Neutral Fractions in Proton Beams Passing through Solids

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Abstract

Neutral fractions of proton beams backscattered from thick C and Au targets and transmitted through thin C, Si, and Au foils were measured in the energy range 100–310 keV. Proton was more neutralized in the case of the Au target than the C and Si targets. An emergence angle dependence was not found within the experimental uncertainty. Effects of the surface contamination were discussed and the thickness of the surface contamination was estimated to be about 10 Å.

1. Introduction

Ion solid interaction is a very interesting field of research. Some information about ion solid interaction can be obtained by measuring the charge states of the ion passing through solids. Proton is adequate as a projectile, because it is the simplest and most fundamental atomic system. Only one electron transfer process is necessary to be taken into account in the high energy region. Furthermore, fractions of ions do not change after emergence from solids in contrast to the case of heavy ions with many electrons.[1]

The charge changing collision of a proton with an isolated atom is fairly well described theoretically.[2] However, knowledge about electronic states of a hydrogen atom in solids is far from sufficient. Recently, several theories were presented about the charge exchange mechanism of protons passing through solid materials. They are divided into two categories: One is that the surface has an important role. The other is that the surface plays a role only as a boundary. Theories of Trubnikov and Yavlinskii[3] and of Kitagawa and Ohtsuki come into the first category,[4] while theories of Cross[5] and of Brandt and Sizmann[6]-[9] come into the second category.

Phillips studied the charge fractions of proton beams in the energy range 3–200

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keV after passing through thin foils which were freshly coated by evaporation in a scattering chamber.[10] He found the target material dependence of the charge fractions, and pointed out that the material independence which had been reported[11] was due to surface contamination.

In the present experiment, the neutral fractions of backscattered particles from thick C and Au targets and those of transmitted particles through C, Si, and Au foils were measured in the energy range 100-310 keV, and the medium dependence of the neutral fraction was studied. The emergence angle dependence of the neutral fraction was also measured. The effects of surface contamination are discussed quantitatively.

2. Experiment

The charge state distributions were measured by the backscattering method as well as the transmission method. Experimental arrangements are shown schematically in Figs. 1 and 2, respectively. The H^+ beam from a Cockcroft-Walton accelerator was used as projectile.

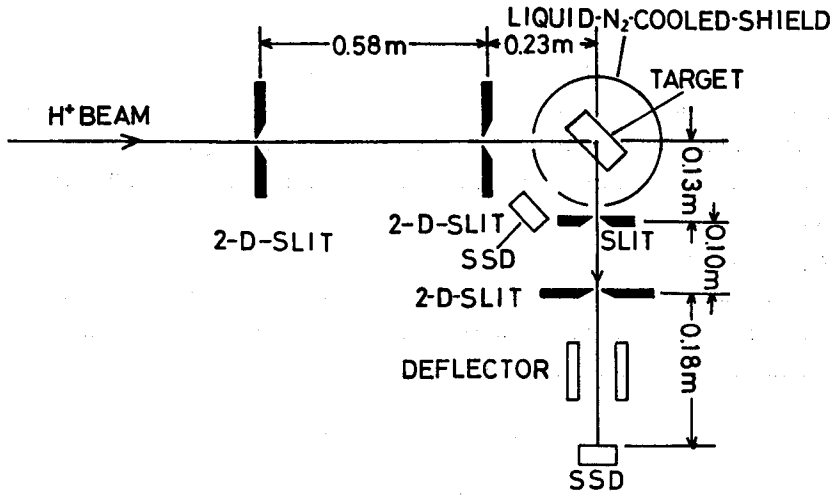

Fig. 1 Arrangement for the backscattering experiment.

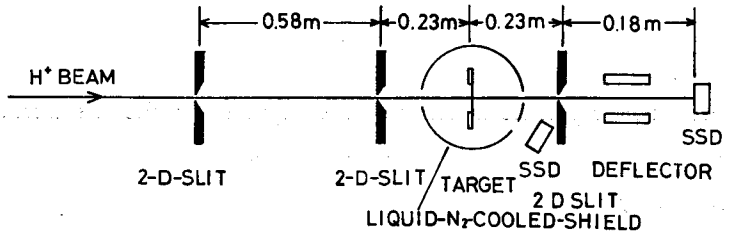

Fig. 2 Arrangement for the transmission experiment.

