IUAC Summer Internship Project
Report

on

Determination of Properties of Nuclear Matter via Computational Methods

Submitted by

YOGITA KUMARI
Hansraj College
University of Delhi

Under the guidance of

Mr. YASHRAJ
Scientist - C
Inter University Accelerator Centre
Aruna Asaf Ali Marg, New Delhi, Delhi - 110067

Summer Internship 2021

ACKNOWLEDGMENT

Foremost, I would like to express my sincere gratitude to Mr. Yashraj for amazing explanation of topic, advice, help and stimulating suggestions.
I would also like to acknowledge with much appreciation crucial role of evening lecture series given by profound speakers.

CHAPTER 1

PROPERTIES OF NUCLEAR MATTER

In 1886, the phenomena of radioactivity was discovered by Henri Becquerel. This was first major event in history of nuclear physics. Then after a lot of discovery come in front of scientific world. In 1911, Ernest Rutherford proposed a central positive charged 'nucleus' inside the atom based on the experimental observation of famous alpha particles scattering from gold foil experiment.

The nucleus is made up of nucleons (protons and neutrons). Nucleons are bound into the nucleus via nuclear forces. In order to describe a nucleus, some static (Electric Charge, Radius, Mass, Binding Energy etc.) and dynamic (decay rate, reaction probability etc.) properties need to be studied. Objective of this report is to explain some of these properties via computational methods.

Nuclear Radius:

Nucleus has no sharp boundaries as observed from scattering experiments. Although it can be considered as spherical in form. The nuclear density can be considered constant to certain distance from centre of nucleus but then it gradually decreases, and finally becomes zero at nuclear surface as shown in Fig. 1. Nuclear Radius (R) can be defined as distance from centre of nucleus to point where the density has decreased to half its original value and is given by:

$$R = R_0 A^{1/3} \quad (1)$$

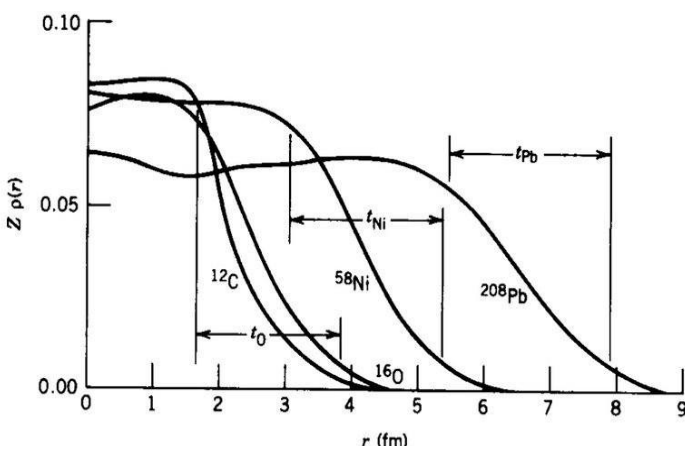


Fig. 1 Nuclear density of various nucleus as a function of nuclear radius [1].

Nuclear Mass:

A nucleus of mass (A), consists of Z protons and N=A-Z neutrons, so its mass is given by:

$$M = Zm_p + (A-Z)m_n \quad (2)$$

where m_p , m_n are mass of proton and neutron. But it was experimentally observed that the mass of a nucleus is always less than as determined by eq. (2). This difference of mass is known as mass defect and can be understood from the concept of binding energy.

Binding Energy:

Binding energy is defined as the energy required to split a nucleus into its constituent nucleons. It is the difference in $(Zm_p+Nm_n)c^2$ and mass of nucleus or (mass defect)c^2.

$$BE=\Delta mc^2 = (Zm_p+Nm_n)c^2 - Mc^2 \quad (3)$$
$$BE= (Zm(^1H) + Nm_n - M_{at})c^2$$

where Δm – mass defect, c – speed of light, M – mass of nucleus (exp. obtained), $m(^1H)$ – mass of Hydrogen atom and M_{at} - atomic mass receptively.

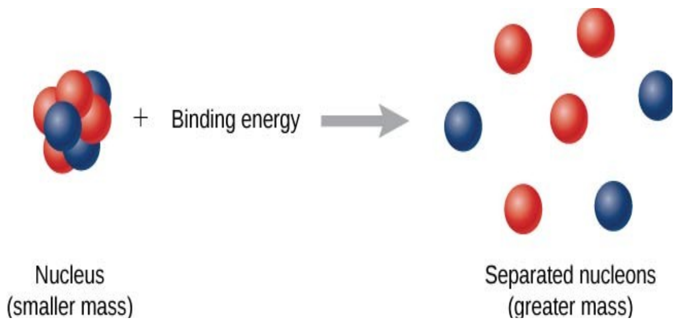


Fig. 2 Binding energy provided a nucleus lead to splitting in constituent nucleons [2].

In order to explain the various experimentally observed properties of nucleus the liquid drop model (LDM) was introduced and it fairly predict many properties , this model is discussed in details in the next chapter.

CHAPTER 2

LIQUID DROP MODEL

A lot of properties of nucleus were experimentally discovered but explanation of these was not easy due to very small size of nucleus and lack of knowledge of nuclear forces among the nucleons. So, various models were developed to explain the observed properties. First in that row was liquid drop model proposed by George Gamow and further developed by Niels Bohr and John Archibald Wheeler. In this model the nucleus is treated as a a charged drop of incompressible fluid of very high density. The shape of nucleus is considered as spherical and is useful in predicting the binding energy of nuclei.

Assumption of Liquid Drop Model :

1) Nucleus is consider to be analogous to a charged liquid drop of incompressible fluid having very high density.
2) It remain spherically symmetric under the action of strong nuclear force just like liquid drop is spherically symmetric due to surface tension,
3) Density is independent of size.
4) Nucleons can move within nucleus just as molecules of liquid inside the drop of liquid.
5) Smaller nuclear can be fussed to form larger drop and larger drop can disintegrated into smaller drops.
6) Binding energy per nucleon is similar to latent heat of vaporization.

Explanation of Binding Energy per nucleon curve:

The experimentally observed binding energy per nucleon (BE/A) curve is shown in Fig. 3. It first increases with A then becomes maximum at A~56 and finally saturates at ~8MeV.

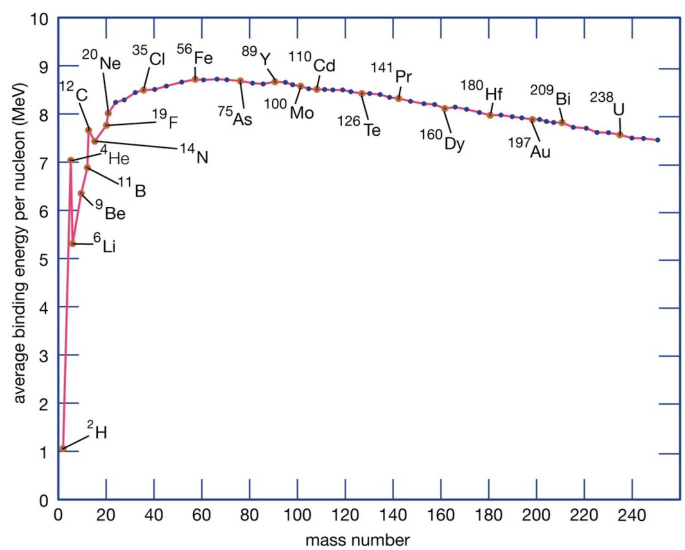


Fig. 3 Experimentally observed BE/A data [3]

The larger the value of BE/A means more is the stable nuclei. Hence it dictates that lower mass nuclei will fuses together (nuclear fusion) while heaver mass one will split into fragments of lower masses (nuclear fission) for maximizing their BE/A.

