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Sammanfattning:

Rate enhancement up to a factor of 10^{15} has been observed in the nuclear fusion $^{7}Li + {}^{2}H \rightarrow {}^{8}Be + n$ with some tens keV deuterons implanted in metallic Li liquid [1, 2]. The enhanced fusion was found to be followed by the break-up of ^{8}Be into unidirectionally emitted paired α-particles. This indicates that recoil momenta of α-particles are sustained coherently by bulk liquid atoms [2]. These remarkable facts urge reconsideration for the mechanism of nuclear fusion through taking into account linked irreversible atomic process [3, 4]. In the nuclear stopping region of atomic collision electrons adjust smoothly to the nuclear fusion reforming electronic configuration and the entropy producing linked irreversible atomic fusion Li + H → Be operates resulting in chemo-nuclear fusion. Here macroscopically distinct parts become correlated and long-range coherence appears in the liquid [5]. These aspects are reflected in the entropy enhancement of chemo-nuclear fusion similar to irreversible chemical reactions in liquids [3]. The observation of unidirectional emission of paired α-particles is another evidence for the long-range coherence in the chemo-nuclear fusion [3].

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Long-range coherence revealed in entropy enhanced chemo-nuclear fusion

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Rate enhancement up to a factor of 10^{15} has been observed in the nuclear fusion $^{7}Li + {}^{2}H \rightarrow {}^{8}Be + n$ with some tens keV deuterons implanted in metallic Li liquid [1, 2]. The enhanced fusion was found to be followed by the break-up of ^{8}Be into unidirectionally emitted paired α-particles. This indicates that recoil momenta of α-particles are sustained coherently by bulk liquid atoms [2]. These remarkable facts urge reconsideration for the mechanism of nuclear fusion through taking into account linked irreversible atomic process [3, 4]. In the nuclear stopping region of atomic collision electrons adjust smoothly to the nuclear fusion reforming electronic configuration and the entropy producing linked irreversible atomic fusion Li + H → Be operates resulting in chemo-nuclear fusion. Here macroscopically distinct parts become correlated and long-range coherence appears in the liquid [5]. These aspects are reflected in the entropy enhancement of chemo-nuclear fusion similar to irreversible chemical reactions in liquids [3]. The observation of unidirectional emission of paired α-particles is another evidence for the long-range coherence in the chemo-nuclear fusion [3].

In irreversible processes time symmetry is broken. Fourier's law is the first example describing an irreversible process. There is privileged direction of time as heat flows according to this law from higher to lower temperature. It is in contrast with the laws of Newtonian's dynamics in which past and future play the same role. This conflict remains in quantum theory and relativity as well because the basic dynamical laws in both theories are also time-reversible [5]. Thermodynamics is the first science which introduced the irreversibility and brought an evolutionary view of nature. Nowadays, at all levels of observation, we see an evolutionary universe [5].

It is the Second Law of thermodynamics or the Principle of entropy increase which expresses the difference between "reversible" and "irreversible" processes. The entropy increase dS that is the entropy produced by irreversible processes in a system is associated with a thermodynamic flow dX such as heat dQ that has released in a time dt. In general the entropy increase can be expressed in the form

$$\mathrm{d}S = F\,\mathrm{d}X \tag{1}$$

where F is the thermodynamic force. In the case of Fourier's law, F is the gradient of temperature T.

In irreversible processes, the rate $k(T)$ of reaction is proportional to the thermodynamic flow dX and thus proportional to the rate of entropy increase as seen in equation (1). This general thermodynamic relation is accurate regardless of nature of microscopic interparticle interactions [5]. Very familiar examples are the solubility of gases in liquids (Henry's law) and the rate of irreversible ($\Delta G_{\mathrm{r}} < 0$) chemical reactions in dilute solutions where ΔG_{r} is the Gibbs energy (chemical potential) change in the reactions. One aspect is, common to these irreversible processes, the appearance of long-range coherence. Here macroscopically distinct parts of liquid become correlated [5, 6].

As indicated in equation (1) this long-range coherence represents the universal spontaneous tendency of bulk liquid corpuscles to dissipate and have a hunt for maximum entropy as a consequence of the Second Law of thermodynamics. These aspects are reflected in the Arrhenius' rate equation for irreversible chemical reactions with an exponential enhancement factor

$$k(T) = k_0 \exp\left(-\frac{\Delta G_{\mathrm{r}}}{k_{\mathrm{B}}T}\right) \quad , \ \Delta G_{\mathrm{r}} < 0 \tag{2}$$

where k_B denotes the Boltzmann constant. The term k_0 is concerned with the two body reaction dynamics. While the exponential enhancement factor corresponds to the Henry's law constant and concerned with the thermodynamic force or the activity of liquids [6].

