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Low Energy Nuclear Fusion Reactions in Solids

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Abstract

The DD fusion reactions in various materials have been studied, and enhancements in the rate of the D(d,p)T fusion reaction over the Gamow function were clearly seen in the materials. Of particular interest is the fact that the reaction rate of the D+D reactions at 2.5 keV in PdO is 60 times (and in Pd 10 times) larger than in Ti, and the deduced screening energy amounts to 600 eV (300 eV). Furthermore, the subsequent study on the Li+d reactions showed large screening energy as 1.7 keV, again, in Pd metal. These cannot be explained by bound-electron screening which may give at most an energy of 20 eV for the DD reaction and of 0.3 keV for the Li+d reaction, 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 fusing nuclei.

1. Introduction

It has been pointed out that there should be two miracles in order to realize the cold fusions; (1) a tremendous reduction of the Coulomb barrier between two deuterons fusing in metals, and (2) branching ratios of the reaction channel are completely different from those known for the normal DD fusions. It might be possible to see a glimpse of such extraordinary phenomena as a precursor of cold fusion, if exists, when one studies fusion reactions with higher energies but in a different condition such as in solids. As reported at the ICCF6[1] and ICCF7[2], we have started a series of measurements of the D(d,p)T reactions in solids with bombardment energies far below the Coulomb barrier, in order to see the possibility of (1).

In nuclear reactions with normal targets, the cross sections at very low energies have already been known to be somewhat larger than those of bare nuclei without electrons: This is explained by the electron screening effect and is described quantitatively by the screening energy Us. However, the reactions concerned here are in different environments from the ordinary condition, since target nuclei are embedded in another material and the number density of target nuclei is nearly equal to that of the host atoms. We have developed a method to measure the reaction rates of such reactions with low-energy deuterons, and have performed a series of measurements on D+D reactions in various materials.

The screening potential for DD fusions in a metal was first deduced in Ti by measuring the proton yield in the D(d,p)T reaction.[3] The result, $U_s = 19 \pm 12$ eV, was almost the same as for the gas target. However, a strikingly large value of 600 eV was obtained for the DD fusions in PdO as reported in ICCF7[2], although the result was preliminary that time. We have continued the measurements of DD fusions in various

metals to find the mechanism of the enhancement as well as to look for more favorable metal. Recently, the investigation on the Li+d reactions in various metals has also started.

In the present work, we report on a series of the temperature controlled measurements of the D(d,p)T reactions in PdO, Pd, Fe, Au and Ti for $2.5 < E_d < 10$ keV, and the first result of the Li+d reaction in Pd for $30 < E_d < 75$ keV.

2. Experimental Procedure

The measurements were performed using a low-energy ion beam generator[3]. For the DD fusions, the generator was operated in the deceleration mode and deuteron beams with energies lower than 25 keV were bent by a charge filter magnet placed just after the decelerator (or accelerator) electrode, in order to reject neutral beams. For the Li+d reactions, the generator was operated in the acceleration mode and deuteron beams with energies from 25 to 80 keV were used to bombard the target. The beams were collimated so as to fix the beam position and size; the beam spot on the target was 4 mm in diameter.

Targets used for the DD fusion reactions were foils of Ti, Fe, Pd, Au and PdO/Pd/Au. Commercially available metallic foils of Ti, Fe, Pd and Au with thickness of 0.2 to 1 mm were annealed in vacuum at about 800°C for several hours. The PdO/Pd/Au foil was prepared in such a way that a rolled Pd foil with thickness-of 40-50 μm was annealed in an oxygen flame at about 1000 °C 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 target used for the Li+d reactions was a foil of the Pd-Li alloy, which was prepared by Sakamoto by arc melting Pd and Li as described in ref. [5].

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 charged particles, protons emitted in the D(d,p)T reactions and α-particles in ^{6,7}Li(d,a)^{4,5}He reaction, a ΔE-E counter telescope consisting of two Si surface barrier detectors was used: The front face of the ΔE detector was covered with a thin Al foil to prevent electrons and scattered deuterons from hitting the detector. The telescope was placed at 2 cm 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 and α-particles from the D(d,p)T and Li(d,a) reaction, respectively.

In the D(d,p)T reactions, 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. The important result concerning the number of the target deuterons during the bombardment is the fact that the number of the target deuterons increases when the metal foil does not contain deuterium initially and at a certain fluence reaches saturation. The saturation number of deuterons depends strongly on both the host metal and on the temperature, as shown in Fig. 1. 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.

