Li+D and D+D Fusion Assisted with Acoustic Cavitation

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Abstract. We have studied the Li+D and D+D fusion reactions in liquid Li by bombarding deuteron beams with energies below 70 keV. In the present work, an ultra sonic target system was developed to form acoustic cavitation bubbles in the liquid Li, in order to investigate the effect of the enhanced dynamic motion of the target. It was found that the ultra sonic effect strongly depends on a target condition and the D+D reaction could be enhanced very much due to the liquid Li cavitation. In addition, the D+D reaction rate is not constant but time dependent. Preliminary analyses indicate that decrease of the Coulomb energy barrier is about 2000 eV for a relatively stable condition. On the contrary, the Li+D reaction shows no meaningful effect for incident energies down to 30 keV. The present results indicate that not only density increase but also another mechanism enhancing reaction rates should be exist in liquid Li acoustic cavitation process.

1. Introduction

It has been shown that the nuclear reaction could be strongly affected by target condition and environment, and has been suggested that a dynamic mobility of deuteron in condensed matter is an essential factor to enhance the D+D reaction rate as well as a high deuterium density. In this paper, we try to establish unusual target conditions and to show enhanced nuclear reactions in such conditions. We employed a liquid metal (Li) as a host material where the D+D and Li+D reactions occur; the advantage of the liquid metal to the solid is possible existence of a screening effect of positive charges due to freely moving ions in addition to that of negative charges. Furthermore, the acoustic cavitation is applied to enhance the effects due to a dynamic motion of the target. In order to achieve these conditions, we developed an ultra sonic target system incorporated into a vacuum chamber to form Li cavitation bubbles in the target.

The reaction rates of the Li+D and D+D reactions in the Li cavitation bubbles were measured for the deuteron beam bombardment with energies below 70 keV; the density and kinematical effects were investigated. We also tried to detect bubble fusion under such a dynamic condition.[1-3]

2. Experiment

2.1 Ultrasonic System and Li Cavitation

Figure 1 (left) shows a schematic view of the ultra sonic system with the situation of vibration amplitudes depending on the position. It should be noted that the sonic wave is not transverse but longitudinal wave to form alternate dense and sparse conditions. A bolt-clamped Langevin-type transducer (BLT) generates a high amplitude sonic wave. A piezoelectric element is lead zirconate titanate (PZT). When the BLT is driven with an appropriate frequency, it outputs a high amplitude wave because of vibration resonance with four piezoelectric elements. Since the resonance condition is determined by the wavelength of the sonic wave, the total length of the system is an important factor. We designed the total length in such a way that the Li target is placed at an anti-node and that the resonance frequency is near 19 kHz. An aluminum horn connected to the BLT amplifies the vibration amplitude; the maximum amplitude is 10 μm. The horn has a flange at the node position of the sonic wave and is fixed with the vacuum chamber.

A situation of bubble growth and collapse through ultra sonic cycles is shown in Fig. 1 (right). At the sparse timing, a nucleus is born, the bubble shrinks and expands through a several cycles and it finally collapses at the dense timing. Thus, it is considered that the state with high pressure, density and temperature can be achieved and light emission, so called sonoluminescence, occurs.

