زانکۆی سەلاحەدین-هەولێر

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College of Education

Study of The Properties of Some Light Atomic Nuclides

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By

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بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

"وما أوتيتم من العلم إلا قليلا"

صَدَقَ اللهُ العَلِيُّ العَظِيمْ

(سورة الاسراء الاية85)

Dedication

To My

Respectful Parents

Dear Brothers and Sisters

Lovely Nieces and Nephews

Aya Najmadin&Solen Ali

Acknowledgment

To begin with, I would like to thank **"Allah"** for the virtues of this blessing for implanting the soul of endurance and faith in me for completing this study. My most gratefulness and respect to my parents. We thank the Deanery of the College of Education – Physics departments for their support during this work. We thank the physics department for their support during this work, particularly Dr. Asaad H. Ismail, the head of the physics department. I am most grateful to my supervisor, Dr. Hiwa Hamad Azeez, for his invaluable guidance, support, and patience during this work.

Table of contents

Content	pages
Chapter One	
1.1 Introduction and History	8
1.2Atomic model and history	10
Chapter Two	
2.1Atomic Structure and properties	15
2.2Properties of nuclei	15
2.3Binding Energy	16
Chapter Three	
3.1 Discussion	24
3.2 Conclusions	27
Reference	27

Table of Figures

1-1 Dalton atomic model	11
1-2 Thomson atomic model	12
1-3 Rutherford atomic model	13
1-4 Bohr atomic model	14
2-1 nucleon at surface of nucleus	20
2-2 the resulting nucleus	21
3-1 average binding energy per nucleon as a function of mass number A	26

List of Tables

2-1 Pairing energy	22
Table 3-1	25
Table 3-2	25
Table 3-3	26

Abstract

This research focuses on calculating the binding energy of some light nuclides using the semi-impractical mass formula. The nuclear force is effective only at very short distances (~fm). At greater distances, the electrostatic force dominates. The nucleus is stable against break-up into individual nucleons because its mass must be less than the mass of these constituents when separated by large distances. The missing mass serves as the binding energy of the nucleus that holds nucleons together. The curve of binding energy is a graph that plots the binding energy per nucleon against atomic mass (A). As the calculated results show, the series of light elements from Hydrogen to Calcium exhibit generally increasing binding energy per nucleon as the atomic mass increases. The binding energy per nucleon is roughly constant over a large part of the periodic table. As nuclei get heavier than helium, their binding energy per nucleon grows more and more slowly. So, we can conclude that the nuclides whose main peaks are prominent are said to be more bound than the neighboring nuclides.

Chapter One

Introduction and History

1.1 Introduction:

Nuclear physics is the field of physics that studies atomic nuclei and their constituents and interactions. Other forms of nuclear matter (nuclear size, nuclear shape, mass, nuclear matter density) are also studied. Nuclear physics should not be confused with atomic physics, which studies the atom as a whole, including its electrons. Discoveries in nuclear physics have led to applications in many fields. This includes nuclear power, nuclear weapons, nuclear medicine and magnetic-resonance imaging, industrial and agricultural isotopes, ion implantation in material engineering, and radiocarbon dating in geology and archaeology. Such applications are studied in the field of nuclear engineering. Particle physics evolved out of nuclear physics and the two fields are typically taught in close association. Nuclear astrophysics, the application of nuclear physics to astrophysics, is crucial in explaining the inner workings of stars and the origin of the chemical elements (Zaw & Soe, 2019).

The Greeks already knew the electrical properties of amber (electron) and the magnetic properties of magnetite. Bieler in 1924 wrote "as the angle increases, the ratio of the actual scattering to what would be expected on the inversesquare law diminishes rapidly. This suggests the existence of an attractive force at short distances from the nucleus". He made an "attempt to explain on a magnetic hypothesis this inverse fourth-power term in the law of force". The neutron was discovered in 1931 by his colleague, Chadwick. The neutron seeming to be uncharged, the electromagnetic hypothesis for the nuclear interaction was abandoned (Schaeffer, 2011).

