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Stability of Nuclei Based on the New Proton and Neutron Model

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ABSTRACT

According to the new proton and neutron nuclear picture described earlier, the structure of the nucleus will also be given a new interpretation. The role of the delocalized electrons detached from the outer shell of neutrons is shown in the binding energy value of the nucleus. It is pointed out that the spatial arrangement of nucleons is also very important for the stability of nuclei according to the analyzation of the magic numbers from a geometric point of view.

1. INTRODUCTION

In stable nuclei the positively charged protons that repel each other are held together by nuclear forces, but in the case of large nuclei with excess neutrons, gravitational action is also of great importance.

According to the results of early scattering experiments, nuclei have a constant density, making them incompressible like liquids. On this basis, the first nuclear model, the so-called liquid drop model, was born [1-3]. Now it is known that with large number of nucleons the density of the core is higher than near the surface [4-9].

It also turned out that nuclei can be excited, and experimentally determined excitation energy levels were tried to be described as analog to the electron shell structure of atoms [10-13]. According to the shell model of nuclei, during the excitation of the nucleus, nucleons (protons and neutrons) are sent to a higher energy level and then fall back to their original state by releasing energy, similar to the excitation of electrons on the outer electron shells surrounding the nucleus. The question rightly arises as to how nucleons much larger than electrons can move in a high-density nucleus. To solve this problem, the presence of vacancy-nucleons in the nucleus was assumed.

The third theory, the so-called cluster model, states that the core consists of several units, or clusters, connected to each other like clusters by Van der Waals-type forces. The internal stability of the clusters is ensured by strong interaction, so during excitation the internal structure of the cluster does not change, they only move relative to each other. It is believed that such a cluster can be considered, for example, the He^4 alpha nucleus, consisting of two protons and neutrons [14-21]. It is an open question whether the internal stability of clusters is ensured by molecular bonds or a special shell structure.

According to the results of the experiments, the stability of nuclei does not change uniformly with the increase in nucleon numbers, but in the case of certain nuclear sizes, *i.e.* proton and neutron numbers, nuclei are much more stable, these nucleon numbers are called MAGIC numbers, since the causes are not yet fully understood. It is hypothesized that these magic nucleon numbers form closed shell structures.

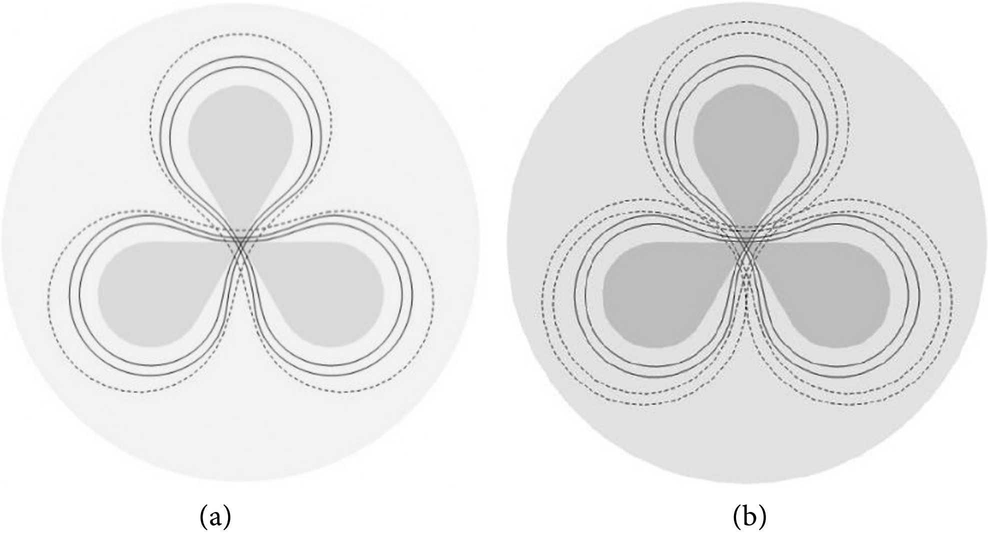
A similar open question is the phenomenon of so-called "anomalous inner pair creation" (formation of positron-electron pairs), which has been observed during the excitation of several nuclei [22-27].

