Effect of deuteron density distribution on the deduction of screening potential from the D(d,p)T reaction in Be metals*

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Abstract: The D(d,p)T reaction in Be metal environments has been measured to investigate the electron screening effect in metals in an energy region of from 5.5 keV to 10 keV in a center of mass system (CMS) at a temperature of 121 K. The depth distribution of deuteron density in Be metals has an impact on the observed reaction yields. A model of deuteron density distribution in metal has been proposed to obtain the original yields. A screening energy of (116±46) eV has been obtained with the assumed deuteron density distribution model.

Key words: D(d,p)T reaction, screening potential, deuteron density distribution

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1 Introduction

The screening effect of the electron cloud outside a nucleus has been investigated for many years in order to understand nuclear reactions in stellar evolutions [1]. The cross section of a nuclear fusion reaction $\sigma(E)$ in the energy region far below the Coulomb barrier is too small to be measured accurately and usually extrapolated from the data at higher energies. Because the target nuclei studied in a laboratory are usually in the form of atoms or molecules, the screening effect should be taken into account and, as a result, the corresponding cross sections are enhanced somewhat compared with those obtained in cases of bare nuclei. The enhanced cross section $\sigma_{\rm s}(E)$ is expressed as $\sigma_{\rm s}(E) = \sigma_{\rm b}(E+U_{\rm e})$, with an electron screening potential $U_{\rm e}$, and the cross section $\sigma_{\rm b}(E)$ for a bare nucleus. Favorable cases for studying the screening effect are particle reactions with positive Q-values involving light target nuclei [2].

The D(d,p)T reaction in different materials in the sub-low energy region has been studied. The screening potential was reported as (25 ± 5) eV for a gas target by Greife et al. [3], and were (190 ± 15) eV, (297 ± 8) eV and (322 ± 15) eV in deuterated metals, Al, Zr, and Ta, respectively, by K.Czerski et al. [4]. However, if calculated by using the adiabatic limit model based on atomic theory, the screening energy was only 14 eV for a gas target, which is one order of magnitude smaller than that in these deuterated metal cases. More than 50 kinds of deuterated metals were used in the study of the D(d,p)T reaction in the DTL (Dynamitron Tandem Laboratorium) at the Ruhr University in Bochum [5–7] and the value of $U_{\rm e}$ in Be metals was given as (180 ± 40) eV.

Although the methods of analysis for the $U_{\rm e}$ in D(d,p)T reaction in metal environments were different, they were all based on the assumption of a stable and homogeneous deuteron density distribution. However, the distribution of deuterons implanted in a metal is uncertain because the ranges of the deuterons with different energies are not the same and the deuterons diffuse quickly in all directions. Therefore, one can suppose that neither a stable nor a homogeneous deuteron density distribution is required by the standard analysis method [8].

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In this work, the D(d,p)T reaction in Be metals was studied in the energy region of 5.5–10 keV. A deuteron density distribution model was proposed and the screening potential was extracted based on this model.

2 Experiment

The experiment was performed at the Laboratory of Nuclear Science at Tohoku University. A detailed description of the experimental setup can be found in Refs. [9, 10] and only the special properties are given here. The main item of experimental equipment is a low-energy high-current beam generator with a duoplasmatron ion source. A deuteron beam with several hundreds of μA from 2 keV to 100 keV with an energy spread smaller than 25 eV can be provided by the generator. The beam extraction voltage is about 25 kV. After passing through the bending magnet, the focusing lenses and the acceleration or deceleration electrode, a beam with suitable energy can be obtained. Finally, the beam is transported to the target after passing through two apertures to fix the beam position and size (5 mm in diameter).

A high-purity Be foil (99.9%) of 20 mm×20 mm× 0.25 mm in size was used for making the deuterated metal target.

An Au-Si Surface Barrier Detector with a thickness of 300 μm and an area of 450 mm^2 was placed around 3 cm away from the target and at 148° to the beam direction to detect the charged particles produced in the reaction. The detector was cooled by liquid nitrogen to obtain a good energy resolution. Furthermore, the detector was covered by a 100 μg/cm^2 thick carbon foil to avoid being hit by δ-electrons and scattered deuterons.

