THE FORMATION OF "SOLID DEUTERIUM" SOLIDIFIED INSIDE CRYSTAL LATTICE AND INTENSE SOLID-STATE NUCLEAR FUSION ("COLD FUSION") *

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The term of "nano-particles" is very much well-known even to the general public.

Recently, studies of "nano-particles" in the world have been considered as national projects in the academic or the industrial world like a "miracle ball" which is able to raise from the dead. However, ever since I pledged myself to this field, I have been thinking most of nano-particles' features have not yet been sufficiently clarified either theoretically or experimentally. It depends upon each person's judgement how to use this term, and how to consider particles' size and physical properties. That is, the expression of "nano-particle" is vague.

For example, according to the Fujita report ([1]) about the size of nanoparticles, an isolated ensemble of nano-particles with diameters less than 150 Å will be called simply "atom cluster". On the other hand, nano-particles embedded inside materials are also regarded as "atom clusters" only when they are less than 50 Å in diameter. In other words, any ensemble of particles all larger than 150 Å, as mentioned above, must be defined as massive or bulk, and the two terms must be regarded as interchangeable in this regard. On the other hand nano-materials within 150 Å in size are classified into two different types of particles: isolated ensembles which show the characteristics of atom clusters throughout and within a range of 150 Å, and embedded particles ensembles, which show the same characteristics only within 50 Å while the characteristics of massiveness or bulk appear even in the larger size range (50–150 Å).

While it has been clarified experimentally that these results relate to the surface energy of such materials, they have not been thoroughly explained by solid state physics, especially by the electronic theory. Therefore, it is difficult for me to accept that the same term "nano-particles" is used to indicate those two kinds of particles which have the same size but present different characteristics. This is the point at issue and a very important one, because "atom clusters" and "massive particles" or just "bulk" behave differently even if they are made out of the same materials.

For instance, when the material A of an "atom cluster" (Au etc.) is mixed with the material B (Cu etc.), a large amount of B diffuses into the "atom cluster" A and its diffusion speed is 10^9 times higher than that into a "bulk" of A (300% atomic of Cu dissolves in an Au "atom cluster") ([2]). On the contrary, if the material A is "bulk" almost no Cu atom can dissolve in A (just as a proper Au bulk). In other words, such phenomena are beyond the explanation of actual electronic theory, besides, any researcher in the field of "nano-particles" always should grasp the boundary between "atom cluster" and "bulk" clearly.

The greatest defect of "atom clusters" is that their particles easily coalesce (sintering) and they become "bulk" when coming close to each other. Therefore it is necessary to avoid contact between particles and to develop new techniques in order to isolate them. But, at the same time, it can be said that this is not easy, and in fact extremely difficult.

We have developed one method in collaboration with the Director A. Inoue at Institute for Materials Research of Tohoku University ([3, 4]). The "atom cluster" (we also call it "host cluster") of Pd, which we have obtained during this study, demonstrated the most wonderful characteristics that impressed me and gave me a great impact which I have never had in my fifty years' research life. I would like to talk about this achievement a little more in detail for the benefit of the future generations and it would be indeed an unexpected pleasure for me if this description could be useful to many young people.

I'll briefly refer on how the goal of our research (which we have consistently pursued for several decades) was since its beginning connected with the idea of nano-particles. On 8th February in 1958, for the first time in Japan, we held a public experiment of nuclear fusion in an ultra-high temperature plasma (thermonuclear fusion) by using a big current discharge amounting to several million amperes. At that time, we also made an experiment of solid plasma nuclear fusion using metals ("strongly coupled plasma") ([5]). (I reported about this experiment in the magazine "Solid State Physics",

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Vol. 35, No. 1 (2000), edited by Agune, and also Mrs. Carol White introduced this in detail in the magazine "21st Century", Summer 1995, 37-44.) About one year later, on 23rd March 1989, while I was in my retirement (Osaka Univ.), there was the surprising announcement by M. Fleischmann and S. Pons, and one week later I started to make experiments in collaboration with Professor Yue-Chang Zhang. For seventeen years, that is till the end of this year (2004), we, I and Professor Zhang, have been focusing on the study of intense solid state nuclear fusion (based on the experience made in 1958, mentioned above), by using the following methods.

