THE NATURE
OF
THE CHEMONUCLEAR TRANSITION

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Preface

In any atoms all s-orbital electrons are interpenetrating the nuclei then and there interacting with protons and neutrons electromagnetically. This feature indicates the possible influences of the s-electrons on the nuclear kinetics, which is predicted already late in the 1930's as the β-decay through orbital electron capture. This nuclear penetration effect was extensively explained in the internal electron conversion early in the 1960's. The electric monopole (E0) isometric transition through the internal electron conversion is the most typical nuclear penetration effect. The author himself was involved in explaining these phenomena from 1950's to 1960's.

The valence s-electrons in the atoms reveal the thermodynamic collective features in the spontaneous chemical reactions in the liquid solutions. These features likely transfer into the nuclear reactions through the collective dynamics of valence and mobile s-electrons in the thermodynamically stable alloy liquid i.e. solution of metallic solvent with valence s-electrons. Here macroscopically distinct parts of the valence s-electrons fixed by the reactant nuclei are correlated and a long range coherence are developed in the liquid revealing the collective dynamics of nuclei through the interaction with the macroscopically correlated valence and mobile s-electrons in the alloy liquid.

The first suggestive evidence supporting the above consideration appeared in the astronomical research on the enormously enhanced pycnonuclear fusion reaction in the metallic hydrogen liquid in stars e.g. supernova progenitors of white dwarfs. The mechanism of this reaction seemed to be the nuclear fusion enhanced by the coupled spontaneous chemical reaction forming the united atoms in the liquid of metal atoms with valence s-electrons. Based on this conjecture, the author observed successfully the enormously enhanced fusion reactions in the metallic Li liquids under the collaborations with R. Pettersson in Uppsala and T. Watanabe in Sakura/Tokyo. The above described enhanced nuclear reations or transitions are generally expected through the spontaneous chemical reactions coupled with the nuclear transitions in the thermodynamically stable liquids.

The enhanced nuclear transitions – chemonuclear reaction/transition called after S. Kullander – open up broad ways providing new energy and matter resources.

In this book introduced are some typical applications of chemonuclear transition:

1. Chemonuclear Fusion of Hydrogen Clusters in Li permeated Metal-Hydrogen Systems
   – Supernova on Earth
2. Hydrogen and Helium Burning Chemonuclear Chain Reactions
   – Big Bang Nucleosynthesis on Earth
3. Chemonuclear Transition Th/U Reactor
   – Switch-over of Reactor to Waste-free Hybrid Reactor
4. Waste-vanishing Induced Nuclear Decay

The author hopes that this publication will stimulate continued development concerning the concept "Chemonuclear Transition".

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Chemonuclear Fusion of Hydrogen Clusters in Li permeated Metal Hydrogen Systems – Supernova on Earth –

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Our decadal basic research confirmed: Chemonuclear fusion of light nuclei in the metallic Li-liquids hold the common mechanism with pycnonuclear reactions in the metallic-hydrogen liquids in stars e.g. white-dwarf supernova progenitors. Both reactions are incorporated with the ionic reactions forming compressed united atoms and induce enormous rate enhancement caused by the thermodynamic activity of the liquids. For the chemonuclear fusion of hydrogen clusters in the Li permeated metal hydrogen systems, the rate enhancement of 2×10^{44} is expected via coherent collapse of hydrogen-hydrogen bonds. Chemonuclear fusion releases a power over one million times as dense as the solar interior power density in the metal hydrogen systems, e.g a 1-mol NiH system is capable of some kW output. The fusion is followed by the successive reactions mostly with Li metal.

1. Pycnonuclear and Chemonuclear Reactions in Metallic Liquids

Nuclear reactions have been known to be enormously enhanced in condensed matter in stars [1]. The reactions are called pycnonuclear reactions after Cameron who coined the term from the Greek $\pi\ \psi\ \kappa\ \nu\ o\ \sigma$, meaning "compact dense"[2]. In the condensed matter, electrons act to screen the Coulomb repulsion between the atomic nuclei and this screening effect becomes so remarkable that rates of reactions at low temeratures are almost independent of the temperature and mostly depend on density of matters. (cf. Eq (5) in Section 3.)

In addition to this screening effect by electrons, the very cohesive effect manifested in solidification of dense liquids tends to enhance greatly the reaction rate [3, 4]. In the metallic-hydrogen liquids, for example, in a white-dwarf progenitor of a supernova, enhancement of the nuclear reaction rate by a factor of some 30 orders of magnitude has been predicted [5]. Substantial parts of the rate enhancement in the metallic-hydrogen liquids are ascribable to this effect. While this enhancement is infeasible in gas plasmas like the solar interior, it is common to spontaneous reactions in liquids irrespective of kinds of the liquids and reactions as seen below.

In 2001, a possible occurrence of new pycnonuclear fusion was pointed out by the present author based on microscopic considerations on the slow ion collision processes in the metallic Li-liquids [6]. Soon after in Uppsala the author and R.Pettersson observed the enormous rate enhancement in the $^7\mathrm{Li(d,n)}^8\mathrm{Be} \to 2{\cdot}^4\mathrm{He}$ reaction through detecting α-particles produced under slow deuterium ion implantation on a Li-liquid target [7]. The observed enhancement was around 10^{10} which was predicted on the consideration that the fusion proceeded through coupling with a spontaneous chemical reaction forming a compressed united atom (quasi-Be atom) where twin oscillatory nuclei coexist at the center of common 1s-electron orbital. In the liquid the spontaneous reaction rate thereby the coupled nuclear reaction rate is enhanced by the factor $K = \exp(-\Delta G_\mathrm{r}/k_\mathrm{B}T)$ specified by the chemical potential (Gibbs energy) change ΔG_r in the reaction. Here k_B and T denote the Boltzmann constant and temperature, respectively.

In the new scheme of nuclear fusion in the Li-liquid, even doubly intensified enhancement $K(\mathrm{Be}_2) = K^2(\mathrm{Be})$ with $\Delta G_\mathrm{r}(\mathrm{Be}_2) = 2\Delta G_\mathrm{r}(\mathrm{Be})$ was expected through forming quasi-Be_2 molecules under the implantation of slow D_2 ions [8]. This prediction was supported through a comparison experiment of atomic- and molecular-ion implantation on the same Li-liquid target by the author and T.Watanabe in Tokyo/Sakura [9]. They observed also an enormous rate enhancement over 10^{40} as predicted [10] in the $^7\mathrm{Li}(^7\mathrm{Li},2\mathrm{n})^{12}\mathrm{C}$ reaction [11].

These empirical results seem to suggest that pycnonuclear reactions take place also in the Li-liquids. This conjecture was supported by thermodynamic data as seen in Section 2. Taking these facts into consideration, the new nuclear fusion has been called "chemonuclear fusion" or "chemonuclear reaction" [10].

2. Liquid Activity revealed in Ionic- and Chemonuclear-Reactions

Ionic reactions in aqueous solutions are typical spontaneous reactions and generally take place with enormously large rate enhancement e.g. as seen in [12],

$$\mathrm{Hg}^{++} + \mathrm{S}^{--} \leftrightarrow \mathrm{HgS(red)} \tag{1}$$

$$K = \overrightarrow{k}/\overleftarrow{k} = 2 \times 10^{53} \ \text{at } 25°\mathrm{C}. \tag{2}$$

Here $\overrightarrow{k}$ and $\overleftarrow{k}$ denote the forward- and backward-reaction rate, respectively. Equation (2) indicates that the forward reaction rate $\overrightarrow{k}$ is enhanced by the factor of equilibrium constant K.

$$\overrightarrow{k} = k_0 K, \ \overleftarrow{k} = k_0 \tag{3}$$

Here k_0 is the intrinsic collision frequency between ions.

Of interest is the fact that the same ionic reaction takes place also in an alcohol solution with the same enhancement. Just in the both solvents, water and alcohol, Hg^{++} and S^{--} ions undergo the same ionic reaction Eq.(1) with the same enhancement Eq.(2). Furthermore, even without solvent the same ionic reaction takes place within fused salts. The ionic reaction takes place with the large enhancement irrespective of kinds of solvents.

This empirical fact is well explained on the basis of the Widom's general concept "thermodynamic activity of liquids" [13], which is common bulk/collective features of spontaneous reactions caused by the thermodynamic force in the liquids consisting of reactant particles. Here macroscopically distinct parts of the liquids surrounding the reactant particles are correlated and a long-range coherence appears. In general, the force is specified by the Gibbs energy change ΔG_r in the reactions. This general thermodynamic relation is strictly independent of kinds of reactant particles and the nature of microscopic interparticle interactions [14].

Now we find that the enhancement mechanism of pycnonuclear reactions in the metallic-hydrogen liquids as dense plasmas is common to ionic reactions in liquids. Thus it is natural that the chemonuclear fusion is pycnonuclear reactions in the metallic Li-liquids.

We had, however, limitted ourselves to the basic research, that is, ion implantation experiments on the metallic Li-liquid surfaces in order to investigate the reaction enhancement mechanism so far. This means caused an instability of reaction rates peculiar to the chemically very reactive Li-liquid surfaces. For instance, at a vacuum of 10^{-7}Torr, it is hard to keep a clean Li surface within 1 sec for the slow D_2 ion implantaion without dissociation of the D_2 ions except for simultaneous sputtering clean up treatments. In this paper, we develop a new scheme of chemonuclear fusion towards the new wasteless energy resources.

3. Electron Screened Hydrogen Burning Nuclear Fusion in Metal Hydrogen Systems

A fusion system under consideration is those of Li permeated hydrogen clusters in metal hydrogen systems or metal hydride molecules. In the fusion system the metal hydrogen systems/metal hydrides are dispersed in a form of fine grains and immersed in a sea of mobile s-electrons and Li^+ ions. The amount of Li is not necessarily superior to the metal hydrogen systems since the mobile Li^+ ions and s-electrons hold their macroscopic correlation. Here, hydrogen H means, generally, protonium ^{1}H, deuterium D and tritium T unless otherwise provided.

We begin with the elementary two body nuclear fusion between hydrogen ions via a H-H bond collapse in the metal hydrogen systems. The hydrogen ions are strongly screened by valence electrons and nearly localized mobile s-electrons in hybridized states of the metal hydrogen systems/hydride molecules [15]. This effect is specified by the short-range screening length D_s. Within the range, low energy fusion reactions are most effectively enhanced.

The ions are confined in respective bond spaces with a number density,

$$n_\mathrm{i} = (4\pi/3)^{-1} a_\mathrm{i}^{-3}, \tag{4}$$

where a_i denotes the ion radius. The screened nuclear fusion rate per number density is given by,

$$R_\mathrm{s} = \lambda_{\mathrm{HH}'} n_\mathrm{H} n_{\mathrm{H}'} = \frac{2S(0) r^*_{\mathrm{HH}'}}{(1+\delta_{\mathrm{HH}'})\hbar} \cdot \sqrt{\frac{D_\mathrm{s}}{r^*_{\mathrm{HH}'}}} \exp\left[-\pi\sqrt{\frac{D_\mathrm{s}}{r^*_{\mathrm{HH}'}}}\right] \cdot n_\mathrm{H} n_{\mathrm{H}'} \,, \tag{5}$$

between the hydrogen ions at low temperature [1]. Here $\lambda_{\mathrm{HH}'}$ denotes the fusion constant, $\delta_{\mathrm{HH}'} = 1$ for the same kind of hydrogen $\mathrm{H}' = \mathrm{H}$ and 0 for a different kind of hydrogen $\mathrm{H}' \neq \mathrm{H}$. The nuclear Bohr radius $r^*_{\mathrm{HH}'}$ is represented by the electron mass $m_\mathrm{e} = 0.511$ MeV$/c^2$, the average nucleon mass $m_\mathrm{N} = 931.5\,\mathrm{MeV}/c^2$, reduced ion mass $\mu_{\mathrm{HH}'}$ and the Bohr radius a_B,

$$r^*_{\mathrm{HH}'} = \frac{m_\mathrm{e}}{2\mu_{\mathrm{HH}'}} \cdot a_\mathrm{B} = 1.45 \times 10^{-14} \frac{A_\mathrm{H} + A_{\mathrm{H}'}}{A_\mathrm{H} A_{\mathrm{H}'}} \ (\mathrm{m}) \,, \tag{6}$$

provided,

$$\mu_{\mathrm{HH}'} = \frac{A_\mathrm{H} A_{\mathrm{H}'} m_\mathrm{N}}{A_\mathrm{H} + A_{\mathrm{H}'}} \,, \tag{7}$$

where A_H and $A_{\mathrm{H}'}$ denote mass numbers of H- and H'- ions, respectively. The factor $S(0)$ refers to the reaction cross-section factor.

For the hydrogen burning fusion reactions, $S(0)$ and Q-values are tabulated in Table I [16, 17]. For these reactions, Eq.(5) is represented, respectively,

$$\mathrm{H}(\mathrm{p}, \mathrm{e}^+\nu_\mathrm{e})\mathrm{D} \ : \ R_\mathrm{s} = 1.5 \times 10^{-45} n_\mathrm{H}^2 \sqrt{\frac{D_\mathrm{s}}{2.9 \times 10^{-14}}} \exp\left[-\pi\sqrt{\frac{D_\mathrm{s}}{2.9 \times 10^{-14}}}\right] \,, \tag{8}$$

$$\mathrm{D}(\mathrm{p}, \gamma)^3\mathrm{He} \ : \ R_\mathrm{s} = 1.2 \times 10^{-25} n_\mathrm{H} n_\mathrm{D} \sqrt{\frac{D_\mathrm{s}}{2.3 \times 10^{-14}}} \exp\left[-\pi\sqrt{\frac{D_\mathrm{s}}{2.3 \times 10^{-14}}}\right] \,, \tag{9}$$

$$\mathrm{D}(\mathrm{d}, \mathrm{p})\mathrm{T} \ : \ R_\mathrm{s} = 1.2 \times 10^{-22} n_\mathrm{D}^2 \sqrt{\frac{D_\mathrm{s}}{1.5 \times 10^{-14}}} \exp\left[-\pi\sqrt{\frac{D_\mathrm{s}}{1.5 \times 10^{-14}}}\right] \,, \tag{10}$$

$$\mathrm{D}(\mathrm{d}, \mathrm{n})^3\mathrm{He} \ : \ R_\mathrm{s} = 1.1 \times 10^{-22} n_\mathrm{D}^2 \sqrt{\frac{D_\mathrm{s}}{1.5 \times 10^{-14}}} \exp\left[-\pi\sqrt{\frac{D_\mathrm{s}}{1.5 \times 10^{-14}}}\right] \,. \tag{11}$$

Here, R_s, n and D_s are given, respectively in the units of $\mathrm{s}^{-1}\mathrm{m}^{-3}$, m^{-3} and m.

4. Chemonuclear Fusion via Hydrogen Bond Collapse

In the fusion system or metal hydride molecules, dimensionless de Broglie wave length Λ_i of atoms with mass number A_i is very small.

$$\Lambda_\mathrm{i} = \frac{\hbar}{a_\mathrm{e}} \left(\frac{2\pi}{A_\mathrm{i} m_\mathrm{N} k_\mathrm{B} T} \right)^{\frac{1}{2}} << 1 \, . \tag{12}$$

Here a_e denotes the Wigner-Seitz radius [18]. The wave mechanical effects are therefore negligible on the atoms. Furthermore, hydrogen pairs reacting within the bonds do not disturb so much surrounding spectator atoms in the molecules because their interaction can be treated as that between two screened particles. These features may confirm the validity of rate enhancement evaluation in the scheme of semi-classical dynamics as far as concerning the nuclear fusion under the condition of hydrogen ions. Their dynamics may be describable as those of electron screened ion cores immersed in the sea of mobile Li^+ ions and s-electrons.

Within the bonds, the hydrogen atoms collide with each other e.g. at $T = 773$ K with the frequency,

$$\nu_\mathrm{H-H} = k_\mathrm{B} T/\hbar = 1 \times 10^{14} \ \mathrm{s}^{-1} \, , \tag{13}$$

which is much smaller than the gyration frequency ν_s of 1s-orbital electrons of hydrogen atoms,

$$\nu_\mathrm{s} = \upsilon_\mathrm{B}/2\pi a_\mathrm{B} = \alpha c/2\pi a_\mathrm{B} = 7 \times 10^{15} \ \mathrm{s}^{-1} \, , \tag{14}$$

where υ_B and α denote the Bohr speed and the fine structure constant, respectively. This means that the orbital electrons adjust their electronic states continuously and smoothly to nuclear collision processes. Thereby nuclear fusion reactions take place via collapse of the hydrogen bonds forming quasi-He atoms in which pairs of oscillatory hydrogen nuclei coexist at centers of common 1s-orbitals.

During the collapse, the volume of two screened hydrogen atoms shrinks by one order of magnitude associated with the Gibbs energy change ΔG_r [10]. Normally the most quasi-He atoms do not necessarily proceed to the nuclear fusion and decay into pairs of hydrogen atoms as before. However, in the Li-liquid, the hydrogen bonds are immersed in the sea of mobile s-electrons and Li^+ ions which reveal the thermodynamic activity of liquid and sustain the shrinking thereby prolong live times of the quasi-He atoms by the factor,

$$K = \exp \left[-\Delta G_\mathrm{r}/k_\mathrm{B} T \right] \tag{15}$$

resulting in the enormously enhanced rate KR_s of chemonuclear fusion caused by the zero-point oscillation.

This result is based on the general thermodynamic relation that the fractional change of reaction rate is exactly proportional to the entropy change in the universe [14].

5. Evaluation of Enhancement Factor

For the fusion reaction producing a He nucleus via a quasi-He atom formation,

$$\mathrm{H} + \mathrm{H} \longrightarrow \text{quasi-He} \longrightarrow \mathrm{He} \, , \tag{16}$$

the Gibbs energy change ΔG_r is evaluated by,

$$\Delta G_\mathrm{r}(\text{quasi-He}) = \Delta G_\mathrm{r}(\mathrm{He}) = \Delta G_\mathrm{f}(\mathrm{He}) - 2\Delta G_\mathrm{f}(\mathrm{H}). \tag{17}$$

Here, ΔG_f denotes the formation Gibbs energy for an atom or ion in the standard state condition and tabulated in the chemical thermodynamic data [12].

For the hydrogen atom or H^- and H^+ ions in the hybridized state [15] of hydride molecules immersed in the Li-liquid, the value of formation Gibbs energy $\Delta G_\mathrm{f}(\mathrm{H_{liq}})$ would be in between $\Delta G_\mathrm{f}(\mathrm{H^-_{liq}})$ and $\Delta G_\mathrm{f}(\mathrm{H^+_{liq}})$. Here the values of ΔG_f for the liquid ions are essentially the same with the aqueous ions, that is, $\mathrm{H^+_{liq}} = \mathrm{H^+_{aq}}$ along the argument in Section.2.

