Screening Potential for Nuclear Reactions in Condensed Matter

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Abstract

Screening for nuclear reactions in metal plays an important role in enhancing reaction cross sections in the ultra-low energy region. A simple extrapolation of the screening potential down to the thermal energy region from the keV beam experiment predicts the occurrence of "cold fusion" D+D reactions. In the present work, results so far obtained in low-energy beam experiments will be overviewed and the origin of the screening potential will be discussed: both electronic screening and ionic screening. For ionic screening we have studied nuclear reactions in liquid metal which can be regarded as a low-temperature dense plasma. In such a condition, the classical ions contribute to the screening more strongly than the quantum electrons do. Results on the ^{7}Li+p and ^{6}Li+d reactions with liquid Li target will be shown. The effects of the solid-liquid phase transition are clearly seen in these reactions. It can be concluded that the ionic Debye screening is much stronger than the electronic screening in low-temperature dense plasmas.

1. Introduction

It is well known that two miracles are necessary to explain the cold fusion experiments. They are a huge reduction of the Coulomb barrier between two deuterons in metals, and an anomalously large branching ratio of the D+D reaction leading to the γ+X channel (X: energy transfer to the lattice). Such conditions are never realized for the free d+d fusion reaction. The study of nuclear reactions in metals using low-energy deuteron beams gives important information to understand the miracles of cold fusion, especially for the Coulomb barrier between deuterons in metals.

We have been investigating the effects of metal environments acting on nuclear reactions. In the present work, results so far obtained in low-energy beam experiments on the DD fusion reaction will be overviewed. The reaction rates are enhanced much larger than expected in metals. Furthermore, our recent work on nuclear reactions in the liquid phase will be discussed in detail; the reaction rate in the liquid phase is larger than the solid. In the liquid phase both the electronic and ionic screenings enhance the reaction rate very strongly.

Finally, the importance of the large-screen potential for low-energy nuclear reactions in condensed matter will be discussed.

2. Overview of DD reactions in metal

The D+D reaction during implantation of deuterium was measured by detecting neutrons already 30 years ago, but the aim of this research was to determine the distribution, trapping and diffusion of the deuterium implanted in the target. After the "cold fusion" claim in 1989, however, the enhancement of the reaction rates of the D+D reaction in metal has been intentionally searched for in the deuteron implantation by several authors. Roth et al. [1] first reported the reaction rate of the D(d,p)T reaction in Ti as a function of the bombarding energy down to 3 keV and showed that the deduced excitation function is consistent with no enhancement in the cross section. Kasagi et al. [2] measured the thick target yields for the D(d,p)T and D(d,n)^{3}He reaction in Ti for $4.5 < E_d < 18$ keV, and concluded that the excitation function for both channels was explained well with the cross section of the compiled data by Bosch and Hale[3]. Yuki et al.[4] succeeded in measuring the reaction rates at lower bombarding energies down to 2.5 keV, and first deduced the screening energy of the DD reaction in metal, which is a quantitative scale of the enhancement at very low energies, as discussed in the next section. Although the screening energy for the DD reaction in Ti (27 eV) was turned out to be similar to the value deduced for a D_2 gas target (25 eV), that in Yb (80 eV) was clearly lager as seen in the enhanced reaction rate of about 1.5 times at 3 keV. This is the first clear evidence that the fusion reaction rate can be enhanced in the metal environment during keV deuteron bombardment.

In subsequent experiments, anomalously large values of screening energy was found for PdO (600 eV), Pd (310 eV) and Fe (200 eV).[5] In this case, the reaction rate for PdO at $E_d = 2.5$ keV became about 100 times of the normal rate. Such large screening energies of the DD reaction were found also in other materials by another group. Czersky et al.[6] has reported enhanced screening energy of the DD reactions in Ta; it was about 300 eV, and was confirmed by Raiola et al.[7] Raiola et al. have carried out a systematic measurement of the screening potentials of the DD reaction for a wide range of host materials including metals, semiconductors and insulators,[8] and claimed that the large screening in metals can be interpreted by the Debye screening based on their measurement of the temperature dependence of the screening potential.[9] However, this interpretation contradicts the fact that the conduction electrons are degenerated Fermi particles which obey the Thomas-Fermi distribution. Thus, there might be some problems to be overcome experimentally, such as how to fix the deuterium density in metal during the bombardment, as pointed out by Huke et al.[10].

