# D + D reaction in metal at bombarding energies below 5 keV

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**Abstract.** In order to study the electron screening effect on low-energy nuclear reactions in metals, the D + D reaction in Ti and Yb was investigated. Yields of protons emitted in the D(d, p)T reactions from the deuteron bombardment of Ti and Yb thick targets with bombarding energies between 2.5 and 7.2 keV were measured. The obtained yields were compared with those predicted by using the parametrization of cross sections at higher energies. It was found that the reaction rates in metals are enhanced over those of the bare nuclei for $E_d < 5$ keV, and the enhancement can be interpreted as caused by the electron screening. The electron screening potentials in Ti and Yb are deduced to be $19 \pm 12$ eV and $81 \pm 10$ eV, respectively.

## 1. Introduction

Nuclear reactions at low energies have been studied to understand the nucleosynthesis of elements in the universe and the generation of energy in fusion reactors. As the cross section of fusion reaction drops nearly exponentially at energy far below the Coulomb barrier, it becomes difficult to measure the cross section with decreasing energy [1]. Thus, the cross sections at very low energies are usually extrapolated from those at higher energies. In this extrapolation it is assumed that the Coulomb potential of the target nucleus as seen by the projectile is that resulting from bare nuclei. However, for nuclear reactions studied in the laboratory the targets are usually in the form of atoms or molecules, and atomic (or molecular) electron clouds surrounding the target nucleus effectively reduce the Coulomb barrier. This in turn leads to a higher cross section $\sigma_s(E)$, than would be the case for bare nuclei $\sigma_b(E)$. $\sigma_s(E)$ can be expressed as $\sigma_s(E) = \sigma_b(E + U_e)$ with the electron screening potential $U_e$. In fact, recently reported experiments showed the non-negligible effects caused by the bound electrons in low-energy reactions with solid or gas targets [2]. Greife *et al* [3] reported the measurement of the D + D reactions with gas targets at centre-of-mass energies down to 1.6 keV and obtained a screening potential of $25 \pm 5$ eV, but this value is larger than a value of 14 eV expected theoretically from atomic physics.

One might expect much stronger effects when the nucleus is embedded in different materials [4]. Ichimaru *et al* [5] suggested that hydrogen nuclei in metals 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 hydrogens in metal is much shorter than that of atomic hydrogen. Kasagi *et al* [6] measured the reaction rate of the D + D reactions in Ti for bombarding energies $E_d$ between 4.8 and 18 keV. The obtained thick target yields are well explained with the cross section deduced from the gas target experiment. Thus, for the D + D reactions in metal, experiments with much lower energies and with good statistics are highly desirable to observe the screening effects of metallic electrons.

Recently, we have started a series of experiments to study the nuclear reactions in metal with much lower energies. So far, we measured the reaction rate of the D + D reaction in Ti [7]. In this report, we show the results on the D + D reaction in Yb, together with the previous ones.

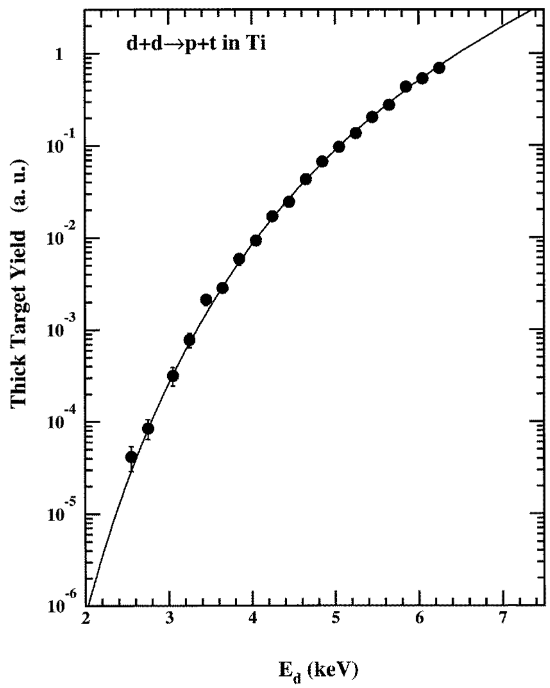


**Figure 1.** Yield of the D(d, p)T reaction occurring in a thick Ti metal target as a function of the deuteron bombarding energy. Data are normalized to the yield at 6.45 keV. A full curve shows a thick target yield calculated with the bare cross section.

