3.34 Possible In-lattice Confinement Fusion (LCF): Dynamic Application of Atomic and Nuclear Data

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New scheme of a nuclear fusion reactor system is proposed, the basic concept of which comes from ingenious combination of hitherto developed techniques and verified facts; 1) so-called cold fusion(CF), 2) plasma of both magnetic confinement fusion(MCF) and inertial confinement fusion(ICF), and 3) accelerator-based D-T(D) neutron source. Details of the LCF reactor physics require dynamics of atomic data as well as nuclear data; interaction of ions with matters in solid and the problems of radiation damage.

Historically the controlled fusion research can be regarded as based on the nuclear physics research which has initiated early in 1930s with the discovery of neutron. The D-T(D) nuclear reaction by use of accelerated D^+ ions impinging upon a T(D)-containing target has been widely used for production of fast neutrons. This should have motivated the fusion research. However, this scheme has a fatal drawback. The bombarding particles lose their energy very quickly, mainly in collisions with electrons. The ratio of nuclear output over the input energy is usually very small, i.e., less than 10^{-2}. It is thus obvious that this process can not be exploited for power generating purposes[1]. To overcome this drawback, the use of accelerated ion-beams(in non-Maxwellian distribution) can still nowadays be found in MIGMA[2].

The origin of the solar energy, a long-term enigma, had been successfully explained by H.A. Bethe and C.F. von Weiszäcker in 1939, as through thermonuclear reactions: either of the proton-proton(p-p) chain in stars of the size of our sun or of the carbon-nitrogen(C-N) chain in larger stars. Both the reactions can be reduced to as nuclear-mass extinguishment converted to energy, where finally four protons get together to one alpha-particle, ^4He. The stellar thermonuclear reactions can be sustained through the confinement of solar-gas plasma by the huge gravity of such solar bodies. With the advent of a new field of plasma physics, the controlled fusion studies, somewhat later after the hydrogen-bomb explosion tests, have started to produce high-density and high-temperature plasma, such as Z-pinch experiments mid in 1950s, then leading to the todays' magnetic confinement fusion(MCF) schemes. From this viewpoint, magnetic force plays a role for confinement of the plasma under the terrestrial environment, instead of the gravity on solar bodies. In MCFs, typical facilities are Tokamaks and Helical Devices. Late in 1960s, the availability of high-power lasers made another scheme of the fusion power studies, known as inertial confinement fusion(ICF). Here the laser power is applied to compress the fusion fuel gas to high density and then high temperature through the implosion of a pellet, containing the fuel gas, of some (sub-)millimeter in size, the mechanism of which resembles to the hydrogen bomb, being driven to extreme implosion by a fission nuclear power. In ICFs, Laser Fusion Facilities are the first runners followed by those of proposed heavy-ion inertial confinement fusion after many proposals of the candidates for the energy drivers such as relativistic electron beams and light-ion beams. Both schemes(MCF and ICF) use Maxwellian high-temperature plasmas of D(or D-T mixture) ions.

In March, 1989, M. Fleishmann and S. Pons had abruptly announced the so-called cold fusion scheme[3]. They had carried out an electrolysis experiment of D_2O+Pd system and claimed that the excess heat generation had been observed due to nuclear fusion reaction inside the lattices of Pd-metal. As well known, some metals, e.g., Ti, Zr, Pd, etc., can solve isotopes of hydrogen in their lattices up to more than $10^{22}cm^{-3}$ in density. The metal-hydrogen system reveals the characteristic features, phases, depending on both concentration and temperature; a phase diagram represents it well. Under some condition, say, in α-phase, the occluded hydrogens behave like plasma. In other words, the confinement time τ, one of the important parameters of plasma fusion, becomes infinite. The occluded hydrogen of $10^{22}cm^{-3}$ in density means that the quantity in a metal block of only 1 cm^3 is almost the same as those in large Tokamas' plasma of 100 m^3, because the density of Tokamaks' plasma is around 10^{14} cm^{-3}. This should implicitly give a physics-basis of the CFs, even though the kinetic energy of the occluded plasma is far small for nuclear reaction threshold; at room temperature, it is at the same order of thermal neutron, 0.025 eV.