If there are A nucleons in nucleus so total number of interaction due to nuclear forces will be A(A-1)/2, so binding energy should be proportional to A^2 and binding energy per nucleon $\propto$ A but experimental data shows that BE/A remain almost constant with increase in A .

Formalism of semi-empirical formula based on experimental observations:

1) Volume term:

Since nuclear forces are of short range, hence one nucleon will interact with only n nucleons (say). So A nucleon will effectively interact with A*n/2 nucleons and BE is given by:

$$BE_V = a_V A \tag{4}$$

2) Surface term:

Nucleon on surface does not interact with n nucleons so the BE have been overestimated. Hence this surface term need to be subtracted:

$$BE_S = -\, a_s A^{2/3} \tag{5}$$

3) Coulomb term:

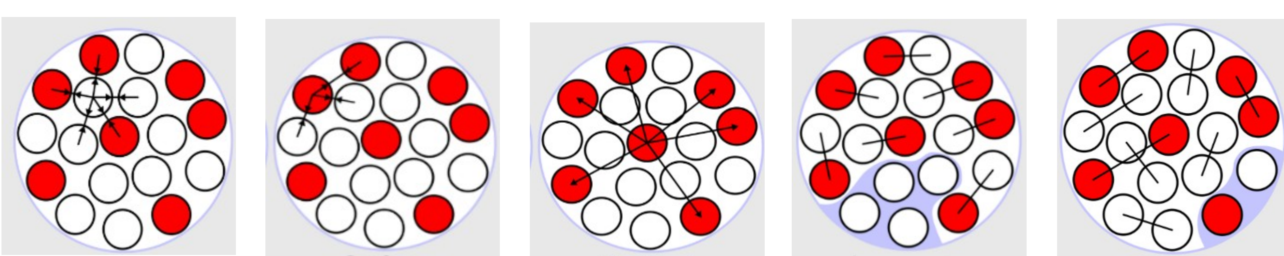
There is Coulombic force between protons which causes repulsion among them, so this Columbic contribution is also taken into account to determine BE. Let there are Z protons inside a nucleus of mass A, so the total number of interactions will be Z(Z-1)/2 and BE will become:

$$BE_C = -a_c\, Z(Z-1)A^{-1/3} \tag{6}$$

4) Asymmetry term:

According to Pauli exclusion principle two identical fermions could not occupy the same quantum energy states. So, as the no. of fermions increases they will occupy higher energy states leads to increase in energy also . Since proton and neutron are different distinct particles , they will occupy different quantum states. For larger values of Z, the Columbic force also come into scene so there will be repulsion between protons also. To compensate this repulsion more no. of neutrons need to bring into picture. Hence, the no. of neutrons won't be equal to no. of protons, so some of neutrons will be in higher energy state than protons. If some neutrons are changed into protons then for the same A there will be decrease in energy. This term is known as asymmetry term which leads to reduction in BE:

$$BE_{sym} = -a_{sym}\,(A-2Z)^2\, A^{-1} \tag{7}$$



(a) Volume (b) Surface (c) Coulomb (d) Asymmetry (5) Pairing

Fig. 4 Schematic of various terms in semi-empirical formula [4]

5) Pairing term:

The nucleons inside the nucleus preferentially forms pairs (proton pairs, neutron pairs) under the influence of short range nuclear force acting among them [5]. It has been observed that even-even nuclei are more stable than odd-even, and odd-odd nuclei are least stable. So, this proves that there is an overall odd-even effect showing that even-even nuclei are more bound than odd-even by an amount δ. Hence the contribution due to pairing term is given by:

$$\begin{aligned} BE_P &= +\delta = a_p A^{3/4} \quad \{\text{for even N,Z (even A)} \\ &= 0 \quad \text{for odd A} \\ &= -\delta = -a_p A^{3/4} \quad \text{for odd N,Z and (even A)}\} \end{aligned} \tag{8}$$

Semi-empirical mass (Weizsäcker) formula:

Combining all the above discussed terms the total BE can be written as:

$$BE\,(A,Z) = a_v A - a_s A^{2/3} - a_c\, Z(Z\text{-}1)A^{-1/3} - a_{sym}\,(A\text{-}2Z)^2\,A^{-1} + (0,\pm)\,\delta$$

and

$$\begin{aligned} M(A,Z) &= Zm(^1H) + Nm_n - B(A,Z)/c^2 \\ &= Zm(^1H) + Nm_n - (a_V A - a_S A^{2/3} - a_C Z(Z\text{-}1)A^{-1/3} - a_{sym}(A\text{-}2Z)^2 A^{-1} + (0,\pm)\,\delta)/c^2 \end{aligned} \tag{9}$$

This is known as Semi-empirical mass formula or Weizsäcker formula. The constants in the formula can be obtained by best fitting of experimental data with above formula and one of set is following:

a_v = 15.5 MeV
a_s = 16.8 MeV
a_c= 0.72 MeV
a_{sym} = 23 MeV
a_p = 34 MeV

A program for computing BE/A was written (refer to Appendix A) and the output of program is shown in Fig. 5.

