A Physical Model for Atoms and Nuclei—Part 2*

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Abstract. A physical Geometrical Packing Model for the structure of the atom is developed based on the physical toroidal ring model of elementary particles proposed by Bergman [1]. From the *physical* characteristics of real electrons from experiments by Compton [2, 3, 4] this work derives, using combinatorial geometry, the number of electrons that will pack into the various physical shells about the nucleus in agreement with the observed structure of the **Periodic Table of the Elements.**

The constraints used in the combinatorial geometry derivation are based upon Joseph's simple but fundamental ring dipole magnet experiments and spherical symmetry. From a magnetic basis the model explains the physical origin of the valence electrons for chemical binding and the reason why the periodic table has only seven periods.

The same Geometrical Packing Model is extended to describe the physical geometrical packing of protons and neutrons in the physical shells of the nucleus. It accurately predicts the nuclear "magic numbers" indicative of nuclear shell structure as well as suggesting the physical origin of the nuclide spin and the liquid-drop features of nuclides.

New Model of the Nucleus

In the first part of this paper a new model of the atom, based on ring electrons, was presented in terms of physical geometrical packing under the constraints of spherical symmetry and some experimental results for ring dipole magnets. Due to the success of this model over competing models, such as the Quantum Model, it seems only natural to attempt to apply it to the packing of nucleons in the nucleus. Bergman's Spinning Charged Ring Model for elementary particles indicates that the structure of the proton is also a toroid like that of the electron, except that it has a much smaller radius in free space and the charge is of opposite sign.

According to traditional physics, the nucleus contains two types of particles: *protons* and *neutrons*. Outside of the free nucleus, the neutron is unstable and decays into an electron and a proton with a half-life of about 13 minutes. According to Bergman's model, the neutron is not a legitimate elementary particle; rather it is really a bound combination of an electron and proton. Thus, in extending the physical packing model to the nucleus, it will be necessary to take into account the **Z** protons per nuclide, plus the **N** neutrons

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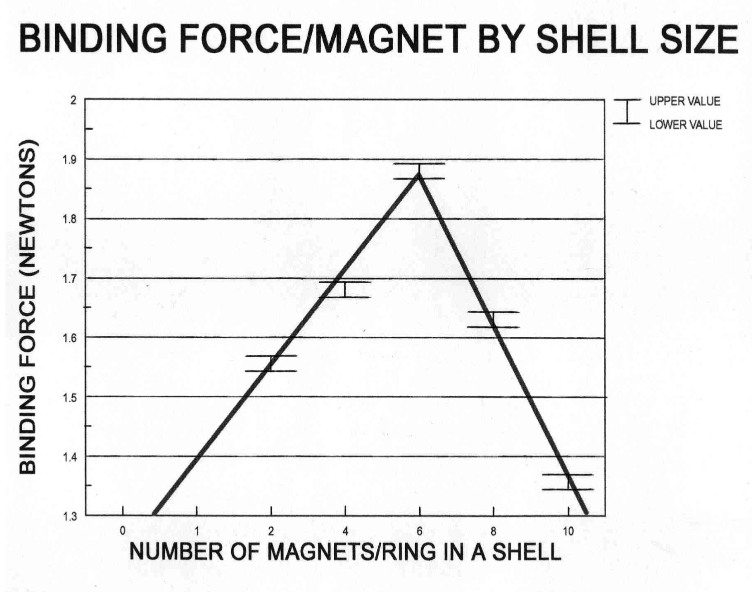
* Most of this paper first appeared IN GALILEAN ELECTRODYNAMICS, Volume 7, Number 1, January/February 1996, and is revised and reprinted by permission.

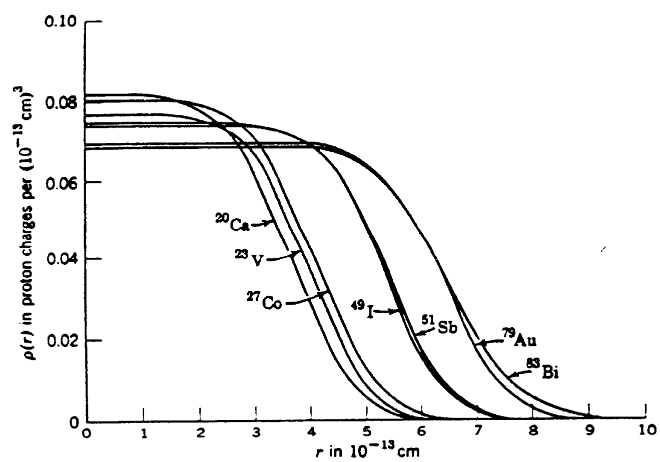
which consist of **N** protons and **N** electrons. One should note that the elastic ring electrons have a much smaller equilibrium size when intimately bound with a proton in a neutron configuration, than when loosely bound to a proton in a hydrogen molecular configuration.



