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Observation of enormously enhanced nuclear fusion in metallic Li liquid

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Deuterons of some tens keV energy have been implanted on a surface of metallic Li liquid. Alpha particles produced in the fusion reaction $^7Li + d \rightarrow {}^8Be + n \rightarrow 2\alpha + n$ were identified using Si surface barrier detectors (SSD) and thin foil energy loss method. The rate of alpha particles was up to one million per second at 1 µA of deuterons. This is a factor of 10^{10} - 10^{15} higher than what is expected based on available nuclear-reaction cross sections [1]. Since we do not observe any alpha particles when the Li sample is solid at room temperature the enhancement must be connected with the macroscopic scale correlation in the liquid [2-4]. The alpha-particles spectrum exhibits a broad peak at the energy of full Q-value of 15.1 MeV of the reaction. Energy loss measurements show that this peak is actually a sum peak of unidirectionally emitted paired α-particles each having 7.56 MeV kinetic energy and their momentum deficit must be covered by bulk liquid Li atoms. This indicates also the macroscopic scale correlation [3, 4].

Nuclei dressed with electronic configurations reveal dynamical features influenced by their surroundings in some cases such as β-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 [2].

In fact enhancement of the rate of nuclear fusion reactions by a factor of some 10 – 30 orders of magnitude has been anticipated in ultra-dense liquids in white-dwarf supernova progenitors [5]. This enhancement is, however, common to entropy producing irreversible processes in liquids [2 – 4, 6]. The well known examples are the Henry's law on the solubility of gases in liquids [6] and the Arrhenius'rate equation for irreversible ($\Delta G_r < 0$) chemical reactions in dilute solutions [2 - 4]. Here ΔG_r denotes the Gibbs'energy (chemical potential) change in the reactions. General speaking the rate of irreversible reactions is exactly proportional to the rate of entropy increase. This general thermodynamic relation is strictly independent of nature of microscopic interparticle interactions [3, 4]. These considerations lead to the enhanced nuclear fusion reaction induced by slow deuterons (E_d <110 keV) implanted in metallic Li liquid [2, 4, 7].

$$^{7}\text{Li} + {}^{2}\text{H} \rightarrow {}^{8}\text{Be} + \text{n} \rightarrow 2\,{}^{4}\text{He} + \text{n} + 15.12\ \text{MeV} \tag{1}$$

In this scheme the liquid consisting of Li ions immersed in a sea of mobile s-electrons takes the parts of solvent reacting with solute deuterons. Orbital electrons of Li ions or atoms are able to adjust electronic state so as to link the atomic fusion process with the nuclear fusion because they gyrate more rapidly than deuteron speed [4]. In the linked irreversible atomic fusion process

$$\text{Li} + \text{H} \rightarrow \text{Be} \tag{2}$$

macroscopically distinct parts of the liquid are correlated and long-range coherence appears [3, 4, 6].

These aspects are reflected in the rate of linked atomic and nuclear fusion reactions in the form of Arrhenius'equation

$$k(T) = k_0 \exp\left(-\frac{\Delta G_r}{k_B T}\right) \quad , \Delta G_r < 0 \tag{3}$$

enhancement of reaction rate expected. Faint beam density operation was found to be useful to avoid the local temperature rise of the Li metal surface due to the non-linear thermal effect [1]. For instance, a temperature rise of 190 ° C above the melting point of Li metal results in a quenching of the enhancement as much as a factor of 10^{-4} as seen in equation (6). In order to match with these requirements a compact ion source of PIG type equipped with permanent magnets was made, which produced ion beams with several tens of μA from 1 keV to 35 keV. A beam of typically 10 μA was extracted from a slit with a hole of 1 mm in diameter and then accelerated after passing through a molecular ion and neutral beam filter system. A faint deuteron beam in the range from a hundred to several nA entered target chamber was implanted vertically on a surface of metallic Li target of 19 mm in diameter and the amounts of about 1 g. The currents of collimator and target were monitored during experiments.

