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An experimental evaluation of spatial distribution for deeply penetrating protons in carbon material

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Abstract

The peak profile of the 4.8-MeV resonance by the $^{12}C(p,p)^{12}C$ reaction in backscattering geometry has been analyzed to examine two kinds of stragglings of proton, i.e. the depth straggling in the incoming path and the energy loss straggling in the outgoing path. The analysis, which is combined with existing theoretical treatments for the stopping process and the energy loss straggling, has made it possible to deduce the penetration depth and its spread at the resonance position in carbon materials. The present method, as a new tool for direct inspection of ion beams inside target material, is explained in detail.

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Keywords: Rutherford backscattering; Nuclear resonant scattering; Stopping power; Energy loss straggling; Spatial distribution

1. Introduction

When an ion beam penetrates matter, the ion loses its energy due to the interaction with electrons and nuclei of target material. The energy loss is of a statistical process because of variations in the number of collisions. Therefore, an energy spread and a spatial spread of the ion continuously occur in the target. When the ion velocity is larger than orbital velocities of target atoms, the energy straggling can be calculated using Bohr's formula [1] based on the free electron gas model.

We have performed Rutherford backscattering (RBS) measurements with a sharp 4.8-MeV resonance (a natural width of 11 keV [2]) in the $^{12}C(p,p)^{12}C$ reaction. The measurements, using a higher energy than the nuclear resonant energy, show a characteristic resonance peak that appears in the energy spectrum. The observed peak profile of the sharp resonance can provide insight into broadening mechanisms on the energy loss straggling and the spatial spread of protons in carbon.

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In this paper, we describe some expressions for the spatial spread, i.e. the depth straggling for protons with the 4.8-MeV resonance energy. Using results of the deconvolution of the observed resonance peak and the stopping power calculated by Andersen and Ziegler [3], we evaluate the spatial spread as well as the energy straggling at the depth of the resonance.

2. Experimental

The measurement for the energy straggling and the depth straggling was made using the nuclear resonance reaction of $^{12}C(p,p)^{12}C$ in backscattering geometry, that was described in the previous paper [4]. Incident proton beam of 5.5-MeV energy was used with the stability that was better than ±2.3 keV. The beam size on the target was 1–2 mm in diameter. The target used is HOPG (Union Carbide) with the density of 2.26 g/cm^3 and a thickness of 500 μm. The scattering angle was set to 179.2° because more backward angles are favorable in gaining larger cross-section for the nuclear resonances. The backscattered protons were detected with a passivated implanted planar silicon (PIPS) detector with an active area of 25 mm^2 and a thickness of 300 μm. The resolution of the detection system was 14.3 keV (FWHM). The distance between the detector system and the target was 117 cm, so that the solid angle extended by the detector is estimated to be 1.83×10^{-5} sr. The vacuum pressure was 1.0×10^{-6} Torr during the measurement.