The value $\Delta G_\mathrm{f}(\mathrm{H^-_{liq}})$ can be evaluated from the relation,

$$\Delta G_\mathrm{f}(\mathrm{H^-_{liq}}) \approx \Delta G_\mathrm{f}(\mathrm{D^-_{liq}}) = \Delta G_\mathrm{f}(\mathrm{LiH}) - \Delta G_\mathrm{f}(\mathrm{Li^+_{liq}}), \tag{18}$$

provided from the data [12],

$$\Delta G_\mathrm{f}(\mathrm{LiH}) \approx \Delta G_\mathrm{f}(\mathrm{LiD}) = -0.78\ (\mathrm{eV}), \tag{19}$$

and

$$\Delta G_\mathrm{f}(\mathrm{Li^+_{liq}}) = \Delta G_\mathrm{f}(\mathrm{Li^+_{aq}}) = -3.04\ (\mathrm{eV}), \tag{20}$$

then, we have

$$\Delta G_\mathrm{f}(\mathrm{H^-_{liq}}) \approx \Delta G_\mathrm{f}(\mathrm{D^-_{liq}}) = +2.26\ (\mathrm{eV}). \tag{21}$$

The formation Gibbs energy $\Delta G_\mathrm{f}(\mathrm{H_{liq}}) \approx \Delta G_\mathrm{f}(\mathrm{D_{liq}})$ for a hydrogen atom / ion in the hybridized state of molecules is obtained as,

$$\Delta G_\mathrm{f}(\mathrm{H_{liq}}) = \frac{1}{2}\left\{\Delta G_\mathrm{f}(\mathrm{H^-_{liq}}) + \Delta G_\mathrm{f}(\mathrm{H^+_{liq}})\right\} = \frac{1}{2}\Delta G_\mathrm{f}(\mathrm{H^-_{liq}}) = +1.13\ (\mathrm{eV}), \tag{22}$$

recalling $\Delta G_\mathrm{f}(\mathrm{H^+_{liq}}) = \Delta \mathrm{G_f}(\mathrm{H^+_{aq}}) = 0$.
Finally we have

$$\Delta G_\mathrm{r}(\text{quasi-He}) = \Delta G_\mathrm{r}(\mathrm{He}) = \Delta G_\mathrm{f}(\mathrm{He}) - 2\Delta G_\mathrm{f}(\mathrm{H_{liq}}) = -2.26\ (\mathrm{eV}), \tag{23}$$

since $\Delta G_\mathrm{f}(\mathrm{He}) = 0$. The value in Eq.(23) is consistent with the value evaluated based on the Born's microscopic model [6]. Recalling Eq.(15), we have the enhancement factor of chemonuclear H-H fusion via the collapse of H-H bond immersed in the Li-liquid as,

$$K(\mathrm{He}) = 5.4 \times 10^{14}\ \text{ at } T = 773\mathrm{K}\ (k_\mathrm{B}T = 0.0666\,\mathrm{eV}). \tag{24}$$

The enhancement gains at lower temperatures, for instance, at T=460K just above the melting point of metallic Li, $K = 6.1 \times 10^{24}$.

6. Evidence of Coherent Chemonuclear Fusion

In the scheme of chemonuclear fusion where hydrogen ion clusters undergo the fusion, the rate enhancement may be further intensified by the coherent bond collapse [8]. In fact we have observed a coherent chemonuclear fusion of molecular D_2 ions implanted with a slow speed $v_\mathrm{i} < \alpha Z_\mathrm{Li} c$ on a Li-liquid surface [9]. During the collision, pairs of atoms in the ions keep their correlation and induce coherent atomic/ionic collisions. Such the coherent collisions were already known in the 1970's, for instance, in the coherent sputtering phenomena of molecular ions [19].

In our experiment [9], observed rate enhancement ($\sim 10^{20}$) of molecular D_2 ion induced fusion was close to the square of rate enhancement of deuteron induced fusion. This enhancement exceeds by far ordinary rate enhancement proportional to the number of correlating particles in the Bose-Einstein condensation.

Furthermore in the molecular D_2 ion induced fusion, we observed the coherent emission of twin α-particle pairs which indicated the coherent decay of an intermediate compound nuclear pair $(^8\mathrm{Be})_2$. In this connection the author remembers the same kind of phenomenon, the coherent decay of positronium molecule Ps_2 into degenerate annihilation photon pairs [20].

7. Intensified Rate Enhancement of Fusion via Coherent Collapse of Hydrogen-Hydrogen Bonds

Since hydrogen bonds consisting of the same kind of ions are bosons irrespective of spins of the ions, they undergo coherent fusion coupled with the coherent collapse of H-H bonds. Thanks to the liquid thermodynamic activity, the coherent fusion intensifies further the enormous rate enhancement.

For the chemonuclear fusion via the coherent collapse of n-sets of H-H bonds,

$$n(\mathrm{H}+\mathrm{H}) \longrightarrow n(\text{quasi-He}) \longrightarrow n\mathrm{He}\,, \tag{25}$$

the Gibbs energy change $\Delta G_{\mathrm{r}}(n\mathrm{He})$ is given by, recalling Eq. (23),

$$\Delta G_{\mathrm{r}}(n\mathrm{He}) = n\Delta G_{\mathrm{r}}(\mathrm{He}) = -2.26n\ (\mathrm{eV})\,. \tag{26}$$

The enhancement factors of chemonuclear fusion at the temperature $T = 773\mathrm{K}$ via the n-fold, doubly -and trebly- coherent collapse of H-H bonds are, respectively,

$$K(n\mathrm{He}) = K^n(\mathrm{He}) = (5.4 \times 10^{14})^n\,, \tag{27}$$

$$K(2\mathrm{He}) = 2.9 \times 10^{29}\,,\ K(3\mathrm{He}) = 1.6 \times 10^{44}. \tag{28}$$

The above values are superior to the rate enhancement of hydrogen burning pycnonuclear reactions in white-dwarf progenitors of supernovae [5].

In the case of mixed H and D systems, however, a coherent collapse of two H-D bonds is unlikely because another coherent H-H and D-D collapse is more favorable.The $\mathrm{D}(\mathrm{p},\gamma)^3\mathrm{He}$ reactions via the coherent H-D bond collapse thus are unrealized.

8. Chemonuclear D-D Fusion through Coherent Chemonuclear H-H Fusion

In the Li permeated metal hydrogen systems with neither deuteride nor D_2 gas, still the chemonuclear D-D fusion takes place through the coherent chemonuclear H-H fusion. In the $\mathrm{H}(\mathrm{p},\mathrm{e}^+\nu_{\mathrm{e}})\mathrm{D}$ reaction via the H-H bond collapse, D atoms/ions are produced in rest because their recoil energy in the positron and neutrino emission is below 0.1 eV. This implies that new D-D bonds are formed through the coherent chemonuclear H-H fusion in the systems.

The D atoms/ions difuse in the metal hydrogen systems. For instance, the diffusion coefficient reaches $D_{\mathrm{o}} = 4 \times 10^{-8}\ \mathrm{m}^2/\mathrm{s}$ in the $\mathrm{Mg_2NiD_4}$ crystal [21]. This implies that the D atoms produced favor to cluster at the same sites in the crystal due to Bose-Einstein condensation and take place the coherent chemonuclear D-D fusion. These features provide us a new control scheme of energy released in the fusion through tuning precisely the fraction of D_2 gas because the intrinsic H-H and D-D nuclear fusion rates differ by a factor of some billions in Ni- and Pd-hydrides, as seen in Table II.

9. Li Permeated Metal Hydrogen Systems

As explained in Section 2, our slow H-, D-, D_2- and Li-ion implantation experiments have given fundamental evidences of chemonuclear fusion together with coherent chemonuclear fusion and confirmed the actuality of Li-liquid thermodynamic activity leading to the enormous rate enhancement. This result was based on simultaneous measurements of α-particle and neutron emission and calorific power released in the nuclear fusion.

The observed rate of chemonuclear fusion depended, however, extremely and delicately on the states of exposed Li-liquid target surfaces. For instance at a vacuum $\sim 10^{-7}$ Torr, it is difficult to keep clean the Li-liquid target surface within 1 sec under keeping out dissociation of implanted D_2 ions on the surface except for simultaneous sputtering clean up treatments. One of solution to this problem would be reactant mixing with liquid Li-alloy, for instance, in a form of Li permeated metal hydrogen systems or metal hydrides.

There are many metal hydrides but here we confine ourselves to call only the density and the screening length of hydrogen atoms in the familiar metal hydrides and select their values from literatures. In Table II listed are parameters pertinent to the electron screened nuclear fusion reactions [22]. The values adopted for NiD have been estimated from those for TiD_2 and PdD based on the data which indicate that both the heat of hydrogen dissolution and the lattice parameter of Ni are closer to those of Pd than Ti [23].

Also listed are the nuclear fusion rate and power released. For the power released in the H-H fusion, average values of about 60% carried out by neutrinos have been subtracted [9]. The D-D fusion rates and the powers are the respective sum of the (d,p) and (d,n) reactions. Here the $D(p,\gamma)^3He$ reaction has been disregarded because any significant contribution caused by the coherent bond collapse is unlikely in the chemonuclear H-D fusion along the argument presented in Section.7.

As seen in the cases of Pd and Ni in Table II, the powers released in the D-D fusion are bigger than those in the respective H-H fusion by a factor over one billion. This implies that in a system of Li permeated metal and pure H_2 still the chemonuclear D-D fusion takes place. The rate equation of chemonuclear fusion shows clearly that almost all energy released in the pure hydrogen system is due to the D-D fusion in succession of the coherent H-H fusion as argued in Section.11.

10. Dynamics of Chemonuclear Fusion in Test Reactor

The basic configuration of chemonuclear fusion test reactor is a Li permeated grain metal hydrogen system sandwiched in between the preheating and cooling plates and a hydrogen gas reservoir of some bars pressure. Compression is effective to gain the Gibbs energy of hydrogen gas especially at high temperature so as to improve the dissolution of hydrogen gas into the grain metal to form steadily metal hydrides.

There are various kinds of metal hydrides. Some hydrides are available to the chemonuclear fusion [24]. However as argued in Section.9, even in a Li permeated metal hydrides with neither deuteride nor D_2 gas, the chemonuclear D-D fusion takes place and generates neutrons, protons, tritons and ^{3}He ions of a few MeV energies. Neutrons are captured by ^{6}Li after slowing down and produce tritons and α-particles. All charged particles induce also successive chemonuclear reactions with the Li permeated metal hydrides and may produce radioactive elements in some cases.

In consideration of these factors, light or medium weight metal hydrides would be preferable, for instance, $\mathrm{MgCaH_{3.72}}$ or $\mathrm{Mg_2NiH_4}$ [24]. For the latter we may apply the treatment for the hydride NiH in Section.9. In Fig.1 is shown the crystal structure of $\mathrm{Mg_2NiD_4}$. In the crystal, hydrogen (H/D) ions cluster up to six at octahedral (O) sites and indicate the possibility of trebly coherent chemonuclear D-D fusion.

Suppose we may charge a test reactor with Ni/$\mathrm{Mg_2Ni}$ grains, mixed LiH/$\mathrm{MgH_2}$ powder and hydrogen gas. When we apply a pressure of 10 bars to the gas, its Gibbs energy increases by 9kJ/mol=0.09eV/molecule at T=773K(k_BT=0.067eV) [25] and results in a gain of dissolution into the Ni/$\mathrm{Mg_2Ni}$ grains by a factor of exp(0.09 / 0.067) = 3.8. This implies the gain of fusion rate and hereby power released by a factor of 15. Through this treatment we may convert the Ni/$\mathrm{Mg_2Ni}$ grains substantially into the hydride NiH/$\mathrm{Mg_2NiH_4}$ grains in which some 10 percent of hydrogen atoms occupy O-sites in the hydride grain crystals forming 3-pairs as seen in Fig.1. This leads to the trebly coherent collapse of H-H bonds with the enhancement of 1.6×10^{44} at 773K recalling Eq.(28).

We begin a test experiment by pre-heating the reactor at room temperature. At first, $\mathrm{MgH_2}$ molecules dissociate and form $\mathrm{Mg_2Ni}$ or $\mathrm{Mg_2NiH_4}$ molecules. The LiH molecules dissociate through the physisorption and then chemisorption processes on the surface of Ni/$\mathrm{Mg_2Ni}$ grains more quick than hydrogen molecules due to their large dipole moment $p(\mathrm{LiH}) = 2.0 \times 10^{-29}(\mathrm{C \cdot m})$ comparable with $p(\mathrm{LiF}) = 2.1 \times 10^{-29}(\mathrm{C \cdot m})$ and weak bond strength $D(\text{Li-H}) = 2.47(\mathrm{eV})$ compared to $D(\text{H-H}) = 4.52(\mathrm{eV})$. The dissociated H atoms are absorbed by the grains leaving $\mathrm{Li^+}$ ions and mobile s-electrons which reveal the thermodynamic activity of liquid resulting in the chemonuclear reactions. When the Li ions and mobile s-electrons moistens the hydride grains if nessecary under an activation by corona discharge or electron or light irradiation, the coherent H-H fusion starts up with an initial large enhancement and quickly heats up the hydride. This produces D-atoms in the hydride together with lattice vacancies which are refilled by H-atoms under the presence of the pressure $\mathrm{H_2}$ gas. The D-atoms diffuse with the diffusion coefficient of $\mathrm{D_0} \sim 10^{-7}\ \mathrm{m^2/s}$ at a high temperature towards the full clustering at O-sites [26, 27], hereby the trebly coherent D-D fusion takes place resulting in the reaction energy released far larger than the H-H fusion as seen in Section.11.

11. Coupled H-H and D-D Fusion Rate Equations

Here we introduce two prior conditions:

1) The total number of hydrogen atoms / ions is conserved in the metal hydride under the presence of pressure $\mathrm{H_2}$ gas in the metal hydrogen system.

$$n_\mathrm{H} + n_\mathrm{D} = n_0 \equiv n_\mathrm{H}(t=0)\ ,\ n_\mathrm{D}(t=0) = 0\ . \tag{29}$$

2) Though the enhanced fusion constants $\lambda_\mathrm{H} \equiv K\lambda_\mathrm{HH}$ and $\lambda_\mathrm{D} \equiv K\lambda_\mathrm{DD}$ are functions of temperature and thereby time as seen in Eq.(15), the ratio $\lambda_\mathrm{H}/\lambda_\mathrm{D} = \lambda_\mathrm{HH}/\lambda_\mathrm{DD}$ is time independent, recalling Eq.(5).

For the H-atoms, the rate equation is represented in the form,

$$\frac{dn_{\rm H}}{dt} = -KR_{\rm s} = -\lambda_{\rm H} \cdot n_{\rm H}^2 \,, \tag{30}$$

recalling again Eqs.(5) and (15). For the D-atoms recalling Eq.(30),

$$\frac{dn_{\rm D}}{dt} = -\frac{1}{2} \cdot \frac{dn_{\rm H}}{dt} - \lambda_{\rm D} \cdot n_{\rm D}^2 = \frac{\lambda_{\rm H}}{2} \cdot n_{\rm H}^2 - \lambda_{\rm D} \cdot n_{\rm D}^2 \,. \tag{31}$$

Here, the first term in the right-hand side comes from the formation of D-atoms caused by the H-H fusion. Recalling Eq.(29), Eq.(31) is rerepresented in the form,

$$\frac{dn_{\rm D}}{dt} = \frac{\lambda_{\rm H}}{2}(n_0 - n_{\rm D})^2 - \lambda_{\rm D} \cdot n_{\rm D}^2 \,,$$

or

$$n_{\rm D}^2 = \frac{\lambda_{\rm H}}{2\lambda_{\rm D}} \cdot n_0^2 \left[1 - \exp(-n_0 \int_0^t \lambda_{\rm D} dt)\right] . \tag{32}$$

At the equilibrium state $t \to \infty$, Eq.(32) becomes,

$$n_{\rm D}(t \to \infty) = \sqrt{\frac{\lambda_{\rm H}}{2\lambda_{\rm D}}} \cdot n_0 \,, \tag{33}$$

and the ratio of H-H and D-D fusion rates is,

$$\frac{dn_{\rm D}/dt}{dn_{\rm H}/dt} = \frac{\lambda_{\rm D} \cdot n_{\rm D}^2}{\lambda_{\rm H} \cdot n_{\rm H}^2} = \frac{n_0^2}{2n_{\rm H}^2} \approx \frac{1}{2} \,, \tag{34}$$

The ratio of H-H and D-D fusion powers released is

$$\frac{P_{\rm D-D}}{P_{\rm H-H}} = \frac{{\rm Q(D-D)}dn_{\rm D}/dt}{{\rm Q(H-H)}dn_{\rm H}/dt} = \frac{\rm Q(D-D)}{\rm 2Q(H-H)} = 6.5 \,. \tag{35}$$

Here, the average energy of about 0.84MeV carried out by neutrinos in the $\mathrm{H(p, e^+\nu_e)D}$ reactions has been subtracted from the Q-value in Table I.

Eq.(35) indicates that 87% energy released is ascribable to the D-D fusion still in a metal pure H- hydrogen system. This situation would be much more remarkable in a system of ordinary hydrogen which contains D_2 gas of a fraction of about 1/6000. This contaminant D_2 gas results in an energy released by a factor $(1.5 \times 10^{-27})(6000)^{-2}/5.2 \times 10^{-37} = 80$ with respect to the H-H fusion power recalling the NiH/NiD data in Table II.

12. Performance of Test Reactor

The theory of chemonuclear fusion predicts:

i) In a test reactor system charging Li permeated Ni/Mg_2Ni fine grains and hydrogen gas, we expect the trebly coherent chemonuclear H-H and D-D fusion but not H-D fusion which generates 5.5MeV gamma ray.

ii) The solution of coupled H-H and D-D fusion rate equations predicts that most (87%) of power released is ascribable to the D-D fusion still in the metal pure H_2 gas system.

iii) In the reactor system charging ordinary hydrogen gas, contribution from the H-H fusion is only 1.1% of the total power released. Most power is released in the D-D fusion caused by D_2 gas which is found by a fraction of about 1/6000 of ordinary hydrogen gas. Even if we take into account the fewer adsorption efficiency of D_2 gas by about 8% compared to H_2 gas [28], the contribution from the H-H fusion is still limited to 4.4%.

iv) For the trebly coherent fusion enhancement of about 1.6×10^{44} at T=773K and around 15% occupation fraction of ordinary hydrogen atoms / ions at O-sites in the Ni hydride grain crystals, we may expect the power output of the D-D fusion close to $1\mathrm{GW} \cdot \mathrm{m}^{-3}$ which is over one million times as dense as the solar interior power density. This means that in the reactor system charging 1 mol Ni/Mg_2Ni grains and ordinary hydrogen gas, expected power output is some kW.

v) In the D-D fusion, neutrons, protons, tritons, and ^{3}He ions of a few MeV energies are produced. Alpha particles are also produced in the $^6\mathrm{Li(n,t)}^4\mathrm{He}$ reaction. Besides the neutrons, substantial charged particles undergo the successive nuclear reactions with the Li permeated Ni/Mg_2Ni grains. However, most of Cu isotopes produced in the (p,n), (t,n) and (^{3}He,p) reactions go back to Ni isotopes through β^+ and EC decays.

13. Comparison between Chemonuclear Fusion Theory and Bologna Experiment

Due to the lack of detailed information on the Bologna experiment, it is not possible to compare rigorously the present prediction and the experimental results. Nevertheless, the observation results of Bologna group seem to be suggestive some coincidences of the prediction in Section 12 [29-33].

1) In Bologna, no 5.5 MeV gamma ray was observed as prediction i). Instead later, the 0.511 MeV annihilation gamma ray might be detected and correspond to the occurence of the reaction Eq.(8).

2) The observed power output of the Bologna device charging some tens gram Ni and ordinary hydrogen gas might be some kW. This is consistent with prediction ii), iii) and iv).

3) The Bologna data on the power output is said to be gained through supplying D_2-gas, which correspond to prediction iii).

4) Corresponding to prediction ii), iii), iv) and vi), a very small percent fraction of Ni might be transmuted into Cu during a few months continued operation of device. A small part of annihilation gamma rays observed might be due to the positron decay of ^{60}Cu produced in the $^{58}\mathrm{Ni}(^3\mathrm{He,p})^{60}\mathrm{Cu}$ reaction.

14. Supernova on Earth

Chemonuclear fusion was found to be pycnonuclear reactions in the metallic Li-liquids. Enormous enhancement mechanism in both reactions is common to ionic reactions in metallic liquids. The enhancement is common bulk / collective features of spontaneous reactions caused by the thermodynamic activity of the liquids. Though the present theory is rather simple, predicted enhancements seem to be reliable because they are evaluated empirically based on the thermodynamic data.

The chemonuclear fusion opens ways towards the wasteless energy resources and has the significance "Supernova on Earth".

