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Separation energies of light nuclei with atomic number from 1 to 20

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Abstract

The 1n and 1p halo nuclei from atomic number 1 to 20 are discussed here to calculate the variation of separation energy with mass defect and binding energy. Semi-empirical mass formula and shell model are the methods applied here. The appearances of p- and r-branches satisfying the selection rules for different isotopes of nuclides are discussed.

***Keywords*:** shell model, halo nuclei, separation energy, r- and p-processes

1. Introduction

The separation energy of a proton or a neutron from a nucleus is the energy required to remove the most loosely bound proton or neutron adiabatically. The effects of the nuclear shell structure on the separation energies of nuclei have been studied by many authors, and the separation energies show the discontinuities at each of the shell edges although the magnitudes of the discontinuities have not been explained in relation to the nuclear structures. The fact that both the electrons in atoms and the nucleons in nuclei are fermions gives a similar character to the ionization and separation energies, but on the other hand, they have quite different characters in many respects. In the atom, there is only one kind of fermions outside the nucleus, the electrons, moving in the strong electric field of the nucleus, whereas in the nucleus there are two kinds of fermions, the protons and the neutrons, interacting strongly with each other. The force acting on an electron in the atom is, in fairly good approximation replaced by the average static force, and when an electron is removed from an atom, the residual atom changes its structure only slightly. As for the nuclei, the validity of the approximation of the single particle model is not clear experimentally as well as theoretically and when a nucleon is removed from a nucleus, the residual nucleus changes its structure appreciably. Therefore, the ionization energies vary monotonically with respect to the numbers of electrons of the atoms except at the shell edges, whereas the separation energies vary in a complicated way with the numbers of protons and neutrons. To understand these variations, we need a theory which gives the total binding energies of nuclei as a function of the numbers of protons and neutrons, because we must take into account the change of the nuclear structure when a nucleon is removed.

Takao Tati [1] studied the systematic deviation of the separation energies from the semi-empirical mass formula calculated in terms of the corrected mass formula by the uniform model which assumes the two-body interaction between symmetric pairs in supermultiplet structure shows some evidence to support the independent particle model.

S. Athanassopoulos et al [2] have developed new global statistical models of nuclides atomic masses based on multilayered forward networks. One goal of such studies is to determine how well the existing data determines the mapping from the p and n number to the mass of the nuclear ground state. Another is to provide reliable predictive models that can be used to forecast mass values away from the valley of stability [2]. K. Vogt et al [3] have shown that the one and two nucleon separation energy can be parameterized in a new way using the neutron to proton ration N/Z and the mass number A. A very simple empirical formula has been achieved using a least squares fit to all available experimental data. Modeling of the structure and evolution of the stars in the quality and diversity of the astronomical observations as well as in the experimental and theoretical understanding of the atomic nucleus and of its spontaneous induced transformations have been studied by M. Arnould and K. Takahashi [4].

2. Methods applied

All the values considered are nearly their exact values and for all the calculations only naturally occurring isotopes and their corresponding values are taken into consideration. Atomic masses of the elements are taken as such provided by the dynamic periodic table values. Though we have taken the values already calculated from that of the data provided by the dynamic periodic table but corresponding data could be obtained by the mathematical expression for calculating the following parameters.

From Weizsacker's semi empirical mass formula the binding energy could be stated as

$$E_B = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(A-2Z)^2}{A} - a_p\, \delta(A,Z) A^{-1/2}$$

The values of the coefficients are:

$a_v = 15.760$, $a_c = 0.711$, $a_s = 17.810$, $a_a = 23.702$, $a_p = 34$

For example if we calculate the value of binding energy for the isotope of oxygen we have

For ${}^{17}O_8$,

Given atomic mass from the precalculated experimental value as = 16.99 a.m.u

Number of protons = 8

Number of neutrons = 9

δ(A,Z) is +1 for even-even nuclei, zero for even odd nuclei and -1 for odd-odd nuclei