Graph 2

One might expect that the number of protons in each type of *nuclear* packing shell should be exactly the same as for electrons in the *atomic* case. Conversely, one might expect some difference due to the presence of two types of particles in the nucleus and the fact that there is no central charge binding all the nucleons to the center of the nucleus.

If one looks at the nuclear magic numbers 2, 8, 20, 28, 50, 82, 126 (the *sums* of complete shell sizes) which represent the size of the various nuclear shells as seen in many types of periodic nuclear data, one soon realizes that something is different about the nucleus. The packing appears, at first, to be quite different from the atomic magic numbers of 2, 10, 18, 36, 54, 86, 118—the total number of electrons when interior atomic shells are filled. (This is one reason why modern science has a theory for the nucleus that is different and separate from atomic theory.)



Graph 3
Nuclear Density for Various Nuclides [6]

An examination of the experimentally measured nuclear density shapes in Graph 3 gives an important clue as to what is happening. From Graph 3, one sees that the density of nuclides at the center decreases with increasing size or mass of the nucleus. In the atomic case, the electron density at a particular radius always increases with more massive atoms until the shell at that radius is filled. After that the density stays constant at that radius with more massive atoms. The nuclear density data seems to indicate that the proton and neutron shells do not remain in a stable configuration once they are filled and additional nucleons are added to make heavier nuclides. Rather, at some point, the balance of electric and magnetic forces in the nucleus is such that the smaller interior shells rearrange into larger shells that are more strongly bound. Thus, the average nuclear density near the center of the nucleus drops, because the small innermost shells are missing.

This observation has been confirmed by a ring magnet experiment in which the strength of binding of the shell was measured versus shell size (see Graph 2). Using the notion that smaller shells may come apart and rearrange themselves into larger more stable shell configurations, the nuclear magic shell numbers can be explained in terms of the combinatorial geometry packing shells as shown in Table 4.

Table 4. Nuclear Shells

	Combinatorial Geometry Shells									
Total Number of Nucleons	2	2	8	8	18	18	32	32	50	50
2	2									
8			8							
20	2				18					
28	2		8		18					
50					18		32			
82							32		50	
126			8		18	18	32		50	

From Table 4 one sees that the notion of shells rearranging into larger more stable shells, due to the lack of an attracting nuclear center, seems capable of explaining the magic number shell-like features of the nuclides. But what about the nuclides in between the magic number shells?

The nuclides between the magic number nuclides have a number of physical properties which the physical Geometrical Packing Model should explain. One of these properties is the *spin* or *magnetic moment* of the nuclides. Magic number nuclides have no spin or magnetic moment, because they consist of only completed (full) shells which are spherically symmetric. Nuclides with an even number of neutrons and protons also have no net spin.

In the nuclear shell model for which Maria Goeppert Mayer received the Nobel Prize in 1963, [7, 8, 9, 10] the odd unpaired nucleons in shells give rise to the net spin and magnetic moment of the nucleus. The spin of a nucleon is a combination of its intrinsic spin plus its orbital angular momentum (from assumed orbiting motion). The Quantum Nuclear Shell Model is a planetary type model in that the nucleons move in orbits about the center of the nucleus and possess orbital angular momentum about the center of the nucleus. *The orbital model fails to predict correct spins for nuclides in 114 out of 339 cases* in the 44 page version of Table 5 (see the first page of Table 5 at the end of this article.)

In the physical Geometrical Packing Model, the nucleons do not normally orbit about the center of the nucleus. Ampere's Law and Faraday's Law in electrodynamics require that charged nucleons radiate energy continuously if they orbit the nucleus. This radiation would cause the nucleus to collapse and never be stable. *In the Geometrical Packing Model the balance of electric and magnetic forces on the finite-size charged electrons and proton rings in the nucleus causes them to come to a balanced equilibrium position some distance from the center of the nucleus without having to orbit the center of the nucleus.* The spin of a nuclide is assumed to be due to the odd, unpaired nucleons in the partially filled shells. Using the rule that odd numbers of neutrons and/or protons in a shell link together like ring dipole magnets in a line to form the nuclear spin or magnetic moment by merely adding their intrinsic nucleon spins or moments together allows the spin of all known nuclides (stable or unstable) to be predicted (see the first page of Table 5 at the end of this article).