J. D. Lawson and W. B. Thompson showed a criterion that the minimal requirement of the plasma for power application must be fulfilled; three parameters, i. e., density n, confinement time τ and temperature T, often a product $n \cdot \tau$ and T, must exceed the critical values. The Lawson diagram indicates conveniently the chronological achievement of both MCFs' and ICFs' performance. The expanded one of Fig. 1 includes the possible location of the CFs, far upmost and far left-sided, indicated by an arrow, and the position of D-T neutron source reduced from the Q-value and of the MIGMA. The superposition of both D-T neutron sources' and MIGMA's may be out of the rigorous definition of statistical property of plasma in the figure. However, this procedure can offer us a good guide to further proceed to a new scheme establishment. A line drawn from the position of D-T neutron source toward the CFs' can fortunately cross the area of $Q_{D-T} \gg 1$. To move the CFs' part toward the D-T neutron source may be equivalent to letting the occluded Ds or Ts be energized in an ordinary sense, differing from the so-called cold fusion that explores a possible new mechanism of nuclear fusion reaction inside the lattices.

A technique of the plasma-heating by the fast(of high energy) neutral beam injection(NBI) in e. g., Tokamaks suggests that the use of fast neutrons favours in this case of LCFs, because the difference(10^8) in desity of between MCF and LCF inevitably leads to use neutral particles much smaller than those of atomic size; the unique candidate is neutron and it should be conceivable that the use of fast neutrons can make other advantages: deep-penetrability inside materials, identical usability of D-T(partially D-D) neutrons, and fuel self-production through the nuclear combination with slow proton after D-D reaction. Fission reactor physics treats well the process of neutron slowing down, where the neutrons lose their energy through multiple collision with nuclei; in turn, the nuclei get the recoil energy dependent on their mass. After the head-on collision of a neutron of energy E_0 against a nucleus of atomic mass A, the resulting neutron energy E can be expressed as $E = \alpha E_0$, where $\alpha \equiv ((A-1)/(A+1))^2$. The transferred(recoil) energy to the nucleus is thus given as $(1-\alpha)E_0$. For a hydrogen ion(a proton), the complete energy transfer can take place, the incident neutron being stopped.
For heavier nuclei, the recoil energy becomes much smaller. For deuteron or triton, an adequate amount of energy transfer can be expected. Some corrections, however, are practically needed to the above discussion due to possible nuclear reactions such as (n, n'), (n, p), (n, 2n), etc. and due to the fact that the collision angles are never fixed and then the recoil energies show a wide spectrum. Thus the quantitative discussion requires computational simulations. However, it could qualitatively be demonstrared that the fast neutron bombardment onto an occluding block yields the selective energization of only light ions, D^+s or T^+s, while the lattice structure may remain unchanged or slightly damaged; whereas damage healing at high temperature takes place. Energized (or recoiled) Ds can easily attain energy high enough to fuse together with other Ds or Ts. As a typical fact, it is well known that the operation of heavy-

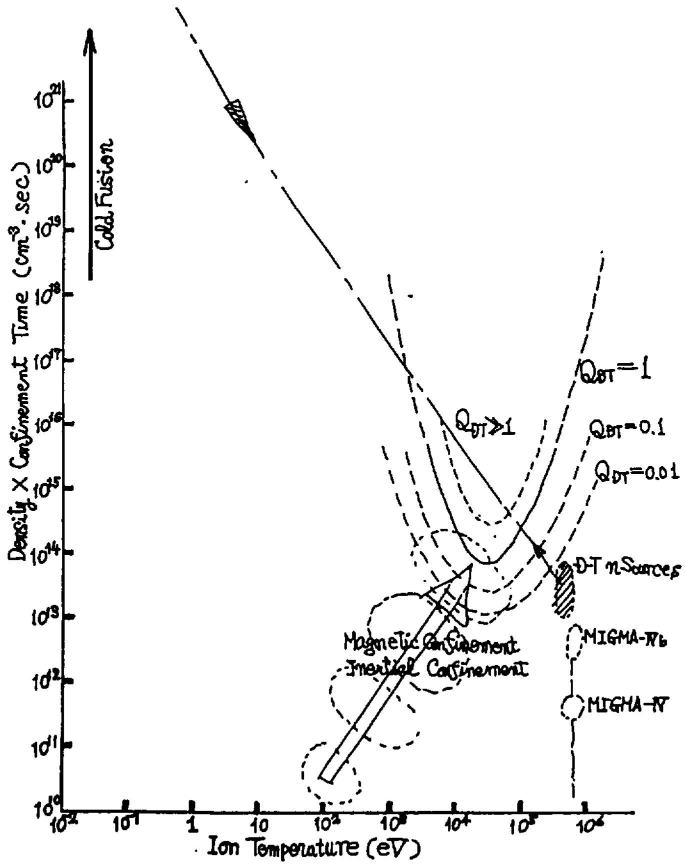

Fig. 1 Expanded Lawson Diagram

water reactors produces resultantly tritiums in moderating and/or cooling heavy water, which can be explained as due to D-D reactions; the first D is recoiled by unmoderated fission neutrons and then energized high enough to fuse with another D in D_2O. This reaction has two branches almost in equal probability as presented below;

