coupling constants is given and analytical expressions are provided. The effects of self-interacting higher order σ and ω fields on nuclear properties are evaluated. An attempt is made to explain the many-body effects which generally occur in high-density region. Both infinite and finite nuclear matter properties are discussed to investigate the behavior and sensitivity of these self interacting terms.

Keywords Relativistic mean field · Nucleon-nucleon potential · Energy density · Pressure density · Binding energy · Excitation energy

✉ S. K. Biswal
sbiswal@iopb.res.in

S. K. Singh
shailesh@iopb.res.in

M. Bhuyan
bunuphy@iopb.res.in

S. K. Patra
patra@iopb.res.in

1 Institute of Physics, Sachivalaya Marg, 751 005 Bhubaneswar, India

1 Introduction

The nucleon-nucleon (NN) interaction has been investigated for over half a century [1, 2]. Probably this is a long standing question in the history of nuclear physics. In fact, describing the nuclear properties in terms of the interactions between nucleon pairs is the main goal of nuclear physicists. The *nucleon-nucleon* (NN) interaction in terms of mediated mesons was put forwarded by Yukawa [3] in 1935. Although the meson theory is not fundamental from the QCD point of view, it has improved our undertanding of the nuclear forces as well as highlighted some good quantitative results [4, 5]. The modern theory of NN potential in terms of particle exchange was made possible by the development of quantum field theory [5]. However, at low-energy, one can assume that the interactions are instantaneous and therefore the concept of interaction potential becomes useful. The derivation of a potential through particle exchange is important to understand the nuclear force as well as the structural properties of nuclei.

Nowadays, there are many nuclear theory models using quark and gluon in connection with the NN potential [6, 7]. These models give the fundamental understanding of the NN interaction at present. Here, we are not addressing all these long standing problems about the NN potential. Our aim is to highlight some basic features of the NN interaction arising from the relativistic mean field (RMF) Lagrangian [8–12]. The behavior of this potential gives an idea about the saturation properties of nuclear force at the high energy limit.

The paper is organized as follows: In Section 2, we briefly discuss the theoretical formalism of the NN interaction based on relativistic mean field (RMF) theory. The general forms of the NN potentials are expressed in the coordinate space (*r-space*) in terms of the masses and coupling constants of the force parameters. In Section 3, we review the effects of the modified term in the Lagrangian on observables in finite nuclei and in infinite nuclear matter In Section 4, we make a few comments about the current form of the NN interaction at saturation/super-saturation condition of nuclear systems.

2 The Theoretical Frameworks

The linear relativistic mean field Lagrangian density for a nucleon-meson many-body system is given as [13–16]:

$$\begin{aligned}\mathcal{L} = &\overline{\psi_i}\{i\gamma^{\mu}\partial_{\mu} - M\}\psi_i + \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma - \frac{1}{2}m_{\sigma}^2\sigma^2 - g_s\overline{\psi_i}\psi_i\sigma \\ &-\frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_w^2 V^{\mu}V_{\mu} - g_w\overline{\psi}_i\gamma^{\mu}\psi_i V_{\mu} - \frac{1}{4}\mathbf{B}^{\mu\nu}.\mathbf{B}_{\mu\nu} \\ &+\frac{1}{2}m_{\rho}^2\mathbf{R}^{\mu}.\mathbf{R}_{\mu} - g_{\rho}\overline{\psi}_i\gamma^{\mu}\tau\psi_i.\mathbf{R}^{\mu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\ &-e\overline{\psi}_i\gamma^{\mu}\frac{(1-\tau_{3i})}{2}\psi_i A_{\mu}, \end{aligned} \tag{1}$$

