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Ionic Debye Screening in Dense Liquid Plasmas Observed for Li＋p, d Reactions with Liquid Li Target*

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Abstract: Thick target yields of α particles emitted in the ^{6}Li(d, α)^{4}He and ^{7}Li(p, α)^{4}He reactions were measured for Li target in the solid and liquid phase. Observed reaction rates for the liquid Li are always larger than those for the solid. This suggests that the stopping power of hydrogen ion in the liquid Li metal might be smaller than in the solid. Using the empirically obtained stopping power for the liquid Li, we have deduced the screening potentials of the Li＋p and Li＋d reactions in both phases. The deduced screening potential for the liquid Li is about 500 eV larger than for the solid. This difference is attributed to the effect of liquefied Li^{+} ions. It is concluded that the ionic screening is much stronger than the electronic screening in a low-temperature dense plasmas.

Key words: low energy nuclear reaction; Li＋p and Li＋d reaction in liquid Li; liquid metal Li screening energy.

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1 Introduction

Low energy nuclear reactions play an important role in nuclear synthesis and energy production in stars, where thermal nuclear reactions take place in various plasma conditions. In order to simulate such processes, reaction rates should be known from the nuclear reaction experiments in a laboratory. The progress of the accelerators made it possible to measure nuclear cross sections for variety of nuclear reactions. However, the reaction rate depends on the environments very strongly. For example, it has been well known that the screening by electrons enhances the nuclear cross section very much, even in the laboratory experiment where a target nucleus is usually in atom or molecule. Thus, the nuclear reactions in various conditions should be explored more, in order to estimate the reaction rates in stars, although it is impossible to prepare for very high density plasmas, at present.

We have developed measurements of low-energy nuclear reactions in metal environments[1], where target nuclei are surrounded by conduction electrons, i. e., target nuclei in degenerated electron plasmas. The screening potentials of the D＋D and Li＋D reactions in such conditions were found out to be very large[2－4]: about 600 eV for D＋D reaction in PdO host, for example. Subsequently, we have tried to prepare another condition of the environment for low-energy nuclear reactions. In the present work, we report on nuclear reactions in liquid Li metal plasmas, for the first

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time, where Li^+ ions are moving freely in a conduction electron sea, and much higher density ($\rho \approx 10^{22}$ ions/cm^3) can be realized than in laboratory gas plasmas.

2 Plasma Properties of Liquid Li

One of the quantites which characterizes plasma is the Wigner-Seits radius, $a_{ws}=(3/4\pi n)^{1/3}$: n is the number density of particles. The radius is 0.17 nm for both the Li^+ ions and the electrons calculated with $n_{Li}=n_e\approx 4.6\times 10^{22}$ electrons/cm^3. The so-called plasma-parameter, $L = h/(2\pi MkT)^{1/2}/a_{ws}$, where M is the mass of particles, is estimated to be 0.1 for the Li^+ ions and 15 for the electrons. The particles with $L\ll 1$ can be considered classical ones, while those with $L\gg 1$ can be considered quantum ones. Therefore, the liquid Li may be regarded as plasma consisting of classical Li^+ ions and quantum electrons. It should be noticed that the number density of particles is much larger than that of gas plasma realized in the laboratory. Thus, the liquid metal plasma in laboratory can realize similar plasma conditions in the core of Jupiter with slightly lower temperature and density.

The present work aims at obtaining the screening potential of the Li + p and Li + d reactions in liquid Li. Since the target Li is surrounded by the conduction electrons in addition to the bound electrons, the screening potential due to both electrons is estimated to be $U_e=3e^2\times(1/\lambda_{be}^2+1/\lambda_{ce}^2)^{1/2}$, where $\lambda_{be(ce)}$ is a screening length due to the bound(conduction) electrons. They are simply estimated to be 24 pm from the adiabatic approximation and 61 pm from the Thomas-Fermi approximation for the bound and conduction electrons, respectively. Thus, the screening potential of 194 eV is expected from the electrons. For the solid Li case, the screening effect is provided only by these electrons, i. e., the screening potential $U_{sol}=194$ eV is predicted.

For the liquid Li, in addition to the electrons, the effect of classical Li^+ ion gas should be considered. In this case, a screening length can be estimated by the Debye model which gives $\lambda_{Li}=6.7$ pm at $T=520$ K; much shorter than those originated from quantum electrons. Thus the screening potential of the Li + p(d) reaction in the liquid Li is estimated to be $U_{liq}=673$ eV; almost 500 eV difference may be expected between the solid and the liquid target.

One of the interesting questions is whether the screening due to positive ions can work effectively or not. Since the mass of ions is much lager than that of electrons, positive ions cannot respond quickly to change, and, hence, the ionic screening might be reduced very much.

