Neutron Skin thickness evaluation for exotic Kr isotopes

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Availability of nuclear exotic beams has inculcated an interest in the symmetry energy term having wide applications of asymmetric nuclear matter (ANM) ranging from nuclei to neutron stars. The volume and surface contributions to the nuclear symmetry energy (NSE) and their ratio for exotic Kr isotopes (A=82-120) have been studied within coherent density fluctuation model (CDFM). We also presented the correlation between the thickness of the neutron skin and NSE for the same.

The nuclear energy given in the Bethe-Weizsäcker formula can be written as

$$E(A,Z) = -c_1A + c_2A^{2/3} + a_a(A)\frac{(N-Z)^2}{A} + \text{shell and pairing corrections} \quad (1)$$

The first three terms in the R.H.S. of above eq. correspond to the volume, surface and symmetry components of energy, respectively. Symmetry energy including volume and surface contributions is expressed as [1]

$$\frac{1}{a_a(A)} = \frac{1}{a_A^V} + \frac{A^{-1/3}}{a_A^S} \quad (2)$$

$$\text{where } a_A^V = S\left(1 + A^{-1/3}\kappa\right) \quad (3)$$

$$a_A^S = \frac{S}{\kappa}\left(1 + A^{-1/3}\kappa\right) \quad (4)$$

are volume and surface coefficients. In the CDFM, NSE S for finite nuclei is[2]

$$S = \int_0^\infty |\mathcal{F}(x)|^2 \, S^{ANM}(x) \quad (5)$$

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where the symmetry energy $S^{ANM}(x)$ for ANM with density $\rho_0(x)$ has the form [2]

$$S^{ANM}(x) = 41.7\rho_0^{2/3}(x) + 148.26\rho_0(x) + 372.84\rho_0^{4/3}(x) - 769.57\rho_0^{5/3}(x) \quad (6)$$

$$\text{and } |\mathcal{F}(x)|^2 = -\frac{1}{\rho_0(x)}\left(\frac{d\rho_{\text{total}}(r)}{dr}\right)\Big|_{r=x} \quad (7)$$

$$\text{with the normalization } \int_0^\infty |\mathcal{F}(x)|^2 = 1$$

$$\text{and } \rho_{\text{total}}(r) = \rho_p(r) + \rho_n(r)$$

$\rho_p(r)$ *and* $\rho_n(r)$ being the proton and neutron densities resp. The weight function $|\mathcal{F}(x)|^2$ in Eq. (7) for monotonically decreasing local density is expressed by the 3-D semiclassical density $\rho(r)$ upto $\mathcal{O}(\hbar^2)$ as [3] :

$$\rho(r) = \frac{1}{3\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} - \left(\frac{1}{24\pi^2}\left(\frac{2m}{\hbar^2}\right)^{1/2} \left[\frac{\nabla^2 V}{(\mu - V(r))^{1/2}} + \frac{(\nabla V)^2}{4\,(\mu - V(r))^{3/2}}\right]\right) \quad (8)$$

where $V = \frac{m\omega^2 r^2}{2}$ is P.E. 3-D for harmonic oscillator. For our calculations, we fixed the chemical potential μ for neutron and proton by following relation using level density given as [3]

$$N, Z = \int_0^{\mu_{n,p}} g_{n,p}(E)\, dE$$

$$\text{and } g_{n,p}(E) = \frac{1}{2\,(\hbar\omega_{n,p})^3}\left[E^2 - \frac{(\hbar\omega_{n,p})^2}{4}\right] \quad (9)$$

using [4] $\hbar\omega_{n,p} = \frac{41}{A^{1/3}}\left(1 \pm \frac{N-Z}{A}\right)^{1/3}$ MeV.