The product charged particles from the target were observed using a 300 μm thick Si surface barrier detector (SSD) positioned at the angle $\theta_{lab} = 115\,°$ with the effective acceptance angle of 0.06 % of 4 π steradian. The front face of SSD was covered with a 5.5 μm thick Al foil to prevent δ-rays and scattered deuterons from hitting the detectors. A movable Al foil was introduced in front of SSD in order to measure the energy loss characteristics of the particles. Throughout the experiments detector output pulses and spectra were monitored comparing with those of α-particles from a calibration source of ^{241}Am (5.48 MeV) mounted near the Li target. Slow neutrons ($E_n = 2E_d = 20 \sim 60$ keV) emitted from the target were monitored using a BF_3 rem-counter covered with a polyetyrene and boron mixed plastic case of about 100 mm thickness.

The experiments were carried out for metallic Li targets in both liquid – and solid – phases for comparasion. In the solid phase at room temperature no event was observed in either case of charged particle and neutron measurements. This fact was consistent with the very faint nuclear fusion probability evaluated by equation (5).

In any case of liquid phase of bulk Li metal or local melting Li surface, a broad peak was observed in the charged particle energy spectra. The observed enormous rate enhancement was, thanks to improvements mentioned above, reproducible and consistent with previous results. It was as reported dramatically dependent on the state of liquid Li surface [1, 4]. Typical examples of spectra are seen where k_B is the Boltzmann constant [2]. The factor k_0 is expressed as

$$k_0 = I_1, N_2 \sigma(E_d) \tag{4}$$

where I_1, N_2 and $\sigma(E_d)$ are number current of implanted deuterons with an acceleration energy E_d , surface number density of Li ions or atoms and nuclear fusion cross-section, respectively.

If there is no correlation in the liquid at all, the rate is $k(T) = k_0$ and almost all implanted deuterons undergo stopping within the depth of a few hundredth μm on the surface of liquid without fusion reaction. Because the intrinsic probability of nuclear fusion

$$P_{intr} = 6.1 \times 10^{-5} \exp\left(-\frac{132.7}{\sqrt{E_d(\text{keV})}}\right) \tag{5}$$

is very faint typically 4×10^{-23} at $E_d = 10$ keV and 8×10^{-18} at $E_d = 20$ keV [2, 4, 7]. However under the presence of macroscopic scale correlation the linked fusion reactions are dominated by the Gibbs energy change ΔG_r in equation (2). In the present fusion scheme the value of ΔG_r has been derived to be around −1.35 eV from the bond energy of metallic Li liquid. This results in the enormous enhancement in equation (3)

$$\exp\left(-\frac{\Delta G_r}{k_B T}\right) = 5 \times 10^{13} \tag{6}$$

just above the melting point of Li metal $T = 460$ K [2].

The predicted enhancement in equation (6) was fully verified in the previous experiment [1]. Observed enhancement was a factor of some $10^{15} - 10^{10}$ depending on the deuteron energy $E_d = 10 - 24$ keV. Furthermore an additional event suggesting the strong correlation in bulk liquid Li atoms was found in the observed α-particle spectra. The aim of present experiment is to confirm the enhancement and also to investigate the correlation aspects of Li liquid.

The present experiment is a natural extension of the previous work [1] and using an improved machine which is constructed for low D_2 gas consumption to diminish LiD formation on the liquid Li surface during experiments. Special attention was paid to generate clean and stable deuteron beam but of faint intensity because of the huge

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in Fig. 1 which were obtained at $E_d = 25$ keV and $I_1 = 75$ nA. The large energy loss characteristics observed in the spectra identified clearly the particles with α-particles.

