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## **Evidence of Enhanced Nonthermal Nuclear Fusion**

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**Evidence of Enhanced Nonthermal  
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# **Evidence of Enhanced Nonthermal Nuclear Fusion**

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## Preface

In this bulletin a new nuclear fusion scheme is presented. Deuterium ions of about 25 keV energy are incident on a Li target operated at temperatures just above the melting point. The detected event rate of around a thousand per second corresponds to an enormous enhancement between  $10^{15} - 10^{10}$  as compared to what is expected for deuterium ions interacting with free Li atoms.

The fusion reaction events are defined by energetic particles escaping from the Li surface and detected in a solid state Si detector which is monitored by 5.3 MeV alpha particles from an americium source. The presumed alpha particles have energies up to three times the energies of the reference americium alphas.

These experimental findings can be explained by a theory where several new concepts and mechanisms such as, buffer energy, adiabatic transition (quantum mechanical resonance) between atomic fusion and nuclear fusion, fusion reactions enhanced by the thermodynamic force and so on have been introduced.

Explanations of the new concepts and interpretations of present experimental results based on these concepts are beyond the scope of a paper in usual academic journals. With considerations of the state of affairs, all results on the new fusion scheme are published as the three-in-a-set papers in the Bulletin of Institute of Chemistry, Uppsala University, September 2002 which can be found at internet. We hope that this publication will stimulate continued works in order to better understand the enhanced fusion rate. We would also welcome any comments or criticism.

September 2002

Karin Markides  
Sven Kullander



## Foreword

The aim of present research would be phrased as:

“ Better creative Prometheus than weary Atlas ”.

Realistic Prometheus favours “ the creation of new fire ” in his own manner instead of shouldering monstrous nuclear fusion machines.

In this creation task, Einstein`s very severe remark was helpful as guiding principle.

“ God does not play dice with the universe ”.

This would be the universal truth. Because whenever a person introduces coherent observation-instruments and methods the person needs not to be involved with any uncertainty problem such as the Heisenberg uncertainty principle in quantum mechanics. Furthermore all macroscopic quantum effects reveal the “ quantum mechanical certainty ” and can be treated in the scheme of Gibbs statistical thermodynamics.

Perhaps the most decisive force dominating reactions of bulk of particles would be the thermodynamic force defined by the change of Gibbs energy in the reactions in metallic liquids. The thermodynamic force represents the spontaneous tendency of bulk of particles to dissipate and have a hunt for maximum entropy, as a consequence of the Second Law of thermodynamics. This universal tendency causes the enormous rate enhancement of atomic fusion which induces the enhanced nuclear fusion through the quantum mechanical resonance.

If a reader would trace systematically problems thoroughly argued in this bulletin, the reader could find how the author aimed at the new nuclear fusion scheme enhanced by the thermodynamic force in metallic Li liquids.

The bulletin consists of following three papers:

“ Buffer Energy Nuclear Fusion ”--- hereafter called BENF NO.1

H. Ikegami, Jpn.J. Appl.Phys. Vol.40, 6092 (2001) with some corrections.

“ Recoilless Nonthermal Nuclear Fusion ”

H. Ikegami and R.Pettersson --- hereafter called BENF NO.2

“ Evidence of Enhanced Nonthermal Nuclear Fusion ”

H. Ikegami and R. Pettersson --- hereafter called BENF NO.3

The first paper BENF NO.1 is essentially the same with that published in Jpn. J.Appl. Phys. but some parts are corrected. The paper presents and explains all new concepts leading to the new nuclear fusion scheme. In BENF NO.2, quenching of enhancement due to nuclear recoil was evaluated and compared with preliminary experimental results obtained under the extensive collaboration with Dr. Roland Pettersson. The paper provides concrete prescriptions of improved experiments and data analysis. The third paper BENF NO.3 is a description of experiments observing the enhancement with Dr. Roland Pettersson along the prescriptions presented in BENF NO.1 and 2.

Finally, the author expresses his heartfelt thanks to his family especially his wife Noriko Ikegami for their continuous helps and encouragements. He also greatly appreciates Professors Kazutake Kohra, Sven Kullander, Karin Markides, and Mr. Masanobu Kato for their promotion of this research. The data could not be obtained without skilful technical assistance from Messrs. Arne Jansson, Robert Peterson, Sven-Olof Eriksson , Lars Einarsson and Dr.Torbjörn Hartman.

September 2002

Hidetsugu Ikegami

# Buffer Energy Nuclear Fusion\*

-----BENF NO. 1-----

Hidetsugu Ikegami;

\*transferred from Jpn.J.Phys. Vol.40 (2001) 6092, with some corrections

## Buffer Energy Nuclear Fusion

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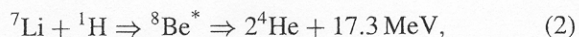
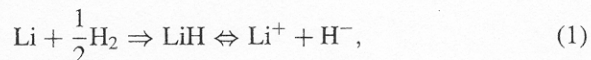
A compact scheme of non-thermonuclear fusion is presented. Hydrogen ions are implanted directly from nonthermal discharge plasma or ion source into a surface of liquid Li metal at a buffer energy of a few tens keV where nuclear stopping occurs. The ions interact with Li atoms or mixed element atoms which are not being internally excited and tend towards the formation of united atoms at the minimum Gibbs free energy point. This leads to the enhanced rate of non-thermonuclear fusion of hydrogen ions due to cohesion in the liquid metal.

KEYWORDS: non-thermonuclear fusion, buffer energy, nuclear stopping, united atom, Gibbs free energy, cohesion

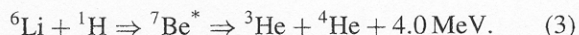
### 1. Basic Features of Atoms and Nuclei undergoing Fusion Reactions

Nuclei dressed with electronic configurations reveal dynamical features influenced by their surroundings in some cases such as  $\beta$ -decay through electron capture, external field effects on its decay life, internal electron conversion in nuclear isomeric transitions and so on. This would be also the case where low energy nuclei undergo fusion reactions under an electron background to suppress the nuclear Coulombic repulsive force. The essential similarities between these conditions and those in chemical reactions might be of significance to notice.<sup>1)</sup>

In this paper, the author confines himself to argue mainly the following chemical- and nuclear-fusion reactions which are caused in liquid Li metal (*cf.* melting point: 180°C, boiling point: 1380°C),



and



Here  ${}^8\text{Be}^*$  and  ${}^7\text{Be}^*$  denote compound nuclei of  ${}^8\text{Be}$  and  ${}^7\text{Be}$ , respectively. As explained below, the atomic and nuclear species Li–H appear to make one of the best systems as far as nuclear fusion treatment of eqs. (2) and (3) is concerned and nuclear reaction products are nonactive helium gas only.

The handling of chemical reaction, eq. (1) may be achieved by hydrogenation of liquid Li metal in a hydrogen atmosphere. The reaction rate  $k_{\text{LiH}}(T)$  at the temperature  $T$  of the liquid has been well explained by the Arrhenius equation,

$$k_{\text{LiH}}(T) = A_{\text{LiH}} \exp\left(-\frac{E_a}{RT}\right), \quad (4)$$

where  $A_{\text{LiH}}$  denotes the frequency factor which depends little on the temperature,  $R$  is the gas constant and  $E_a$  is the activation energy of intermediate complex formed at the contact point of reactant molecules.

Resulted LiH is a typical ionic hydride of melting point: 690°C and density:  $0.78 \text{ g cm}^{-3}$  at 20°C which is higher than the value  $0.53 \text{ g cm}^{-3}$  of Li metal. When lithium is converted to pure solid LiH, all electrons in the conduction band are

consumed and insulating but conductive above the melting point.<sup>2,3)</sup> LiH is the simplest heteronuclear diatomic molecule successfully explained based on the molecular orbital model together with covalent electron-pair bond homonuclear diatomic molecules. Though the bond in LiH has a partial ionic character due to the different electronegativity of Li and H atoms, it has some common features with the metallic bond which is also closely related to the covalent electron-pair bond.

The hydride anion  $\text{H}^-$  radius  $1.37 \text{ \AA}$  is comparable to the Li metal radius  $1.52 \text{ \AA}$  (*cf.*  $\text{Li}^+$  cation radius  $0.74 \text{ \AA}$ ) indicating that the  $\text{H}^-$  anions move around together with Li ions in liquefied LiH similar to metallic ions in liquid eutectic alloys.<sup>2)</sup> This reminds us of an empirical and unexplained speculation on the metal hydrides that deuterides and tritides of actinide metals probably play an important role in thermonuclear fusion reactions such as thermonuclear (hydrogen) weapons.<sup>3)</sup>

A reasonable interpretation would be found, however, in the features of highly dense hydrogen ions and mobile electrons produced in the liquefied actinide metals. This results in the cohesive effect between atomic nuclei in the liquid metals and enhances the fusion reaction rate.

As seen in §3.1 and 3.4, the rate equation of nuclear fusion reactions in liquid is reduced to the Arrhenius equation through transferring the cross-section factor intrinsic to the reacting nuclei into the frequency factor.<sup>1)</sup> The implication of this fact characteristic of nuclear fusion in liquid is that both chemical- and nuclear-fusion reactions eqs. (1)–(3) are describable in the same scheme of Coulombic interaction dynamics under appropriate scaling treatments. In fact the electron screening and cohesive effects are common in both the reaction cases. These considerations lead to a new boundary concept “buffer energy”, where both atomic- and nuclear-process would take place cooperatively in atomic and nuclear systems such as united atoms under certain surroundings.

The buffer energy may be specified by the geometric mean of atomic- and nuclear-excitation energies. If one assumes the typical values 5 eV (bond energy of  $\text{H}_2$  molecule) and 16 MeV (volume term in the nuclear mass formula) for the former and the latter, respectively, the buffer energy would be  $E_b \sim 10 \text{ keV/amu}$ . The verification of this concept has been found in systematic investigations on the nuclear stopping component in the total stopping cross-section of ions in

matter.

## 2. Ion-Condensed Matter Interactions

It would be instructive to consider this problem for ions implanted in a uniform condensed matter.<sup>4)</sup> When an energetic but non-relativistic ion which has been produced in a plasma or an accelerator impinges upon the surface of uniform condensed matter, it experiences a series of elastic and inelastic collisions with the atoms which lie in its path. These collisions occur because of the electrical forces between the nucleus and electrons of the ion and those of atoms which constitute the condensed matter. They result in the transformation of the kinetic energy  $E_0$  of the ion into internal excitation of the condensed matter. The precise nature of this excitation and the resulting physical processes are determined largely by the implantation conditions. The most principal determining factors are the species of ion, its energy, the condensed matter composition, its temperature and the condition of its surface.

When the ion moves past at high velocity the average force acting on the stationary ion is perpendicular to the trajectory of the moving ion. This force acts for a brief period of time and gives the stationary ion a small momentum. This allows us an argument based on the impulse approximation assuming that the target particle of mass  $m$  does not move very much during the collision and the ion is not significantly deflected by it. The magnitude  $\Delta p$  of the momentum acquired by the struck particle is independent of its mass so that the energy that it receives in the collision is  $(\Delta p)^2/2m$ . Thus an electron will receive much more energy from a collision than a nucleus (called electronic stopping). This explains the stopping power having a slope proportional to  $E_0^{-1}$  for a heavy ion in a condensed matter, which is called the Bethe region. Here the ion penetrates the medium as a bare nucleus devoid of electrons because they have been stripped away in collisions.

As an ion's energy is lowered below the Bethe region, typically around 100 keV for hydrogen ions it begins to capture electrons from the medium. Very roughly, a new electron is quickly captured when the velocity of the ion in the medium is comparable to the velocity of the electron in its quantum mechanical orbit about the ion. The presence of these captured electrons surrounding the penetrating nucleus shields it from the electrons of the medium and thus reduces the stopping power. However, collisions with target electrons (electronic stopping) continue to dominate the stopping power below this energy region, which is labeled the Lindhard region, and the stopping power has an  $E_0^{1/2}$  dependence.

A qualitatively new kind of stopping power occurs below the Lindhard region. For heavy ions with energies typically around a few hundreds keV and for hydrogen ions a few tens keV, the collisions are not simply with electrons but are elastic and inelastic collisions between whole atoms. This is called nuclear stopping since the nuclei of struck atoms acquire significant amounts of kinetic energy. This does not happen in conjunction with electronic stopping because the large mass difference makes it difficult for energy initially given to electrons to be transferred to nuclei.

The nuclear stopping component can be separated clearly from the electronic stopping dominant in the Bethe- and the Lindhard regions. Because the heavy struck nucleus can be considered to leave its spectator atoms i.e. non-reacting atoms

untouched during the passage of the ion and thus the interaction can be treated simply as the kinetic scattering of two "screened" particles in a stable medium.<sup>5)</sup>

There are several detailed theories<sup>5,6)</sup> of nuclear stopping related to the sputtering yields after the basic theory of Bohr<sup>7)</sup> which led to a simple well-known formula called LSS nuclear stopping.<sup>8)</sup> Measurements of sputtering yields of uniform amorphous or polycrystalline solids under carefully controlled conditions are in good agreement with these theories. The theories have predicted that the nuclear stopping emerges around the buffer energy. Typically the maximum sputtering yield of Si by Ar ion bombardment is observed at the ion energy of about 40 keV.<sup>9)</sup>

The concept "buffer energy" ( $E_b$ ; defined in the laboratory system) leads to a non-thermonuclear fusion scheme. Suppose that hydrogen ions of mass  $m_N$  are accelerated up to an effective buffer energy  $E_0 = E_b + \Delta E_0$  with  $E_b \sim 10$  keV and  $\Delta E_0$  being the energy loss before reaching reaction points. The ions extracted from low pressure arc are at low temperature never more than a few hundred Kelvins and directly implanted from nonthermal discharge plasma or ion source into a surface of liquid Li metal mounted on a cathode.