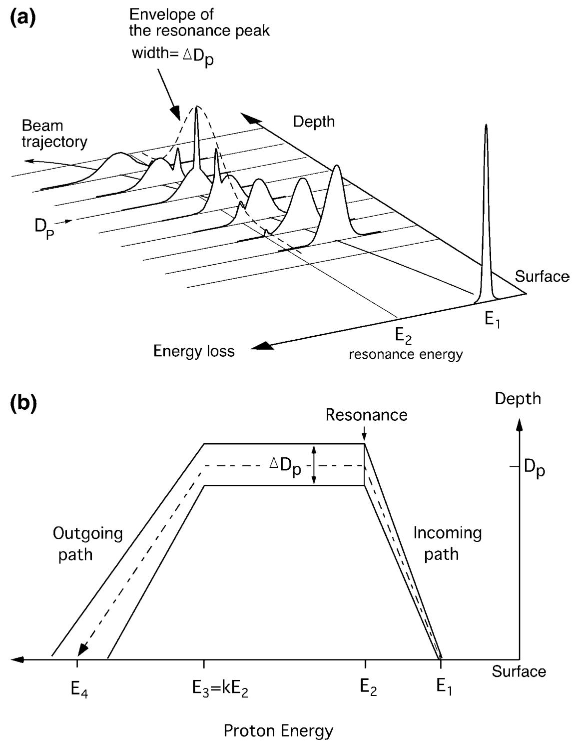

Fig. 1. A schematic illustration of the relation between the energy straggling and the depth straggling for penetrated proton beams: (a) shows the energy distribution of incident protons penetrating through the target around the nuclear resonance of 4.8 MeV. The dotted curve indicates the envelope curve of the peak points of the resonance, which indicates the spatial distribution of protons with the resonance energy in target; (b) shows the aspect in which the spatial spread in the incoming path is reflected in the energy straggling at the resonance peak. The dash-dot line is the proton mean-trajectory that indicates mean energy versus mean penetrating depth. E_1 incident energy of 5.5 MeV; E_2 the resonance energy of 4.8 MeV; E_3, the energy just after the scattering; k, kinematic factor 0.714; E_4, energy of outgoing protons at the surface; D_p mean resonance depth; ΔD_p depth straggling for the mean resonance depth.

3. Analysis

Fig. 1 illustrates the relation between the energy and penetration depth of protons in the RBS measurements. In the incoming path, the energy loss straggling, i.e. the width of the energy distribution, increases with larger penetration depth. When the energy distribution contains the energy of the sharp resonance, the yield at the resonance energy is strongly enhanced, as shown in Fig. 1(a). The energy distribution has two components: a sharp peak as the 4.8-MeV resonance and the broadening distribution as result of the energy loss straggling. The dotted curve in Fig. 1(a) shows an envelope that traces top positions of the resonance peak. The curve means a spatial distribution of penetrating protons with the resonance energy of 4.8 MeV. As shown in Fig. 1(b), the observed width of resonance peak at the energy of E_4 is affected by the energy loss straggling for the outgoing path length as well as the depth straggling ΔD_p.

Therefore, using the experimental results for the resonance peak and the stopping power, we can estimate the depth straggling and energy loss straggling at the penetration depth where the sharp resonance occurs.

The penetration depth D_p from the surface to the resonance point is

$$D_p = -\int_{E_1}^{E_2} \frac{dE}{S(E)}, \tag{1}$$

where E_1 and E_2 are the initial and final energies of protons in the path, respectively, and $S(E)$ is the stopping power as a function of the proton energy E. According to Eq. (1), the fluctuation in the penetration depth, δD_p, at the energy E_2 is expressed as

$$\delta D_p = \delta S \cdot \int_{E_1}^{E_2} \frac{dE}{S^2(E)}. \tag{2}$$

In this derivation, it is assumed that the fluctuation of the stopping power, δS, does not depend on the energy of protons, according to the theoretical treatment by Bohr. Then, for the depth straggling, ΔD_p, i.e. the average of δD_p, we obtain

$$\Delta D_p = \Delta E_2 \cdot F(E_1, E_2), \tag{3}$$

where ΔE_2 is the energy straggling at the energy E_2 and $F(E_1, E_2)$ is given by

$$F(E_1, E_2) \equiv \frac{\int_{E_1}^{E_2} \frac{dE}{S^2(E)}}{\int_{E_1}^{E_2} \frac{dE}{S(E)}}. \tag{4}$$

As explained before, the broadening of the resonance peak at the energy E_4 results from two stragglings. One is the depth straggling in the incoming path, which corresponds to the region of proton energy from E_1 to E_2 in Fig. 1(b). The other is the energy straggling in the outgoing path which occurs in the region from E_3 to E_4 in Fig. 1(b). Note that E_3 is the proton energy just after the resonance scattering, which is lower than resonance energy by the amount of the kinematics of the scattering. The relation between the fluctuation in E_4 and that in D_p is obtained as

$$\delta D_p = (D_p + \delta D_p) - D_p = -\int_{E_3}^{E_4+\delta E_4} \frac{dE}{S(E)} - \left(-\int_{E_3}^{E_4} \frac{dE}{S(E)}\right) = \frac{\delta E_4}{S(E_4)}. \tag{5}$$

Then, the energy spread at the energy of E_4 is given by

$$(\Delta E_4)^2 = (\Delta E_2)^2 + \{S(E_4) \cdot \Delta D_p\}^2, \tag{6}$$

where the first term is the contribution of the energy straggling in the outgoing path and the second term is that of the depth straggling in the incoming path. Substituting Eq. (3) into Eq. (6), we obtain

$$(\Delta E_2)^2 = \frac{(\Delta E_4)^2}{1 + S^2(E_4) \cdot F^2(E_1, E_2)}, \tag{7}$$

for the energy straggling by the penetration depth of D_p The result from Eq. (7) should be equal to the Bohr's energy straggling for the depth of D_p.