On the other hand, atomic physics is the physics of the behavior of atoms and in particular of their electronic Structure. That layer of the Structure of matter depends for its existence on the nuclear atom but it is not markedly affected by the properties of the nucleus. Similarly the behavior of the nucleus is little affected by the electronic Structure surrounding it so that nuclear physics can, as a subject, be almost completely isolated from atomic physics (Zaw & Soe, 2019).

A nucleus is made of two types of discrete nucleons having practically the same mass, the neutron and the proton. Thus the binding energy of a nucleus is a dis- continuous function of its mass. Adding one nucleon to a nucleus increases its mass. If the binding energy of a nucleon to a nucleus is negligible, the total binding energy remains the same. Therefore the binding energy per nucleon decreases (Schaeffer, 2013).

Electrons and nuclei are kept together by electrostatic attraction (negative attracts positive). Furthermore, electrons are sometimes shared by neighboring atoms or transferred to them, and this link between atoms is referred to as a chemical bond, and is responsible for the formation of all chemical compounds. The force of electric attraction does not hold nuclei together, because all protons carry a positive charge and repel each other. Thus, electric forces do not hold nuclei together, because they act in the opposite direction. It has been established that binding neutrons to nuclei clearly requires a non-electrical. Therefore, another force, called the nuclear force (or residual strong interaction) holds the nucleons of nuclei together. It consists of two portions: attractive portion and repulsive one. In the attractive core, the nucleons tend to attract strongly and on the other hand, the repulsive core prevents the nucleons not to confuse . This force is a residuum of the strong interaction, which binds quarks into nucleons at an even smaller level of distance. The nuclear force must be stronger than the electric repulsion at short distances, but weaker far away, or else different nuclei might tend to clump together. Therefore, it has short-range characteristics. The nuclear force is a close-range force: it is strongly attractive at a distance of 1.0fm and becomes extremely small beyond a distance of 2.5fm, and virtually no effect of this force is observed outside the nucleus. The nuclear force also pulls neutrons together, or neutrons and protons. This property is called the saturation. An analogy to the nuclear force is the force between two small magnets: magnets are very difficult to separate when stuck together, but once pulled a short distance apart, the force between them drops almost to zero. Unlike gravity or electrical forces, the nuclear force is effective only at very short distance (~fm). At greater distances, the electrostatic force dominates: the protons repel each other because they are positively charged, and like charges repel. They cannot get close enough for the nuclear force, which attracts them to each other, to become important. Only under conditions of extreme pressure and temperature for example, within the core of a star, can such a process take place (Beiser, 2003).

Nuclear binding energy can be computed from the difference in mass of a nucleus, and the sum of the masses of the number of free neutrons and protons that make up the nucleus. Once this mass defect or mass deficiency, is known, Einstein's mass-energy equivalence formula $E = \Delta mC^2$ can be used to compute the binding energy of any nucleus (Zaw & Soe, 2019).

1.2 Atomic model and history:

The history of development of the understanding of atomic Structure is of special significance because it was the first systematic attempt through which, the relationship between the macroscopic properties of matter and its microscopic

Structure was investigated. By 19th century, it was firmly established that the matter was composed of atoms and molecules. The kinetic theory of gases provided direct evidence and realistic information regarding mass and size of atoms and molecules. The kinetic theory was based on the application of ordinary laws of mechanics to the motion of molecules in gases and provided relationship between some structural properties of its molecules and the properties of gases.

The discovery of electron by J.J. Thomson (1996) gave indication that the atom had inner Structure. This led physicists to speculate about the internal Structure of atom. Attempts made in this direction manifested in terms of various atomic models (Singh, 2008).

Physicist John Dalton:

English chemist and physicist John Dalton converted the atomic philosophy of the Greeks into a scientific theory.It involves the following postulates:

(1) Elements consist of indivisible small particles (atoms).

