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Stopping cross-section and energy straggling of protons in SiC obtained by nuclear resonant reaction of protons with ^{12}C and ^{28}Si

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ABSTRACT

In order to evaluate stopping cross-section and energy straggling of protons in compound material SiC and its constituents C and Si, resonant backscattering spectra have been measured using proton beams in an energy range 4.9–6.1 MeV per a 100 keV step. We have observed two sharp nuclear resonances at proton energies of 4.808 MeV by ^{12}C and 4.879 MeV by ^{28}Si. By systematic analyses of the resonance peak profiles, i.e., energy shift of the peak position and broadening of the peak width, the values of the stopping cross-section and the energy straggling have been deduced to be compared with SRIM-2006 and Bohr's prediction.

1. Introduction

The profiling of sharp nuclear resonances is useful to investigate energy-loss processes in ion-matter interaction. In backscattering measurements by using incident beams with an energy higher than nuclear resonance, a prominent resonance peak is observed. The resonance peak contains some basic information for the ion beam analysis such as peak position, peak width and peak area, which are closely related to energy loss and energy straggling. Therefore, providing a detailed analysis of the observed resonances on backscattering spectra, we can obtain information of the energy loss and the energy straggling. By varying incident proton energy, the resonance depth in material can be changed because protons penetrate into material with its energy loss to reach the resonance energy. Thus we can control the resonance depth, i.e., the penetrating depth of protons.

Experimental and theoretical treatments on the resonance in elastic backscattering were described in the previous works [1,2]. Using the $^{12}C(p, p)^{12}C$ reaction, we successfully analyzed the sharp 4.808 MeV resonance of carbon materials: homogeneous and inhomogeneous [3]. The merit of this method is the fact that target thickness as a resonance depth can be controlled by the incident proton energy and the resonance width is very sharp even if the resonance occurs deeply in material. In this study, we have applied our method to a compound SiC as well as the constituents C and Si. For Si, there is also a sharp resonance at 4.879 MeV in the $^{28}Si(p, p)^{28}Si$ reaction. Therefore we can investigate the compound SiC using resonances at the varying resonance depth.

In the present work, we evaluate the stopping cross-section and the energy straggling in the compound SiC using the sharp resonances in the resonant elastic scattering. The obtained stopping cross-section and energy straggling of protons in the compound SiC are compared with the values of SRIM-2006 and Bohr's prediction, respectively. Moreover, in order to test Bragg's rule, the linear additivity of stopping cross-section and that of energy straggling in the compound are also discussed.

2. Experimental

The experimental method used in this study is the same as that described in the previous paper [1]. The targets used were commercial available materials: highly oriented pyrolytic graphite (HOPG) (2.26 g/cm^3), Si (2.32 g/cm^3) and 3C–SiC (3.21 g/cm^3), which are crystal-like materials. The interesting resonances occur at the proton energies of 4.808 MeV by ^{12}C and 4.879 MeV by ^{28}Si of which natural line widths are 12 and 8.7 keV at FWHM, respectively [4,5]. The incident proton energies were 4.9–6.1 MeV; the energy was varied in 100-keV steps. The energy increment of 100 keV corresponds to an increasing resonance depth of about 7 μm. The beam stability was less than ±2.3 keV at 5.5 MeV. The beam spot on target was about 2 mm in diameter. The scattering angle was set to 179.2° as more backward angles are favorable in obtaining larger cross-section enhancements due to nuclear resonances. The scattered protons were detected with a passivated implanted planar silicon (PIPS) detector with an active area of 25 mm^2 and a depletion layer thickness of 300 μm. The resolution of the detection system was

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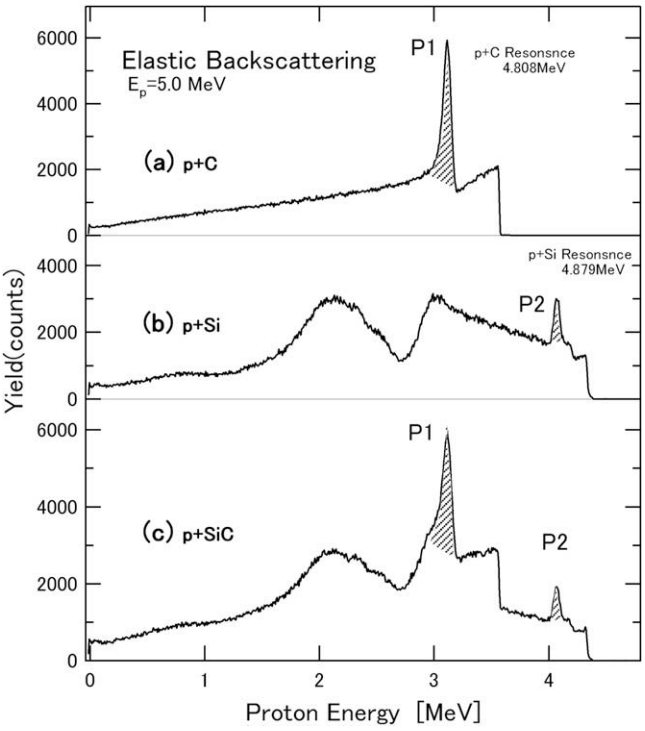

Fig. 1. The measured elastic backscattering spectra of incident proton energy 5.0-MeV by (a) C (HOPG), (b) Si and (c) SiC targets; the peak P1 indicates the $p + {}^{12}C$ resonance at 4.808 MeV and the P2 indicates the $p + {}^{28}Si$ resonance at 4.879 MeV.

