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The Nuclear World: The Kernel of Matter

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Instead of an attic with a few test tubes, bits of wire and odds and ends, the attack on the atomic nucleus has required the development and construction of great instruments on an engineering scale. – Ernest Lawrence

The Atomic Nucleus and its Constituents: *Visions need revisions in science.*

When Dalton dubbed the smallest units of chemical matter as *atoms*, little did he realize that he was perpetrating an etymological error. For, the word atom, we remember, means that which cannot be cut further. Like the ancients, Dalton pictured the basic bricks of matter to be unbreakably hard ultimate entities, tiny beyond direct detection and rigid beyond cleavage.

For a whole century this picture of matter at the lowest level served well the cause of physics and chemistry. On its basis could be understood and explained chemical reactions and the laws of combining gases. Even the phenomena of heat and temperature could be well described in terms of the motional energy of rigid billiard-balls-like tiny atoms.

But as new generations of scientists kept probing more and more into the deep recesses of matter with ingenious experiments, insightful concepts, and intelligent interpretations of what was observed, it became clear (as we have seen earlier) that ultimately atoms are empty, consisting of insubstantial electrons whizzing around tiny cores called nuclei.

Like the sturdy seed at the heart of a mango, the atomic *nucleus* sits smack in the center of every atom[1]. It is the atom's core. The size of an atomic nucleus is of the order of a few femtometres (10^{-15} m).

Nuclear Numbers: *Every atomic nucleus is determined by three simple numbers.*

The total number of nuclear particles or nucleons (protons and neutrons) in an atomic nucleus is known as its *mass number*; it is represented by the letter A. The number of protons in the nucleus is called its *atomic number*; it is represented by Z. The number of neutrons in the nucleus is its *neutron number*; it is denoted by N. If X is the chemical symbol for an element, then by convention its nucleus is indicated by the symbol $^{Z}X_{A}$. Thus for example the symbols

1 The word *nucleus* means *little nut* in Latin.

for the helium and the oxygen nuclei are $_2He^4$ and $_8O^{16}$ respectively[2].

Consider the nucleus of the carbon atom. It contains 6 protons and 6 neutrons. Could there be a carbon nucleus with more or less protons? Of course not, because any change in the number of protons in the nucleus would make it the nucleus of a different element. However, a carbon nucleus can have a different number of neutrons, say 7 or 8. In other words, there are carbon nuclei with mass numbers 13 and 14 also. They have symbols, $_6C^{13}$ and $_6C^{14}$. All the three types of carbon nuclei are known as *isotopes* of carbon. The name literally means *same place* (in the Periodic Table). Isotopes are nuclei with the same atomic number but different mass numbers. They have found numerous practical applications in medicine and in industry. Isotopes are also indicated by the abbreviation for the element followed by their mass number. Thus, for example, $_2He^3$ and $_2He^4$ would be He-3 and He-4; $_{92}U^{235}$ and $_{96}U^{238}$ would be simply U-235 and U-238.

Now consider the two nuclei $_8O^{15}$ and $_7N^{15}$. These differ in their atomic numbers, hence belong to different elements. But they have the same mass numbers. Such nuclei are called *isobars*: Literally, *same heaviness*.

It may be mentioned in passing that soon after the discovery of the neutron in 1932 some astrophysicists suspected from theoretical considerations that there could be stars made up purely of neutrons. A few decades later this was firmly established, so that today we talk about neutron stars: degenerate states of some stars wherein incredibly large masses (1 to 2 solar masses) are compressed into balls with a diameter of about ten kilometers. These are celestial bodies of unimaginable densities[3]. Nowhere else does gravitation act so powerfully on nuclear entities.

This change in the picture of the atom is just one example of the running refrain in science: No picture of perceived reality is perfect and permanent. Its power and value lies in how well it accounts for the currently known aspects of the world, and not on the prestige of authorities or the sanctity of the works, much less on the sacredness associated with ancestral thinkers.