References

1. S.Ichimaru and H.Kitamura: Phys. Plasma. **6** (1999) 2649.
2. A.G.W. Cameron: Astrophys. J. **130** (1959) 916.
3. B. Jancovici: J. Stat. Phys. **17** (1977) 357.
4. S. Ichimaru and H. Kitamura: Publ. Astron. Soc. Jpn. **48** (1996) 613.
5. S. Ichimaru: Phys. Lett. **A266** (2000) 167.
6. H. Ikegami: Jpn J. Appl. Phys. **40** (2001) 6092. See also No.1 paper in Ref.7.
7. H. Ikegami and R. Pettersson: "Evidence of Enhanced Nonthermal Nuclear Fusion" Bull. Inst. Chem. (Uppsala Univ. Uppsala, September 2002) No.3; http://www.inst.kemi.uu.se/Bulletin/Bulletinen_1.pdf
8. H. Ikegami: "Ultradense Nuclear Fusion in Metallic Lithium Liquid", Revised Edition of Swedish Energy Agency Document ER2006: **42** (Sakaguchi, Tokyo/Sakura, 2007) **3**-1 - **3**-30, Order fax: +81-43-498-4890, e-post: watanabe@sakaguchi.com (ed.1 available at publikationservice@energimyndigheten.se).
9. H. Ikegami and T. Watanabe: ibid. **4**-1 - **4**-21.
10. H. Ikegami: ibid. **1**-1 - **1**-22. The term "chemonuclear fusion" was coined by S. Kullander for this united atomic and nuclear reaction.
11. H. Ikegami and T. Watanabe: ibid. **2**-1 - **2**-12.
12. G. Aylward and T. Findlay: SI Chemical Data ed.3 (Wiley, Brisbane, 1998).
13. B.Widom: J. Chem. Phys. **39** (1963) 2808.
14. D. Kondepudi and I. Prigogine: Modern Thermodynamics (Wiley, Chichester, 1998).
15. Y. Fukai: The Metal Hydrogen System (Springer, 1993), Chap.6.
16. W.A. Fowler, G.R. Caughlan and B.A. Zimmerman: Ann. Rev. Astron. Astrophys. **5** (1967) 523.
17. A. Krauss, H.W. Becker, H.P. Trautvetter, O. Rolfs and K. Brand: Nucl. Phys. **A465** (1987) 150.
18. E. Wigner and F. Seitz: Phys. Rev. **43** (1933) 804.
19. H.H. Andersen and H.L. Bay: J. Appl. Phys. **45** (1974) 953.
20. H. Ikegami: Int. J. Quant. Chem. **83** (1999) 71.
21. Y. Fukai and H. Sugimoto: Adv. in Physics **34** (1985) 263.
22. S. Ichimaru: Rev. Mod. Phys. **65** (1993) 255.
23. P. Nordlander, J.K. Nørskov and F. Besenbacher: J. Phys. F **16** (1986) 1161.
24. G. Sandrock, S. Suda and L. Schlapbach: Hydrogen in Intermetallic Compounds II, L. Schlapbach ed. (Springer, 1992), Chap.5.

25. H. Sugimoto and Y. Fukai: Acta Metall. **40** (1992) 2327.
26. J. Völkl and Alefeld: Hydrogen in Metals I (Springer, 1978), Chap.12.
27. H. Wipf: Hydrogen in Metals III (Springer, 1997), Chap.3.
28. H. Conrad, G. Ertl and E.E. Latta: Surf. Sci., **41** (1974) 435.
29. A. Rossi: United States Patent Application, http://www.wipo.it/pctdb/en/wo.jsp?WO=200912544.
30. S. Focardi and A. Rossi: http://www.journal-of-nuclearphysics.com/?p=66, February 2010.
31. H. Essén and S.Kullander: Experimental test of a mini-Rossi device at the Leonardocorp: http://www.nyteknik.se/incoming/article3144955.ece/BINARY/Ladda+ner+Kullanders+oc h+Ess%C3%A9ns+rapport+%28pdf%29, Bologna 29 March 2011.
32. D. Bianchini: Experimental evaluation, http://www.journal-of-nuclear-physics.com.
33. G. Levi: Report on heat production during preliminary tests on the Rossi "Ni-H" reactor, http://www.journal-of-nuclear-physics.com.

Table I. Cross-section factors $S(0)$ and Q-values of hydrogen burning fusion reactions [16, 17].

	$S(0)$ (MeV $\cdot$ b)	Q (MeV)
$\mathrm{H(p, e^{+}\nu_e)D}$	3.4×10^{-25}	1.4
$\mathrm{D(p, \gamma)^3He}$	2.5×10^{-7}	5.5
$\mathrm{D(d, p)T}$	0.053	4.0
$\mathrm{D(d, n)^3He}$	0.050	3.3

Table II. Parameters in Eqs. (8) - (11) for the screened low temperature nuclear fusion rate and power released in metal hydrogen systems.

	$\mathrm{TiH_2/TiD_2}$	NiH/NiD	PdH/PdD
$n_{\mathrm{H}}/n_{\mathrm{D}}(\mathrm{m^{-3}})$	9.4×10^{28}	7.3×10^{28}	6.3×10^{28}
$D_{\mathrm{s}}(10^{-11}\mathrm{m})$	2.8	2.2	1.9
$R_s(\mathrm{s^{-1} \cdot m^{-3}}), \mathrm{H-H}$	1.7×10^{-28}	5.8×10^{-24}	1.8×10^{-21}
$R_s(\mathrm{s^{-1} \cdot m^{-3}}), \mathrm{D-D}$	1.0×10^{-21}	2.6×10^{-15}	8.9×10^{-12}
$P(\mathrm{W \cdot m^{-3}}), \mathrm{H-H}$	1.5×10^{-41}	5.2×10^{-37}	1.7×10^{-34}
$P(\mathrm{W \cdot m^{-3}}), \mathrm{D-D}$	5.9×10^{-34}	1.5×10^{-27}	5.2×10^{-24}

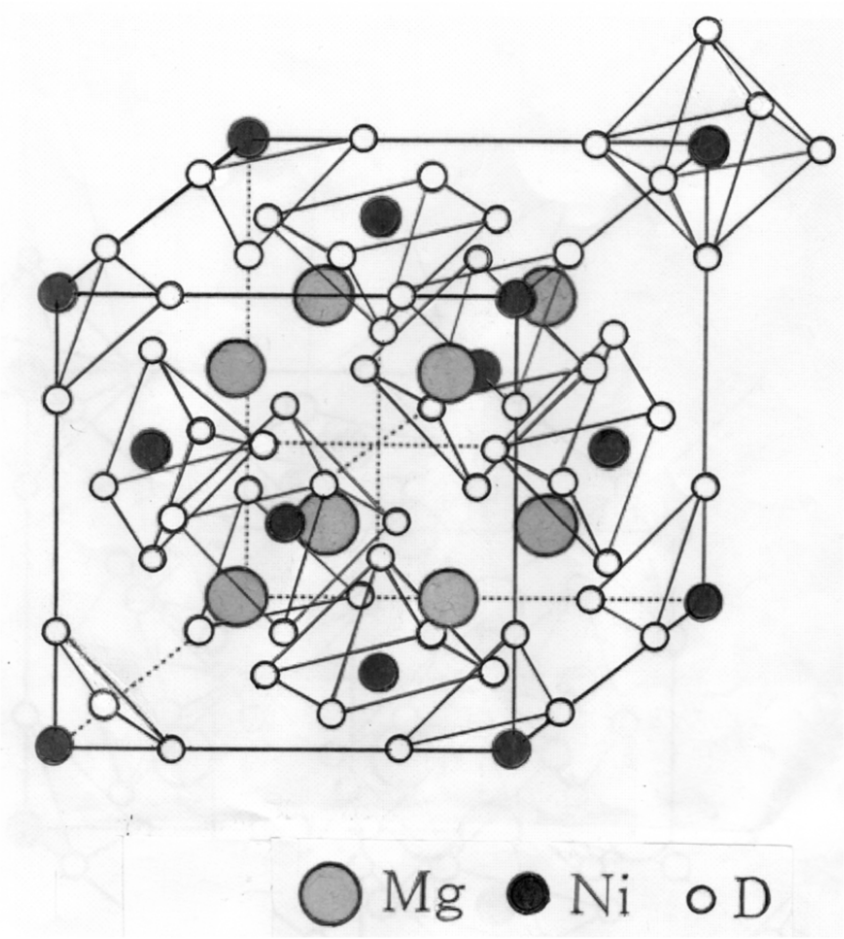

Fig 1: Crystal structure of Mg_2NiD_4 molecules [21]. Hydrogen (H/D) ions are strongly screened and correlated by valence electrons and nearly localized mobile s-electrons in hybridized states of molecules immersed in the metallic Li-liquid. These effects are, respectively, specified by the short range screening length D_s and the Gibbs energy change ΔG_r in the fusion reaction and lead to the enormously enhanced rate of chemonuclear fusion passing through the coherent collapse of hydrogen bonds.

Hydrogen and Helium Burning Chemonuclear Chain Reactions
– Big Bang Nucleosynthesis on Earth –

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In the scheme of chemonuclear fusion in the metallic Li-liquids, a number of slow light ions likely undergo nuclear fusion with the enormous rate enhancement caused by the thermodynamic activity in the liquids. The chemonuclear fusion holds the common reaction mechanism with the pycnonuclear reactions in the metallic-hydrogen liquids in stars e.g. white-dwarf supernova progenitors and keeps a possibility of new chain reactions sustained by charged particle chain carriers and neutrons. For example a thermodynamically stable Li-alloy liquid containing well dissolved boron is capable of chemonuclear chain reaction which is partly similar to the Big Bang nucleosynthesis reactions such as $^{11}\mathrm{B}(\alpha,\mathrm{n})^{14}\mathrm{N}$ and $^{11}\mathrm{B}(\alpha,\mathrm{p})^{14}\mathrm{C}$ reactions in an inhomogeneous universe. Furthermore, nuclei revealing the coupled t- and α-clustering features such as ^{11}B, ^{15}N, ^{23}Na, ^{27}Al and ^{31}P are capable of cyclic $(\alpha,\mathrm{p})-(\mathrm{p},\alpha)$ chemonuclear chain reactions in the liquid. The chain reactions would provide the waste free nuclear fusion reactors.

1. Chemonuclear Chain Reaction System

A reaction system under consideration is those of Li-alloy liquid where the reactant solute is uniformely dissolved forming a dilute stable alloy. The liquid contains α-particle capturing elements such as beryllium or boron. Some metal borides might be preferable because of their material characteristics such as the solubility in the Li-liquid. Furthermore produced α-particles and ^{7}Li ions take the essential part in the Li- and B- burning nucleosynthesis as well as other chain carriers, neutrons and tritons and lead to the chain reaction in the liquid.

The system is associated with a weak neutron source such as a $^{210}\mathrm{Po}-\mathrm{Be}$ source or exposed to a neutron flux so as to induce the thermal neutron capture reactions:

$$
\begin{gathered}
{}^{6}\mathrm{Li} + \mathrm{n} \longrightarrow \mathrm{t} + {}^{4}\mathrm{He}\,,\ {}^{6}\mathrm{Li}(7.5\%\ \text{abundance}), \\
\sigma_{\text{therm}} = 940\mathrm{b}\,,\ \mathrm{Q} = 4.78\,\mathrm{MeV}\,, \qquad (1)
\end{gathered}
$$

and

$$
\begin{gathered}
{}^{10}\mathrm{B} + \mathrm{n} \longrightarrow \alpha + {}^{7}\mathrm{Li}\,,\ {}^{10}\mathrm{B}(19.9\%\ \text{abundance})\,, \\
\sigma_{\text{therm}} = 3840\mathrm{b}\,,\ \mathrm{Q} = 2.79\,\mathrm{MeV}\,, \qquad (2)
\end{gathered}
$$

In the reaction Eq.(1), tritons and α-particles are emitted with respective energies, $E_\mathrm{t} = 2.73\,\mathrm{MeV}$ and $E_\alpha = 2.05\,\mathrm{MeV}$. In the reaction Eq.(2), α-particles and ^{7}Li-ions are produced with the energies $E_\alpha = 1.78\,\mathrm{MeV}$ and $E_\mathrm{Li} = 1.01\,\mathrm{MeV}$, respectively. All these charged particles or ions undergo chemonuclear reactions and play a role of chain carriers.

2. Chemonuclear Reaction in Metallic Liquids

The ions produced in the reactions Eqs.(1) and (2) reduce their speed in the liquid. When the energy of ions falls close to the nuclear stopping energy $A_1 Z_2^2 m_\mathrm{N} v_\mathrm{B}^2/2 = 0.025 A_1 Z_2^2\,(\mathrm{MeV})$ where the speed of ions becomes comparable to the velocity $Z_2 v_\mathrm{B}$ of electrons in the colliding atom 1s-orbital, the ions begin to capture electrons from the liquid atoms. Here, v_B, m_N, A_1 and Z_2 denote, respectively, Bohr speed, atomic mass unit, mass number of the ions and atomic number of liquid atoms. The presence of these captured electrons surrounding nuclei of the penetrating ions shield them from the electrons of the liquid. For the ions with energies around the nuclear stopping energy, their collisions in the liquid are thus not simply with electrons but are elastic and inelastic collisions between whole atoms [2]. This state of things of ions reflects to their united atomic and nuclear collision towards the united atomic and nuclear fusion [3]. Generally speaking, in the condensed matters, the electrons act to screen the Coulomb repulsion between the atomic nuclei and this screening effect becomes so remarkable especially in highly dense plasmas that rates of nuclear reactions at low temperatures are almost independent of the temperature and mostly depend on density of matters as seen in Eq.(5) in the first paper in this book – this is the origin of the word "pycnonuclear reaction" [4].

However, in some metallic liquids the very cohesive effect manifested in solidification of dense liquids tends to enhance greatly the reaction rate [5, 6]. In the metallic-hydrogen liquids in stars e.g. white-dwarf supernova progenitors, the enhancement of nuclear reaction rate by a factor of some 30 order of magnitude has been predicted [6, 7]. Substantial parts of the rate enhancement in the metallic-hydrogen liquids are ascribable to this effect.

While this enhancement is infeasible in gas plasmas like the solar interior, it is common to spontaneous reactions in liquids irrespective of kinds of liquids. In fact, essentially the same enormous enhancement has been observed in the chemonuclear fusion of slow ions in metallic Li-liquids [3, 8-15]. Observed rate enhancement was comparable with those of enhanced pycnonuclear reactions in the metallic-hydrogen liquids. This empirical fact is well explained in the Widom's general concept "thermodynamic activity of liquids" [16], which is bulk/collective features of spontaneous reactions caused by the thermodynamic force in the liquids consisting of reactant particles.

In general, the thermodynamic force is specified by the Gibbs energy (chemical potential) change in the reactions. This general thermodynamic relation is strictly independent of kinds of reactant particles and the nature of microscopic interparticle interactions [17].

3. Fusion Rate Enhancement

For the nuclear fusion,

$$\mathrm{X}_1 + \mathrm{X}_2 \longrightarrow \mathrm{M}\,, \tag{3}$$

the reaction cross-section is generally given in the form,

$$\begin{aligned}\sigma &= \frac{S(E)}{E^{1/2}(E+E_\mathrm{S})^{1/2}}\exp\left[-\pi\sqrt{\frac{E_\mathrm{G}}{E+E_\mathrm{S}}}\right] \\ &\sim \frac{S(E)}{E}\exp\left[-\pi\sqrt{\frac{E_\mathrm{G}}{E}}\right].\end{aligned} \tag{4}$$

Here,

$$\text{Gamov energy } E_\mathrm{G} \gg \text{ relative kinetic energy } E \gg \text{ screening energy } E_\mathrm{S}, \tag{5}$$

has been assumed. In Eq.(4), the exponential decay factor is the Coulomb penetration factor, while the cross-section factor $S(E)$ is a quantity intrinsic to the nuclear fusion. The Gamov energy E_G is given by,

$$E_\mathrm{G} = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 r_{12}^*} = \frac{0.0992(Z_1Z_2)^2 A_1 A_2}{A_1 + A_2}\,(\mathrm{MeV}). \tag{6}$$

In Eq.(6) r_{12}^* denotes the nuclear Bohr radius of colliding ions.

In the chemonuclear fusion, the reaction cross-section Eq.(4) is effectively magnified by the enhancement factor,

$$K = \exp\left[-\frac{\Delta G_r}{k_\mathrm{B}T}\right]. \tag{7}$$

Here, the factor K corresponds to the equilibrium constant of the atomic fusion reaction united with the nuclear fusion and k_B and T denote the Boltzmann constant and temperature of the liquid, respectively. The Gibbs energy change ΔG_r in the atomic fusion reaction is given by the formation energy $\Delta G_\mathrm{f}(\mathrm{X})$ of reactants and $\Delta G_\mathrm{f}(\mathrm{M})$ of product atom,

$$\Delta G_\mathrm{r} = \Delta G_\mathrm{f}(\mathrm{M}) - \Delta G_\mathrm{f}(\mathrm{X}_1^*) - \Delta G_\mathrm{f}(\mathrm{X}_2)\,, \tag{8}$$

where X_1^* is the atom/ion on traverse in the liquid.

In the Li-alloy liquids, atoms dissolved or produced in the reaction are more or less in the meta-stable states and partly in the ionized states. In fact, alloy data on the chemical potentials $\phi^*(\mathrm{Li})$ and $\phi^*(\mathrm{Be})$ which correspond to the formation energies $-\Delta G_{\mathrm{f}}(\mathrm{Li})$ and $-\Delta G_{\mathrm{f}}(\mathrm{Be})$ of atoms implanted in Be [18] provide, respective values fairly close to $-\Delta G_{\mathrm{f}}(\mathrm{Li}^+_{\mathrm{aq}})$ and $-\Delta G_{\mathrm{f}}(\mathrm{Be}^{++}_{\mathrm{aq}})$ [19]. This is understandable because the formation energies of aqueous light ions are identical to those of ions in fused salts and irrespective to kinds of solvents. Further, from the liquid alloy data analyses, an empirical approximation relationship,

$$\phi^* \equiv -\Delta G_{\mathrm{f}} = 2.5\chi \,, \tag{9}$$

has been deduced, where χ indicates Pauling electronegativity [20, 21]. In Table I, the values of ΔG_{f} of elements are listed.

For the ions on traverse, a reduction of the Gibbs energy is expected and this effect can be taken into account through introducing the effective charge of ions. The effective charge Z_{eff} is referred to the equilibrium charge state of the ions. A semi-empirical expression has been developed based on measurements on the transmission of ions through the films [22].

$$Z_{\mathrm{eff}} \sim Z_1 \left\{ 1 + \left[0.122 \left(\frac{E_{\mathrm{lab}}(\mathrm{keV})}{A} \right)^{1/2} Z_1^{-0.45} \right]^{-1/0.6} \right\}^{-0.6} . \tag{10}$$

Eq.(10) gives,

$$Z_{\mathrm{eff}}(^7\mathrm{Li\ ions\ of\ 1\ MeV}) \sim 1.86 \,. \tag{11}$$

Since the formation energy is a linear function of the effective number of orbital electrons of atoms/ions as seen in Table I,

$$\Delta G_{\mathrm{f}}(\mathrm{ion\ on\ traverse}) \sim [1 - (Z_{\mathrm{eff}}/Z_1)]\Delta G_{\mathrm{f}}(\mathrm{ion\ in\ rest}) \,. \tag{12}$$

Recalling Eqs.(11) and (12), we have,

$$\Delta G_{\mathrm{f}}(^7\mathrm{Li\ ions\ of} \sim 1\ \mathrm{MeV\ energy}) \sim -0.93\,(\mathrm{eV}) \,. \tag{13}$$

Referring to Table I, we obtain the Gibbs energy change and the enhancement factor of fusion reactions induced by hydrogen-, helium- and Li-ions as seen in Table II, III and IV. In the tables, the values of 2.5χ have been adopted for the formation Gibbs energy except for hydrogen ions on traverse for which

$$\Delta G_{\mathrm{f}}(\mathrm{H}^+) = 0 \,, \tag{14}$$

has been adopted as well,

$$\Delta G_{\mathrm{f}}(\mathrm{He}) = 0 \,. \tag{15}$$

4. Significance of Fusion Enhancement

It would be instructive to consider the mechanism of the enormous fusion enhancement from the microscopic view point by referring Fig.1 which indicates evolution of a ^{7}Li-^{7}Li chemonuclear fusion through formation of a united atom i.e. quasi- C-atom induced by a ^{7}Li atom or ion with a nuclear stopping energy $\sim$ 1 MeV produced in the reaction Eq.(2) in the Li-liquid.