## 2. Experimental procedure

Since experimental details have been described in [7], here we briefly show the experimental procedure. Deuteron beams, which are extracted from the low-energy high-current ion beam generator with energies between 2.5 and 7.5 keV, were used to bombard metals. Targets were thick plates of Ti (10 mm × 30 mm × 2 mm) and Yb (10 mm × 10 mm × 1 mm). In Ti plate, deuterium gas was absorbed beforehand by the method which is described in [8]. In Yb plate, a deuteron beam was implanted at $E_{\mathrm{d}} = 6.45$ keV for a long time until proton yield became almost constant. A liquid nitrogen trap was set at the scattering chamber and no carbon build-up on the target was observed.

In order to detect the protons emitted in the D(d, p)T reactions, a $\Delta E - E$ counter telescope consisting of 50 $\mu$m and 200 $\mu$m thick Si surface barrier detectors was employed, since a spectrum measured with a single Si detector was found out to contain much electrical noise at low bombarding energies. A requirement of a coincidence between two Si detectors almost completely reduced the electrical noise.

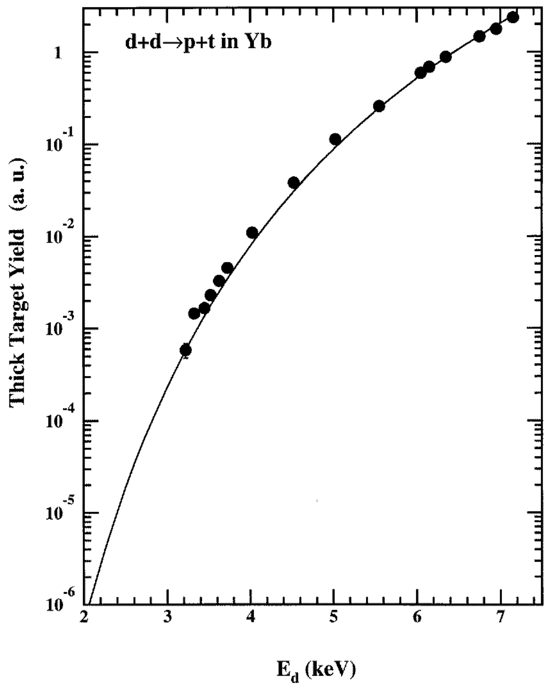


**Figure 2.** Yield of the D(d, p)T reaction occurring in a thick Yb metal target as a function of the deuteron bombarding energy. Data are normalized to the yield at 6.45 keV. A full curve shows a thick target yield calculated with the bare cross section.

The total dose of the deuteron beam for each run was deduced from the electric current from the target, which might depend on the bombarding energy since an amount of secondary electron emission from the target may depend on the energy. Thus, the electric current was also measured with a Faraday cup and was compared to the target current. Ratios of the current from the target to that from the Faraday cup were found to be quite constant for $2.45 \leqslant E_\mathrm{d} \leqslant 7.95$ keV; they fall between 1.02 and 1.06. The target current was about 500 $\mu$A at $E_\mathrm{d} = 6.45$ keV and 100 $\mu$A at $E_\mathrm{d} = 2.55$ keV.

In this experiment, the difficulty is to determine the number of target deuterons in the D + D reaction. Since the deuterons are accumulated in metal plate during the deuteron bombardment, the number of target deuterons changes. In the present work, the yields of protons at $E_\mathrm{d} = 6.45$ keV were frequently measured during the run; for example, the yields at $E_\mathrm{d} = 6.45$ keV were measured every 2 mC of the beam charge accumulation for 200 mC of the total bombardment at $E_\mathrm{d} = 2.55$ keV. The measured thick target yields per the dose of the beam were normalized to the yield at $E_\mathrm{d} = 6.45$ keV.