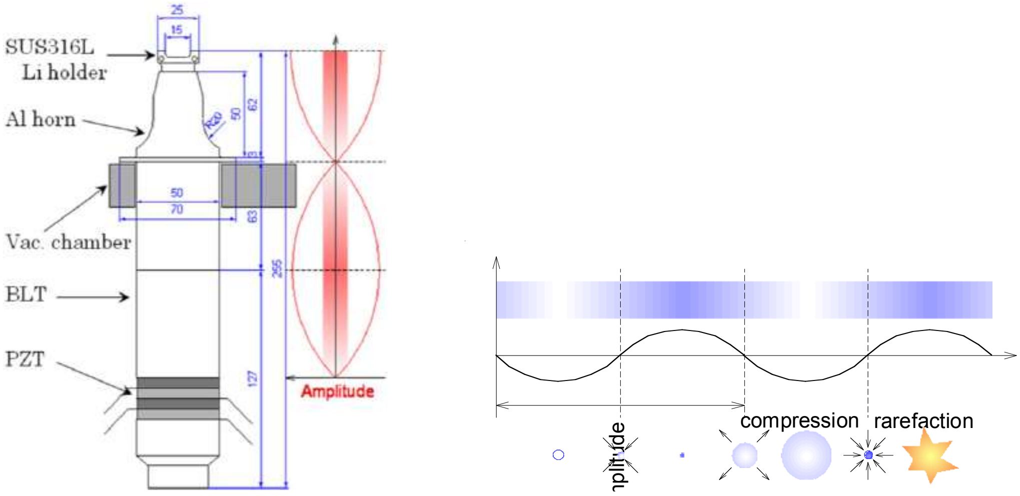

Fig. 1 – (left) A schematic view of an ultra sonic system. (right) Bubble growth and collapse through ultra sonic cycles.

However, the acoustic cavitation is a very complex process and there is no general theory to explain the mechanism and characteristic. Furthermore, almost no reports are found on the cavitation of the liquid metal. In a simple model, the threshold pressure for cavitation formation is mainly determined by surface tension of the liquid σ(T) and expressed as

$$P_{th} \sim P_0 - P_s + \sqrt{\frac{16\pi(\sigma(T))^3}{3kT \cdot const.}}, \tag{1}$$

$$P_{th}(Li) \sim 10 \times P_{th}(H_2O) \sim 1.6[GPa]. \tag{2}$$

From the empirical eq. (1), we need ten times higher pressure than water to produce cavitation bubbles.

Figure 2(a) shows a surface of clear liquid Li in the vacuum chamber; we see a distinct reflection of the light from outside of the chamber. When we apply the ultra sonic wave, the cavitation occurs and bubbles reflect the light diffusely; we see countless white dots as shown in Fig. 2(b). We note that these white dots are not sonoluminescenece but diffused light reflection since they appear just as a reflection of the light. The cavitation bubbles cover all Li surface as shown in Fig. 2(c).

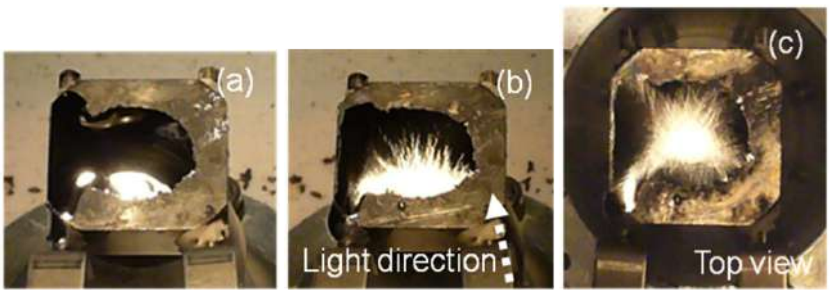

Fig. 2 – Liquid Li cavitations. (a) Clear liquid Li surface without ultra sonic wave. (b, c) Li cavitation bubbles. White dots are bubbles reflecting the light.

2.2Li+D and D+D Measurement

We used enriched ^{6}Li metal, consisting of 95% ^{6}Li and 5% ^{7}Li. The Li metal is very active material, and the surface is easily oxidized and/or contaminated. Therefore we designed and constructed a new vacuum chamber which has a glove box. In order to keep the surface clean, we handled the Li metal in Ar atmosphere in the glove box. The contamination, however, cannot be avoidable because of the residual gas when the chamber is evacuated. Thus, we removed the contamination every 1 or 2 hours by using a scraper attached to the chamber. We kept the Li temperature considerably higher than the melting point (180 ºC). Below 300 ºC, the vapor pressure of Li (10^{-6} Pa) is much lower than the vacuum of the chamber (typically $5\text{x}10^{-5}$ Pa). Thus Li evaporation can be avoided even in the cavitation condition.

The liquid Li was irradiated by deuteron beams with energy ranging from 30 to 70 keV. We kept the input power constant to be about 500 mW, in order to stabilize the ultra sonic effect. The beam was injected to the chamber at an angle of 60° with respect to the vertical direction. A Si detector placed at 125° was used to detect charged particles emitted in the nuclear reactions.