Radioactivity: *Inert matter can spill out invisible radiation.*

In the last decade of the nineteenth century (1896), Henri Becquerel (1852–1908) was studying the phenomenon of fluorescence in which some substances exposed to ultraviolet light re-radiate the same as visible light. In the course of his studies he discovered that the salt uranyl sulfate, even when completely covered with photographic film in a pitch dark paper, affected the film when not kept in sunlight. After several repetitions of this experiment Becquerel

[2] These notations which are not fully codified, began to emerge in the literature only in the mid-1930s.

[3] The concept of a neutron star was proposed soon after the discovery of the neutron in 1932. But it was only in the mid-1960s that they were beginning to be discovered in the sky.

realized that uranyl sulfate has the intrinsic property of emitting some kind of hitherto unknown radiation. More experiments revealed that what was emitted was affected by magnetic fields, showing that they are also electrically charged entities[4].

This altogether new phenomenon in which some inert matter incessantly spill out minute entities was given the name *radioactivity* by Marie Curie (1867–1934)[5]. The discovery of radioactivity was a fundamental discovery. There is a difference between an important discovery and a fundamental discovery in science. The former is of great relevance in the explanation of particular phenomena. The latter, beyond that, has major impacts on civilization and even on our philosophical perspectives. Treatment of cancer, estimation of the age of the earth, even politics and history have been affected by the discovery of radioactivity.

In olden times, major philosophies, religious doctrines and God symbols significantly influenced (as they still do) the thoughts and behavior of people at large. In the modern world, lifestyle and longevity, comfort levels and employment possibilities of peoples and nations are affected by scientific knowledge and technology. The economic development of nations resulting in the improved standard of living and longevity of its people would be impossible without modern science and technology.

Radioactive Emanations: ***The emissions from radioactive materials are of various kinds***.

Careful studies of the entities given out from the radioactive nuclei have shown that there are, in fact, four distinct types of radioactivity. That is to say, four different kinds of entities are given out from radioactive nuclei. These are:

(a) *Alpha particles* (α). These are very stable (i.e., not easily breakable) entities consisting of two protons and two neutrons. They are simply nuclei of helium[6]. They may also be represented as $_2He^4$ or as $_2\alpha^4$.

(b) *Beta particles* (β). These are positive or negative electrons (e^+ or e^-). Note that although the nucleus does not contain electrons, it can eject electrons. How does this happen? The answer lies in the fact that within the nucleus a proton may occasionally become a neutron and a positive electron; or a neutron may become a proton and a negative electron: $p \rightarrow n + e^+$; $n \rightarrow p + e^-$, where p, n, and e stand for proton, neutron, and electron respectively.

4 The story of the discovery of radioactivity illustrates the fact that no major scientific discovery has been or can be made without careful observations and deep insights, and that no single individual can unravel all its intricacies.

5 In this context read the biography of Madame Curie by her daughter Eve Curie (Da Capo Press, 2001). This book should be compulsory reading for all students of physics.

6 Most of the helium we use for a variety of purposes comes from the radioactive decay of elements like uranium. It is often mixed with natural gases, and is distilled from it.

(c) *Gamma rays* (γ). These are very short wavelength (very high frequency) electromagnetic waves. We may look upon them as highly energetic *photons* (bundles of electromagnetic energy). They have great penetrating power, which means that they can go through thick objects that are opaque to ordinary light.

(d) *Neutrinos* (ν). These are almost massless particles. They carry no electric charge. But they do have a property called *spin*. Their existence was predicted on theoretical grounds, and experimentally verified more than two decades later. One of the many ways in which modern science differs from ancient science is that in the former, predictions can be made and the existence of unknown entities can be affirmed from theories. Incredibly large numbers of neutrinos are showering the earth (from the sun and other stars). They go right through the planet as if it was not even there. Some have speculated that one day we may be able to tap the energy of these neutrinos[7].