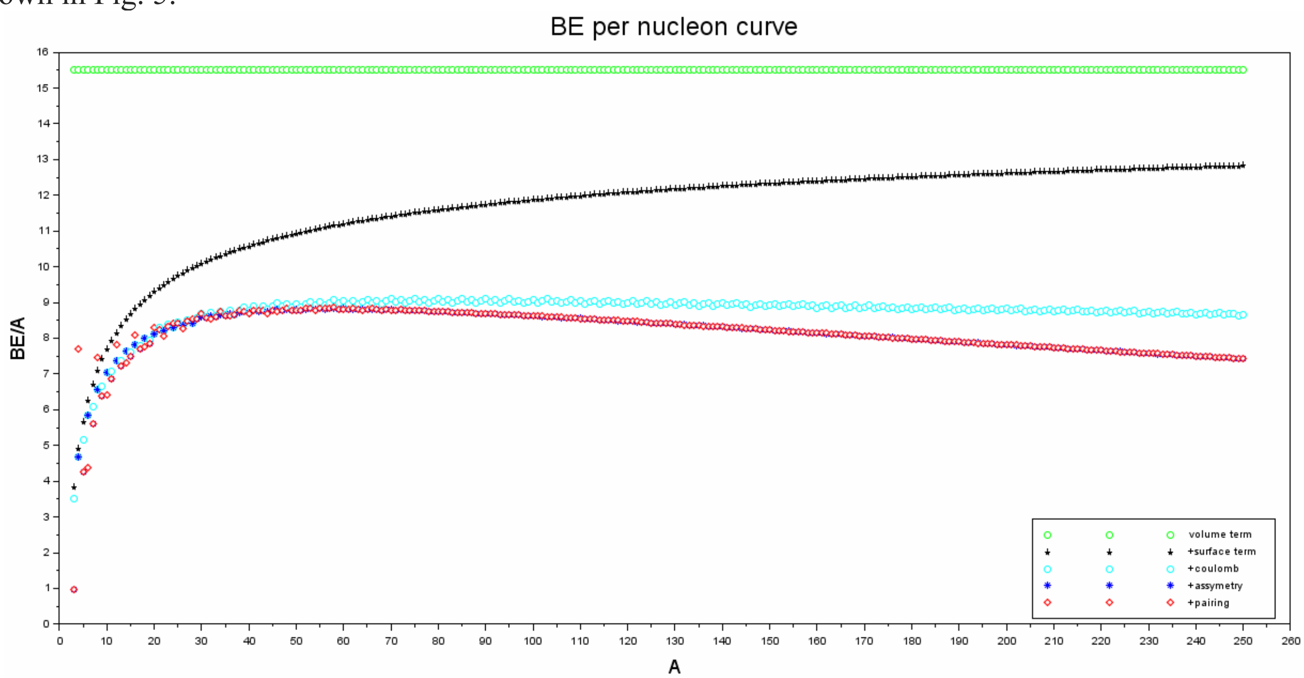


Fig. 5 BE/A computed for A ≤ 250 using semi-empirical formula

CHAPTER 3

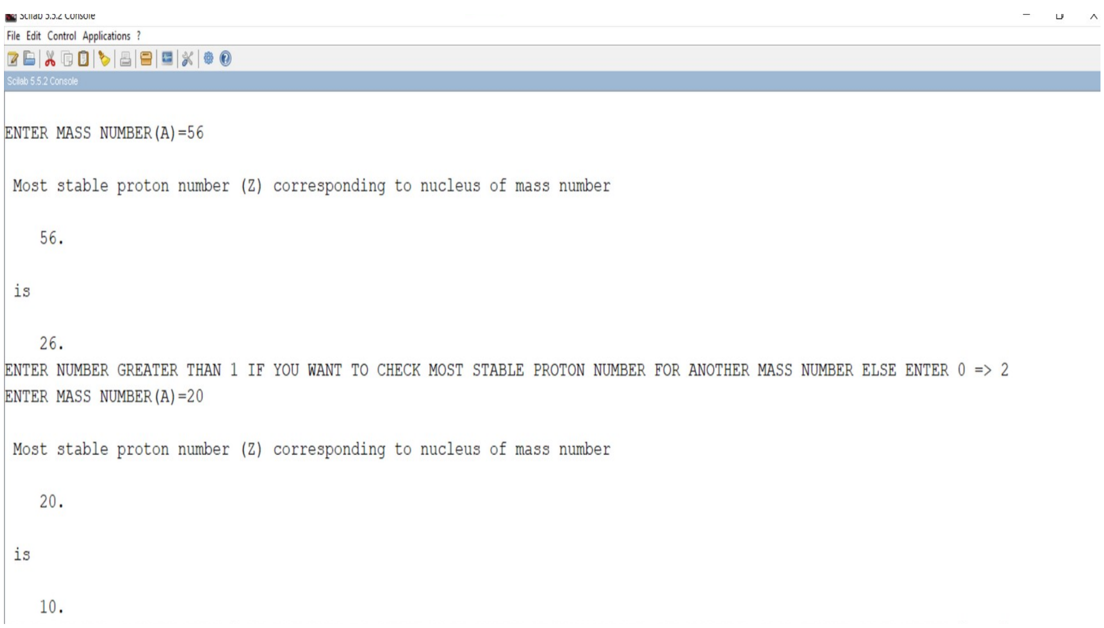
APPLICATIONS OF SEMI-EMPIRICAL FORMULA

(1) Most stable proton number (Z):

For a given mass number A , various combination of Z and N are possible, but only the combination will be most stable for which the mass or energy is minimum. To find that the mass formula (given in eq. 9) is differentiated w.r.t. Z and equated to zero to obtain Z_{min}, and is given by:

$$Z_{min} = 0.5*A/(1+ 0.25*A^{2/3}*(a_C/a_{sym})) \tag{10}$$

A program for obtaining Z_{min} is given in Appendix B and the output of program is shown in Fig. 6.



```
ENTER MASS NUMBER(A)=56

 Most stable proton number (Z) corresponding to nucleus of mass number

    56.

 is

    26.
ENTER NUMBER GREATER THAN 1 IF YOU WANT TO CHECK MOST STABLE PROTON NUMBER FOR ANOTHER MASS NUMBER ELSE ENTER 0 => 2
ENTER MASS NUMBER(A)=20

 Most stable proton number (Z) corresponding to nucleus of mass number

    20.

 is

    10.
```

Fig 6. Output of program for obtaining Z_{min} for a given A

(2) Line of stability (N vs Z curve):

For smaller Z nuclei N~Z, but as the value of Z increased the N vs Z curve (red) starts deviating from N=Z curve (blue). It is due to the fact that at larger values of Z, the Coulomb repulsion contribution is very high, so to compensate this more neutrons are brought in to becomes stable. A program for obtaining experimental N vs z is given in Appendix C and the output of program and experimental data are shown in Fig. 7

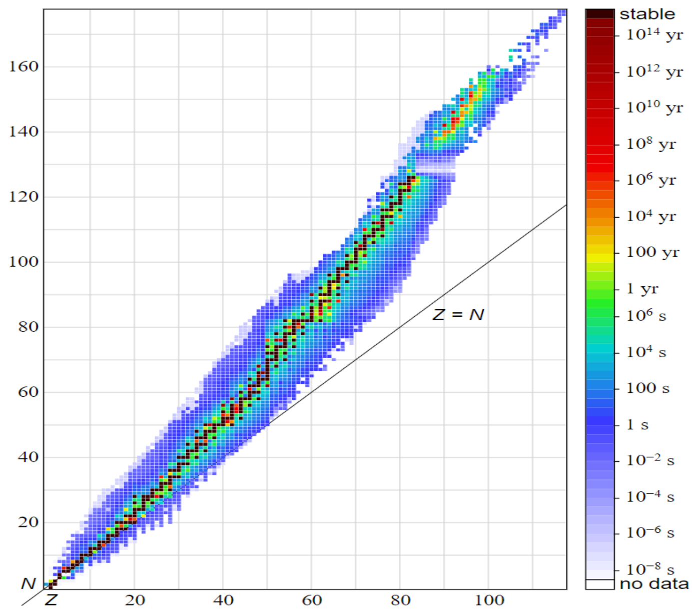
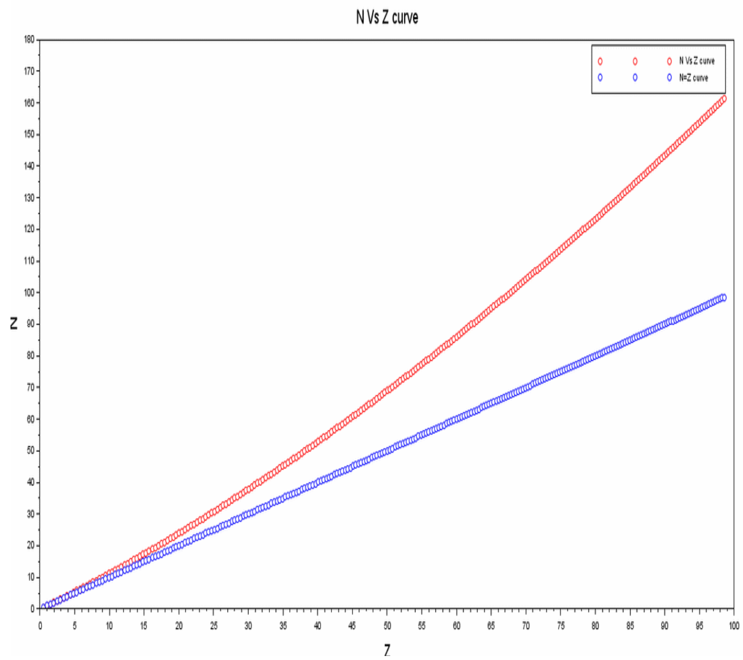