This paper deals with these questions in the light of the new proton and neutron models. According to the new model of proton and neutron, nuclei can be thought of as protons held together by collectivized electrons detached from the outer shell of neutrons [28]. Neutrons are therefore very important for stabilizing nuclei. Excess neutrons, increasing the average electron density of the nucleus, play a significant role in stabilizing nuclei with high atomic numbers, together with their gravitational effect, of course.

2. STRUCTURAL MODEL OF NUCLEI

In nuclei made up of protons and neutrons, the shell model imagines the nucleons in orbits with specific energy levels. Energy levels can be determined from the results of excitation experiments. The question remains open as to what the displacement of nucleons within a very dense nucleus actually means. Another interesting problem is what causes the giant resonances detected in high-energy excitations. Goldberg and Teller explained the phenomenon by dipole oscillations of protons and neutrons. Later, Harakecb and Van der Wounde discussed the oscillation of the electric giant dipole of atomic nuclei on a similar basis. Apart from the fact that the neutron is neutral, dipole oscillation also assumes the displacement of protons in the very dense nucleus.

According to the new model of protons and neutrons [28], quarks are not elementary particles because they cannot be detected individually, but exist only in a bound state. Corresponding to the new model, quarks, and thus protons and neutrons, are made from truly stable elementary particles; of electrons (e^-), positrons (e^+) and neutrinos (ν). Their complex motion (shell structure) forms the triple structure of the three quarks in the proton and neutron. In **Figure 1**, only the outermost loaded shells for protons and neutrons are plotted. For clarity, neutral neutrino orbitals and inner shell structure are not indicated.



(a) (b)

Figure 1. Structural model of proton (a) and neutron (b), where only the outer loaded shells of quarks are indicated. (Schematic diagram.) A solid line indicates the positron, a dashed line indicates the electron orbitals.

As you can see, the outer shell of a proton has two positrons and only one electron giving its positive charge, while a neutron has two positrons and two electrons, so it is fully loaded and neutrally charged.

The shortcomings of the currently accepted proton model are also highlighted by the fact that the proton size values determined from the measurements vary widely. The opinion of De Rújula [29] is in line with the idea of the above model, who sees the reasons for the scattering of proton sizes determined by different measurement methods in the fact that the incorrect charge distribution within the proton was used during the evaluation. According to him, the inner nucleus of the proton is neutral.

The outer electron of the neutron is very loosely bound because it spontaneously decays in a few minutes when free, giving off an electron and an antineutrino, leaving it as a positively charged proton (see Figure 2).

A similar thing happens inside the nucleus, since the outer electron of the neutron is loosely bound and can no longer be considered stationary under the influence of an electric attraction near the positively charged proton. The simplest illustration is deuteron, which consists of a proton and a neutron.

The electron shell shown in schematic Figure 3(a) shows a looser bond between the two protons, while Figure 3(b) shows the tightest possible space filling, where the shared electron moves on the external, originally unfilled level of protons.

Space fill can be calculated from the nucleus and nucleon sizes determined from the experiments. For small nuclei, this value is 57%, which approximates the space fill of regularly arranged crystalline materials between 52% and 75%, which means that in the case of nuclei with a small nucleon number and the high-density nucleus core of larger nuclei, the arrangement shown in Figure 3(b) better describes the bounding of protons.

As shown in Figure 3, the nucleus of deuteron can actually be thought of as consisting of two protons, where the two protons are connected by the seared electron, resembling a covalent bond. The existence of such complex hexa-quarks is already known in the literature, and studies show that the two triple quark knots are held together by a molecule-like bond, which corresponds to the new model. The average electron density providing bonding is 0.5/nucleon.