The above arguments are based only on the "local equilibrium assumption". Still, the information we obtain from thermodynamics is quite valuable precisely because of its generality. This reminds us of the significance of Albert Einstein's optinion [5].

" A theory is more impressive the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended its area of applicability. Therefore the deep impression which classical thermodynamics made upon me. It is the only physical theory of universal content concerning which I am convinced that, within the framework of the applicability of its basic concepts, it will never be overthrown".

The thermodynamic arguments may also be applicable to nuclear processes if they take place with linking irreversible atomic processes [3]. From this viewpoint the author investigated a new scheme of non-thermal nuclear fusion

$$^{7}\mathrm{Li} + {}^{2}\mathrm{H} \rightarrow {}^{8}\mathrm{Be} + \mathrm{n} \rightarrow 2\,{}^{4}\mathrm{He} + \mathrm{n} + 15.12\ \mathrm{MeV} \qquad (3)$$

induced by slow deuterons implanted in metallic Li liquid [3]. Here momenta of deuterons and neutrons are matched and ^{8}Be nuclei are formed in rest because nuclear reaction rates are in general maximum under the momentum matching.

For the nuclear fusion the factor k_0 is expressed simply in the form

$$k_0 = I_1 N_2 \sigma(E_d) \qquad (4)$$

where I_1 and N_2 denote implanted particle number current and surface number density of Li ions or atoms, respectively [3]. The cross-section of nuclear fusion $\sigma(E_d)$ is given by the nuclear cross-section factor S_{12} as

$$\sigma(E_d) = \frac{S_{12}}{E} \exp\left[-\pi \left(\frac{E_G}{E} \right)^{\frac{1}{2}} \right] \qquad (5)$$

where E_G is the Gamov energy and $E = (m_{Li}/m_{Li}+m_d)E_d$ with E_d denoting the acceleration energy [3].

If there is no correlation between liquid atoms at all the nuclear fusion rate is $k(T) = k_0$ and almost all deuterons undergo stopping without nuclear fusion within the depth of a few hundredth μm on a surface of Li liquid because the intrinsic nuclear fusion probability P_{intr} is very faint typically 4×10^{-23} for $E_d = 10$ keV and 8×10^{-18} for $E_d = 20$ keV as seen in Fig. 1 [4]. This is the common case where nuclei are unable to increase entropy in their system through nuclear reaction products under usual state conditions and no thermodynamic force works.

However this situation will be dramatically changed in the action of thermodynamic force. In a metallic Li liquid system, Li ions are immersed in a sea of mobile s-electrons. The de Broglie wavelength of the s-electrons covers the space of some tens Li atoms. Furthermore the density of these coherent s-electrons is nonvanising inside Li nuclei. The liquid system is thus capable to take the parts of solvent for nuclear processes as well as for atomic processes to some extent if the nuclear processes were linked with the irreversible atomic processes as seen below.

The interaction time between deuterons and Li atoms is $\tau = d / v_d$, where d is a characteristic dimension of the atoms e.g. the diameter of outer shell electron orbit, and $v_d = [2(m_{Li}/m_d)E_d /(m_{Li}+m_d)]^{1/2}$ is the relative speed of deuterons. The characteristic period of internal motion of outer shell orbit electrons is $\tau_0 = \pi d / v_0$ where v_0 is the speed of an electron on the orbit. When deuterons interact slowly with the Li atoms compared with the characterestic period e.g. $\tau > \tau_0$ the electrons adjust continuously and smoothly to the nuclear fusion, reforming their electronic configuration state. In this case the atomic fusion process is able to be linked with the nuclear fusion. The degree of linking or the linkage factor F_{link} of the fusion (hereafter called chemo-nuclear fusion) is expressed as

$$F_{link} = \exp\left(-\frac{\tau_0}{\tau}\right) = \exp\left[-\pi\left(\frac{E}{E_0}\right)^{\frac{1}{2}}\right] = \exp\left(-0.623E_d^{\frac{1}{2}}\right) \qquad (6)$$

with $E_0 = (m_d/2)\, v_0^2 = 19.8$ keV, the energy of deuterons with a speed equivalent to an electron in the ground state of a Li atom. Within the degree of linking, equation (6), the Li nuclei and deuterons are no more isolated from their surrounding bulk liquid atoms of which macroscopically distinct parts are correlated.