The method developed by us was very different not only from that of Fleischmann and Pons, but also from those of all other people including those who have made reproducible tests. While other people used cathodes made by bulk materials (like plates, rods, wires), what we have developed was a Double Structure Cathode ("DS"-cathode) ([6]), which is a rod shaped cathode with a vacuum cavity inside and filled with Pd black (as fine as possible) or nano-particles. (Reference: "Solid State Physics" mentioned above, page. 73.)

As the electrolysis proceeded in the electrolyte of D_2O/H_2O, this ultra-vacuum cavity inside the Pd rod could easily accommodate highly pure D_2/H_2 gas at over 1000 atm, following Sievert law. It is well known that generally 70-80% of D/H atoms (atomic ratio: [D/Pd]%) are absorbed into Pd bulk. However, we have verified that 100-150% of D/H atoms dissolved into Pd black. This value depends on the particles' size, and Pd black forms the "two-dimensional atom cluster" on its surface. Furthermore, Pd host cluster of nano-particles (three-dimensional atom cluster) could dissolve 200-400% of hydrogen isotope (D/H) as "guest atoms" ([7]).

Recently, we have developed a method to produce Pd nano-particles in the size of 5 nm (shortly Pd*) embedded in ZrO_2 matrix, (ZrO_2•Pd*), as the sample powder, which was made by baking in air amorphous $Zr_{65}Pd_{35}$ ([3,4,7]). It was proved that these Pd* (nano-particles) had conspicuous characteristics since abundant D-atoms ([D/Pd]: 200-400%) could be instantly absorbed into the Pd*. These host Pd* lattices were composed of the mixture of unit cells, whereas each cell contained solidified 200%, 300%, or 400% D-atoms. In other words, these condensed D-atoms were locally solidified as ultrahigh density "deuterium-lumps" (shortly "Pycnodeuterium") in the octahedral space of each cell in the host Pd* lattices ([8]). On the contrary, matrix ZrO_2 could not absorb any D-atoms.

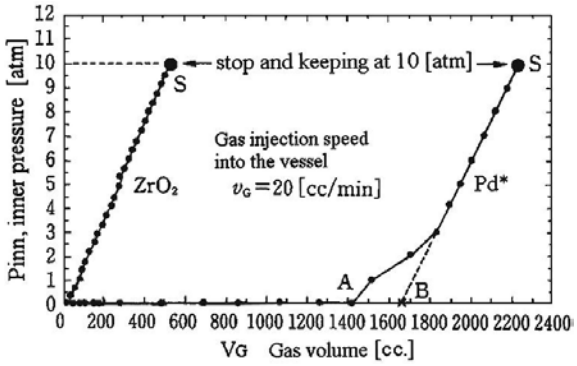

Fig. 1. – Deuterium gas absorption characteristic of Pd nano-particles (Pd*).

For example, fig. 1 shows characteristic curves of "deuterium-absorption" into the sample powder; ZrO_2•Pd*. There, nano Pd (= 50 Å) particles are dispersed in the matrix ZrO_2 and D-atoms can penetrate only into nano Pd (Pd*) but never stay in ZrO_2. In order to understand this well enough, here, it is necessary to comprehend the minutest details of the octahedral space structure as shown in fig. 2. We call this space which can accomodate D/H atoms "Octa vessel". Unfortunately, it is well known that this space has been generally shown in text books as an inscribed sphere (r_0) shown in fig. 2 (a) and it