(2) All atoms of the same element are identical; different elements have differenttypes of atoms.

(3) Atoms can neither be created nor destroyed.

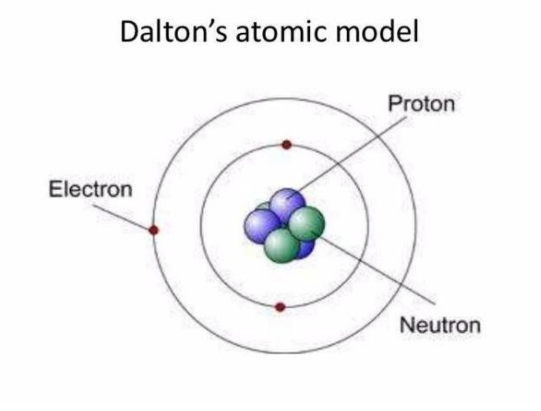


Figure 1-1: John Dalton's atomic model.

1.2.1 Thomson atomic model

In the years after Dalton described his atomic model, multiple experiments were performed that proved that charged particles exist. In 1897, English physicist J. Thomson discovered a negatively charged particle, which he called the electron. The existence of the electron showed that the 2,000-year-old conception of the atom as a homogeneous particle was wrong and that in fact the atom has a complex structure. Thomson noted that the Dalton model of the atom did not include the idea of charge, and he theorized that the electrons must be within the atoms of elements.

After the discovery of negatively charged electrons, it was realized that the electrons were the constituent particles of atom. Since atom is electrically neutral, Thomson proposed that the atom might be regarded as a sphere of positive charge in which negatively charged electrons were embedded in it. The magnitude of positive charge in the sphere was equal to the total charge carried by electrons.

This model of atom, called plum-pudding model, received serious set back because it could not explain the experimental observations made in the famous alpha-particle scattering experiment conducted by Geiger and Marsden under the guidance of Lord Rutherford(Singh, 2008).

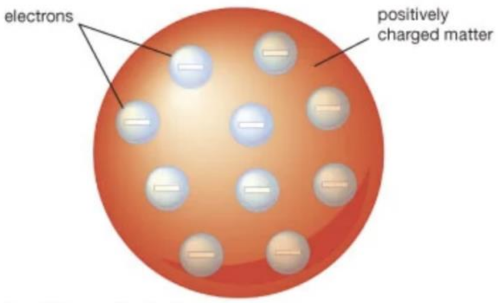


Figure 1-2: Thomson's atomic model.

1.2.2 Rutherford atomic model:

In 1911 a former student of Thomson's, New Zealand-born British physicist Ernest Rutherford, in cooperation with other scientists, performed alpha particle experiments that led to the overturning of Thomson's model. They aimed alpha particles at a thin sheet of gold foil and then recorded the location of the alpha particle with a fluorescent screen after the interaction. They found that the majority of the alpha particles passed through the gold foil as if the foil was not there. They also found that a very small number of these alpha particles deflected at angles from the initial path, with some of the alpha particles even bouncing back along the initial path. By this experiment he found the positive nucleus at the centre of the atom.

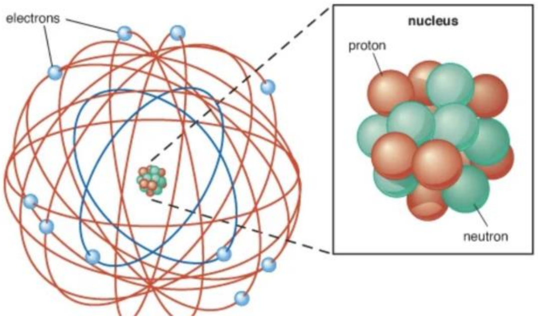


Figure 1-3: Rutherford’s atomic model.