where the field for σ meson is denoted by σ, for ω by V_{μ}, and for the iso-vector $\rho-$meson by $\mathbf{R}_{\mu}$. The ψ_i, τ, and τ_3 are the Dirac spinors, iso-spin, and the 3^{rd} component of the iso-spin of the nucleon, respectively. Here, g_{σ}, g_{ω}, and g_{ρ} are the coupling constants for σ, ω, and ρ mesons and their masses are denoted by m_{σ}, m_{ω}, and m_{ρ}, respectively. The field tensors for V^{μ} is $\Omega^{\mu\nu}$ and for $\mathbf{R}_{\mu}$ is denoted by $\mathbf{B}_{\mu\nu}$. If, we neglect the $\rho-$ meson, it corresponds to the original Walecka model [14]. From the above Lagrangian, we obtain the field equations for the nucleons and mesons. In the limit of one-meson exchange and mean-field (the fields are replaced by their expectation values), for a heavy and static baryonic medium, the solution of single nucleon-nucleon potential for scalar (σ) and vector (ω, ρ, and Coulomb) fields are given by [8, 9],

$$V_{\sigma}(r) = -\frac{g_{\sigma}^2}{4\pi}\frac{e^{-m_{\sigma}r}}{r}, \tag{2}$$

and

$$\begin{aligned}V_{\omega}(r) &= +\frac{g_{\omega}^2}{4\pi}\frac{e^{-m_{\omega}r}}{r}, \quad V_{\rho}(r) = +\frac{g_{\rho}^2}{4\pi}\frac{e^{-m_{\rho}r}}{r}, \\ V_C(r) &= +\frac{e^2}{4\pi r}.\end{aligned} \tag{3}$$

The total effective NN potential is obtained from the scalar and vector parts of the meson fields. This can be expressed as [8],

$$\begin{aligned}v_{eff}(r) = V_{\omega} + V_{\rho} + V_C + V_{\sigma} = &\frac{g_{\omega}^2}{4\pi}\frac{e^{-m_{\omega}r}}{r} + \frac{g_{\rho}^2}{4\pi}\frac{e^{-m_{\rho}r}}{r} \\ &+\frac{e^2}{4\pi r} - \frac{g_{\sigma}^2}{4\pi}\frac{e^{-m_{\sigma}r}}{r}.\end{aligned} \tag{4}$$

2.1 Nonlinear Case

The Lagrangian density (1) contains only linear coupling terms, which is able to give a qualitative description of the nuclear system [14–16]. The essential nuclear matter properties like incompressibility and the surface properties of finite nuclei cannot be reproduced quantitatively within this linear model. The replacement of mass terms $\frac{1}{2}m_{\sigma}^2\sigma^2$ of σ field by $U(\sigma)$ and $\frac{1}{2}m_{\omega}^2 V^{\mu}V_{\mu}$ of ω field by $U(\omega)$, acts as a smoothing mechanism and hence lead in the direction of the one-body potential and shell structure [17–20]. This can be expressed as

$$U(\sigma) = \frac{1}{2}m_{\sigma}^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4, \tag{5}$$

$$U(\omega) = \frac{1}{2}m_{\omega}^2 V_{\mu}V^{\mu} + \frac{1}{4}c_3\left(V_{\mu}V^{\mu}\right)^2. \tag{6}$$

The cubic and quartic terms on the right hand side of (5–6) arise from the self couplings of the σ and ω mesons [17–20]. Keeping $c_3 = 0$, the values of g_2 and g_3 due to $\sigma-$fields along with other parameters are obtained by a least square fitting of various nuclear properties [17]. In general, most of the successful fits like NL1 [21] and NL3 [22] sets yield a $+ve$ and a $-ve$ sign for g_2 and g_3, respectively. The negative value of g_3 is a serious problem in quantum field theory and responsible for the divergence of a solution in the lighter mass region of the periodic table [23]. As, we are dealing within the mean field level and with normal nuclear matter density, the corresponding σ field is very small and the $-ve$ value of g_3 is still allowed for slightly heavier mass nuclei [23]. Again, allowing $c_3 = \frac{1}{6}\zeta_0$ non-zero, one get a different parameter set like TM1 and TM2 [20] with a positive g_3. The field equations for $\sigma-$ and ω-mesons obtained from the nonlinear Lagrangian as:

$$\begin{aligned}\left(-\nabla^2 + m_{\sigma}^2\right)\sigma(r) &= -g_{\sigma}\rho_s(r) - g_2\sigma^2(r) - g_3\sigma^3(r), \\ \left(-\nabla^2 + m_{\omega}^2\right)V(r) &= g_{\omega}\rho(r) - c_3 W^3(r),\end{aligned} \tag{7}$$

with $W(r) = g_{\omega}V_0(r)$. Because of the difficulty in solving the above nonlinear differential equations, it is essential to have a variation principle for the estimation of the energies [24–26]. In the static case, the negative sign of the third term in the Lagrangian is computed with the correct source function and an arbitrary trial wave function. The limit on the energy has a stationary value equal to the proper energy when the trial wavefunction is in the infinitesimal

Table 1 The values of m_σ, m_ω, m_ρ (in MeV), and g_σ, g_ω, g_ρ for RMF (NL3) force, along with the *ad hoc* addition of self-interacting $\omega-$ field with coupling constant c_3

set	m_σ	m_ω	m_ρ	g_σ	g_ω	g_ρ	$g_2(fm^{-1})$	g_3	c_3
NL3	508.194	782.5	763.0	08.31	13.18	6.37	−10.4307	−28.8851	0.0±0.6

neighborhood of the correct one. Now, the solution for the modified σ and ω fields are given as [9]:

$$V_\sigma = -\frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{r} + \frac{g_2^2}{4\pi}\frac{e^{-2m_\sigma r}}{r^2} + \frac{g_3^2}{4\pi}\frac{e^{-3m_\sigma r}}{r^3},$$

$$V_\omega = \frac{g_\omega^2}{4\pi}\frac{e^{-m_\omega r}}{r} - \frac{c_3^2}{4\pi}\frac{e^{-3m_\omega r}}{r^2}. \quad (8)$$

and the modified effective nucleon-nucleon interaction is defined as [8, 9]:

$$\begin{aligned} v_{eff}(r) &= V_\omega + V_\rho + V_\sigma + V_C \\ &= \frac{g_\omega^2}{4\pi}\frac{e^{-m_\omega r}}{r} + \frac{g_\rho^2}{4\pi}\frac{e^{-m_\rho r}}{r} - \frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{r} + \frac{e^2}{4\pi r} \\ &\quad + \frac{g_2^2}{4\pi}\frac{e^{-2m_\sigma r}}{r^2} + \frac{g_3^2}{4\pi}\frac{e^{-3m_\sigma r}}{r^3} - \frac{c_3^2}{4\pi}\frac{e^{-3m_\omega r}}{r^3}. \quad (9) \end{aligned}$$

Neglecting the contribution for $\rho-$meson and Coulombic interaction for NN interaction, the above equation reduces to

$$\begin{aligned} v_{eff}(r) &= V_\omega + V_\sigma \\ &= \frac{g_\omega^2}{4\pi}\frac{e^{-m_\omega r}}{r} - \frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{r} \\ &\quad + \frac{g_2^2}{4\pi}\frac{e^{-2m_\sigma r}}{r^2} + \frac{g_3^2}{4\pi}\frac{e^{-3m_\sigma r}}{r^3} - \frac{c_3^2}{4\pi}\frac{e^{-3m_\omega r}}{r^3}. \quad (10) \end{aligned}$$