## 3. Experimental result and discussion

In figures 1 and 2, the thick target yields of the D(d, p)T reaction in Ti and Yb are plotted against the bombarding energy, respectively. The data are corrected for the ratio of the detector solid angle $(\Delta\Omega)_\mathrm{cm}/(\Delta\Omega)_\mathrm{lab}$ (the angular distributions are isotropic in the centre-of-mass system at such low bombarding energies [9]), and normalized at 6.45 keV as mentioned above. Errors associated with the data in the figure include only statistical ones; i.e. statistics

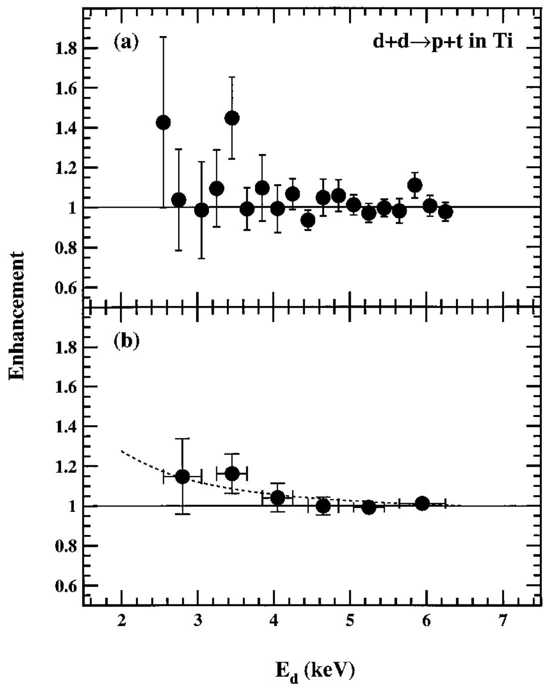


**Figure 3.** Ratios of the thick target yield of the D(d, p)T reaction in Ti metal to the calculated value. The calculation was made with the bare cross section so that the ratio shows enhancement of the reaction rate. The ratios for each bombarding energy are shown in (a), and the weighted averages of the ratios of several points are shown in (b). A dashed curve in (b) shows the calculation with the electron screening potential of 19 eV.

of the yield at each bombarding energy and those at 6.45 keV for the normalization runs. As shown in the figures, the yield decreases very rapidly as the bombarding energy decreases.

Since the incident deuterons are slowed down in target metal and the reactions can occur until the deuteron stops, the thick target yield $Y_\mathrm{t}$ at the bombarding energy of $E_\mathrm{d}$ is given as follows,

$$Y_\mathrm{t}(E_\mathrm{d}) = A\int_0^{X_\mathrm{d}} N_\mathrm{D}(x)\sigma_\mathrm{lab}(E)\,\mathrm{d}x = A\int_0^{E_\mathrm{d}} N_\mathrm{D}(x(E))\sigma_\mathrm{lab}(E)(\mathrm{d}E/\mathrm{d}x)^{-1}\,\mathrm{d}E \qquad (1)$$

where $X_\mathrm{d}$, $N_\mathrm{D}(x)$, $\sigma_\mathrm{lab}(E)$ and $\mathrm{d}E/\mathrm{d}x$ are the path length of incident deuteron, the number of the target deuterons per unit area, the reaction cross section and the stopping power for the deuteron, respectively. Thus, the obtained thick target yields should be compared with those calculated with the reaction cross section of the bare $\mathrm{D}+\mathrm{D}$ reaction, in order to see whether the reaction rates in Ti and Yb are larger than that of the reaction in vacuum or not.

The parametrization of Bosch and Hale [10] has been used for the cross section. The parametrization is based on the $R$-matrix theory and was made with the high-energy data where no electron screening effects occur.

Although an accurate value of the stopping power is important, no experimental information on the stopping power for the deuteron has been available in the region of the present bombarding energies. Thus we followed the recipe of Anderson and Ziegler [11] in which the electronic stopping power is assumed to be proportional to the velocity of the projectile