In the case of the backscattering experiment, the 250 keV proton beam was collimated to 1mm×1.5mm with two 2-dimentional slits. The 90° backscattered particles from thick C and Au targets mounted on a goniometer were selected in their direction with two 2-dimentional slits and were detected with a Si surface barrier detector. In this way both neutral and charged particles were detected. When the electric deflecting field is applied just in front of the detector, only the neutral particles can be detected. From these two measurements the neutral fraction was estimated. Another Si surface barrier detector was mounted in a scattering chamber as a beam monitor. Since backscattered particles have various energies according to the scattering angle and pass length in solids, the charge fraction over a wide range of energy below the projectile energy can be obtained at one time.[12]

In the transmission experiment, the 100-310 keV proton beam was collimated to 0.4mm×0.4mm with two 2-dimentional slits. The transmitted beams through C, Si, and Au foils were detected after collimation with a 2-dimentional slit, with or without an electric deflecting field, just the same as in the case of the backscattering method. The foil was mounted on a target holder which had an aperture of 2.5mm in diameter and was tilted to measure the emergence angle dependence of the neutral fraction. There is a possibility that the particles are scattered from the holder edge resulting in a change of the measured neutral fraction. The beam course was carefully set so that the collimated beam would pass through the center of the target.

The residual gas pressure in the scattering chamber was $1\text{-}2\times10^{-6}$ Torr. In the case of the backscattering experiment, the Au target was evaporated on a thick Au substrate just before the measurement, so as to make surface contamination as small as possible. The following procedures were done to avoid a carbon build up and to reduce gas adsorption. The targets were heated up to more than 300°C and surrounded by a liqiud nitrogen cooled surface.

3. Results and Discussion

The neutral fractions of the backscattered and the transmitted particles are shown in Fig. 3 for the Au, Si, and C targets. There is no difference between the results of the two different methods. The neutral fractions of the Si and C targets are almost equal, while those of the Au target become larger than those of the Si and C targets at higher energies.

If the description is possible in terms of the capture and the loss cross sections in solids, the neutral fraction can be described as follows,

$$\Phi_0=(1+\sigma_l/\sigma_c)^{-1}. \qquad (1)$$

Cross[5] used the gas phase cross section to predict the charge states of protons in

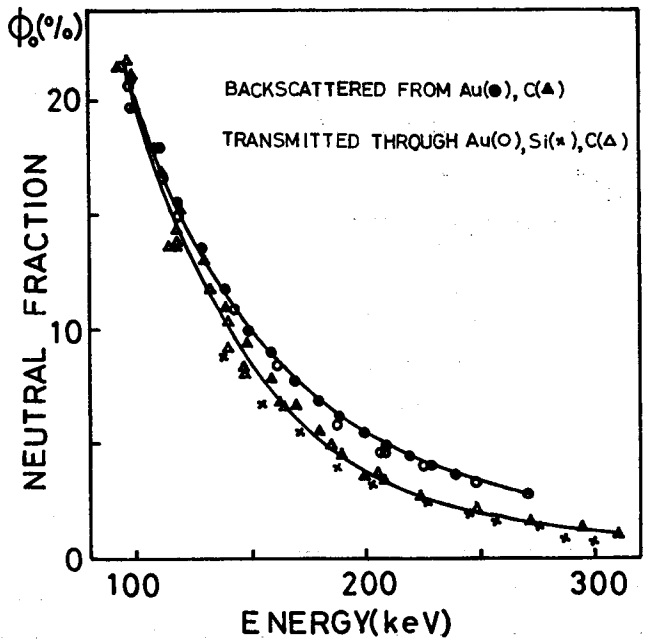

Fig. 3 Neutral fractions of proton beams backscattered from Au (●) and C (▲) targets and transmitted through Au (○) Si (×) and C (△) foils. Solid curves are drawn for eye fit.