The new NN interaction analogous to $M3Y$ and is able to improve the incompressibility and deformation of the finite nuclei results [17, 27]. In addition to this, the nonlinear self coupling of the σ and ω-mesons help to generate the repulsive and attractive part of the NN potential at *long* as well as at *short* distance, respectively, to satisfy the saturation properties (Coester-band problem) [27, 28]. We are dealing with two type of mesons, one is scalar (σ) and other is vector (ω). The range of their interactions are also different due to their different masses. Consider the case of $\sigma-$meson, where the range of interaction is $\sim \frac{\hbar}{m_\sigma c}$ fm. In this range, the attractive part of the potential comes from the exchange of the $\sigma-$meson. The density dependent many body effect demands a repulsive part in this region [29]. This is given by the self interacting terms like σ^3 and σ^4 [9, 30, 31]. The total NN potential generated from the nonlinear $\sigma-\omega$ Lagrangian for nuclear matter is able to reproduce the proper effective interaction satisfying the Coester band problem. Generally, the exchange of $\omega-$meson gives the repulsive potential in the short-range part of the hard core region. However, the self-coupling of $\omega-$meson gives an attractive component at very short distance ($\sim$ 0.2 fm) of the nuclear potential. The nonlinear terms also generate the most discussed $3-body$ interaction [30, 31].

3 Results and Discussions

Equation (10) represents the effective NN potential in terms of the well-known mesonic degrees of freedoms (σ and ω meson fields) and their coupling strengths. Here, we have used RMF (NL3) force parameter along with varying c_3 for ω-self interaction to determine the nuclear properties. The values of the parameter set for NL3-force are listed in Table 1. Although the ω^4 term is already there in several interactions, such as FSU-Gold parameter [32, 33], here we are interested to see the effects of nonlinear self coupling for $\omega-$meson. Thus, we have added the self-interaction of ω with coupling constant c_3 on the top of NL3 set and observed the possible effects.

First of all, we have calculated the NN-potential for linear and nonlinear cases. The obtained results for each cases are shown in Fig. 1. From the figure, it is clear that without the nonlinear coupling for RMF (NL3), one cannot reproduce a better NN-potential. In other word, the depth of the potential for linear and nonlinear is $\sim$ 150 and 50 MeV, respectively. Thus, the magnitude of the depth for linear case is unreasonable to fit the NN data. Again, considering the values of c_3, there is no significant change in the total *nucleon-nucleon* potential. For example, the NN-potential does not change at all for $c_3 \simeq \pm$ 0.6, which can be seen from Fig. 1.

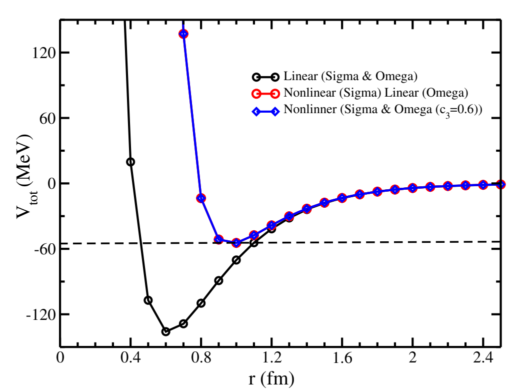

Fig. 1 The effective NN interaction potentials as a function of distance r from (7–10) for NL3 parameter set

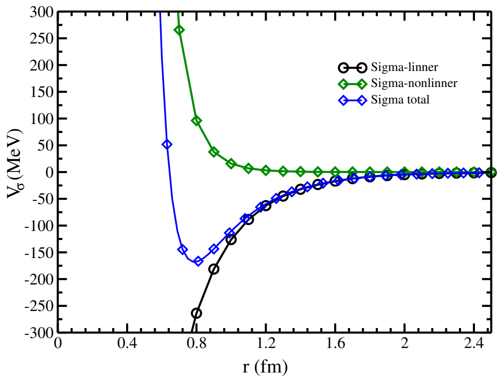

Fig. 2 The contribution of σ-potential from linear, non-linear and total as a function of distance r for NL3 parameter set

Further, we have calculated the individual contribution of meson fields to the NN potential in particular cases of σ and ω-mesons. In case of σ-field, we have calculated the linear and nonlinear contributions separately and combined to get the total σ-potential as shown in Fig. 2. From the figure, one can find the nonlinear self-interacting terms in the σ-field play an important role (contributing a repulsive interaction) in the attractive part of the $\sigma-$meson domain, giving rise to a repulsive potential complementing the 3-body effect of the nuclear force in the total NN potential [24, 29]. The linear and nonlinear contributions of the ω-field at various c_3 are shown in Fig. 3. The important feature in this figure is that the linear term gives an infinitely large repulsive barrier at $\sim$ 0.5 fm, in which range, the influence of the nonlinear term of the $\omega-$meson is zero. However, this nonlinear term is extremely active at very short distance ($\sim$ 0.2 fm), which can be seen from the figure.