The liquid system exchanges entropy with the exterior through heat release and the entropy producing irreversible atomic fusion process operates. The chemo-nuclear fusion, equation (3) is also dominated through the Gibbs energy change in the linked atomic fusion process. In the present paper the value of Gibbs energy change has been derived using thermodynamic data (in eV)

$$\Delta G_r = \Delta G_f(\text{Be in Li}) - \Delta G_f(\text{Li}) - z_{\text{eff}}\,\Delta G_f(\text{LiD}) = -1.57 + 0.704\,z_{\text{eff}} \qquad (7)$$

with

$$z_{\text{eff}} \approx \left\{1+\left[0.122\left(\frac{E_d}{2}\right)^{\frac{1}{2}}\right]^{\frac{1}{0.6}}\right\}^{-0.6} \qquad (8)$$

where ΔG_f denotes the standard Gibbs energy of formation for an atom or a molecule in the state specified under standard state condition [7]. Here ΔG_f (Be in Li) = – 2.88 eV was estimated from the data on metastable microalloys of Li in Be prepared by ion implantation [8]. In equation (7) ΔG_f (Li) = – 1.31 eV is the bond strength of metallic Li and ΔG_f (LiD) = $-0.704 z_{\text{eff}}$ is a dissolving energy of deuterons in the metallic Li liquid where the deuterons traverse as an ion with an effective charge z_{eff} caused by the charge exchange effect [3, 4].

Equations (7) and (8) in turn lead to the prediction of effective enhancement F_{link} exp (– Δ G_r / k_0T) and enhanced nuclear fusion probability

$$P_{\text{enh}} = F_{\text{link}} P_{\text{intr}} \exp\left(-\frac{\Delta G_r}{k_B T}\right) \qquad (9)$$

recalling equation (6).

The predicted effective enhancement is typically 2.4×10^{14} for E_d = 10keV and 1.0×10^{12} for E_d = 20keV just above the melting point of Li metal, T = 460 K. Observed enhancement was around 10^{15} for the deuteron energy E_d = 10 keV and 4×10^{10} for E_d = 20 keV [1, 2], which are well compared with the predicted values of P_{enh} as seen in Fig. 1. These results are in contrast to the one century retained assessment that nuclear reactions are never affected by temperature and compound in which an element occurs.

Nuclei ^{8}Be formed in rest are in thermal equilibrium with the bulk liquid Li atoms of which macroscopically distinct parts are correlated and the nuclei would be entirely bound in the bulk [1]. This makes the break-up of ^{8}Be into unidirectionally emitted paired α-particles possible. Here recoil momenta of α-particles are coherently sustained by the bulk liquid Li atoms. Under this sustainment dynamics the paired α-particles favour the coherent emission similar to the Bose-Einstein condensation. These α-particles yield a sum peak at the energy of 15.12 MeV in an SSD (Si surface barrier detector) spectrum [1, 2]. However, when the paired α-particles scatter with contaminant molecules in the Li liquid and lose their unidirectivity or coherency, the SSD becomes able to detect α-particles with the energy of 7.56 MeV one by one. This explanation is consistent with the systematic observation results [1, 2]. These discoveries will no doubt lead to a more understanding of the nature of chemo-nuclear fusion in metallic liquids.

Slow neutrons produced are monochromatic $E_n = 2\,E_d$ due to the momentum matching in the enhanced chemo-nuclear fusion reaction and expected to provide new cold neutron sources. When the liquid Li target chamber is covered with Li or Li compound say Li_2O layer the neutrons are absorbed by ^{6}Li and ^{7}Li nuclei and produce associated energy release of about 11 MeV/neutron in average. The total energy release is thus about 26 MeV for one deuteron [4]. This implies that the intrinsic energy gain defined by the ratio of energy release to acceleration energy is about 260 for deuterons of 100 keV energy where fusion probability would be close to 100% as seen in Fig. 1. The new scheme of enhanced chemo-nuclear fusion could provide mankind with sustainable waste-less energy.