Nuclei with higher atomic numbers have a similar structure. With the same number of protons and neutrons (Z = N), the electron density caused by the exposed electrons is still 0.5/nucleon. N = Z nuclei occur only among nuclei smaller than Ca nuclei with 40 nucleons.

In nuclei with higher atomic numbers, the number of neutrons gradually increases relative to protons (Z < N), but their ratio never increases above 1.6/nucleon, so the average density of delocalized electrons does not exceed 0.61/nucleon.

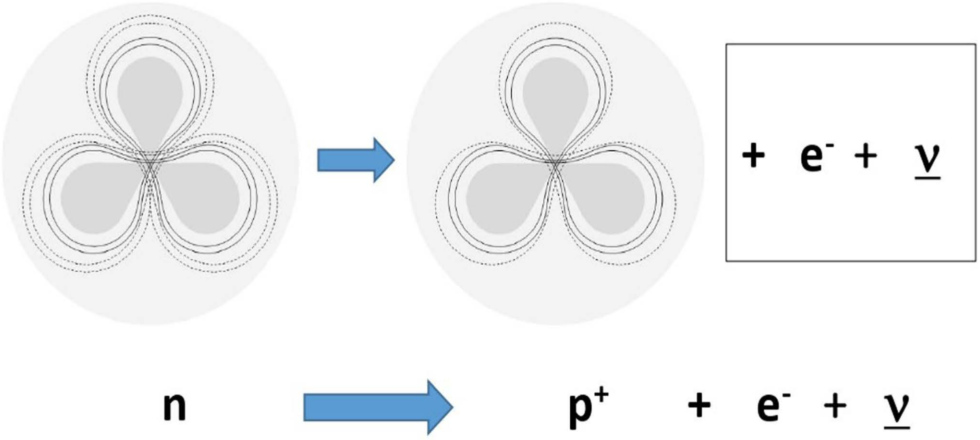
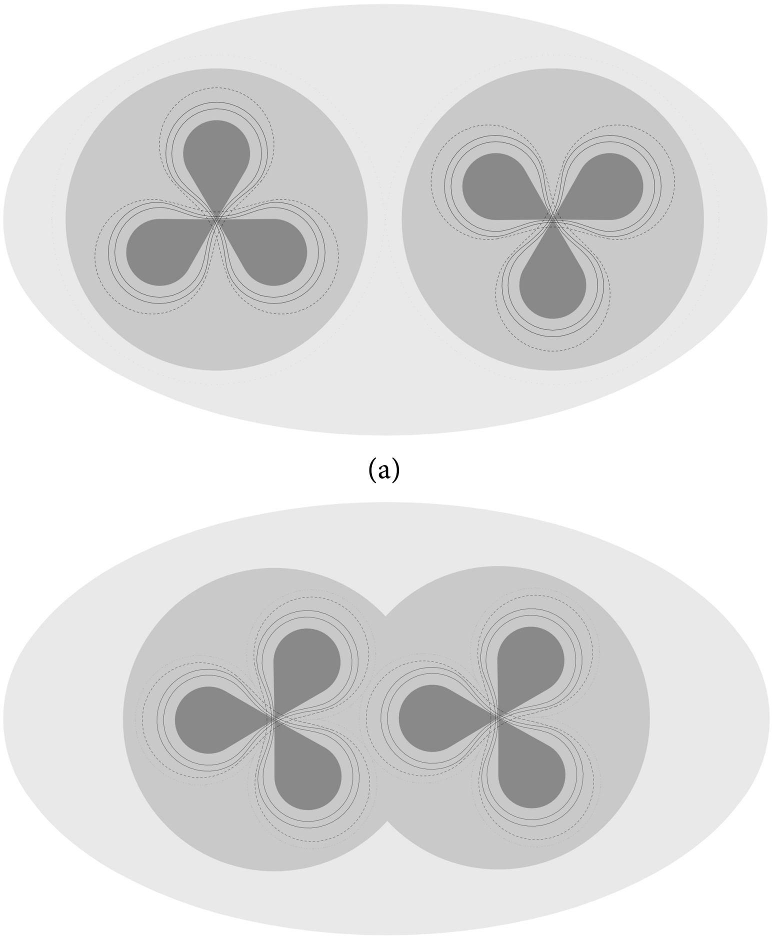


Figure 2. During the spontaneous decay of a neutron, an electron and the antineutrino moving with it leave, leaving only one electron on the outer shell of the remaining proton. (See. dashed lines indicating electron-filled orbits).