That means, mostly the (i) linear term of the $\sigma-$ meson is responsible for the attractive part of the nuclear force (nuclear binding energy); (ii) the nonlinear terms are responsible for the repulsive part of the nuclear force at long distance, which simulate the 3-body interaction of the nuclear force [24, 30, 31], which also help to explain the Coester band problem; (iii) similarly, the linear term of the $\omega-$ meson is restraint for the repulsive part of the nuclear force (*known as hard core*); and (iv) the nonlinear self-coupling of the $\omega-$ meson ($\frac{1}{4}c_3 V_\mu V^\mu$) is responsible for the attractive part in the very shortest ($\sim 0.2 fm$) region of the NN potential. It is worthy to mention that the exact values of these constants are different for different forces of RMF theory. Hence, the NN potential somewhat change a little bit in magnitude by taking different forces, but the nature of the potential remains unchange.

3.1 Energy Density and Pressure Density

To our knowledge, for the first time, the self-coupling of vector meson term is introduced by Bodmer [18] and subsequently by Gumca [19] and Sugahara et al. [20]. In their calculations, they added the vector meson self-coupling term and constructed a new parameter set in equal footing with other coupling constants. Thus, the inclusion of this term is not new, it is already taken into account for different forces of RMF and effective field theory motivated relativistic mean field theory (E-RMF). Here, our aim is to see the effects of c_3 on the nuclear system and the contribution to the attractive part of the hard core of NN potential. We have solved the mean field equations self-consistently and estimated the energy and pressure density as a function of baryon density for symmetric nuclear matter. Thus, the contributions of Coulomb and $\rho-$fields are neglected. The obtained results for different values of c_3 are shown in Figs. 4 and 5. The empirical binding energy per particle $e^{emp}(\rho)$ for symmetric nuclear matter at saturation is 15.98 MeV [34] and that of NL3 set $e(\rho)(NL3)$ are depicted in Fig. 4 to have an understanding on the influence of c_3. It can be seen that these two values coincide with each other at saturation density for $c_3 = 0$ including with a small variation of c_3. That means, the change in $e(\rho)$ with c_3 is almost

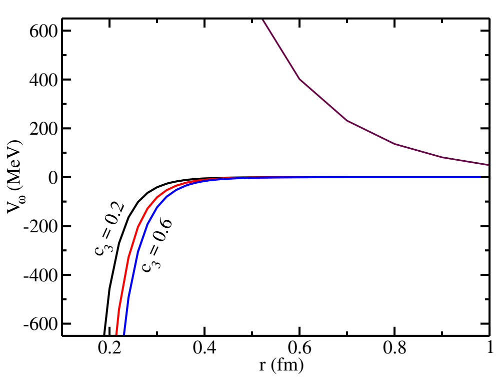

Fig. 3 The contribution of ω-potential from linear, non-linear and total as a function of distance r for NL3 parameter set

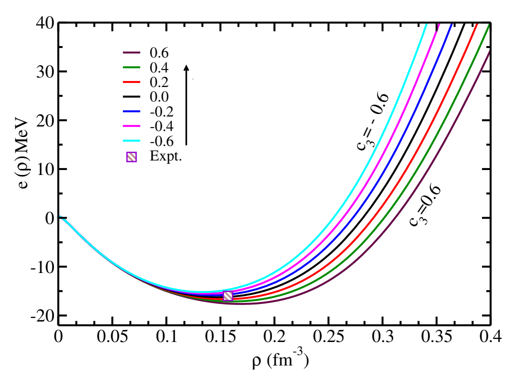

Fig. 4 The energy per particle of symmetric nuclear matter as a function of baryon density for various values of c_3. The empirical and nuclear matter saturation values for NL3 set are also given