Fig.7 (a) Experimental N vs Z [6]



(b) Computed using program

(3) Isobaric Mass Parabola (Valley of β-stability):

For a given value of A the semi-empirical mass formula can be written as:

$$M = a + bZ + cZ^2 + \delta \tag{11}$$

where $a = Am_n - a_V + a_S + Aa_{sym}$, $b = m(^1H) - m_n - a_C A^{-1/3} - 4Aa_{sym}$ and $c = a_C A^{-1/3} + 4\, a_{sym} A^{-1}$

So for any even A nuclei there will be two parabolas (one for even-even combination of N,Z for which pairing = +δ and other for odd-odd combination for for which pairing = -δ), while for odd A there is only one parabola exist. Any point exist on parabola want to attain minimum (or $Z_{min/stable}$) by ±β deacy or e^- capture processes. A program for obtaining mass parabola for any A is given in Appendix D and the output of program and experimental observations are shown in Fig. 8.

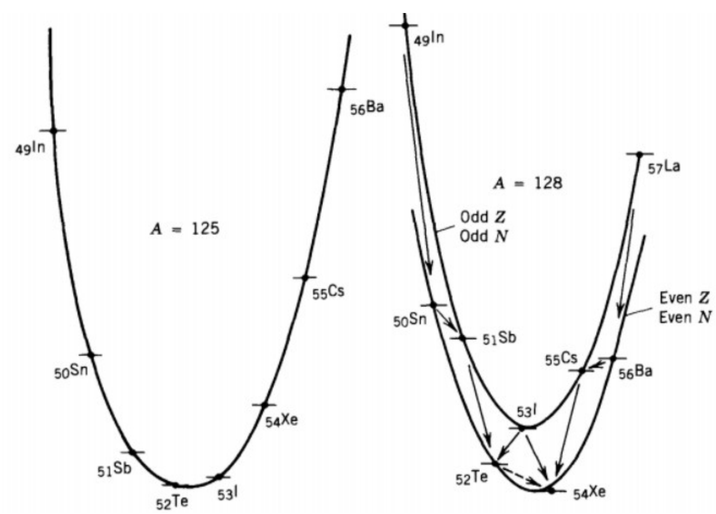
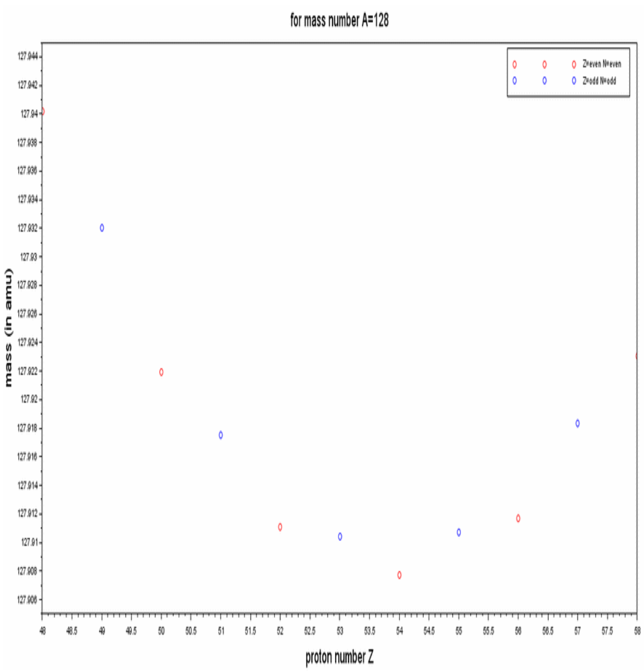
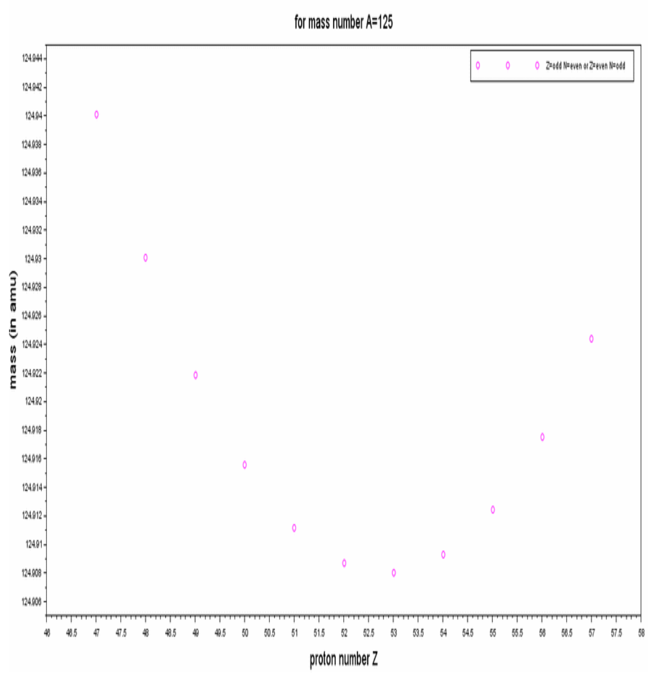


Fig. 8 (a) Experimentally observed isobaric mass parabola for A=125 (odd) and A=128 (even) [7]

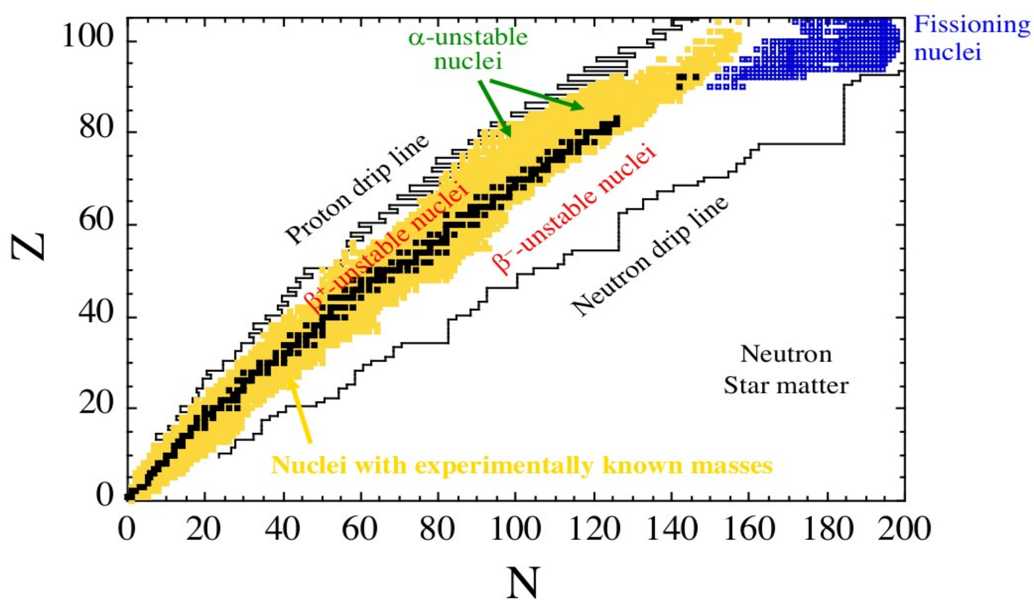




<u>Fig. 8 (b)</u> Program output for A=128 (even) **(c)** For A=125 (odd)