In order to complete the shell structure for all the nuclides that have been observed, the balance of electric and magnetic forces in the shells must be taken into account. The mathematics for handling large numbers of toroidal rings spatially distributed and allowed to deform is very complicated, so this was done systematically in a crude way through a series of assumed rules obtained by an analysis of nuclide data as follows:

Rule 1. Inside the nucleus, neutrons polarize into electrons and protons which participate in the formation of packing shells.

Rule 2. Neutrons cause protons to be more tightly bound in packing shells by forming a triplet of shells*, i.e.* p-e-p, with an electron shell in the middle binding the proton shells by Coulomb attraction.

Rule 3. Due to the binding effect of the neutrons, shells of 50 protons are now bound, whereas atomic shells of 50 electrons are not.

Rule 4. Most stable nuclides have protons only in the outermost shells.

Rule 5. The balance of electric and magnetic forces in the nucleus causes the innermost shells of nucleons to break up to form larger, more stable shells.

Rule 6. The balance of electric and magnetic forces in the nucleus causes the nucleons to rearrange to form a minimum number of shells.

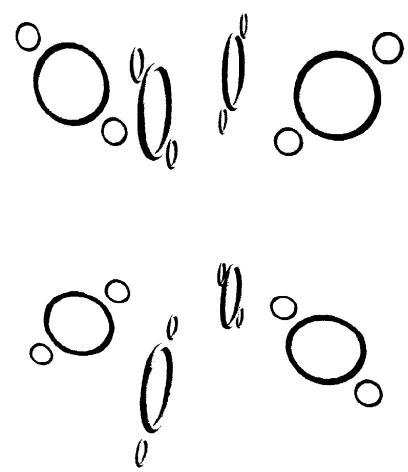


Figure 8
Arrangement of O_{16} Nucleus

Rule 7. When there are an odd number of neutrons and/or protons in a shell, the magnetic fields or spins of the odd nucleons add.

Rule 8. The number of neutrons and protons in a partially filled shell cannot differ by more than 25 percent.

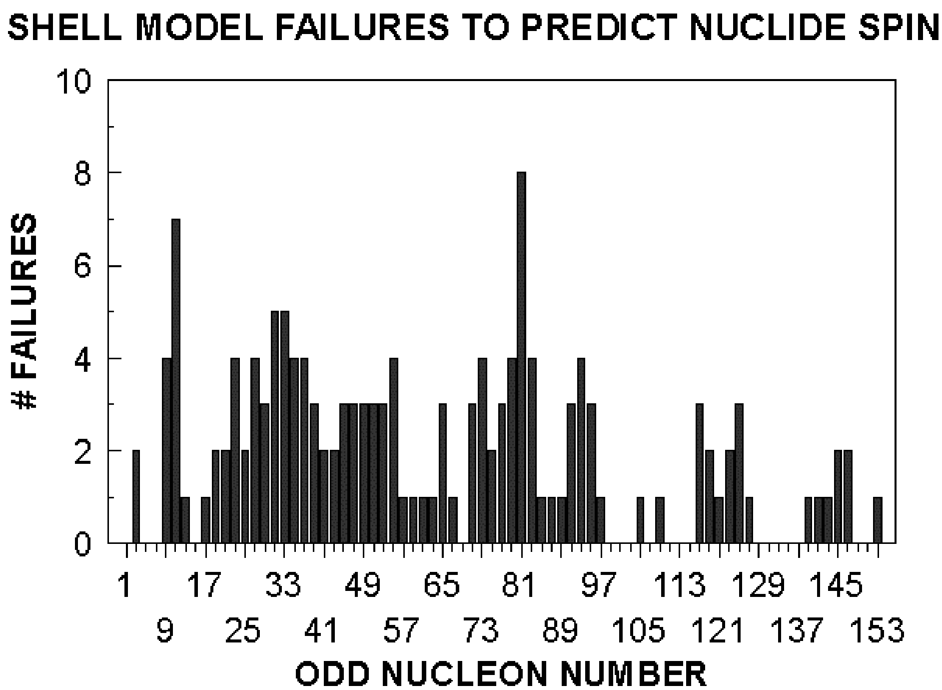
Rule 9. The number of neutrons and protons in a shell cannot exceed the shell's maximum number for each.

Rule 10. When the number of neutrons and protons must differ by two or more in a shell, the difference occurs in the most weakly bound shells first.

Rule 11. When one shell can be partially filled, or a second more strongly bound shell completely filled and the first shell partially filled, the latter occurs.

Rule 12. Two shells will combine to form a larger shell when they can populate at least 75 percent of the shell.