Half-life: ***Radioactive nuclei are unstable, and their decay-rate can be measured.***

The number of nuclei that decay in a given time interval depends on the number of nuclei in the sample. Thus, suppose that there are 4096 nuclei in a sample of Ra-226. Then in 1620 years 2048 nuclei of this sample would have decayed. Of these 1024 would decay in another 1620 years, 512 in the next 1620 years, and so on. This brings in the notion of *half-life* of a radioactive nucleus as the time it takes for 50% of the nuclei in a sample to decay. It results from the fact that the rate of radioactive decay, like in some other cases, is proportional to the amount of the radioactive material in a sample, and this leads to an exponential decay[8]. Nuclei which are not radioactive are the stable nuclei which constitute much of ordinary matter we see around us. Heavier nuclei tend to be unstable. What this implies is that many elements at the higher end of the Periodic Table have a greater proportion of radioactive isotopes than lighter elements. This also explains why there are not many naturally occurring radioactive elements beyond uranium.

Age of The Earth: ***It is possible to determine the age of our planet and of long-dead organisms.***

The fact that lead is always present in uranium minerals led to the suspicion that this was probably the eventual byproduct of radioactive decay. This knowledge, combined with precise measurements of radioactive samples in rocks, enabled geologists to determine the ages of rocks

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7 For a fascinating account of the history of neutrino see Frank Close, *Neutrino*, Oxford University Press, 2010.

8 In mathematical terms, $dN/dt = -\lambda N$, giving $N = N_o e^{-\lambda t}$. The measurement of the half-life of radioactive elements is a well-developed experimental technique. Today we know the half-lives of all radioactive elements with great precision. This is an intrinsic property of all nuclei.

on earth. Thus, the discovery of the phenomenon of radioactivity enabled us to estimate how old our planet is[9].

Another powerful application of the half-life idea relates to the determination of the age of fossils and of other long-dead organisms. In the earth's atmosphere there is an almost steady proportion of ordinary carbon and its radioactive isotope C-14 whose half-life is 5730 years. This relative proportion is maintained by the steady stream of cosmic rays that impinge on the carbon nuclei in our atmosphere. As long as an organism is alive it takes in carbon from the atmosphere (from carbon dioxide). But when it ceases to live, the C-14 in its body is not replenished, and its proportion is affected by radioactivity. Thus, by measuring the C-14 content in a fossil we can determine when the organism died. This technique is known as radioactive carbon dating[10].

Transmutation: ***It is possible for elements to change their identity.***

Since every element is characterized by the composition of the nucleus, an important consequence of radioactivity is that one element can change to a different element. Thus, for example when the nucleus of an atom of radium ($_{88}Ra^{226}$) emits an alpha particle ($_2\alpha^4$), it loses two protons and two neutrons. This makes it the nucleus of a radon atom whose atomic number is 86 and mass number is 222.

This is an example of *transmutation*, another astounding discovery of twentieth century physics. It is a radical departure from the classical chemical view that it is impossible to change elements. A dogma of post seventeenth century chemistry was that the dream and efforts of alchemists to transmute elements were misguided, unachievable, and nonsensical[11]. Now we know that transmutation does occur in Nature.

Not all naturally occurring elements are radioactive. Only the heavier elements have this propensity. The heavy elements are continually decaying into other elements through radioactivity. The resulting nuclei may also be radioactive. These are thus transmuted to yet other elements. This process continues until one reaches a stable (non-radioactive) nucleus. In this manner there are a series of radioactive elements, each member of the series deriving from another.

9 This recognition is due to Bertram Borden Boltwood (1870–1927), a little remembered American scientist. Biblical chronology once gave the age of the earth to be less than 5000 years, whereas *puranic* cosmology speaks of trillions of years. That some educated people in the modern world still take these figures seriously is among the marvels of human culture.

10 See in this context, Sheridan Bowman, *Interpreting the Past*: *Radiocarbon Dating*, University of California Press, Berkeley, 1990.

11 The goal of alchemists was to transmute lead and copper (base metals) into silver and gold (noble metals).

Physicists and chemists have studied in great detail the various radioactive elements occurring in Nature. They have established that there are three radioactive series in Nature. Their starting points are ${}_{92}U^{238}$, ${}_{92}Th^{232}$, and ${}_{92}U^{235}$. All of them eventually end up as three different isotopes of lead. These naturally occurring radioactive series are known as the uranium series, the thorium series and the actinium (old name for U-235) series.