On solving;

$E_B = 7.750731$Mev for oxygen

Calculation of separation energy for 1n halo of oxygen atom:

Given binding energy for the ${}^{16}O_8$ is 7.976206 and for ${}^{17}O_8$ is 7.750731

$S_{1n} = M(Z,N-1)+M_n-M(Z,N) \approx B(Z,N)-B(Z,N-1)$

$S_{1n} = -0.225475$ MeV

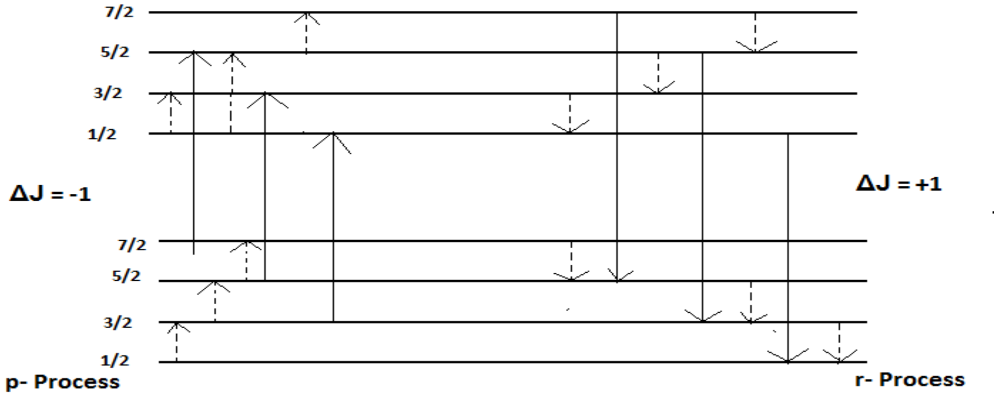
If we interprete this by the uniform model we see that the magnitudes of the separation energies of $S_p(Z,A)$ and $S_n(N,A)$ depend mainly on the proton excess (2Z – A) and the neutron excess (2N-A), apart from the charge effects and even-oddness of Z and N. Hence it seems convenient to denote $S_p(Z,A)$ and $S_n(Z,A)$ as $S_p(X_p,Z)$ and $S_n(X_n,Z)$. X is defined as,

$X=X_p=2Z-A$ for protons

$X=X_n=2N-A$ for neutrons

Where Z, N and A are the number of protons, number of neutrons and the mass number.

r- and p-process



P-branches appear when there is transition from J → J-1 or ΔJ= -1 for absorption of energy. Similarly when there is transition from the lower level to the higher level ΔJ= 1 or J→J+1 emission of energy occurs, the branches satisfying the selection rule is known as branches of r-process. The isotopes of the nuclide near and far from the stability line show this branching process.

3. Result and discussion

The graphs of separation energy with mass defect are plotted for isotopes of argon, sulphur, calcium and with binding energy for different elements. Fig.1 and table-1 show that lowest value of separation energy of Ar is 0.328Mev and maximum value is 0.375Mev. For different isotopes of sulphur the separation energy value varies in a zigzag manner with respect to the mass defect (fig 2). Fig.3 and table-4 show that separation energy for all cases is positive where as the mass defect varies from -0.0046Mev to 0.115Mev for Ca. The separation energy versus binding energy for light nuclei shows a fascinating clustering effect after 8Mev. The separation energy varies from -8Mev to 2Mev. Some points lie in the positive axis, some on the negative axis while others lie near the axial line (fig 4).

Some of the elements are not indicated as they do not have a 1n halo structure as compared to their base nuclei. The graph shows a linear decrease for carbon. Where the plotting form a cluster, it indicates that at the closing for the light nuclei most of the elements show nearly same separation energies that means they have nearly the same reactive rate. Many elements at the positive side of the graph have even-even nuclei and that at negative end have odd-even nuclei which indicates that the energy required to separate the nucleons from that of the paired structure is comparatively more for loosely bound neutron in the unpaired nucleus in elements.