1.2.3 Bohr atomic model:

Just two years after the Rutherford atomic model had been introduced, Danish physicist Niels Bohr, a student of Rutherford's, developed the Bohr model of the atom, in which he proposed that energy levels of electrons are discrete and that the electrons revolve in stable orbits around the atomic nucleus but can jump from one energy level (or orbit) to another.

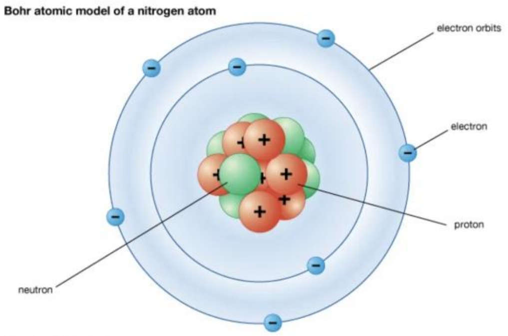


Figure 1-4: Bohr’s atomic model.

Aim of this research

In this research we focus our discussion on two concepts: the masses of nuclides and the corresponding nuclear binding energies. These are two of the first nuclear properties to be encountered, but they can easily built upon to devlve further into the physics of the nucleus.

Chapter Two

Atomic Structure and Properties

2.1 Properties of nuclei:-

2.1.1 Charge and Mass

Atoms consist of a tiny, dense nucleus made of protons and neutrons, surrounded by a cloud of orbiting electrons. In a neutral atom, the number of electrons balances the number of protons. Protons and neutrons are very much heavier than electrons by a factor of about 1836, so the vast majority of the mass of an atom is contained within the nucleus. The number of protons in a nucleus Z—also called the atomic number— defines the element to which it belongs, and associated with each element is a symbol, e.g. carbon = C, magnesium = Mg, lead = Pb, which we generically denoted by X. Though all nuclei of a given element will have the same number of protons Z, they may have different numbers of neutrons N, giving different mass numbers $A = Z + N$. These are called isotopes. If we want to refer to a particular sort of nucleus, with specific Z and N, we use the word *nuclide*3, denoting a particular nuclide by ${}_{Z}^{A}X$. Since the element symbol X uniquely specifies the number of protons, Z and N are often neglected (Simpson & Shelley, 2017).

The proton carries a single positive charge, equal in magnitude to the electron charge (where e= 1.602 1773 X 10^{9} C). The neutron is electrically neutral, as its name implies. Because the neutron has no charge, it is more difficult to detect.Atomic mass (the mass of an atom containing a nucleus and Z electrons) can be measured with great precision with the mass spectrometer.

Radius of Nuclide

Nuclear mass distributions can be studied, for example, by the scattering of fast neutrons on nuclei. Such experiments were performed in a wide energy range of bombarding neutrons (14–1,400 MeV) and led to the following result:

$R= R_0A^{1/3}$

where 1.3 fm $< R_0 <$ 1.4 fm. This means that the nuclear mass parameter R0 is only slightly greater than the charge parameter, R_0 = 1.23

3-Nuclear masses and binding energies

The total mass of a nucleus is always less than the sum of the masses of its nucleons. Also, because mass is another manifestation of energy, the total energy of the bound system (the nucleus) is less than the combined energy of the separated nucleons. This difference in energy is called the binding energy of the nucleus and can be thought of as the energy that must be added to a nucleus to break it apart into its separated neutrons and protons .

We can therefore learn about nuclear forces by examining how tightly bound the nuclei are. We define Binding Energy of nucleus to be the energy required to separate an atomic nucleus completely into its constituent protons and neutrons.Or, equivalently, the energy that would be liberated by combining individual protons and neutrons into a single nucleus(Beiser, 2003; Meyerhof, 1967; Simpson & Shelley, 2017):

$$\text{Binding energy} = (\text{Mass deficit})c^2 = (\Delta m)c^2$$

-Total Binding Energy:

$$B.E_{tot}(A,Z) = \left\{ ZM_p + NM_n - \bar{M}(\text{ A, Z})\right\}c^2 \text{In units of joules}$$

$$B.E_{tot}(A,Z) = \{ ZM_H + NM_n - M(\text{ A, Z})\}c^2 \text{In units of Joules}$$

$$B.E_{tot}(A,Z)(MeV) = \{ ZM_H + NM_n - M(\text{ A, Z})\}x\ 931.49 \quad \frac{MeV}{amu}$$