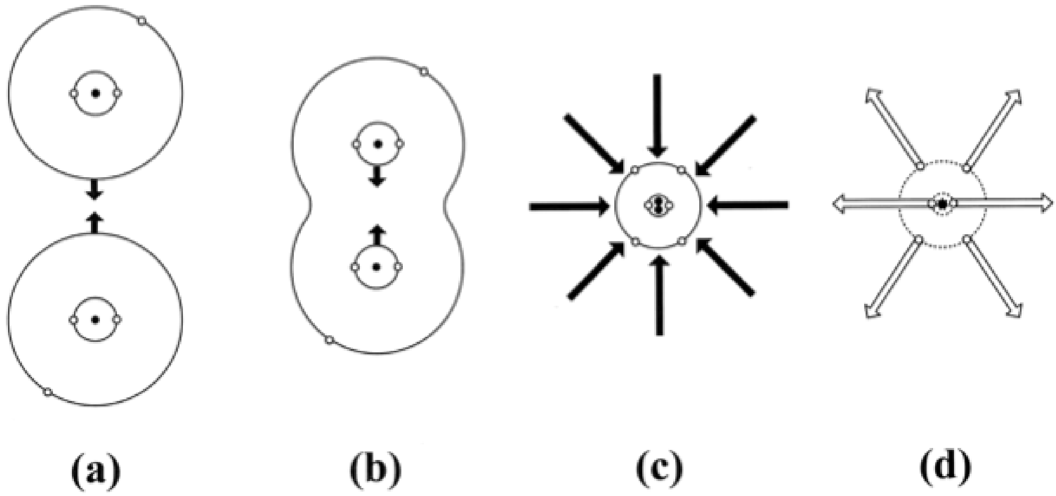

Fig. 1

(a) Twin colliding ^{7}Li atoms with a relative kinetic energy of $E = 0.50$ MeV in the metallic Li liquid. At this energy a nuclear collision takes place but all electrons (open circles) in the K- and L-shell orbitals adjust electronic states continuously and smoothly to the nuclear collision process, because the electrons gyrate much more rapidly than the colliding atom speed. The de Broglie wave length of mobile s-electrons of the Li liquid covers the space of some tens Li atoms and yields collective activity of the liquid. The liquid, consisting of Li ions and collective mobile s-electrons, thus takes the part of macroscopically correlated solvent reacting with the solute atoms/ions on traverse in the incorporated atomic and nuclear fusion reaction.

(b) Intermediate diatomic molecule Li_2 formation. On the first phase of collision process the colliding atoms tend towards diatomic molecule Li_2 formation at the minimal Gibbs energy point of chemical process. However this Gibbs energy is not the minimum point any longer for the atoms colliding with the energy. They are directed to form a new dense intermediate complex – quasi-C atom at their colliding or turning point.

(c) Quasi-C atom formation associated with the formation of an ultradense intermediate ^{7}Li-^{7}Li nuclear complex (twin closed circles). During the quasi-C atom formation, the colliding Li atoms collapse and result in sharp reduction in their atomic volume by a factor of 0.065 [12]. The cohesion in the liquid, exactly speaking, the thermodynamic force specified by the formation Gibbs energies, $\Delta G_\mathrm{f}(\mathrm{Li})$ and $\Delta G_\mathrm{f}(\mathrm{C})$ dominates the united atomic and nuclear fusion as seen in Eqs.(7) and (8). The collision time is characterized by the period of zero point oscillation of colliding nuclei at their classical turning point and very short $\tau_0 \sim 1 \times 10^{-21}$ s (see Eq.(3) in reference [12]). But under the presence of thermodynamic force (shown by octaval arrows), the collision time is prolonged by a factor of $\exp(-\Delta G_\mathrm{r}/k_\mathrm{B}T) \sim 8.0 \times 10^{32}$ in Table IV at the melting point of Li metal (460K) and a meta-stable united atom or quasi-C atom is formed. Inside the quasi-C atom a pair of colliding nuclei are confined within the sphere of zero-point oscillation $7.4 \times 10^{-5}\,(\mathrm{pm})^3$ (see Eq.(2) in ref.[12]) and form themselves into an ultradense intermediate nuclear complex. The density of this complex ($3 \times 10^{14}\,\mathrm{kg\,m^{-3}}$) is a billion times as high as the solar interior density ($\sim 10^5\,\mathrm{kg\,m^{-3}}$) and compared to white-dwarf progenitors of supernovae ($\sim 10^{13}\,\mathrm{kg\,m^{-3}}$).

The quasi-atoms formed in the metallic Li liquid thus is a packing unit of ultradense nuclear complex immersed in a macroscopically coherent sea of mobile s-electrons. There is a fair chance of chemonuclear reactions in the packing unit similarly to those in white-dwarf progenitors of supernovae. Now this elementary process of united atomic and nuclear fusion was found to be the pycnonuclear reaction itself, that is, the nuclear reaction induced by the zero point oscillation in the ultradense nuclear matters.

(d) Nuclear fusion releasing spectator neutrons via a highly excited intermediate nucleus $^{12}\mathrm{C}^*$ or a pair of $^{8}\mathrm{Be}^*$ and $^{4}\mathrm{He}$ nuclei. Rate of the nuclear fusion is enhanced by the factor of $\sim 10^{33}$ as seen in Table IV and most of colliding Li ions produced in the reaction Eq.(2) undergo nuclear fusion as seen in the next section.

5. H-, He- and Li-Burning Chemonuclear Chain Reactions

The Li-alloy liquid containing boron as a reactant solute is capable of sustaining the chemonuclear chain reaction which is partly similar to the Big Bang nucleosynthesis reactions such as the $^{11}\mathrm{B}(\alpha,\mathrm{n})^{14}\mathrm{N}$ and $^{11}\mathrm{B}(\alpha,\mathrm{p})^{14}\mathrm{C}$ reactions in an inhomogeneous universe [1]. In this section, the author takes up typical chemonuclear reactions inducing the chain reaction.

5.1. $^{11}\mathbf{B}(\mathbf{t},\mathbf{2n})^{12}\mathbf{C} \longrightarrow \mathbf{3}\cdot{}^{4}\mathbf{He}$ and $^{11}\mathbf{B}(\mathbf{t},\mathbf{n})^{13}\mathbf{C}$ Reactions

Tritons produced in the reaction Eq.(1) begin to take place the chemonuclear reactions after slowing down below the speed $5v_{\mathrm{B}}$ in the liquid. For instance, tritons with a relative kinetic energy $E \sim 0.3\,(\mathrm{MeV})$ i.e. $v \sim 2v_{\mathrm{B}}$ undergo the $^{11}\mathrm{B}(\mathrm{t},2\mathrm{n})^{12}\mathrm{C}$ reaction with the cross-section,

$$\sigma = 3\times10^{-6}S \sim 3\times10^{-3}\,(\mathrm{b})\,, Q = 7.48\mathrm{MeV} \tag{16}$$

recalling Eq.(4). Here, the value $S \sim 10^{3}\,(\mathrm{MeV}\cdot\mathrm{b})$ has been adopted [8]. The reactions take place through forming the quasi-C atoms and are expected to be enhanced by the factor $K \sim 1\times10^{14}$ in Table II. The effective cross-section enhanced in the liquid is $K\sigma \sim 3\times10^{11}\,(\mathrm{b})$ which is far over the stopping cross-section $\sim 10^{6}\,(\mathrm{b})$ [9] of tritons in the liquid and implies that all tritons most likely undergo successive reactions and breed neutrons.

5.2. $^{11}\mathbf{B}(\alpha,\mathbf{n})^{14}\mathbf{N}$ and $^{11}\mathbf{B}(\alpha,\mathbf{p})^{14}\mathbf{C}$ Reactions

Alpha-particles produced in the reactions, Eqs.(1) and (2) is around 2 MeV which corresponds to the speed of about $4.4v_{\mathrm{B}}$ and slower than the gyration speed $5v_{\mathrm{B}}$ of electrons in the inner shell orbitals of B-atoms. The α-particles are likely take place the chemonuclear fusion side by side with reducing their speed in the liquid, typically, at $E = 0.4$ MeV, $v = 2v_{\mathrm{B}}$ with the respective cross-section,

$$\sigma(\alpha,n) = 6\times10^{-12}S(\alpha,n) \sim 10^{-8}\,(\mathrm{b})\,,\ Q = 0.16\,\mathrm{MeV} \tag{17}$$

and

$$\sigma(\alpha,p) = 6\times10^{-12}S(\alpha,p) \sim 10^{-8}\,(\mathrm{b})\,,\ Q = 0.78\,\mathrm{MeV}\,. \tag{18}$$

The S-factors are estimated from the data on the reaction, $^{9}\mathrm{Be}(\alpha,\mathrm{n})^{12}\mathrm{C}$ [23]. Both reactions take place through the quasi-N atom formation in the liquid and their rate enhancement factor has been estimated in Table III as $K \sim 3 \times 10^{27}$. Both reactions undergo with the effective cross-sections $> 10^{19}$ (b) and indicate that all α-particles play the role of chain carriers in the chain reaction.

5.3. $^{7}\mathrm{Li}(^{7}\mathrm{Li}, 2\mathrm{n})^{12}\mathrm{C} \longrightarrow 3 \cdot {}^{4}\mathrm{He}$ reactions

In the chemonuclear chain reaction, ^{7}Li ions produced in the reaction Eq.(2) contribute to the lithium and boron burning and produce quite many chain carriers, neutrons and α-particles. The ^{7}Li ions have an energy of 1.01 (MeV) which is an energy in the range of nuclear stopping and undergo the successive $^{7}\mathrm{Li}(^{7}\mathrm{Li}, 2\mathrm{n})^{12}\mathrm{C}$ reaction immediately. The intrinsic reaction cross-section is,

$$\sigma = 1.2 \times 10^{-10} S \sim 2.4 \times 10^{-9}\,(\mathrm{b})\,,\ Q = 6.40\,\mathrm{MeV}\,. \tag{19}$$

Here, the values $S \sim 20\,(\mathrm{MeV} \cdot \mathrm{b})$ has been adopted [12].

Recalling the rate enhancement factor $K \sim 8 \times 10^{32}$ in Table IV, one may expect the effective cross-section of $K\sigma \sim 2 \times 10^{24}$ (b) which is far superior than the stopping cross-section of the ions.

5.4. $^{10}\mathrm{B}(^{7}\mathrm{Li}, \mathrm{n}\alpha)^{12}\mathrm{C}$ and $^{11}\mathrm{B}(^{7}\mathrm{Li}, 2\mathrm{n}\alpha)^{12}\mathrm{C}$ Reactions

The ^{7}Li ions produced in the reaction Eq.(2) undergo the burning of boron as well as the burning of lithium. The cross-section of the $^{11}\mathrm{B}(^{7}\mathrm{Li}, 2\mathrm{n}\alpha)^{12}\mathrm{C}$ reaction is,

$$\sigma = 1.4 \times 10^{-14} S\,(\mathrm{MeV} \cdot \mathrm{b}) > 10^{-12}\,(\mathrm{b})\,,\ Q = 5.01\mathrm{MeV}\,. \tag{20}$$

The same order of cross-section may also be expected for the $^{10}\mathrm{B}(^{7}\mathrm{Li}, \mathrm{n}\alpha)^{12}\mathrm{C}$ reaction. Both the reactions undergo through the formation of quasi-O atoms and remarkably enhanced.

Recalling the rate enhancement, $K = 2 \times 10^{28}$ in Table IV, the effective cross-section becomes 10^{16} (b). This means that all the ^{7}Li ions produced undergo the boron and lithium burning.

5.5. Nucleosynthesis in Chemonuclear Chain Reaction

The C and N nuclei in the chain reaction undergo further nucleosynthesis reactions, for instance, $^{14}\mathrm{C}(\alpha, \gamma)^{18}\mathrm{O}$, $^{14}\mathrm{C}(\alpha, \mathrm{pn})^{16}\mathrm{N}$, $^{14}\mathrm{C}(\alpha, 2\mathrm{n})^{16}\mathrm{O}$ and $^{14}\mathrm{N}(\mathrm{t}, \mathrm{n})^{16}\mathrm{O}$ reactions. In these C + He and N + H reactions, enhancement factors are 2×10^{24} in Table III and 10^{11} in Table II, respectively. All α-particles and tritons undergo chemonuclear fusion forming the quasi- O atoms towards the synthesis of medium weight elements.

Similar remarkably enhanced reactions, $\mathrm{C} + \mathrm{Li} \longrightarrow \mathrm{F}$ and $\mathrm{N} + \mathrm{He} \longrightarrow \mathrm{F}$ are also expected as seen in the large respective enhancement, 10^{29} in Table IV and 10^{26} in Table III, respectively.

6. Cyclic Hydrogen-Helium Burning Chemonuclear Chain Reactions

In the previous section, we investigated mostly reactions in which neutrons took place the leading part of chain carrier. In the scheme of chemonuclear reactions, however, we may take the advantage of several kinds of charged particle chain carriers as seen below.

Nuclei revealing the coupled t- and α-clustering features such as ^{11}B, ^{15}N, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P and ^{35}Cl take place both the α-particle emitting and absorbing exothermic reactions. Among them ^{11}B, ^{23}Na, ^{27}Al and ^{31}P are capable of nuclear reactions united with the spontaneous atomic fusion reactions. The nucleus ^{10}B has the coupled *d*- and α-clustering features and take place the cyclic $(\alpha - \mathrm{d})$ and $(\mathrm{d} - \alpha)$ chain reactions besides the cyclic $(\alpha - \mathrm{p})$ - $(\mathrm{p} - \alpha)$ chemonuclear chain reactions.

Here, the author presents a blanket introduction of the cyclic chemonuclear chain reactions of ^{10,11}B, ^{23}Na and ^{27}Al which are fuel elements of special significance.

6.1. Cyclic $^{10}\mathrm{B}(\alpha,\mathrm{d})^{12}\mathrm{C}$ - $^{10}\mathrm{B}(\mathrm{d},\alpha)2\cdot{}^{4}\mathrm{He}$ Chemonuclear Chain Reactions

In likewise the $^{11}\mathrm{B}-\alpha$ reaction cases argued in Section 5.2, α-particles produced in the reactions Eqs.(1) and (2) undergo the $^{10}\mathrm{B}(\alpha,\mathrm{d})^{12}\mathrm{C}$ chemonuclear fusion, $Q = 1.34$ MeV, during the slowing down in the Li-alloy liquid. The reaction cross-section is somewhere in the neighborhood of the value given in Eq.(17),

$$\sigma \sim 10^{-8}\,(\mathrm{b}) \text{ at } E = 0.4\,\mathrm{MeV}\ (v = 2v_{\mathrm{B}}). \tag{21}$$

Recalling the rate enhancement, $K = 3 \times 10^{27}$ in Table III, we may expect that a substantial fraction of α-particles take place the reaction.

Deuterons produced in the (α,d) reaction begin to capture electrons from the Li-alloy liquid and take place the reaction $^{10}\mathrm{B}(\mathrm{d},\alpha)2\cdot{}^{4}\mathrm{He}$, $Q = 17.91$ MeV after reducing their kinetic energy below around 0.5 MeV. The intrinsic value of cross-section is,

$$\sigma > 3 \times 10^{-5}\,(\mathrm{b})\,, \tag{22}$$

at the energy of 0.2 MeV $(v \sim 2v_{\mathrm{B}})$ estimating from the value $S \sim 10\,\mathrm{MeV}\cdot\mathrm{b}$ of the reaction $^{10}\mathrm{B}(\mathrm{p},\alpha)^{7}\mathrm{Be}$ [23]. This reaction unites with the atomic fusion forming the quasi-C atoms through which the reaction is enhanced by the factor, $K = 1 \times 10^{14}$ (at $T = 460$ K) as seen in Table II. The enhanced value of cross-section $> 10^{9}$ (b) implies that the deuterons most likely undergo the chemonuclear fusion towards the cyclic chain (α,d) - (d,α) reactions.

6.2. Cyclic $^{11}\mathrm{B}(\alpha,\mathrm{p})^{14}\mathrm{C}$ - $^{11}\mathrm{B}(\mathrm{p},\alpha)2\cdot{}^{4}\mathrm{He}$ Chemonuclear Chain Reactions

In the Li-alloy liquid, substantial part of α-particles undergo the $^{11}\mathrm{B}(\alpha,\mathrm{p})^{14}\mathrm{C}$ chemonuclear reactions as argued in Section 5.2. Protons produced in this reaction take place also the $^{11}\mathrm{B}(\mathrm{p},\alpha)2\cdot{}^{4}\mathrm{He}$ reaction, $Q = 8.68$ MeV, enhanced by the factor $K = 1 \times 10^{14}$ (Table II) in likewise the $^{10}\mathrm{B}(\mathrm{d},\alpha)2\cdot{}^{4}\mathrm{He}$ reaction described in the previous section towards the cyclic $(\alpha,\mathrm{p}) - (\mathrm{p},\alpha)$ chain reactions.

6.3. Cyclic $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}$ - $^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ Chemonuclear Chain Reactions

On a per cubic cm basis, sodium metal is the cheapest of all metals but play an important role in the chemonuclear chain fusion reactions and one of the favorable fuel of clean fusion reactors.

Alpha-particles produced in the reaction Eq.(1) are much slower than the gyration speed $11v_{\mathrm{B}}$ of electrons in the 1s-orbitals of sodium atoms and ready to take place the chemonuclear reaction, ${}^{23}\mathrm{Na}(\alpha,\mathrm{p}){}^{26}\mathrm{Mg}$, $Q = +1.82$ MeV. Intrinsic value of reaction cross-section is,

$$\sigma(\alpha,\mathrm{p}) = 2\times10^{-5}\ (\mathrm{b}),\ \mathrm{at\ E} = 1.6\ \mathrm{MeV}\ (v = 4v_{\mathrm{B}}). \tag{23}$$

Here, the factor S $\gtrsim 2\times10^{9}$ (MeV·b) has been estimated from data on the ${}^{21}\mathrm{Na}(\alpha,\mathrm{p}){}^{24}\mathrm{Mg}$ reaction [23]. In the Li alloy liquid, the reaction is enhanced by the factor, $K = 4\times10^{18}$ in Table III. The most α-particles are thus converted into protons of about 3 MeV kinetic energy.

The protons reduce their speed during traverse in the liquid. At around the energy $E > 0.4$ MeV ($v \sim 4v_{\mathrm{B}}$), they begin to take place the chemonuclear reaction ${}^{23}\mathrm{Na}(\mathrm{p},\alpha){}^{20}\mathrm{Ne}$, $Q = +2.38$ MeV. The intrinsic cross-section is,

$$\sigma(\mathrm{p},\alpha) = 3(\mathrm{b}) \quad at\ E = 0.4\,\mathrm{MeV}\,, \tag{24}$$

using the value $S \sim 3\times10^{7}$ (MeV·b) [23]. The reaction is enhanced by the factor $K = 2.5\times10^{10}$ in Table II and results in the effective cross-section $K\sigma \sim 10^{13}$(b). Through this reaction most of protons are converted into α-particles of about 3 MeV energy. A small fraction of protons undergo the ${}^{6}\mathrm{Li}(\mathrm{p},\alpha){}^{3}\mathrm{He}$ reaction producing ${}^{3}\mathrm{He}$ particles which play an invaluable role in the waste burning chemonuclear reactions, ${}^{90}\mathrm{Sr}({}^{3}\mathrm{He},\mathrm{n}){}^{92}\mathrm{Zr}$, $Q = +9.39$ MeV and ${}^{137}\mathrm{Cs}({}^{3}\mathrm{He},\mathrm{n}){}^{139}\mathrm{La}$, $Q = +7.49$ MeV.