3 Experimental Procedure

The experiments were performed by using proton and deuteron beams obtained from a low-energy ion generator at Laboratory of Nuclear Science at Tohoku University. Natural Li (92.4% ^{7}Li, 7.6% ^{6}Li) and enriched ^{6}Li were used for ^{7}Li + p and ^{6}Li + d reactions, respectively. A technique to generate the liquid Li metal target has been developed. A lump of natural Li or enriched ^{6}Li metal was placed horizontally on a small saucer which can be heated up to 500 ℃ in a vacuum chamber. The temperature of the surface of the Li target was monitored directly by a radiation thermometer. The melting point of the Li metal is about 180 ℃; a phase change was easily known by watching the temperature. A beam was injected from the upper part of the chamber, with its angle of 30° with respect to the vertical line. Alpha particles emitted in the ^{6}Li(d, α) ^{4}He and ^{7}Li(p, α) ^{4}He reactions were measured with a Si detector of 300 μm in thickness. A 5 μm thick Al foil covered the detector surface to prevent electrons and scattered beam particles from hitting the detector directly.

Thick target yields of α particles from the ^{7}Li(p, α)^{4}He and ^{6}Li(d, α)^{4}He reactions were meas-

ured for the solid ($T \approx 60$ ℃) and the liquid ($T \approx 250$ ℃) Li target as a function of bombarding energy between 25 and 70 keV by 2.5 keV steps. The beam current was measured from the target, on which a permanent dipole magnet was placed to suppress secondary electron emissions. Its intensity was adjusted for each bombarding energy so as to keep the input beam power constant.

4 Results and Discussion

Observed excitation functions show clear difference for the liquid and the solid target. It turned out that the reaction rates for the liquid Li are always larger than those for the solid one in both the ^{7}Li(p, α)^{4}He and ^{6}Li(d, α)^{4}He reactions. The thick target yield at the bombarding energy E_b is described as

$$Y(E_b) = (\text{const.}) \times \rho_{Li} \int_0^{E_b} \frac{\sigma(E+U_s)}{dE/dx} dE . \quad (1)$$

Here, ρ_{Li} is the number density of Li, dE/dx is the stopping power of Li metal, and $\sigma(E)$ is the cross section of the ^{7}Li(p, α)^{4}He or ^{6}Li(d, α)^{4}He reaction. The enhancement due to the screening potential U_s is expected only at very low bombarding energies. Thus, larger reaction rates for the liquid target observed for $E_{p,d} > 40$ keV are considered mainly due to the reduction of the stopping power in the liquid phase.

In the following preliminary analysis, the density of Li is taken from Ref. [5] and the stopping power for the solid Li is from Ref. [6]. For the cross sections, astrophysical S-factor is taken from Ref. [7] for the ^{7}Li(p, α) ^{4}He reaction and from Ref. [8] for the ^{6}Li(d, α)^{4}He reaction.

Ratios of the reaction rates in the liquid target to the solid are shown in Fig. 1 as a function of bombarding energy per nucleon (E/u). The data plotted with solid squares correspond to the ^{7}Li(p, α) ^{4}He reaction for $E_p > 35$ keV, and solid circles to the ^{6}Li(d, α) ^{4}He reaction for $E_d > 40$ keV. As seen in the figure, the ratio becomes larger and larger as the E/u increases. This surprises us very much, but the phenomena were easily reproduced in the continuous measurement of the yield versus temperature. In such measurements, the yield is suddenly decreased when the target phase is changed from the liquid to the solid.

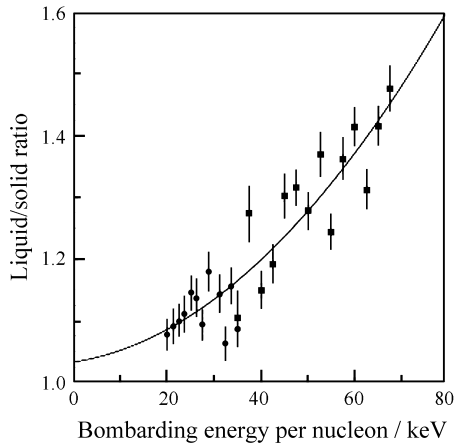

Fig. 1 Ratio of the reaction rates in the liquid to solid phase as a function of E/u. Data plotted with solid squares are from the ^{7}Li(p, α)^{4}He reaction and those with solid circles from the ^{6}Li(d, α)^{4}He reaction.

In Fig. 1, the two data sets are smoothly connected as if described by a function of E/u or velocity of the hydrogen. This indicates that the stopping power of hydrogen ion in the liquid Li metal might be smaller than that in the solid one. In order to compare the screening potential for both in the liquid and solid phase, the stopping power in the liquid Li metal is indispensable. It is, then, deduced empirically so as to reproduce the data in Fig. 1. The stopping power for the liquid target used in the following analysis is $(dE/dx)_{liq} = F(E/u) \times (dE/dx)_{sol}$; the function F is a quadratic function of E/u and is determined to reproduce the solid curve in Fig. 1. The origin of the reduction of the stopping power in the liquid is not known at present. However, we try to deduce the screening potential in the liquid target as well as in the solid target.