Average Binding Energy:

$$B.E_{av}(A,Z) \ = \frac{B.E_{tot}(A,Z)}{A}$$

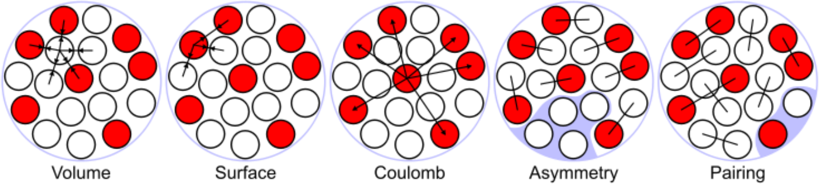
$$B.E_{av}(A,Z) = \frac{\{ ZM_{H+}\, NM_n - M(\text{ A, Z}) \}c^2}{A}$$

2.2 ***Semi-empirical Mass Formula for nuclear binding energy***

The liquid drop model led to the famous semi-empirical mass formula from which the dependency of nuclear mass upon A and Z.First, the nucleus is considered as a collection of interacting particles like a liquid drop.

The masses of atomic nuclei can be determined by mass-spectrometers or from nuclear reaction and decay energies. According to Einstein's theory of relativity, the energy (E) and mass (m) are related by equation E = mc^2 , where c is the speed of light in vacuum. The binding energy B.E is the equivalent mass, obtained by subtracting the mass of the nucleus from the sum of the masses of the constituent nucleons. The main features of this behavior can be understood on the basis of the liquid drop model (von Weizsa¨cker 1935; Bethe and Bacher 1936). According to this model, the nucleus is an incompressible liquid drop, in which the electric charge is distributed uniformly. The binding energy B.E is described by the Weizsa¨cker formula(Fényes, 2011; Meyerhof, 1967):

$$B.E_{tot}(A,Z) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{A} (0, \pm) \frac{a_p}{A^{3/4}} \delta \quad (3\text{-}8\ )$$



In the liquid drop model, nucleons are not described individually; they are considered as averaged values. Therefore, this model has been successful in describing some properties of nuclei such as average binding energy per nucleon, whereas for other nuclear properties such as nuclear excited states, magic numbers and nuclear magnetic moments have not so much to present.

A formula which would allow the calculation of nuclear mass or binding energies accurately.It is related to the liquid drop model of the nucleus.

As before,the binding energy of the nucleus with A nucleon is;

$$B.E_{tot}(A,Z) = \{ ZM_H + NM_n - M(\mathrm{A,Z})\}c^2 \ (3\text{-}1)$$

or $\mathrm{M(A,Z) = ZM_H + NM_n - \frac{B.E_{tot}(A,\ \ Z)}{c^2}}$ (3-2)

The mass $M(A,Z)$ can be considered accurately if the total binding energy $B.E_{tot}(A,Z)$ were considered accurate. The different factors which affect the nuclear binding energy,

$$B.E_{tot}(A,Z) = B.E_1 + B.E_2 + B.E_3 + B.E_4 + B.E_5 + \ldots\ldots \quad (\ 3\text{-}3\ \ )$$

The first term $B.E_1$(Volume energy term)$B.E_v$

The mass dependence of this term follows directly from the saturation of the nuclear force. A nucleon in the nuclear interior interacts, on average, with an affixed number of neighbouring nucleons within a short range of the nuclear force, the binding energy per nucleon, therefore, will be constant and the total contribution to the nuclear binding energy will be proportional to mass number A and proportional to the nuclear volume(Meyerhof, 1967).