In order to elucidate the ultra sonic effect, we compared the yields of the Li+D and D+D reactions for the ultra sonic ON and OFF measurement. However, it was found that the target condition was very sensitive and was easily changed within a several minutes due to high activity of Li. Therefore a data acquisition system, in which the measurements with and without the ultra sonic were performed alternatively, was developed to reduce systematic errors. As is shown in Fig. 3, the beam was turned OFF and ON every 3 or 10 seconds while the ultra sonic wave was turned OFF and ON every 13 seconds so as to accumulate the 4 data sets in one cycle.

In Fig. 3, the reading of the infrared thermometer, which is considered to show the temperature of the Li surface, is also shown. It periodically increases and decreases synchronized with the ultra sonic ON/OFF cycle. It is not plausible that the change of the reading corresponds to real change of the temperature because of its instant response. At present, we conjecture that near-infrared lights are emitted in the Li cavitation as the sonoluminescence.

Time (sec)	3	10	3	10	3	10	3	10
Beam	B.G.	F.G.	B.G.	F.G.	B.G.	F.G.	B.G.	F.G.
U.S.	OFF		ON		OFF		ON	

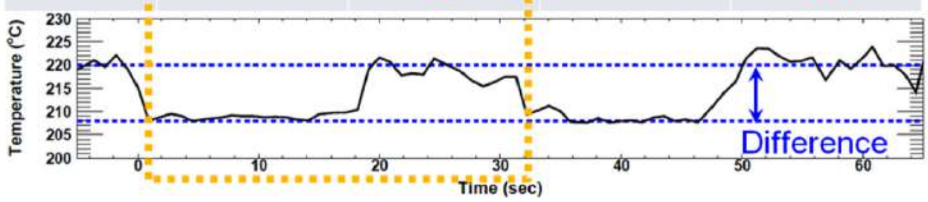

Fig. 3 – An alternate data acquisition cycle and infrared thermometer output.

3. Result

A typical energy spectrum is shown in Fig. 4. The blue peak is the 11.2-MeV α particle from the ^{6}Li+D reaction. During the deuteron bombardment, deuterons are being accumulated in the Li target and an incident deuteron collides with them to make the D+D reaction. The red peak is 3-MeV proton from the D+D reaction. We can estimate the deuteron density in the Li liquid by counting α and proton counts as

$$\frac{Y_p}{\frac{1}{2}Y_\alpha} = \frac{\int N_D(x)\cdot\sigma_{D+D}(x)\cdot dx}{N_{Li}\cdot\int\sigma_{Li+D}(x)\cdot dx} \Leftrightarrow \frac{N_D}{N_{Li}} \sim \frac{2\int\sigma_{Li+D}(E)(x)\cdot\frac{1}{dE/dx}\cdot dE}{\int\sigma_{D+D}(E)\cdot\frac{1}{dE/dx}\cdot dE}\cdot\frac{Y_p}{Y_\alpha}. \quad (3)$$

The maximum deuteron density deduced in the present measurements is 0.1% of the Li.

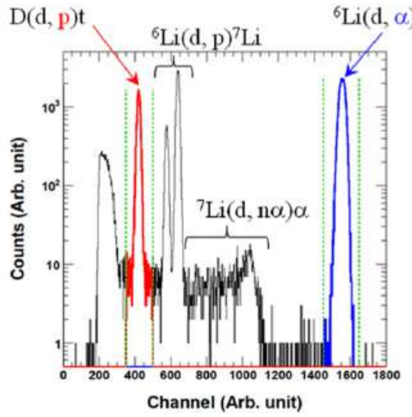

Fig. 4 – Energy spectrum.

We show an example of measurements in Fig. 5. We plot the yield of the Li+D and D+D reactions as a function of elapsed time with black marks for ultra sonic OFF and blue marks for ON. In the case of the Li+D reaction shown in Fig. 5(a), the yield is constant and the difference between the ultra sonic ON and OFF is within the error. On the other hand, the yield of the D+D reaction increases gradually probably due to increase of deuteron density in the liquid Li. Of particular significant, however, is the fact that the D+D reaction is enhanced by the ultra sonic wave. In Fig. 5(c) one already sees large difference between ON and OFF. Figure 5(b) shows the ratio of the yield for the ultra sonic ON to that for OFF. One can see that the D+D reaction with the ultra sonic is really enhanced several times, while no enhancement is observed for the Li+D reaction. In this run, we obtained the averaged ON/OFF ratio to be 3.5 for the D+D reaction. After 2 hours, the ultra sonic effect was lost and the ratio became back to unity.