For a protium atom undergoing a collision with a Li atom of mass  $A$ , the center of mass (CM) kinetic energy  $E$  is

$$E = \frac{A}{1+A} E_b. \quad (5)$$

The energy  $E$  in eq. (5) results in the Coulombic penetration factor much larger compared to low thermal energy ion cases. Further, atomic effects such as the image force on the surface and the cohesive force effect arisen in the liquid metal enhance cooperatively the fusion rate as seen in the following sections.

## 3. Theory of Buffer Energy Nuclear Fusion

### 3.1 Arrhenius equation of nuclear fusion reactions

According to the Arrhenius's indication in 1889, eq. (4) represents that molecules must acquire a certain critical energy  $E_a$  before they can react, the Boltzmann factor  $\exp(-E_a/RT)$  being the fraction of molecules that managed to obtain the necessary energy. Here the word molecule is used in its general sense to include atomic/ionic reactants also. This interpretation is still held to be essentially correct. In fact, the famous Eyring equation derived in 1935 based on the quantum statistics has the same factor and the significance of activation is greatly clarified.<sup>10)</sup>

In the Eyring equation, the reaction rate is formulated in terms of properties of the reactants and of the transition state at which interacting molecules have formed the "intermediate or activated complex" for the particular reaction. The rate of reaction is the number of intermediate complexes passing per second over the top of the potential energy barriers. This rate is equal to the concentration of intermediate complexes times the average frequency with which a complex moves across to the product side. This intermediate complex or transition state theory has been applied to a wide variety of rate processes especially those on the transport phenomena.

The theory has introduced a little temperature dependence of frequency factor arisen from the vibrational degree of freedom in the reacting molecules. However, on the basis of Arrhenius's assumption of rigid sphere reactants, this degree of



freedom may be disregarded and there is no interaction between the reactants until the spheres contact at which point a reaction occurs. In this case, such as the buffer energy nuclear fusion reaction, the frequency factor  $A_{12}$  of the reaction between nuclei of 1 and 2 species is not temperature dependent and expressed simply in the form,

$$A_{12} = I_1 N_2 \sigma_{12}(E), \quad (6)$$

and the rate equation is reduced to the Arrhenius equation,

$$k_{12}(T) = A_{12} \exp \left[ -\frac{\Delta G}{k_B T} \right], \quad (7)$$

with

$$\Delta G = E_a / N_A. \quad (8)$$

Here,  $I_1$ ,  $N_2$ ,  $\sigma(E)$ ,  $k_B$  and  $N_A$  denote particle current of buffer ions of species 1, surface number density of nuclei of species 2, cross-section of nuclear fusion between species 1 and 2, the Boltzmann constant and the Avogadro constant, respectively. The chemical potential or Gibbs free energy of activation  $\Delta G$  is defined for an intermediate complex. This however depends on neither structure nor dynamical behavior of nuclei at all.

Intrinsic features of the nuclei have already been fully transferred to the frequency factor through the fusion cross-section and hence yield nothing any statistical or collective effect in a bulk as in the usual nuclear reaction cases. This is a natural consequence due to the complete lack of collectivity in short range force few body systems.

### 3.2 United atom formation in liquid metal

The formation of intermediate complex dominates the statistical feature of the reaction through the Gibbs free energy  $\Delta G$  at the transition state. This feature becomes remarkable if  $\Delta G < 0$  and reveals a collectivity in the reaction. It leads to the enhancement  $\exp[-\Delta G/k_B T] \gg 1$  of reaction rate such as seen in the spontaneous reaction between ions of opposite sign in ionic solutions as compared with similar reactions in which one or both of the reactants are uncharged.<sup>10)</sup> The buffer energy nuclear fusion would be also the case as explained below.

Consider a case where light ions of species 1 are implanted into a surface of liquid metal of species 2. As the ions approach to the surface, they are subjected to a net attraction towards the bulk metal through three kinds of forces in turn, the mirror force, the surface tension and the cohesion in the bulk. Among them, the top-strength force is the cohesion and it is the origin of greatly enhanced stability of metals and surface tension on the liquid surface.

The cohesion of metals can be understood in qualitative terms as the consequence of an electrostatic attraction between the positive cores of the metal atoms (ions) and the negative fluid of mobile electrons. Because, in the metal the atomic potential wells for the electrons are not far apart and the electrons can tunnel through the barriers. We are thus no longer concerned with energy levels of individual atoms of the metal instead the bulk of metallic ions immersed in the collective mobile electrons under the explanation by Wigner and Seitz.<sup>11,12)</sup>

Such the collective features are also revealed in liquid metals. When the ions implanted are travelling in a liquid

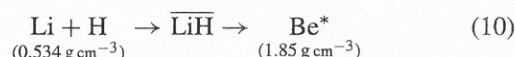
metal, atoms of the metal surrounding the ions tend towards metastable phase formation at the minimum Gibbs free energy point. The concept of metastable phase formation during the implantation process have been well recognized even in solid metals by a usual alloying definition though ion implantation is a grossly non-equilibrium process. Typical implants into Si will results in the production of an amorphous surface layer, itself a metastable phase.<sup>9)</sup>

However this Gibbs free energy is not the minimum point any longer for the buffer energy atoms/ions. They are directed to form the new dense intermediate complex "united atom". For a reacting pair of buffer energy the radius of the classical turning point,

$$\frac{r_{TP}}{(10^{-9} \text{ cm})} = \frac{z_1 z_2 e^2}{4\pi \epsilon_0 E} = \frac{0.144 z_1 z_2}{E(\text{keV})}, \quad (9)$$

is extremely small compared to the size of atoms, where  $\epsilon_0$  denotes the dielectric constant of vacuum. It is only a few percent of their K-shell electron orbital radius. This leads to the formation of united atoms of which physical characteristics such as Gibbs free energy, mass density and so on are expected to be almost the same with those of product atom of nuclear fusion.

It would be instructive to consider these features for the reactions eqs. (1)–(3) caused in a liquid metallic medium. The comprehensive processes would be advanced as follows,



Here  $\overline{\text{LiH}}$  denotes a united atom and  $\text{Be}^*$  is a Be atom as the product side of the united atom but its nucleus is a highly excited compound nucleus. The numbers in parentheses indicate respective mass densities.

For example, in a case of reaction eq. (10) with a colliding energy  $E = 8 \text{ keV}$ , the radius of classical turning point is  $5.4 \times 10^{-11} \text{ cm}$  which is about 180 times bigger than the nuclear radius of  $^8\text{Be}$  but only 4% compared to the radius of the K-shell orbit of Be atom. Therefore the reaction eq. (10) would proceed consecutively towards higher density products under the cohesive action inside the liquid metal.

The Gibbs free energy difference between metallic Li and metallic Be and that between LiH compound and metallic Be are  $-1.65 \text{ eV}$  and  $-0.95 \text{ eV}$ , respectively.<sup>13)</sup> The free energy difference in the reaction eq. (10) may thus be in between depending on the condition of medium surrounding the reacting pair. If one assumes  $\Delta G = -1 \text{ eV}$  for the reaction, its rate would be enhanced by a factor  $\exp[-\Delta G/k_B T] \sim 10^{11}$  at the melting point of metallic Li,  $460 \text{ K}$  ( $k_B T = 0.0396 \text{ eV}$ ).

### 3.3 Donor catalysis of nuclear fusion

In §3.2, we found that ions implanted with an effective buffer energy would lead to practicable nuclear fusion reactions in liquid metals. This finding is however premised on condition that the cohesion indwelling in the metals is sufficiently strong to realize the nuclear fusion. In general, liquid metals have approximately close-packed structures quite similar to those of the solids with the interatomic spacing expanded by about 5% except a few cases like Bi. The number of nearest neighbors in a close-packed structures is 12. In liquid Na, for instance, each atom is found to have on the average 10 nearest neighbors.<sup>10)</sup> This is also the case for liquid

Li metal. Thus metallic liquids consists of ions and mobile electrons hold together by somewhat (2–3%) reduced metallic bonding compared to the solid.<sup>12)</sup> This results in the cohesive energy of around 1 eV per metallic valence electron in the liquid metals as well in the solids. The cohesive energy reveals the surface tension on the interface of the liquid since the tension equals to the partial derivative of Gibbs free energy with respect of the surface area.

These features indicate that the gain of electron density in the liquid metals would enhance the fusion rate dramatically through the gain of cohesion. This consideration leads to a new concept “donor catalysis” doped in metallic liquids. Some transition elements such as those of Cr, Mn, Fe, Co and Ni would be useful as catalysis through mixing preferably in the form of fine amorphous powder in the liquid Li metal. The number density of mobile electrons of these metals is around  $5 \times 10^{23} \text{ cm}^{-3}$  which can be compared with the value of metallic hydrogen under an ultra high pressure of some Mbar. Presumably one of the most useful catalysis/fuel would be a finely divided, micron-sized amorphous boron. This forms a large number of lithium borides  $\text{Li}_2\text{B}$ ,  $\text{LiB}$ ,  $\text{LiB}_2$ ,  $\text{LiB}_4$ ,  $\text{LiB}_6$  and  $\text{LiB}_{12}$  which exhibits characteristics of typical metals, for example, high electrical conductivity though boron is not metal in its normal state. The remarkably large proton capturing cross-section of  $^{11}\text{B}$  indicates also the capability of useful fusion fuel as argued in §5.

### 3.4 Nuclear fusion cross-section

The cross-section as the kernel of the frequency factor  $A_{12}$  is given in the form,<sup>14)</sup>

$$\sigma_{12}(E) = \frac{S_{12}}{E^{1/2}(E + E_s)^{1/2}} \exp \left[ -\pi \left( \frac{E_G}{E + E_s} \right)^{1/2} \right]. \quad (11)$$

Here,

Gamov energy  $E_G \gg$  relative kinetic energy  $E \gg k_B T$  (12)

has been assumed. In eq. (11) the exponential decay factor is the Coulombic penetration factor, while the cross section factor  $S_{12}$  is a quantity intrinsic to the nuclear reaction.<sup>15)</sup> The Gamov energy  $E_G$  is given as,

$$E_G = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 r_{12}^*} = \frac{99.2(z_1 z_2)^2 A_1 A_2}{A_1 + A_2} \text{ keV}. \quad (13)$$

In eq. (13),

$$r_{12}^* = \frac{4\pi\epsilon_0 \hbar^2}{2\mu_{12} z_1 z_2 e^2}, \quad \mu_{12} \equiv \frac{A_1 A_2}{A_1 + A_2} m_N, \quad (14)$$

corresponds to the nuclear Bohr radius with  $\mu_{12}$  denoting the reduced mass between the nuclei 1 and 2 with respective charges  $z_1$  and  $z_2$  and mass numbers  $A_1$  and  $A_2$ .

The presence of electrons or other light particles such as negative muons may act to modify the inter-nuclear potential. This results in the correction of the screening energy  $E_s$ , eq. (15) to the kinetic energy  $E$  through the replacement of  $E$  with  $E + E_s$  as seen in eq. (11).<sup>16)</sup>

$$E_s = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 D_s} = 0.144 z_1 z_2 \left( \frac{D_s}{10^{-9} \text{ cm}} \right)^{-1} \text{ (keV)}. \quad (15)$$

Here  $D_s$  denotes the short range screening length of electron systems surrounding the nuclei and the following expression

has been widely adopted,<sup>17)</sup>

$$D_s = 0.8853 a_B \left( z_1^{1/2} + z_2^{1/2} \right)^{-2/3}, \quad (16)$$

or<sup>8)</sup>

$$D_s = 0.8853 a_B \left( z_1^{2/3} + z_2^{2/3} \right)^{-1/2}, \quad (17)$$

provided  $a_B$  being the Bohr radius,

$$a_B = \frac{4\pi\epsilon_0 \hbar^2}{m_e e^2} = 5.29 \times 10^{-9} \text{ cm}. \quad (18)$$

### 3.5 Enhancement

In the present fusion scheme, buffer ions are implanted into a liquid medium at an ordinary temperature and pressure. This implies that the dimensionless thermal de Broglie wavelength  $\Lambda_i$  of atoms with a mass number  $A_i$  is very small in the medium.

$$\Lambda_i \equiv \frac{\hbar}{a_e} \left( \frac{2\pi}{A_i m_N k_B T} \right)^{1/2} \ll 1. \quad (19)$$

Here  $a_e$  is the Wigner–Seitz radius. The wave mechanical effects are therefore negligible on the ions. Furthermore, the reacting pair of buffer energy does not disturb surrounding spectator atoms very much and its interaction can be treated as that between two screened particles as argued in §2. These features may confirm the validity of enhancement evaluation in the scheme of semi-classical dynamics as far as concerning the buffer energy nuclear fusion rate. Their dynamics may thus be describable as those of ion cores immersed in the collective mobile electrons of liquid metal.

Consider a concrete example where protons of an effective buffer energy are implanted into a surface of liquid Li metal. On the surface, the protons are quickly neutralized within several tens Å passage because of very large electron capturing cross-section. They are subjected to the nuclear stopping effect and may interact with Li ion cores screened by mobile electrons and tend towards the nuclear fusion at the minimum Gibbs free energy point through the formation of united atoms.