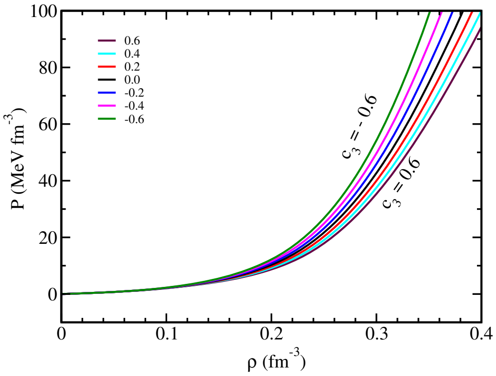

Fig. 5 The pressure density of symmetric nuclear matter as a function of baryon density for various values of c_3

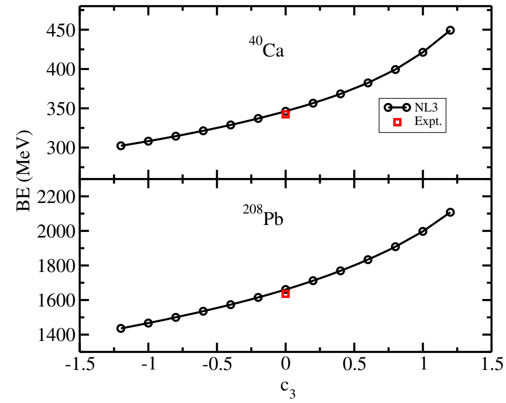

Fig. 6 The binding energy of ^{40}Ca and ^{208}Pb in their ground state for different values of c_3. The experimental data for these nuclei are also given

negligible at the saturation point, while this variation is substantial for higher density region. From the figures, it is identified that the $-ve$ value of c_3 gives a *stiff* equation of state (EOS), meanwhile the $+ve$ value shows a *soft* EOS. It is to be noted that mass and radius of the neutron star depend on the softness and stiffness of EOS [35]. In some investigations, it is observed that the softening of the EOS depends on the nonlinear coupling of the $\omega-$ meson [20, 33]. The recent measurement of neutron star mass by Demorest et al. [36] constraints a new direction that the NL3 force needed to produce a softer EOS. However, when we deal with G2 (E-RMF) model [35], the results of Ref. [37] demand a slightly stiffer EOS. This implies that the value of c_3 should be fixed according to solve the above discussed problems in equal footing with other parameters of the set.

3.2 Binding Energy, Excitation Energy, and Compressibility Modulus

To see the sensitivity of c_3 on finite nuclei, we calculate the binding energy (BE), giant monopole excitation energy (E_x), and compressibility modulus K_A for ^{40}Ca and ^{208}Pb as representative cases as a function of c_3. The excitation energy and compressibility modulus are calculated by scaling method within the framework of extended Thomas-Fermi (RETF) approximation [38, 39]. The obtained results are shown in the upper and lower panel of Figs. 6 and 7. The experimental or empirical data are also displayed for comparison.

From the figure, one observes a systematic variation of binding energy by employing the isoscalar-vector self-coupling parameter c_3. For example, the binding energy monotonically changes for all values of c_3. When $c_3 = 0$, the NL3 set reproduces the original binding energies for both ^{40}Ca and ^{208}Pb, which are fitted with the data while constructing the force parameters. As soon as the self-coupling constant is non-zero, the calculated BE deviates from the data, because of the influence of c_3. Again, analyzing the excitation energy, we find reasonable match of E_x with the observation (lower panel of Fig. 7). These values of E_x remain almost constant for a wide range of c_3 (~ -2 to ~ 1), beyond which E_x increases drastically for positive value only. Further, we analyze the variation of compressibility modulus with c_3 for ^{40}Ca and ^{208}Pb (upper panel of Fig. 7). We include both positive and negative values of c_3 (-2 to $+2$) to know the effects on the sign of c_3. Similar to the monopole excitation energy, we find that the compressibility modulus does not change with the increase of c_3 up to some optimum value. The empirical (nuclear matter compressibility modulus K_∞) data of $K_\infty^{emp} = 210 \pm 30$ MeV [40] and the nuclear matter compressibility modulus for NL3 set $K_\infty(NL3) = 271.76$ MeV are given in the figure to have an idea about the bridge between the nuclear

