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Research Article

Screening Energy of the d+d Reaction in an Electron Plasma Deduced from Cooperative Colliding Reaction

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Abstract

We have measured protons and tritons from the d (d,p) t reaction in liquid In, Sn, Pb and Bi during the D_3^+ molecular deuterium beam bombardment for $15 < E < 60$ keV. Observed energy spectra and yield excitation functions are anomalous and suggest that the target deuteron is also in motion. It is found that the reaction mechanism is unique to the molecular beam in such a way that one deuteron in a molecule is elastically scattered by a host metal atom and then it collides with the other to cause the d+d reaction. We call it as the cooperative colliding mechanism (CCM). Experimental data are compared with the CCM calculation and values of the screening energy of the d+d reaction are deduced. They are 380 ± 80, 570 ± 80, 670 ± 100 and 490 ± 100 eV for In, Sn, Pb and Bi, respectively. It is concluded that the screening energy of the d+d reaction in an electron plasma in metal is really large: the averaged value of 530 eV is more than ten times larger than the simple Thomas–Fermi screening prediction.
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Keywords: Cooperative colliding mechanism, DD reaction in metal, Liquid metal, Low-energy deuteron beam, Screening potential

1. Introduction

Conduction electrons in metal behave as a Fermi plasma with low temperature ($T<10^3$ K) and high density ($\rho \sim 10^{22}$/cm^3). The interaction between two deuterons under such an electron plasma is very much different from that of naked deuterons. Obviously, the interaction potential between the two nuclei may be characterized by a large reduction of the repulsive Coulomb part. Consequently, the nuclear reaction rate in low energies may be enhanced by many orders of magnitude. Thus, it is very important to study low-energy d+d reactions in a metallic electron environment in order to predict the reaction rate of nuclear fusion. Such environments include cold fusion in metal, nuclear fusion in high-density plasma as well as nuclear synthesis and energy productions in stars.

Up to the present, the screening potential of the d+d reaction in the various metals has been measured [1–3]. However, the deduced values are anomalously larger than expected; at least several times larger than theoretical predictions using the Thomas–Fermi approximation. Huke et al. [4] discussed the experimental difficulties in deducing

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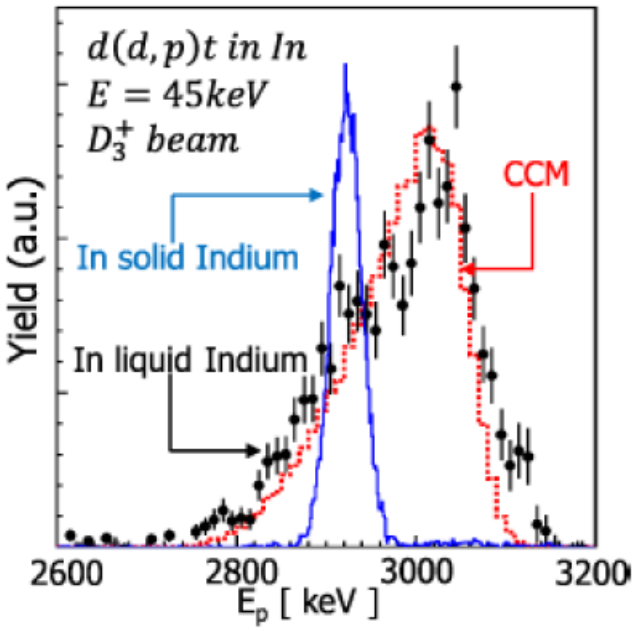

Figure 1. Energy spectra of the d (d,p) t proton measured at θ = 142° for 45 keV D_3^+ beam bombardments. Solid circles show the one for the liquid In, while the solid blue line for the solid In. the dotted red line shows calculated one based on CCM.

the screening potential of the d+d reaction in metal: most of the uncertainty originates from the target deuteron density distribution as well as the surface cleanness. Although experiments have been performed to minimize such systematic errors, it is highly desirable to know the target deuteron density more accurately.

