Exotic behavior of Ni isotopes and model dependent shell structures

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The study of nuclear shell structures away from the valley of stability is one of the current topics in nuclear structure physics. The changes in the shell structure are due to nuclear forces, referred to as *shell evolution.* Recent theoretical and experimental studies on exotic nuclei with unbalanced *Z* and *N* cast challenge these pictures. Of particular relevance are the changes observed in the nuclear shell structure, such as the emergence of new magic numbers at *N*=14, 16, 32, and 34, which may occur in neutron-rich nuclei. We trust this argument because the imbalance of neutrons and protons strongly modifies the spin-orbit potential that in turn determines the shell structure. It is, thus, of much interest to explore the structures of exotic nuclei for a wide range of Ni isotopes here. Focusing on these points we use well accepted Bethe-Weizsäcker mass Formula and its modified forms to study this nucleus as a recent study says N=34 may be the next new magic number [1]. This is expected because some of the standard shell closures can disappear and new ones are known to appear[2, 3].

So, to get a clearer picture about the possible neutron shell closure we calculate binding energy per nucleon (B.E./A), two neutron separation energy (S_{2n}), differential variation of S_{2n} (dS_{2n}), the energy gap (ΔE), and also three point differences of binding energy (B) as ($\Delta^{(3)}_{1n}\mathrm{B.E.}$).

By combining the five energy terms we get binding energy formula for Bethe-Weizsäcker formula[4] as follows:

Bethe-Weizsäcker (BW) [4]

$$\mathrm{B.E.}(\mathrm{A,Z}) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_{sym} \frac{(A-2Z)^2}{A} + \delta \qquad (1)$$

where the pairing term,

$$\delta = \begin{cases} +a_p A^{-\frac{3}{4}}, if\ N\ and\ Z\ are\ even \\ -a_p A^{-\frac{3}{4}}, if N\ and\ Z\ are\ odd \\ 0,\ if\ A\ is\ odd \end{cases}$$

Also we have considered two modified formulas of Bethe-Weizsäcker as follows:

Modified-1 [5]

$$\mathrm{B.E.}(\mathrm{A,Z}) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_{sym} \frac{(A-2Z)^2}{A} + \delta \qquad (2)$$

Where the pairing term, $\delta = \pm a_p A^{-1/2}$ or 0 based on odd-even pairing.

Modified-2 [6]

$$\mathrm{B.E.}(\mathrm{A,Z}) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_{sym} \frac{(A-2Z)^2}{\frac{A}{[(1+e^{-\frac{}{K}})A]}} + \delta_{new} \qquad (3)$$

Where

$$\delta_{new} = \left(1 - e^{-\frac{A}{c}}\right)\delta, \qquad c = 30, \qquad k = 17$$

the pairing term, $\delta = \pm a_p A^{-1/2}$ or 0 based on odd-even pairing.

Table-1: Values of energy coefficients constants of above three formulas as follows:

Coefficient terms	Bethe-Weizsäcker formula [4] (MeV)	BW Modified -1[5] (MeV)	BW Modified -2[6] (MeV)
a_v	15.76	14.64	15.777
a_s	17.80	14.08	18.34
a_c	0.71	0.64	0.71
a_{sym}	23.69	21.07	23.21
a_p	33.53	11.54	21

Using the B.E values we obtain the following quantities [7,8,9].

$$\mathrm{S_{2n}(N,Z) = B.E.(N,Z) - B.E.(N-2,Z)}$$

$$\mathrm{dS_{2n}(N,Z)} = \frac{\mathrm{S_{2n}(N+2,Z) - S_{2n}(N,Z)}}{2}$$

$$\Delta E = 2[\Delta^{(3)}_{1n} B.E(N,Z) - \Delta^{(3)}_{1n} B.E(N+1,Z)]$$

Where

$$\Delta^{(3)}_{1n} B.E.(N,Z) = \frac{1}{2}(-1)^N[B.E(N+1,Z) - 2B.E(N,Z) + B.E(N-1,Z)]$$

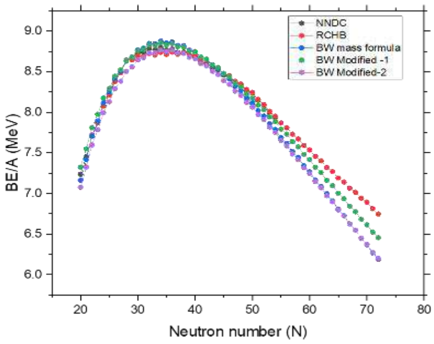

Fig.1 - The graph between B.E./A verses Neutron number of Nickel isotopes (Z=28). The data of NNDC and RCHB taken from [10,11].

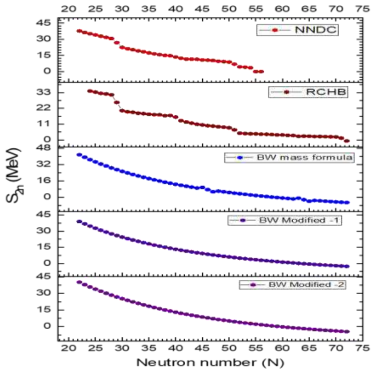

Fig.2- The graph between two neutron separation energy verses neutron number of Nickel isotopes (Z=28)

From Fig.1, it is observed that the B.E./A is maximum at N=34. It is supported by Ref [10,11] as shown in Fig.2 3 and 4. But with modified BW mass formula shows little impact of iso-spin and pairing effect. While the present study reveals that the new shell and sub-shell closure are found at N= 28, 34, 40, 45, 50, and 70 which highlights our limited understanding of the neutron-rich nuclei but needs further investigations.

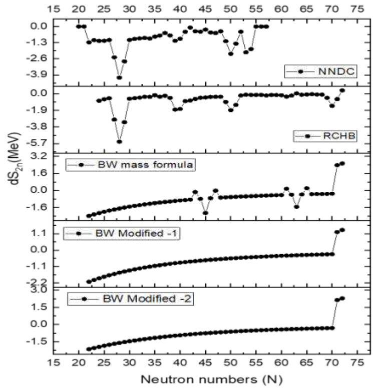

Fig.3- The graph between *dS₂ₙ* verses neutron numbers of Nickel isotopes (Z= 28)

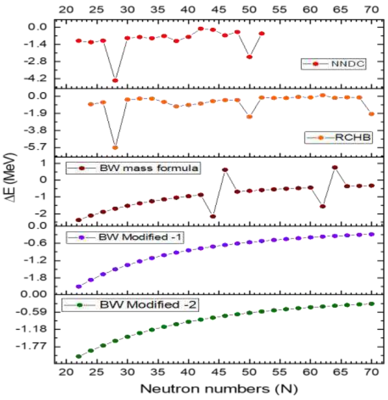

Fig.4- The graph between ΔE verses neutron number of Nickel isotopes (Z=28)

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