Strongly Enhanced DD Fusion Reactions at Very Low Energies in Solids(I. Nuclear Physics)

Strongly Enhanced DD Fusion Reactions at Very Low Energies in Solids

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Abstract : The interplay between a nucleus and its environment is known to play an important role in nuclear reactions when the incident energy has been reduced far below the Coulomb barrier, where the cross section described by the Gamow function decreases drastically due to the steep drop in the quantum mechanical penetration of the barrier. For the fusion reactions in metals, experimental techniques were developed in which target nuclei were implanted in a metal. The DD fusion reactions were studied, so far, and an enhancement in the rate of the D(d, p)T fusion reaction over the Gamow function was found for deuterons in Ti and Yb. Here we report on further measurements of the D+D reactions in other materials. Of particular interest is the fact that the reaction rate of the D+D reactions at 2.5 keV in PdO is 50 times larger than in Ti, and the deduced screening potential amounts to 600 eV. This cannot be explained by bound-electron screening which may give a potential of 20 eV at most, but suggests the existence of an additional, and important, mechanism. Perhaps there is a fluidity of deuterons in metals that also reduces the Coulomb barrier between the interacting deuteron pair. An exhaustive study of nuclear reactions in metal would be very significant ; one would then not only simulate nuclear fusion reactions in a stellar plasma where the nuclei are immersed in a sea of electrons, but also explore the limitations of nuclear fusion at room temperature.

§ 1. Introduction

Low-energy nuclear reactions with light nuclei have shown that the cross sections are affected by electrons surrounding the interacting nuclei[1-5]. These cross sections are somewhat larger than those of bare nuclei without electrons. The enhancement is called the electron screening effect and is described quantitatively by the screening potential U_s. The greater the enhancement, the larger the value of U_s is. For the D+D reaction with a gas target, the screening potential was deduced as $U_s = 25 \pm 5$ eV[3] by comparing the experimental cross section with the prediction based on the Gamow function and the parameterization of ref [6].

For the nuclear reactions in metals, experimental techniques were developed in which target nuclei were implanted in a metal[7,8]. The screening potential in a metal was first deduced for the D+D reaction in Ti by measuring the proton yield in the D (d,p) T reaction[9]. The result, $U_s = 19 \pm 12$ eV, is almost the same as for the gas target. For the subsequent measurement with Yb, however, $U_s = 81 \pm 10$ eV was deduced[10] ; this is certainly larger than expected for deuterium atom and molecule [11]. Thus, we have continued the measurements for various metals to find the mechanism of the enhancement as well as to look for more favorable metal for the DD fusion reaction. In the present work, we report on a series of the measurements of the D(d,p)T reactions in PdO, Pd, Fe, Au and Ti for $2.5 < E_d < 10$ keV.

§ 2. Experimental Procedure

The measurements were performed using a low-energy ion beam generator[9]. A deuteron beam intensity of several hundred mA was collimated by passing through two slits so as to fix the beam position and size; the beam spot on the target was 4 mm in diameter.

For the DD fusion reactions, foils of Ti, Fe, Pd, Au and PdO/Pd/Au were bombarded. Commercially available metallic foils with thickness of 0.2 to 1 mm were bombarded as targets. They were annealed in vacuum at about 800℃ for several hours. The PdO/Pd/Au foil was prepared in such a way that a rolled Pd foil with thickness of 40-50 mm was annealed in an oxygen flame at about 1000℃ and Au was electrochemically deposited on one side of the foil.

The PdO surface side was bombarded and the thickness of PdO layer measured by the SEM technique was about 30 nm. The targets were cooled during the bombardments by liquid nitrogen and the temperature of the foil surface was monitored by a thermocouple. The total dose of the deuteron beam was deduced from the electric current on the target, with a small correction for secondary electron emission.

In order to detect protons emitted in the D(d,p)T reactions, a ΔE-E counter telescope consisting of 50- and 200-μm thick Si surface barrier detectors was used. The front face of the ΔE detector was covered with a 15-μm thick Al foil to prevent electrons and scattered deuterons from hitting the detector. The telescope was placed at 2cm from the target and at 90° to the beam direction. Requiring a coincidence between the ΔE and E detectors completely eliminated electrical noise and enabled unambiguous identification of protons from the D (d,p)T reaction.