We have developed nuclear reactions in liquid metal in order to explore another environment which enhances the reaction rate more. In the present work, we bombarded liquid In, Sn, Pb and Bi with a D_3^+ molecular beam and found a new reaction mechanism, which is unique to the molecular beam and is called the cooperative colliding mechanism (CCM). It turned out that the CCM is very useful for determining the screening potential of the d+d reaction without the uncertainty of the target deuteron density. The screening potential in the liquid metals is determined by using the CCM, for the first time.

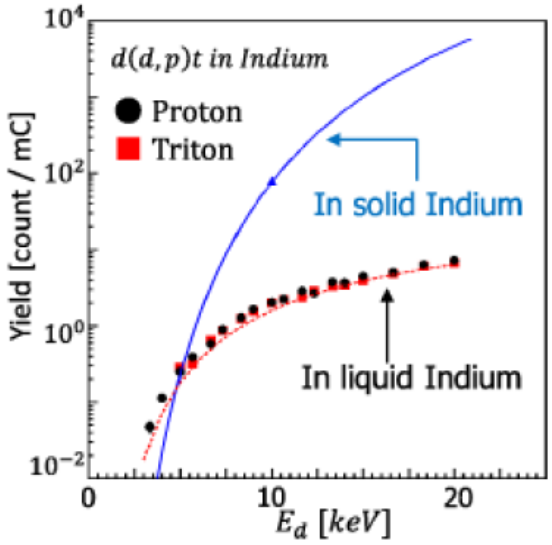

Figure 2. Excitation functions of the protons and the tritons by D_3^+ beam bombardment at θ = 142°. Solid circles and solid squares show the yield of the protons and that of the tritons for the liquid In, solid blue line shows the yield of the protons for the solid In, a dotted red line shows calculated one based on CCM, respectively.

2. Experimental Setup

The experiment was performed by using a low-energy deuteron beam from the high-current ion beam generator [5] at the Research Center for Electron Photon Science of Tohoku University. The experimental procedure is almost the same as described in our previous work [6], and will be briefly mentioned here.

The low-energy D_3^+ beam of several 10 μA was mostly used with bombarding energies ranging from 10 to 60 keV, corresponding to 3.3–20 keV for single deuteron. The beam was vertically bent by 60° with respect to the horizontal and injected into the target chamber from an upper port. The pressure in the target chamber is kept 10^{-5}–10^{-6} Pa. Inside the chamber, the beam passes through a 6-mm-diameter aperture and collides with a liquid target which is placed in the target holder equipped with a heater. For the liquid metal targets, In, Sn, Pb and Bi were, respectively, heated up to 200–380°C (T_m: 156.6°C), 360–390°C (T_m: 231.9°C), 380–410°C (T_m: 327.5°C) and 325–355°C (T_m: 211.5°C). During the measurement, the beam current was measured by inserting a Faraday cup for periodic sampling at a rate that was controlled by a data acquisition program (3-second sampling in every 10 s). The charged particles emitted during beam bombarding were detected with a silicon semiconductor detector (SSD). The SSD had an active area of 450 mm^2 and thickness of 100 μm, and was placed at 124° and 142° with respect to the beam direction and 30 mm away from the target. A 2-μm-thick Al foil was placed in front of the SSD to stop elastically scattered deuterons and sputtered particles. The energy resolution for this setup was about 55.1 keV in FWHM for 2.96 MeV protons.

3. Experimental Results

Protons and tritons emitted from the d (d,p) t reaction were measured in various conditions: with liquid and solid target; with two detection angles at 124° and 142°, bombarding energies from 10 to 60 keV by 2.5 keV steps with D_3^+ beams (i.e., from 3.3 to 20 keV for a single deuteron), and beam currents from a few μA to about 100 μA. In addition, D_2^+