Fig. 5(d) shows time spectra of events; the abscissa is the correlated time with the ultra sonic. The BLT is driven with the resonance frequency of 18.85 kHz, corresponding to a 53-μs cycle. We measured the time difference between the standard signal and the event signal. In the case of the ultra sonic OFF, the reaction occurs randomly and the time spectrum is flat as is shown with a black line. However, we cannot find clear time correlation with the ultra sonic, either, as shown with a blue line up to now.

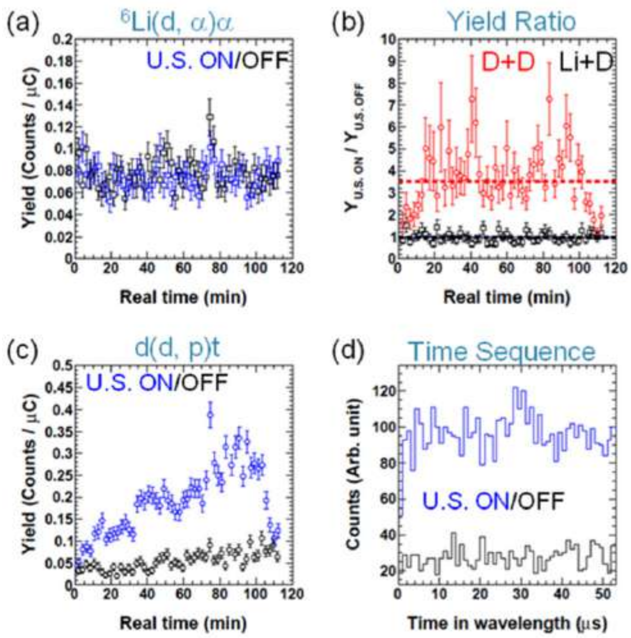

Fig. 5 – Time behaviors of Li+D and D+D reaction yields. (a) Li+D reaction yield, (b) yield ratio: ultra sonic ON/OFF, (c) D+D reaction yield, (d) micro time sequence of D+D reaction.

Fig. 6 (left) shows a histogram on the time correlation between two successive events; the abscissa corresponds to the time interval of the two successive events. It is known that reactions occur randomly and constantly, i.e., for Poisson distribution, the expected spectrum shows an exponentially decreasing function. For the generalized Poisson process in which the reaction rate is not constant but varies as time, the probability expressed

$$P = \frac{(\lambda(t))^k}{k!} e^{-\lambda(t)},$$
$$f(t) \sim e^{-\lambda(t)}, (\lambda(t) = \int_0^t r(x)dx) \quad (4)$$

where f(t) and r(t) are reaction interval and reaction rate, respectively.
In Fig. 6 (left), a histogram for the measurement without the ultra sonic (the black line) shows an exponential curve as expected. On the contrary, the blue line for the ultra sonic ON has three components; (1) homogeneous Poisson process (high reaction rate), (2) homogeneous Poisson process (low reaction rate) and (3) non- homogeneous Poisson process. The reaction rate r(t) for each process is estimated as shown in Fig. 6 (right). First, there is a high density phase (1) that is 13 times larger than the normal phase (2). Furthermore, we found the shoulder, not exponential component, in the time interval spectrum as shown in red curve (3). That means the reaction rate is not constant λ_0 but has time dependence $\lambda(t)$.