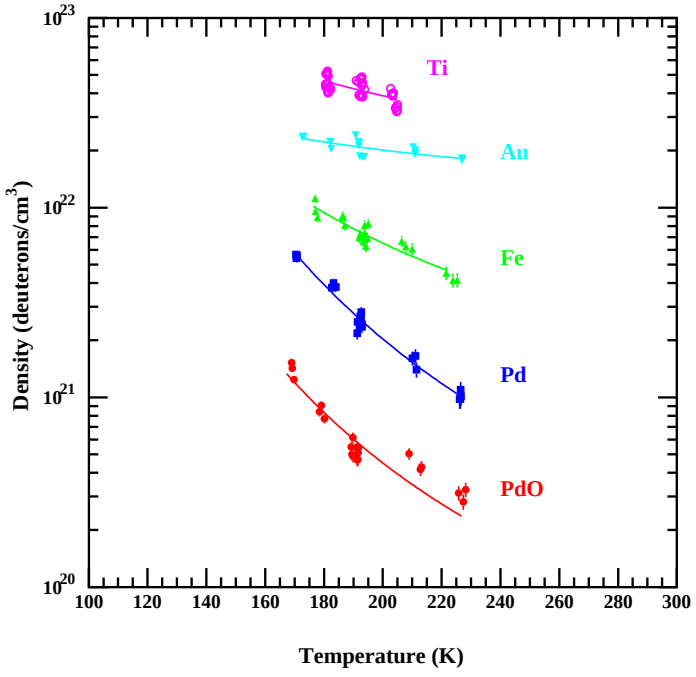

Fig. 1. Saturation density of deuterons versus target temperature.

For the Li(d,α)He reactions in Pd, we measure the excitation function in a similar manner as described above: we kept the temperature of the target nearly constant by adjusting the beam intensity and checked the number of Li in Pd by the frequent measurements of α-particle yields at 75 keV. Then, the yield at each bombarding energy was normalized to that at 75 keV.

3. Results

In the upper half of Fig. 2, plotted are the relative yields of the D(d,p)T reaction in metals against the bombarding energy. Figure 2(a) shows results of two independent measurements for PdO, Fig. 2(b) results for Pd and Fe, and Fig. 2(c) for Au and Ti. 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 Y_p at the bombarding energy Ed is the integrated one down to the zero energy (thick target yield). We estimated a standard thick target yield by using the reaction cross sections parametarized by Bosh and Hale[5] and the stopping cross sections by Anderson and Ziegler[6]. The solid line in Fig. 2 indicates the calculated standard thick target yield corresponding to the bare D+D reaction, *i.e.,* without any enhancement of the reaction rate. As seen, the standard calculation without any enhancement completely fails to explain the data at the lower energies, especially for PdO, Pd and Fe.

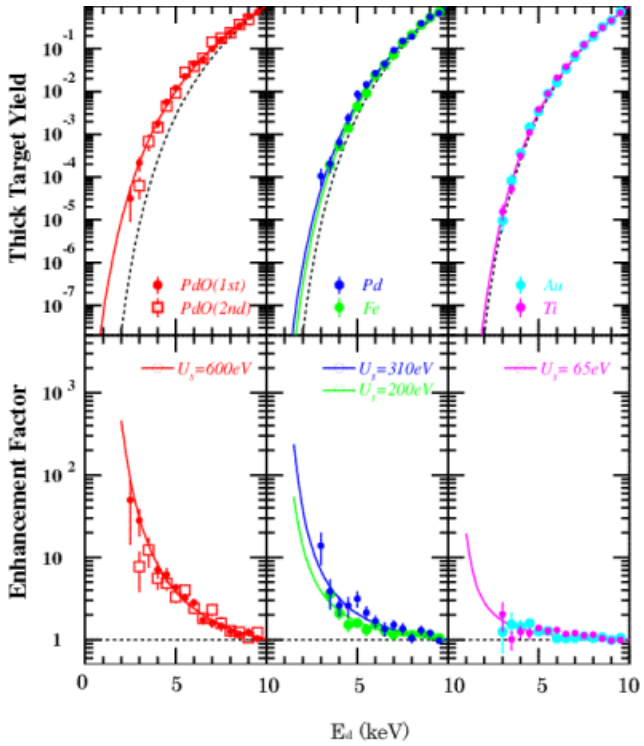

Fig. 2. Relative yields of the D(d,p)T reaction in metals against the bombarding energy. In the lower part, the ratios of the experimental yield to the standard calculation are shown.

In the lower part of Fig. 2, 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[7], we have naively attempted to parameterize the enhanced reaction rate by a screening potential (U_s) which reduces the Coulomb barrier between two deuterons.

We calculated thick target yields for various values of U_s as described in [3], and determined the values of U_s to give the best fits to the enhancement factor data (Table 1). These fits are shown by the curves in Fig. 2. Since the screening energy caused by electrons in metal is only several tens of eV [8], the values obtained for PdO, Pd and Fe are extraordinary large; especially 600 eV for PdO.