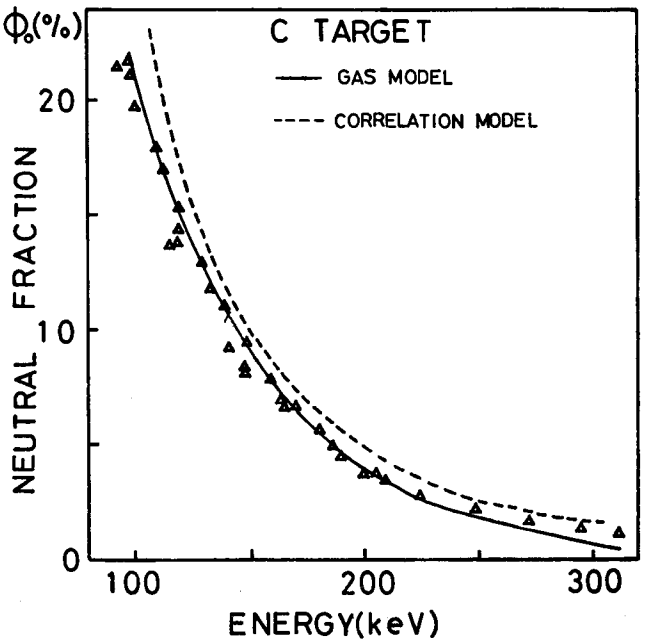

Fig. 4 Neutral fraction by the C target compared with the gas model (solid line) and the correlation model (dashed line).

solids. In the case of the C target, the neutral fractions which were obtained from gas phase cross sections[3] are shown in Fig. 4. They are in good agreement with the experimental results. Brandt and Sizmann gave the following expressions for the correlation gain and loss of electrons in solids,[9]

$$\sigma_c = \pi a_0^2 \frac{2^{18}}{5} \frac{Z_2^5}{V^6\left(V^2+\frac{2^6}{\sqrt[3]{40}} Z_2^{14/9}\right)^3} \qquad 0.3MeV < E_p \qquad (2)$$

$$\sigma_l = \pi a_0^2 \frac{Z_2^{2/3}}{Z_2^{2/3}+V} \frac{4Z_2^{1/3}(Z_2+1)}{4Z_2^{1/3}(Z_2+1)+V} \ ,$$

where Z_2 is the target atomic number, a_0 is the Bohr radius, and V is the proton velocity. There is no expression below 300 keV. Application of these cross sections in expression (1) gives the results shown by the dashed curve in Fig. 4. They are slightly larger than the experimental results.

Fig. 5 shows a comparison of the experimental results of Phillips and our methods as well as the calculation based on the cross sections of Brandt and Sizmann. The calculated values are slightly larger than the experimental values. Those by Phillips are also larger than the present results. The reason is considered as follows. Phillips

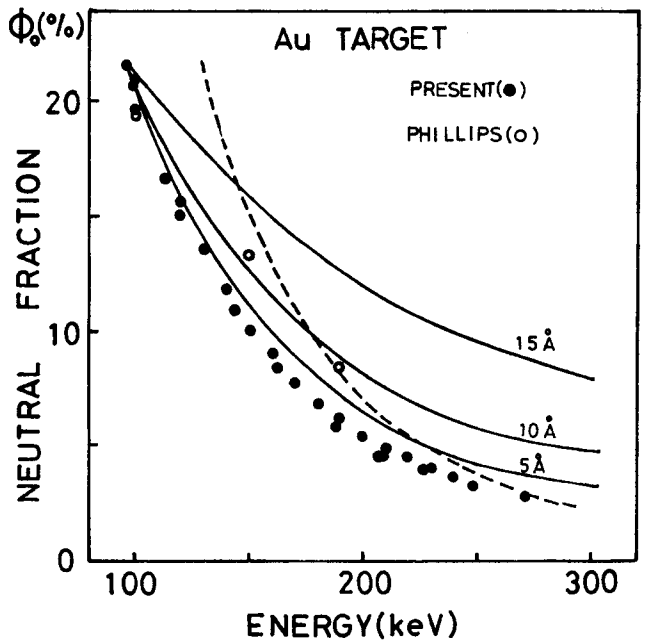

Fig. 5 Neutral fraction by the Au target compared with the correlation model (dashed line). Solid lines are estimated neutral fractions by the clean surface by assuming that the present results are obtained with the 5 Å, 10 Å and 15 Å carbon contaminated layers.

measured the neutral fractions just after evaporation and when the target surface was fairly clean. However, the procedure of the surface cleaning was not done in the present experiment. Hence, there is a possibility of surface contamination, which affects the neutral fraction.

We can estimate the thickness of the surface contamination as follows. The neutral fraction Φ_{osx}, after passing through contaminated layer of thickness x becomes

$$\Phi_{osx}=\Phi_{oc}+(\Phi_{oa}-\Phi_{oc})e^{-(\sigma_c+\sigma_l)\cdot n\cdot x} \tag{3}$$

where Φ_{oc} is the eqilibrated neutral fraction by the contaminated material, Φ_{oa} is that by bulk material, σ_c and σ_l are the cross sections in the contaminated material, and n is the atomic density of the contaminated material. If the contaminated material is assumed to be carbon, the Φ_{oa} by a clean Au target can be calculated. In this way, Φ_{oa} by an Au target with a 5 Å, 10 Å and 15 Å carbon contaminated layer was calculated and shown in Fig. 5. When $x=10$ Å, the values of the neutral fractions agree with those of Phillips. If the results of Phillips were obtained with no contamination, the surface contamination in the present experiment should be 10 Å in thickness.