Table 5 shows how these very reasonable rules work out for some of the observed stable



Graph 4
Number of nuclear shell model failures to predict nuclide spin by nucleon number

and unstable nuclides. (The entire 44 page table is available from the authors.) Figure 8 illustrates the arrangement of electrons and protons in the nucleus of the oxygen O_{16} atom. One filled shell of eight electrons is surrounded by two shells of protons, forming a proton-electron triplet. The eight large rings represent electrons, and the sixteen small rings represent protons, although no attempt has been made to show the ring diameters in scale. The electron could be the same size as the proton in the nucleus due to its elasticity.

Note that the Geometrical Packing Model approach is more successful than the Quantum Nuclear Shell Model. The full 44 page version of Table 5 reveals that quantum models are unable to predict the correct spin for two-thirds of the odd **N** and/or **Z** nuclides, indicating serious deficiencies in the Quantum Nuclear Shell Model. Graph 4 shows the failures of the Quantum Nuclear Shell Model by **N** and **Z**. Note that the quantum model is best close to magic number shells.

Liquid Drop Properties of the Nucleus

There are some nuclear properties, such as the binding energy per nucleon and certain nuclear properties such as spontaneous nuclear fission, that the Quantum Nuclear Shell Model has been unable to adequately describe. However, these things can be satisfactorily described by the Liquid Drop Model of the nucleus. The Quantum Nuclear Shell Model and the Liquid Drop Model are incompatible in that the surface of the nucleus in shell models should not act like a liquid surface. In the Geometrical Packing Model, however, there is a physical basis for the Liquid Drop Model. This can be seen from Figures 9, 10, 11 and 12. For these figures, the structure of the spherical shells has been symbolically represented by a slice cross section through the center of the nucleus such that each spherical shell shows up as a circle or ring. Each proton shell is shown explicitly. Each neutron shell is depicted as an electron shell plus a proton shell, *i.e.* the neutrons polarize in such a way that the neutron shell appears to be an electron shell plus a proton shell.

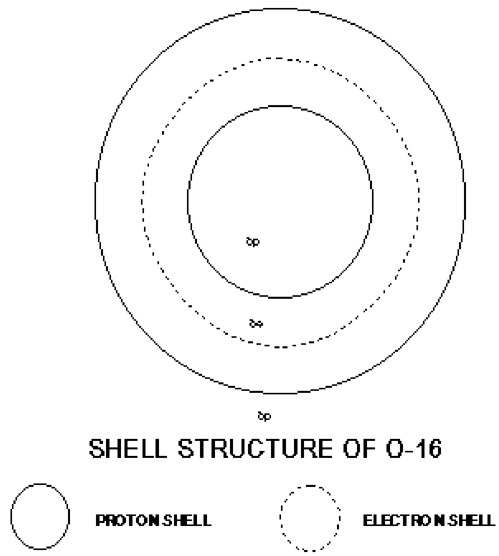


Figure 9

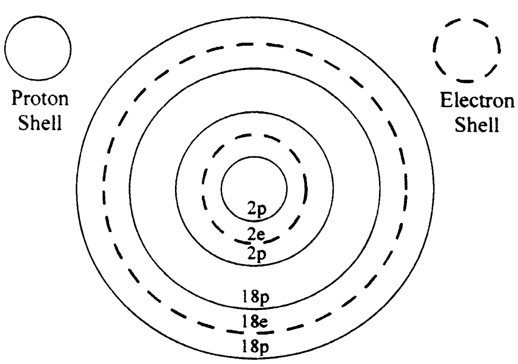


Figure 10
Shell Structure of CA-40

Note that in each of Figures 9, 10, 11 and 12 that in the innermost part of the nucleus, electron and proton shells alternate as one proceeds from the center of the nucleus outward. This alternating sandwich effect keeps them tightly bound together. However, at three shells in from the outermost shell, there are always two proton shells in a row for the larger nuclides. This causes the last three alternating sandwich of bound shells to be repulsed by the inner nucleus. Thus, they are only weakly bound to the inner nucleus.

This weak binding allows the outermost triplet of shells to have liquid-like properties and forms the proper justification for a Liquid Drop Model of the nucleus. Such an effect does not exist in quantum shell models of the nucleus, because they are based on a central force potential instead of allowing a dynamic rearrangement of shells to minimize the binding energy of the nucleus.