The Be metal was first bombarded by d^+ with 10 keV CMS energy (the beam current is 40 μA) until a saturated proton yield was obtained. The proton spectra were then measured to obtain the yields. The beam power was kept constant during the experiment to keep the target temperature at 121 K. Furthermore, proton counts were accumulated for at least 100 000 at each bombarding energy to decrease statistical error.

3 Results and analysis

Because the target is thick enough to stop incident deuterons, the observed proton yield $Y_t(E_d)$ at the bombarding energy E_d is given as follows [8]:

$$Y_t(E_d) = n_d \int_{\Omega_{lab}} \int_0^{X_d} N_D(x) \left(\frac{d\sigma(E(x))}{d\Omega}\right)_{lab} d\Omega_{lab} dx$$

$$= n_d \frac{\Omega_{lab}}{4\pi} \int_0^{E_d} N_D(E)\sigma_{lab}(E)\varepsilon^{-1} dE, \quad (1)$$

where n_d, Ω_{lab}, X_d, $N_D(x)$, $\sigma_{lab}(E)$ and ε are the number of incident deuterons, the solid angle in the laboratory system, the mean range of the incident deuterons, the density of target deuterons as a function of the depth beneath the surface of the target, the reaction cross section in the laboratory system and the stopping power of deuterons in Be metals, respectively. The parameterization of cross sections was taken from Bosch and Hale [11], which is based on the R-matrix theory and the high-energy data. Furthermore, ε comes from Anderson and Ziegler [12], who provided an already-confirmed assumption [13] that the electronic stopping power was proportional to the projectile velocity at energies as low as 1 keV for various metals.

In Eq. (1), the key term cross section drops exponentially with the decreasing projectile energy. The reaction contributing most to the yield should then occur in the surface layer of the target if N_D is constant. The peak positions of the proton spectra measured by the same detector should be close in different metal targets at the same E_d, because the proton energy loss in the target surface layer can be neglected. The experimental results, however, show clearly that there is an obvious divergence between them, especially for Al and other metals.

The divergence of proton peak positions in Al and Dy metal targets at different E_d is shown in Fig. 1.

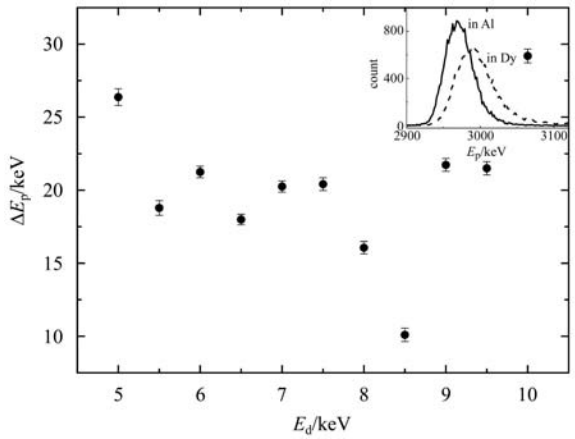

Fig. 1. The peak position divergence of the proton spectra in D(d,p)T reactions in Al and Dy at different E_d.

The inset graph is the measured proton spectra in Al and Dy metal at $E_d = 7.5$ keV. The divergence at

around 20 keV cannot be explained either in error or in the difference of $U_{\rm e}$ (in electron-volt). Therefore, the most possible reason is that the deuteron density distribution in the target is not homogeneous.

As was pointed out in Ref. [14], it is difficult to obtain the density of deuterons in metal because of the complex depth distribution of the deuterons. Deuterons implanted into a metal keep moving under interactions such as backscattering and diffusion. Thus, a model of the deuteron distribution in metal has to be proposed to obtain a reasonably thick target yield for the bare D(d,p)T reaction in metals because the depth distributions of deuterons in targets are significant in data processing.