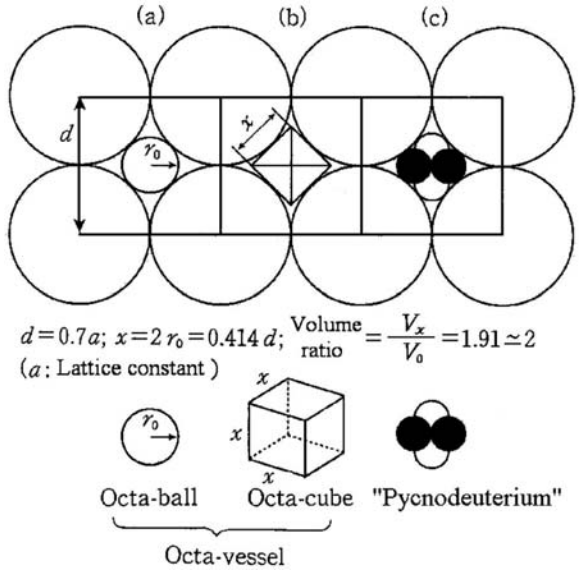

Fig. 2. – Atomic gap location of the Octahedron and its denomination, (a) Octa-ball, (b) Octa-cube, (c) "Pycnodeuterium", inside the Octa-vessel.

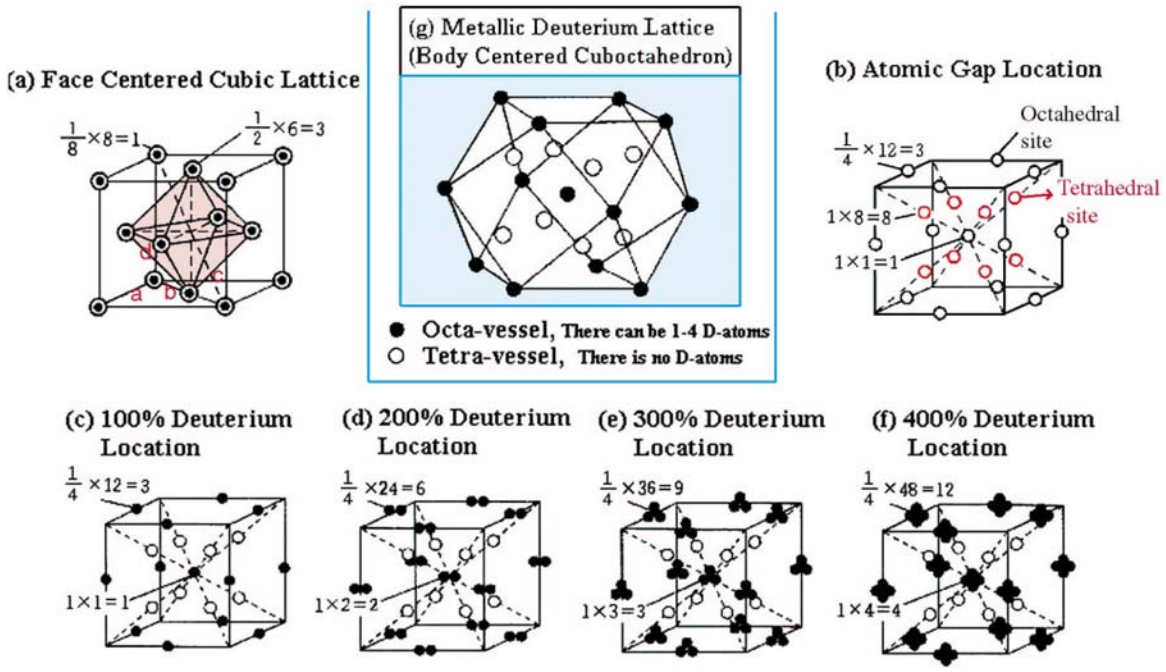

Fig. 3. – Face-centered cubic lattice and its atomic Gap Location, and each unit lattice in which 100, 200, 300, 400% of deuterium is absorbed are shown. In this case, octahedral-vessles accommodate 1-4 D-atoms. The "deuterium-lump" with more than 2 condensed deuterium is called "Pycnodeuterium-lump" or simply "Pycnodeuterium". A higher density "Metallic Deuterium Lattice" like (g) is formed as the "lattice points" of the "Pycnodeuterium". "Solid fusion" happens in this "Pycnodeuterium" and never happens in bulk materials, because the deuterium density of each unit lattice in bulk is less than 100%, so that D-atoms hardly ever meet mutually.