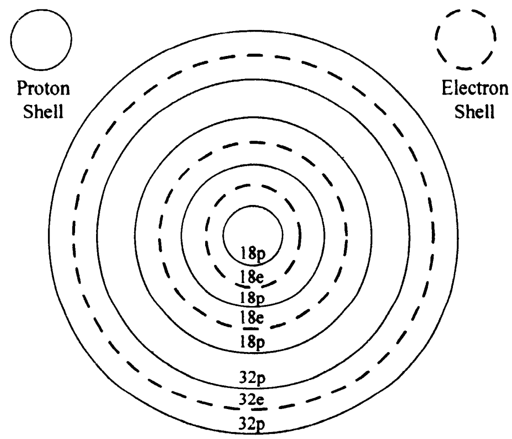


Figure 11
Shell Structure of Sn-118

Another quantity the physical Geometrical Packing Model should be able to predict is the mass of each nuclide (stable or unstable) or an equivalent quantity known as the binding energy **W** per nucleon **A**, *i.e.*, **W/A**. The Liquid Drop Model of the nucleus has been the most successful of all previous nuclear models in predicting the binding energy per nucleon using the semi-empirical mass formula with each term determined by least-square fitting to the nuclide data. However, the semi-empirical mass formula of the Liquid Drop Model that is used in the least-square fitting is ill-conditioned, making the results obtained from least-square fitting a function of the initial guess for each of the parameters in the formula. This is indicative of a formula whose terms do not uniquely describe the binding of the nucleons. One set of initial guesses for the parameters in the semi-empirical mass formula leads to a good fit of the light nuclei. Another set of initial guesses leads to a good fit of the heavy nuclei. However, no set of initial guesses for the least-square analysis leads to a good fit of both light and heavy nuclei.

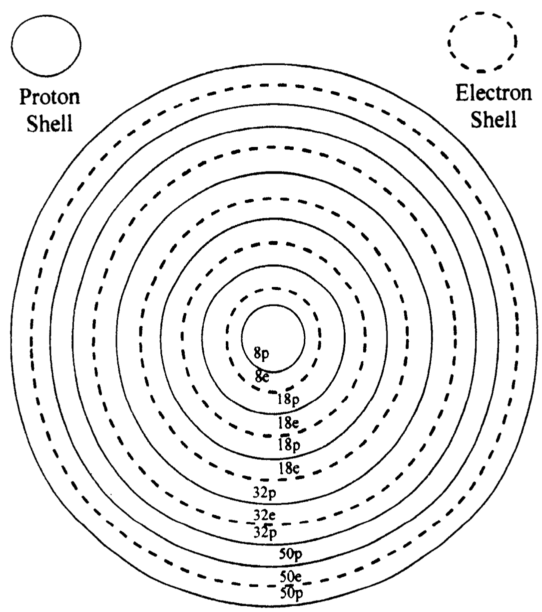


Figure 12
Shell Structure of Pb-208

In the Geometrical Packing Model, a somewhat different formula is used for the binding energy per nucleon (**W/A**). The terms represent similar effects, but the terms are dependent on the physical shell structures as shown below and are not ill-conditioned.

$$\mathbf{W/A = K_1}$$

$$\mathbf{-K_2\,(\#\ Neutrons + \#\ Protons\ in\ outermost\ shell)\ /\ A}$$

$$\mathbf{-K_3\,Z\,(Z-1)\,A^{-4/3}}$$

$$\mathbf{-K_4\,(\#\ paired\ Neutrons - \#\ paired\ Protons)^2\ /\ A}$$

$-K_5$ (# unpaired Protons + # unpaired Neutrons) / A

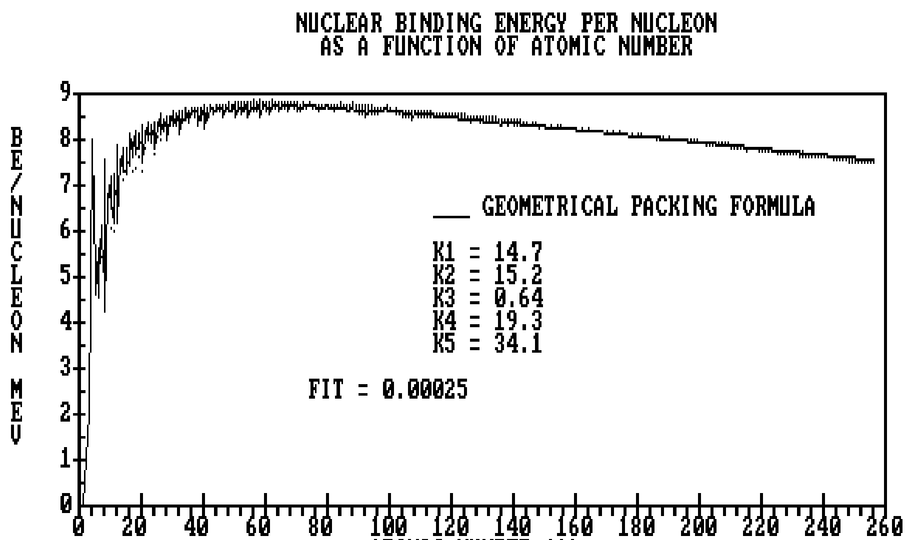
The first term, K_1, represents a constant energy density for nuclear binding. From the assumption of constant energy density within the nucleus, the Geometrical Packing Model has the same first term as the semi-empirical mass formula with all the other terms being of opposite sign and corrections to this assumption.