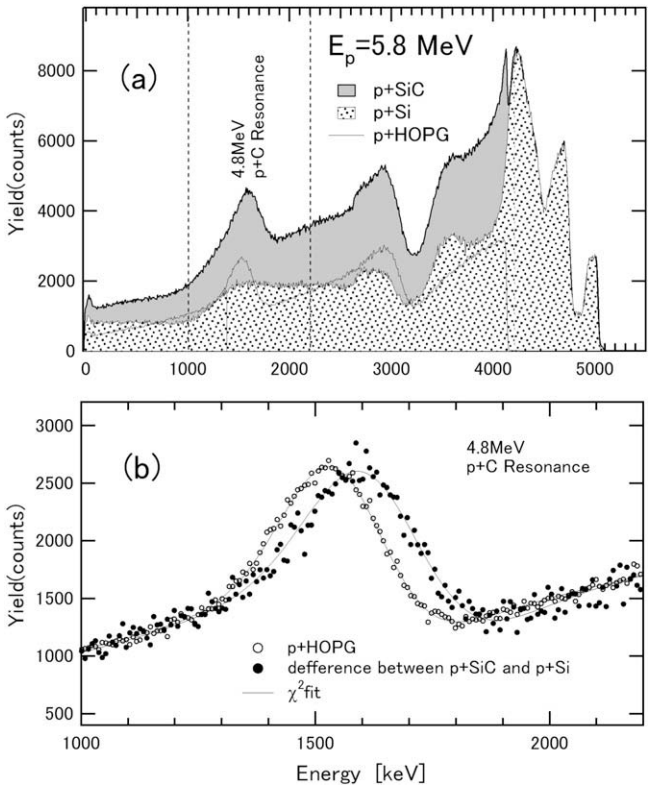

Fig. 2. The elastic backscattering spectra at 5.8 MeV by C (HOPG), Si and SiC targets. (a) The shaded area shows a backscattering yield by C in SiC; the yields of Si and SiC are normalized at that around 5.0 MeV. (b) The comparison of the P1 peak profiles between the C resonance in $p + C$ (Fig. 1a) and $p + SiC$ (Fig. 1(c)) which is corresponding to the shaded area in Fig. 2(a); the solid lines shows the results of χ^2 fit.

15 keV (FWHM). The vacuum pressure during measurements was 1.3×10^{-4} Pa.

We have measured resonance profiles of the $p + C$ resonance at 4.808 MeV in the incident proton energy from 4.9 to 6.1 MeV by C and SiC targets and that of the $p + Si$ resonance at 4.879 MeV from 4.9 to 5.6 MeV by Si target. For the $p + C$ resonance we used the data in our previous work [3]. The energy spectra for C, Si and SiC targets at 5.0 MeV are shown in Fig. 1, where P1 and P2 indicate the $p + C$ resonance and the $p + Si$ resonance, respectively. In particular, the spectrum for SiC (see Fig. 1(c)) contains both resonances.

3. Analysis method

3.1. Resonance profile

Fig. 2(a) shows the backscattering spectra for C, Si and SiC which were normalized by yields at the surface scattering. In Fig. 2(b) shows a comparison of two C resonances; one is the C resonance peak from C target and the other is that from SiC target, which is the differential yield between Si and SiC spectra in Fig. 2(a). The observed resonance peak shows an asymmetry shape, which is due to the interference between nuclear resonance and elastic backscattering [6] and also by energy straggling and kinematics. A deconvolution of the asymmetry shape of resonance peaks has been performed by a least squares analysis (χ^2 fit) [2]. The result of the fitting for the 4.8-MeV resonance is shown in Fig. 2(b). To evaluate the stopping cross-section and the straggling of protons in the compound SiC, C resonance profile obtained by subtracting Si spectrum from SiC spectrum was analyzed.

3.2. Energy loss

For a single element target, we have derived a formula to deduce the stopping cross-sections using two different incident energies E^1_{in} and $E^2_{in}\left(E^1_{in} < E^2_{in}\right)$, and the corresponding resonance exit energies are E^1_{out} and E^2_{out}, respectively, of which an illustration is shown in Fig. 3(a). The stopping cross-section as a function of proton energy is expressed by:

$$S(E) = \frac{1}{N}\left(\frac{dE}{dx}\right), \tag{1}$$

where N is the volume density of atom and (dE/dx) is the stopping power; the average energy loss per unit path length. Thus the ratio of the stopping cross-section $S(E)$ is given by the energy difference between resonance peaks at incoming and outgoing [3]:

$$\frac{S(\bar{E}_{out})}{S(\bar{E}_{in})} = \frac{E^2_{out} - E^1_{out}}{E^2_{in} - E^1_{in}}, \tag{2}$$

where $\bar{E}_{in}$ is an average of E^1_{in} and E^2_{in} and $\bar{E}_{out}$ is that of E^1_{out} and E^2_{out}.

For the compound SiC, extending the above treatment to a case of two target materials containing C, we can evaluate the stopping cross-sections by a comparison of the $p + C$ resonance profiles on between C spectrum and SiC spectrum. As shown in Fig. 3(b), when we treat two energy losses through the same resonance, the difference between two incident energies, $E^2_{in} - E^1_{in}$, must be same for the two materials, C and SiC. Thus, we obtained the energy loss at incoming path:

$$\frac{f(\bar{E}_{in})}{g(\bar{E}_{in})} = \frac{N_g \cdot \Delta d_g}{N_f \cdot \Delta d_f}, \tag{3}$$

where $f(E)$ is the stopping cross-section of C, $g(E)$ is that of SiC. N_g and N_f are the volume densities of C and SiC, respectively. Δd_f and Δd_g are the penetrating depths corresponding to their energy losses.