has been explained that this space is able to accommodate only 1 D/H atom inside. Here, for convenience, we call that sphere space "Octa ball", but such way of representing it like the "Octa ball" leads to an extreme mistake. Therefore, I have shown this space not only as a ball but as a cube, as shown in fig. 2 (b), and have named these two types of space as "Octa vessel" by taking them together. The "Octa cube" has twice as much volume as that of "Octa ball" and is able to accommodate 4 units of D/H atoms inside. We named such highly condensed multiple deuterium state "Pycnodeuterium" ([7,8]), that is, this is a short name for "ultrahigh density deuterium-lump", which corresponds to a density about 40 times higher than that of Pd and/or 50 times higher than that of ultralow temperature hexagonal solid deuterium at 4 K and/or equivalent to ultra highly compressed deuterium gas state under several 10^8 [atm].

"Pycnodeuterium" in the octa-vessels forms metallic deuterium lattice of body-centered cuboctahedron structure as shown in fig. 3 (g) and this is the indispensable state to induce solid state nuclear fusion (= "solid fusion"). Once, in an article entitled "An Error of so-called Cold Fusion" in the magazine "Solid State Physics", Vol. 35, No. 1 (2000), (edited by Agune), I referred to the importance of deuterium density and I insisted repeatedly that nuclear fusion phenomenon could never happen as long as bulk materials are used. However, it looks strange to me that people have still continued to use "bulk" metals ever since Fleischmann's first announcement, up to the present. Therefore, once more I would like here to provide a comprehensive explanation of why "bulk" metals do not work.

Figire 3, (a) and (b), respectively, show the face-centred cubic (fcc) lattice and it is location of the "atomic gap space", (○: Octahedral site, ○: Tetrahedral site : for simplicity, each space is called Octa-vessel or Tetra-vessel). An Octa-vessel shown in fig. 4 (a) is able to accommodate 4 deuterium atoms, whereas, a Tetra-vessel usually cannot accommodate even one deuterium atom. (This is the important point.) However, if Tetra-vessel could accommodate one deuterium atom, an Octa-vessel should become almost the same state so as to accommodate 5 deuterium atoms, as shown in fig. 4 (b) and (c). In other words, it becomes a common

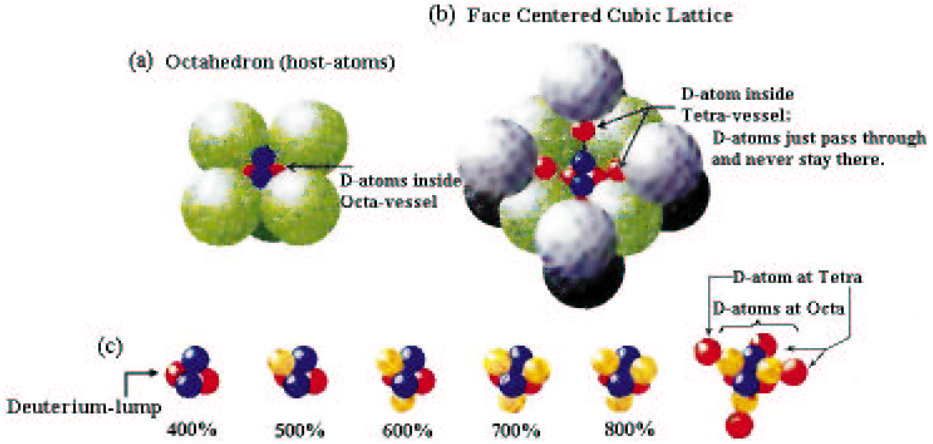

Fig. 4. – Face-Centered Cubic Lattice and its structure of "Pycnodeutrium" in the Octahedron (Note: The probability of 5 D-atoms (500%) settling in Octa-vessel, and that of 1 D-atom settling in Tetra-vessel are almost in the same rate, but it is impossible to realize because the extreme strain energy in host lattice will be produced in this process. D-atoms, therefore, cannot stay at Tetra-vessel, but it is possible the D-atoms pass through it instantly.