Whenever the Li liquid surface was pure or clean and its local temperature rise was well controlled within the beam density of about 1μA/cm^2 the broad peak with a width of about 2 MeV was observed at the energy of full Q-value of 15.12 MeV. It is, however, unlikely to consider that one of the α-particles produced in the reaction carries away the full energy because observed energy loss due to the 11μm thick Al-foil was about 2.2 MeV which is much bigger than the expected loss of 0.9 MeV for the α-particle having 15.1 MeV kinetic energy as seen in Fig. 1. Instead the observed loss is consistent with the loss of two simultaneous α-particles each having 7.56 MeV kinetic energy. This observation indicates that the broad peak is actually a sum peak of unidirectionally emitted α-particle pairs and the momentum deficit after the emitted pair must be covered by the medium consisting of liquid Li atoms. This is puzzling result and indicates that there must be a macroscopic scale correlation at play; in some way the recoil momentum is absorbed by bulk liquid Li atoms [4].

In some Li liquids contaminated by artificial mixture of non-metallic materials or by some chemicals accumulated during experiments such as LiD, the broad peak appeared at the energy of 7.56 MeV and shifted gradually towards the zero energy [1]. The observation results indicate the decay of thermodynamic activity of the liquids, which are however left for further systematic investigations.

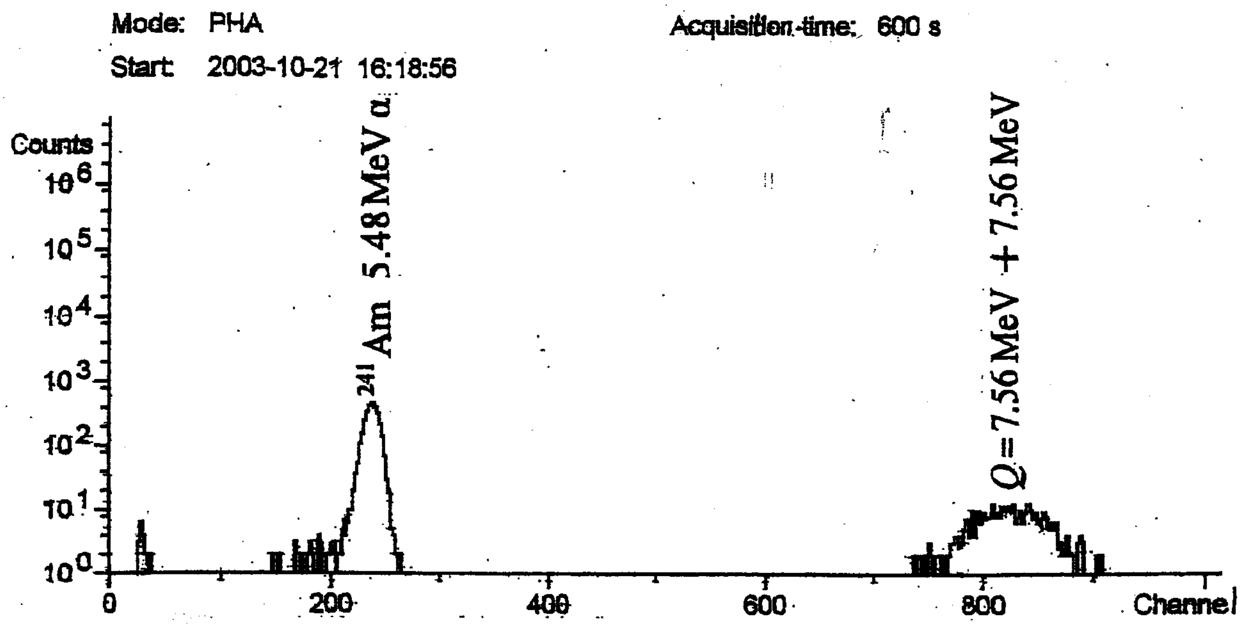
In principle there is a possibility of other fusion reactions

$$\left.\begin{aligned} &\mathrm{D} + \mathrm{d} \rightarrow \mathrm{T} + \mathrm{p} + 4.04\ \mathrm{MeV} \\ &\mathrm{D} + \mathrm{d} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.27\ \mathrm{MeV} \end{aligned}\right\} \qquad (7)$$