Here the author develops a simple argument similar to that presented by Born to estimate the free energy of solvation of an ion in aqueous solution.<sup>18)</sup> If the ion of charge  $z_i$  and radius  $a_i$  is implanted into liquid Li, without disturbing its surrounding medium, the electrical free energy  $G$  is,

$$G = -\frac{z_i^2 e^2}{8\pi\epsilon a_i} = -\frac{72.0 z_i^2}{(\epsilon/\epsilon_0) a_i (10^{-9} \text{ cm})} \text{ eV} \quad (20)$$

where  $\epsilon$  denotes the dielectric constant of the liquid. The equation is not accurate, however, because bulk dielectric constants are not valid in the immediate neighborhood of an ion due to the screening effect.

Latimore and coworkers tried to correct for this effect by using an effective radius of the ion that was larger than the crystal radius, thus excluding a volume of solvent around each ion from the bulk solvent with dielectric constant  $\epsilon$ . For univalent cases, they arbitrarily added 0.85 Å to  $a_i$  for metallic ion.<sup>19)</sup> The correction introduced by Latimor seems to be considerably large which is presumably owing to the high dielectric constant of water  $\epsilon/\epsilon_0 = 78$  (at 300 K). However the Lati-



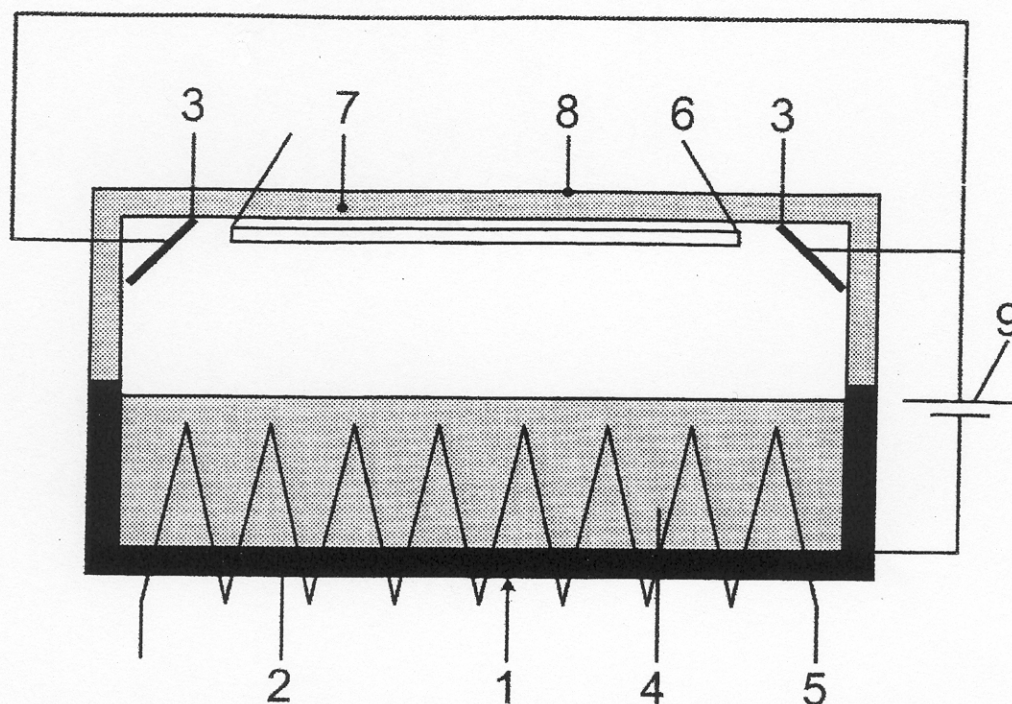


Fig. 1. Diagram showing the principle of operation of a buffer energy nuclear fusion device: 1. whole device system; 2. cathode box; 3. anode; 4. liquid Li metal; 5. thermocouple pile for taking out energy; 6. semi-conductor electric generator; 7. insulator; 8. case; 9. driving power supply. Ion source and nuclear fusion material supply system are not shown.

more correction values are fairly close to the respective values of atomic radius.<sup>20)</sup> This exactly corresponds to the arguments in §2 on the kinematic scattering of two screened particles. Therefore the Gibbs free energies are calculated for neutral atoms in the liquid metal.

The Gibbs free energy for a Li atom is

$$G_{\text{Li}} = -\frac{9}{\varepsilon/\varepsilon_0} \times \frac{72.0}{a_{\text{Li}}(10^{-9} \text{ cm})} \text{ eV}, \quad (21)$$

with  $a_{\text{Li}} = 15.2 \times 10^{-9} \text{ cm}$ .

This energy should be the bond energy of liquid Li metal at  $T = 460 \text{ K}$ ,  $-1.12 \text{ eV}$  and results in  $(\varepsilon/\varepsilon_0)^{-1} = 0.0264$ . The free energy change for the reaction  $\text{H} + \text{Li} \rightarrow \text{Be}$  is thus

$$\Delta G = -72.0 \times 0.0264 \left\{ \frac{16}{a_{\text{Be}}} - \frac{9}{a_{\text{Li}}} - \frac{1}{a_{\text{H}}} \right\} = -1.25 \text{ eV}, \quad (22)$$

with  $a_{\text{Be}} = 11.1 \times 10^{-9} \text{ cm}$  and  $a_{\text{H}} = 5.2 \times 10^{-9} \text{ cm}$ .

The value of  $\Delta G$  is consistent with the argument in §3.2 and leads to the enhancement at  $T = 460 \text{ K}$ ,

$$\exp[-\Delta G/k_B T] = 4.6 \times 10^{13}. \quad (23)$$

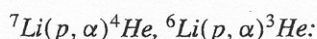
However the enhancement might be reduced to  $4 \times 10^9$ , if  $\Delta G$  decreases for example by 30% due to possible recoil or quenching effects in the united atom formation.

#### 4. Buffer Energy Nuclear Fusion Device and Operation

The configuration of device for the present fusion scheme is basically the same with glow (nonthermal) discharge tubes used by Grove in 1853 and Faraday in 1854 when they noted

sputtering, or with low energy hydrogen ion implanting devices. Essential points of difference between the devices are artificial buffer energy ion formation and implantation into liquid Li metal mounted on a cathode for the united atom formation.

Figure 1 is a diagram showing the principle of operation of a buffer energy nuclear fusion device.<sup>21)</sup> In the figure, numeral 1 is a whole device system and numeral 2 denotes a cathode box made from porous catalytic materials such as Ni cermet which transmits and/or adsorbs fuel materials if necessary. Numeral 3 denotes an anode or a hydrogen ion source. Both the cathode and the anode are equipped with a respective supply system of fuel materials. Numeral 4 denotes a liquid Li metal which is kept at a temperature just above the melting point  $453 \text{ K}$ . Numeral 5 is a thermocouple pile for energy taking out. Numeral 6 is a semiconductor electric generator. Numeral 7 denotes an insulator and numeral 8 is a case. Numeral 9 is a driving power supply. Numerals 5 and 6 may be replaced by thermodynamic cycle systems.



For the fusion reactions in Li metal, the surface to be implanted is placed in hydrogen ion plasma and a voltage of a few tens kV is applied with respect to the anode. The ions are accelerated across a boundary layer of the plasma or the acceleration space surrounding the part and are implanted directly into the surface. By tuning the voltage a reaction layer on the surface is formed at a mean depth of a few  $\mu\text{m}$  where bulk cohesion is stable and the ions move at a buffer energy.

Consider the interaction between a hydrogen ion of buffer



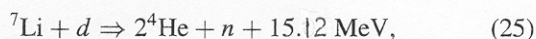
energy and a  ${}^7\text{Li}$  atom with a CM kinetic energy  $E = 10\text{ keV}$ . They interact under the presence of electron screening of  $D_s = 2.4 \times 10^{-9}\text{ cm}$  and  $E_s = 0.180\text{ keV}$  which are estimated by eqs. (15) and (16). The cross-section of reaction eq. (2) is very faint because of its non-resonant incoming reaction channel and its value derived from eq. (11) is  $\sigma_{12}(E) = 6.5 \times 10^{-12}\text{ b}$  with  $S_{12} = 59\text{ keV}\cdot\text{b}$ .<sup>22)</sup> However the enhancement factor eq. (23) results in an effective cross section for the reaction  ${}^7\text{Li} + {}^1\text{H}$  about 300 b, which is compared favorably with the uranium fission cases.

The enhanced value of fusion yield of  ${}^6\text{Li} + {}^1\text{H}$  is close to 20000 b superior compared to the reaction  ${}^7\text{Li} + {}^1\text{H}$  case because of its big cross section factor  $S_{12} = 2860\text{ keV}\cdot\text{b}$ .<sup>22)</sup> These results imply that a considerable fraction of implanted ions undergoes the nuclear fusion reactions within a depth of a few  $\mu\text{m}$  on the Li metal surface if the cohesion is not quenched very much.

## 5. Related Nuclear Fusion Reactions in Liquid Li Metal

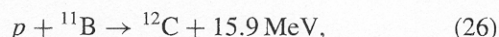
${}^6\text{Li}(d, \alpha){}^4\text{He}$ ,  ${}^7\text{Li}(d, \alpha n){}^4\text{He}$ :

There is a possibility giving rise to the fusion reactions,



if the hydrogen ions are replaced with deuterium ions. For deuterium ions of colliding energy  $E = 15\text{ keV}$ , the cross sections of reactions eqs. (24) and (25) become  $1.8 \times 10^{-10}\text{ b}$  with  $S_{12} = 17400\text{ keV}\cdot\text{b}$ <sup>22)</sup> and  $1.3 \times 10^{-11}\text{ b}$  with  $S_{12} = 2100\text{ keV}\cdot\text{b}$ ,<sup>23)</sup> respectively. These values yield enhanced cross sections 8200 b and 580 b, respectively, recalling the enhancement factor in eq. (23).

There are also some possibilities to cause nuclear reactions of hydrogen ions with light nuclei such as  ${}^{10,11}\text{B}$ ,  ${}^{14,15}\text{N}$  and  ${}^{19}\text{F}$  which are immersed in the liquid Li metal. Among them,  ${}^{11}\text{B}$  is of special significance because of its donor catalysis property and the remarkably large cross-section factor  $S_{12} = 197\text{ MeV}\cdot\text{b}$ <sup>24)</sup> of the fusion reaction,



which realizes the neutron-less energy release. There are however some unknown factors on the chemical state of micron-sized amorphous boron dispersed in the liquid Li metal such as solubility, mobile electron density and so on.

If one assumes a fully immersed state of B atoms which are surrounded by mobile electrons supplied by the Li metal and apply the same treatment in §3.5, the Gibbs free energy change in the reaction is,

$$\Delta G = -72 \times 0.0264 \left\{ \frac{36}{a_C} - \frac{25}{a_B} - \frac{1}{a_H} \right\} = -3.27\text{ eV} \quad (27)$$

with  $a_C = 7.11 \times 10^{-9}\text{ cm}$ , and  $a_B = 7.95 \times 10^{-9}\text{ cm}$ .

The value of  $\Delta G$  leads to the enhancement at Li melting point  $T \sim 460\text{ K}$ ,

$$\exp[-\Delta G/k_B T] \sim 8 \times 10^{35}. \quad (28)$$

For the reaction eq. (26), the screening length and the screening energy estimated by eqs. (15) and (16) are  $D_s = 1.35 \times 10^{-9}\text{ cm}$  and  $E_s = 0.533\text{ keV}$ , respectively. The cross-section derived from eq. (11) is extremely small  $\sigma_{12} = 8 \times 10^{-24}\text{ b}$  for protons of colliding energy  $E = 5\text{ keV}$

but its enhanced value is  $6 \times 10^{12}\text{ b}$  and seems to be very promising even some quenching effects occur due to above unknown factors.

## 6. Epilogue towards Compact Nuclear Fusion Science and Technology

We have argued the new scheme of buffer energy nuclear fusion in liquid Li metal. Semi-classical treatments on the fusion rate have also been presented on the basis of Arrhenius equation. The mechanisms of rate enhancement caused by the united atom formation under cohesion in the liquid metal are essential for leading to practical nuclear fusion and further systematic investigations are required. The new scheme prescribed in this paper would open up the way towards the compact nuclear fusion science and technology.

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## Supplementary Note

The new scheme has also been investigated experimentally by the author and Professor Roland Pettersson at the Department of Analytical Chemistry of Uppsala University.

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# Recoilless Nonthermal Nuclear Fusion

-----BENF NO.2-----

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# Recoilless Nonthermal Nuclear Fusion

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## Abstract

The effect of thermodynamic force on the nuclear fusion with protons of 10 keV energy was observed in metallic Li liquids exhibiting an enhancement of rate by a factor of about  $10^4$  in spite of quenching due to nuclear recoil. In an improved reaction scheme, deuterons are implanted into a Li liquid at an energy of several tens keV. They tend to the recoilless proton transfer nuclear fusion without electronic excitation and inner shell ionization of liquid atoms via enhanced atomic fusion, that is, united atoms formation which induces the momentum matched  ${}^7\text{Li}(\text{d},\text{n}){}^8\text{Be}^* \rightarrow 2{}^4\text{He}$  reaction. An enhancement of some 13 orders of magnitude is expected without quenching. Monochromatic intermediate neutrons produced are absorbed in the Li liquid releasing additional energy through the reactions,  ${}^7\text{Li}(\text{n}, \gamma\beta){}^8\text{Be}^* \rightarrow 2{}^4\text{He}$  and  ${}^6\text{Li}(\text{n}, \gamma){}^7\text{Li}$ . The scheme also provides new monochromatic intermediate neutron and gamma-ray sources.