(4) <u>Nuclear Drip Line :</u>

The boundaries for nuclear particle stability are known as drip lines. An arbitrary combination of proton and neutron does not necessarily yield a stable nucleus. If one type of nucleons are keep on adding, after a certain limit it separate itself without any external energy. Colloquially speaking nucleon has leaked or dripped out of nucleus. So beyond drip lines , no bound nuclei exist.



<u>Fig. 9</u> Nuclear drip lines and stable nuclides [8]

Proton and Neutron Drip Lines:

For given no. of neutrons if we keep on adding proton then after a certain limit proton separation energy becomes positive which means it need not energy from outside to separate from nuclei (means its emission becomes energetically favorable) mentioned in eq. (12). Same thing is applicable for a given no. of protons and neutron separation energy, Sn is given by eq (13):

$$Sp = M(A,Z) - M(A-1,Z-1) \geq 0 \tag{12}$$
$$Sn = M(A,Z) - M(A-1,Z) \geq 0 \tag{13}$$

Using computational method we can find out limit of protons which can be add for stable nuclei when neutron number is fixed (Appendix E) and similarly the limit of neutrons (to Appendix F) .

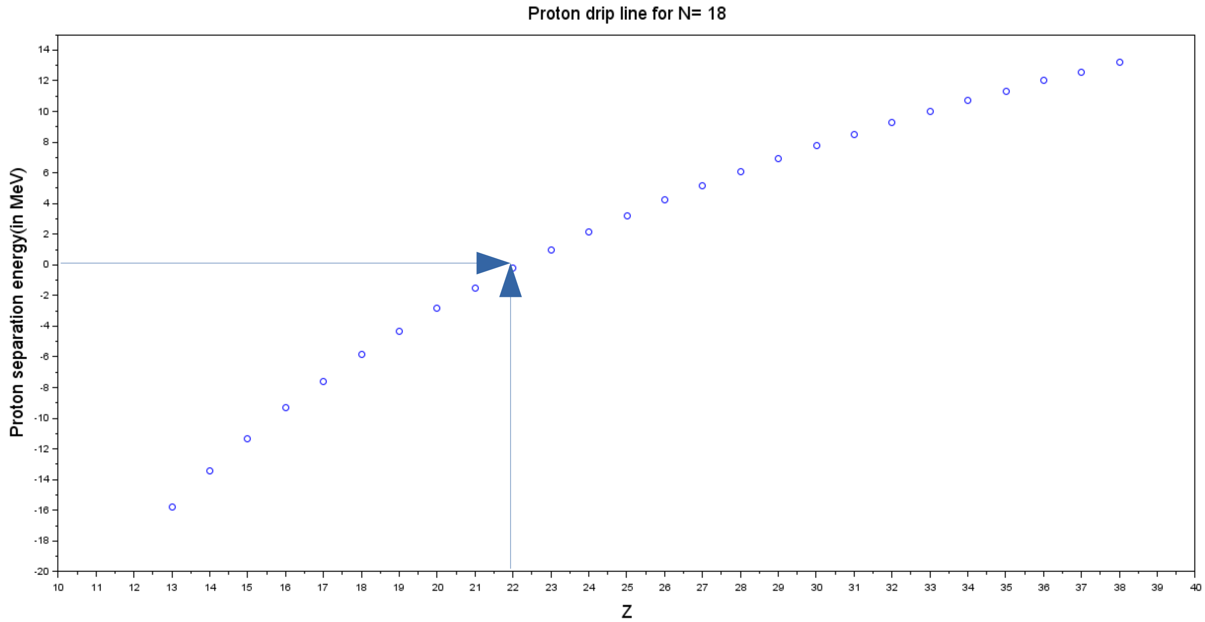


Fig. 10 (a) Proton drip line for N=18

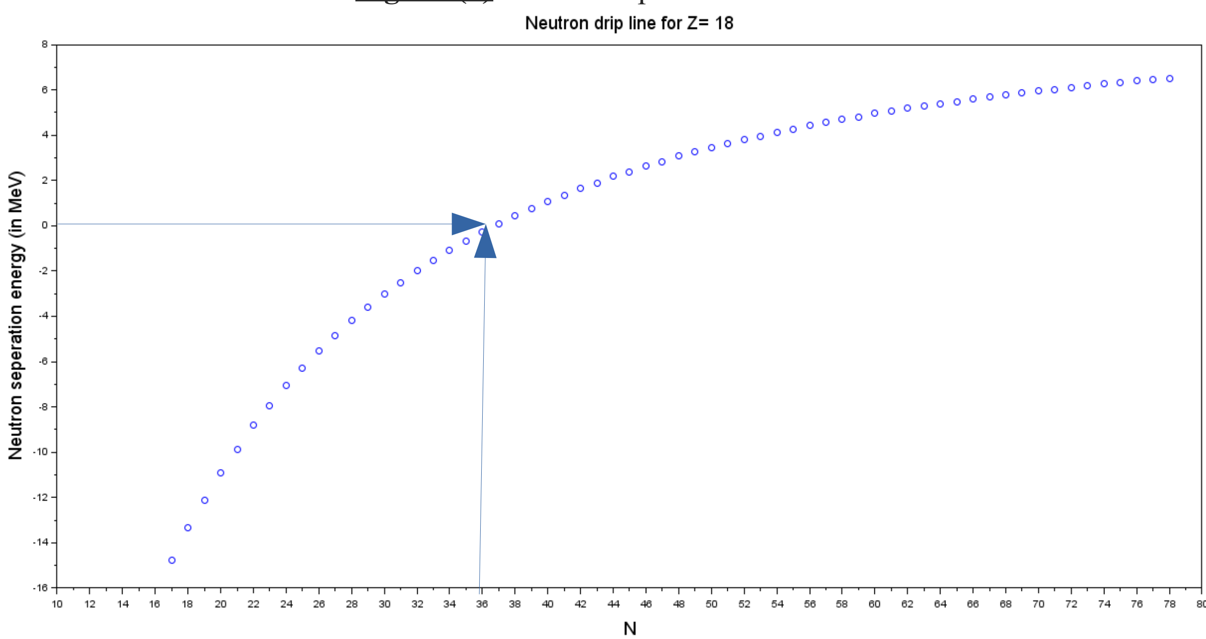


Fig. 10 (b) Neutron drip line for N=18

(5) **Alpha Decay:**

Alpha emission is due to Coulombic repulsion effect .As the size of nucleus increases there is increase in disruptive Columbic force compare to binding nuclear force. That is why α-decay is prominent in heavy nuclei. The spontaneous α-decay will be possible only when the alpha separation energy, $S_\alpha > 0$ as mentioned in eq. 14:

$$S_\alpha = M(A,Z) - M(A-4,Z-2) \geq 0 \tag{14}$$

The S_α is computed using a program (Appendix G) and its output of shown in Fig. 11.