A different method of estimation of contamination layer is to measure the emergence angle dependence of the neutral fraction. If the emergence angle dependence does not exist under a clean surface condition,* the appearance of an emergence angle dependence should be due to the surface contamination, because the path-length of the beam in the contaminated layer changes with the emergence angle. The dependence of the neutral fraction on the emergence angle is given as follows,

$$\Phi_0(\theta)=\Phi_{oc}+(\Phi_{oa}-\Phi_{oc})e^{-(\sigma_c+\sigma_l)\cdot n\cdot x/\cos\theta}. \tag{4}$$

Emergence angle dependences of the neutral fraction of transmitted and backscattered particles are shown in Figs. 6(a) and (b), respectively. The values of the neutral fraction of the θ emergence case are normalized by those of $\theta=0^0$ (transmitting) and $\theta=20^0$ (backscattering). Experimental accuracy of the backscattering technique is poorer than that of the transmitting technique due to the difficulty of an experimental setup. The emergence angle dependences were not appreciably found in any case. The calculations with eq. (4) are shown in Figs. 6(a) and (b) in the cases of the carbon contamination layer of 5 Å, 10 Å and 20 Å on the gold target. Considering the experimental errors, we concluded that the contaminated layer was less than 10 Å.

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* Theories of Brandt and Sizmann and of Cross do not show at all the emergence angle dependence if the solid surface is clean. The theory of Kiiagawa and Ohtsuki shows only a weak dependence on the emergence angle in the present energy region.

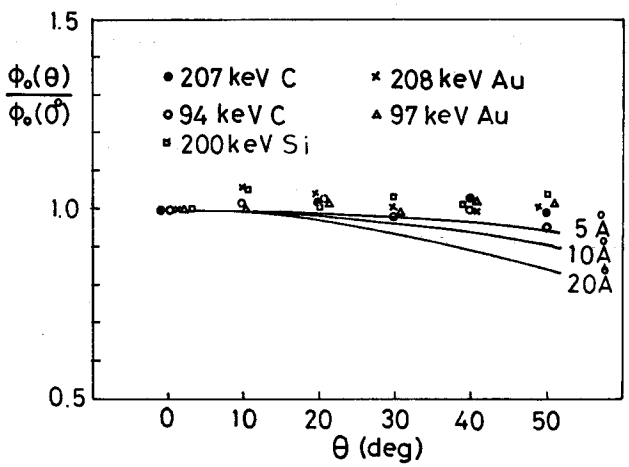

Fig 6(a) Emergence angle dependence of the neutral fraction measured in transmission experiment. Solid lines are the calculations with the contaminations of 5 Å, 10 Å and 20 Å thicknesses.

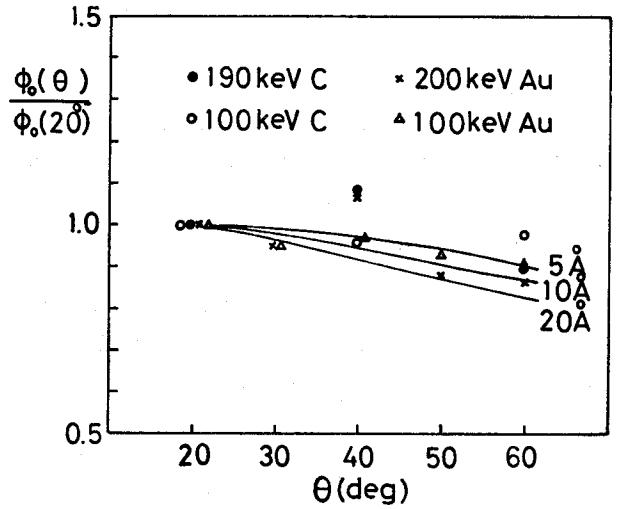

Fig. 6(b) Emergence angle dependence of the neutral fraction measured in backscattering experiment. Solid lines are the calculations with the conbaminations of 5 Å, 10 Å and 20 Å thicknesses.

From the above discussions on the medium dependence and the emergence angle dependence of the Au target, we can conclude that about a 10 Å contaminated layer exists on the Au surface.

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