6.4. Cyclic ${}^{27}\mathrm{Al}(\alpha,\mathrm{p}){}^{30}\mathrm{Si}$ - ${}^{27}\mathrm{Al}(\mathrm{p},\alpha){}^{24}\mathrm{Mg}$ Chemonuclear Chain Reaction

The cyclic chain reactions of ${}^{27}\mathrm{Al}$ are very similar to those of ${}^{23}\mathrm{Na}$. Here only characteristic reaction quantities are introduced.

$$\begin{gathered}
{}^{27}\mathrm{Al}(\alpha,\mathrm{p}){}^{30}\mathrm{Si},\ Q = +2.37\,\mathrm{MeV}, \\
\sigma = 10^{-5}(\mathrm{b}),\ S \sim 1\times10^{10}\ (\mathrm{MeV}\cdot\mathrm{b}) \quad \mathrm{at}\ E = 2\,\mathrm{MeV}\ (v = 4.5v_{\mathrm{B}}) \qquad (25) \\
K = 8\times10^{15}\ \mathrm{at}\ T = 460\mathrm{K}\ (\mathrm{TableIII}) \\
{}^{27}\mathrm{Al}(\mathrm{p},\alpha){}^{24}\mathrm{Mg},\ Q = +1.60\,\mathrm{MeV}, \\
\sigma = 0.4(\mathrm{b}),\ S \sim 1\times10^{7}\ (\mathrm{MeV}\cdot\mathrm{b}) \quad \mathrm{at}\ E = 0.5\,\mathrm{MeV}\ (v = 4.5v_{\mathrm{B}}) \qquad (26) \\
K = 8\times10^{7}\ \mathrm{at}\ T = 460\mathrm{K}\ (\mathrm{TableII})\,.
\end{gathered}$$

As seen above, both sodium and aluminium are very useful fuels of the fusion chain reactions and known as the economical and 100% abundance metals.

7. Control of Chemonuclear Chain Reaction

The chain reaction is triggered in both ways through external neutron or radiation sources and self trigger mode. As seen in the previous paper in this book, chemonuclear fusion of hydrogen clusters generates neutrons if one introduces the Li-alloy or mixed LiH/MgH$_2$ salt liquid with solute metal hydride systems such as nickel hydride or those of similar metal hydride systems.

Since the chemonuclear chain reaction is sustained by all charged particle chain carriers and neutrons, usual reactor control means through the cadmium or boron rods is insufficient. However, the enhancement of chemonuclear reactions depends supersensitively on the temperature of Li-alloy liquid as seen in Eq.(7), in concrete terms, rising the temperature is reflected in the sharp suppression of reaction rate.

Suppose the most reliable control means is the regulation of amounts and kind of fuels dissolved in the liquid especially the amounts of solute boron.

8. Significance of Chemonuclear Chain Reaction

The new scheme of fusion chain reaction has the significance:

(1) The new scheme would provide the stable waste-free new energy sources.

(2) In the Li-alloy liquids, even radioactive wastes would burn away and release considerable energy as seen in the $^{90}\mathrm{Sr}(^{3}\mathrm{He}, \mathrm{n})^{92}\mathrm{Zr}$ and $^{137}\mathrm{Cs}(^{3}\mathrm{He}, \mathrm{n})^{139}\mathrm{La}$ reactions.

(3) We could substitute sodium and magnesium for boron to some extent.

(4) Scientific researches on the chain reaction products and yields would provide knowledges to reconsider the speed of nucleosynthesis in the universe.

References

1. G.R. Caughlan and W.A. Fowler, Atomic Data and Nuclear Data Tables **40** (1988) 283.
   W.A. Fowler, G.R. Caughlan and B.A. Zimmerman: Ann. Rev. Astron. Astrophys. **5** (1967) 523.
2. R.A. Weller: Ion-Solid Interactions, ed. S.D. Parker (McGraw-Hill, New York, 1992) McGraw-Hill Encyclopedia of Science and Technology, 7th ed., vol.9, p384.
3. H. Ikegami: Jpn J. Appl. Phys. **40** (2001) 6092. See also No.1 in Ref.7.
4. A.G.W. Cameron: Astrophys. J. **130** (1959) 916.
5. B. Jancovici: J. Stat. Phys. **17** (1977) 357.
6. S. Ichimaru and H. Kitamura: Publ. Astron. Soc. Jpn. **48** (1996) 613.
7. S. Ichimaru: Phys. Lett. **A266** (2000) 167.
8. H. Ikegami: "Evidence of Enhanced Nonthermal Nuclear Fusion" Bull. Inst. Chem. (Uppsala Univ. Uppsala, September 2002) No.1; http://www.inst.kemi.uu.se/Bulletin/Bulletinen_1.pdf
9. H. Ikegami and R. Pettersson: ibid. No.2.
10. H. Ikegami and R. Pettersson: ibid. No.3.
11. H. Ikegami, R. Pettersson and L. Einarsson: Prog. Theo. Phys. Suppl. **154** (2004) 251.
12. H. Ikegami: "Ultradense Nuclear Fusion in Metallic Lithium Liquid", Revised Edition of Swedish Energy Agency Document ER2006: **42** (Sakaguchi, Tokyo/Sakura, 2007) **1**-1 - **1**-22, Order fax: +81-43-498-4890, e-post: watanabe@sakaguchi.com (ed.1 available at publikationservice@energimyndigheten.se).
13. H. Ikegami and T. Watanabe: ibid. **2**-1 - **2**-12.
14. H. Ikegami: ibid. **3**-1 - **3**-30.
15. H. Ikegami and T. Watanabe: ibid. **4**-1 - **4**-21.
16. B.Widom: J. Chem. Phys. **39** (1963) 2808.
17. D. Kondepudi and I. Prigogine: Modern Thermodynamics (Wiley, Chichester, 1998).
18. E.N. Kaufmann, R. Vianden, J.R. Chelikowsky and J.C. Phillips: Phys. Rev. Lett. **39** (1977) 1671.
19. G. Aylward and T. Findlay: SI Chemical Data ed.3 (Wiley, Brisbane, 1998).
20. R. Boom, F.R. de Boer and A.R. Miedema, J. Less-Common Metals **46** (1976) 271.
21. L. Pauling, The Nature of the Chemical Bond, 3rd. ed. Cornell University Press, Ithaca, 1960.
22. R.E. Johnson, "Atom and Molecule Collisions" in Encyclopedia of Physical Science and Technology ed. by R.A. Mayers (Academic Press, Inc., N.Y., 1987) Vol.2, p224.
23. C. Angulo et al., Nucl. and Hadron Phys. **A656** (1999) 3.

Appendix

Table I(a)
Formation Gibbs energy $-\Delta G_{\mathrm{f}}$ and chemical potential ϕ^*

Z	1	3	4	5	6	7	8	9
Element	H	Li	Be	B	C	N	O	F
$-\Delta G_{\mathrm{f}} = 2.5\chi$ χ : Pauling electronegativity	5.50	2.45	3.93	5.10	6.38	7.60	8.60	9.95
Adopted semi-empirical formula $-\Delta G_{\mathrm{f}} = (5/4)(Z-1)$	0	2.50	3.75	5.00	6.05	7.50	8.75	10.0
ϕ^* : atom implanted in Be		2.85	4.20	4.80	6.23	7.00		
$-\Delta G_{\mathrm{f}}$: ion in aqueous solution	0	3.04	3.94					

Table I(b)
Formation Gibbs energy $-\Delta G_{\mathrm{f}}$ and chemical potential ϕ^*

Z	11	12	13	14	15	16	17
Element	Na	Mg	Al	Si	P	S	Cl
$-\Delta G_{\mathrm{f}} = 2.5\chi$	2.33	3.28	4.03	4.75	5.48	6.45	7.90
Adopted semi-empirical formula $-\Delta G_{\mathrm{f}} = (4/5)(Z-8)$	2.50	3.20	4.00	4.80	5.60	6.40	7.20
ϕ^* : atom implanted in Be	2.70	3.45	4.20	4.70			
$-\Delta G_{\mathrm{f}}$: ion in aqueous solution	2.71	4.71	5.10				

As seen in Table I, the values of formation Gibbs energy / chemical potential obtained in different ways are fairly in good agreement. The adopted semi-empirical formula in Table I(a) indicates that for H^+ ions on traverse in the Li alloy liquid, one may adopt $\Delta G_{\mathrm{f}}(H^+) = 0$.

Table II
Gibbs energy change $-\Delta G_{\mathrm{r}}(\mathrm{M}) = -\Delta G_{\mathrm{f}}(\mathrm{M}) + \Delta G_{\mathrm{f}}(\mathrm{X})$ in the chemonuclear
X + H → M fusion reaction and the associated rate enhancement factor
K at $T = 460$ K.

X	Li	Be	B	C	N	Na	Mg	Al
M	Be	B	C	N	O	Mg	Al	Si
$-\Delta G_{\mathrm{r}}$(eV)	1.48	1.17	1.28	1.22	1.00	0.95	0.75	0.72
$\log_{10} K$	16.2	12.8	14.0	13.4	11.0	10.4	8.23	7.90

Table III
Gibbs energy change $-\Delta G_{\mathrm{r}}(\mathrm{M}) = -\Delta G_{\mathrm{f}}(\mathrm{M}) + \Delta G_{\mathrm{f}}(\mathrm{X})$ in the chemonuclear X + He → M fusion reaction and the associated rate enhancement factor K at $T = 460$ K.

X	Li	Be	B	C	N	Na	Mg	Al
M	B	C	N	O	F	Al	Si	P
$-\Delta G_{\mathrm{r}}$(eV)	2.65	2.45	2.50	2.22	2.35	1.70	1.47	1.45
$\log_{10} K$	29.1	26.9	27.4	24.3	25.8	18.6	16.1	15.9

Table IV
Gibbs energy change $-\Delta G_{\mathrm{r}}(\mathrm{M}) = -\Delta G_{\mathrm{f}}(\mathrm{M}) + \Delta G_{\mathrm{f}}(\mathrm{X}) + \Delta G_{\mathrm{f}}(\mathrm{Li\,ion\,of}\,E_{\mathrm{lab}} = 1\mathrm{MeV})$ in the chemonuclear X + Li → M fusion reaction and the associated rate enhancement factor K at $T = 460$ K.

X	Li	Be	B	C
M	C	N	O	F
$-\Delta G_{\mathrm{r}}$(eV)	3.00	2.74	2.57	2.64
$\log_{10} K$	32.9	30.0	28.2	29.0

Chemonuclear Transition Th/U Reactor
– Switch over of Reactor to Waste-free Hybrid Reactor

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In any nuclear transitions undergoing gently compared to the atomic transitions e.g. nuclear fusion or fission reactions undergoing considerably slower than the gyration speed of electrons in the 1s-orbitals of reactant atoms, the atomic electrons adjust their electronic states continuously and smoothly to the nuclear transitions. Thereby in the thermodynamically stable alkali/alkaline earth alloy liquids, the united atomic and nuclear transitions called chemonuclear transitions take place and reveal enormous transition rate enhancement caused by the thermodynamic activity of the liquids consisting of bulk/collective mobile s-electrons and metallic ions. The charged particle induced chemonuclear fission reaction is one of the most typical case of chemonuclear transitions and this opens up the ways of wasteless Th and U reactors and also remodelling of conventional reactors into the wasteless reactors.

1. The Nature of the Chemonuclear Transition

In any nuclear transition undergoing gently compared to atomic transitions e.g. nuclear collisions, in its turn, nuclear fusion or fission reactions going on more slowly than the gyration speed of electrons Zv_{B} in the 1s-orbital of reactant atoms, the electrons adjust their electronic states continuously and smoothly to the nuclear transitions or reactions. Here Z and v_{B} denote the atomic number of reactant atoms/nuclei colliding with light ions and Bohr speed respectively. Thereby united nuclear and atomic transitions are likely to take place. In fact such united transitions have been observed in the united atom formation in the high energy heavy ion collision experiments through detecting the characteristic X-rays of united atoms in which pairs of colliding nuclei coexist at the center of common 1s-electron orbitals [1].

In metallic Li alloy liquids or generally, alkali/alkaline earth alloy liquids solute reactant atomic nuclei are surrounded by solvent metallic ions and bulk/collective mobile s-electrons which reveal the thermodynamic activity i.e. macroscopic correlation in their spontaneous atomic transitions. The united spontaneous atomic and nuclear transitions are thus subject to the thermodynamic activity of the liquids through the contact interaction between the s-electrons and the reactant nuclei. This feature reflects to the enormous rate enhancement of nuclear transitions as seen in the spontaneous atomic transitions or chemical kinetics in the liquids. In general, the rate enhancement is specified by the chemical potential change in the spontaneous transitions. This general principle is strictly independent and of the nature of microscopic interparticle interactions in the transitions. The united atomic and nuclear transitions are called chemonuclear transitions [2-7].

2. Hybrid chemonuclear reactions

The concept of chemonuclear transitions is naturally applicable to the slow fusion and fission reaction in the thermodynamically stable Li-alloy or generally, alkali/alkaline earth alloy liquids. In the chemonuclear fusion a compound nucleus is formed associated with the shrinked united atom formation during a collision of nucleus with a slow $v_{\mathrm{i}} << Zv_{\mathrm{B}}$ light ion. In the liquid, the shrinked united atom is subject to the thermodunamic force and takes a new lease of life resulting in the probability gain of collisions within the paired nuclei caused by the zero point oscillation in the united atom and thereby the rate enhancement of nuclear fusion. This fusion enhancement was predicted in 2001 and really has been observed in the slow ion implantation experiments on the D-Li, D_2-Li_2 and Li-Li collisions [2-7].

In the nuclear fission, average values of charge, mass and kinetic energy of fragment nuclei are, respectively, around $Z = 45$, $A = 100$ and 100MeV. Thus their average fission speed is $v_{\mathrm{f}} \sim 6.3v_{\mathrm{B}}$. The gyration speed of electrons in the 1s-electron orbital of $Z = 45$ atoms is $45v_{\mathrm{B}}$ which is much more quick than the speed of fragment atoms/nuclei. This implies that the fragment nuclei pass through the liquid in a form of almost perfect atoms/atomic ions. Thereby we can expect the rate enhancement effect caused by the thermodunamic activity of surrounding metallic liquid atoms in the fission. We are able to argue the light ion induced fission as the hybrid chemonuclear transitions i.e. fusion/fission reactions and apply the thermodynamic treatment for the transitions.

3. Chemical kinetics of chemonuclear fission reaction

Here we develop arguments on the chemonuclear transitions induced by a slow ion x

$$\mathrm{X} + \mathrm{x} \longrightarrow \mathrm{M}^* \longrightarrow \mathrm{Y}_1 + \mathrm{Y}_2 + \nu \mathrm{n}\,, \quad \nu : \text{ integer}\,, \tag{1}$$

provided

$$Z_{\mathrm{M}} = Z_{\mathrm{Y}_1} + Z_{\mathrm{Y}_2}\,. \tag{2}$$

Here, M^* denotes an intermediate excited compound nucleus and Y_1 and Y_2 are fission fragments. In the Li-alloy liquid, the compound nuclear formation in Eq.(1) is associated with the formation of a united atom $\overline{\mathrm{Xx}}$ or quasi-M^* atom which corresponds to the transition state treated in the chemical kinetics [8].

In this scheme of chemonuclear transitions, the fusion reaction yield $k(\mathrm{Xx} \to \mathrm{M})$ is given by the Arrhenius equation.

$$k(\mathrm{Xx} \to \mathrm{M}) = A \exp\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{M}^*)}{k_{\mathrm{B}}T}\right]. \tag{3}$$

Here, A is the intrinsic yield of nuclear fusion reaction i.e. formation of the intermediate compound nucleus or the transition state and corresponds to the frequency factor in the Arrhenius equation. The change ΔG_{r} of Gibbs energy (chemical potential) in the reaction corresponds to the activation energy of Arrhenius equation.

The Gibbs energy change ΔG_{r} is generally given by,

$$\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{M}^*) = \Delta G_{\mathrm{f}}(\mathrm{M}^*) - \Delta G_{\mathrm{f}}(\mathrm{X}) - \Delta G_{\mathrm{f}}(\mathrm{x})\,, \tag{4}$$

where ΔG_{f} is the Gibbs energy of formation for an atom in the liquid and given by the thermodynamical data of metallic alloy [9, 10].

As in the same way, for the backward reaction,

$$k(\mathrm{YY} \to \mathrm{M}^*) = A' \exp\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{YY} \to \mathrm{M}^*)}{k_{\mathrm{B}}T}\right]. \tag{5}$$

The constant K of equilibrium between the forward and backward reaction is,

$$\begin{aligned} K &= \frac{k(\mathrm{Xx} \to \mathrm{M}^*)}{k(\mathrm{YY} \to \mathrm{M}^*)} \\ &= \frac{A}{A'} \exp\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{M}^*) - \Delta G_{\mathrm{r}}(\mathrm{YY} \to \mathrm{M}^*)}{k_{\mathrm{B}}T}\right] \\ &= \frac{A}{A'} \exp\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{Xx} - \mathrm{YY})}{k_{\mathrm{B}}T}\right], \end{aligned} \tag{6}$$

provided,

$$\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{Y}_1\mathrm{Y}_2) = \Delta G_{\mathrm{f}}(\mathrm{Y}_1) + \Delta G_{\mathrm{f}}(\mathrm{Y}_2) - \Delta G_{\mathrm{f}}(\mathrm{X}) - \Delta G_{\mathrm{f}}(\mathrm{x})\,. \tag{7}$$

In the case $\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{YY}) = 0$, $K = 1$ thus

$$A = A' \tag{8}$$

and

$$K = \exp\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{Y}_1\mathrm{Y}_2)}{k_{\mathrm{B}}T}\right]. \tag{9}$$

The factor K has the significance of the yield enhancement of chemonuclear reaction coupled with the chemical reaction through the transition state which corresponds to the united atom.

$$k(\mathrm{Xx} \to \mathrm{Y_1Y_2}) = k_0 K = k_0 \mathrm{exp}\left[-\frac{\Delta G_{\mathrm{r}}(\mathrm{Xx} \to \mathrm{Y_1Y_2})}{k_{\mathrm{B}}T}\right] . \tag{10}$$

Here k_0 denotes the intrinsic reaction yield.

Equation (10) indicates that the overall yield does not depend on the intermediate transition states and the exponential factor reduces the dependence of fragment (elements) spectrum on the energy of fission inducing ions. However the transition states have the significance as the bottleneck dominating the fusion reaction through Eq.(3).

In the final analysis, we find that the induced fission reaction yield is governed by Arrhenius equation Eq.(3) whereas the spectrum of fragment element distribution is determined by the overall yield equation Eq.(10).