Assuming that the original distribution of the deuterons implanted into a metal per unit time follows the regularity of the calculated results in a Monte-Carlo simulation (SRIM code [15]) and then that the deuterons diffuse in the metal according to the one dimension diffusion equation with a source

$$D\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial x^2}+s\left(x,t,u,\frac{\partial u}{\partial x}\right), \tag{2}$$

where D, u and s are the diffusion coefficients of deuterons in metal, the distribution function of deuterons and the source function, respectively. For a thick target, the right-side (downstream side) boundary condition and the initial conditions are all valued as zero and the left-side (upstream side) boundary condition is taken to be the number of deuterons diffused per second. Initial conditions are deduced from the Sievert law. The initial conditions define the deuteron density gradient at the beginning and have an effect on diffusion velocity and the time of reaching balance. The left-side boundary condition determines the deuteron density value on the target's surface. As the deuterons are injected, the deuteron density gradually increases and homeostasis eventually occurs. Taking deuterons injected into metal over time as the source function, deuteron distribution u is obtained when deuterons near the range come to a saturated density $(N_{\rm D})_{\rm max}$ which is quoted from Ref. [5].

In Eq. (2), the diffusion coefficient is calculated by the Arrhenius formula

$$D=D_0\exp\left(-\frac{Q}{kT}\right), \tag{3}$$

where D_0, Q and k are the frequency factor, the diffusion activation energy and the Boltzmann constant, respectively. For Be metals, they are taken from Ref. [16]. However, the parameters are obtained at a temperature above 600 K and this will lead to uncertainty in the deuteron density from Eq. (2).

As shown in Fig. 2, the deuteron density in the Be metal is plotted against the depth from the target surface. The triangle, the dot and the diamond points correspond to the 5.5 keV, 8 keV and 10 keV injected deuterons, respectively. In the surface layer of the Be metal, the deuteron density decreases at a small amplitude, with the projectile energy increasing.

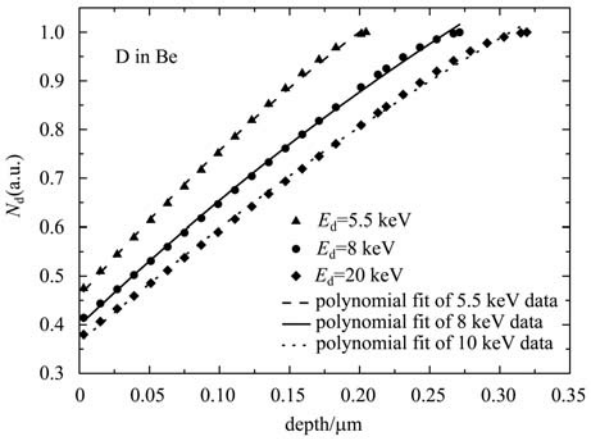

Fig. 2. Deuteron density distribution against depth from target surface at different $E_{\rm d}$ in Be.

Dividing the target into n layers, Eq. (1) can be turned into

$$\begin{aligned}Y_{\rm t}(E_{\rm d})&=\sum_{i=1}^{n}n_{\rm d}N_{{\rm D}i}\Omega_i^{\rm lab}(\theta,E_{{\rm d}i})K_{\Omega}(E,\theta)\sigma_{\rm lab}\varepsilon^{-1}\Delta E\\&=\sum_{i=1}^{n}n_{\rm d}N_{{\rm D}i}Y_i^{'}.\end{aligned} \tag{4}$$

where $K_{\Omega}(E,\theta)$ is the transformation of solid angle between the CMS and the laboratory system, and θ is the ejecting angle. One can change $\Omega_i^{\rm lab}(\theta,E_{{\rm d}i})$ into $\Omega_i^{\rm lab}(E_{\rm p})$ ($E_{\rm p}$ is the proton energy in laboratory system) based on the conversion relation of angle and energy between the CMS and the laboratory system. Therefore, $Y_i^{'}$ is the "proton spectrum of the ith layer". Using the deuteron density deduced from the model to take the place of $N_{{\rm D}i}$, one can obtain the proton spectra.

Figure 3 is the proton spectra in the Be metal at $E_{\rm d}=8$ keV, the square points are the experimental data, and the solid curve and dash curve are the calculation results, where $N_{\rm D}$ are taken from the model and kept as a constant of $(N_{\rm D})_{\rm max}$, respectively. It indicates that the proposed model of deuteron density distribution is reasonable. Obviously, the dash (solid) curve overestimates (underestimates) the deuteron density on the target surface. It should be considered that the present model is improved in future work.