§ 3. Behavior of Deuterons in Solids during the Bombardment

The proton yield is proportional to the number of projectiles and targets as well as the reaction cross section. In the present case, deuterons impinging upon the metal play a dual role, projectiles and targets of the reaction. Since the fusion enhancement factors we seek are obtained from only the energy dependence of the proton yield, it is not necessary to know the absolute number of targets. But it is necessary to keep that number reasonably constant as the deuteron energy is varied. Hence, a method for controlling the number of target deuterons had to be developed.

We have measured the proton yield from the D(d,p)T reaction in our targets under various conditions and deduced the dependence of the number of targets on the deuteron dose, metal temperature and beam current. Furthermore, deuterium depth profiles were obtained by the elastic recoil detection method[12] for 5 keV deuteron implantation into Pd and PdO.

Here, we briefly show the important results concerning the number of the target deuterons during the bombardment. (1) The number of the target deuterons increases when the metal foil does not contain deuterium initially, and at a certain fluence reaches saturation, in confirmation of that reported in ref [13]. (2) The saturation number of deuterons depends strongly on both the host metal and on the temperature, as shown in Fig.1, where the proton yields versus target temperature are plotted for a deuteron bombardment energy of 10 keV. In general, the larger the fluidity of the deuteron is, the smaller the number becomes. (3) The depth profiles of deuterons implanted into Pd and PdO show

that the deuteron density increases with depth into the surface and saturates at a depth being much greater than the range of the bombarded deuteron.

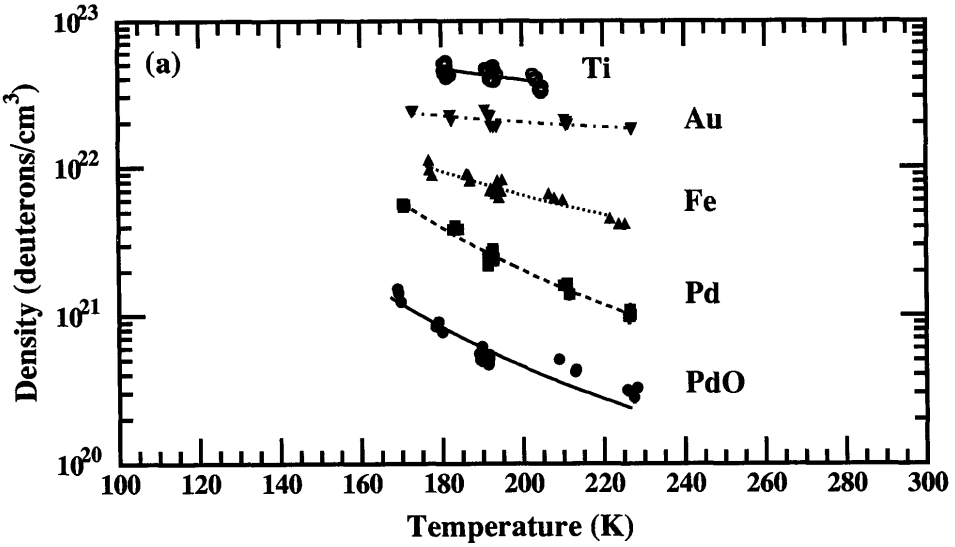

Fig.1. Saturation density of deuterons versus target temperature.