4. Quantitative analysis of enhancement factor

In the Li alloy liquid, atoms dissolved or produced in the reaction are more or less in the meta-stable states and partly in the ionized states. In fact, data on the chemical potentials ϕ^* of metastable microalloys of Li and Be atoms injected in the solvent Be lattice provide respective values $\phi^*(\mathrm{Li}) = 2.85$ (eV) and $\phi^*(\mathrm{Be}) = 4.20$ (eV) which are fairly close to those of aqueous ions $-\Delta G_{\mathrm{f}}(\mathrm{Li}^+_{\mathrm{aq}}) = 3.04$ (eV) and $-\Delta G_{\mathrm{f}}(\mathrm{Be}^{++}_{\mathrm{aq}}) = 3.94$ (eV), respectively [9-11]. This is naturally understandable because the formation energies of aqueous ions are known empirically identical to those of ions in fused salts and irrespective to the kind of solvent. Further, from comparison of the chemical potential for electrons ϕ^* with the electronegativity χ(Pauling scale) [11], the approximate linear relationships have been found corresponding to $\phi^* \sim -\Delta G_{\mathrm{f}} = 2.5\chi$ [10-12].

In Table I, the values of ΔG_{f} of elements are listed together with chemical potential for electrons of atoms implanted in the solvent Be lattice [9, 10].

5. Chemonuclear ^{232}Th and ^{238}U fission

In the Li alloy liquid where chemonuclear chain reactions are going on, light ions such as hydrogen, helium and Li ions are produced with the kinetic energy of some MeV. They collide with ^{232}Th or ^{238}U nuclei/atoms in the liquid and tend to induce their fission through collective excitation states of these deformed nuclei. In the fission reactions atomic electrons of inner orbitals of ^{232}Th and ^{238}U atoms adjust their electronic states continuously and smoothly to the nuclear collision process since the speed of ions is far slower than the gyration speed $\sim 90 v_{\mathrm{B}}$ of the electrons in the 1s-orbital of these atoms.

Here, we consider the chemonuclear fission induced by an ion x through its inelastic collision generating excited nuclei $^{\mathrm{m}}$X,

$$\mathrm{X} + \mathrm{x} \longrightarrow {}^{\mathrm{m}}\mathrm{X} + \mathrm{x}' \longrightarrow \mathrm{Y_1} + \mathrm{Y_2} + \nu \mathrm{n} + \mathrm{x}' \, , \; \nu : \text{integer} \tag{11}$$

provided

$$Z_{\mathrm{X}} = Z_{\mathrm{Y_1}} + Z_{\mathrm{Y_2}} \, . \tag{12}$$

The fragment yield of this fission is given by,

$$k(\mathrm{X} \to \mathrm{Y}_1\mathrm{Y}_2) = k_0(\mathrm{Y}_1\mathrm{Y}_2)K = k_0(\mathrm{Y}_1\mathrm{Y}_2)\exp\left[-\frac{\Delta G_{\mathrm{r}}}{k_{\mathrm{B}}T}\right] , \qquad (13)$$

with

$$\Delta G_{\mathrm{r}} = \Delta G_{\mathrm{f}}(\mathrm{Y}_1) + \Delta G_{\mathrm{f}}(\mathrm{Y}_2) - \Delta G_{\mathrm{f}}(\mathrm{X}) .$$

Here, k_0 denotes the intrinsic fragment yield of fission induced by the inelastic collision of ions and provides the intrinsic fission fragment distribution. The distribution function consists of two component Gaussian distribution functions with two peaks at $Z(\mathrm{Y}_1) \sim 40$ and $Z(\mathrm{Y}_2) \sim 50$ extending in the range $25 \lesssim Z \lesssim 65$. This intrinsic distribution is dramatically deformed by the exponential factor in Eq.(13).

In Table II and III are presented ΔG_{r} and the enhancement factor $K = \exp[-\Delta G_{\mathrm{r}}/k_{\mathrm{B}}T]$ at $T = 460$ K for the fission of $^{232\mathrm{m}}$Th and $^{238\mathrm{m}}$U, respectively.

6. Chemonuclear fission fragment distribution

6.1. $^{232\mathrm{m}}$Th fission

In Fig.1 the solid line showes the fragment distribution $k_0(\mathrm{Y}_1\mathrm{Y}_2)K$ of $^{232\mathrm{m}}$Th chemonuclear fission induced by slow ions. Black dots indicate the yield enhancement factor K of chemonuclear fission fragments whereas the broken line indicates the intrinsic fission fragment distribution $k_0(\mathrm{Y}_1\mathrm{Y}_2)$. This state of affairs is also the same in the $^{232}\mathrm{Th(t,p)}^{234\mathrm{m}}$Th fission case. As seen in the figure, the fragment distribution reveals a remarkable trend towards the sharp symmetric distribution centered around Rh isotopes. We may expect the fragments of chemonuclear $^{232\mathrm{m}}$Th fission are mostly noble metals such as Ru, Rh and Pd isotopes. This is due to the big amount of formation Gibbs energy (chemical potential) of these metals. This is the general feature of noble metals and results in the big change ΔG_{r} in the chemonuclear fission. Hereby the enormous rate enhancement is expected in the fission producing noble metal fragments.

The maximum neutron excess of Rh isotopes is 20 for $^{110}\mathrm{Rh}(\mathrm{T}_{1/2} = 5\mathrm{s.} \xrightarrow{\beta^-} {}^{110}\mathrm{Pd})$. This means that the number of liberated neutrons is around 12 in the ^{232}Th fission. The number is larger than the usual fission cases. The chemonuclear transition ^{232}Th reactor is thus expected as a useful neutron source e.g. for the breeding of nuclear fuel from fertile materials as well as the wasteless reactor.

6.2. $^{238\mathrm{m}}$U fission

In Fig.2 the solid line showes the fragment distribution $k_0(\mathrm{Y}_1\mathrm{Y}_2)K$ of the $^{238\mathrm{m}}$U chemonuclear fission induced by slow ions. Black dots indicate the yield enhancement factor K of chemonuclear fission fragments whereas the broken line indicates the intrinsic fission fragment distribution $k_0(\mathrm{Y}_1\mathrm{Y}_2)$.

As seen in the figure, the fragment distribution reveals again a sharp symmetric distribution centered around Pd isotopes. We expect that fragments of the ^{238m}U fission are mostly Pd, Ag, In, Rh and Tc isotopes owing to the big amounts of their formation Gibbs energy resulting in the enormous enhancement of their production yield in the fission.

The maximum neutron excess of Pd isotopes is 23 for $^{115}\mathrm{Pd}(\mathrm{T}_{1/2} = 45\mathrm{s} \xrightarrow{\beta^-} {}^{115}\mathrm{Ag} \xrightarrow{\beta^-} \mathrm{Cd} \xrightarrow{\beta^-} {}^{115}\mathrm{In})$. This means that in the case of $^{238\mathrm{m}}$U fission into two Pd isotopes, the number of liberated neutrons is around 8 which is larger than the usual fission cases. The chemonuclear transition ^{238}U reactors are thus expected as an useful neutron source like the $^{232\mathrm{m}}$Th chemonuclear fission case.

6.3. ^{232}Th and ^{238}U chemonuclear fission through respective excitation states of Pa and Np nuclei

There are many reaction channels of induced ^{232}Th and ^{238}U fission such as $^{232}\mathrm{Th(d,n)}^{233\mathrm{m}}\mathrm{Pa} \longrightarrow$ fission and $^{238}\mathrm{U(d,n)}^{239\mathrm{m}}\mathrm{Np} \longrightarrow$ fission. For these fission cases, we can apply the arguments developed in the previous sections. The difference is a slight modification of the fragment distribution. For instance, the peak fragment elements are Rh and Pd isotopes in the $^{233\mathrm{m}}$Pa fission whereas the peak fragments are Pd and Ag isotopes in the $^{239\mathrm{m}}$Np fission. This implies that one could trace the intermediate states of fission through analyzing the fragment distribution.

7. Remodelling of conventional reactor to waste free fusion reactor

7.1. Li(Na) alloy liquid reactor

Suppose the simplest scheme of chemonuclear fusion chain reactions would be those in the Li(Na) or Li(Na Mg) alloy liquid. The alloy has an eutectic point ($\mathrm{t}_m = 170.6$ °C) at the 3.4 atomic percent of Na mixture. Above this temperature both Li and Na liquids are in equilibrium between 3.4 and 91.6 atomic percent of Na mixing and give a plenty scope of mixture. In the liquids, mobile s-electrons and both Li$^+$ and Na$^+$ ions yield the thermodynamic activity to cause the chemonuclear reactions.

Following elementary chemonuclear reactions may take place in the chain reactions with respective Q-value and Gibbs energy change ΔG_r

$$
\begin{aligned}
&{}^{6}\mathrm{Li} + \mathrm{n} \longrightarrow \mathrm{t} + \alpha + 4.79\,\mathrm{MeV}\,, && (14)\\
&{}^{23}\mathrm{Na} + \mathrm{t} \longrightarrow 2\mathrm{n} +{}^{24}\,\mathrm{Mg} + 3.21\,\mathrm{Mev}\,,\ \Delta G_\mathrm{r} = -0.95\,(\mathrm{eV})\,, && (15)\\
&{}^{23}\mathrm{Na} + \mathrm{t} \longrightarrow \alpha +\ {}^{22}\mathrm{Ne} + 11.02\,\mathrm{MeV} && \\
&\qquad\qquad \longrightarrow \mathrm{n} + \alpha +\ {}^{21}\mathrm{Ne} + 0.66\,\mathrm{MeV}\,,\ \Delta G_\mathrm{r} = -0.95\,(\mathrm{eV})\,, && (16)\\
&{}^{23}\mathrm{Na} + \alpha \longrightarrow \mathrm{p} +\ {}^{26}\mathrm{Mg} + 1.82\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -1.70\,(\mathrm{eV})\,, && (17)\\
&{}^{23}\mathrm{Na} + \mathrm{p} \longrightarrow \alpha +\ {}^{20}\mathrm{Ne} + 2.38\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -0.95\,(\mathrm{eV})\,, && (18)\\
&{}^{26}\mathrm{Mg} + \alpha \longrightarrow \mathrm{n} +\ {}^{29}\mathrm{Si} + 0.03\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -1.47\,(\mathrm{eV})\,, && (19)\\
&{}^{26}\mathrm{Mg} + \mathrm{t} \longrightarrow \mathrm{n} +\ {}^{28}\mathrm{Al} + 7.52\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -0.75\,(\mathrm{eV})\,, && (20)\\
&{}^{28}\mathrm{Al}(2,3\mathrm{m}) \longrightarrow \mathrm{e}^- + \overline{\nu} +\ {}^{28}\mathrm{Si} + 4.64\,\mathrm{Mev}\,. && (21)
\end{aligned}
$$

Here, the ^{6,7}Li + t reactions have been disregarded, since tritons of sub-MeV energy undergo preferably chemonuclear reactions Eqs.(15) and (16) before their energy is reduced to the energy range of chemonuclear Li + t reaction ($\sim 0.08\,\mathrm{MeV}$). As seen in Eqs.(17), (19) and (20), the reaction product ^{26}Mg plays the role of a chain carrier. Since ^{25}Mg atoms take place also both He- and ^{3}H-burning chemonuclear reactions,

$$^{25}\mathrm{Mg} + \alpha \longrightarrow \mathrm{n} + {}^{28}\mathrm{Si} + 2.65\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -1.47\,(\mathrm{eV})\,, \tag{22}$$

$$^{25}\mathrm{Mg} + \mathrm{t} \longrightarrow \mathrm{n} + {}^{27}\mathrm{Al} + 10.88\,\mathrm{MeV}\,, \Delta G_\mathrm{r} = -0.75\,(\mathrm{eV})\,, \tag{23}$$

the Li (Na Mg) alloy would be useful.

7.2. Na(BN) alloy liquid reactor

The functions of Li in the chemonuclear chain reaction such as the thermodynamic activity of collective mobile s-electrons and ions liquid may be taken over through the Na(BN) alloy liquid in which some amounts of lubricating fine BN powder are dissolved. The neutron capturing action of ^{6}Li is covered by ^{10}B and ^{14}N as,

$$^{10}\mathrm{B} + \mathrm{n} \longrightarrow \alpha + {}^{7}\mathrm{Li} + 2.79\,\mathrm{MeV}\,, \tag{24}$$

$$^{14}\mathrm{N} + \mathrm{n} \longrightarrow \mathrm{p} + {}^{14}\mathrm{C} + 0.63\,\mathrm{MeV}\,. \tag{25}$$

In the reaction, Eq.(24), ^{7}Li ions produced have an energy of about 1.0 MeV and undergo immediately the chemonuclear fusion reaction enhanced remarkably with $\Delta G_\mathrm{r} = -3.0\,(\mathrm{eV})$ and $\log K = 33$ at $T = 460\mathrm{K}$,

$$^{7}\mathrm{Li} + {}^{7}\mathrm{Li} \longrightarrow 2\mathrm{n} + 3\alpha + 6.40\,\mathrm{MeV}\,, \tag{26}$$

and produce many chain carriers, if a small amount, say, several atomic percent of Li is mixed in the alloy.

Helium ions produced in the reactions, Eqs.(24) and (26) undergo reactions again remarkably enhanced with $\Delta G_\mathrm{r} = -2.50\,(\mathrm{eV})$ and $\log K = 27$ at $T = 460\mathrm{K}$,

$$^{10}\mathrm{B} + \alpha \longrightarrow \mathrm{n} + {}^{13}\mathrm{N} + 1.06\,\mathrm{MeV}\,, \tag{27}$$

$$^{11}\mathrm{B} + \alpha \longrightarrow \mathrm{n} + {}^{14}\mathrm{N} + 0.16\,\mathrm{MeV}\,, \tag{28}$$

$$^{10}\mathrm{B} + \alpha \longrightarrow \mathrm{p} + {}^{13}\mathrm{C} + 4.06,\ \mathrm{MeV}\,, \tag{29}$$

$$^{11}\mathrm{B} + \alpha \longrightarrow \mathrm{p} + {}^{14}\mathrm{C} + 0.78\,\mathrm{MeV}\,. \tag{30}$$

The enhanced rate of the reactions, Eqs.(27) and (28) compete well with the helium burning reaction Eq.(17).

The key problem would be, however, the thermodynamically stable Na(BN) alloy making through an appropriate flux mixture.

8. Remodelling of conventional reactors into hybrid nuclear reactors

All the chemonuclear reactions Eqs.(14-20) and Eqs.(22-28) are concerned directly or indirectly with neutrons as the chain carrier. The chemonuclear fission chain reactions of Th and U nuclei are also the cases in the Li and/or Na alloy liquids. This implies that the chemonuclear transitions i.e. fusion and fission chain reactions are practically controllable through the tuning of thermal neutron flux in the alloy liquids using conventional control rods and the amount of burning elements.

This state of things opens the way of remodelling of conventional nuclear reactors into the waste free chemonuclear fusion reactors or hybrid chemonuclear transition reactors through replacing conventional nuclear fuel rods by respective chemonuclear transition fuel rods.

9. Characteristics of chemonuclear transition reactors

The chemonuclear transition reactors have following features quite its own.

i) Waste free reactions

The elementary chemonuclear fusion reactions in the reactors do not produce long lived radioactive isotopes as seen in section 7.

In the ^{232}Th and ^{238}U chemonuclear fission, there is no place to produce long lived ^{90}Sr and ^{137}Cs isotopes. Instead substantial fission fragments are Ru, Rh, Pd and Ag isotopes. Among them the isotope lived longer than 1 year is ^{107}Pd, $T_{1/2} = 7 \times 10^6$ y but its maximum energy of β^--decay is only 0.035 MeV and no problem from the practical view point.

ii) Enrichment free fission reactions

The chemonuclear fission reactions need not any enrichment procedure because the reactions are induced by a great variety of chain carriers such as protons, deuterons, tritons and also He- and Li- ions.

iii) The world common natural fuels

For the Li(Na)- and Na(BN)- alloy liquid reactors, the main fusion chain reaction fuels are Li, B, N, Na and Mg isotopes. Among them Na and Mg isotopes are, respectively, the sixth and eighth most abundant elements on earth and the world common natural nuclear fuels as well as nitrogen.

iv) Interchangeability between chemonuclear transition reactors and conventional reactors

Conventional nuclear reactors could be remodelled into the chemonuclear transition Th/U reactors as argued in section 8.

10. Concluding remark

Since the discovery of the concept "nuclear fission" by L. Meitner and O.R. Frish and the observation by O. Hahn and F. Strassman (1938), we have fully concerned with the nuclear chain reactions induced by thermal neutrons. However, the chemonuclear transition would break new nuclear chain reactions sustained by various kind of light ions and also new nuclear fission chain reactions of thorium, natural uranium and even depleted uranium. This state of affairs opens the extensive ways of new waste free chemonuclear transition reactors i.e. hybrid nuclear reactors.

The chemonuclear transition reactors would provide a great boon to the problem of energy and natural resources.

References

1. R. Müller: Atomic Physics of Highly Ionized Atoms, ed. R. Marrus (Plenum, New York, 1989).
2. H. Ikegami: Jpn J. Appl. Phys. **40** (2001) 6092. See also No.1 in Ref.7.
3. H. Ikegami and R. Pettersson: "Evidence of Enhanced Nonthermal Nuclear Fusion" Bull. Inst. Chem. (Uppsala Univ. Uppsala, September 2002) No.3; http://www.inst.kemi.uu.se/Bulletin/Bulletinen_1.pdf
4. H. Ikegami: "Ultradense Nuclear Fusion in Metallic Lithium Liquid", Revised Edition of Swedish Energy Agency Document ER2006: **42** (Sakaguchi, Tokyo/Sakura, 2007) **3**-1 - **3**-30, Order fax: +81-43-498-4890, e-post: watanabe@sakaguchi.com (ed.1 available at publikationservice@energimyndigheten.se).
5. H. Ikegami and T. Watanabe: ibid. **4**-1 - **4**-21.
6. H. Ikegami: ibid. **1**-1 - **1**-22. The term "chemonuclear fusion" was coined by S. Kullander.
7. H. Ikegami and T. Watanabe: ibid. **2**-1 - **2**-12.
8. H. Eyring: J. Chem. Phys. **3** (1935) 107; Chem. Rev. **17** (1935) 65.
9. E.N. Kaufmann, R. Vianden, J.R. Chelikowsky and J.C. Phillips, Phys. Rev. Lett. **26** (1977) 1671.
10. R. Boom and F.R. Boer, J. Less Common Metals, **46** (1976) 271.
11. G. Aylward and T. Findlay: SI Chemical Data ed.3 (Wiley, Brisbane, 1998).
12. L. Pauling, The Nature of the Chemical Bond, 3rd edn, Cornell University Press, Ithaca 1960.

Table I
Formation Gibbs energy deduced from the empirical relationship $-\Delta G_\mathrm{f} = 2.5\chi$,
χ: Pauling electronegativity [10-12] and chemical potential ϕ^* of atom implanted in Be [9, 10]

Z	3	4	5	6	7	8	9	11	12	13	14	15	16	17	19	20
Element	Li	Be	B	C	N	O	F	Na	Mg	Al	Si	P	S	Cl	K	Ca
$-\Delta G_\mathrm{f}$	2.45	3.93	5.10	6.38	7.60	8.60	9.95	2.33	3.28	4.03	4.75	5.48	6.45	7.90	2.05	2.50
ϕ^*	2.85	4.20	4.80	6.23	7.00			2.70	3.45	4.20	4.70				2.25	2.55

21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Sc	Br	Kr	Rb	Sr
3.40	3.85	4.08	4.15	3.88	4.58	4.70	4.78	4.75	4.13	4.53	5.03	5.45	6.38	7.40	7.25	2.05	2.38
3.25	3.65	4.25	4.65	4.45	4.93	5.10	5.20	4.55	4.10	4.10	4.55	4.80				2.10	2.40

39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Cs	Ba
3.05	3.33	4.00	5.40	4.75	5.50	5.70	5.50	4.83	4.23	4.45	4.90	5.13	5.25	6.65	6.50	1.98	2.23
3.20	3.40	4.00	4.65	5.30	5.40	5.40	5.45	4.45	4.05	3.90	4.15	4.40				1.95	2.32

57	72	73	74	75	76	77	78	79	80	81	82	83	90	91	92	93	94
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Th	Pa	U	Np	Pu
2.75	3.25	3.75	5.90	4.75	5.50	5.50	5.70	6.35	5.00	5.10	5.83	5.05	3.25	3.75	3.45	3.40	3.20
3.05	3.55	4.05	4.80	5.40	5.40	5.55	5.65	5.15	4.20	3.90	4.10	4.15	5.30		4.05		3.80

Table II

Gibbs energy change $\Delta G_{\mathrm{r}} = \Delta G_{\mathrm{f}}(\mathrm{Y}_1) + \Delta G_{\mathrm{f}}(\mathrm{Y}_2) - \Delta G_{\mathrm{f}}(\mathrm{Th})$ and the rate enhancement factor K of fragment pair production in the ^{232}Th fission at $T = 460$K.