$^2D+^2D \rightarrow$ $^3T(1.01)+p(3.03)$ [4.04], ······ (1)

$^3He(0.82)+n(2.45)$ [3.27], ······ (2)

where the numbers in round and square parentheses are the energy in a unit of MeV of each reactioned particle and of totally released one, respectively. In the second branch, helium-3(^3He) is produced as much as tritium in amount. The detection of ^3He, however, should be hindered by a huge volume of natural helium(containing 0.00014% of ^3He) gas filled up atop of the heavy water. Instead, ^3Ts is radioactive, emitting β-rays of 18.6 keV, thus being easily detectable. Another source of tritium production may be conceived as in the neutron-capture by deuterons. Howevre, the neutron-capture (absorption) cross-section of deuteron is so small that heavy water is preferred to light water as moderator in a sacrifice of smaller slowing-down power, even if this can not completely be ruled out. In addition, the tritium production may be rather troublesome for the operation of heavy-water reactors; the less in amount, the more favorable.

The energy gain Q of any accelerator-based D-T(D) reaction is less than 10^{-2}, even though such the reactions are genuine for the first(and second) candidate of fusion power application and widely used for fast neutron sources. The D-T reaction is expressed as below together with a hopeful aneutronic D-^3He reaction, if ^3He were supplied enough,

$^2D+^3T \rightarrow$ $^4He(3.52)+n(14.06)$ [17.58], ······ (3)

$^2D+^3He \rightarrow$ $^4He(3.67)+p(14.67)$ [18.34]. ······ (4)

The terminology, energy gain Q, here has a few synonymous ones: fusion energy(or power) multiplication factor, Q-value, or pellet gain(limited to ICFs), which is defined as $Q=E_{out}/E_{in}$(or $=P_{out}/P_{in}$), where P_{out} is the nuclear output power while P_{in} is the input power to driving the nuclear reactions. When Q=1, the situation is called "Break Even". In MCFs, the self-ignition condition is defined as that the energetic alpha-particles(of 3.5 MeV as seen in (3)) can serve enough for the plasma heating by themselves; Q-value looks virtually infinite. This α-particle heating should be effective also in ICFs. As seen in (3), 80% of the nuclear fusion energy is carried out by fast neutrons, so that both MCFs and ICFs have to provide a blanket, in which the neutron energy is converted to thermal energy with optionally fortunate tritium production and gain amplification through the reaction, $n+^6Li\rightarrow^3T+^4He$. The break-even condition, as well known as Lawson's, for D-T fuel gas plasma, at T≈10 keV, the product $n\cdot\tau$ should be above $10^{14}sec\cdot cm^{-3}$.

Typical neutron sources such as RTNS(Rotating Target Neutron Source-I(II), LLNL), INS(Intense Neutron Source, ANL, proposal), OKTAVIAN(Osaka Univ.), and FNS(Fusion Neutron Source, JAERI) use D-T reaction, because their primary mission is for D-T fusion material testing and nuclear data measurement. This D-T reaction is much easier and then preferable at the first step for fusion power application, because its reaction cross section shows at maximum 5 barns at 107 keV releasing totally 17.58 MeV, while D-D's is less promising. If only the D-T reaction can take place without any electronic or non-nuclear processes, which is, of cource, absolutely improbable, then the Q-value yields 164, being calculated plainly from the ratio of 17.58MeV/107keV. When colliding particles can be realized, the Q-value will roughly be doubled. In reality, the obtained Q-Values lie under the value of 10^{-2}; the nuclear reaction rate is less than 10^{-4}; the accelerated D^+ particles of more than 10,000 can only generate one neutron dependent on the target condition; the above exampled sources show the similar rate. Charged particles such as D^+s can not penetrate deep into material, so that the neutron target is usually thin, where only alpha-particles heat the target; however, sometimes this causes a problem of the target cooling. Almost all neutrons escape from the target; this is the true purpose of neutron generation. Here let us assume that the target is made enough thick and wide, and occluding D ions or D-T mixture: something like a large block or core assembly, the size of which covers the mean-free path λ of fast neutron by several times. Then the neutrons recoil Ds or Ts that can react with neighbouring ones; such the reaction generates again neutron inside the target, acting as the primary one. Thus the regenerative effect can take place. Taking β as the probabilty of how many neutrons the primary ones can next produce in solid, the regenerative(or amplification) factor α will follow in a simplified manner as;