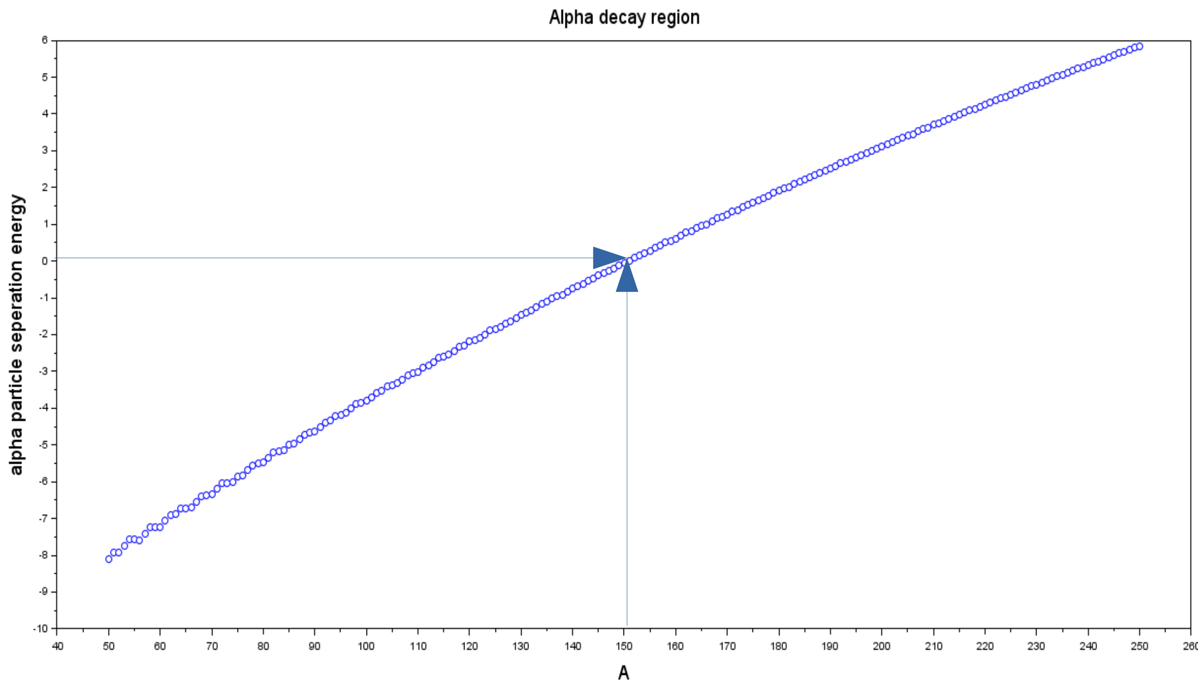


Fig. 11 Output of program for computing S_α for various A (i.e. α emission activated region)

(6) **Neutron Star:**

When the core of a massive star (mass ~ 10- 25 solar masses) undergoes gravitational collapse at the end of its life, protons and electrons are literally scrunched together, leaving behind one of nature's most wondrous creations: a neutron star. Neutron stars cram roughly 1.3 to 2.5 solar masses into a city-sized sphere perhaps 20 kilometers (12 miles) across. Matter is packed so tightly that a sugar cube-sized amount of material would weigh more than 1 billion tons, about the same as Mount Everest! The formation of neutron star is explained in Fig. 12.

The semi-empirical mass formula obtained by observation of various properties of nucleus (~ fm, few nucleon system) only will be applied to such huge system (~km, extremely large no. of neutrons) just for test purpose.

For a nuclide to exist its BE ≥ 0, let us assume that neutron star is made up of neutrons only (i.e. Z=0) and neutron star volume is really large ($Aa_V >> A^{2/3}a_S$), δ can be also ignored. Now BE is going to be:

$$BE = (a_V - a_{sym})A \tag{15}$$

as $a_V < a_{sym}$, so BE =-ve, hence neutron star should not exist. Its existence is due to gravitational attraction which bounds the neutron star so if there are enough no. of neutrons, the gravitational force will overcome asymmetry induced instability and neutron star existence becomes feasible. So to exist neuron star BE should be:

$$BE = (a_V - a_{sym})*A + (3*G*m_n^2*A^{5/3}/ 5*R_0) > 0$$
$$A \geq (a_V - a_{sym})*5*R_0 / 3*G*m_n^2)^{3/2} \quad (16)$$

This condition (eq. 16) is computed (refer to Appendix H) and output of program is shown in Fig. 13.