Fragment pair	Ca Yb	Sc Tm	Ti Eb	V Ho	Cr Dy	Mn Tb	Fe Gd	Co Eu	Ni Sm	Cu Pm	Zn Nd	Ga Pr	Ge Ce
$-\Delta G_{\mathrm{r}}$	2.00	3.16	3.70	3.91	3.95	3.63	4.33	4.45	4.46	4.50	3.73	4.11	4.58
$\log_{10} K$	21.9	34.7	40.6	42.9	43.3	39.8	47.5	48.8	48.9	49.4	40.9	45.1	50.2

Fragment pair	As La	Se Ba	Br Cs	Rb I	Sr Te	Y Sb	Zr Sn	Nb In	Mo Cd	Tc Ag	Ru Pd	Rh Rh
$-\Delta G_{\mathrm{r}}$	4.95	5.36	6.13	5.45	4.38	4.93	4.98	5.20	6.38	6.33	7.75	8.15
$\log_{10} K$	54.3	58.8	67.2	59.8	48.0	54.1	54.6	57.0	70.0	69.4	85.0	89.4

Table III

Gibbs energy change $\Delta G_{\mathrm{r}} = \Delta G_{\mathrm{f}}(\mathrm{Y}_1) + \Delta G_{\mathrm{f}}(\mathrm{Y}_2) - \Delta G_{\mathrm{f}}(\mathrm{U})$ and the rate enhancement factor K of fragment pair production in the ^{238}U fission at $T = 460$K.

Fragment pair	Ca Hf	Sc Lu	Ti Yb	V Tm	Cr Er	Mn Ho	Fe Dy	Co Tb	Ni Gd	Cu Eu	Zn Sm	Ga Pm	Ge Nd	As Pr
$-\Delta G_{\mathrm{r}}$	2.30	3.13	3.15	3.76	3.80	3.51	4.18	4.25	4.33	4.30	3.61	4.08	4.43	4.83
$\log_{10} K$	25.2	34.3	34.5	41.2	41.7	38.5	45.8	46.6	47.5	47.2	39.6	44.7	48.6	53.0

Fragment pair	Se Ce	Br La	Kr Ba	Rb Cs	Sr Xe	Y I	Zr Te	Nb Sb	Mo Sn	Tc In	Ru Cd	Rh Ag	Pd Pd
$-\Delta G_{\mathrm{r}}$	5.73	6.70	6.03	0.58	5.43	6.25	5.13	5.68	6.85	5.75	6.28	7.08	7.55
$\log_{10} K$	62.8	73.5	66.1	6.4	59.6	68.5	56.3	62.3	75.1	63.1	68.9	77.6	82.8

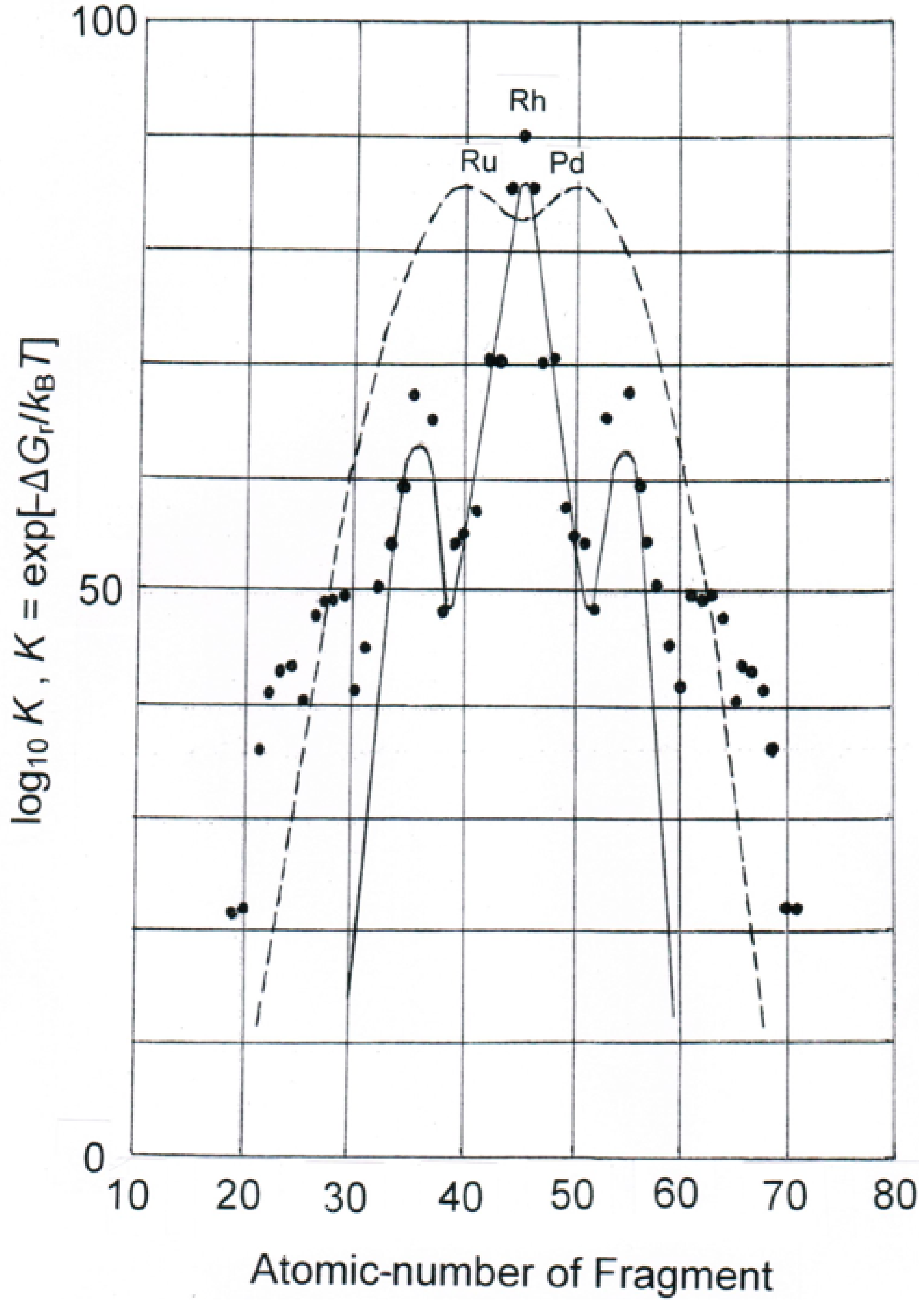

Fig. 1
Fragment charge distribution $k_0(Y_1Y_2)K$ (solid line) of ^{232m}Th/^{234m}Th chemonuclear fission. Black dots indicate the yield enhancement K in the chemonuclear fission. The broken line indicates the intrinsic fission fragment charge distribution $k_0(Y_1Y_2)$. As seen in the chemonuclear fission fragment distribution $k_0(Y_1Y_2)K$, fragments of chemonuclear ^{232m}Th/^{234m}Th fission are mostly noble Ru, Rh and Pd metals.

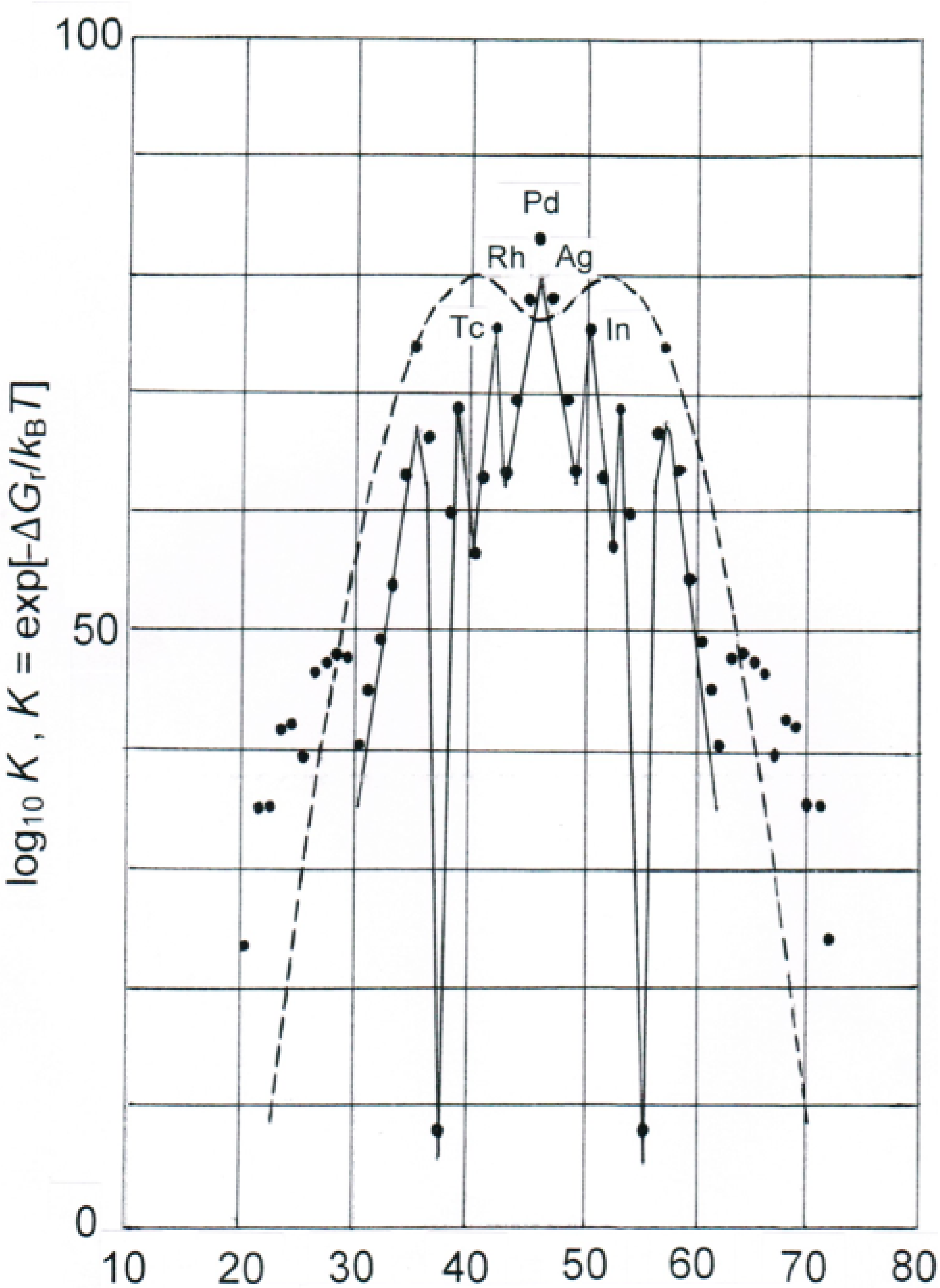

Fig. 2
Fragment charge distribution $k_0(Y_1Y_2)K$ (solid line) of ^{238m}U chemonuclear fission. Black dots indicate the yield enhancement K in the chemonuclear fission. The broken line indicates the intrinsic fission fragment charge distribution $k_0(Y_1Y_2)$. As seen in the chemonuclear fission fragment distribution $k_0(Y_1Y_2)K$, fragments of chemonuclear ^{238m}U fission are mostly noble Pd, Ag, In, Rh and Tc metals.

Waste-vanishing Induced Nuclear Decay

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Chemonuclear reactions in the thermodynamically stable Li alloy liquids hold the mechanism in common with the pycnonuclear reactions in the metallic hydrogen liquids in stars e.g. white-dwarf progenitors of supernovae. Both reactions take place cooperatively with the spontaneous chemical reactions coupled with the nuclear fusion reactions and induce astronomically large rate enhancement caused by the thermodynamic activity of liquids specified by the Gibbs energy (chemical potential) change ΔG_r in the spontaneous reactions. The mechanism of this rate enhancement can be applied to the transmutation of radioactive wastes as seen in the cases of ^{65}Zn, ^{90}Sr and ^{137}Cs isotopes. However, the waste vanishing may be achieved in the ~~much~~ more ~~con~~1~~act~~ scheme based on the general concept, chemonuclear transition. In the scheme, ~~nu~~2~~ear decays are induced through the spontaneous chemical reactions of decaying parent atom~~s.

1. simple

2. beta-decay is induced by colliding particles through intermediate excited states lie toward the isobaric analogue state and enhanced by the liquid activity.

1. Chemonuclear reactions in metallic Li liquids

In the metallic hydrogen liquids in stars, for example, white-dwarf progenitors of supernovae, the rate enhancement of nuclear reaction (called pycnonuclear reaction) by a factor of some tens order of magnitude has been reported [1, 2]. The same enhanced reaction (called chemonuclear reaction) was discovered in the metallic Li liquids in 2001 and has been understood as the pycnonuclear reaction projected in the Li liquids [3, 4]. Both reactions take place coupled with respective spontaneous chemical reactions and induce the astronomical rate enhancement under the presence of cohesive force or, exactly speaking, the thermodynamic activity of liquids. Such an enormous rate enhancement has been known in the spontaneous chemical reactions especially ionic reactions in liquids.

The rate enhancement mechanism of all reactions in the liquids is well explained on the basis of the Widom's concept "thermodynamic activity of liquids" [5]. In general, the activity is specified by the Gibbs energy change ΔG_{r} in the respective reactions and their enhancement is given by,

$$K = \exp[-\Delta G_{\mathrm{r}}/k_{\mathrm{B}}T]\,, \tag{1}$$

at the temperatures T of liquids. Here k_{B} denotes the Boltzmann constant. This general thermodynamic relation is strictly independent of kinds of reactant particles and the nature of microscopic interparticle interactions.

2. Waste vanishing chemonuclear transmutation

There have been many efforts that went into the researches for waste vanishing. The accelerator waste vanishing or transmutation is a typical example. However, in practice, it is required for an accelerator to extract over some hundreds mA particle beam of several hundreds MeV energy but, in any sense, neither efficient nor economical. Nevertheless such the waste vanishing is the significant problem to be solved. Here the author applies a light and easy scheme to a solution of this problem.

Liquid Li alloys reveal the activity of highly dense liquid plasmas, as argued in the previous paper (paper No.2 in this book). For instance, in the liquid Li alloys with B, Na and Al isotopes, both the (p,α) and (α,p) exothermic reactions take place generating chain fusion reactions. In these alloys, p, d and α particles play a role of chain carriers. In the liquid alloys these charged particles take place the (p, ^{3}He), (d,n) and (n,t) reactions. The liquid alloys are thus found to be an active space filled up by p, d, t and α particles and ^{3}He ions. All these particles are capable to induce exothermic chemonuclear reactions vanishing radioactive nuclei.

2.1. Chemonuclear transmutation of ^{90}Sr

In the Li alloy liquid, ^{3}He ions are produced in the reaction [6],

$$^{6}\mathrm{Li} + \mathrm{p} \longrightarrow {}^{3}\mathrm{He} + {}^{4}\mathrm{He}\,,\ \mathrm{Q} = 4.02\,\mathrm{MeV}\,. \tag{2}$$

These ^{3}He ions have the speed of about $v \sim 5.5 v_{\mathrm{B}}$ where v_{B} denotes the Bohr speed. The speed is much slower than the gyration speed of electrons in the 1s-orbitals of Sr atoms. In this case, a collision between ^{3}He ions and ^{90}Sr nuclei is no more a simple nuclear collision but a collision between whole atoms/ions. This results in a nuclear reaction through the formation of united atoms i.e. quasi-Zr atoms, which is subjected to the thermodynamic force i.e. the activity of the Li alloy liquid. We can expect the exothermic chemonuclear reactions [6],

$$^{90}\mathrm{Sr} + {}^{3}\mathrm{He} \longrightarrow {}^{92}\mathrm{Zr} + \mathrm{n} + 9.39\,\mathrm{MeV}\,, \tag{3}$$

and

$$^{90}\mathrm{Sr} + {}^{3}\mathrm{He} \longrightarrow {}^{91}\mathrm{Zr} + 2\mathrm{n} + 1.02\,\mathrm{MeV}\,, \tag{4}$$

where the Gibbs energy change is obtained in the thermodynamic alloy data [7],

$$\Delta G_{\mathrm{r}} = \Delta G_{\mathrm{f}}(\mathrm{Zr}) - \Delta G_{\mathrm{f}}(\mathrm{Sr}) = -3.40 + 2.40 = -1.00\,(\mathrm{eV})\,. \tag{5}$$

Both reactions are enhanced by the factor K,

$$\log_{10} K = 11.0 \quad \mathrm{at}\, T = 460\,\mathrm{K}\,. \tag{6}$$

This enhancement in Eq.(6) has been drawn from a simple prior condition that the ^{90}Sr atoms are dispersed in a metallic form in the liquid.

In the case where the ^{90}Sr atoms are dissolved in the chemical form $\mathrm{Sr(OH)_2}$ in the liquid, the reactions Eqs.(3) and (4) are going on accompanying with the chemical reaction forming quasi-molecules consisting of quasi-Zr atoms,

$$\mathrm{Sr(OH)_2} + 2\mathrm{Li} + \mathrm{He} \longrightarrow (\text{quasi-Zr})\mathrm{O_2} + 2\mathrm{LiH}\,, \tag{7}$$

since the nature favors the final state of the lowest chemical potential. The Gibbs energy change in the reaction Eq.(7) is [7, 8, 9],

$$\begin{aligned}\Delta G_{\mathrm{r}} &= \Delta G_{\mathrm{f}}(\mathrm{Zr}) + \Delta G_{\mathrm{f}}(\mathrm{ZrO_2}) + 2\Delta G_{\mathrm{f}}(\mathrm{LiH}) - \Delta G_{\mathrm{f}}(\mathrm{Sr}) - \Delta G_{\mathrm{f}}(\mathrm{Sr[OH]_2})\\ &= -3.40 - 10.81 - 2\times 0.70 + 2.40 + 9.43 = -3.78\,(\mathrm{eV})\,,\end{aligned} \tag{8}$$

and the associated enhancement is,

$$\log_{10} K = 41.5 \quad \mathrm{at}\, T = 460\,\mathrm{K}\,. \tag{9}$$

This implies that all reacting ions undergo the chemonuclear reactions Eqs.(3) and (4).

Alpha particles produced in the reaction Eq.(2) are capable of inducing the chemonuclear reaction,

$$^{90}\mathrm{Sr} + \alpha \longrightarrow {}^{94}\mathrm{Zr} + \gamma + 3.76\,\mathrm{MeV}\,, \tag{10}$$

because the α-particles are fairly slow $v < 4v_{\mathrm{B}}$. For this reaction we may expect the same enhancement shown in Eq.(6) or Eq.(9). However, due to the very small intrinsic cross-section of the reaction Eq.(10), its contribution would be marginal compared to the ^{3}He ions.