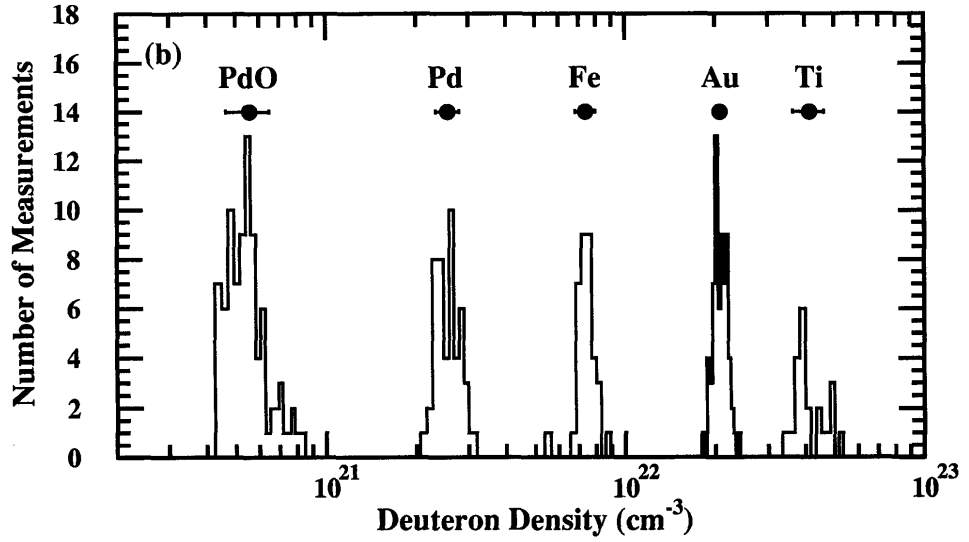

Fig.2. Stability of deuteron density in various metals during the bombardments.

Therefore, the measurements of the excitation function of the D(d,p)T reaction in metal have been carried out by controlling and monitoring the number of the target deuterons as follows.

Prior to the measurement, the metal foil was bombarded by 10 keV deuterons with a beam current of 60 μA until the proton yield together with the temperature of the metal becomes constant. This basically ensures the saturated condition on the deuterium concentration at the equilibrium temperature; we always confirmed that proton emission rate converged to nearly same number whether initially the foil contained no deuterons or was full of them. At other bombarding energies, the beam current must be adjusted so as to keep the input power (and, hence, the temperature) constant; the temperature of the target was always monitored. In this way, the number of target deuterons was hold constant during the measurement. Nevertheless, the proton yield at 10 keV was measured at frequent intervals to verify this constancy. During the accumulation of the data at 2.5 keV, for example, such measurements were carried out more than ten times (a few minutes at 10 keV, a few hours at 2.5 keV, again and again). The proton yield is, then, always divided by the yield at 10 keV measured just before and after the run. This procedure of normalization gives the relative reaction rate as a function of the bombarding energy.

In order to examine the stability of the deuteron target density during the measurements, we show, in Fig.2, a histogram of the deuteron density in metal deduced from the frequent measurements at 10 keV, 22 times for Ti, for example, by using the cross section of the bare D(d,p)T reaction [6] and assuming the constant density distribution for deuterons. Solid circles plotted at the upper part show the most probable values with a one standard deviation error. It should be emphasized that the deuteron density is very stable during the measurements; the values scatters only within 20% even for the high fluidity host materials, PdO and Pd. The present method of sampling the deuteron density is justified by the fact that the effective depth contributing to the D+D reaction is very small (5 nm for 2.5 keV and 15 nm for 10 keV, for Pd metal) and more than 70% of the yield at 10 keV originates from the first 5 nm layar.

§ 4. Reaction Rates

In the upper half of Fig.3, plotted are the relative yields of the D(d,p)T reaction in metals against the bombarding energy. Figure 3 (a) shows results of two independent measurements for PdO, Fig.3 (b) results for Pd and Fe, and Fig.3 (c) for Au and Ti. As expected from the bare D+D reaction, the yields decrease very rapidly as the bombarding energy decreases. However, it is clearly seen that the yield at lower energies very much depends on the host metal ; the largest yield is observed in PdO followed by Pd, Fe, Au and Ti, in order. Since the projectile deuterons are slowed down in the metal and the reactions can occur until the deuteron stops, the observed proton yield Yp at the bombarding energy Ed (the thick target yield) isgiven by

$$Y_p = A \int N_D(x)\, \sigma(E)\, (dE/dx)^{-1}\, dE ,$$

where $N_D(x)$, $\sigma(E)$ and dE/dx are number density of target deuterons as a function of depth beneath the