(a)

(b)

Figure 3. The structure of deuteron according to the new model, where the two protons are connected by an electron detached from the outer shell of the neutron. The "common used" electron orbits indicated by dotted lines around the two protons, in (a) a looser connection and (b) the tightly bound. (Schematic picture).

It is assumed that the average electron density within the nucleus core (derived from electrons detached from neutrons) is only 0.5 even with larger nuclei, but due to the increased surface area of the nucleus, more and more protons are placed on the edge of the nucleus, *i.e.* on its surface. To overcome the repulsive effect of positively charged protons located on the surface of the nucleus, which are weakly bound to the nucleus, the electron density increases, creating a layer of nearly-neutral nucleons, or neutrons, called neutron skin. Experiments have shown that the density of the nucleus is higher than the band forming the surface of the nucleus, which is neutrally charged [30-36]. Thus, the nucleus is bounded by neutrally charged nucleons, that is, the nucleus is surrounded by so-called neutron skin.

3. INTERPRETATION OF KNOWN PHENOMENA BASED ON THE NEW NUCLEAR MODEL

3.1. Giant Resonances

Under the influence of high-energy excitations, giant resonances were detected in the nucleus, which was explained by dipole oscillations of protons and neutrons in the nucleus. However, the density of the nucleus is high, the nucleons are relatively large, and only one of them has a charge and the other is neutral. According to the above nuclear model, collectivized electrons in a dense nucleus that are relatively easy to move can indeed be polarized relative to the positively charged protons that make up the nucleus. Under the influence of high-energy excitation, a true dipole oscillation can occur with the shift of positive and negative centers creating the detected giant resonance.

3.2. Anomalous Pair Creation Phenomenon

When certain elements, such as ^{4}He and ^{8}Be, were excited, the combined exit of electrons (e^-) and positrons (e^+) was detected [22-27]. The energy of the resulting pair e^--e^+ pair was equal to the excitation energy of the nucleus.

Since it is generally accepted that protons and neutrons made up of quarks do not contain electrons and positrons, their "formation" could only be interpreted by introducing a new interaction, and the phenomenon was called anomalous pair creation. The anomalous pair creation was explained by the formation of a hypothetical particle, the X7 boson, and this boson was thought to decay into e^+ and e^-. The phenomenon of anomalous pairing was also observed during heavy ion collisions and was also treated as a process occurring during the excitation of the nucleus. Based on mathematical considerations, P. Kálmán, T. Keszthelyi tried to interpret anomalous pairing without assuming a new particle, the X7 boson [26, 27].

The described new nuclear model assumes the presence of positrons and electrons in nucleons (p, n) from the outset, because quarks are considered to be made up of them. During high-energy excitation of the nucleus, it is therefore not surprising that these "easily moving" particles are ejected from the nucleus. According to the new model, there is no need to introduce a new interaction and a new boson.

The excitation energy levels of nuclei can be measured well, and the fact that the total energy of the electron-positron pairs produced during anomalous pairing is equal to the excitation energy of the nucleus also shows that during the excitation of nuclei it is not the large nucleons themselves (protons and neutrons) that are excited to a higher energy level, but the collectivized electrons in the nucleus or at higher excitation energies, together with the positrons located at deeper levels of nucleus.

4. SPACE FILLING OF NUCLEI

Looking at nucleons as rigid spheres, it was estimated the radius of the sphere in which the magic number of nucleons could fit.

Knowing the size of nuclei, considering nucleons as rigid spheres, it is possible to determine their space fill.