The ratio of volume to surface energy coefficients using symmetric energy dependence on density $S(\rho)$ is given as [1]

$$\kappa = \frac{a_A^V}{a_A^S} = \frac{3}{r_0\rho_0}\int_0^\infty \left[|\mathcal{F}(x)|^2 x\rho_0(x) \left(\frac{S(\rho_0)}{S(\rho_0(x))} - 1\right)\right] dx \quad (10)$$

$$S(\rho_0) = S^{ANM}(\rho_0)\ ,\ S[\rho_0(x)] = S^{ANM}(\rho_0(x))$$

where ρ_0 is the nuclear matter equilibrium density and $r_0 = 1.15 fm$ is the radius of the nuclear volume per nucleus given as

$$\rho_0 = \frac{3}{4\pi r_0^3}\ \mathrm{fm}^{-3},\ \rho_0(r) = \frac{3A}{4\pi r^3}\ \mathrm{fm}^{-3}$$
$$r = r_0 A^{1/3} fm$$

The neutron skin thickness is calculated as the difference of the r.m.s. radii of neutrons and protons given by [5]

$$\Delta R = (0.77\ r_0\ A^{1/3}) \frac{A}{6\ N\left(1 + \frac{A^{2/3}}{\kappa}\right)} \left[\frac{N - Z}{Z} - \frac{0.7103\ A^{2/3}}{28\ a_A^V}\left(\frac{10}{3} + \frac{A^{1/3}}{\kappa}\right)\right]. \quad (11)$$

The contribution of symmetry energy to the binding energy can be made analogous to two connected capacitors of capacitances [5] $C_V = A/2a_A^V$ and $C_S = A^{2/3}/2a_A^S$, respectively to yield net capacitor energy in terms of charge and capacitance as $E = E_0 + \frac{Q^2}{C_V + C_S}$.

where, $Q = N - Z = (N_S - Z_S) + (N_V - Z_V)$

E_0 corresponds to the sum of surface and volume energy terms. Thus, the total capacitance is given as $C = \frac{A}{2\ a_a(A)}$ [5].

The numerical results for symmetry energy, its volume and surface coefficients and their ratio κ along with asymmetric capacitance are calculated in following table. Our results show that the values of the ratio κ for even-even Kr isotopes (A=82-120) lie in the range $2.10 \leq \kappa \leq 2.90$. A linear dependence of neutron skin thickness on mass number is observed in fig.1 with the change in slope at $A = 106$.

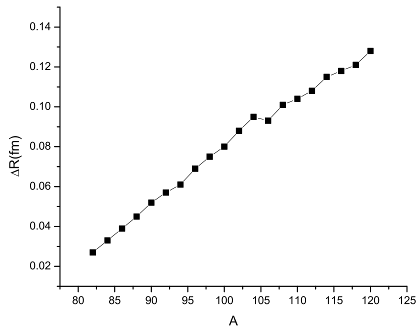

FIG. 1: Neutron skin thickness plotted w.r.t. A

A	S (MeV)	κ	S_A^V (MeV)	S_A^S (MeV)	C
82	26.445	2.319	40.560	17.491	1.550
84	26.439	2.345	40.594	17.313	1.589
86	26.431	2.361	40.567	17.184	1.627
88	26.425	2.386	40.597	17.018	1.665
90	26.417	2.418	40.668	16.822	1.703
92	26.411	2.418	40.556	16.774	1.742
94	26.406	2.399	40.338	16.815	1.780
96	26.400	2.484	40.720	16.395	1.818
98	26.393	2.537	40.914	16.129	1.857
100	26.388	2.554	40.909	16.016	1.895
102	26.381	2.651	41.350	15.597	1.933
104	26.375	2.716	41.607	15.319	1.972
106	26.369	2.515	40.382	16.056	2.010
108	26.364	2.613	40.831	15.625	2.048
110	26.359	2.578	40.538	15.727	2.087
112	26.353	2.577	40.443	16.693	2.125
114	26.348	2.632	40.649	15.446	2.163
116	26.344	2.618	40.486	15.463	2.202
118	26.339	2.591	40.254	15.534	2.240
120	26.334	2.649	40.478	15.279	2.278

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