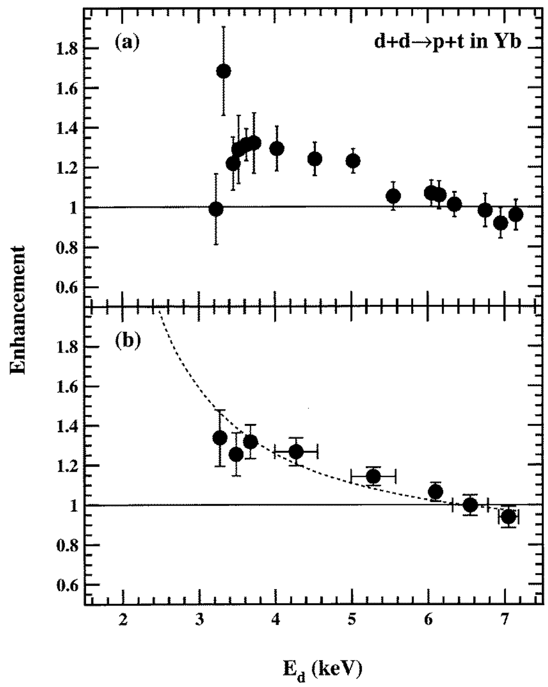


**Figure 4.** Ratios of the thick target yield of the D(d, p)T reaction in Yb metal to the calculated value. The calculation was made with the bare cross section so that the ratio shows enhancement of the reaction rate. The ratios for each bombarding energy are shown in (a), and the weighted averages of the ratios of several points are shown in (b). A dashed curve in (b) shows the calculation with the electron screening potential of 81 eV.

(normalized to the experimental data at higher energies) at very low energies in accordance with the Thomas–Fermi model of the atom and the nuclear stopping power predicted in [12] is employed. The electronic stopping power is considered only for the Ti and Yb atom, whereas the nuclear stopping power of the D atom is included as well as that of the Ti and Yb atom. The atomic ratio of D/Ti and D/Yb are both assumed to be 2.0 in the analysis.

The density distribution of the target deuterons along the incident deuteron path is also important for estimating the reaction rate. The projected range of the 6.45 keV deuteron is only ∼30–40 nm in metal, and the target deuterons are assumed to be uniformly distributed.

The thick target yields calculated with equation (1) are normalized to those at 6.45 keV and they are plotted with the full curve in figures 1 and 2. Since it is difficult to compare the experimental data with the calculations quantitatively in a log-scale graph, the ratios of the experimental yields to the calculated values are plotted in figures 3(a) and 4(a) as a function of the bombarding energy. In figures 3(b) and 4(b) the weighted average values of the ratios of several points are plotted. Since a fine structure of the excitation function of the thick target yield cannot be expected, the averaging process is an effective method for reducing the statistical errors. In these figures, the enhancements of the reaction rate can be seen clearly and seem to increase as the incident energy decreases. Thus they can be naively interpreted as the reduction of the effective Coulomb barrier due to the electron screening potential in metal.

We calculated thick target yields for various values of $U_e$ and compared them with the experimental values. A quadratic curvature of a $\chi^2$-plot gives the most probable value and standard deviation. Therefore, we can conclude that the electron screening potentials affecting the D + D reaction in Ti metal and in Yb metal are obtained as $U_e = 19 \pm 12$ eV and $U_e = 81 \pm 10$ eV, respectively, for the first time. The dashed curves in figures 3(b) and 4(b) are the calculated values with $U_e = 19$ eV and $U_e = 81$ eV, respectively, and they explain the data very well.

The systematical errors of the deduced screening potentials in Ti and in Yb are considered to be $\pm 12$ eV and $^{+25}_{-35}$ eV due to the uncertainty of the stopping power and $+4$ eV and $+13$ eV due to uncertainty of the number of the deuterons in metal during the bombardment, respectively.

It is concluded that the D + D reaction rates are enhanced both in Ti and Yb. However, the deduced electron screening potential ($U_e = 81 \pm 10$ eV) in Yb is much larger than that ($U_e = 19 \pm 12$ eV) in Ti, and than that ($U_e = 25 \pm 5$ eV) obtained in the gas target measurement by Greife *et al* [3], even if the errors are considered. This indicates that the screening effect in metal depends strongly upon the kind of host metal. A theoretical treatment for the low-energy nuclear reaction including the effect of the electronic environment is highly desirable.

## 4. Summary

We have presented the measurement of the reaction rate of the D + D reaction in Yb metal at very low bombarding energies together with that in Ti metal [7]. The enhancements of the reaction rate are clearly seen below 5 keV, and can be interpreted as the reduction of the effective Coulomb barrier due to the electron screening in metal. The deduced screening potential in Yb ($U_e = 81 \pm 10$ eV) is much larger than that in Ti ($U_e = 19 \pm 12$ eV). A theoretical treatment for the low-energy nuclear reaction including the effect of the electronic environment is highly desirable.

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