Possible Improvements in the Infinite Nuclear Matter Model of Atomic Nuclei

* R. C. Nayak*
Dept. of Physics, Berhampur University, Berhampur-760007, INDIA

The recently developed Infinite Nuclear Matter (INM) model[1–3] of atomic nuclei has been found to be successful both in predicting nuclear masses far away from the β-stable valley[3] as well as the nuclear saturation properties[4, 5]. More importantly the constituent local energy η of the model which happens to be characteristic of a given nucleus, has been found[6] to exhibit typical shell structure in the form of sharp hills signifying the magic shell-closure for closed-shell nuclei followed by troughs for deformed nuclei when plotted as isolines. Consequently mapping of these local-energy isolines in the exotic neutron-rich regions of the nuclear chart was found to smear out the signifying structure indicating[6] strong quenching of the otherwise closed shell-structure, in agreement with the recent astrophysical nuclidic-abundance studies[7, 8] and experimental observations[9, 10].

Although the local energies η exhibit shell structure, they cannot be compared quantitatively with the usual shell correction energies. The reason being that some of the possible corrections[11] like surface-symmetry, Nolen-Schiffer charge-anomaly, the finite-size proton-form factor and other terms are not explicitly included in the INM model. In fact, the structure of the INM model is such that these neglected terms do not affect the INM model because of their cancellations [4, 5] in the corresponding INM equations. But such cancellations do not necessarily mean that those terms are irrelevant in a mass model. Therefore it is highly desirable to make a critical analysis by incorporating those neglected terms in the INM model and redetermine the characteristic local energies. This is expected to improve the model to some extent and more importantly would generate the local energies free from those correction terms, which then can be compared with the usual shell correction energies. As a matter of fact the latter are definitely more meaningful physical quantities as far as mass models are concerned.

For highlighting those neglected terms, it is essential to discuss the model in brief. In the INM model the energy of a finite nucleus is written as the sum of three characteristically different quantities as

$$E^{\mathrm{F}}(A,Z) = E(A,Z) + f(A,Z) + \eta(A,Z). \quad (1)$$

E being the property of nuclear matter at ground state, should satisfy the generalized HVH theorem[12]

$$\frac{E}{A} = \frac{1}{2}[(1+\beta)\epsilon_{\mathrm{n}} + (1-\beta)\epsilon_{\mathrm{p}}], \quad (2)$$

where $\epsilon_{\mathrm{n}} = (\partial E/\partial N)_Z$ and $\epsilon_{\mathrm{p}} = (\partial E/\partial Z)_N$ are the neutron and proton Fermi energies respectively. Its solution is given by

$$E = -a_{\mathrm{v}}^{\mathrm{I}}\, A + a_{\beta}^{\mathrm{I}}\, \beta^2\, A, \quad (3)$$

where $a_{\mathrm{v}}^{\mathrm{I}}$ and a_{β}^{I} are the global parameters, which can be termed as volume and asymmetry coefficients pertaining to INM liquid. The 2nd term $f(A,Z)$ denoting the finite-size effects is given by

$$f(A,Z) = a_s^I A^{2/3} + a_C^I [Z^2 - 5(\frac{3}{16\pi})^{2/3} Z^{4/3}] A^{-1/3} - \delta(A,Z), \quad (4)$$

where a_s^I, a_c^I are the usual universal parameters characterizing the surface and coulomb terms of the INM sphere and $\delta(A,Z)$ is the

*Electronic address: rcnayak00@yahoo.com

usual pairing energy given by

$$\delta(A,Z) = \begin{cases} +\Delta\, A^{-1/2} & : \; even - even \; nuclei, \\ 0 & : \; odd - A \; nuclei, \\ -\Delta\, A^{-1/2} & : \; odd - odd \; nuclei. \end{cases}$$

Eqs. (1) and (2) together with the nature of local and global terms lead to two separate INM equations

$$S(A,Z) = \frac{E^{\rm F}}{A} - \frac{1}{2}\left[(1+\beta)\epsilon_{\rm n}^{\rm F} + (1-\beta)\epsilon_{\rm p}^{\rm F}\right], \quad (5)$$

and

$$\frac{\eta(A,Z)}{A} = \frac{1}{2}\left[(1+\beta)\frac{(\partial\eta}{\partial N)}_Z + (1-\beta)\frac{(\partial\eta}{\partial Z})_N\right]. \quad (6)$$

Here, $S(A,Z)$ given by $f/A - (N/A)(\partial f/\partial N)_Z - (Z/A)(\partial f/\partial Z)_N$ is a function exclusively of finite-size coefficients and hence has been used to determine the model parameters a_s^I, a_c^I first and consequently the other model parameters $a_{\rm v}^{\rm I}$ and $a_\beta^{\rm I}$ as described elsewhere [3–5]. Eq. (6) is used to obtain the local energies both for known and unknown nuclei by solving it in an Interactive Local Area Network[3] followed by Ensemble Averaging Procedure[6].

It has been shown[4, 5] earlier that the proton form factor term given by $\sim Z^2/A$, Nolen-Schiffer charge anomaly term given by $\sim (N-Z)$, surface-Symmetry term $\sim \beta^2 A^{2/3}$ get canceled in the Eq. (5) and hence are ignored in the INM model. It should be mentioned here that such cancellations rather helped the INM model in disguise as the five global parameters were determined both accurately and free from possible correlations. Thus although these terms are irrelevant in the INM model, they cannot be discarded as to their role in the total mass of finite nuclei. Therefore in the present work we include these terms treating them as perturbations and consequently obtain values of the corresponding parameters by fitting the total mass of all known nuclei[13], in which the usual INM model parameters already determined earlier[3] are used. Apart from the three terms mentioned above we also include two coulomb related terms namely volume and surface distribution and the curvature term in this analysis as given by

$$\begin{aligned} f'(A,Z) &= a_{ss}\beta^2 A^{2/3} + a_{NS}(N-Z) \\ &+ a_{pf}Z^2/A + a_{cv}A^{1/3} \\ &+ a_{vd}Z^2A^{2/3} + a_{sd}Z^2. \end{aligned} \quad (7)$$

As a result the usual finite-size term $f(A,Z)$ now gets replaced by $f + f'$ in Eq. (1).

Consequently the local energy η of a given nucleus is expected more or less to consist of energy arising exclusively from the shell structure, because of the fact that energy due to deformation for a given nucleus is considered shell-driven. Accordingly they should reveal the shell-structure in a better way. All these results in detail would be presented apart from the features associated with the newly predicted masses far from the β-stable valley.

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