$$\alpha = 1 + \beta + \beta^2 + \beta^3 + \cdot\cdot\cdot = 1/(1-\beta) > 1.$$

For the estimation of α or β, the following discussion would be helpful;In the case of the neutron sources, the acceleration voltage of D^+s is experimentally adjusted as 400 to 600 keV for giving a maximum yield as a whole, while the cross-section maximum appears at 107 keV. The reason seems due to the energy losses of the incident D^+s through electronic interactions during penetration near at the surface of the target; the stopping power of materials becomes important. On the other hand, one 14-MeV neutron, for example, can most optimistically produce 100 particles of 140 keV inside the target without the surface effect;this implies that the efficiecy increases nearly by hundred. This approach can be regarded as to move the position of D-T neutron source toward the area of $Q_{D-T} \gg 1$ in the direction to the CF's in Fig. 1.

The neutron yield n is usually linear to the beam power P_{in} of D^+s; $n \propto P_{in}$ or $n = \eta \cdot P_{in}$, where η is the D-to-n conversion efficiency. The output power P_{out} due to the nuclear reaction is also proportional to n; $P_{out} \propto n$ or $P_{out} = \varepsilon \cdot n$, where the coefficient ε depends on the incident neutron energy, D, T-concentration, and the protonic number, Z, of the target material and includes the previous α. Here the Q can be expressed by ε and η; howevre it seems far deficient. Thus the key issue at this point is how to increase the Q-value above unity, break-even or more, overcoming the linear relationship between the input and output. The plasma fusion suggests that the output power density P_{FS} can be expressed in the D-T case as, $P_{FS} = n_D n_T \langle \sigma v \rangle E_{DT}$, where n_D and n_T are, respectively, the density of Ds and Ts, $\langle \sigma v \rangle$ is the fusion reaction rate, and E_{DT} is the nuclear energy released thereby. For the same kind particle, the above equation is to contain a part of square proportionality; this should be the basis of plasma-fusion power application, guaranteeing the Q-increase.

In order that the reaction rate of the present case could include a term proportional to the square number of incident neutrons, the assembly geometry should be invented together with both the spatial and temporal control of the incident neutrons, so as to generating many transient micro-plasmas, the individual particles of which have kinetic energy high enough to fuse together. The word, transient micro-plasma, comes from an empirical figure of energetic charged particles' collision with occluded ions; fast neutrons recoil charged particles of similar mass; the situation may be the same except that neutrons can travel long distance(mean free path λ), while charged ones interact with others very closely; making a so-called shower found in high-energy particle experiments or a unidirectional star or a jet. When two showers in reverse direction take place simultaneously at the same spatial position, the resultant one can be regarded as a micro-plasma, whose life-time is very short compared with an ordinary Tokamaks' or Helical devices' plasma, but longer than ICFs'. Thus the output power P_{out} can include a term proportional to square number of n, where the Q can be increased in principle; $P_{out} = \varepsilon_1 \cdot n + \varepsilon_2 \cdot n^2$, where the previous ε is suffixed as ε_1, and ε_2 depends on both the number and the density of micro-plasmas; They further depend on the configuration(size and shape of the core, the number and position of the neutron injectors) and the peak neutron intensity(in pulse-operation inevitably).

Details of the LCF reactor physics require dynamics of the atomic data as well as nuclear data; specifically the microscopic stopping power, including channeling effect, of energetic light ions inside the lattice of such materials, i.e., the interaction of ions with matter in solid and the problems of (neutron)radiation damage.

A proposed system consists of a reactor core of D- or D, T-occluding metal block assembly with several pulsed fast neutron injectors symmetrically equipped similar to the configuration of direct ICFs' drivers. Here six units of the neutron injector are equipped, as the core being simply cubic, perpendicular to each facet. The core is not necessarily a one block of metal, but a pile of laminated sheet of the metal. The generated heat is transferred by liquid metal, e.g., lead eutectic, flowing through the cooling pipes. The core is encased by a pressure vessel, with which an inlet of fuel D- or D-T mixed gas and an outlet of burnt alpha are connected.

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