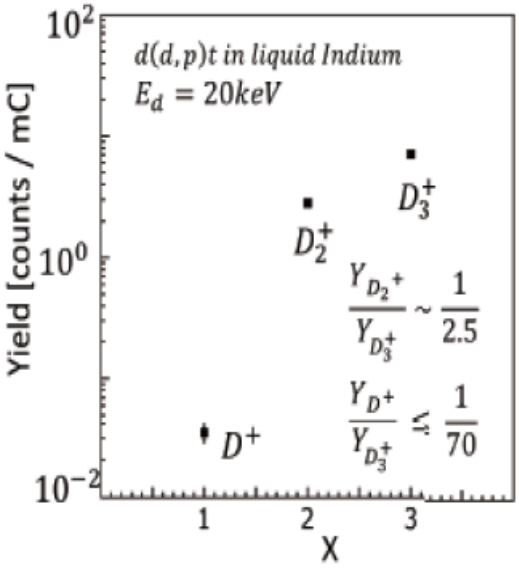

Figure 3. The proton yields versus the number of deuterons (X) in a deuterium molecular of the beam (D_X^+) bombarding the liquid In.

and D^+ beams were also used to bombard the liquid In.

The energy spectrum of protons from the d (d,p) t reaction measured for the liquid In by D_3^+ beam bombardment is plotted in Fig. 1 with solid circles, which is compared with the one for the solid In plotted with a solid blue line. As seen, the spectrum for the liquid In target is quite different from the one for the solid. Usually, deuterons impinging upon the material play a double role, i.e., projectiles and targets of the d+d reaction. In this case, target deuterons are usually at rest and distributed from the surface.

For the solid In, the spectrum having a sharp peak structure can be well reproduced by a kinematical calculation for such a condition. Thus, we can say that the spectrum for the liquid is quite different from the usual one. The observed shape is very broad and largely skewed. Moreover, the peak position shifts to the higher energy side as compared with the normal spectrum for the solid In. The triton spectrum for the liquid In also shows the same characteristics.

The excitation function measured for the liquid In are shown in Fig. 2, where solid circles and squares show the yield of protons and tritons, respectively. A solid line shows a function $Y \propto \exp(-B/\sqrt{E_\mathrm{d}})$ with $B = 44.39$, which is known to approximate the energy dependence of the thick-target yield of the d (d,p) t reaction. The solid line which is normalized to the experimental yield at E_d = 10 keV well reproduces the other one at $E_\mathrm{d} = 5$ keV. Thus, the excitation function of the yield for the solid In can be well explained as the normal d+d reaction, while the excitation function for the liquid In cannot. The yield for the liquid decreases much more slowly with decrease of incident energy than the one for the solid does.

Figure 3 shows the proton yields versus the number of deuterons (X) in a deuterium molecular beam (D_X^+) bombarding the liquid In. The yield depends on X very strongly: the yield of the d+d reaction almost diminishes to nothing when bombarded by an atomic beam (D^+). This suggests that the anomalous behavior of the d (d,p) t reactions in the liquid In should be related with the use of the molecule beam.

4. d+d Cooperative Collision in Liquid Metal

The anomalous features seen in energy spectra as well as in the excitation function strongly indicate that the target deuteron of the d (d,p) t reaction is not at rest but is in motion with a finite momentum. As a result of spreading of the collision energy, the energy of emitted particles spreads widely and the excitation function becomes less steep. Since these phenomena are observed only for the molecular beams, we have inferred that two deuterons in the same molecule collide to cause the d (d,p) t reaction. Figure 4 shows a schematic presentation of this process. In this case, the reaction proceeds by two steps: First, one deuteron in a molecule is elastically scattered by an In atom, and then, it collides with the other deuteron. Since the reaction occurs with the partner in the same molecule, kinematical variables of the secondary d (d,p) t reaction depends only on the scattering angle of the elastic scattering In(d,d)In. This process is called the cooperative colliding mechanism (CCM). We do not see the normal d (d,p) t reaction in the liquid In for the reason that deuterons diffuse quickly in the liquid In due to the lack of the lattice structure so that target deuterons for the subsequent deuterons scarcely exist at the surface region of the liquid.