vessel in which Tetra- and Octa-vessel are combined together. In this combined state, normally one Pd atom should shift more than 10% from the steady position. For this reason, it is difficult to accommodate 5 deuterium atoms in Octa-vessel and also even 1 deuterium atom in the Tetra-vessel. However, it is possible that deuterium can pass through a Tetra-vessel just for a moment. Then, it can be considered that the Tetra-vessel has a function of a barrier against transporting D atoms. In short, deuterium atoms as shown in fig. 5 (a) always have to pass through the barrier of the Tetra-vessel when they move from one Octa-vessel to another. Therefore, a Tetra-vessel barrier is located at the crossing "T" point on the paths linking 4 octa-vessels in order to accomplish their movement.

On the other hand, the barrier of the Tetra-vessel in the case of "bulk" (metals) is very rigid, so deuterium atoms are restrained, their transport velocity (diffusion velocity) is small, that is they move with difficulty. Moreover, with the raise of the dissolved deuterium density in "bulk" metals, those barriers become more rigid. When that deuterium density reaches to 70-80% levels, the diffusion speed reaches the minimum and the dissolved density almost saturates because deuterium can hardly go through the barrier. On the contrary, the barrier of the Tetra-vessel of nano-particles (atom cluster) is really loose. Because of the usual

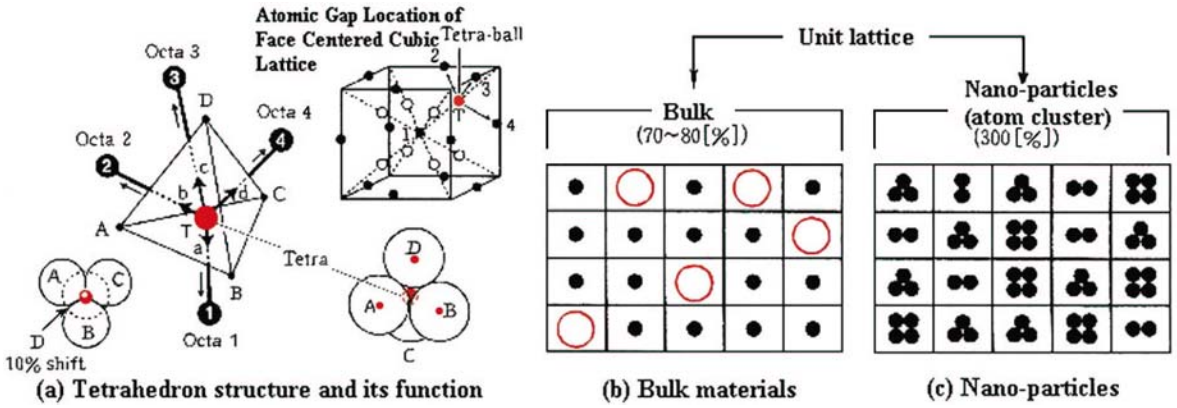

Fig. 5. – The functional of "Tetra barrier" and the formation of "Pycnodeuterium". (a) Tetrahedron structure and its function (Tetra-vessel is the small barrier space connecting 4 Octa-vessels and controlling movement of deuteriums to be accomodated into their vessels). (b) (c) Extreme difference of deuterium distribution inside Pd unit cell in (b) bulk materials and (c) nano-particles.

occurrence of around 10% shift of the distance between Pd atoms, deuterium atoms can pass through this "barrier" almost freely, and hence can diffuse 10^9 times quicker than in the "bulk". For example, even with 0.1 atm of pressure, the dissolved deuterium in Pd nano-particles reached more than 200% in a short time, still more, could reach more than 250% with several atm, and more than 300% was confirmed with 100 atm. Such a difference of dissolved deuterium or hydrogen density between "bulk" and "nano-particles" plays a decisive role in the obtainment of "solid fusion". We have recently recognised that this is the essentially important point in formulating the goal of the research.