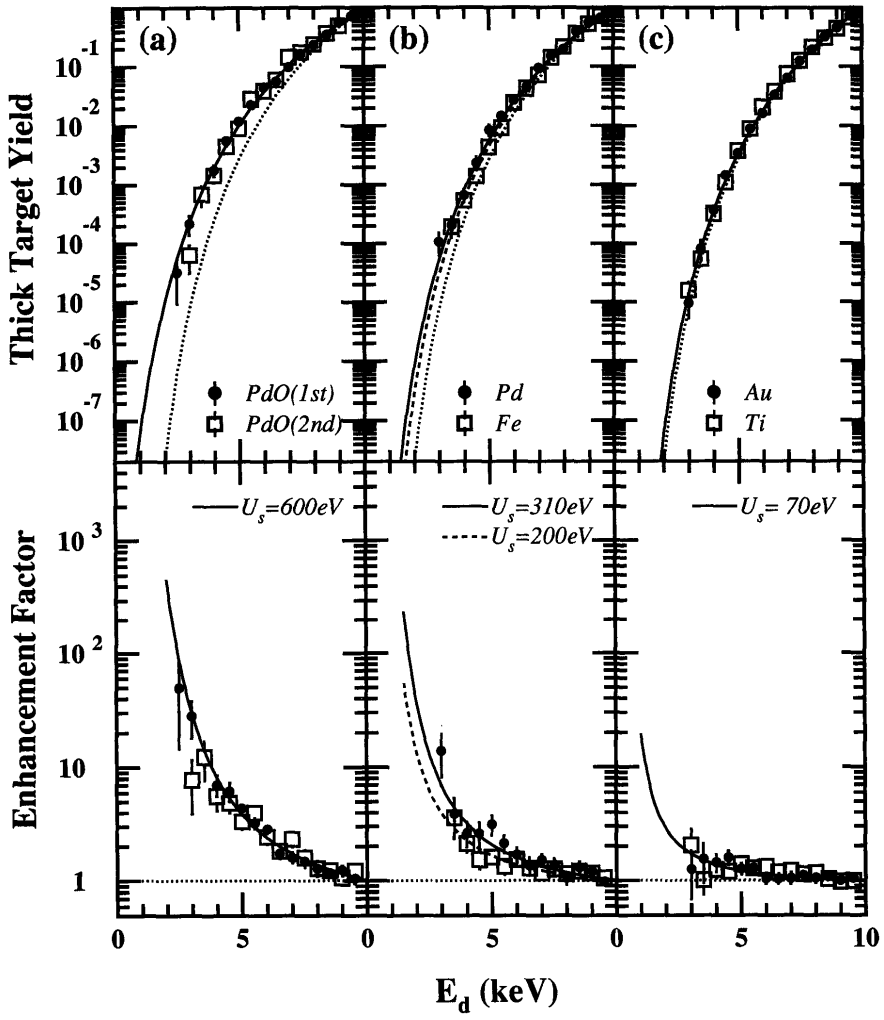

Fig.3. Relative yields of the D (d,p)T reaction in metals against the bombarding energy. In the lower part, the ratios of the experimental yield to the standard calculation are shown.

surface, the reaction cross section and the energy dependent stopping power for the deuteron, respectively. The solid line in Fig.3 indicates a standard thick target yield corresponding to the bare D+D reaction, *i.e.,* without any enhancement of the reaction rate.

In the calculation, constant target density is assumed for $N_D(x)$ and the parameterization of Bosch and Hale [6] is used for σ(E). Further, the graphs of dE/dx vs. E of Anderson and Ziegler [14] are employed. Their assumption that the electronic stopping power is proportional to the projectile velocity at low energies has been confirmed down to deuteron energies as low as 1 keV for various metals [15]. As seen in Fig.3, the standard calculation without any enhancement completely fails to explain the data at the lower energies, especially for PdO, Pd and Fe.