Since$\frac{B.E_{tot}}{A}$ ≈Constant

$$B.E_{tot} \approx constant\ A$$

$$B.E_{tot} \propto \quad A$$

Since the volume of the nucleus $V = \frac{4}{3}\ \pi\ R_o^3 \left(A^{\frac{1}{3}}\right)^3 = \frac{4}{3}\ \pi\ {R_o}^3 A$ is proportional to A ,this term is regarded as volume energy.

$B.E_v\ =\ a_v A$ where a_v is the proportional constant.(3-4)

Surface Energy Term ($B.E_s$)

In a finite nucleus, a nucleon near the surface interacts with fewer nucleons and, therefore, is less tightly bound than if it is in the interior. Thus a term proportional to the surface area (or the square of the nuclear radius R)must be subtracted from the volume term to correct for this, since(Meyerhof, 1967):

The surface area of the sphere is $S = 4\pi R^2\ = 4\ \pi\ R_0^2 A^{2/3}$

$$S \propto\ A^{2/3}$$

$$\therefore B.E_s\ \propto A^{2/3}$$

$B.E_s = -a_s A^{2/3}$ (3-5)

Since there is a larger fraction of surface nucleons in light nuclei than in medium and heavy nuclei the total binding energy is smaller for small A.

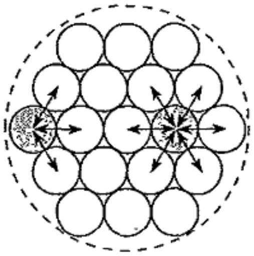


Fig (2-1);A nucleon at the surface of a nucleus interacts with fewer other nucleonsthan one in the interior of the nucleus and hence its binding energy is less.

Coulomb Energy Term($B.E_c$)

The Coulomb energy between the protons tends to lower the binding energy and its effect appears as a term with a minus sign. The coulomb repulsion becomes important for heavier nuclei, because of saturation of attractive nuclear force.

The Coulomb energy $B.E_c$ is directly proportional to the number of proton pairs in the nucleus(Meyerhof, 1967):

$$B.E_c \propto \frac{Z(Z-1)}{2}$$

$B.E_c \propto \frac{1}{R}$and $\because R = R_0 A^{1/3}$

$$\therefore B.E_c \propto \frac{Z(Z-1)}{2 R_0 A^{1/3}}$$

$$B.E_c = -a_c \frac{Z(Z-1)}{A^{1/3}} \quad (3\text{-}6)$$

Asymmetry Parameter Term ($B.E_{as}$)

In the absence of the coulomb force, the most stable nuclei would have an equal number of neutrons N and Z protons; In the absence of the coulomb effect, a departure from the condition N=Z or $Z = \frac{A}{2}$ would tend to lead to instability and a smaller value of the binding energy, A term proportional to $(N-Z)^2$ and inversely with A(Meyerhof, 1967).

The asymmetry energy is the difference in the nuclear energy of a nucleus with neutron and proton numbers N and Z and that of the isobar with neutron andproton numbers both equal to $Z = \frac{A}{2}$

$$B.E_{as} \propto (N-Z)^2$$

$$B.E_{as} \propto \frac{1}{\mathrm{A}}$$

$B.E_{as} = -a_{as}\frac{(N-Z)^2}{A}$ (3-7)

where a_a is the asymmetry parameter. The asymmetry energy is negative because it reduces the binding energy of the nucleus.

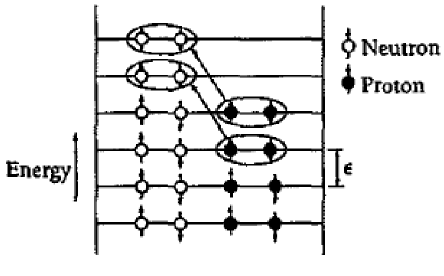


Figure 2.2 In order to replace 4 protons in a nucleus with N == Z by 4 neutrons, the work(4)(4ε/2) must be done. The resulting nucleus has 8 more neutrons than protons.