Figure 3 (c), (d), (e) and (f), respectively, indicate dissolved deuterium of 100, 200, 300, 400% atomic ratios (D/Pd) in Pd unit cell of face-centred cubic (fcc), whereas, fig. 3 (g) shows body-centred cuboctahedral metallic deuterium lattice which belongs to the fcc. The unit cell of nano-particles dissolve 300% deuterium, which means that the crystalline condition of the mixed cells which contain 200%, 300%, and 400% of coagulated deuterium-lump ("Pycnodeuterium") at Octa-vessels of each unit cell, leads to an average deuterium density of about 300% as a whole (fig. 3 (c), (d), (e), (f) and fig. 5 (c)).

By the way, in order to produce nuclear fusion, more than two deuterons need to come close at first, and secondly, they must meet (just molecule) and join hands. When coming close to each other within the distance of 0.74 Å, they form molecules and generally cannot come closer because of the space charge between the ions. But if some strong external force exists which somehow could counteract this space charge, or else, if that barrier reduces or nearly disappears, deuterons can fuse even when they approach as near as 10^{-3}–10^{-4} Å. As one example of external strong forces, it is well known from the Rutherford reaction that deuterons can get over their barrier (= 2-body collision reaction) if accelerated at about 10000 volts. The reaction products are in almost even ratio as follows:

$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \quad \text{or} \quad {}^{3}_{1}\mathrm{T} + {}^{1}_{1}\mathrm{p} $$

Namely, ${}^{2}_{1}\mathrm{D}$ (d, n) ${}^{3}_{2}\mathrm{He}$ or ${}^{2}_{1}\mathrm{D}$(d, p) ${}^{3}_{1}\mathrm{T}$ reaction happens in about the same ratio.

The thermonuclear fusion planned at present based on the ultrahigh temperature deuterium plasma using "gaseous deuterium" (or D, T mixed gas) as a fuel will happen according to these reactions.

On the contrary, several times we have insisted that the new fusion reaction, peculiar to metals' inside, using "solid deuterium" as a fuel, that is in a condition which makes space charge barrier reduce or disappear, is

$$ {}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} = {}^{4}_{2}\mathrm{He} + \text{lattice energy}. $$

This reaction has been reported by us up to now not only in the "columns" of the journal "Solid State Physics"(Vol. 35; 38)/ICCF(9,10) but also in many other previous papers ([5-9]).

If this formula is valid, generation of ${}^{4}_{2}\mathrm{He}$ and extraordinary heated metals should be found. As described later, we have recently verified both remarkable large amounts of ^{4}He and excess heat.

Figure 5 (b), (c) illustrate two models, one is the "bulk" condition (b) and the other is the "nano-particles" condition (c), which are both quite different from anything that was published before.

Each shows a unit cell in which the deuteriums are located in Octa-vessel positions.

Here, the mark ●, shows one deuterium and ●●, ●●●, ⁘, are "Pycnodeuterium" of two, three or four deuteriums, respectively, whereas, the mark ○ shows a unit cell in which no deuterium exists.

"Bulk" metals have such rigid Tetra barriers (shown in fig. 5 (a)) that it is extremely difficult for neighbour deuterium to move for meeting, that is together pass through the barriers in the saturated deuterium solution region, as shown in fig. 5 (b). Therefore it is obvious that nuclear fusion can hardly happen within such "bulk" metals.

On the other hand, nano-particles already have such condensed conditions consisting of more than two deuteriums, as shown in fig. 5 (c), so it is not necessary for them to move at all in order to fuse, and this is the most important key point. However, although little, some space charge barrier still remains between deuterons under a stable condition, so that without some external stimulation energy it is not easy for deuterons to come close within a distance of 10^{-3}–10^{-4} Å. For this reason, we consider impact energy like ultrasound, magnetic field, current, neutron beam, plasma beam, electron beam, laser beam, or condensed conditions induced by laser implosive force (not necessary powerful) or something else, as necessary stimula for the fusion to occur.