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## 1. Nonthermal Nuclear Fusion in Liquids

In the previous paper [1] (here after called ref. 1), it has been shown that, the rat  $k_{12}(T)$  of ion implanted fusion reaction between nuclei of 1 and 2 speies in a metallic liquid is expressed in the form of the Arrhenius' equation for spontaneous chemical reactions in dilute solutions through transferring the capturing cross-section  $\sigma_{12}(E)$  intrinsic to the nuclei into the frequency factor  $A_{12}$ ,

$$k_{12}(T) = A_{12} \exp\left[-\frac{\Delta G}{k_B T}\right], \quad (1)$$

with  $A_{12} = I_1 N_2 \sigma_{12}(E)$  and  $\Delta G/k_B T < 0$ , (2)

under certain conditions. Here  $T$ ,  $I_1$ ,  $E$ ,  $N_2$ ,  $k_B$  and  $\Delta G$  denote the temperature of liquid, particle current and reaction (C.M.) energy of implanting ions of speies 1 such as H or D ions, effective surface number density of nuclei of species 2, for instance, Li in the liquid, the Boltzmann constant and the reaction Gibbs energy, that is, the Gibbs energy (chemical potential) change in the reaction, respectively.

In general the reaction Gibbs energy dominates the statistical features of reaction through the thermodynamic exponential factor in eq. (1). This consideration is particularly remarkable in the case of  $-\Delta G/k_B T \gg 1$ , where the rate of reaction is enhanced revealing the bulk or collective feature of reaction in the liquid. A typical example is the equilibrium constant of chemical reactions between ions of opposite sign in certain ionic solutions for example  $K = [\text{CuS}]/[\text{Cu}^{++}][\text{S}^{--}] = 10^{37}$ ,  $K$  being the equilibrium constant – the ratio of rate constants.

The same bulk feature is also seen in the Henry's law – the relationship between gas pressure and the concentration of gas dissolved in liquids. If one replaces the Gibbs energy (chemical potential) of solute gas by the reaction Gibbs energy, the Henry's law reduces to the same form with the Arrhenius' equation as shown in §2. A similar correspondence is also seen between the concentration of solute gas in liquids and the rate of united atoms formation and associated nuclear fusion in metallic Li liquids, where an ensemble of Li ion cores immersed in a collective mobile valence s-electron sea is a solvent and implanted H or D ions are the solute gas molecules [1]. The verification of this correspondence has been found in the fact that all electrons of Li and H or D atoms occupy s-orbitals and thus their wave functions and densities are finite inside nuclei of the atoms. For all of these reactions in liquids, respective forces can be interpreted as the statistical or thermodynamic forces, that is, the slope or the derivative of the respective chemical potentials which represent the spontaneous tendency of bulk atoms/molecules to react as a consequence of the Second law and the hunt for maximum entropy.

Both the Henry's law and the Arrhenius' equation are obeyed most accurately for dilute solutions but they don't correctly represent the behavior of certain solutes in the solutions. This indicates that the applicability of the Arrhenius' equation eq. (1) to the nuclear fusion has also to be investigated based on the starting point of statistical thermodynamics. In this paper the authors define the condition premised for the nuclear reactions in liquids to achieve their enhanced rate without any quenching effect.

## 2. Thermodynamic Activity of Liquids enhancing Nonthermal Nuclear Fusion

Here arguments are developed on the mechanism of enhanced nonthermal nuclear fusion based on the Widom's concept "thermodynamic activity of liquids" [2]. Considerations on this concept would also explain the mechanism of quenching effect pointed out in ref. 1.

The configuration integral  $Q_N$  for a liquid of  $N$  identical particles in a volume  $V$  at the temperature  $T$  is

$$\begin{aligned} Q_N &= \int_V \cdots \int_V \exp\left(\frac{-W_N}{k_B T}\right) d\tau_1 \cdots d\tau_N, \\ &= \int_V \cdots \int_V \exp\left(-\frac{\Psi}{k_B T}\right) \exp\left(-\frac{W_{N-1}}{k_B T}\right) d\tau_1 \cdots d\tau_N, \\ &= Q_{N-1} V \left\langle \exp\left(-\frac{\Psi}{k_B T}\right) \right\rangle, \end{aligned} \quad (3)$$

where  $d\tau_1 \cdots d\tau_N$  is the element of volume in the configuration space of the  $N$  molecules,  $W_N$  is the potential energy of interaction of the  $N$  particles such as atoms or molecules as a function of their positions in the volume  $V$ , and  $\Psi$  is the potential energy of interaction of one molecule with the remaining  $N-1$  molecules as a function of the positions of all  $N$  of them. The mean value symbolized by  $\langle \rangle$  is a canonical average.

Let  $z$  be the thermodynamic activity of the liquid molecules, defined so as to become asymptotic to the number density  $N/V \equiv n$  in the limit  $n \rightarrow 0$ . Then

$$\begin{aligned} z &= \frac{N Q_{N-1}}{Q_N}, \\ \text{so from Eq. (3),} \\ n/z &= \left\langle \exp\left(-\frac{\Psi}{k_B T}\right) \right\rangle. \end{aligned} \quad (4)$$

In a mixture of several kinds of molecules, if  $n$  and  $z$  are the density and activity of one species, and  $\Psi$  the interaction energy of a molecule of that species with the rest of the liquid, then eq. (4) still holds. If the liquid consists almost entirely of molecules of one kind (solvent), and  $\Psi$  is the energy of interaction of a molecule of another kind (solute) with a solvent liquid, then  $\langle \exp(-\Psi/k_B T) \rangle$  is essentially the reciprocal of the Henry's law constant, which corresponds to the thermodynamic factor  $\exp(-\Delta G/k_B T)$  in the Arrhenius' equation. In what follows, however, the concern is entirely with pure liquids.

Referring to eq. (4), a solute molecule interacts with all molecules of the solvent liquid instead of two body interaction with an isolated liquid molecule. The thermodynamic activity of liquid is thus found to be bulk/collective feature caused by the thermodynamic force in the liquid and the derivation of eq. (4) is a consequence of a major proposition that the solvent liquid consists of interacting molecules or particles at thermal equilibrium.

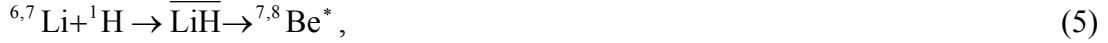
The thermodynamic activity of metallic liquids is closely related to the cohesion of metals produced by collective mobile electrons. In fact, the

thermodynamic enhancement factor  $\exp(-\Delta G/k_B T)$  of the p+Li and d+Li reactions has been derived from the bond energy of liquid Li metal in ref. 1. Each atom in a metal forms covalent bonds sharing electrons with its nearest neighbors, but the number of orbitals for bond formation exceeds the number of electron pairs available to fill them. As a result, covalent bonds resonate among the available interatomic positions. This resonance extends throughout the entire structure, thereby producing greatly enhanced stability. Another bulk feature of metals is also seen in the difference of electric conductivity between metals (e.g. Ag) and typical insulators by a factor up to some 20 orders of magnitude.

Now it would be noteworthy that certain bulk features of matters are due to macroscopic quantum effects caused by coherent dynamics of mobile valence electrons of which de Broglie wave length stretches over a bond length of some tens metallic atoms for instance Li atoms at melting point. These effects can be treated in the scheme of statistical thermodynamics. Such features may also be expected in certain nuclear reactions through atomic fusion, that is, united atoms formation enhanced by the thermodynamic force in metallic liquids [1].

When implanted ions are travelling in a metallic liquid, atoms of the liquid surrounding the ions tend towards formation of a meta stable phase such as an alloy or compound at the minimum Gibbs energy point. However this Gibbs energy is not the minimum point any longer for the buffer energy ( $\approx 25$  keV/amu) ions. They penetrate the Coulomb barrier of liquid atoms to form a new reaction intermediate, that is, united atoms at their turning points. Physical characteristics such as the Gibbs energy and density of united atoms are expected to be almost the same with those of product atoms of nuclear fusion [1] implying the possibility of nuclear fusion induced by united atoms.

For the  ${}^6\text{Li}(p,\alpha){}^3\text{He}$  and  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  reactions via the formation of united atoms  $\overline{\text{LiH}}$  and excited nuclei  ${}^{7,8}\text{Be}^*$  in a metallic Li liquid,



the reaction Gibbs energy has been estimated using the bond energy of metallic Li liquid to be about  $\Delta G = -1.25$  eV for a reacting atom pair [1]. This, in turn, results in an enhancement of fusion reaction rate by a factor

$$\exp\left[-\frac{\Delta G}{k_B T}\right] = 4.6 \times 10^{13}, \quad (6)$$

just above the melting point of metallic Li,  $T = 460$  K [1].

### 3. Quenching Effects on Fusion Enhancement

The enhancement argued in §2 has however never been observed in nuclear reactions due to possible quenching effects which will be explained below.

Consider a case where hydrogen ions of buffer energy  $E_{\text{Lab}} \approx 25$  keV/amu are implanted into a metallic Li liquid around its melting point. The ions quickly become neutralized in the metal. On traversing the metal, however, the neutralized particles ionize again [3]. The depth, in the metal at which the equilibrium charge state is achieved, is related to the atomic density or electron density of the metal and also the



average electron capture and loss cross sections. This depth corresponds to several tens of monolayers of metal atoms.

Meanwhile certain hydrogen ions undergo collisions with nuclei of metallic Li atoms, because the nuclear stopping is marked for buffer energy ions [1]. During the collisions an ion transfers considerable amounts of recoil momentum and kinetic energy to an interacting Li atom. It is therefore unlikely that the recoil Li atom will be at thermal equilibrium with the rest of the liquid Li atoms. In such the case the reaction rate would deviate from that of the Arrhenius' equation, thereby quenching the thermodynamic enhancement  $\exp(-\Delta G/kT) > 1$ .

The colliding Li atom receives a recoil energy of about  $E_R = 1 \sim 2 \text{ keV}$  from the buffer energy ion without its electronic excitation as argued in ref. 1. The Li atom is thus not hot and still keeps a correlation with the rest of Li atoms to some extent. Recalling the arguments in §2, the ensemble of metallic atoms at thermal equilibrium is regarded as a thermodynamic resonator which may be specified by zero resonance energy and the half width of  $k_B T$ . The recoil process can therefore be treated as a problem of resonance scattering of particles by the resonator and the quenching or correlation factor  $\rho(E_R, T)$  of the enhancement is expressed in a simple resonance formula. Actually one can derive the formula as a correlation function of the potential activity of the recoil atom defined by  $\exp(-\Psi/E_R)$  and the thermodynamic activity of the rest atoms  $\langle \exp(-\Psi/k_B T) \rangle$  derived by eq. (4).

$$\rho(E_R, T) = \text{Re} \left[ \int_0^\infty \left\langle \exp \left( -\frac{i\Psi}{k_B T} \right) \right\rangle \exp \left( \frac{-\Psi}{E_R} \right) d \left( \frac{\Psi}{E_R} \right) \right] = \frac{(k_B T)^2}{E_R^2 + (k_B T)^2}. \quad (7)$$

This results in a quenching of the enhanced reaction rate eq. (1) as,

$$k_{12}(T) = A_{12} \cdot \rho(E_R, T) \exp \left( -\frac{\Delta G}{k_B T} \right). \quad (8)$$

In a case where a beam proton is implanted with an acceleration energy of 10 keV into a Li liquid at its melting point 454 K, the proton transfers a recoil energy of 1.25 keV to a metallic  $^7\text{Li}$  atom during their interaction, and the correlation factor in eq. (7) would be

$$\rho(E_R, T) \sim 5.7 \times 10^{-10}. \quad (9)$$

This may reduce the effective enhancement up to  $\rho(E_R, T) \cdot \exp(-\Delta G/k_B T) \sim 2.6 \times 10^4$  recalling the unquenched value  $4.6 \times 10^{13}$  in eq. (6).

The reduced value of effective enhancement is in good agreement with recent Uppsala and Tokyo data of preliminary experiments on the buffer energy  $^7\text{Li}(p, \alpha)^4\text{He}$  reaction [4,5]. In both experiments proton beams extracted from ion sources entered target chambers equipped with Si detectors and were injected vertically on metallic Li liquid surfaces. The reaction product  $\alpha$ -particles of 8.6 MeV were observed with the detectors positioned at the angles  $\theta_{\text{Lab}} = 115^\circ$  (Uppsala) and  $135^\circ$  (Tokyo).

Whereas the reaction rates observed at non-buffer energies of 45, 40, 35 keV showed an energy dependence consistent with previous data [6] and intrinsic values presented in Appendix, the rates observed at buffer energies of 25, 24 and 10 keV showed certain deviations from the dependence as seen in Fig. 1. In particular the rate



observed at 10 keV indicated an enhancement of about  $3 \times 10^4$  compared to the value expected from this dependence. These facts indicate the validity of the scheme of buffer energy nonthermal nuclear fusion in metallic Li liquids [1] together with the present arguments on the quenching effect.