Size of nuclei (R):

$$R = R_0 A^{1/3}$$

where: for small nuclei $R_0 = 1.2$ fm, for large nuclei $R_0 = 1.4$ fm, nucleon number A.

From the above data, the space fill of nuclei can be determined, which is 57% for small nuclei and 34% for large nuclei. Using these data it was calculated the radius (R) of the enveloping sphere in proton radius (r) units and the results are given in **Table 1**.

Table 1 shows that oxygen (O) with 16 nucleons can be placed in a sphere with radius $R = 3.02r$, where r represents the nucleon radius. This roughly means the 15 first neighbors surrounding the central nucleon and so, the first layer is saturated in the case of oxygen. In the case of Ca, this value is close to $5r$ ($4.86r$), which means the formation and completed of the next layer.

We know that for N > Z, the density of the inner part is higher than near the surface of the nuclei, so the above estimates are only a good approximation up to Z = N, *i.e.* Ca (A = 40). At larger nuclei, it is difficult to say anything based on the average space filing, but it is noteworthy that for stable Sn and Pb $R = 6.99r$ and $R = 8.41r$, respectively, indicating saturation of the following layers.

It is worth returning to the radius of the tetrahedral He^4 nucleus, which is $1.9r$ fm according to the space fill determined by the measurements. A tetrahedron of rigid spheres of radius r, on the other hand,

Table 1. **Radius (*R*) of stable nuclei with a magic number of nucleons, in proton radius (*r*) units. 57% for small nucleon counts, but 34% for large sizes with average void fill.**

Stable nuclei	*R* (57% void fill)	*R* (34% void fill)
He^4	1.90 r	
O^{16}	3.02 r	
Ca^{40}		$4.86r$
Fe^{56}		$5.45r$
Sn^{118}		$6.99r$
Pb^{208}		$8.41r$

can only fit in an envelope with radius $2.2r$. It follows that nucleons (or the quarks that make up them) are very closely linked, and the bond is provided by the delocalized electrons according to schematic **Figure 3(b)**.

This idea does not contradict the so-called quark-like model, which considers the nucleus to be a quark-gluon plasma rather than a nucleon [37-39]. According to the new model, the cohesive role of gluons is represented by delocalized electrons due to the structure of quarks.

5. BINDING ENERGY, GEOMETRY AND MAGIC NUMBERS OF STABLE NUCLEI

Looking at the periodic system, among the nuclei of different elements, some are more stable than others. In terms of proton numbers, they are:

2, 8, 20, 28, 50, 82, 126, that is, the nuclei He, O, Ca, Ni, Sn, Pb.

Not knowing the reason, they were called magic numbers. Especially stable are nuclei where the neutron number is also a magic number, *i.e.* they have a double magic number. These are trivial nuclei where protons and neutron numbers are the same (Z = N), *i.e.* He (2 + 2), O (8 + 8), Ca (20 + 20). Pb with proton number 82 also has a doubly magic number, since it has 126 neutrons, *i.e.* its mass number is 208.

Wigner, Goppert, Mayer explained the stability of nuclei with magical numbers by the filling of the nuclear shells. In their opinion, this is when closed nuclear shells are formed.

Agreeing that magic numbers show the loading of shells corresponding to the measured energy levels, here we will try to give an illustrative geometric interpretation using the new model.

According to the model described, the nucleus is considered to consist of protons, which are held together by delocalized electrons detached from neutrons (along with gravitational attraction, of course). The resulting electron density value is 0.5 for (Z = N), while for (Z < N) nuclei this value ranges from 0.5 to 0.61. According to the above, there is no need to distinguish between protons and neutrons in terms of the geometric arrangement of nucleons, *i.e.* their space filling.

In parallel with geometric aspects, it is worth monitoring the binding energy of the nuclei. For ease of comparison, the well-known binding energy values measured on each nucleus are quoted in **Figure 4**.

The binding energy of the nuclei increases with decreasing the surface/volume ratio, which is minimal for spherical shapes.