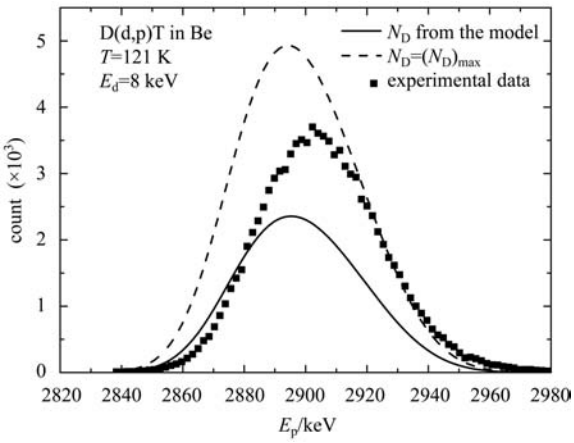

Fig. 3. The proton spectra in Be at $E_{\rm d} = 8$ keV.

The elastic scattering becomes considerable in the low energy region. As simulated by SRIM code, about 2% incident deuterons were scattered in the Be metal in the experimental energy region. As a result, the nuclear reaction at non-normal angle would become considerable. However, the density distribution of the target deuterons along the incident deuteron path is crucial for estimating the reaction rate.

The thick target yields of protons emitted from the D(d,p)T reaction occurring in the Be metal at 121 K, which are normalized to the 10 keV data, are plotted in Fig. 4 against the deuteron bombarding energy.

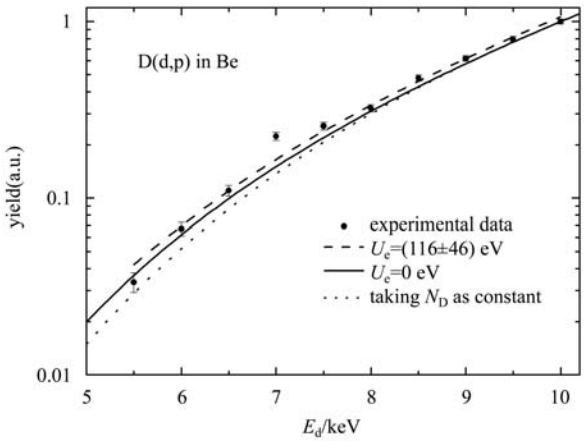

Fig. 4. Relative thick target yield of protons emitted in the D(d,p)T reaction in the Be metal.

The dot points are the experimental data, and the errors associated with the data include only statistical ones. The systematic errors (about 12%) include the uncertainty of the bombarding energy (2%), the fluctuation of the deuteron density (10%), the uncertainty of the target current measurement (3%–5%) and the ambiguity of the stopping power(3%). The solid curve is the calculated result based on Eqs. (1) and (2), which shows the bare D(d,p)T reaction without screening. It is clear that the D(d,p)T reaction rate in Be metals is higher than that in the bare nuclei, that means the screening effect should be taken into account. Therefore, if taking $U_{\rm e} = 116$ eV, one can fit the experimental data nicely. Considering the data error, a value of $U_{\rm e} = (116 \pm 46)$ eV is obtained.

If the deuteron density distribution is considered stable and homogeneous, the value of $U_{\rm e} = (165 \pm 51)$ eV can be deduced. This value is comparable with that reported in Refs. [5–7]. The dot curve in Fig. 4 is the yield curve taking $N_{\rm D}(E)$ as constant.

Obviously, one can conclude that the deuteron distribution in the metal is of importance to the deduction of $U_{\rm e}$. However, the distribution of deuterons in metal must be studied carefully.

4 Summary

In the present work, thick target yields of protons emitted from the D(d,p)T in a Be metal under the low temperature condition ($T = 121$ K) were measured at the bombarding deuteron energies of 5.5 keV$\leqslant E \leqslant$ 10 keV. A model of deuteron density distribution is introduced to consider the utmost high mobility of deuterons. The density of deuterons in the surface layer decreases with increasing projectile energy, and the deeper layer has a higher density within the range. The corresponding screening potential in Be metals deduced here is smaller than that of the previous studies [6]. The character of the depth distribution of deuterons is significant to the enhancement of the cross sections at low energies and must be investigated in detail.

We would point out that the model of deuteron density should be improved and that more detailed studies of different metals are required.

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