The screening energy for the deuteron in metal was also theoretically studied. Ichimaru et al.[11] suggested that hydrogen nuclei in metal are strongly screened, since the electrons both in metallic d-band and hydrogen induced s-band can contribute to the screening effect. They calculated the effective static potential for hydrogen in Ti and Pd, and proposed that the screening distance between two hydrogen nuclei in metal is much shorter than that of atomic hydrogen. The calculated screening energy is 51 eV for Ti and 75 eV for Pd and cannot explain the large enhanced reaction rate at all. Czersky et al.[12] calculated the screening energy for the DD reactions in metal by applying a dielectric functional method which allows to treat the electron screening as a static polarization of the metallic medium induced by the positively

charged deuteron. Their results including the cohesion effects give clearly larger values of the screening energy in the metal environment, for example, about 130 eV for Pd, but less than half of the observed values.

Thus, one can summarize the present situation as follows: The low-energy DD reactions are enhanced very much when the reaction occurs in a metal environment. The mechanism of the enhancement is not fully understood, especially for the environment which provides screening energy of a DD reaction of more than 200 eV. All these arguments motivate further studies of screening due to positive charge ions which can move almost freely.

3. Liquid Li + p,d reactions

Liquid Li may be regarded as a plasma consisting of classical Li^+ ions and quantum electrons, and it has a much higher density ($\rho \sim 5 \cdot 10^{22}/cm^3$) than can be realized in laboratory gas plasmas. In a low-temperature dense plasma, the classical ions contribute to the screening more strongly than the quantum electrons do, because of a difference of the mean kinetic energy of the particles under equilibrium conditions. Since the mass of ions is much larger than that of electrons, the positive ions cannot respond quickly. For this reason, it is claimed that the ionic screening is reduced in stellar plasmas [13], while there is a strong assertion that the ionic screening is applicable to stellar plasmas [14]. Therefore, one of the interesting questions is whether or not the screening due to positive ions can work effectively. The present study of nuclear reactions in liquid Li may provide a good testing ground for the screening effect due to the positive ions in dense plasmas.

The experiments were performed using proton and deuteron beams obtained from a low-energy ion generator at the 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°C 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°C; a phase change was easily confirmed 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.
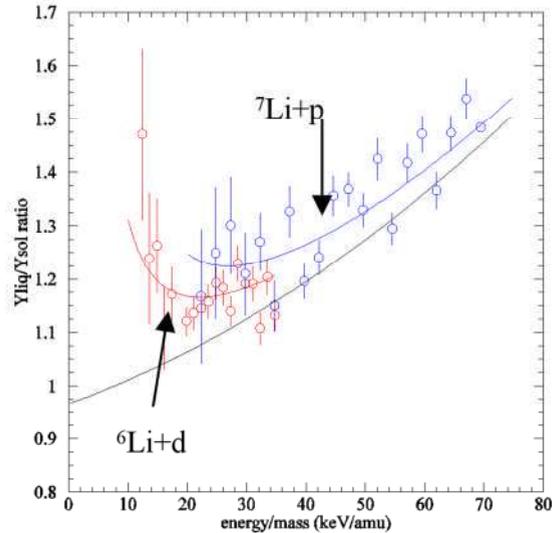
Figure 1. Ratio of α particle yield for the liquid target to that for the solid, plotted as a function of bombarding energy per nucleon. Red squares show the data of the 6Li(d,α)4He reaction and blue circles show those of the 7Li(p,α)^{4}He reaction.

Thick-target yields of α particles from the ^{6}Li(d,α)^{4}He and ^{7}Li(p,α)^{4}He reactions were measured for solid (T～330 K) and liquid (T～520 K) Li targets as a function of bombarding energy between 22.5 and 70 keV in 2.5 keV steps. We measured the beam current on the target, around which a permanent dipole magnet was placed to suppress secondary electron emission. The beam intensity was varied for each bombarding energy level so as to keep the input beam power constant. Since Li combines easily with hydrogen (deuterium) to become LiH (LiD), the target surface was cleaned every 2 hours during the bombardment by a wiper attached to the chamber. Furthermore, the α particle yield at E_p = 70 keV (E_d = 60 keV) was measured at frequent intervals to check on any change in the target condition.