In the case of 4 nucleons, *i.e.* He^4, the tetrahedron arrangement is the closest approximation to the spherical shape. In the He^4 nucleus, protons are located at the corners of a tetrahedron and are held together by two electrons separated from the two neutrons. This is reflected in the value of the high binding energy (see **Figure 4**).

Studying the evolution of binding energies, it is understandable that He^4, which has greater symmetry, has a much higher binding energy than deuteron.

It is also understandable that the binding energy of H^3 and He^3 nuclei containing 3 nucleons falls between the previous two, but is surprising, how close their binding energy values are, whereas He^3 contains two repulsive protons, whereas H^3 contains only one. Of course, H^3 has the higher binding energy, but the difference is very small, which draws attention to the fact that geometric arrangement (symmetries) plays a very important role in the stability of nuclei too. The two nuclei have the same symmetry, the number of which lies between deuteron and helium.

Continuing the line; additional nucleons to the He^4 nucleus reduces its symmetry, which is reflected in a decrease in binding energy, even though the stability of these nuclei can only be compensated by the incorporation of excess neutrons, *i.e.* by an increased average electron density. These are the Li, Be, and B nuclei, where the proton number does not match the neutron number.

Further increasing the number of nucleons, see C^{12}, O^{16}, we again arrive at a nearly spherically symmetrical arrangement, which is reflected in the increase in energy values, and there is no need to incorporate excess neutrons, *i.e.* increase the ideal average electron density of 0.5 for one nucleon. The 12 nucleons of nucleus C can be arranged in an icosahedral format approximating spherical surface, so their binding energy is higher than that of the previous nuclei and contains no excess neutrons.

In order to learn more about the type of bond that holds protons and electrons together, the coordination numbers of nuclei containing 16 nucleons were compared with those of different crystal structures.

It has been found that the very stable O nucleus with 16 nucleons has the same coordination number as a diamond made of tetrahedrons, where each carbon atom is part of another tetrahedron see Figure 5. In the O^{16} nucleus, three others are closest to an arbitrarily selected nucleon at the same distance, corresponding to the tetrahedral arrangement of He^4 nucleons. This can be synchronized with the cluster model's idea that the nucleus is made up of tetrahedral clusters of He^4 alpha particle. This correspondence shows that there is indeed a covalent bond within the nucleus core, *i.e.* it is molecular-like, but its excitations can be described using the shell model.