Artificial transmutation was first brought about by Ernest Rutherford in 1917. While the political arena in Europe was in turmoil with the First World War, Rutherford kept bombarding nitrogen nuclei with alpha particles, and managed to transmute some nitrogen into oxygen.

People who disparage science by saying it has not produced life in the laboratory, has not explained what is human consciousness, etc., generally don't have the faintest idea of the extraordinary breakthroughs in human knowledge achieved by modern scientific discoveries.

Statistical Nature: ***Nuclei decay in a systematically random manner.***

Suppose that we have a thousand radioactive nuclei in a sample and that the half-life for alpha-decay is ten years. This means that in ten years 50 % of the sample (i.e., 500 of the nuclei) would have disintegrated. Now we may ask which particular nuclei would undergo disintegration? The answer is, we cannot tell. In other words, radioactive disintegration is a completely statistical process: the first of its kind in the physical world of which we became aware.

This discovery has had a drastic impact in our understanding of natural phenomena which, until then, had been regarded as being governed by strict deterministic laws and cause-effect relations. We find here intrinsic randomness in a purely physical process which revealed an aspect of the world that was completely hidden from the worldview of classical physics. What is also interesting is that radioactive randomness is quantifiable. This is not unlike the randomness in life expectancy. On the basis of statistical records one can predict how many individuals are likely to die in a given population in the next five years, say; but one cannot predict with certainty who those individuals would be.

Energy Liberation in Radioactivity: ***Radioactivity involves the release of enormous amounts of energy.***

Radioactivity is always accompanied by significant releases of energy. Consider, for example, the alpha decay of a radium nucleus. In the process, the nucleus is transmuted into a radon nucleus. When this happens, 4,800,000 eV of energy is liberated[12]. We may compare this to the energy released when an atom of carbon is oxidized into carbon dioxide as per the formula:

[12] The electron-volt (eV) is a unit of energy generally used in atomic physics. By definition, 1 eV is almost equal to 1.602×10^{-19} J.

$C + O_2 \rightarrow CO_2$. In this chemical reaction some 3 eV of energy is released. The energy carried by a visible photon of light is about 2 eV. The kinetic energy acquired by a water molecule as it falls through a height of 450 feet is only about 0.00025 eV.

Compared to these, the energy release in radioactivity is stupendous. It has been estimated that the energy reserves in the radioactive elements in the earth's crust, if they could be tapped, would be enough to supply human energy needs for the next three billion years, even assuming that our rate of consumption becomes a hundred times its current rate!

A Strong Force: ***There exists in Nature another fundamental force.***

When one considers the constitution of the atomic nucleus one is struck by the fact that the nucleus contains protons which are all positively charged, as well as electrically neutral neutrons, all so close to one another. Remembering Coulomb's law of repulsive force between like electric changes, a force which increases as the separating distance between the charges decreases, one may wonder how protons stick together within nuclei.

To account for this anomaly one theorized the existence of a hitherto unrecognized force in the universe. This force, which came to be called the *strong force* (or *strong interaction*) is as universal as gravitation and electromagnetism. That is to say, it exists in the cosmos as one of its fundamental features. Three things should be noted about the strong force: First, its strength exceeds by far that of either gravitation or electromagnetism; or else the Coulomb force will make the protons fly apart instantaneously. Secondly, the strong force is also the glue that keeps protons and neutrons together in the nucleus, and acts equally strongly between two neutrons. Thirdly, its strength diminishes rapidly with distance. Thus the effect of the strong force is virtually zero between two nuclei in a molecule.

The idea of a nuclear strong interaction was proposed and elaborated by the young Japanese physicist Hideki Yukawa (1907–1981) in 1935[13]. It also followed from his analysis that just as the photon is an intermediary particle responsible for the interaction between electric charges, there must be a similar field particle of considerably greater mass to bring about the strong interaction between nucleons. Such a postulated particle was detected in cosmic ray showers by Carl David Anderson (1905–1991). The mass of these particles was determined to be between that of the electron and the proton. So the name *meson* (particle of middle or intermediary mass) was suggested by Homi Bhabha (1909–1966)[14].