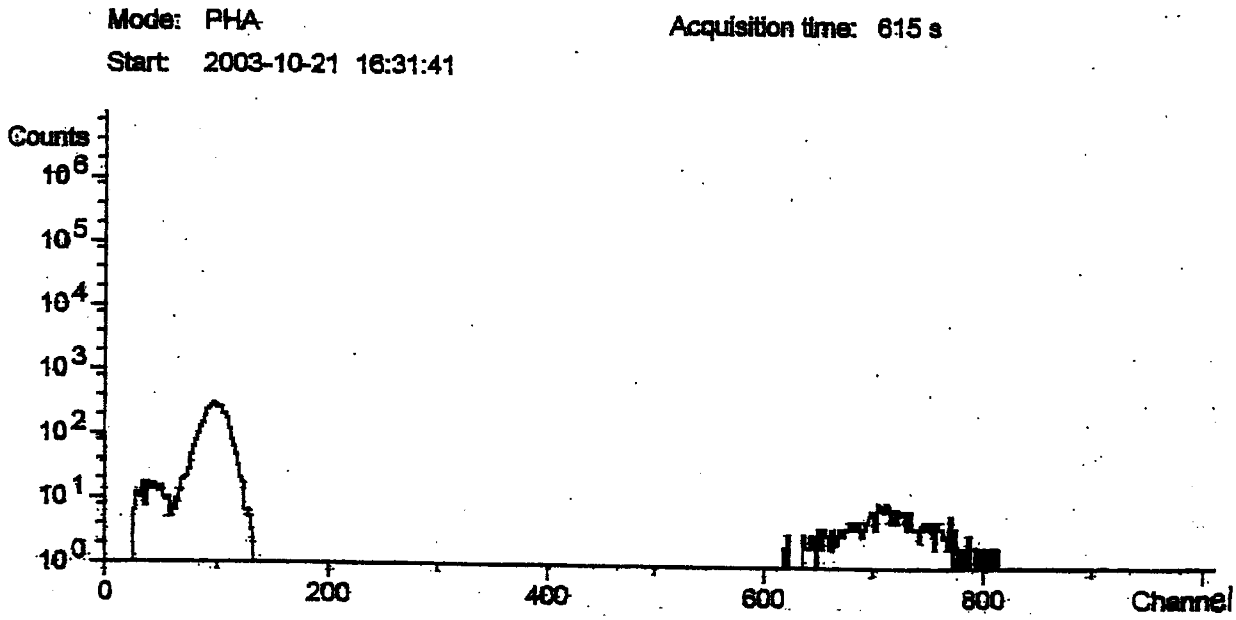
caused in a slug layer accumulated mainly in the form of LiD on the Li surface. This possibility was however clearly rejected from observed particle spectra and also independent particle energy loss measurements. Furthermore the observed fusion rate was always diminished when the thickness of accumulated slug becomes appreciable.

In conclusion, it is of importance to understand the present findings on the interplay of chemistry and nuclear physics much more precisely.

Figure 1. Spectra of α-particles observed with a deuteron beam of 25 keV and 75 nA. (a) Broad peak with a width of 2.0 MeV located at the energy of full Q-value of the reaction, $^{7}Li + d \rightarrow {}^{8}Be + n \rightarrow 2\alpha + n$. Another peak shows simultaneously observed α-particles from a calibration source of ^{241}Am mounted near the liquid Li target. (b) Peaks shifted by inserting an 11 μm Al-foil in front of SSD. The shift 2.2 MeV should be compared with the estimated loss of 0.9 MeV for one 15.1 MeV α-particle traversing the Al-foil. The loss is however consistent with the loss of two simultaneous α-particles each having 7.56 MeV kinetic energy.


Mode: PHA
Start 2003-10-21 16:18:56
Acquisition time: 600 s
Counts
^{241}Am 5.48 MeV α
Q = 7.56 MeV + 7.56 MeV
Channel

(a)


Mode: PHA
Start 2003-10-21 16:31:41
Acquisition time: 615 s
Counts
Channel

(b)