2.2. Chemonuclear helium ions induced transmutation of ^{137}Cs

In the Li alloy liquid, likewise the ^{90}Sr case, ^{3}He ions transmute ^{137}Cs isotopes to rare metal La isotopes in the exothermic chemonuclear reactions [6],

$$^{137}\mathrm{Cs} + {}^{3}\mathrm{He} \longrightarrow {}^{139}\mathrm{La} + \mathrm{n} + 7.49\,\mathrm{MeV}\,, \tag{11}$$

$$^{137}\mathrm{Cs} + {}^{3}\mathrm{He} \longrightarrow {}^{138}\mathrm{Ba} + \mathrm{d} + 3.51\,\mathrm{MeV}\,, \tag{12}$$

$$^{137}\mathrm{Cs} + {}^{3}\mathrm{He} \longrightarrow {}^{137}\mathrm{Ba} + \mathrm{t} + 1.15\,\mathrm{MeV}\,. \tag{13}$$

These reactions take place through forming the same united atoms i.e. quasi-La atoms and subjected to the thermodynamic force. The Gibbs energy change in the reactions Eqs.(11-13) is [7],

$$\begin{aligned} \Delta G_{\mathrm{r}} &= \Delta G_{\mathrm{f}}(\mathrm{La}) - \Delta G_{\mathrm{f}}(\mathrm{Cs}) = -3.05 + 1.95 \\ &= -1.10\,(\mathrm{eV})\,, \end{aligned} \tag{14}$$

which results in the enhancement factor of these reactions,

$$\log_{10} K = 12.1 \quad \mathrm{at}\, T = 460\,\mathrm{K}\,. \tag{15}$$

2.3. Chemonuclear hydrogen ions induced transmutation of ^{137}Cs

Hydrogen ions produced in the liquid are sufficiently slow to take place the hydrogen capturing chemonuclear reactions with ^{137}Cs nuclei [6],

$$^{137}\mathrm{Cs} + \mathrm{p} \longrightarrow {}^{134}\mathrm{Xe} + \alpha + 6.43\,\mathrm{MeV}\,, \tag{16}$$

$$^{137}\mathrm{Cs} + \mathrm{d} \longrightarrow {}^{134}\mathrm{Ba} + \mathrm{n} + 6.78\,\mathrm{MeV}\,, \tag{17}$$

$$^{137}\mathrm{Cs} + \mathrm{t} \longrightarrow {}^{136}\mathrm{Xe} + \alpha + 12.39\,\mathrm{MeV}\,. \tag{18}$$

These reactions undergo through forming united atoms i.e. quasi-Ba atoms,

$$\mathrm{Cs} + \mathrm{H} \longrightarrow \text{quasi-Ba}\,. \tag{19}$$

This reaction is specified by the Gibbs energy change [7],

$$\Delta G_{\mathrm{r}} = \Delta G_{\mathrm{f}}(\mathrm{Ba}) - \Delta G_{\mathrm{f}}(\mathrm{Cs}) = -2.32 + 1.95 = -0.37\,(\mathrm{eV})\,, \tag{20}$$

and the reaction rate enhancement becomes,

$$\log_{10} K = 4.1 \quad \mathrm{at}\, T = 460\,\mathrm{K}\,. \tag{21}$$

If the ^{137}Cs isotopes are dissolved in the chemical form CsOH in the Li alloy liquid, the CsOH molecules are dehydrogenized through the chemical reaction,

$$\mathrm{CsOH} + 2\mathrm{Li} \longrightarrow \mathrm{CsLiO} + \mathrm{LiH}\,. \tag{22}$$

In this case, the chemonuclear reactions Eqs.(16) - (18) take place through forming quasi-molecules consisting of quasi-Ba atoms,

$$\mathrm{CsLiO} + \mathrm{H} \longrightarrow (\text{quasi-Ba})\mathrm{O} + \mathrm{Li}\,. \tag{23}$$

This reaction is specified by the Gibbs energy change referring the thermodynamic alloy data and chemical data [7, 8],

$$\begin{aligned} \Delta G_{\mathrm{r}} &= \Delta G_{\mathrm{f}}(\mathrm{Ba}) + \Delta G_{\mathrm{f}}(\mathrm{BaO}) - \Delta G_{\mathrm{f}}(\mathrm{Cs}) - \Delta G_{\mathrm{f}}(\mathrm{CsLiO}) \\ &= -2.32 - 5.44 + 1.95 + 4.50 = -1.31\,(\mathrm{eV})\,, \end{aligned} \tag{24}$$

and enhanced by the factor,

$$\log_{10} K = 14.4 \quad \mathrm{at}\, T = 460\,\mathrm{K}\,. \tag{25}$$

The value in Eq.(25) implies the possibility that most hydrogen ions undergo the ^{137}Cs vanishing reactions in the liquid.

3. cooperative nuclear and

4. Particles produced in the liquid induce the beta-decay through exciting intermediate states lie toward the isobaric analogue state and the decay is enhanced under the presence of the liquid activity.

3. Induced nuclear decay

We have argued the waste vanishing through the chemonuclear reactions in the thermodynamically stable Li alloy liquids so far. However, the concept of chemonuclear reaction would be extended to the general concept, "chemonuclear transition" inducing induced α-decay and induced β-decay as well. By intuition, one might not foresee any thermodynamical enhancement effect on the β-decays because of their weak interaction characteristics. However this conjecture has to be corrected because the arguments of chemonuclear reactions are developed based on the fundamental principle of thermodynamics and applicable to any spontaneous reactions irrespective of the nature of interaction between reactant particles and kinds of particles [10]. In fact this argument is supported by the observation of the enhanced $H(p,e^+\nu_e)D$ chemonuclear fusion reaction in the Li permeated metal hydrogen systems. (See paper No.1 in this book.)

On further reflection, the role of atoms in the nuclear reaction and transition has been treated mostly as a kind of atomic phenomena such as those treated in the recoil atom or hot-atom chemistry. Radiation chemistry is also concerned with the chemical change induced by various kinds of radiations. None has ever investigated the atomic effect on the nuclear reactions and transitions. In other active words, no general argument has been developed on the nuclear phenomena induced by the atomic or chemical enviroments surrounding the reacting nuclei.

However, in the liquids of metallic hydrogen and alkali metals, every nuclei are immersed in the sea of dense mobile s-electrons of the liquid metals forming the dense plasmas. Here the nuclei behave as the reactant solutes of chemonuclear reaction in the dilute solution. As an inevitable consequence, the nuclei interact with the s-electrons in the macroscopic scale and subjected to the thermodynamic force through the spontaneous chemical reactions. Above mentioned enormously enhanced pycnonuclear reactions in the metallic hydrogen liquids in progenitors of supernovae and chemonuclear reactions in the metallic Li liquids are just these cases.

The concept "chemonuclear reaction" may be extended to the general concept "chemonuclear transition" under certain surroundings. For concrete discussion, the author takes up the s-orbital electron capture of nuclei in ions in the metallic liquid where the ions are spontaneously reduced through the recombination capturing electrons in the outermost orbitals. This s-electron capturing action of ions results in the s-electron density accreation with respect to the nuclear positions. Generally the gain of decay rate due to this density accreation is insignificant, say, some orders of magnitude small fraction in the cases of medium weight nuclei. However, the density accreation effect is no more a mere few body problem and collective mobile s-electrons takes the part of macroscopically correlated solvent reacting with the solute atoms and/or ions. Because in the metallic Li liquid atomic potential wells for the electrons are not far apart and the electrons can tunnel through the potential barriers. Furthermore their de Broglie wavelength covers a space of some tens Li atoms and yields the collective activity of the liquid in the macroscopic scale [3, 5]. We thus are no longer concerned with energy levels of individual Li atoms and/or ions instead of the bulk of liquid metallic Li-ions and solute reacting ions immersed in the collective mobile s-electron density accreation with respect to the nuclear positions in the macroscopic scale associated with the spontaneous reduction reaction of ions. Here the electron capture by nuclei is no more decay of isolated nuclei and subjected to the thermodynamic force. The recombination of ions through filling their s-electron orbitals associated with the spontaneous reduction in the liquid is just this case and we may expect the large enhancement of electron capture decay of nuclei.

Statistical features of this coupled atomic and nuclear transition are dominated by the thermodynamic force in the liquid. Here macroscopically distinct parts of the liquid surrounding the decaying ion systems are correlated and a long-range coherence appears [3, 4, 9, 10].

Similar arguments are applicable to the negatron and positron decays as well because huge enhancement effects are anticipated under appropriate atomic and molecular conditions surrounding the decaying nuclei, though intrinsic influences caused by these conditions are usually negligibly small.

Induced α-decay may be the most understandable induced nuclear transition. In the wave functions of parent decaying nuclei, there exist very faint but non-vanishing fraction of wave function components consisting of α-particles and daughter nuclei due to the tunneling and fluctuation effects. The components would result in the enormous contribution to the decay rate caused by the thermodynamic force specified by the Gibbs energy change in the coupled spontaneous atomic and/or ionic transition as seen in section 2.

5. and enhanced by cooperative nuclear and

Induced β-decays are the nuclear transitions induced ~~by~~ atomic transitions. Here the emission and capture of electrons by parent atoms very likely induce, respectively, the emission and capture of electrons by the parent nuclei. Such the phase matching atomic and nuclear transitions of parent atoms and nuclei are feasible in the proper chemical form of the parent atoms dissolved in the stable liquid solution. Here the author takes up some cases of vanishing fission products in the following.

4. Induced β decay

4.1. Induced electron capture decay of ^{109}Cd

In the $CdCl_2$ molecules, ^{109}Cd atoms are in the form of Cd^{++} ions. When the $CdCl_2$ solution is mixed with the thermodynamically stable Li alloy liquid, the $^{109}Cd^{++}$ ions begin to capture electrons from the Li alloy liquid in the chemical reduction,

$$\mathrm{Cd^{++}\,Cl_2^{--} + 2Li \rightarrow Cd + 2Li^{+}Cl^{-}}\,. \tag{26}$$

This spontaneous reduction of Cd ions likely induce the electron capture of ^{109}Cd nuclei ($T_{1/2} = 463$ d) from their outermost s-electron orbitals,

$$^{109}_{48}\mathrm{Cd} + \mathrm{e}^- \longrightarrow {}^{109\mathrm{m}}_{47}\mathrm{Ag} + \nu_{\mathrm{e}}\,, \tag{27}$$

in the liquid and results in the coupled atomic and nuclear electron capturing transition,

$$\mathrm{CdCl_2 + 2Li \xrightarrow{E.C.} Ag + 2LiCl}\,. \tag{28}$$

In the liquid, the rate of the coupled transition Eq.(28) is subjected to the thermodynamic force specified by the Gibbs energy change ΔG_{r} in the transition [7, 8].

$$\begin{aligned}\Delta G_{\mathrm{r}} &= \Delta G_{\mathrm{f}}(\mathrm{Ag}) + 2\Delta G_{\mathrm{f}}(\mathrm{LiCl}) - \Delta G_{\mathrm{f}}(\mathrm{Cd}) - \Delta G_{\mathrm{f}}(\mathrm{CdCl_2})\\ &= -4.83 - 7.96 + 4.23 + 3.56 = -5.00\,(\mathrm{eV})\,. \end{aligned}\tag{29}$$

The value in Eq.(29) results in the rate enhancement factor K of the outermost s-orbital electron capture,

$$\log_{10} K = 54.8 \quad \text{at}\, T = 460\,\mathrm{K}\,. \tag{30}$$

The half life of the induced electron capture is

$$T_{1/2}/fK = 2 \times 10^{-40}\,(\mathrm{s})\,, \tag{31}$$

assuming $f \sim 10^{-5}$.

The ^{109}Cd nuclei would decay instantly with the dissolution of $\mathrm{CdCl_2}$ molecules in the liquid through the electron capture.

4.2. Induced β^- decay of ^{137}Cs

During the dissolving of a CsOH solution in the Li alloy liquid, the CsOH molecules are dehydrogenized and form CsLiO molecules as seen in Eq.(22). There by the ^{137}Cs nuclei in the molecules likely undergo the β^- decay ($T_{1/2}$ = 30.2 y),

$$^{137}_{55}\mathrm{Cs} \longrightarrow {}^{137}_{56}\mathrm{Ba} + e^- + \overline{\nu_e}\,, \tag{32}$$

coupled with the spontaneous oxidation of $\mathrm{Cs^+}$ ions,

$$\mathrm{Cs^+Li^+O^{--}} \overset{\beta^-}{\longrightarrow} \mathrm{Ba^{++}O^{--}} + \mathrm{Li}\,. \tag{33}$$

This oxidation, that is, the electron release from the decay parent atoms/ions gains the phase space volume in the β^- decay. This implies that the coupled electron emitting transition of nuclei and atoms/ions Eq.(33) likely undergo during the dissolution reaction Eq.(22) as,

$$\mathrm{CsOH} + \mathrm{Li} \overset{\beta^-}{\longrightarrow} \mathrm{BaO} + \mathrm{LiH}\,. \tag{34}$$

The rate of the coupled transition in the liquid is specified by the Gibbs energy change ΔG_r in Eq.(34) [7, 8].

$$\begin{aligned}\Delta G_\mathrm{r} &= \Delta G_\mathrm{f}(\mathrm{Ba}) + \Delta G_\mathrm{f}(\mathrm{BaO}) + \Delta G_\mathrm{f}(\mathrm{LiH}) - \Delta G_\mathrm{f}(\mathrm{Cs}) - \Delta G_\mathrm{f}(\mathrm{CsOH}) \\ &= -2.32 - 5.44 - 0.70 + 1.95 + 3.89 = -2.62\,(\mathrm{eV})\,. \end{aligned} \tag{35}$$

The value in Eq.(35) gives the decay rate enhancement factor,

$$\log_{10} K = 28.7 \quad \text{at}\, T = 460\,\mathrm{K} \tag{36}$$

The value may be reduced by the very small fraction of phase space volume gain. Taking into account this reduction, still we can expect,

$$\log_{10} K_\mathrm{eff} \sim 20 \quad \text{at}\, T = 460\,\mathrm{K} \tag{37}$$

The half-life of induced β^- decay is,

$$T_{1/2}/K_\mathrm{eff} \sim 6 \times 10^{-10}\,\mathrm{s}\,. \tag{38}$$

The ^{137}Cs isotopes is expected to decay simultaneously with the dissolution of CsOH in the liquid.

4.3. Induced cascade β^- decays of ^{90}Sr

In the cascade transition A → B → C, if the life time of intermediate B states is short, that is, the intrinsic transition rate relation $k_0(\mathrm{B} \to \mathrm{C}) >> k_0(\mathrm{A} \to \mathrm{B})$ holds, the over all transition rate becomes $k_0(\mathrm{A} \to \mathrm{B} \to \mathrm{C}) \approx k_0(\mathrm{A} \to \mathrm{B}) \propto T_{1/2}^{-1}(\mathrm{A})$. Whereas the Gibbs energy of state B formation $\Delta G_\mathrm{f}(\mathrm{B})$ is marginal in the cascade transition as seen in,

$$\begin{aligned}\Delta G_\mathrm{r}(\mathrm{A} \to \mathrm{B} \to \mathrm{C}) &= \Delta G_\mathrm{r}(\mathrm{A} \to \mathrm{B}) + \Delta G_\mathrm{r}(\mathrm{B} \to \mathrm{C}) \\ &= \Delta G_\mathrm{f}(\mathrm{C}) - \Delta G_\mathrm{f}(\mathrm{A}) = \Delta G_\mathrm{r}(\mathrm{A} \to \mathrm{C})\,. \end{aligned} \tag{39}$$

The life time of A-state $T_{1/2}(\mathrm{A})$ in the induced cascade transition A → B → C is given by,

$$T_{1/2}(\mathrm{A})/K(\mathrm{A} \to \mathrm{C}) = T_{1/2}(\mathrm{A}) \cdot \exp\left[-\frac{\Delta G_\mathrm{r}(\mathrm{A} \to \mathrm{C})}{k_\mathrm{B}T}\right]\,. \tag{40}$$

Now, we apply this argument to the cascade β^- decay of ^{90}Sr,

$$^{90}\mathrm{Sr} \xrightarrow[T_{1/2}=28.1\,\mathrm{y}]{\beta^-} {}^{90}\mathrm{Y} \xrightarrow[T_{1/2}=64\,\mathrm{h}]{\beta^-} {}^{90}\mathrm{Zr}\,. \tag{41}$$

We consider the ^{90}Sr isotope in the form of Sr^{++} ions inside the $\mathrm{Sr(OH)_2}$ molecules dissolved in a stable solvent liquid. During the course of dissolution of the $\mathrm{Sr(OH)_2}$ solution into the Li alloy liquid through dehydration, this spontaneous dehydration of ions releasing double electrons may induce the cascade β^- decay of ^{90}Sr in the $\mathrm{Sr(OH)_2}$ molecules and result in the coupled atomic and nuclear transition,

$$\mathrm{Sr(OH)_2} + 2\mathrm{Li} \xrightarrow{\beta^-\beta^-} \mathrm{ZrO_2} + 2\mathrm{LiH}\,. \tag{42}$$

In the liquid, the reaction Eq.(42) is subjected to the thermodynamic force specified by the Gibbs energy change in Eq.(42). This consideration provides the same values of ΔG_r and the enhancement factor K, respectively, with those on Eqs.(8) and (9) as,

$$\Delta G_\mathrm{r} = -3.78\,(\mathrm{eV}) \quad \log_{10} K = 41.5 \quad \mathrm{at\ T} = 460\,\mathrm{K}\,. \tag{43}$$

The half life of ^{90}Sr of induced cascade β^- decay is, thus

$$T_{1/2}/K_\mathrm{eff} = 3 \times 10^{-13}\,(\mathrm{s})\,. \tag{44}$$

This result implies that the induced cascade decays may become induced double β^- decay and take place during the dissolution of $\mathrm{Sr(OH)_2}$ molecules in the liquid.

5. Epilogue

During the past over one century we have conceived in imagination that any nuclear transitions i.e. nuclear reactions and decays are never induced by chemical reactions of atoms and molecules surrounding the reactant nuclei. However, in metallic hydrogen and lithium liquids consisting of collective mobile s-electrons, nuclear transitions are subjected to the thermodynamic activity of the liquids revealed in the spontaneous coupled chemical transitions through the coupling between the nuclei and the collective s-electrons.

Typical examples are chemonuclear fusion in the metallic Li liquids where the slow nuclear collisions are coupled with atomic collisions and result in the astronomically enhanced nuclear fusion. In the liquids, enormously enhanced nuclear decays are also induced. Here, the s-electron density respect to the nuclear positions plays the essential role through the coupling between the nuclear transitions and the spontaneous atomic and molecular transitions. In the liquids, all these extraordinary enhancement mechanisms are strictly subjected to the thermodynamic force specified by the Gibbs energy changes in the transitions.

This conclusion would be an extension of Einstein's unwavering confidence that thermodynamics is not based on any hypothesis.

The chemonuclear transitions would provide a great boon to mankind.

References

1. S. Ichimaru, Phys. Lett. **A266** (2000) 167.
2. S. Ichimaru and H. Kitamura, Phys. Plasma. **6** (1999) 2649.
3. H. Ikegami, Jpn. J. Appl. Phys. **40** (2001) 6092.
4. H. Ikegami, Ultradense Nuclear Fusion in Metallic Li Liquid, No.1, Swedish Energy Agency ER 2006:42
   Revised Ed. Sakaguchi E.H. VOC Co. Tokyo/Sakura, 2007
5. B.J. Widom, Chem. Phys. **39** (1963) 2808.
6. N.B. Gore and A.H. Wapstra, Nucl. Data Tables **11** 127 (1972) Academic Press Inc.
7. R. Boom, F.R. de Boer and A.R. Miedema, J. Less-Common Metals, **46** (1976) 271.
8. G. Aylward and T. Findlay, SI Chemical Data, John Wiley (2001) Australia, Ltd.
9. H. Ikegami, Ultradense Nuclear Fusion in Metallic Li Liquid, ibid. No.3.
10. D. Kondepudi and I. Prigogine, Modern Thermodynamics, John-Wiley of Sons Ltd: Chichester (1998).
11. E. Wigner and F. Seitz, Phys. Rev. **43** (1933) 804.