The reaction yield is essentially a product of two factors: the probability of the elastic scattering In(d,d)In and that of the d (d,p) t reaction. When the deuteron A scattered by In within the small solid angle $\mathrm{d}\Omega_\mathrm{A}$ at the angle of $(\theta_\mathrm{A},\phi_\mathrm{A})$, the proton yield measured at the angle of $(\theta_\mathrm{lab},\phi_\mathrm{lab})$ is expressed as

$$\mathrm{d}Y(\theta_\mathrm{lab},\phi_\mathrm{lab}) = I_\mathrm{d}\rho_\mathrm{In}\mathrm{d}x\frac{\mathrm{d}\sigma_\mathrm{R}}{\mathrm{d}\Omega_\mathrm{A}}(E_\mathrm{d},\theta_\mathrm{A},\phi_\mathrm{A})\,\mathrm{d}\Omega_\mathrm{A}\times N_\mathrm{d}\frac{\mathrm{d}\sigma_\mathrm{dd}}{\mathrm{d}\Omega_\mathrm{CM}}(E_\mathrm{CM},\theta_\mathrm{CM},\phi_\mathrm{CM})\frac{\mathrm{d}\Omega_\mathrm{CM}}{\mathrm{d}\Omega_\mathrm{lab}}\Delta\Omega_\mathrm{lab}. \quad (1)$$

where I_d is the number of beam deuterons, ρ_In the number density of In, $\mathrm{d}x$ the thickness of the liquid In (x the distance from the surface), $\mathrm{d}\sigma_\mathrm{R}/\mathrm{d}\Omega_\mathrm{A}$ the cross section of the first In(d,d)In scattering, E_d the deuteron incident energy, N_d the number of the target deuterons/(unit area), $\mathrm{d}\sigma_\mathrm{dd}/\mathrm{d}\Omega_\mathrm{CM}$ the cross section of the d (d,p) t reaction at the energy of E_CM in the center of mass (CM) system, θ_CM and ϕ_CM stand for the angle of emitted protons in the CM system, $\mathrm{d}\Omega_\mathrm{CM}/\mathrm{d}\Omega_\mathrm{lab}$ the ratio of the solid angle, and $\Delta\Omega_\mathrm{lab}$ is the solid angle subtended by the detector. It should be noted that the following relations can be easily deduced because of the CCM; $E_\mathrm{CM} = E_\mathrm{d}(1-\cos\theta_\mathrm{A})$ (by neglecting the recoil of In) and $N_\mathrm{d} = (X-1)/2\pi R_\mathrm{dd}^2$ (X is the number of deuterons in a molecule and R_dd is the bond length of the molecule ion).

5. Screening Energy deduced from the CCM d+d Reaction

For the calculations, we use the screened Rutherford scattering cross section for $\mathrm{d}\sigma_\mathrm{R}/\mathrm{d}\Omega_\mathrm{A}$ and $\mathrm{d}\sigma_\mathrm{dd} = \mathrm{d}\Omega_\mathrm{CM}$ is calculated from the astrophysical S factor and angular distributions reported in [7]. In Eq. (1), E_d and I_d are not constants but decrease as x increases. Thus, we divide the liquid target into thin layers and calculate the energy and the

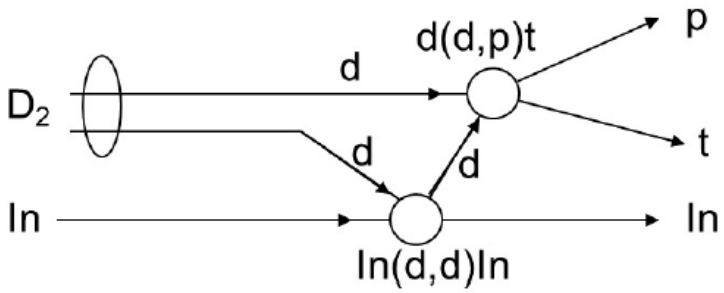

Figure 4. Schematic presentation of CCM causing the d+d reaction. Both deuterons are from the same molecule.