Pairing energy E_δ

Nuclei with an even-even number of protons and neutrons are the most abundant and presumably the most stable. Nuclei with odd numbers of both proton and neutron are the least stable, while nuclei, for which either the proton or neutron is even intermediate instability. The value of the odd-even effect can be represented by a term called **Paring energy E$_\delta$** depending on N or Z as follows (Meyerhof, 1967);

The paring term δ should be roughly equal to ½ of the pairing energy.

$$Ep = (0, \pm)\frac{a_p}{A^{3/4}}$$

Table 2-1: Pairing energy for different atomic Structure.

A	Z	N	E_δ
even	even	even	+δ/2
odd	even	odd	0
odd	odd	even	- δ/2
even	odd	odd	0

Finally, the formula of binding energy is obtained by combining all of the terms just discussed into the equation. The semi-empirical mass formula is then:

$$B.E_{tot}(A,Z) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{A}(0, \pm)\frac{a_p}{A^{3/4}}\delta \text{(3-8)}$$

Substituted equation(3-8)into equation (3-2)to get equation of mass formula;

$$M(A,Z) = Z\,M_H + N\,M_n - \left\{\frac{a_v A}{c^2} - \frac{a_s A^{\frac{2}{3}}}{c^2} - a_c \frac{Z(Z-1)}{c^2 A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{c^2 A}(0, \pm)\frac{a_p}{A^{3/4}}\right\} \text{(3-9)}$$

The values of constants: $a_v = 14.1\ MeV, a_s = 13.0 MeV, \quad a_c = 0.595\ MeV$, $a_a = 19.0 MeV, and \quad a_p = 33.5\ MeV$.

Other sets of coefficients have also been proposed. Equation (2-8) agrees better

with observed binding energies than does Eq. (3-9), which suggests that theliquid-drop model, though a good approximation, is not the last word on thesubject.

Chapter Three

Results and Discussion

Nuclear binding energy increases with the total number of nucleons **A.** Therefore, it is common to quote the average binding per nucleon $B.E_{av}(A,Z)$.

In **table 3.2-3**, we have data between the following elements (He-4, C-12,N-14,O-16, F-19,Ne-20, Mg-24, Al-27, Si-30, Cl-35), That we find average binding energy for them means for lightly nuclide. When the minimum data is for Cl-35=5.403keV and the maximum data is for He-4=11.700keV.

As binding energy increase the volume energy decrease as in helium, the volume binding energy =56.4keV and in chlorine =493.5keV. As binding energy increase the surface binding energy decrease as in helium the surface energy=32.757keV and in chlorine=139.098keV.

These results are obtained by comparing binding energy values of several nuclei , we see that the theoretical value is near from the experimental value. For example in carbon the exp value = 7.680keV and the theoretical value=6.860 keV.

My geometrical schemas are not designed to build a structure of nuclei but are destined to be a visual support for my research, especially to see the kinship between the binding energy distribution within the various nuclei.

Table 3.1: Atomic structure, radius, and charge for light nuclides under study.

Nuclide	A	Z	N	Radius (Fm)	Charge (Coulomb)
He-4	4	2	2	1.984	3.2E-19
C-12	12	6	6	2.861	9.6E-19
N-14	14	7	7	3.012	1.12E-18
O-16	16	8	8	3.149	1.28/E-18
F-19	19	9	10	3.335	1.44E-18
Ne-20	20	10	10	3.393	1.6E-18
Mg-24	24	12	12	3.605	1.92E-18
Al-27	27	13	14	3.75	2.08E-18
Si-30	30	14	16	3.884	2.24E-18
Cl-35	35	17	18	4.088	2.72E-18

Table 3.2: Volume, surface, Coulomb, asymmetry, and pairing energy for light nuclides under study.