Table 1: Isotopes of Argon with separation energies

Isotopes of Argon	Separation energy	Mass defect
Ar 37,18	0.328718	0.00723
Ar 38,18	0.341428	0.094364
Ar 39,18	0.350093	0.350093
Ar 40,18	0.359107	0.359107
Ar 41,18	0.365655	0.365655
Ar 42,18	0.375775	0.375775

Table 2: Variation of separation energy with binding energy

ELEMENTS /ISOTOPES	BINDING ENERGY	SEPARATION ENERGY (S1n)
H 3,1	2.827266	1.714983
Li 7,3	5.606291	0.273946
Be 9,4	6.462758	1.091358
B 11,5	6.927711	0.45264
C 13,6	7.469849	-7.68013
N 15,7	7.699459	0.223845
O 17,8	7.750731	-0.225475
F19,9	7.779015	0.14741
Ne 21,10	7.971713	-0.060527
Na 23,11	8.111493	0.195784
Mg 25,12	8.2235	-0.037209
Al 27,13	8.33154	0.18177
Si 29,14	8.448634	0.00089
P 32,15	-	-
S 33,16	8.497634	-0.017048
Cl 36,17		
Ar 37,18	8.527139	0.00723
K 39,19	-	-
Ca 41,20	8.5467	-0.0046

Table 3: For sulphur and its isotopes

Isotopes of sulphur	Separation energy	Mass defect
S 32,16	0.292263	0.0039
S 34,16	0.304424	0.08928
S 35,16	0.311922	0.044125
S 36,16	0.322539	0.081657

Table 4: For calcium and its isotopes

Isotopes of calcium	Separation energy	Mass defect
Ca 40,20	0.365087	-0.0046
Ca 41,20	0.377412	0.0652
Ca 42,20	0.385929	0.04935
Ca 43,20	0.397878	0.10687
Ca 44,20	0.405838424	0.07924
Ca 45,20	0.416997413	0.117585
Ca 46,20	0.424808994	0.087957
Ca 47,20	0.435485823	0.115167

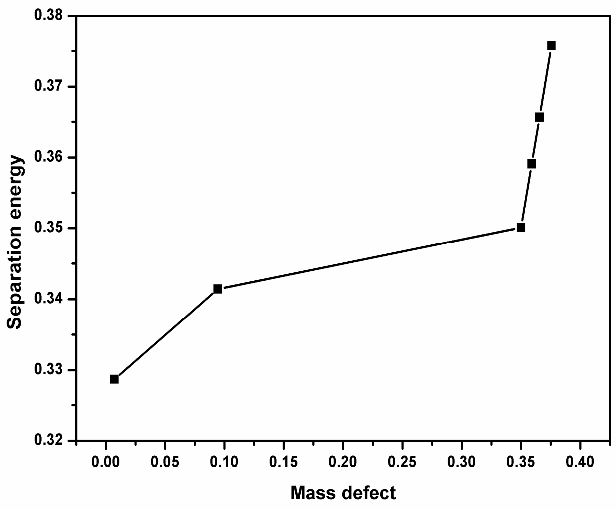


Figure 1: Variation of separation energy with mass defect for different isotopes of Argon