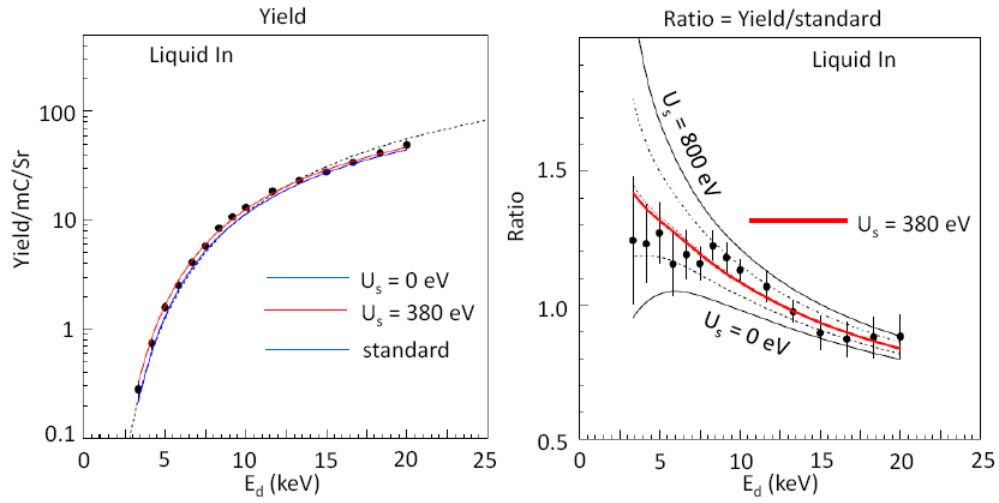

Figure 5. Excitation function of proton yields measured for the liquid In target. The left-hand side figure shows raw yields vs incident energy per deuteron. On the right-hand side figure, the yields are divided by a standard analytical function $S(E_\mathrm{d}) = A \exp\left(-B/E_\mathrm{d}^{1/2}\right)$. The CCM calculations are shown by several lines corresponding to different screening energies of from 0 to 800 eV.

flux loss for each layer. The calculation based on the CCM is compared with the experimental data. In Fig. 1, we show the calculated proton spectrum with the red dotted line. The anomalous features of the spectrum are well reproduced by the calculation. The excitation function of the proton yield for the liquid In target is compared in Fig. 5.

In the liquid metals, the d (d,p) t reaction occurs in a sea of the conduction electrons of the liquid metal. Thus, we introduce the screening energy U_s and simply replace E_d in

$$\frac{\mathrm{d}\sigma_\mathrm{dd}}{\mathrm{d}\Omega_\mathrm{CM}}(E_\mathrm{d}) \text{ as } \quad E_\mathrm{d} + U_\mathrm{s}, \quad \text{i.e.,} \quad \frac{\mathrm{d}\sigma_\mathrm{dd}}{\mathrm{d}\Omega_\mathrm{CM}}(E_\mathrm{d} + U_\mathrm{s}).$$

In the left-hand side figure, the excitation function of raw yields are plotted. Although the calculation with $U_\mathrm{s} = 380$ eV gives the best fit to the data, it is not so clear in this plot. In the right-hand side figure, we show the yields divided by a standard analytical function $S(E_\mathrm{d}) = A \exp(-B/E_\mathrm{d}^{1/2})$; $A = 2500$ (In and Sn), 3700 (Pb and Bi), and $B = 17$ for all. They are compared with calculations for various values of U_s. The curves shown are the CCM calculations with U_s from 0 to 800 eV by 200 eV steps. It is clear that the experimental yields are enhanced over the calculation without the screening, and $U_\mathrm{s} = 380 \pm 50$ eV is determined for the d+d reaction in conduction electrons in liquid In.