In the lower part of Fig.3, we plot the ratio of the experimental yield to the standard calculation (no enhancement) in order to make comparisons more clearly. As seen, the reaction rate in PdO is enhanced very much, about 50 times larger than the standard at E_d = 2.5 keV. On the other hand, the deduced enhancement is very small for Au and Ti. Since the fact that the enhancement increases as the bombarding energy decreases is a feature of the reaction characterized with a screened Coulomb potential [16], we have naively attempted to parameterize the enhanced reaction rate by a screening

potential (U_s) which reduces the Coulomb barrier between two deuterons. The cross section $\sigma_b(E)$ of the fusion reaction between bare nuclei can be expressed as sb $\sigma_b(E) = SE^{-1} \exp(-2\pi\eta)$, where S is the astrophysical S-factor and $2\pi\eta = 2\pi Z_1 Z_2 \alpha (\mu/2E)^{1/2}$ is the Sommerfeld parameter (Z_1 and Z_2 = atomic numbers of the interacting nuclei, μ = reduced mass and E = center-of-mass energy). The penetration through a screened Coulomb barrier at projectile energy E is equivalent to that of bare nuclei at energy $E_{eff} = E + U_s$ and thus the fusion cross section increases as ss $\sigma_s(E) = \sigma_b(E_{eff})$.

We calculated thick target yields for various values of U_s as described in [9], and determined the values of Us to give the best fits to the enhancement factor data. These fits are shown by the curves in Fig.2. The results are $U = 600 \pm 20$, 310 ± 20, 200 ± 15, 70 ± 10 and 65 ± 10 eV, respectively, for PdO, Pd, Fe, Au and Ti. The errors only include the statistical ones. Systematic errors originate from various sources : uncertainty of the bombarding enegy ± 13 eV), fluctuation of the deuteron density (± 60 eV for PdO, ± 30 eV for Pd, ± 20 eV for Fe and Ti and ± 10 eV for Au), uncertainty of the depth dependence of the deuteron density (+20 eV) and ambiguity of the stopping power (± 30 eV).

§ 5. Discussion

Since the screening potential caused by electrons in metal is only several tens of eV [17], the presently deduced values for PdO, Pd and Fe can never be due to the electron screening alone. Of