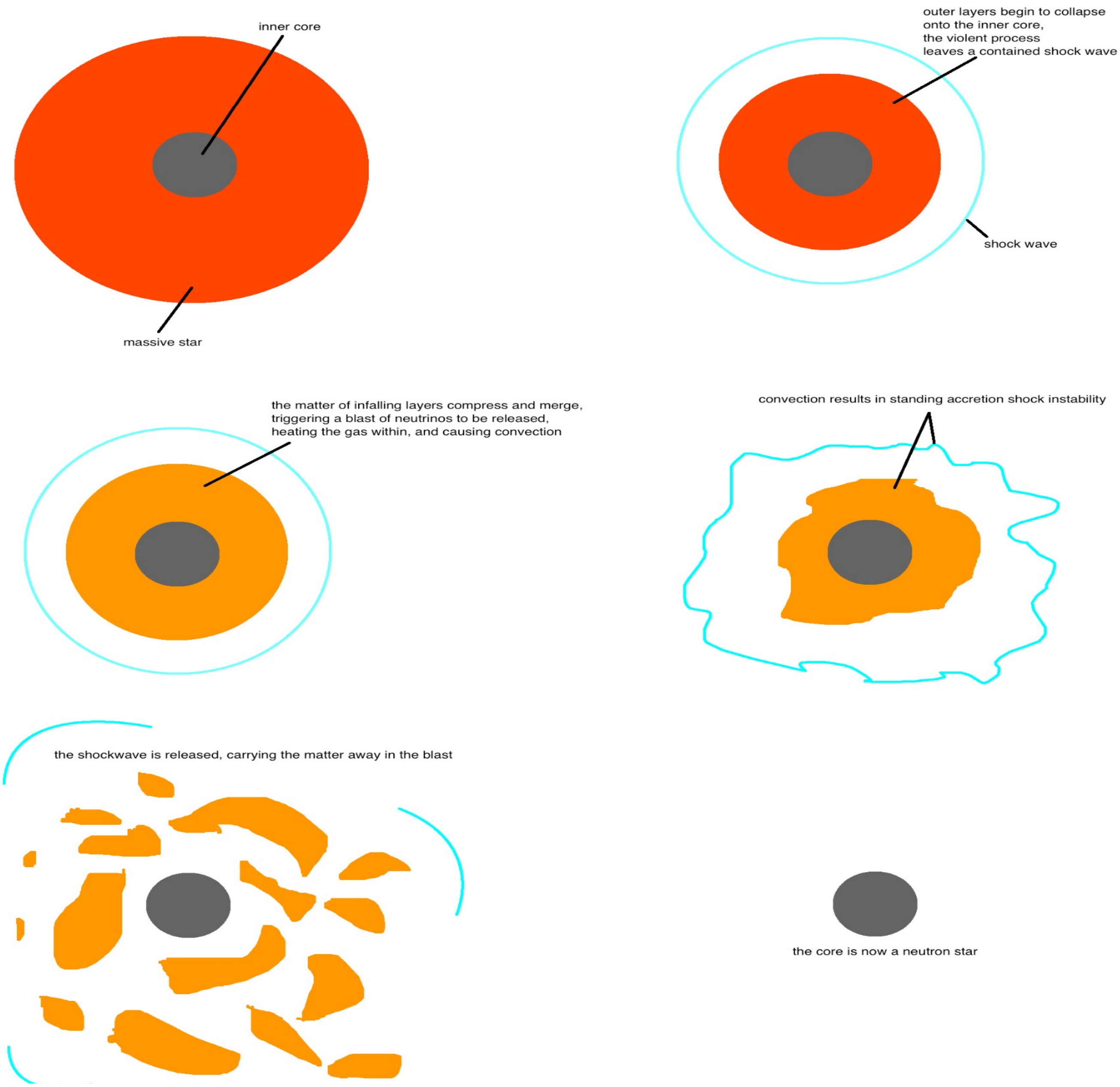


Fig. 12 Formation of a Neutron Star [9]

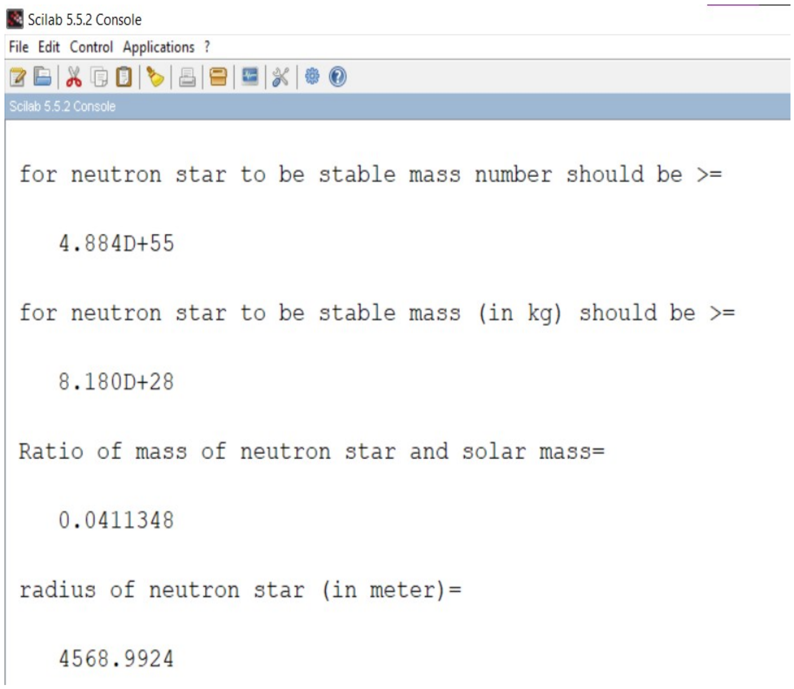


Fig. 13 Output of program for computing various conditions for existence of neutron stars

So, for a neutron star to exist the no. of neutrons inside the star > 10^{55}, and on the basis of that its mass was calculated and found out to be ~0.04 of solar mass and radius ~ 4.5 km. Hence it proves that even the observation were made on extremely small scale object, but these are as par for extremely large system also, this shows the beauty of semi-empirical mass formula and its strengths to explain various properties in a very simple manner.

References:

1. nuclear-density-jpg.228388 (800×446) (physicsforums.com)

2. CNX_UPhysics_43_02_BindEnergy.jpg (650×231) (jobilize.com)

3. https://www.britannica.com/science/nuclear-binding-energy

4. Basic ideas and concepts in nuclear physics by Kris L. G. Heyde

5. https://en.wikipedia.org/wiki/Semi-empirical_mass_formula

6. https://upload.wikimedia.org/wikipedia/commons/8/80/Isotopes_and_half-life.svg

7. Introductory Nuclear Physics by Kenneth S Krane

8. https://www.google.com/search?q=neutron+proton+drip+line&sxsrf=ALeKk01-1pbwmnPakeuSm4h3_nDWQ:1624703110588&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjcjpbeirXxAhVhzTgGHRDuDhcQ_AUoAXoECAEQBA&biw=1920&bih=949#imgrc=YJsrgisY2RO4EM

9. Neutronstarsimple.png (2000×2500) (wikimedia.org)

* All the programs in Appendix are written in Scilab

APPENDIX - A

(Program to calculate BE/A):

```
clc//to clear console window
clear//to kill all variables
clf()
//define constants
av=15.5 //in MeV
as=16.8 //in MeV
ac=0.72 //in MeV
asym=23 //in MeV
ap=[-34 0 34] //in MeV
for A=3:250
  Z=(A/2)/(1+(0.0078*(A^(2/3))))
  Z=ceil(Z)
  plot(A,av,'og')
  plot(A,av+(-as/(A^(1/3))),'pk')
  plot(A,av+(-as/(A^(1/3)))+(-(ac*Z*(Z-1))/(A^(4/3))),'oc')
  plot(A,av+(-as/(A^(1/3)))+(-(ac*Z*(Z-1))/(A^(4/3)))+(-(asym*((A-(2*Z))^2))/(A^2)),'*b')
 if modulo(A,2)==0 then
    if modulo(Z,2)==0 then
              plot(A,av+(-as/(A^(1/3)))+(-(ac*Z*(Z-1))/(A^(4/3)))+(-(asym*((A-(2*Z))^2))/(A^2))
+(-ap(1)/(A^(7/4))),'dr')
    else
      plot(A,av+(-as/(A^(1/3)))+(-(ac*Z*(Z-1))/(A^(4/3)))+(-(asym*((A-(2*Z))^2))/(A^2))
+(-ap(3)/(A^(7/4))),'dr')
    end
  else
    plot(A,av+(-as/(A^(1/3)))+(-(ac*Z*(Z-1))/(A^(4/3)))+(-(asym*((A-(2*Z))^2))/(A^2))
+(-ap(2)/(A^(7/4))),'dr')
  end
end
title('BE per nucleon curve','fontsize',5)
xlabel('A','fontsize',4)
ylabel('BE/A','fontsize',4)
legend(['volume term';'+surface term';'+coulomb';'+assymetry';'+pairing'],opt=4)
```

APPENDIX - B

(Program to calculate most stable Z for a given A):

```
clc
clear
t=6
while t>1
A=input("ENTER MASS NUMBER(A)=")
Z=(A/2)/(1+(0.0078*(A^(2/3))))
Z=ceil(Z)
disp(Z,"is",A,"Most stable proton number (Z) corresponding to nucleus of mass number")
t=input("ENTER NUMBER GREATER THAN 1 IF YOU WANT TO CHECK MOST STABLE PROTON NUMBER FOR ANOTHER MASS NUMBER ELSE ENTER 0 => ")
end
```