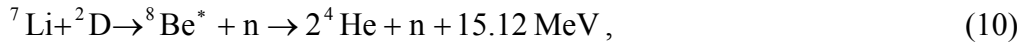
There is another quenching effect characteristic of buffer energy nuclear fusion. The penetration range of buffer energy ions is very small, for instance, for protons of 10 keV, the range in metallic Li is only within a few hundredth  $\mu\text{m}$  and local heating might be intense on the metallic surface. If the surface temperature is raised about 150 K from the melting point during the implantation, the enhancement factor would be reduced to  $1.8 \times 10^{10}$  from the value of  $4.6 \times 10^{13}$  at  $T = 460$  K. This quenching would however be cancelled out partly by an additional enhancement due to charge exchange effect on ions traversing in the metal. This effect results in the smaller effective charge than the intrinsic one, for instance,  $z_{\text{eff}} = 0.345$  for 10 keV H-ions and 20 keV D-ions as argued in Appendix. This in turn decreases the Gibbs energy of ions in the metal and changes the reaction Gibbs energy of fusion reactions from  $\Delta G = -1.25$  eV to  $\Delta G = -1.57$  eV increasing the thermodynamic enhancement factor from  $4.6 \times 10^{13}$  in eq. (6) to  $1.6 \times 10^{17}$ . For higher energy ions, the effective charge increases, thereby reducing the gain of thermodynamic enhancement. This is consistent with the trend of enhancement shown in Fig. 1, which decreases with the ion acceleration energy more quickly than that explained by eq. (7).

The last quenching effect is spurious and rather a technical problem. It is likely that surfaces of metallic Li liquid are concealed by a slag of certain contaminant Na compounds such as  $\text{Na}_2\text{O}$ ,  $\text{NaOH}$ ,  $\text{Na}_3\text{N}$  and  $\text{Na}_2\text{CO}_3$ . They are more dense than the metallic Li liquid as much as a factor of 5 or 4 and have much bigger stopping power by a factor of orders of magnitude. This results in an effective ion energy in the liquid lower than the implantation energy by an energy loss in the slag and the associated suppression of reaction yield. In some cases of our preliminary tests, this effect hindered us even from observing the thermodynamic enhancement but this has been eliminated through scraping out the slag or raising the implantation energy by the energy loss [1].

#### 4. Recoilless Nonthermal Nuclear Fusion

As argued in §3, the nuclear recoil effect results in microscopic perturbation in the reacting Li liquid at thermal equilibrium and hence quenches the enhancement of proton capture rate.

This quenching would however be removed if the proton capture could be achieved adiabatically through recoilless nuclear reactions. In the momentum-matched proton transfer reactions, for instance, the  ${}^7\text{Li}(\text{d}, \text{n}){}^8\text{Be}^* \rightarrow 2{}^4\text{He}$  reaction, argued in ref. 1,

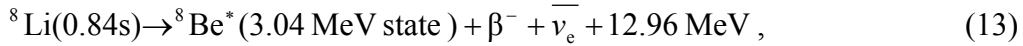


both reacting  ${}^7\text{Li}$  and product  ${}^8\text{Be}^*$  atoms will be in rest if the momenta of incoming deuteron ( $p_d$ ) and outgoing neutron ( $p_n$ ) are exactly the same. Furthermore the reaction time of eq. (10) is far shorter than the characteristic correlation time  $\tau_c \sim \hbar/k_B T$  of the Li liquid at thermal equilibrium and thus the reaction takes place adiabatically without disturbing the liquid atoms. The initial and final momenta of the reaction are matched naturally for deuterons of buffer energy ( $E_d \leq 50$  keV) due to the maximum reaction yield at the momentum matching and the fairly large non-resonant

(d,n) reaction cross-section around the buffer energy which corresponds to the 15 MeV excited levels of  $^8\text{Be}$ . This non-resonant strength may be ascribed to the very broad width (about 3 MeV) of 11.4 MeV level in  $^8\text{Be}$  [7-9].

These features provide an improved fusion reaction scheme. In the scheme, whenever deuterons of buffer energy  $E_d$  are implanted into a metallic Li liquid intermediate neutrons of energy  $E_n \simeq 2E_d$  are emitted through fulfilling the momentum matching condition  $p_n = p_d$  and leave reacting atoms in rest  $E_R = 0$  without quenching the enhancement of reaction rate. For deuterons of acceleration energy of 20 keV (C.M. energy  $E = 15.6$  keV), the intrinsic cross-section of the reaction, eq. (10) is about  $1.7 \times 10^{-11}$  b with the cross-section factor  $S_{12} = 2100$  keV·b [8]. This yields an enhanced value of the cross-section 800 b recalling the enhancement factor of about  $4.6 \times 10^{13}$  in eq. (6). Here, the reaction Gibbs energy in the D + Li reaction has been assumed to be nearly the same with that of the H + Li reaction for the simplicity. The enhanced value of cross-section is bigger than that of  $^{235}\text{U}$  fission.

The intermediate neutrons are monochromatic because their energy is strictly limited by the deuteron energy through the matching condition  $E_n \simeq 2E_d$ . They are absorbed by  $^6\text{Li}$  and  $^7\text{Li}$  nuclei under certain configurations of the Li liquid and produce associated energy releases as seen in the reactions,



Consider a case of combined nuclear reactions, eq. (10, 12-14). If one subtracts the average energy of about 7.7 MeV carried out by an antineutrino  $\bar{\nu}_e$  in the beta decay, eq. (13), the useful energy release is about 26 MeV, that is, 13 MeV for one  $^7\text{Li}$  atom. This implies the power production density 50 MWh/g of  $^7\text{Li}$  which is superior than that of usual nuclear energy generation 24 MWh/g of  $^{235}\text{U}$ . In the combined reactions eqs. (10,11), the energy release of Li is even bigger. Furthermore, both products of nuclear reactions of  $^7\text{Li}$  and  $^6\text{Li}$  are non-active and rather a useful helium gas only.

However the reaction probability of deuterons before stopping in the Li liquid would be the matter of utmost concern because it provides the measure of energy gain with respect to the implantation energy. In general, charge exchange dominates the stopping of buffer energy deuterons in metallic Li as argued in Appendix. The argument based on the Lindhard's formula [10] of stopping leads to a simple expression of reaction probability, eq. (A8). It provides very small intrinsic values of reaction probability.

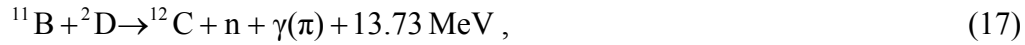
$$P = 6.1 \times 10^{-5} \exp \left\{ -\pi \left[ \frac{1785}{E_{\text{Lab}} (\text{keV})} \right]^{\frac{1}{2}} \right\}, \quad (15)$$

for the  $^7\text{Li}(d,n)^8\text{Be}^*$  reaction. But the probability would be enhanced in the Li liquid,

$$P_{\text{enh}} = 2.8 \times 10^9 \exp \left\{ -\pi \left[ \frac{1785}{E_{\text{Lab}} (\text{keV})} \right]^{\frac{1}{2}} \right\}, \quad (16)$$

under an assumption that the thermodynamic enhancement factor in eq. (6) does not change so much with the deuteron energy. The enhanced probability is 0.04% for deuterons of  $E_{\text{Lab}} = 20$  keV but it increases very quickly with the energy such as 10% for  $E_{\text{Lab}} = 30$  keV and reaches at 100% for  $E_{\text{Lab}} = 37$  keV. Since the energy release is about 25.5 MeV per deuteron through the reactions eqs. (10,12-14), the energy gain of deuterons of  $E_{\text{Lab}} = 37$  keV will be 690 which is bigger than the long term target figure of world scale plasma fusion projects by a factor of one order of magnitude.

Taking the arguments in §2 into consideration, there are also some possibilities to cause the recoilless proton transfer reactions of buffer energy deuterons with light nuclei such as  $^{10,11}\text{B}$ ,  $^{14,15}\text{N}$  and  $^{19}\text{F}$ , a small amount of which is immersed in metallic Li liquids. Among them  $^{11}\text{B}$  is of special significance because of its large rate enhancement of some 16 orders of magnitude [1] in the reactions,



In the reaction eq. (17), a fraction of isomeric transitions undergoes through the  $\pi$  transition, that is, the nuclear pair ( $e^+e^-$ ) formation [9]. Intermediate neutrons produced in the reaction result in associated energy release through the reactions eqs. (11) and (12) and also



## 5. The Significance of Nonthermal Nuclear Fusion in Metallic Liquids

On the contrary to the one century retained assessment that atoms never change identity in the chemical reactions whereas nuclear reactions are not affected by temperature, catalysts and the compound in which an element occurs, both chemical and nuclear reactions take place cooperatively in certain ensembles such as metallic Li liquids at thermal equilibrium. In the liquids, the thermodynamic force produced by collective mobile valence s-electrons dominates buffer energy nuclear reactions via enhanced atomic fusion, that is, formation of united atoms and results in the nuclear reaction enhancement of exponential magnitudes.

The observed quenching of enhancement in the proton capture reactions in metallic Li liquids has been explained based on the concept “thermodynamic resonator” and it is prescribed how the quenching can be removed in an improved scheme of recoilless nonthermal nuclear fusion reactions.

The new scheme could provide mankind with sustainable clean energy together with new monochromatic intermediate neutron and gamma-ray sources and lead to an industrial revolution.

## **Acknowledgements**

The author (H.I.) expresses his heartfelt thanks to Professors Kazutake Kohra, Sven Kullander and Karin Markides for their continuous encouragements. The data could not be obtained without skilful technical assistance from Messrs. Arne Jansson, Robert Pettersson, Sven-Olof Eriksson and Lars Einarsson.

## **Supplementary Note**

During the submittment of this paper, the recoilless nonthermal nuclear fusion was observed by the authors in metallic Li liquids exhibiting the enormous enhancement. The first report on the observation is presented in the following article in this journal.

## Appendix

### Reaction Probability of Buffer Energy Hydrogen and Deuterium Ions

For hydrogen and deuterium ions ( $z_1 = 1$ ) of buffer energy  $E_{\text{Lab}} \approx 25$  keV/amu, charge exchange dominates the stopping power of ions in metallic Li ( $z_2 = 3$ ) because both electronic excitation and inner-shell ionization are very unlikely [1,3]. In this description, energy loss due to charge exchange is in fact a two-step process differing, therefore, from other single-collision contribution. That is, on traversing metals, ions capture an electron becoming neutral and later ionize again. This process of capture and loss at low velocities can be described in the metals as a drag force on the ions. This force comes about as the electron cloud is distorted (polarized) by the passing ions, thereby increasing the electron density in the vicinity of the ion. The drag force produced by this distortion of the electron cloud changes roughly as  $-dE_{\text{Lab}}/dx \propto v$ ,  $v$  and  $x$  being the ion speed and the penetration depth, respectively.

Lindhard has given a very simple formula for the stopping power based on the Thomas–Fermi model of the atom that is accurate for large ions and atoms but also reasonable for light ions and atoms for  $v < v_e$ ,  $v_e$  being the speed of K-shell orbital electron on the hydrogen atom [3,10].

$$\frac{dE_{\text{Lab}}}{dx} = -8\pi e^2 a_B \cdot \xi_e \frac{z_1 z_2}{z} \cdot n_2 \left( \frac{E_{\text{Lab}}}{E_0} \right)^{\frac{1}{2}}, \quad (\text{A1})$$

$$\text{with } z \equiv (z_1^{2/3} + z_2^{2/3})^{3/2} \text{ and } \xi_e \approx z_1^{1/6}. \quad (\text{A2})$$

Here  $a_B$  and  $E_0 = (1/2) A_1 M v_e^2 = 25 A_1$  keV denote the Bohr radius and the energy of hydrogen or deuterium ions with mass  $A_1 M$  and speed  $v = v_e$ , respectively and  $M$  is the nucleon mass. The formula, eq. (A1) has been given for the initial charge state of implanted ions  $z_1$ . However the charge exchange cycle is always included as the metals are macroscopically thick. This means that the values of  $dE_{\text{Lab}}/dx$  are not necessarily those of the initial charge state of the ions as they enter the metals, instead are referred to as equilibrium charge state  $z_{\text{eff}}$  stopping cross-sections. A semiempirical expression of  $z_{\text{eff}}$  has been developed based on measurements on the transmission of ions through thin films [3].

$$z_{\text{eff}} \approx z_1 \left\{ 1 + \left[ 0.122 \left( \frac{E_{\text{Lab}}}{A_1} \right)^{\frac{1}{2}} z_1^{-0.45} \right]^{-\frac{1}{0.6}} \right\}^{-0.6} = \left\{ 1 + \left[ 0.122 \left( \frac{E_{\text{Lab}}}{A_1} \right)^{\frac{1}{2}} \right]^{-\frac{1}{0.6}} \right\}^{-0.6} \quad (\text{A3})$$

Eq. (A3) can be used to evaluate  $dE_{\text{Lab}}/dx$ , in eq. (A1) by substituting  $z_{\text{eff}}$  for  $z_1$ , which results in a slight energy dependence of the charge factor  $\xi'_e z_{\text{eff}} z_2/z'$ ,  $\xi'_e$  and  $z'$  being the functions of  $z_{\text{eff}}$  given in eq. (A2'). For example  $\xi'_e z_{\text{eff}} z_2/z' = 0.210$  for deuterons of  $E_{\text{Lab}}=20$ keV in the metallic Li, 0.246 for  $E_{\text{Lab}}=30$  keV and 0.273 for  $E_{\text{Lab}}=40$  keV in contrast to the remarkable change of Coulombic penetration factor in the nuclear

reaction cross-section, eq. (A5). For the  $d+{}^7\text{Li}$  reaction case, the factor  $\exp\{-\pi[(A_1+A_2)E_G/A_2E_{\text{Lab}}]^{\frac{1}{2}}\}$  is  $1.3\times 10^{-13}$  for  $E_{\text{Lab}} = 20$  keV,  $3.0\times 10^{-11}$  for  $E_{\text{Lab}}=30$  keV and  $7.7\times 10^{-10}$  for  $E_{\text{Lab}} = 40$  keV. It is thus reasonable to introduce associated substitutions,

$$z \rightarrow z' \equiv (z_{\text{eff}}^{2/3} + z_2^{2/3})^{2/3}, \quad \xi_e \rightarrow \xi'_e = z_{\text{eff}}^{1/6}, \quad (\text{A2}')$$

and

$$\xi_e \frac{z_1 z_2}{z} \rightarrow \xi'_e \frac{z_{\text{eff}} z_2}{z'} \approx 0.245 \quad (\text{A4})$$

for the buffer energy  $d+{}^7\text{Li}$  reaction.