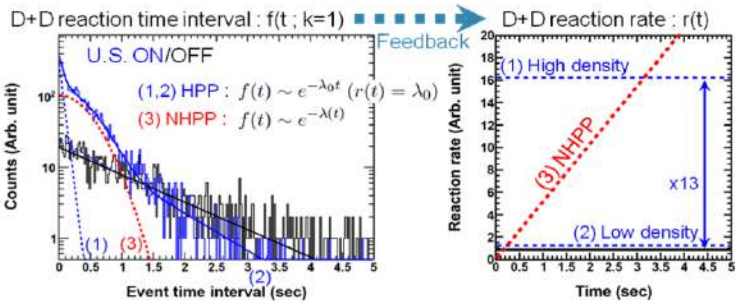

Fig. 6 – D+D reaction time interval (left) and reaction rate (right).

Vibration amplitude dependences and incident energy dependences of the Li+D and D+D reactions are shown in Fig. 7. In the figure, Y axis corresponds to the ultra sonic ON/OFF ratio. The intensity of cavitation is obviously increased with increase of the vibration amplitude. However, the yield ratio decreases for the D+D reaction because the intense cavitation stirs the liquid Li and absorbed deuterons diffuse out immediately from the spot where part of the beam is being accumulated. We carried out many measurements and found that the cavitation effect strongly depends on the target condition. Up to now, we have not found the way to keep the good condition for a long period.

We selected the data measured under a relatively stable condition and show the energy dependence of the yield ratio in Fig. 7 (right); i.e., the data under the condition of vibration amplitude of 1.9 μm, surface temperature of 220 °C, and beam input of 500 mW. The D+D reaction yield ratio has obvious energy dependence. As the incident energy becomes lower, the yield ratio increases. If the reaction is enhanced by the change of the deuteron density only, the energy dependence cannot be observed. Thus, the observed dependence on the incident energy clearly indicates that not only density effect but another mechanism to enhance the reaction should be effective in the liquid Li cavitation process. We fitted the experimental ratios to the calculations with the following equation

$$\frac{\sigma_{U.S.ON}(E)}{\sigma_{U.S.OFF}(E)} \sim \frac{\sigma(E+U)}{\sigma(E)} \sim \exp(15.64 z_1 z_2 \sqrt{\mu} \frac{U}{E^{3/2}}), \quad (5)$$

and obtained an effective energy difference U. If we assume that the enhancement is caused by Gamow factor only, the effective energy difference is U = 1980 eV for D+D fusion in center of mass system as shown in solid lines in Fig. 7.

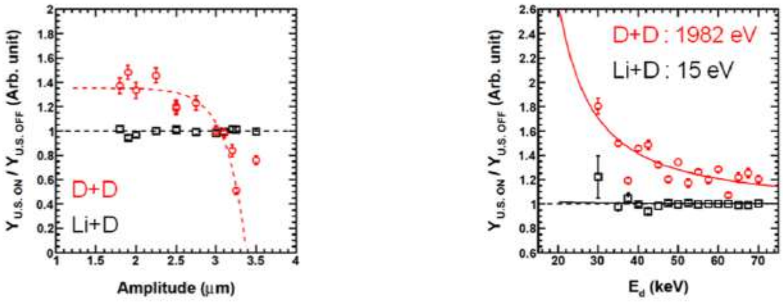

Fig. 7 – Vibration amplitude dependence and incident energy dependence of Li+D and D+D reactions.

4. Conclusion

We have developed an ultra sonic target system to form the Li acoustic cavitation bubbles in the vacuum chamber. The Li+D and D+D fusion reactions were measured during the low energy deuteron bombardment to the Li target. In this paper, we show the first experimental result with acoustic cavitation. It is found that the ultra sonic effect strongly depends on the target condition, the D+D reaction could be quite enhanced under the cavitation, and the reaction rate is not constant but time dependent. The decrease of the Coulomb energy barrier is about 2000 eV for the relatively stable condition. On the contrary, the Li+D reaction shows no meaningful effect. The present results indicate that not only density effect but also another mechanism to enhance the reaction rate should exist in liquid Li acoustic cavitation.

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5. References

[1] R.P. Taleyarkhan, *et al*., *Science* **295** 1868 (2002)
[2] R.P. Taleyarkhan, *et al*., *Phys*. *Rev*. *E* **69** 36109 (2004)
[3] R.P. Taleyarkhan, *et al*., *Phys*. *Rev*. *Lett*. **96** 179903 (2006)