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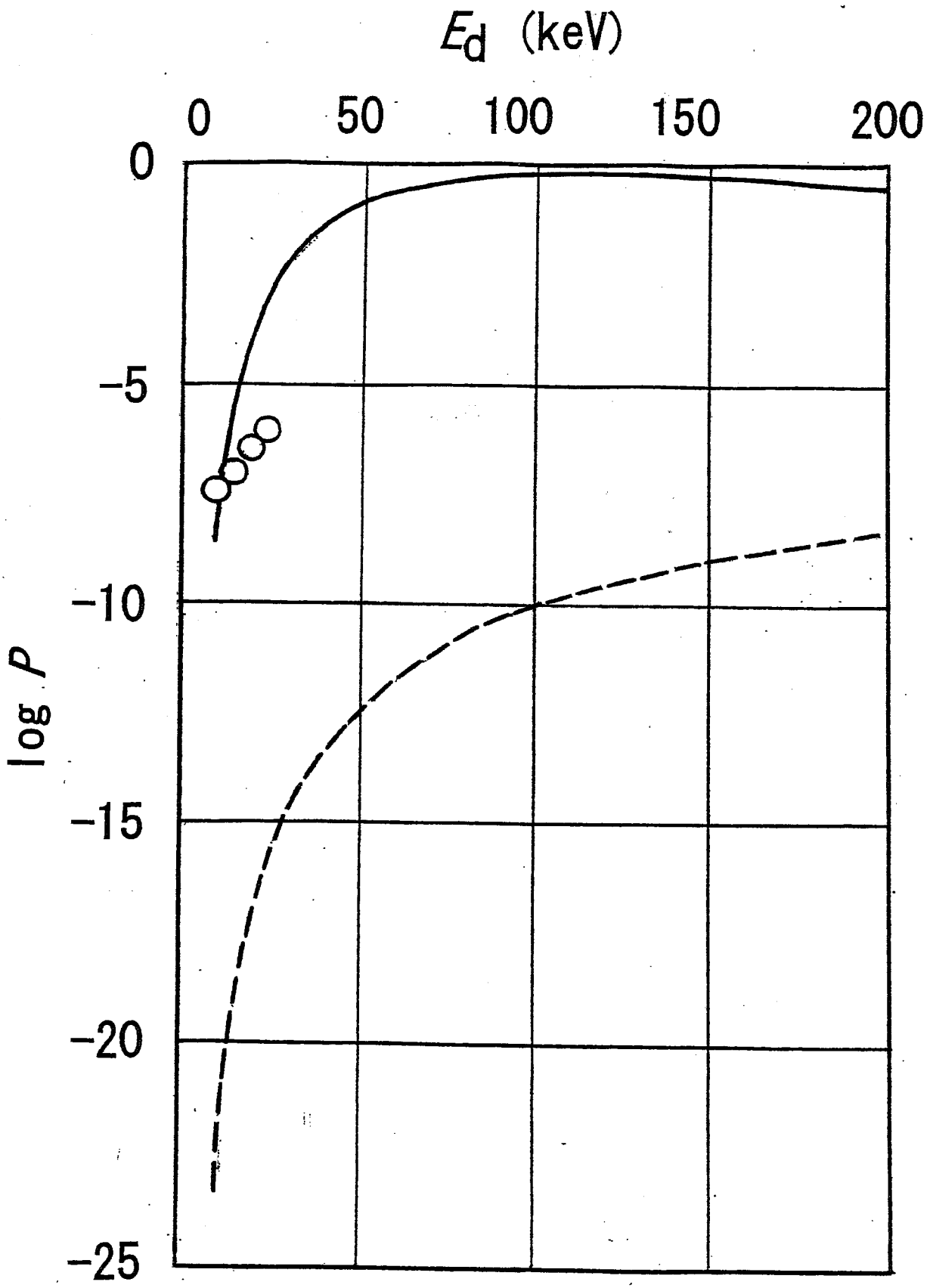
Figure 1 Fusion probability of deuterons before stopping in Li metals. The broken line indicates the intrinsic nuclear fusion reaction probability P_{intr} calculated based on the cross-section factor $S_{12} = 2100$ keV b of the reaction $^{7}Li + {}^{2}H \rightarrow {}^{8}Be + n$ and the Lindhard formula for the stopping power [4]. The solid line is the enhanced fusion probability $P_{enh} = F_{link} P_{intr} \exp (-\Delta G_r / k_B T)$ where F_{link} is the factor of linkage between atomic- and nuclear- processes and $\Delta G_r (< 0)$ is the Gibbs energy change in the irreversible atomic process, Li + H $\rightarrow$ Be. The factor is expressed as $F_{link} = \exp (-\pi v_d / v_o)$ where v_d and v_o are the deuteron speed and the speed of an electron on the orbit of Li atoms, respectively. Open circles show observation results.


E_d (keV)
0
50
100
150
200
0
-5
-10
-15
-20
-25
log P