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[13] For more on Yukawa see, N Kemmer, Hideki Yukawa, *Biographical Memoirs of Fellows of the Royal Society*, Vol.29, pp.660–626, 1983.

[14] For more on this, see B V Sreekantan, Homi Bhabha and Cosmic Ray Research in India, *Resonance*, Vol.3, No.7, pp.18–27, 1998.

Nuclear Reactions: ***There are processes which alter the elemental nature of matter and involve vast amounts of energy.***

Radioactivity is an example of nuclear reactions. In chemical reactions molecules interact. In the process they change the compositions of the interacting molecules. Thus, for example, the interaction of oxygen with methane leads to carbon dioxide and water: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.

In a nuclear reaction, nuclei interact, altering their proton content. This means, as we saw earlier, that they transmute the elements involved. When a nucleus of U-238 emits an alpha particle it is transformed into a Th-234 nucleus: ${}_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}\alpha^{4}$. When a deuterium nucleus (which contains a proton and a neutron) is accelerated fast enough and made to collide with the lithium nucleus, the result could be the production of two helium nuclei: ${}_{1}H^{2} + {}_{3}Li^{6} \rightarrow {}_{2}He^{4} + {}_{2}H^{4}$.

All nuclear reactions involve vast amounts of energy. The origin of these incredible amounts of energy is in the mass-energy equivalence, $E = mc^2$. To see this, consider the nucleus of helium. Precise measurements show that its mass[15] is 4.00383 u. The helium nucleus consists of two protons and two neutrons.

Two proton mass	=	2.01519 u
Two neutron mass	=	2.01796 u
Their total mass	=	4.03315 u
Mass of He nucleus	=	4.00383 u

There is a mass difference of (4.03315 u – 4.00383 u =) 0.03034 u between the composite nucleus and the sum of the masses of its components. This difference is called the *mass defect*. The mass defect is in the form of the energy binding the protons and neutrons together in the nucleus. When the component parts are separated, the energy equivalent of the mass defect is released. In other words, in nuclear reactions, the classical principle of conservation of mass does not hold.

Nuclear Fission: ***In one type of artificial nuclear reaction a heavy nucleus is split into two parts with the release of neutrons and much energy.***

Radioactivity is one of the most common types of nuclear reactions. But there are also other types of nuclear reactions. In most cases – especially in artificial nuclear reactions – there is

[15] The u (atomic mass unit), also known as the Dalton, is used in atmomic and nuclear physics. 1 u = $1.660538921(73) \times 10^{-27}$ kg.

generally a target nucleus X and a projectile particle x. When the projectile particle hits the target nucleus, a new nucleus Y is formed and another particle y may be emitted. This is represented symbolically as x(X,Y)y.

In the type of reaction known as nuclear *fission* a heavy nucleus splits into two nuclei of roughly equal masses[16]. This splitting is generally accomplished by neutrons. One way of picturing fission is by considering the target to be a heavy drop of liquid which, on being given a little more material, is unable to sustain itself as a single unit, and breaks up into two roughly equal parts.

Three characteristics of fission make it an interesting and important reaction:

(a) *Great energy release*. When nuclear fission occurs, there is always release of a great amount of energy. Thus, a fission reaction may be represented as, neutron + heavy nucleus $\rightarrow$ fission products + energy.

The energy release arises from the fact that the sum of the masses on the left side is greater than the sum of the masses on the right side. The following is a typical fission reaction:
$n + {}_{92}U^{235} \rightarrow {}_{54}Xe^{140} + 38Sr^{94} + 2n + 200$ MeV (of energy).

(b) *Neutron liberation*. Generally, in fission reactions the fission products include one or more neutrons. In other words, aside from two medium-sized fission products, one or more neutrons emerge as a result of the reaction. In the example above, two neutrons are released.

(c) *Chain reaction possibility*. Because of (b) an interesting possibility arises. If we initiate fission reaction in one nucleus of a sample by using a single neutron, it will produce two or more neutrons. Each of these may, in turn, produce fission of other nuclei. In this manner one can, in principle, bring about the fission of all the nuclei in the sample. This process is known as a *chain reaction*[17].