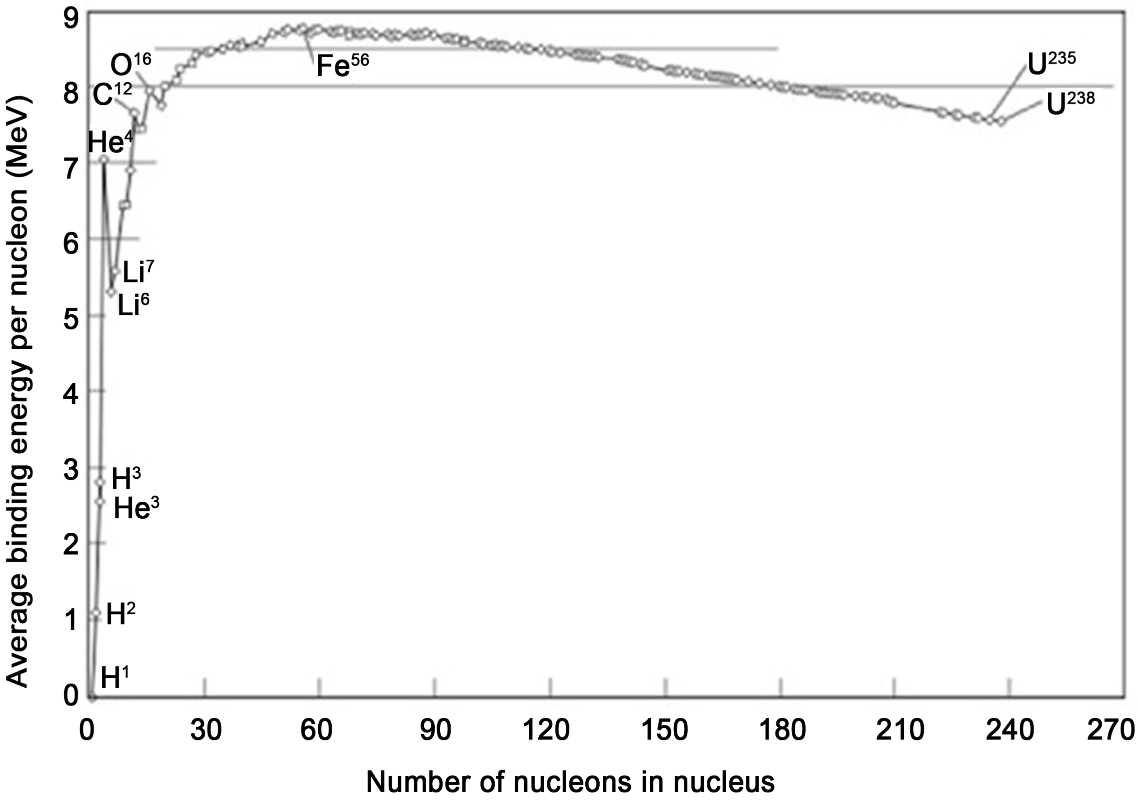


Figure 4. **Binding energy of nuclei as a function of mass number [Wikipedia].**

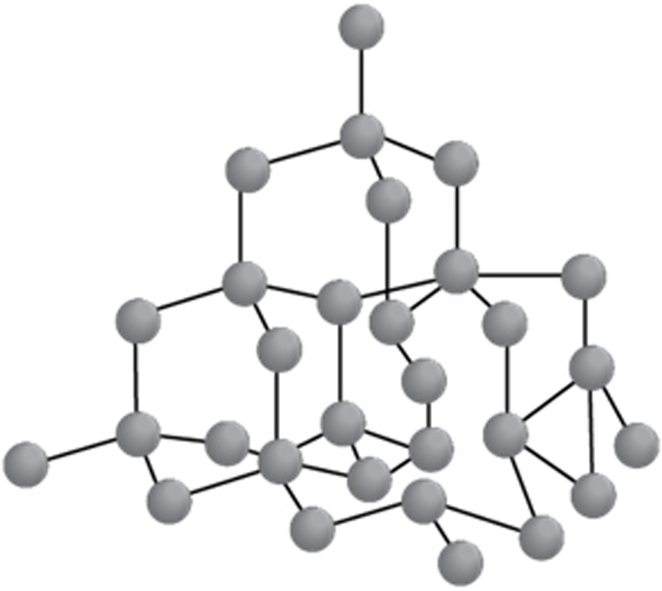


Figure 5. **Diamond structure.**

6. CONCLUSION

- Based on the new model of protons and neutrons, the binding forces holding nuclei together can be interpreted. Nuclei consist of protons held together by delocalized electrons stripped from neutrons.
- The ideal electron density is 0.5/nucleon, but for large nuclei with excess neutrons, this value reaches 0.61/nucleon in order to retain protons located on the increased surface area. The electron density increases on the surface of the nucleus, creating a nearly neutrally charged layer called neutron skin.
- The incorporation of excess neutrons is necessary even in the case of small nuclei, if the shape of the nucleus is very different from the spherical shape, because in this case only the increased average electron density can ensure the stability of the nucleus.
- The spatial arrangement of nucleons plays a very important role in the stability of nuclei, which is reflected in binding energy values.
- Due to the analysis of bond types formed in the nucleus, it has been compared the coordination numbers of the magic number of nuclei with those of known crystal structures, and they can be correlated with those of diamonds made up of tetrahedrons.
- The nucleus is considered to consist of molecule-like, tetrahedral He alpha clusters. Structural changes in the electron shell of alpha clusters during excitations can be discussed using the shell model.

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CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

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