The second term takes into account the effect of the surface in reducing the binding energy. In the Geometrical Packing Model, the exact count of the number of neutrons and protons in the outermost shell is used, instead of an approximation to that number.

The third term corrects for the effect of Coulomb repulsion of protons on the binding energy. This is the same as in the Liquid Drop Model.

The fourth term represents the magnetic tendency to have equal numbers of proton and neutron magnets paired in the nucleus as a whole. This term is proportional to the actual difference between the number of paired neutrons and protons, instead of an approximation to that number employed by the Liquid Drop Model.

The last term takes into account the odd number of neutron and/or protons in a shell that are not paired up. These values were taken from the complete version of Table 5.



Graph 5
Nuclear Binding Energy per Nucleon

Graph 5 shows an excellent least-square fit of the formula to all known stable and unstable nuclide binding energies. The Geometrical Packing Model is able to predict the binding energy per nucleon to four significant figures for the average nuclide. This is better than the Liquid Drop Model which can only fit well either the light stable nuclei or the heavy stable nuclei [11]. The Geometrical Packing Model can fit both light and heavy stable nuclei simultaneously as well as the unstable nuclei with one set of parameters.

Summary

A simple physical Geometrical Packing Model has been presented to describe the packing of electrons about the nucleus in layers or shells as well as the packing of neutrons and protons in the nucleus itself. An example of this packing scheme is shown in Figure 13 for the Ne_{20} atom. The arrangement of electrons for the neon atom was determined by hanging ten ring dipole magnets by strings in the symmetrical pattern of the appropriate shells. Of all the possible configurations the one that experimentally achieves stability is shown in Figure 13. This configuration minimizes the sum of magnetic moments for each shell and achieves symmetry by locating the electrons of each shell on a great circle.

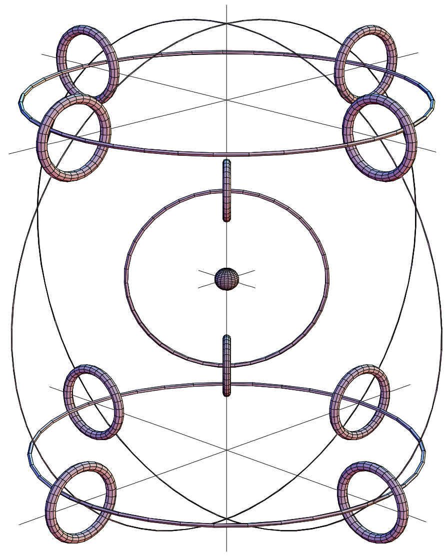


Figure 13
Approximate Arrangement of Ne_{20} Atom

The packing model is completely electromagnetic in origin. It is based upon the 1917 experiments of Compton [2, 3, 4] in which he showed that the size and shape of the electron could be determined by analysis of hard X-ray and gamma ray scattering to be thin flexible rings of charge. One of Compton's last graduate students, Winston Bostick, proposed in 1966 [12, 13] that the closed string or fiber of charge that makes up the electron has the configuration of a helical spring that is connected end-to-end to form a deformable ring or toroid. The size and structure of the neutron and proton is based upon the electron scattering experiments of Nobel Laureate Robert Hofstadter [14]. The shape and structure of the packing shells comes from our ring magnet experiments and the work of David Bergman [1].

This new Geometrical Packing Model for the atom does *not* incorporate the objectionable assumptions of Quantum Mechanics for the atom that (1) electrons move in orbits about the nucleus with definite angular momentum, (2) electrons are point-like particles with no size or structure, and (3) electron orbits with no angular momentum are in stable mechanical equilibrium with the nucleus with no known physical basis. The first assumption violates Ampere's Law and Faraday's Law in electrodynamics which require that electrons in orbit about the nucleus must radiate energy continuously. The second assumption is false, because it disagrees with the experiments of Compton, Bostick, and Hofstadter and it requires an infinite density concentration of energy. The third assumption violates mechanical conditions for stability.