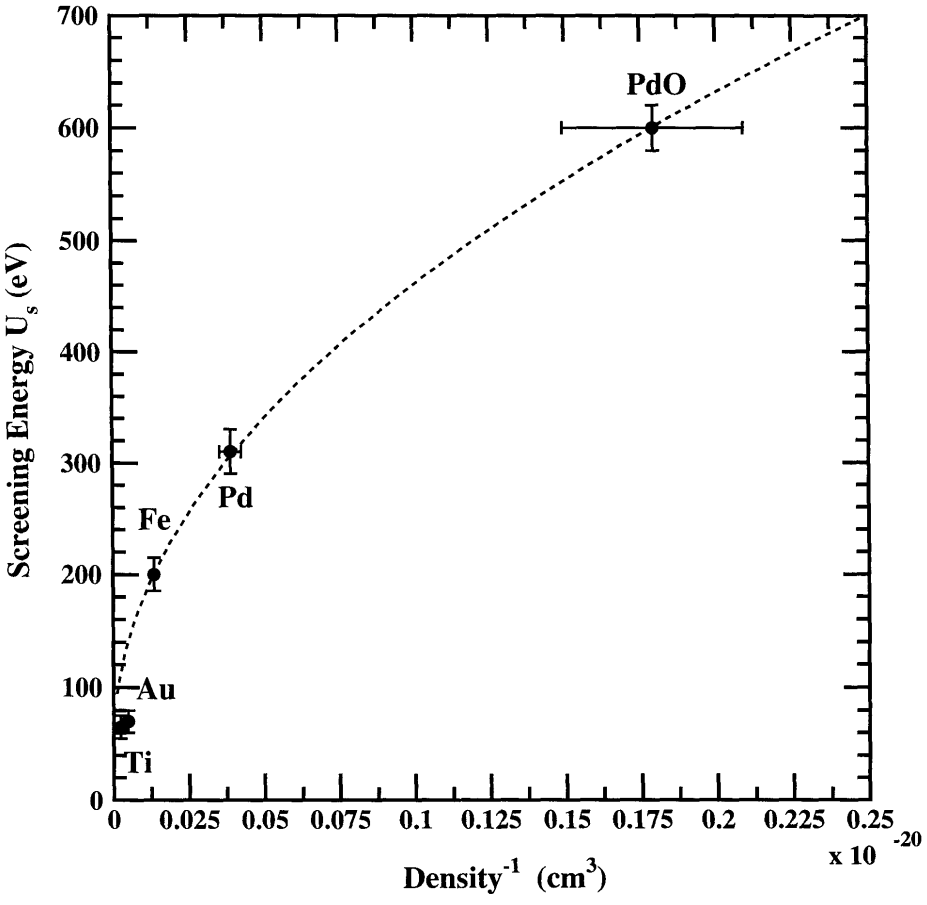

Fig.4. Deduced screening potential versus (deuteron density)$^{-1}$.

particular interest is the existence of a strong correlation between the screening potential and the deuteron density in metal during the bombardment, as shown in Fig.4, where the deduced screening potentials are plotted against (density)$^{-1}$. The deuteron density during the bombardment is an index of the fluidity of deuteron; it might be proportional to the inverse of the density. Thus, we infer that for the D+D reaction in metal at very low energies there exists a significant screening mechanism, the effect of which increases drastically with an increase of the fluidity of deuteron in metal, in addition to the electron screening known previously.

For Pd metal, the deuteron density during the bombardment is much lower than that achieved in electrochemical loading, where atomic ratio D/Pd becomes 0.95. This peculiarity may be connected with deuterium diffusivity in metals under D^+ bombardment. In general diffusivity or mobility decreases with increasing deuterium concentration, because with increasing deuterium concentration the number of vacant interstitial positions into which the deuteron can jump diminishes. The diffusion constants of deuteron for ordinary condition at $T = 300°K$ are $\sim 5 \times 10^{-7}$, $\sim 4 \times 10^{-5}$ and $\sim 3 \times 10^{-13} cm^2 s^{-1}$ in Pd, Fe and Ti, respsctively[18]. Enhanced deuteron diffusivity has also been reported under stress and under deuteron implantation. Although the mechanism to increase the diffusion is not understood completely, the diffusion constant can easily be changed under such special conditions. In the present work, thus, it is said very roughly that large diffusivity of deuteron results in low deuteron density.

A classical picture of screening has been discussed in a growth process of colloidal particles in electrolyte solution, for example in the textbook of electromagnetism [19]. In this case, an essential point is the fact that both negative and positive ions are fluid and, hence, their electric charges can be distributed so as to satisfy simultaneously the Poisson equation and the statistical distribution. As a result, the Coulomb repulsion is reduced not only by the negative ions but also by the positive ions. A jellium model for the electrostatic screening with the electron and D^+ gas in metal[20], being an extension of the above consideration, shows that the screening potential due to the fluid deuterons can be one order of magnitude larger than that due to the electrons because of the difference between Boson (d) and Fermion (e) statistics. Thus, we suggest the possibility of such a dynamic mechanism during the D^+ bombardment into the metal ; there, the fluidity of deuterons must play a decisive role.

§ 6. Conclusions

It is most important in this work that the DD fusion reaction can be enhanced extraordinarily when the reaction occurs in a particular host material such as PdO. The anomalously large screening potential, $U_s = 600$ eV deduced for PdO, clearly indicates the existence of a new mechanism to enhance the reaction rate. The value $U_s = 600$ eV gives a good fit to the PdO data of Fig.4 from 10 keV down to 2.5 keV. The existence of such a large screening potential may affect the astrophysical scenarios, in which the atoms are in most cases completely stripped of their atomic electrons and the nuclei are immersed in a sea of free electrons, as D^+ surrounded by conduction electrons in metal.

Moreover, if the reaction cross section can be extrapolated to thermal energies with the same screening potential and with the same deuteron density we had, $1.2 \times 10^{21}/cm^3$, then one can presume

the DD fusion rate to be $> 10^7$ $sec^{-1}cm^{-3}$ at room temperature.

It may be possible in the future to explore such conditions, first by increasing the beam intensity to directly measure the reaction rate below 2.5 keV.

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