Finally, the spatial spread, i.e. depth straggling, is given by

$$(\Delta D_p)^2 = \frac{(\Delta E_4)^2 \cdot F^2(E_1, E_2)}{1 + S^2(E_4) \cdot F^2(E_1, E_2)}. \tag{8}$$

The spatial distribution of protons in carbon has been estimated from the Eq. (8), employing the calculation values of $S(E)$ by Andersen and Ziegler and the present experimental results.

4. Results and discussions

Fig. 2 shows the energy spectrum of the incident proton energy of 5.5 MeV. Prominent peak around 2.3 MeV is at the resonance of 4.8-MeV protons. The deconvolution of the resonance peak has been performed by the technique of χ^2 fit [5]. The shape of the symmetry resonance peak is given by Voigt profile [6], i.e. the convolution of Lorentian and Gaussian. The model function of the RBS spectrum consists of the straight line to express the background continuum, the Voigt profile to express the resonance peak and the interference term [7]. The obtained best fit is also shown in Fig. 2. Values of adjustable parameters in the present analysis were 2311 ± 0.6 keV for the energy of the peak position and 158.3 ± 2.4 keV for the FWHM width of Gaussian in Voigt profile.

Using the values of the energy loss for the penetrating protons, i.e. the energy difference between

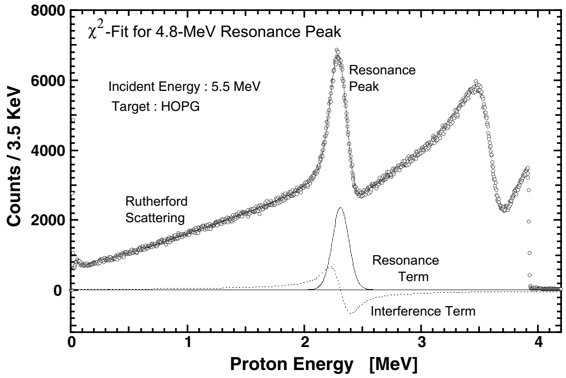

Fig. 2. The measured energy spectrum for 5.5-MeV proton bombardment of the HOPG target and the curve-fit result for the 4.8 MeV resonance peak by the model calculation. The solid and dotted curves at the bottom indicate the resonance term and the interference term.

E_1 and E_2 and that between E_3 and E_4 in Fig. 1(b), we can easily estimate the path length for the incoming and the outgoing from Eq. (1). Using the stopping power by Andersen and Ziegler [3], we obtain 44.5 ± 0.7 μm for the penetration depth in the incoming path and 45.1 ± 0.3 μm for that of the outgoing path. In the present experiment, the stopping power by Andersen and Ziegler gives a consistent result in the relation between the energy loss and the depth. Using the obtained width of 158.3 keV, the energy straggling at the resonance depth is estimated to 75.1 ± 3 keV from Eq. (7). The energy straggling calculated by the Bohr's formula is 66.4 keV for the path length of 45 μm. Thus, the difference between the present result and the Bohr's theory is 13%.

The spatial spread of 4.8 ± 0.24 μm is obtained from Eq. (8). As shown in Fig. 1(a), the spatial spread of ΔD_p indicates the width of the longitudinal distribution which has the resonance energy of 4.8 MeV. Thus, the spatial spread in the incoming path induces a fluctuation of the outgoing path-length, causing the broadening of resonance peak on RBS spectrum.

5. Concluding remarks

We have investigated the resonant peak profiles in Rutherford backscattering using the sharp resonance in $^{12}C(p,p)^{12}C$ reaction. It was found that the peak profile reflects the longitudinal spatial distribution of sharp resonance in material. Using the results of the resonant backscattering and the stopping power formulated by Andersen and Ziegler, the energy loss straggling and the spatial distribution of protons are obtained from the present theoretical treatment. The calculated results were consistent in the relation between the mean energy and the mean depth by the stopping power. Although the present work gives an experimental technique for evaluating the spatial spread in target, there is room to consider other effect of the straggling processes. For further discussions of the straggling processes, elaboration of the present analysis method is now in progress.

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