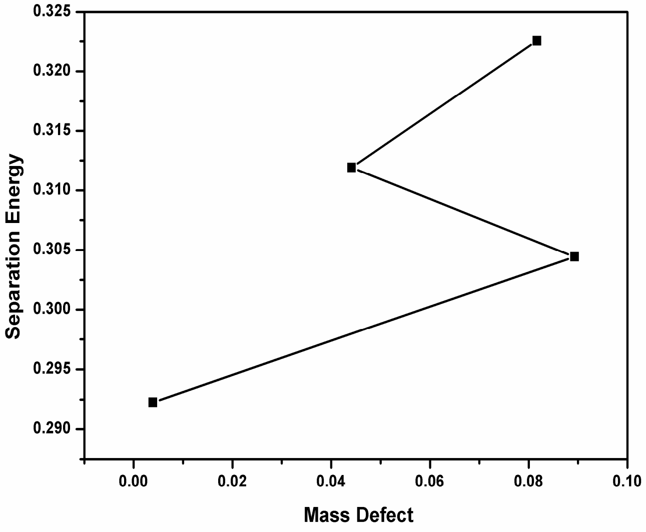


Figure 2: Variation of separation energy with mass defect for different isotopes of sulphur

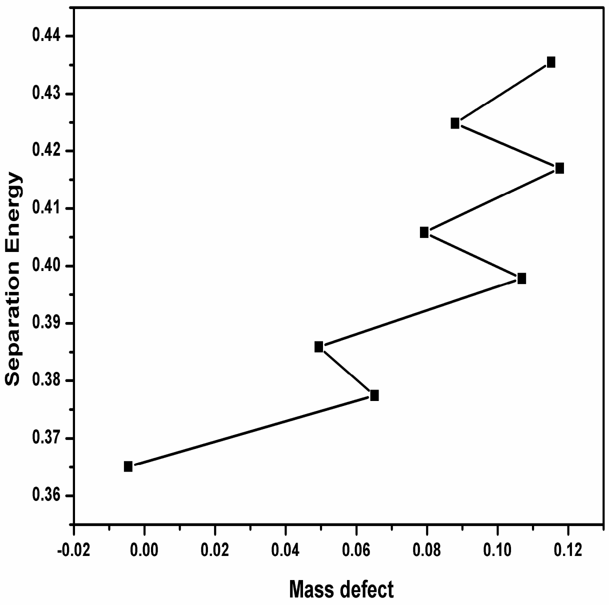


Figure 3: Variation of separation energy with mass defect for different isotopes of calcium

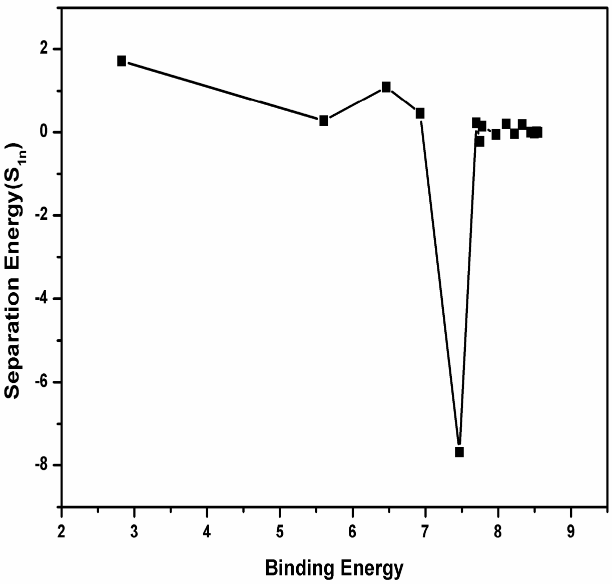


Figure 4: Separation energy versus binding energy for different elements

4. Conclusions

From the above analysis we find that the separation energy plays a very important role in understanding the nuclear stability. The results obtained from the graphs show that there is a non linear relation when we consider the isotopes of various elements along with the binding energy of the nucleus. From the data for 1n separation energies we can interpret that the binding energy for most of the even lighter nuclei lie in the positive side. For those elements which lie on the negative side of the stability line, pairing is not possible. The clustering for the light nuclei from the nuclear drip line graph indicates that most of the elements along with their isotopes lie on the nuclear drip line indicating that they have a low binding energy and are almost stable elements. The calculation of binding energy has applications in astrophysics, stellar object like a star, planet, comet formation and deformation. Binding energy term and separation energy term help us to study various nuclear models in finding stable nucleons that could be associated with various nuclear reactions.

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