APPENDIX - C

(Program for computing N vs Z curve):

```
clc
clear
clf
ac=0.72 //in MeV
asym=23 //in MeV
for A=1:260
Z=(A./2)/(1+((ac/(4*asym))*(A.^(2/3))))
N=A-Z
NZ=Z
plot(Z,N,'or')
plot(Z,NZ,'o')
end
title('N Vs Z curve','fontsize',4)
xlabel('Z','fontsize',4)
ylabel('N','fontsize',4)
legend('N Vs Z curve' ,'N=Z curve')
```

APPENDIX – D

(Program for computing Isobaric mass parabola):

```
clc
clear
//define constants
av=15.5 //in MeV
as=16.8 //in MeV
ac=0.72 //in MeV
asym=23 //in MeV
ap=[-34 0 34] //in MeV
q=9
while q>1
   clf
A=input("Enter  mass number A=")
Z1=(A/2)/(1+(0.0078*(A^(2/3))))
Z1=round(Z1)
Zi=Z1-5
Zn=Z1+5
if modulo(A,2)==0 then
for Z=Zi:Zn
               M=(Z*1.00783)+((A-Z)*1.00867)+(-(av*A)+(as*(A^(2/3)))+((ac*Z*(Z-1))/(A^(1/3)))+
((asym*(A-(2*Z))^2)/A))/931.478
   if modulo(Z,2)==0 then
         t=ap(3)/(A^(3/4))
         M1=M-(t/931.478)
   plot(Z,M1,'or')
      else
         t=ap(1)/(A^(3/4))
         M1=M-(t/931.478)
   plot(Z,M1,'o')
  legend('Z=even N=even','Z=odd N=odd')
end
end
 else
    for Z=Zi:Zn
    M=(Z*1.0078)+((A-Z)*1.0087)+(-(av*A)+(as*(A^(2/3)))+((ac*Z*(Z-1))/(A^(1/3)))+(asym*(A-
(2*Z))^2)/A)/931.478
      t=ap(2)/(A^(3/4))
      M1=M-(t/931.478)
   plot(Z,M1,'om')
   legend('Z=odd N=even or Z=even N=odd')
end
end
```

```
title('for mass number A='+string(A)+'','fontsize',4)
xlabel('proton number Z','fontsize',4)
ylabel('mass (in amu)','fontsize',4)
q=input("ENTER VALUE GREATER THEN 1 IF YOU WANT TO SEE CURVE FOR ANOTHER MASS NUMBER ELSE ENTER 0 => ")
end
```

APPENDIX - E

(Program for computing Proton Separation energy/ p-drip line):

```
clc
clear
clf
N=input("ENTER ANY NEUTRON NUMBER (N)=")
//define constants
av=15.5 //in MeV
as=16.8 //in MeV
ac=0.72 //in MeV
asym=23 //in MeV
//proton drip line
if N<20 then
   k=5
elseif N>=20 & N<50 then
   k=10
else
   k=20
end
for Z=N-k:N+20
   A=N+Z
   A1=A-1
   Z1=Z-1
   if modulo(A,2)==0 then
      if modulo(Z,2)==0 then
                  BE=  (av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
+(34/(A^(3/4)))
                        BE1=  (av*A1)+(-as*((A1)^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))+(34/(A1^(3/4)))
      else
               BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))+(-
34/(A^(3/4)))
                         BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))+(-34/(A1^(3/4)))
      end
   else
      BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
                         BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))
   end
   Sp=BE1-BE
   plot(Z,Sp,'o')
```

```
end
title('Proton drip line for N= '+string(N)+'','fontsize',4)
xlabel('Z','fontsize',4)
ylabel('Proton separation energy(in MeV)','fontsize',4)
```

APPENDIX - F

(Program for computing Neutron Separation energy/ n-drip line):

```
clc
clear
clf
Z=input("ENTER ANY PROTON NUMBER Z=")
//define constants
av=15.5 //in MeV
as=16.8 //in MeV
ac=0.72 //in MeV
asym=23 //in MeV
ap=[-34 0 34] //in MeV
if Z<20 then
   k=60
elseif Z>=20 & Z<50
   k=100
else
   k=150
end
//neutron drip line
for N=Z-1:Z+k
   A=N+Z
   A1=A-1
   if modulo(A,2)==0 then
      if modulo(Z,2)==0 then
                BE=  (av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
+(34/(A^(3/4)))
                        BE1=   (av*A1)+(-as*((A1)^(2/3)))+(-(ac*Z*(Z-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z))^2))/(A1))+(34/(A1^(3/4)))
      else
              BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))+(-
34/(A^(3/4)))
         BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z*(Z-1))/(A1^(1/3)))+(-(asym*((A1-(2*Z))^2))/(A1))
+(-34/(A1^(3/4)))
      end
   else
      BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
      BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z*(Z-1))/(A1^(1/3)))+(-(asym*((A1-(2*Z))^2))/(A1))
   end
   Sn=BE1-BE
   plot(N,Sn,'o')
end
title('Neutron drip line for Z= '+string(Z)+'','fontsize',4)
xlabel('N','fontsize',4)
ylabel('Neutron seperation energy (in MeV)','fontsize',4)
```

APPENDIX - G

(Program for computing alpha separation energy/ α-active nuclides):

```
clc
clear
clf
av=15.5 //in MeV
as=16.8 //in MeV
ac=0.72 //in MeV
asym=23 //in MeV
BEa=28.3169312 //in MeV
for  A=50:250
Z=(A/2)/(1+(0.0078*(A^(2/3))))
A1=A-4
Z1=Z-2
if modulo(A,2)==0 then
    if modulo(round(Z),2)==0 then
            BE=  (av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
+(34/(A^(3/4)))
                BE1=  (av*A1)+(-as*((A1)^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))+(34/(A1^(3/4)))
     else
          BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))+(-
34/(A^(3/4)))
                BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))+(-34/(A1^(3/4)))
     end
  else
     BE=(av*A)+(-as*(A^(2/3)))+(-(ac*Z*(Z-1))/(A^(1/3)))+(-(asym*((A-(2*Z))^2))/(A))
                BE1=(av*A1)+(-as*(A1^(2/3)))+(-(ac*Z1*(Z1-1))/(A1^(1/3)))+(-(asym*((A1-
(2*Z1))^2))/(A1))
  end
Sa=BE1+BEa-BE
title('Alpha decay region','fontsize',4)
xlabel('A','fontsize',4)
ylabel('alpha particle seperation energy','fontsize',4)
plot(A,Sa,'o')
end
```

APPENDIX - H

(Program for computing conditions for existence of Neutron star):

```
clc
clear
av=15.5 //in MeV
asym=23 //in MeV
G=6.67D-11 //in Nm^2/kg^2
mn=1.67493D-27 //in kg
Ro=1.25D-15 //in m
msun=1.98847D30 //in kg
A=((((asym-av)*(1.6D-13)*5*Ro)/(3*G*mn*mn))^1.5)
M=A*mn
w=(M)/msun
disp(A,"for neutron star to be stable mass number should be >=")
disp(M,"for neutron star to be stable mass (in kg) should be >=")
disp(w,"Ratio of mass of neutron star and solar mass=")
r=Ro*(A^(1/3))
disp(r,"radius of neutron star (in meter)=")
```