Observed excitation functions show a clear difference for the liquid and the solid target. In Fig. 1, we show ratios of the reaction rates in the liquid target to the solid as a function of E/mass (keV/AMU); red circles are for the ^{6}Li(d,α)^{4}He reaction and blue circles for ^{7}Li(p,α)^{4}He. As seen, the reaction rates for the liquid Li are always larger than those for the solid in both the ^{7}Li(p,α)^{4}He and ^{6}Li(d,α)^{4}He reactions. Except for the very low energy region, two sets of data are connected smoothly, and one may say that the ratios are well scaled by E/M, that is, by velocity. This suggests that stopping power is a significant part of phenomena seen in Fig, 1. Stopping power is different in the liquid and solid phases; it is smaller in liquid Li than in solid Li. This smaller stopping increases the projectile path length and, therefore, the effective target thickness.

For the following analyses, we define and approximate the reduced yield and yield ratio for the thick target method as follows. This approximation works here to better than 2% accuracy.

$$Y_{red}(E_b) \equiv Y_{exp}(E_b) / \int_0^{E_b} \frac{d\Omega_{cm}}{d\Omega_{lab}} \sigma_{bare}(E) \ dE \cong (const) \exp\left(B\sqrt{\mu}\frac{U_s}{E_{cm}^{3/2}}\right) \cdot S^{sol(liq)}(E_b) \qquad (1)$$

$$\frac{Y_{liq}}{Y_{sol}} = \frac{N^{liq}}{N^{sol}} \exp\left(B\sqrt{\mu}\frac{\Delta U_s}{(E_{cm})^{3/2}}\right)\frac{S^{sol}}{S^{liq}} \cong \frac{N^{liq}}{N^{sol}} \exp\left(B\sqrt{\mu}\frac{\Delta U_s}{(E_{cm})^{3/2}}\right) \cdot \left(0.98 + b_1\left(\frac{E_b}{m}\right) + b_2\left(\frac{E_b}{m}\right)^2\right). \quad (2)$$

Here, $d\Omega_{cm}/d\Omega_{lab}$ is the solid angle ratio of the cm to the laboratory (lab) system, $\sigma_{bare}(E)$ is the reaction cross section for bare nuclei, $E_{b(cm)}$ is the bombarding (cm) energy, S is the stopping power for the incident beam, m is the reduced mass of target and projectile nuclei, and ΔU_s is the difference of the screening potential ($U_{liq} - U_{sol}$). For the stopping power of the liquid Li we made a correction based on the stopping power of the solid. In eq. 2, the ratio of the stopping power for the solid to the liquid is simply assumed as a quadratic function of E/m, and b_1 and b_2 are parameters to be determined so as to give a best fit to the experimental ratios. For $\sigma_{bare}(E)$, the astrophysical S-factors are taken from ref. [15], because they agree with the values obtained recently by the so-called Trojan horse method [16] which may give the S-factor free from the Coulomb effect in the initial channel.

In Fig. 2, we show the reduced yield of the ^{6}Li(d,α)^{4}He as a function of the bombarding energy for the solid and liquid Li target, respectively, in the upper and lower graph. In order to obtain the screening potential together with the stopping cross section from the data in both phases, the values of the parameters in eqs. 1 and 2, U_{sol}, U_{liq}, b_1 and b_2, are searched for so as to give the best fit to the data in Figs. 1 and 2. The resulting values (preliminary) of the screening potential were $\Delta U_s = 300\pm30$ eV, and $U_{sol} = 400\pm50$ eV and $U_{liq} = 700\pm60$ eV. The solid curves through the red and blue circles in Figs. 1 and 2 are the fits. The black solid curve in Fig. 1 shows the liquid/solid yield ratio due to the difference of the stopping power in both phases.