Table 1. Best Fits To Enhancement Factor Data

Compound	**U_s**
PdO	600 ± 20
Pd	310 ± 20
Fe	200 ± 15
Au	70 ± 10
Ti	65 ± 10

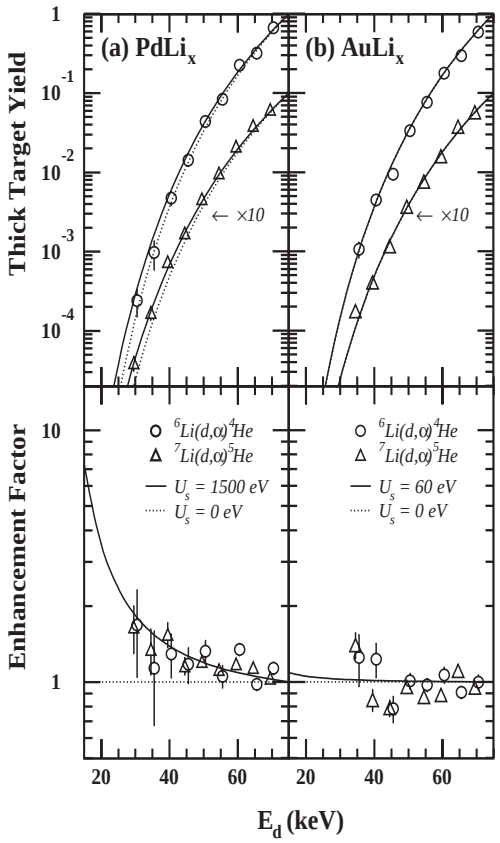

Fig. 3. Relative yields of the ^{6,7}Li(d,α)^{4,5}He reaction in Pd against the bombarding energy. In the lower part, the ratios of the experimental yield to the standard calculation are shown.

In Fig. 3, we show results of the ^{6,7}Li(d,α)^{4,5}He reaction in Pd. Solid lines show the standard thick target yield corresponding to the bare Li+d reaction, *i.e.,* without enhancement. Again, significant enhancement can be seen at low energy. We deduced the values of U_s to give the best fits to the enhancement factor data. These fits are shown by the dotted curves in Fig. 3. The results are $U_s = 1.55 \pm 0.40$ and 1.76 ± 0.30 keV, respectively, for the ^{6}Li(d,α)^{4}He and ^{7}Li(d,α)^{5}He reactions in Pd. Since the screening energy due to the bound electrons is only about 0.3 keV, these values in Pd are really large.

4. Discussion and conclusion

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

The diffusion constants of deuteron for ordinary condition at T = 300 °K are ~5 × 10^{-7}, ~4 ×10^{-5} and ~3 ×10^{13} cm^2s^{-1} in Pd, Fe and Ti, respectively.[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.

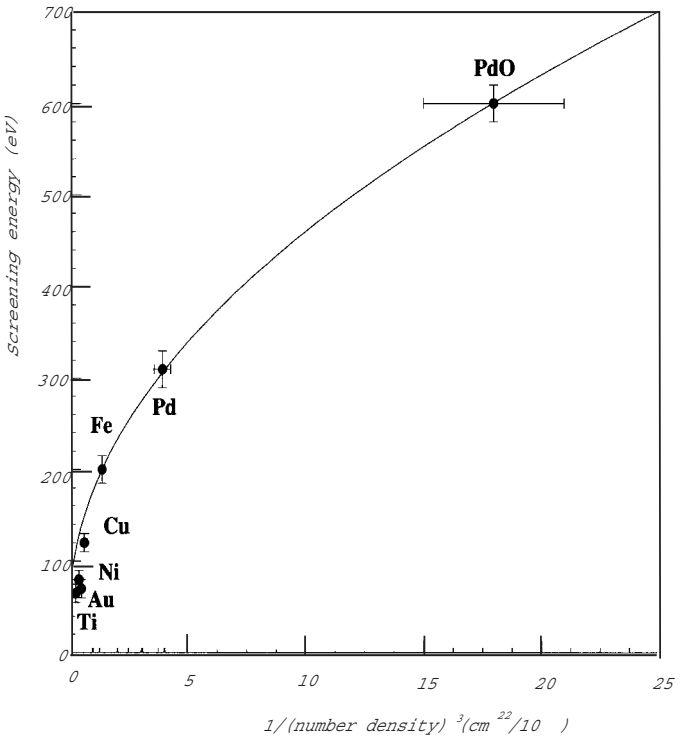

Fig. 4 Deduced screening energy for DD in solids versus (deuteron density)$^{-1}$.

It is most important in this work that the DD fusion and the Li+d reactions can be enhanced extraordinarily when the reaction occurs in a particular host material such as PdO and Pd. The anomalously large screening potential clearly indicates the existence of a new mechanism to enhance the reaction rate.

Moreover, if the reaction cross section can be extrapolated to thermal energies with the same screening energy and with the deuteron density of 1.2 × 10^{21}/cm^3, then one can presume the DD fusion rate to be > 10^7 $sec^{-1}cm^{-3}$ at room temperature. For the Li+d reaction case, however, the reaction rate would be about 10^{-4} $sec^{-1}cm^{-3}$.

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