We call each unit cell "Lattice Reactor" regarding it as the smallest reactor. Besides, we

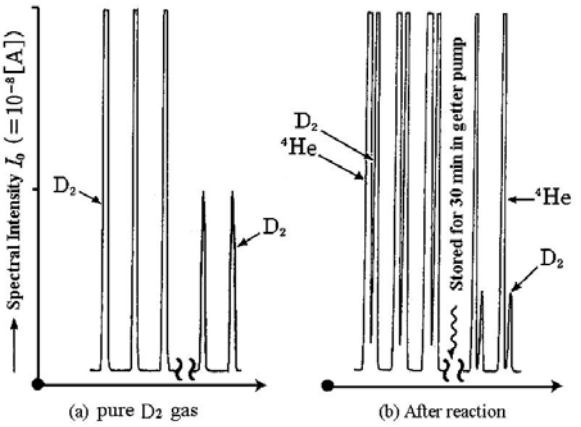

Fig. 6. – The results of mass M4 (D_2/^{4}He) spectrum analysis of pure D_2 gas and after reaction inside fusion reactor. (a) Pure D_2 gas spectrum ("before" reaction), (b) ^{4}He(+D_2) gas spectrum ("after" reaction).

conceived of causing a "Latticequake" in the "Lattice reactor" (Reference: the previous "columns" in the magazine "Solid State Physics") by feeding ultra-sound energy in order to overcome the residual barrier in "solid deuterium", and to induce the nuclear fusion reaction. As a consequence, in our experiments, for the first time in the world, we succeeded in producing intense nuclear fusion reactions inside metals, and generated a significantly large amount of ^{4}He and thermal energy by using "solid deuterium" as a new fuel.

I am amazed and impressed by this mechanism of "nature" as much as I respect it. Simultaneously, only proper experiments enable us to comprehend its mechanism. Furthermore, we should not forget our current understanding of science is based on previous excellent experiments done by the earlier generations. As seen in recent discoveries of new materials one after the other, our knowledge is confined to comprehend only some parts of the mechanisms of nature. Hence one should not repeat such a foolishness as denying "heliocentricism" at some time in the past, which resulted from adhering too strongly to one's own knowledge or to what was common sense in those days. For myself, I always warn myself with a voice not to be too much possessed by my own current knowledge.

Incidentally, fig. 6 shows results of mass M_4 of the reaction tank gas "before"(a) and "after" (b) irradiation by ultrasounds ([10]), obtained by Quadrupole Mass Spectrography (QMS). In fig. 6 (a), M_4 is pure D_2 gas which decreased with time by being absorbed into the getter pump (no sign of ^{4}He), whereas, fig. 6 (b) shows the remaining D_2 gas which was not still absorbed into getter pump, and shows the existence of constant and large amounts of ^{4}He, which have not been absorbed. In other words, a large amount of pure deuterium gas (a) reacted to convert into ^{4}He, that is, the reactor tank converted the tank deuterium into $^4_2$He. In addition, it is an ideal energy source in that no neutrons nor gamma-rays were produced.

The following two key points characterise our experiments. First, the preparation of "solid deuterium" as a nuclear fuel; that is an ultrahigh density deuterium metallic lattice consisting of "Pycnodeuterium". Second, to have supplied a "Latticequake" to those lattices by feeding them with a stimulating energy through concentrated powerful high energy density beams like laser beam, electron beam, plasma beam, ultrasonic beam and so on. We are sure that our discovery will be useful to achieve practical applications. At the same time we shall go on pursuing our aim of research which is to develop different reactors according to the theoretical lead of "Pycnodeuterium" inside metals ("Solid deuterium") and "Latticequake".

Finally, it is concluded that such "solid deuterium" is by far the better fuel for the "gaseous deuterium" in the thermonuclear fusion.

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