Thus, one may say that it is established experimentally that the screening potential for the liquid phase is very large: larger than for the solid phase by about 300 eV or about 1.75 times the solid value. Thus, a stronger screening from the ionic fluid is clearly shown in the present work.
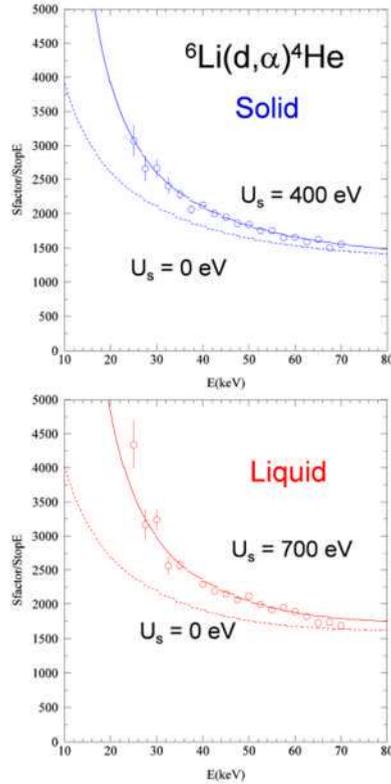
Figure 2. Reduced yield for the 6Li(d,a)4He reaction in the solid phase (upper graph) and the liquid (lower).

For the solid Li, the screening originates only from the electrons, i.e., the bound and conduction electrons. The electronic screening from both may be described by $U_e = 3e^2 \times (1/\lambda_{be}^2 + 1/\lambda_{ce}^2)^{1/2}$, where $\lambda_{be(ce)}$ is a screening length due to the bound (conduction) electrons. The screening potential due to the bound electrons is estimated to be 186 eV as the adiabatic limit value [15], which gives $\lambda_{be} = 23.2$ pm. The Thomas-Fermi screening approximation [17] applied to the conduction electrons gives $\lambda_{ce} \sim (E_F/(6\pi e^2 n_e))^{1/2} = 61$ pm (E_F is the electron Fermi energy and n_e is the electron number density). Thus, the screening potential of the solid Li is expected to be $U_{sol} = U_e = 194$ eV, a value which is about 200 eV smaller than the present result. The discrepancy has already been pointed out for the bound electrons, i.e., for the screening potential measured with a LiF target (~ 340 eV) [15]. The larger value of U_{sol} found here might mean that the screening energy of the bound electrons is not explained well, since the estimated contribution from the conduction electrons is only 1/8 that of the bound electrons.

For liquid Li, the ionic screening should be included. Since the mobile Li^+ ion can be treated as a classical particle, the screening length is estimated with the Debye screening model, which gives $\lambda_{ion} \sim (kT/(4\pi e^2 n_{Li}))^{1/2} = 6.7$ pm at T = 520 K; much shorter than lengths originating from the degenerate quantum electrons. The screening potential due to the Li^+ ion alone is, then,

estimated as $U_{ion} = 3e^2/\lambda_{ion} = 645$ eV. As a consequence, the screening potential of the liquid Li, again using $U_e = 194$ eV, should be $U_{liq} = (U_e^2 + U_{ion}^2)^{1/2} = 673$ eV. Although the prediction is quite close to the experimental value (700 eV), the experimentally deduced value of U_{ion} is 580 eV, slightly larger than the prediction.

Summary

In the past ten years, the strong enhancement of the reaction rate for D+D reactions in metals has been independently observed in low-energy beam experiments by three groups. Although the values of the screening potentials of the D+D reaction obtained for the various host metals do not completely agreed with each data set, we can conclude that the large screening mechanism exists for the D+D reaction in metals. The origin of the large screening potential, for example, 300 eV or more deduced for the Pd host, is not yet understood. Probably, electronic screening due to the conduction electrons can contribute to 200 eV together with the cohesion effects. It should be noted here that one of the miracles of cold fusion is no longer miraculous from an experimental point of view, although the mechanism has not been revealed.

In order to study the effects of positive ions on the screening, we have investigated the ^{7}Li+p and ^{6}Li+d reactions with a 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 not only the screening potential but also the stopping power in the liquid Li is different from those in the solid. Using the data of the yield ratio between the liquid and the solid we have deduced an empirical correction factor for the stopping power between the liquid and solid Li.

Screening potentials for the Li+p,d reaction are successfully obtained for the liquid Li as well as the solid. It turns out that the liquid Li provides much lager screening potential than the solid: the difference is about 300 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 low-temperature dense plasmas. The present observation of the screening in the liquid phase is very important to understand the mechanism of the large screening of the D+D reaction in metals. For example, if deuterons in Pd metal behave like liquid, then the screening effect of D$^+$ ions should be considered; the screening potential would be much larger than the electronic screening alone.

Acknowledgements

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