The nuclear fusion reaction cross section  $\sigma_{12}(E)$  has been given [1].

$$\begin{aligned} \sigma_{12}(E) &= \frac{S_{12}}{E^{1/2}(E+E_s)^{1/2}} \exp\left[-\pi\left(\frac{E_G}{E+E_s}\right)^{\frac{1}{2}}\right] \\ &= \frac{S_{12}}{E} \exp\left[-\pi\left(\frac{E_G}{E}\right)^{\frac{1}{2}}\right] = \frac{A_1+A_2}{A_2} \cdot \frac{S_{12}}{E_{\text{Lab}}} \exp\left[-\pi\left(\frac{A_1+A_2}{A_2}\right)^{\frac{1}{2}} \cdot \left(\frac{E_G}{E_{\text{Lab}}}\right)^{\frac{1}{2}}\right]. \end{aligned} \quad (\text{A5})$$

In the second line of eq. (A5) the screening energy  $E_s$  has been disregarded for buffer energy ions because it changes the cross-section within only several tens percent in contrast to the thermodynamic enhancement by some 13 orders of magnitude [1]. In the equation the Gamòv energy  $E_G$  is [1],

$$E_G = \frac{99.2(z_1 z_2)^2 A_1 A_2}{A_1 + A_2} \text{ keV}. \quad (\text{A6})$$

The intrinsic nuclear fusion reaction probability of the ions in the penetration depth  $dx$  is

$$dP = \frac{k_{12}(T \rightarrow \infty)}{I_1} = N_2 \sigma_{12}(E) = n_2 \sigma_{12}(E) dx, \quad (\text{A7})$$

where  $n_2$  is the number density of nuclei of species 2 (Li). The reaction probability of ions before stopping in the metals is thus obtained by integrating eq. (A7) by  $E_{\text{Lab}}$  recalling eqs. (A1), (A2') and (A4).

$$\begin{aligned} P &= \int n_2 \sigma_{12}(E) dx \\ &= \int_0^{E_{\text{Lab}}} \frac{\sigma_{12}(E)}{8\pi e^2 a_B} \cdot \frac{z'}{\xi'_e z_{\text{eff}} z_2} \cdot \left(\frac{E_0}{E_{\text{Lab}}}\right)^{\frac{1}{2}} dE_{\text{Lab}} \end{aligned}$$

$$= \frac{z' S_{12}}{4\pi^2 e^2 a_B \xi_e' z_{\text{eff}} z_2} \left( \frac{E_0}{E_G} \right)^{\frac{1}{2}} \left( \frac{A_1 + A_2}{A_2} \right)^{\frac{1}{2}} \exp \left[ -\pi \left( \frac{A_1 + A_2}{A_2} \right)^{\frac{1}{2}} \left( \frac{E_G}{E_{\text{Lab}}} \right)^{\frac{1}{2}} \right]. \quad (\text{A8})$$

The reaction probability of the ions and hence the reaction rate depends on the energy  $E_{\text{Lab}}$  only through the Coulombic penetration factor,

$$\exp \left[ -\pi \left( \frac{E_G}{E} \right)^{\frac{1}{2}} \right] = \exp \left[ -\pi \left( \frac{A_1 + A_2}{A_2} \right)^{\frac{1}{2}} \left( \frac{E_G}{E_{\text{Lab}}} \right)^{\frac{1}{2}} \right].$$

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## Figure Caption

*Fig.1.* The fusion rate of the  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  reaction as a function of acceleration energy of protons observed with metallic Li liquid targets at the temperature 470-510 K. Closed and open circles indicate experimental data on targets of pure Li and Li with a few percent mixture of B, respectively. The solid curve represents the fusion rate calculated using eq. (A8). Present data are normalized with the calculated value with  $S_{12} = 2100$  keV·b at the energy  $E_{\text{Lab}}=45$  keV.



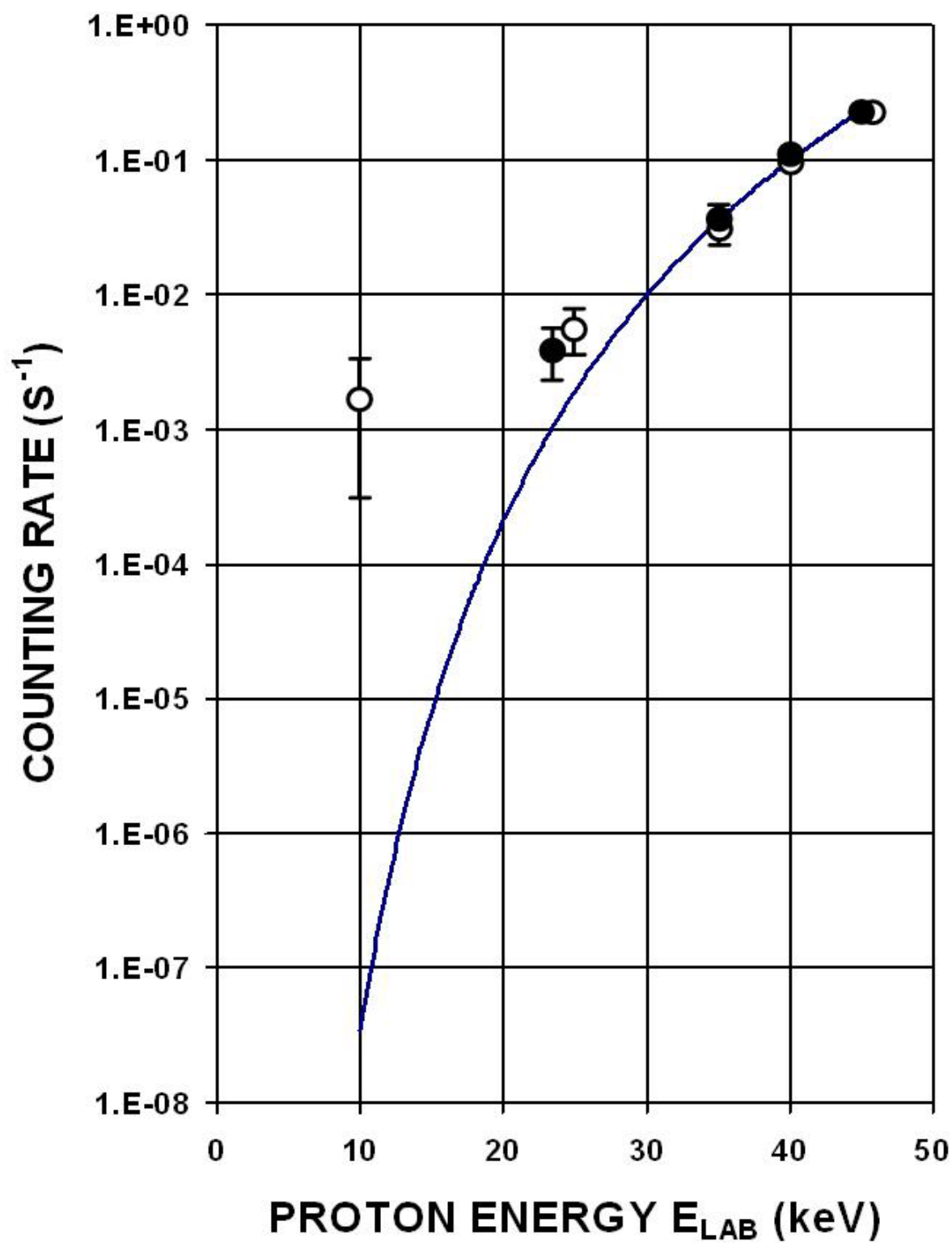


Fig. 1 H. Ikegami and R. Pettersson desired breadth 7.5 cm

# Evidence of Enhanced Nonthermal Nuclear Fusion

-----BENF NO. 3-----

Hidetsugu Ikegami and Roland Pettersson

# Evidence of Enhanced Nonthermal Nuclear Fusion

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Abstract:

The  ${}^7\text{Li}(\text{d}, \text{n}\alpha){}^4\text{He}$  reaction has been studied with 10~24 keV deuterons implanted on metallic Li. Alpha-particles were measured using a solid state detector and neutrons by a  $\text{BF}_3$  counter. When the liquid target was in the solid phase, no single event was observed as interfered from known reaction cross-section data. Using metallic Li in the liquid phase we observed a rate enhancement by a factor of  $10^{10}$ - $10^{15}$ . This enhancement is explained by united atoms  $\overline{\text{LiD}}$  formation enhanced by the thermodynamic force in metallic Li liquids, which induces adiabatically the recoilless  ${}^7\text{Li}(\text{d}, \text{n}){}^8\text{Be}^* \rightarrow 2{}^4\text{He}$  reaction.

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## 1. Aim of Experiments

Nuclei dressed with electronic configurations reveal dynamical features influenced by their surroundings in some cases such as  $\beta$ -decay through capture of atomic electrons, internal electron conversion in nuclear isomeric transitions and so on. In these nuclear processes, penetration effects have been well known for atomic electrons which interact with nucleons inside nuclei. This would be also the case where low energy nuclei undergo fusion reactions under an electron background to suppress nuclear Coulombic repulsive force.

In a previous paper [1] (hereafter called ref. 1) it has been shown that nuclei in metallic liquids are no more isolated from the bulk of surrounding metallic atoms and nuclear reactions between them are dominated by the thermodynamic force defined by the Gibbs energy change  $\Delta G$  in the reactions in the same way as in chemical reactions. As a result, the rate  $k_{12}(T)$  of a reaction between nuclei of 1 and 2 species in a metallic liquid at the temperature  $T$  is expressed in the form of the Arrhenius equation for spontaneous ( $\Delta G < 0$ ) chemical reactions in dilute solutions,

$$k_{12}(T) = A_{12} \exp\left[-\frac{\Delta G}{k_B T}\right]. \quad (1)$$

Here,  $k_B$  denotes the Boltzmann constant and  $A_{12}$  is the frequency factor which is proportional to the nuclear reaction cross-section.

This means that the rate  $k_{12}(T)$  of spontaneous reaction with  $-\Delta G \gg 1$  is remarkably enhanced by the exponential factor in eq. (1). In ref. 1, the factor has been estimated to be around  $5 \times 10^{13}$  for the proton transfer reactions in metallic Li liquids just above the melting point ( $T = 460\text{K}$ ). Regarding the  ${}^7\text{Li} (p, \alpha) {}^4\text{He}$  reaction ( $Q = 17.3 \text{ MeV}$ ), we have however observed some quenching effects on the enhancement due to nuclear recoil [2]. In this paper, results of test experiments on the recoilless  ${}^7\text{Li} (d, n\alpha) {}^4\text{He}$  reaction ( $Q = 15.1 \text{ MeV}$ ) will be reported.

Typically for deuterons of acceleration energies of  $E_d = 10 \text{ keV}$  and  $20 \text{ keV}$  (C.M energies of  $7.8$  and  $15.6 \text{ keV}$ ), the intrinsic cross-sections of the nuclear reaction are expected to be about  $1.6 \times 10^{-16} \text{ b}$  and  $1.7 \times 10^{-11} \text{ b}$ , respectively, based on the experimentally obtained cross-section factor  $S_{12} = 2100 \text{ keV}\cdot\text{b}$  [1-3]. Combining the fusion cross-section formula with the Lindhards' stopping power formula [4], the intrinsic reaction probability of deuterons before their stopping in the range within a few hundredth  $\mu\text{m}$  in metallic Li targets has been estimated [2],

$$P_{\text{int}} = 6.1 \times 10^{-5} \exp\left\{-\pi \left[\frac{1785}{E_d(\text{keV})}\right]^{\frac{1}{2}}\right\}. \quad (2)$$

Eq. (2) provides reaction rates  $2.3 \times 10^{-7} \text{ event/year}$  at  $E_d = 10 \text{ keV}$  and  $0.5 \text{ event/year}$  at  $E_d = 20 \text{ keV}$  for our present experimental conditions indicating that it is not feasible to observe the reaction unless any enhancement effect is manifested.

## 2. Experimental Procedure and Results

The experiments were carried out for metallic Li targets in both liquid- and solid-phase for comparison.