	nuclide	Volume energy	Surface energy	Coulomb Energy	Asymmetry Energy	Pairing energy
1	He-4	56.4	32.757	0.749	0	13.294
2	C-12	169.2	68.139	7.796	0	6.391
3	N-14	197.4	75.514	10.368	0	5.767
4	O-16	225.6	82.544	13.223	0	5.275
5	F-19	267.9	92.564	16.054	1	4.704
6	Ne-20	282	95.784	19.727	0	4.546
7	Mg-24	338.4	108.164	27.228	0	4.0262
8	Al-27	380.7	117	30.94	0.703	3.722
9	Si-30	423	125.513	34.850	2.533	3.469
10	Cl-35	493.5	139.098	49.476	0.542	3.130

Table 3.3: Comparison between the calculated value of total and average binding energy per nucleon for light nuclides under study with the previous research.

Nuclide	Total Binding Energy (KeV)	Average binding energy per nucleon (MeV)	Average binding energy per nucleon (MeV) (Zaw & Soe, 2019)	Average binding energy per nucleon (MeV) (Wang et al., 2017)
He-4	46.802	11.700	6.818	7.073
C-12	82.327	6.860	7.424	7.680
N-14	91.650	6.546	7.219	7.475
O-16	101.043	6.315	7.720	7.976
F-19	109.619	5.769	7.536	7.779
Ne-21	120.059	6.002	7.728	7.971
Mg-25	139.418	5.809	7.978	8.223
Al-27	148.643	5.505	8.085	8.331
Si-30	162.897	5.429	8.282	8.520
Cl-37	189.117	5.403	8.335	8.570

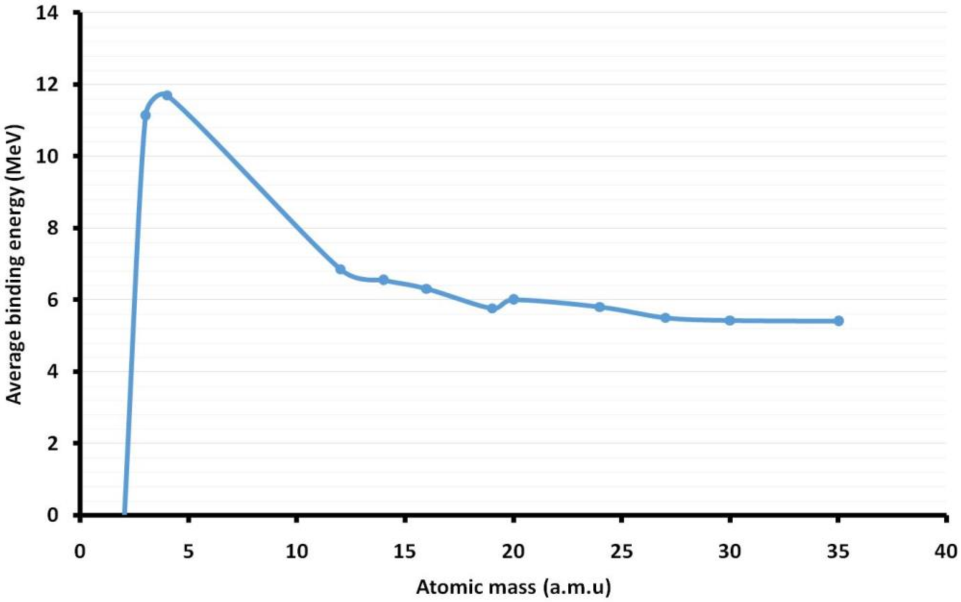


Figure 3-1: Average binding energy per nucleon as a function of mass number A.

Conclusions

The results show that the nuclear binding energy per nucleon (B/A) varies as a function of A. The higher the binding energy, the more lightly the nucleons are bound together. The curve peaks at Helium (He-3) and then slowly decreases again. So, we can conclude that the nuclides whose main peaks of the graph shown in Figure 3.1 are said to be more bound than the neighboring nuclides.

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