Nuclear Fusion: ***Enormous amounts of energy are liberated when nuclei fuse to form heavier nuclei.***

As noted earlier, the mass of a helium nucleus is less than the total masses of its constituents. The mass defect is equivalent to some 28 MeV. From this one may calculate how much energy

[16] The idea of nuclear fission was first proposed by Ida Noddack in 1934. Its actual discovery and confirmation are generally attributed to Otto Hahn, Lise Meitner, and Fritz Strassmann.

[17] The utilization of nuclear energy through nuclear reactors began in 1942 in Chicago, USA. Highly developed since then, it is one of the dubious hopes to meet the future energy needs of humanity. But that hope is fading, especially after the tsunami caused Fukushima Daiichi nuclear catastrophe of 2011.

is involved in the formation of, say, half a kilo of helium from protons and neutrons. This is equivalent to the energy liberated on burning 1500 tons of coal. Fission reactions are highly energetic, but fusion reactions are much more so.

Just as we need a match stick to initiate the burning of coal, we need some initial energy to bring about nuclear fusion. It turns out that temperatures of the order of a few billion degrees are required. But even when a sample is at a million degrees Kelvin, some particles in it may possess energies corresponding to a billion degrees. Such temperatures exist in the core of the sun and of other stars[18]. Therefore fusion reactions are constantly occurring there[19].

Different possible fusion reactions occur in stars. One of them is the hydrogen cycle which involves the following series of reactions:

$${}_op^1 + {}_on^1 \to {}_1d^2 \;;\; {}_op^1 + 1d^2 \to {}_1t^3 + e^+ \;;\; {}_1t^3 + {}_2He^3 \to {}_2He^4 + 2{}_op^1.$$

Here p, d, and t represent the proton, deuteron, and triton respectively.

On the basis of the observed energy output of the sun, it has been calculated that within the sun about 2×10^{19} kg of hydrogen are converted into helium each year. This may seem like an enormous quantity on our scale. But the mass of the sun is about 2×10^{30} kg. It will take some five billion years to use up some 5% of this. At that time the sun is expected to become much hotter. Then it will gradually cool down and eventually become inert forever. It is highly unlikely that there will be anybody on our planet to watch this astrophysically predicted anticlimax of our sun.

18 As early as in 1920, more than a decade before the discovery of the neutron, the astrophysicist Arthur Stanley Eddington surmised that stars generate energy from nuclear fusion.

19 Unfortunately, the first fusion reaction on earth occurred in the core of a hydrogen bomb. Peaceful exploitation of fusion energy is still a matter of research.

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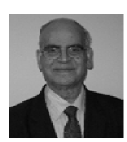
Previous Parts: The World Above: Vol.15, No.10, pp.954–964; No.11, pp.1021–1030, 2010; **The Physical World**: Vol.15, No.12, pp.1132–1141, 2010; Vol.16, No.1, pp.76–87, 2011; **On the Nature of Heat**: Vol.16, No.2, pp.190–199, 2011; **Sound: The Vehicle for Speech and Music**, Vol.16, No.3, pp.278–292, 2011; **Light: The Revealer of Chromatic Splendor**, Vol.16, No.4, pp.359–371, 2011; **More on Light**, Vol.16, No.5, pp.468–479, 2011; **Matter: The Stuff the World is Made of**, Vol.16, No.7, pp.670–681, 2011; **More on Matter**, Vol.16, No.8, pp.784–793, 2011; No.10, pp.987–998, 2011; No.11, pp.1061–1070, 2011; **More on Force**: Vol.17, No.1, pp.83–91; **Waves**: No.2, pp.212–224, 2012; **Sound**: No.3, pp.299–309, 2012; **Electricity: An Underlying Entity in Matter and Life, A Sustaining Principle in Modern Civilization**, Vol.17, No.4, pp.393–405, 2012; **Magnetism**: No.5, pp.512–522, 2012; **Atoms and Molecules: Beneath the Tangible World**: No.6, pp.604–615.



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