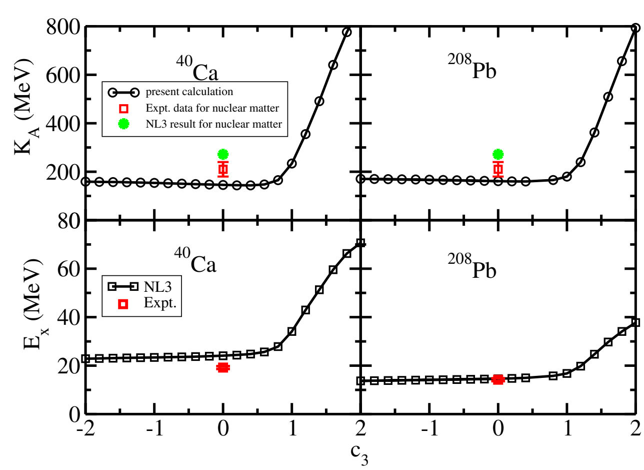

Fig. 7 *Lower panel:* The excitation energy E_x as a function of c_3 for ^{40}Ca and ^{208}Pb. The experimental data are also given. *Upper panel:* The incompressibility of ^{40}Ca and ^{208}Pb as a function of c_3. The experimental and incompressibility at saturation for NL3 set $K_\infty(NL3)$ values are also given

matter limit for finite nuclei. In general, these two values along with the finite nuclei compressibility modulus gives an overall estimation about a possible link among them in finite nuclei and nuclear matter limit. It is interesting to notice that although we get a stiff equation of state with negative value of c_3 for infinite nuclear matter system, this behavior does not appear in finite nuclei, i.e. the K_A and E_x do not change with sign of c_3. May be the density with which we deal in the finite nucleus is responsible for this discrepancy. However, K_A and E_x increase substantially after certain value of c_3, i.e. the finite nucleus becomes too much softer at about $c_3 \sim 1.0$ resulting a larger incompressibility.

4 Summary and Conclusions

In summary, we analyzed the effects of the non-linear self-coupling of the $\sigma-$scalar and $\omega-$vector mesons. At long range, i.e., at distances larger than 0.5 fm, the self coupling of the $\sigma-$meson gives a repulsive component contrary to the attractive part of the linear term. This repulsive nature of the nuclear potential originated from the nonlinear terms of the $\sigma-$meson couplings simulate the 3-body force. This 3-body force may solve the Coester band problem in RMF formalism. On the other hand, at extremely short distance, the nonlinear term of the $\omega-$meson coupling gives a strongly attractive potential for both $positive$ and $negative$ values of c_3 upto ± 0.6. This short range distance is about $0.2 fm$, beyond (more than 0.2 fm) which the $vector-$meson interaction gives a strong repulsion due to its linear term and responsible for the saturation of nuclear force. Thus, one concludes that the effects of the vector self-coupling is crucial for the attractive nature of the nuclear force at the extremely short range region and should be taken in equal footing while constructing the force parameters in relativistic mean field theory.