In liquid phase experiments the temperature of Li target was set just at the melting point before the implantation taking account of the temperature rise during the implantation. Deuterons of about 300  $\mu\text{A}$  were extracted from a spherical plasma of about 3 mm in diameter in a mini-duoplasmatron ion source shown in Fig. 1 and accelerated at an energy of a few tens keV. Through a Pt slit with a hole of 300  $\mu\text{m}$  in diameter deuterons of 2 ~ 1.5  $\mu\text{A}$  entered a target chamber, were implanted vertically on a surface of metallic Li target of 19 mm in diameter and the amounts of about 1 g. A Si surface barrier detector (SSD) of about 1  $\text{cm}^2$  of active area was used. The product  $\alpha$ -particles from the target were observed using the detector positioned at the angle  $\theta_{\text{lab}} = 115^\circ$  with the effective acceptance angle of 0.6 % of  $4\pi$ . Throughout the experiments, detector output pulses and spectra were monitored comparing with those of  $\alpha$ -particles from a calibration source of  $^{241}\text{Am}$  (5.58 MeV $\alpha$ ) covered with a 5  $\mu\text{m}$  thick Al foil and mounted near the Li target.

In the solid phase, no single event was observed by the  $\alpha$ -particle and neutron detectors, which was consistent with the reaction rate estimation obtained based on the intrinsic nuclear reaction cross-section data indicated in the previous section.

In the liquid phase, remarkably broad peaks of width ranging between 1.5~5.0 MeV were observed in the  $\alpha$ -particle spectra as seen in Fig. 2. When the metallic Na mixture in the Li targets was enough to relax the local temperature rise on the reaction surface, implantation with the beam density of about 0.5  $\mu\text{A}/\text{cm}^2$  resulted in a broad peak of upper end point energy of around 15 MeV and width ranging over 2.5~5.0 MeV. An example of this case is indicated in Fig. 2(a).

After some implantation periods, the upper end point energy of the broad peak jumped from 15 MeV to 7.5 MeV increasing a counting rate from about 1000 cps to 2000 cps (enhancement of about  $10^{10}$ ) as seen in Fig. 2 (a) and (b). Thereafter the broad peak shifted continuously towards the zero energy showing the substantial energy loss of  $\alpha$ -particles on traversing the surface lithium deuteride (LiD) layer and slag at angle. An initial shift is seen in Fig. 2(c). The shift was associated with the decrease of reaction rate indicating the decay of thermodynamic activity of Li liquid [2] in the reaction space and/or the local temperature rise due to the evaporation off of mixed metallic Na. Throughout the experiments, some broad peaks showed time dependent variation in their shape including the appearance of a sub-peak as seen in Fig. 2 (a). Presumably this may be due to the time dependent conditions of Li liquid targets.

In cases where the target was visually clean but metallic Na mixture was evaporated off or not enough to relax the local temperature rise, the broad peak never appears but a very faint peak at 7.5 MeV energy.

Low speed neutrons ( $E_n \approx 2E_d = 20 \sim 48$  keV) were also observed using a  $\text{BF}_3$  counter covered with a polystyrene case. Reflecting to the enhanced reaction rates, their radiation levels were always high typically over  $10^3$   $\mu\text{Sv/h}$  at a distance of 30 cm from the target in the case of 10 keV deuterons of 1.5  $\mu\text{A}$  (see Fig. 2(c)).

Regarding local temperature rise problems, we tried to measure the surface temperature unsuccessfully using an infrared pyrometer but observed a visible red radiation from the surface at high density ( $>1 \text{ W}/\text{cm}^2$ ) of deuteron beam. This indicates black body radiation from that local area having a surface temperature of about 800°C. Of course, the minor Na component of the target was quickly evaporated off

at that high temperature. Under normal conditions beam power density was kept below 20 mW/cm<sup>2</sup> and we had no possibilities to detect surface temperature at the moment but only the bulk temperature using a thermo-couple.

### 3. Interpretation of Observed Phenomena

The experimental values of reaction enhancement ranging between 10<sup>15</sup>~10<sup>10</sup> can be explained by the theory of “buffer energy nuclear fusion” [1] and furthermore the theory explains some phenomena observed in the present experiments as follows.

Metallic Li liquids are filled with mobile valence s-electrons which reveal collective features i.e. thermodynamic activity of metallic liquids [2]. Their de Broglie wave length stretches over a bond length of some tens Li atoms. Density distribution of mobile s-electrons is non-vanishing inside Li nuclei resulting in the penetration effects. In a sea of these collective mobile s-electrons, an ensemble of Li nuclei is immersed as well as Li ion cores and very likely forms a solvent for atomic fusion and associated nuclear fusion reactions. In the solvent Li liquids, implanted deuterons behave as solute or reacting atoms in dilute solutions.

At an energy below 110keV which is a product of the lowest electronic excitation energy of Li atoms and mass ratio of deuterons and electrons, most deuterons cause neither electronic excitation nor inner shell ionization of Li atoms and keep the solvent Li liquids at thermal equilibrium [1] which guarantees the thermodynamic activity of liquids [2]. This energy range has been named as the buffer energy in ref. 1. The deuterons undergo atomic fusion, that is, united atoms  $\overline{^7\text{LiD}}$  formation at their turning points [1]. Since atomic wave functions and the Gibbs energies  $G$  of  $\overline{\text{LiD}}$  and Be are almost identical, the united atoms  $\overline{\text{LiD}}$  induce adiabatically the nuclear fusion reaction of recoilless proton transfer [1,2],



through the complex  $\overline{^8\text{Be}^* \text{n}}$ ,  $\overline{^8\text{Be}^*}$  being the nuclear isomer of  $^8\text{Be}$ . In the reaction, momenta of implanted deuterons and produced low speed neutrons are matched i.e.  $E_{\text{n}} \approx 2E_{\text{d}}$  because in general nonresonance reaction cross sections are maximum under momentum matching.

All things considered the atomic fusion and thereby induced nuclear fusion reactions of deuterons in the solvent can be well treated within the scheme of thermodynamics of chemical reactions in dilute solutions. As a consequence the Arrhenius' equation for spontaneous chemical reactions is naturally applicable to the atomic fusion and induced nuclear fusion reactions in the metallic Li liquids. These features provide an underlined preconcept of nuclear reaction enhancement due to the thermodynamic force in the liquids. There is not necessarily a real force pushing the nuclei down the slope of the chemical potential (Gibbs energy). The thermodynamic force may represent the spontaneous tendency of the bulk nuclei to disperse as a consequence of the Second Law and the hunt for maximum entropy.

In the theory [1], the value of Gibbs energy change  $\Delta G$  has been derived to be about  $\Delta G = -1.25\text{ eV}$  for a reacting Li-D atoms pair from the bond energy of metallic Li liquids. This in turn results in the enormous enhancement of nuclear reaction, eq. (3) of about  $5 \times 10^{13}$ . The value of enhancement may be gained due to the charge exchange or polarization effect on the deuterons passing through the Li liquids in

particular at low acceleration energy which reduces the effective charge of deuterons [2]. This expected trend is consistent with the measured values of enhancement of around  $10^{15}$  for  $E_d = 10$  keV, about  $4 \times 10^{10}$  for  $E_d = 20$  keV and about  $10^{10}$  for  $E_d = 24$  keV.

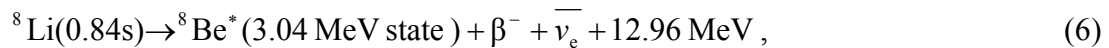
There are certain possibilities to quench these values depending on the experimental conditions such as effective reaction area of Li surface, thickness of slag concealing the surface, in particular local temperature rise in the reaction space within a few hundredth micron depth on the surface and so on. According to eq. (1), a temperature rise of  $190^\circ\text{C}$  above the melting point results in a quenching of enhancement as much as by a factor of  $10^{-4}$ . In fact, high deuteron beam power density hindered us even from observing the reaction. Small amounts (a few atomic %) of metallic Na mixture in the Li target were found to be very useful to relax the temperature rise through the evaporation of metallic Na. Based on our tests, it has been found that improved experimental conditions e.g. clean vacuum and better temperature control of liquid surface would yield still larger enhancement.

Now it would be of significance to examine some dynamical features revealed through the broad peaks. The width of peaks ranging between  $1.5 \sim 5.0$  MeV indicates that product nuclei  $^8\text{Be}^*$  are extremely short lived i.e.  $\sim 10^{-21}$ s or less in the Li liquid. The observed upper end point of peaks around the Q-value (15.12 MeV) is incomprehensible within the scheme of usual two body break up dynamics. This might imply that one of the  $^4\text{He}$  atoms produced in the reaction, eq. (3) was bound in the bulk of Li liquid as well as the nucleus  $^8\text{Be}^*$  through the cohesion fully developed by the mobile s-electrons.

This explanation is very surprising but seems to be consistent with the counting rate increase as much as by a factor of two associated with the peak energy jumping from 15 MeV to 7.5 MeV. Except this explanation based on the energy conservation law, we can not find any other comprehensible dynamics to interpret this phenomenon. This jumping suggests a phase transition of Li liquid, which is very likely explained as that during the implantation a lithium deuteride (LiD) concentrated layer is formed on the Li liquid surface and diminishes the cohesion in the reaction space resulting in the quasi free dual  $\alpha$ -particle break up of  $^8\text{Be}^*$  nucleus.

#### 4. Significance of Nonthermal Nuclear Fusion in Metallic Liquids

As argued in previous section, there are some possibilities to improve the reaction rate observed in the present experiments. If an enhancement of about  $5 \times 10^{12}$  is achieved for deuterons of buffer energy, say about 50 keV they could undergo the nuclear reaction eq. (3) with nearly 100% probability in Li liquids. Intermediate neutrons produced in the reaction, eq. (3) are monochromatic  $E_n \doteq 2E_d$ . They are absorbed by  $^6\text{Li}$  and  $^7\text{Li}$  nuclei and produce associated energy releases as seen in the reactions,



$$^8\text{Be}^* (3.04 \text{ MeV state}) \rightarrow 2^4\text{He} + 3.13 \text{ MeV}. \quad (7)$$

Considering a case of combined nuclear reactions, eq. (3, 5-7), if one subtracts the average energy of about 7.7 MeV carried out by an antineutrino  $\bar{\nu}_e$  in the beta decay, eq. (6), the useful energy release is about 26 MeV for one deuteron. This implies that the energy gain – the ratio of energy release to the acceleration energy – is close to about 520 for the 50 keV deuterons. This means that the new scheme of nonthermal nuclear fusion could provide mankind with sustainable wasteless energy. Furthermore, the quenching of enhancement due to the Li temperature rise exhibits clearly fail proof characteristics (no melt down of fusion reactor) of the new nuclear fusion scheme in contrast with those of chain reacting chemical reactions and nuclear fission chain reactions.

The above corroborative evidence of the enhanced nonthermal nuclear fusion elucidates the following noteworthy significance.

On the contrary to the one century retained assessment that atoms never change identity in the chemical reactions whereas nuclear reactions are not affected by temperature, catalysts and the compound in which an element occurs, both chemical and nuclear reactions take place cooperatively in certain ensembles such as metallic Li liquids at thermal equilibrium. In the liquids, the thermodynamic force produced by collective mobile valence s-electrons dominates the nuclear reactions via enhanced atomic fusion, that is, formation of united atoms and results in the nuclear reaction enhancement of exponential magnitudes.

### **Acknowledgements**

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## Figure captions

*Fig.1* Test device: 1, D<sub>2</sub> gas inlet and filament stem (Pyrex glass); 2, to turbo-molecular pump; 3-8, mini-duoplasmatron ion source; 3, intermediate electrode (soft iron); 4, filament; 5, duoplasmatron chamber (Pyrex glass); 6, permanent magnet rod; 7, anode (soft iron); 8, extraction electrode; 9, acceleration chamber (Pyrex glass); 10, acceleration electrode; 11, to liquid nitrogen trap and diffusion pump; 12, Si surface barrier detector (SSD); 13, target chamber (Pyrex glass); 14, high speed rotating slag scraper; 15, liquid Li target cup (stainless steel) with thermocouple; 16, heater; 17, to Penning gauge.

*Fig.2.* Spectra of  $\alpha$ -particles obtained with a deuteron beam of 2.0 - 1.5  $\mu$ A. The broad peaks observed have been found to change their shape and height depending on the condition of the Li surface. (a) An example of a broad peak observed within an acquisition time of 32 s (dead time 4.0%) at a deuteron energy of 24 keV. The upper end point energy of the peak is around 15 MeV (Q value of the  $^7\text{Li}(\text{d}, \text{n}\alpha)^4\text{He}$  reaction). A small peak shows a simultaneously observed  $\alpha$ -particles emitted from a calibration source of  $^{241}\text{Am}$  (5.48 MeV) covered with a 5  $\mu\text{m}$  thick Al foil and mounted near the liquid Li target. (b) A broad peak observed 21 minutes after the time of data taking (a) within an acquisition time of 17s (dead time 7.4%) at the same deuteron energy 24 keV. The upper end point energy jumped from 15 MeV to 7.5 MeV while the counting rate increased as much as by a factor of two. (c) A broad peak observed 4 minutes after the time of data taking (b) within an acquisition time of 163s (dead time 0.3%) at a deuteron energy of 10 keV. After this observation, the peak shifted gradually towards the lower energy side diminishing its height with the deterioration of the Li target surface. That deterioration was visually observed through the Pyrex glass wall of target chamber.