The new physical packing model successfully predicts all the known properties of the Periodic Table of the Elements, including the reason why there are only seven periods due to the geometrical properties of the nucleons' magnetic fields. The quantum models cannot show why there are only seven periods.

The new packing model explains the physical origin of the structure of nuclear shells in agreement with the observed charge density of nuclides. The Quantum Nuclear Shell Model l, which is based upon a central force potential, cannot explain the observed decrease of central nuclide density with increasing number of nucleons.

The new model explains the physical origin of nuclear spin in agreement with practically all observed nuclei, whether stable or unstable (of the 339 nuclei listed in the full version of Table 5, even Hg-204 was correctly predicted—although the reported datum was in error). Quantum Nuclear Shell Models cannot do this with so few assumptions.

The Geometrical Packing Model gives a physical basis for why the outer surface of the nucleus has liquid-like properties. Thus, the Liquid Drop Model of the nucleus is physically compatible with the Geometrical Packing Model, but not with any quantum shell model of the nucleus based upon a central force potential.

The Geometrical Packing Model is capable of improving upon the Liquid Drop Model of the nucleus in that it gives rise to a better defined semi-empirical mass formula that is not ill-conditioned for least-square fitting. This allows the least-square fitting process to produce a better fit to the nuclear binding energy per nucleon over the entire range of nuclides.

Conclusions

The Geometrical Packing Model presented for the atom and nucleus is very successful in describing some atomic and nuclear data. The approach taken is more fundamental and straightforward than the methods used by Quantum Mechanics. The new model does not incorporate any of the objectionable assumptions of Quantum Mechanics and replaces those features of the quantum models that are known to be inconsistent or in violation of proven laws. Unlike the quantum models, the Geometrical Packing Model for ring particles is not simply mathematical, but it is a physical model with boundaries, sizes and detailed structure. Thus it satisfies one of the major goals of physics which is to physically describe the matter of the physical universe.

Although the framework of a new theory of matter has been presented, the basic approach needs to be extended to give successful descriptions of blackbody radiation, the photoelectric effect, and the energy levels of the atom giving rise to absorption and emission spectra before it can more fully qualify to displace the quantum models[15]. Also, the Geometrical Packing Model needs to be extended to develop a new, comprehensive theory of elementary particles that can displace the Standard Model of Elementary Particles, the Supersymmetric String Model, and Quantum Mechanics on all size scales. This work is currently under way and promises to be just as successful as the Geometrical Packing Model.

References

1. Bergman, D. L. and Wesley, J. P., "Spinning Charged Ring Model of Electron Yielding Anomalous Magnetic Moment," **Galilean Electrodynamics**, Vol. 1, No. 5, pp. 63-67 (Sept/Oct 1990).
2. Compton, Arthur H., American Physical Society address December 1917, **Physical Review Series II**, p. 330 (1918).
3. Compton, Arthur H., **Physical Review Series II**, Vol. XIV, No. 1, pp. 20-43 (1919).
4. Compton, Arthur H**., Physical Review Series II,** Vol. XIV, No. 3, pp. 247-259 (1919).
5. Lucas, J., and Lucas, Jr., C. W., "A Physical Model for Atoms and Nuclei—Part 1," Foundations of Science, Vol. 5, No. 1 (May 2002).
6. Eisberg, R. M., **Fundamentals of Modern Physics**, John Wiley & Sons, Inc., New York & London, p. 571 (1961); Hofstadter, R. **Annual Review of Nuclear Science**, Vol. 7, Annual Reviews, Stanford (1957).
7. Mayer, M. G., **Physical Review**, Vol. 74, p. 235 (1948).
8. Mayer, M. G., **Physical Review**, Vol. 75, p. 1969 (1949).
9. Mayer, M. G., **Physical Review,** Vol. 78, pp.
10. Mayer, M. G., and Jensen, J. H. D., **Elementary Theory of Nuclear Shell Structure**, John Wiley & Sons, New York (1955).
11. Howard, Robert A., **Nuclear Physics**, Wadsworth Publishing Co., Belmont, CA (1963) pp. 304-313.
12. Bostick, Winston H., **Physics of Fluids**, Vol. 9, p. 2079 (1966).
13. Bostick, Winston H., "Mass, Charge and Current: The Essence and Morphology," **Physics Essays**, Vol. 4, No. 1, pp. 45-49 (1991).
14. Hofstadter, R., **Reviews of Modern Physics**, Vol. 28, p. 213 (1956).
15. Please note that this work has already been successfully completed in the author's 1994-1995 science fair project "A New Classical Basis for Quantum Physics" which was awarded a Grand Prize at the 1995 International Science and Engineering Fair in Hamilton, Ontario, Canada.
16. Lide, D. R., editor, **CRC Handbook of Chemistry and Physics, 73rd Edition**, CRC Press, Ann Arbor (1993).