References

1. H.A. Bethe, What holds the nucleus together. Sci. Am. **189**, 58 (1953)
2. J.W. Alcock, W.N. Cottingham, Nucl. Phys. B **41**, 141 (1972)
3. H. Yukawa, On the interaction of elementary particles. Proc. Phys. Math. Soc. Jpn **17**, 48 (1935)
4. Y. Fujiwara, K.T. Hecht, Nucl. Phys. A **451**, 625 (1986)
5. Y. Fujiwara, K.T. Hecht, Phys. Lett. B **171**, 17 (1986)
6. F. Gross, T.D. Cohen, E. Epelbaum, R. Machleidt, Conference discussion of the nuclear force. Few-Body Syst. **50**, 31 (2011). arXiv:1110.3761[nucl-th]
7. R. Machleidt, Q. MacPherson, E. Marji, R. Winzer, Ch. Zeoli, D.R. Entem, Recent progress in the theory of nuclear forces. arXiv:1210.0992[nucl-th]
8. B. Singh, M. Bhuyan, S.K. Patra, R.aj.K. Gupta, J. Phys. G: Nucl. Part. Phys. **39**, 025101 (2012)
9. B.B. Sahu, S.K. Singh, M. Bhuyan, S.K. Patra, Phys. Rev. C **89**, 034614 (2014)
10. W.G. Love, G.R. Satchler, Nucl. Phys. A **159**, 1 (1970)
11. W.G. Love, L.J. Parish, Nucl. Phys. A **157**, 625 (1970)
12. W.G. Love, Nucl. Phys. A **192**, 49 (1972)
13. L.D. Miller, A.E.S. Green, Phys. Rev. C **5**, 241 (1972)
14. J.D. Walecka, Ann. Phys. (NY) **83**, 491 (1974)
15. C.J. Horowitz, B.D. Serot, Nucl. Phys. A **368**, 503 (1981)
16. B.D. Serot, J.D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986)
17. J. Boguta, A.R. Bodmer, Nucl. Phys. A **292**, 413 (1977)
18. A.R. Bodmer, Nucl. Phys. A **526**, 703 (1991)
19. S. Gmuca, Nucl. Phys. A **547**, 447 (1992)
20. Y. Sugahara, H. Toki, Nucl. Phys. A **579**, 557 (1994)
21. P.G. Reinhard et al., Z. Phys. A **323**, 13 (1986)
22. G.A. Lalazissis, J. Köning, P. Ring, Phys. Rev. C **55**, 540 (1997)
23. P.G. Reinhard, Z. Phys. A **329**, 257 (1988)
24. L.I. Schiff, Phys. Rev **84**, 1 (1950)
25. L.I. Schiff, Phys. Rev. **80**, 137 (1950)
26. L.I. Schiff, Phys. Rev. **83**, 239 (1951)
27. R. Brockmann, R. Machleidt, Phys. Rev. C **42**, 1965 (1990)
28. F. Coester, S. Cohen, B.D. Day, C.M. Vincent, Phys. Rev. C **1**, 769 (1970)
29. J. Jr. Morales, V.R. Pandharipande, D.G. Ravenhall, Phys. Rev. C **66**, 054308 (2002)
30. J.-i. Fujita, H. Miyazawa, Prog. Theo. Phys. **17**, 360 (1957)
31. S.C. Pieper, V.R. Pandharipande, R.B. Wiringa, J. Carlson, Phys. Rev. **64**, 014001 (2001)
32. C.J. Horowitz, J. Piekarewicz, Phys. Rev. Lett. **86**, 5747 (2001)
33. B.G. Todd-Rutel, J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005)
34. H.A. Bethe, Annu. Rev. Nucl. Sci. **21**, 93 (1971)
35. P. Arumugam, B.K. Sharma, P.K. Sahu, S.K. Patra, T. Sil, M. Centelles, X. Viñas, Phys. Lett. B **601**, 51 (2004)
36. P.B. Demorest, T. Pennucci, S.M. Ransom, M.S.E. Roberts, J.W.T. Hessels, Nature (London) **467**, 1081 (2010)
37. S.K. Singh, M. Bhuyan, P.K. Panda, S.K. Patra, J. Phys. G: Nucl. Part. Phys **40**, 085104 (2013)
38. S.K. Biswal, S.K. Patra, Cent. Euro. J. Phys. **12**, 582 (2014)
39. S.K. Patra, X. Viñas, M. Centelles, M. Del Estal, Nucl. Phys. A **703**, 240 (2002)
40. J.P. Blaizot, Phys. Rep. **64**, 171 (1980)