We try to deduce the screening potentials of the Li+p and Li+d reactions in the liquid and sol-

id phase. The thick target yields of α particles measured in the ^{6}Li+d reaction are shown in Fig. 2; the left part for the solid Li and the right part for the liquid Li. In the upper part, the thick target yields normalized at 70 keV are plotted as a function of the bombarded energy. In the lower part, the enhancement factor which is the experimental yield divided by that calculated by Eq. (1) with $U_s=0$ is plotted.

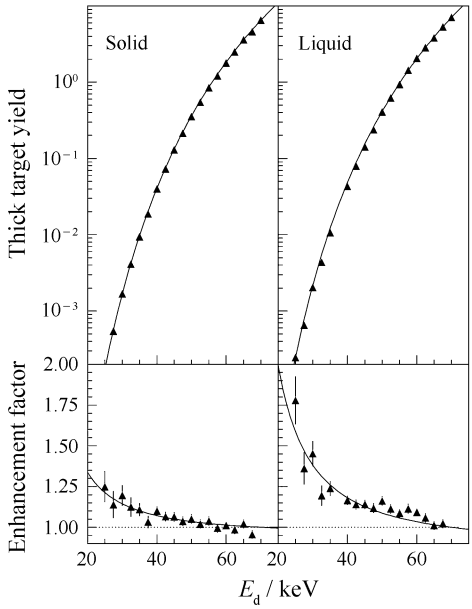

Fig. 2 Thick target yield of a particles emitted in the ^{6}Li(d, α)^{4}He reaction for the solid and liquid target. In the upper part, the data normalized to the yield at 70 keV are plotted. In the lower part, the experimental yields divided by the yield calculated without screening energy are plotted.

It is clear that the reaction rates are more strongly enhanced with the decrease of the bombarding energy, as can be seen in the lower part of Fig. 2. Also noticed is the fact that much larger enhancement is observed in the liquid target. The screening potential U_s of the Li+d reaction is deduced by fitting the calculated yields to the experimental ones. The deduced values are $U_{sol}=(350\pm50)$ eV and $U_{liq}=(900\pm50)$ eV, respectively for the solid Li and the liquid Li. The difference of the screening energies is about 550 eV.

For the ^{7}Li+p reaction, similar results of the screening potential have been obtained. In this case, however, the data only for $E_p<45$ keV are analyzed, because of large uncertainties of the stopping power for higher energy region. The screening energies from the ^{7}Li+p reaction are $U_{sol}=(360\pm100)$ eV and $U_{liq}=(1\,000\pm200)$ eV, respectively for the solid Li and the liquid Li. Again, very large difference between solid and liquid is obtained.

As already discussed, the simple plasma picture gives the screening energies, $U_{sol}=194$ eV and $U_{liq}=673$ eV, respectively, for the solid and the liquid Li metal. The experimental ones deduced in the present analysis gives slightly larger values, $U_{sol}=(350\pm50)$ eV and $U_{liq}=(900\pm50)$ eV. Although the simple plasma picture does not explain well the screening energy for each phase, the difference between the solid and the liquid is well explained. Therefore, we can conclude that the ionic screening mechanism affects the reaction rate very much in the liquid Li metal.

5 Summary

We have investigated the ^{7}Li+p and ^{6}Li+d reactions for bombarding energies between 25 and 70 keV with liquid Li target, for the first time. The effects of the solid-liquid phase transition are clearly seen in the reaction rates. The reaction yield in the liquid phase is always larger than in the solid phase. This observation suggests that the stopping power in the liquid Li is smaller than that in the solid one. Using the data of the yield ratio between the liquid and the solid for $E_b>40$ keV, we have made an empirical correction to the stopping power of the liquid Li.

Screening potentials for the Li+p, d reaction are successfully obtained for the liquid Li as well as the solid one. It turns out that the liquid Li provides much lager screening potential than the solid: the difference is about 500 eV in the present preliminary analysis. This difference is very well

explained by a simple plasma picture of the solid and the liquid Li metal. It can be concluded that the ionic screening is much stronger than the electronic screening in a low-temperature dense plasmas.

References:

[1] Kasagi J, Prog Theor Phys, 2004, 154 (Supp): 365.

[2] Yuki H, J. Kasagi, Lipson A G, *et al*. JETP Lett, 1998, 68: 823.

[3] Kasagi J, Yuki H, Baba T, *et al*. J Phys Soc Jpn, 2002, 71: 2881 .

[4] Kasagi J, Yuki H,Baba T, *et al*. J Phys Soc Jpn, 2004, 73: 608.

[5] Shimizu Y, Mizuno A, Masaki T *et al*., Phys Chem Phys, 2002,4: 4431.

[6] Ziegler J F, Biersack J P, code SRIM, http://www. srim. org.

[7] Engstler S, Raimann G, Angulo C, *et al*., Z. Phys, 1992, A342: 471 .

[8] Lattuada M, Pizzone R G, Typel S, *et al*. Astro J, 2001, 562 : 1076.