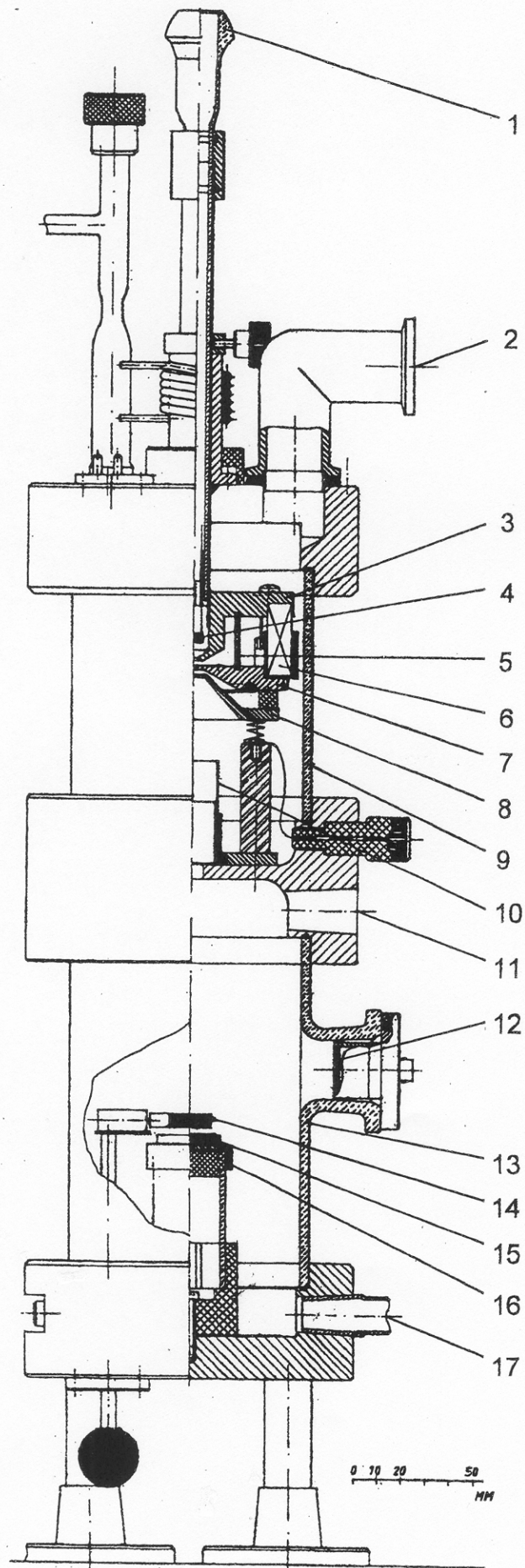
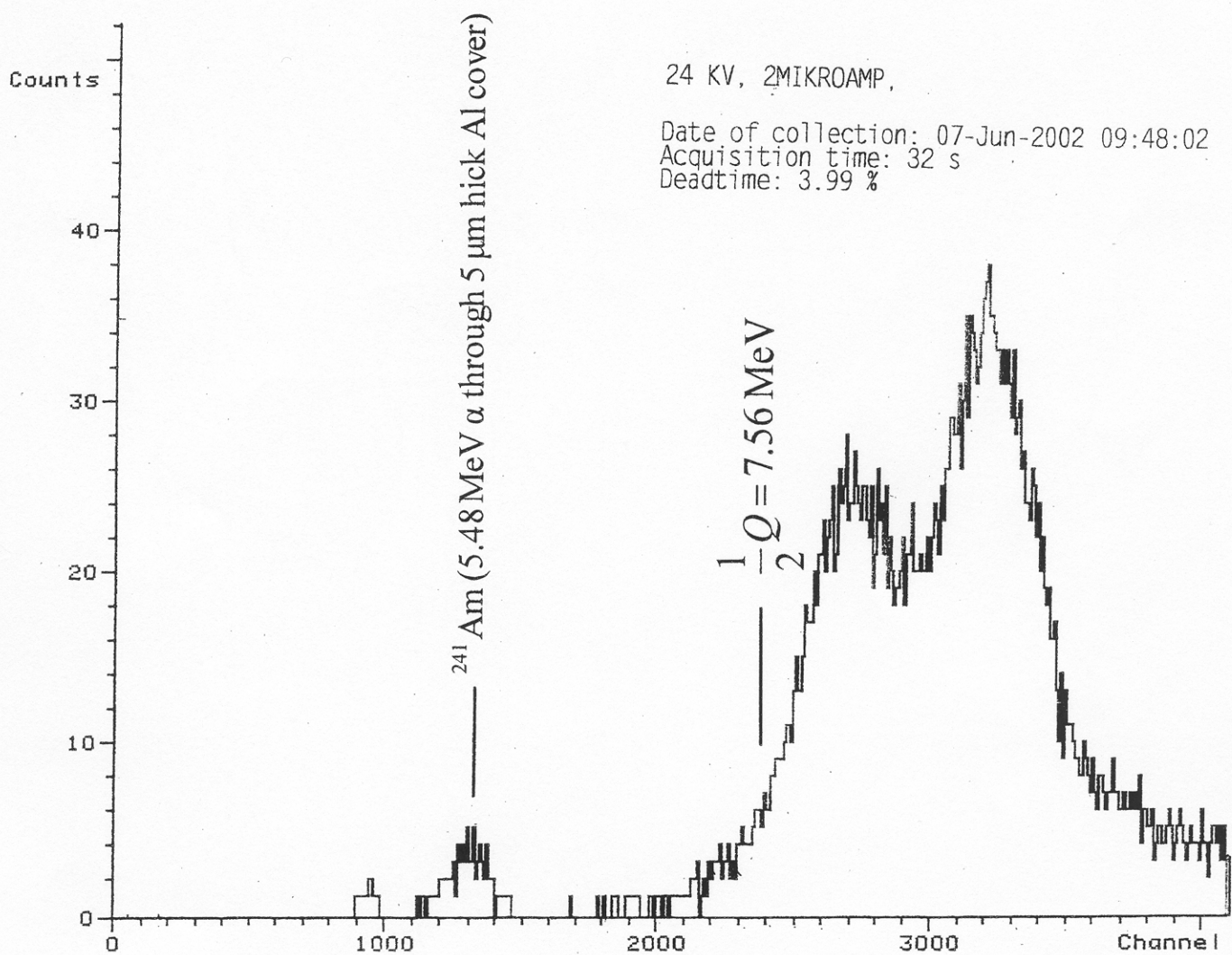
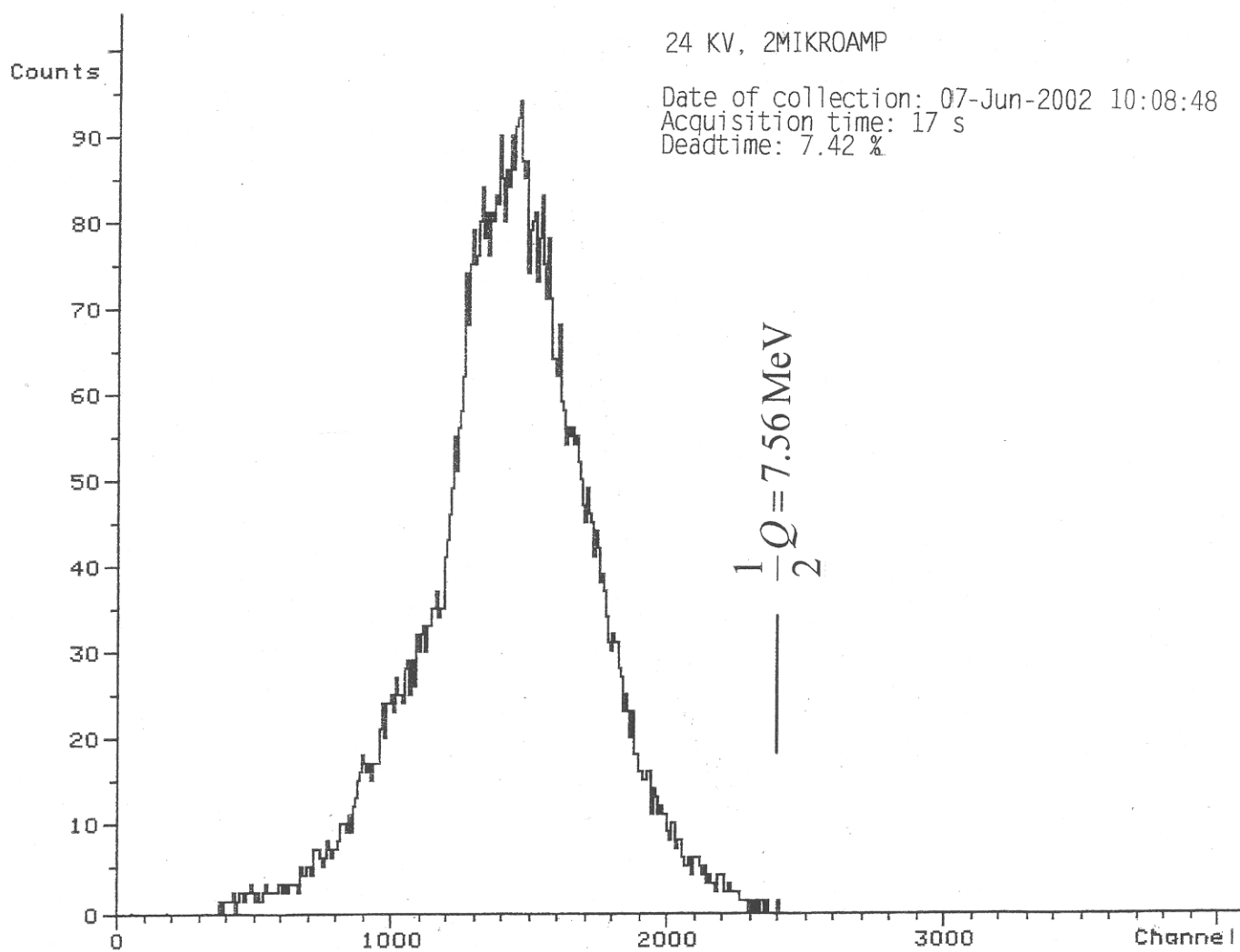


Fig. 1



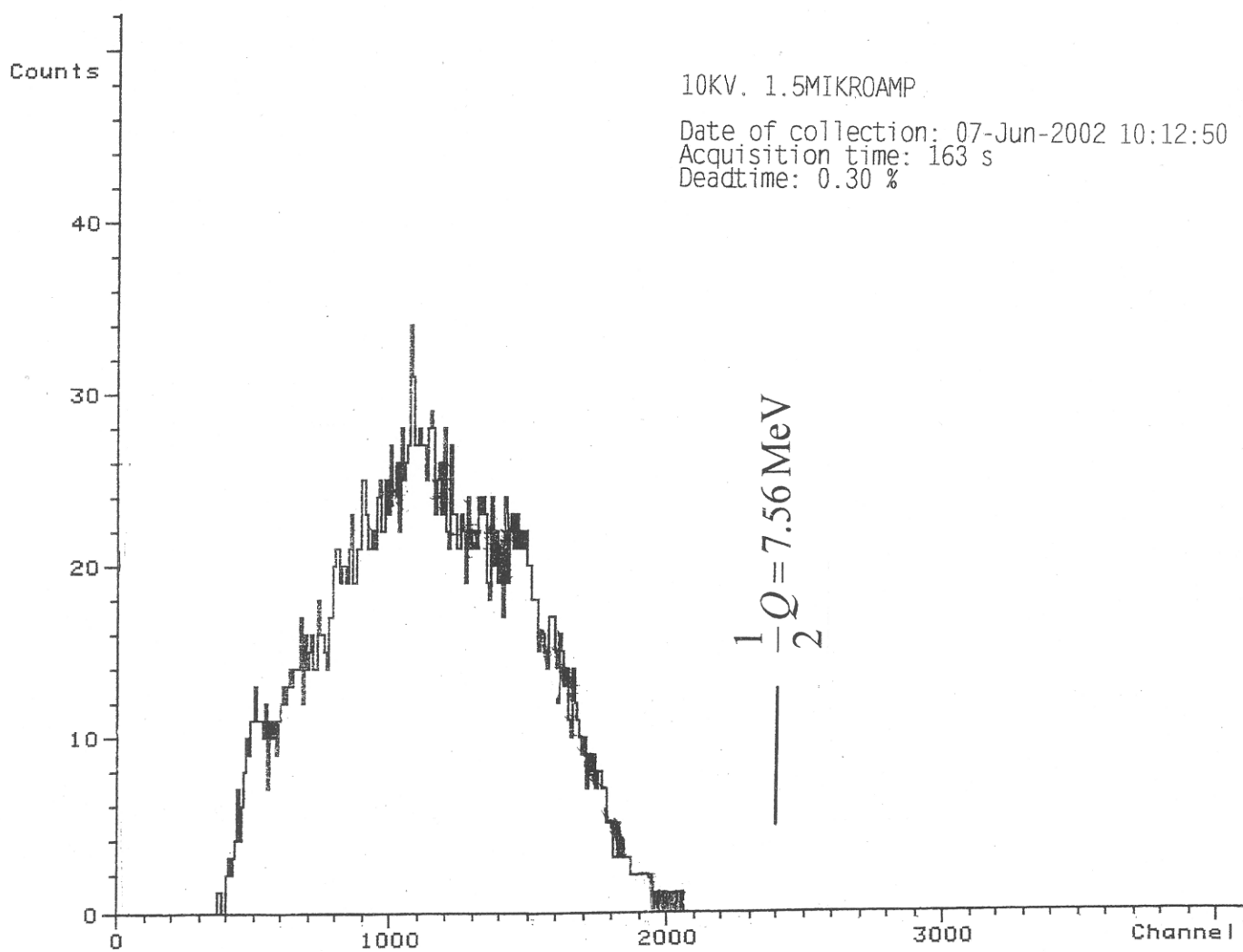
(a)

Fig. 2 (a)



(b)

Fig. 2 (b)



(c)

Fig. 2 (c)