TABLE 5

TABLE OF NUCLIDE DATA [16]

ATOMIC SYMBOL	A	Z	P1	N1	P2	N2	P3	N3	P4	N4	P5	N5	P6	N6	P7	N7	P8	N8	ACTUAL MEASURED SPIN	RING MODEL SPIN	SHELL MODEL SPIN	HALF-LIFE	ABUNDANCE
n	1	0	0	1															1/2	1/2	1/2	13. m	0.000
H	1	1	1																1/2	1/2	1/2		99.985
H	2	1	1	1															1	1,0	1,0		0.015
H	3	1	1	2															1/2	1/2	1/2	12.26 y	0.000
H	4	1	1	3															2	2,1	2,1		0.000
He	3	2	2	1															1/2	1/2	1/2		0.000
He	4	2	2	2															0	0	0		100.000
He	5	2	2			3													3/2	3/2	3/2		0.000
He	6	2	2			4													0	0	0		0.000
He	10	2	2			8													0	0	0		0.000
He	7	2	2	2		3													(3/2)	3/2	3/2		0.000
He	8	2	2			6													0	0	0		0.000
He	9	2	2	1		6													(1/2)	1/2	5/2		0.000
Li	4	3		1	3														2	2,1	2,1		0.000
Li	5	3		2	3														3/2	3/2	3/2		0.000
Li	6	3	2	2	1	1													1	1,0	3,0		7.500
Li	7	3			3	4													3/2	3/2	3/2		0.000
Li	8	3	2	2	1	3													2	2,1	3,0		0.000
Li	9	3		2	3	4													3/2	3/2	3/2		0.000
Li	10	3		2	3	5													?	4,1	4,1		0.000
Li	11	3			3	8													3/2	3/2	3/2		0.000
Be	6	4	2	2	2														0	0	0		0.000
Be	7	4	2		2	3													3/2	3/2	3/2		0.000
Be	8	4	2	2	2	2													0	0	0		0.000
Be	9	4	2	2	2	3													3/2	3/2	3/2		100.000
Be	10	4	2	2	2	4													0	0	0		0.000
Be	11	4		1	4	6													1/2	1/2	1/2	13.7 s	0.000
Be	12	4		2	4	6													0	0	0		0.000
Be	13	4			4	4		5											(5/2)	5/2	5/2		0.000
Be	13	4		1	4	8													(1/2)	1/2	1/2		0.000
Be	14	4	2	2	2	2		6											0	0	0		0.000
B	7	5	2	2	3														(3/2)	3/2	1/2		0.000
B	8	5	2	2	3	1													2	2,1	2,1		0.000
B	9	5	2	2	3	2													3/2	3/2	3/2		0.000
B	10	5	2	2	3	3													3	3,0	3,0		18.700
B	11	5	2	2	3	4													3/2	3/2	3/2		81.300
B	12	5	1	1	4	6													1	1,0	2,1		0.000
B	13	5	2	2		2	3	4											3/2	3/2	3/2		0.000
B	14	5			1	3	4	6											2	2,1	4,1		0.000
B	15	5	2	2	3	8													?	3/2	3/2		0.000
B	16	5	2		3	3		8											0	3,0	4,1		0.000
B	17	5	2		3	4		8											(3/2)	3/2	3/2		0.000
B	18	5	2		3	5		8											?	4,1	4,1		0.000
B	19	5	2	2	3	4		8											?	3/2	3/2		0.000
C	8	6	2		4	2													0	0	0		0.000
C	9	6	2		4	3													(3/2)	3/2	3/2		0.000
C	10	6	2		4	4													0	0	0		0.000

Notes for Table 5:

1. The complete 44 page table is available from the authors for $3.00 postage and handling in U.S.
2. **Z** is the number of protons per nuclide. **N** is the number of neutrons per nuclide. **A = Z + N** is the nuclide's atomic number.
3. **P1, P2**, *etc*., give the number of protons in that nuclear shell.
4. **N1, N2**, *etc*., give the number of neutrons in that nuclear shell. (Each neutron shell consists of one proton and one electron shell.)
5. **Actual Measured Spin** is the experimentally measured nuclide spin. A parenthesis around the spin value means that the spin is inferred but not actually measured.
6. **Half-life** gives time in seconds (s), minutes (m), hours (h), days (d) or years (y).
7. **Abundance** gives the relative abundance of the nuclide for the element.