Plots of the ratio vs E_d of the present work are shown in Fig. 6. Obtained values of the screening energy are 480 ± 80, 620 ± 80, 700 ± 100 and 540 ± 100 eV for In, Sn, Pb and Bi, respectively. It should be noticed that the values of the screening energy deduced from the CCM d (d,p) t reaction are more reliable than those from the normal d (d,p) t reaction in solid metals, because the number of the target deuterons can be known more precisely. Raiola et al. [9] reported the values of the screening energy for the same metals; they are 520 ± 50 (In), 130 ± 20(Sn), 480 ± 50 (Pb) and 540 ± 60 (Bi) eV. Except for In, the presently deduced values are larger than the previously reported ones. Thus, it is concluded that the screening energy of the d+d reaction in an electron plasma in metal is really large. However, this large screening effect cannot be explained by the Thomas–Fermi screening model; the present averaged value $U_\mathrm{s} = 570$ eV is more than ten times larger than the Thomas–Fermi screening prediction. Czerski et al. [8]

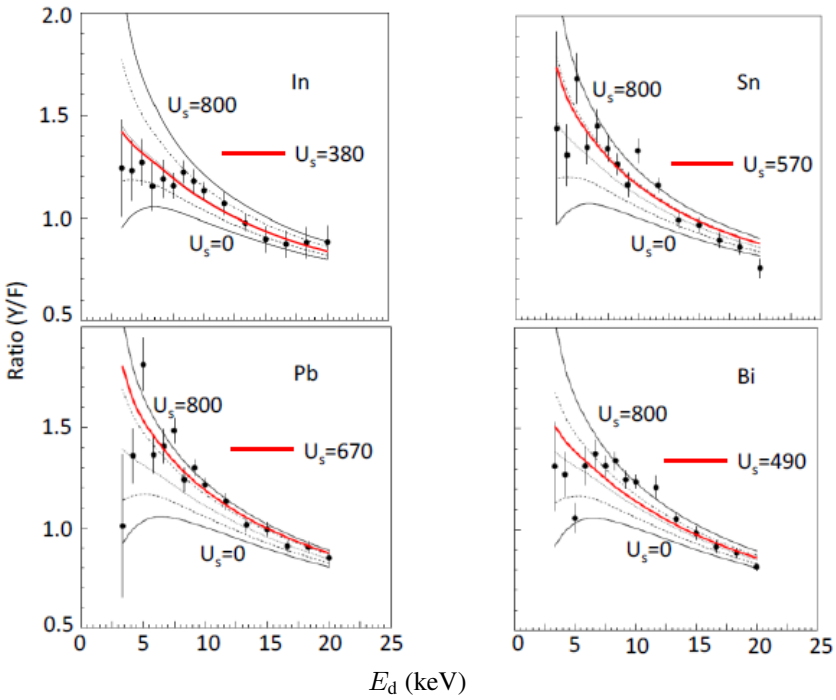

Figure 6. Plots of ratio (yield/$S(E_{\rm d})$) vs deuteron energy for In, Sn, Pb and Bi. Curves are the CCM calculations. The red curve corresponds to the deduced $U_{\rm s}$ value.

calculated the screening energy including the cohesive effect, but their reported values are still 400 eV smaller than the experimental values.

6. Conclusions

We have found a new reaction process called the cooperative colliding d+d reaction in liquid metal bombarded with low-energy D_3 molecular beam. The CCM d+d reaction has turned out to be useful in measuring the screening energy of the d (d,p) t reaction in conduction electrons in liquid metals. Using the CCM reaction, we have established that d+d reactions are really enhanced in conduction electrons; obtained values of the screening energy are 480 ± 80, 620 ± 80, 700 ± 100 and 540 ± 100 eV for In, Sn, Pb and Bi, respectively. It should be emphasized that the values of the screening energy presently deduced are more reliable than those from the normal d (d,p) t reaction in solid metals.

The obtained large screening energy of $U_{\rm s} \sim 570$ eV would give huge reaction cross section of about 100 pb at the room temperature in metals, if a simple extrapolation could be made. This enables the formation of ^{4}He* with the rate of $\sim 10^{10}$/cm^3/s. (The energy dissipation mechanism from ^{4}He* is another issue.)

The mechanism to give such a large $U_{\rm s}$ is unknown. If conduction electrons in metals behave as classical gas, then the screening energy can be 600 eV for 2×10^{23} electrons/cm^3. However, they are low-temperature Fermi particles following the Fermi statistics. In this case, we need 10^6 larger electron density than the normal one, in order to explain the large screening energy. Cohesive effects (d+d)→(dd) in dense electrons should be understood more deeply.

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