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TOF analysis of reflection of low-energy light ions from solid targets using coaxial impact collision ion scattering spectroscopy (CAICISS)

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Abstract

The energy spectra of He and D particles reflected from the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$ Sb surface at the angle of π in the sub-keV regime have been studied by means of a CAICISS system. The quantum efficiency of the microchannel plate for the particle detector in the CAICISS system has been determined as a function of the kinetic energy from the comparison of the experimental peak intensity from Sb atoms in the sub-monolayer regime with the theoretical one. The latter is calculated by use of the elastic scattering cross-section derived from the Thomas–Fermi model of the screened Coulomb potential. The energy spectra of He particles backscattered from the Si(1 1 1) substrate on incidence of 2 keV He$^+$ ions have been also obtained by use of the quantum efficiencies determined and compared with the theoretical ones calculated on the large angle single deflection model. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

For detailed understanding of the particle balance as well as the energy balance in the recycling of fuel and ash particles at the plasma facing materials of fusion devices, it is of essential importance to measure directly the energy spectra of the neutral particles emitted through the boundary plasma via the charge exchange processes in dependence on time. One of the most promising techniques for measuring the energy of neutral particle is the time-of-flight (TOF) analysis. For the detection of neutral particles [1], the post-ionization of them by collisions with gas target and by electron and laser irradiation, in the low energy regime, is utilized mostly, which would be responsible for a technical hardness to the direct measurement.

Recently, a microchannel plate used in a commercial coaxial impact collision ion scattering spectroscopy (CAICISS) system [2] has been eventually found to have a significant quantum efficiency in detection of low energy neutral particles. In order to use the microchannel plate for neutral particle detection, it is primarily necessary to determine the absolute value of the quantum efficiency in dependence on the particle energy. So far we have studied the energy spectra of sub-keV helium and deuterium ions reflected from well-characterized Metal/Si(1 1 1) surfaces in the monolayer regime using the CAICISS system in order to develop the technique for measuring the quantum efficiency under the large helical device (LHD) Join Planning Research in National Institute for Fusion Science.

In this paper, we report the experimental data on the quantum efficiencies of the microchannel plate for detection of sub-keV D and He particles in dependence on the kinetic energy. The quantum efficiencies have been estimated from the ratio of the peak intensities of particles reflected from the monolayer metal adsorbates on the Si(1 1 1) surface to the theoretical one calculated

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using the elastic scattering cross-section assumed. Moreover, the experimental energy spectrum of He scattered from the Si(1 1 1) crystal corrected with the quantum efficiency is presented and compared with the theoretical calculation based on the large angle single deflection model [3].

2. Experimental

Silicon specimens used were mirror-polished n-type Si(111) wafers with a resistivity of 3Ω-cm and a size of 25 × 4 × 0.5 mm^3. The specimen was placed on a manipulator in a conventional ultra-high vacuum (UHV) chamber [4], shown schematically in Fig. 1, which was evacuated to a base pressure less than 2×10^{-10} Torr and was equipped with a four-grid optics for low energy electron diffraction (LEED), a double pass cylindrical mirror analyser for Auger electron spectroscopy (AES), a water-cooled solid-state detector for Rutherford backscattering spectrometry (RBS) and an evaporation source for Sb deposition. The UHV chamber was connected through a differentially pumped chamber to a beam line of MeV van de Graaff accelerator and also to the CAICISS system, shown schematically in the inlet.

The specimen surface was cleaned by repeated direct current heatings, during which the specimen was kept around 1050°C for 5 min at a pressures below than 7×10^{-10} Torr. After the cleaning process, the LEED pattern of distinct 7 × 7 spots was observed and the AES spectra did not show any traces of impurities such as C and O. Specimen temperatures higher than 600°C were measured with a radiation thermometer; those lower than 600°C were measured with an alumel–chromel thermocouple.

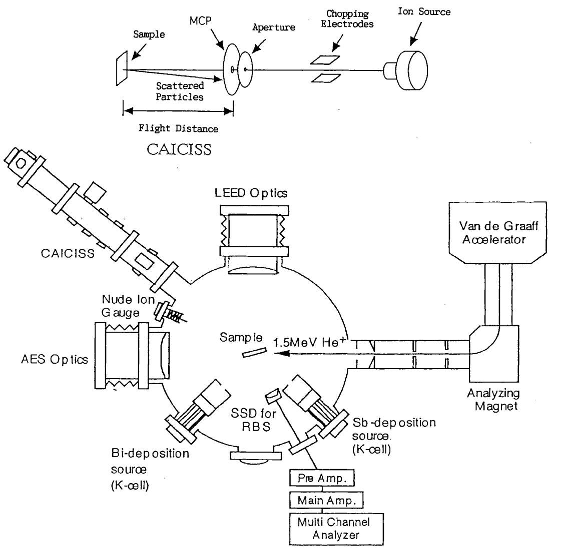

Fig. 1. A schematic diagram of the experimental arrangement and the CAICISS system.

The Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$ Sb surface was prepared by deposition of thin Sb films of about one monolayer (1 ML, 7.8×10^{14} atoms cm^{-2}) in thickness onto the Si(1 1 1)-7 × 7-surface and subsequent heating for 10 min at 300°C. The Sb thickness measured by RBS was 0.90 ML, thus suggesting that there were no Sb islands on the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$ Sb surface.

The time of flight measurements of neutral particles reflected at an angle of ~180° from the sample, irradiated with He$^+$ ions or D_2^+ ions at different incident energies of 2.0, 1.5, 1.0, 0.75 and 0.50 keV, were carried out using the CAICISS system, in which the sample surface was placed at 95 and 120 cm from the microchannel plate (MCP) and the exit edge of chopping electrodes, respectively, and the width and the repetition cycle of the pulsed incident ion beam were 150 ns and 50 kHz, respectively. Although the incident angle of He$^+$ and D_2^+ ion beams was tilted to the surface normal, the crystalline effect could not be removed out from the energy spectra of particles reflected from the Si(1 1 1) substrate, as shown below.

3. Experimental results

Typical TOF spectra of He particles scattered at a scattering angle of $\sim \pi$ from the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$-Sb surface irradiated with He$^+$ ion beam at incident energies of 2.0, 1.5, 1.0, 0.75 and 0.50 keV are shown as a function of time of flight in Fig. 2. At the upper part of Fig. 2, the energy corresponding to the time of flight for scattered He particles is scaled in units of eV. The TOF spectra of D particles were essentially similar to those of He particles. It is clearly seen from Fig. 2 that each TOF spectrum consists of a sharp peak scattered from the Sb adsorbates and a broad peak tailing to the low energy from the Si crystalline substrate, which are laid on the background decreasing very gradually with increasing the time of flight. Moreover, a close inspection of the spectrum for $E_0 = 0.75$ keV indicates that the microchannel plate (detector) responds to bombardment of He particles at round 300 eV. The peak intensity from the Sb adsorbates at the surface of Si substrate in each spectrum of Fig. 2 is shown against the corresponding value of theoretically calculated intensity in Fig. 3. The similar relation was obtained for D particles. The latter values were calculated as the product of the ion fluence, the solid angle of the detector, the elastic scattering cross-section and the quantum efficiency of the detector. The quantum efficiency was assumed to be unity and the scattering cross-sections were calculated from the Thomas–Fermi approximation of the screened Columb potential [5]. It is clearly seen from Fig. 3 that the experimental values deviate from the theoretical straight

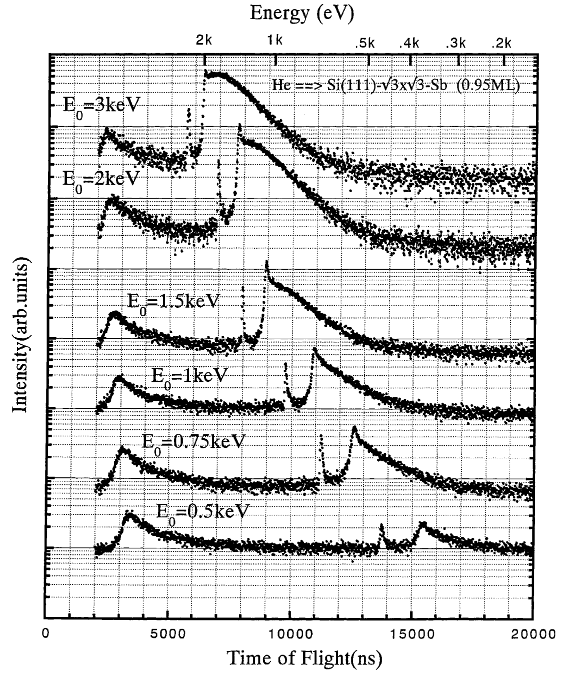

Fig. 2. TOF spectra of He particles reflected from the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$ Sb surface at incident energies of 3.0 2.0, 1.5, 1.0, 0.75 and 0.50 keV.

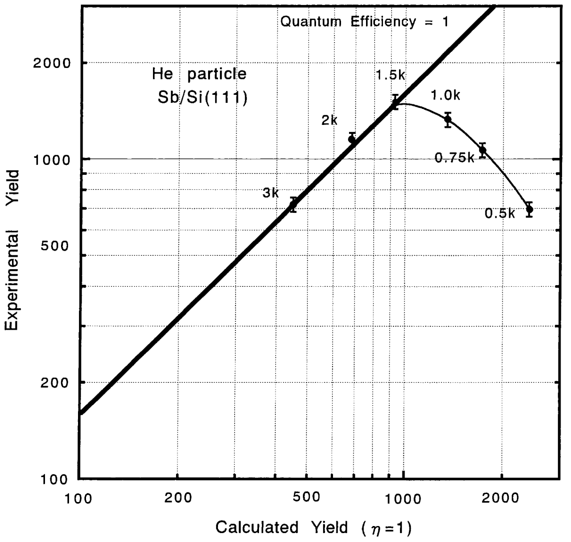

Fig. 3. A plot of the experimental scattering yields of He particles from Sb atoms at incident energies of 3, 2, 1.5, 1, 0.75 and 0.50 keV to the corresponding theoretical ones calculated on assumption that quantum efficiency = 1.

solid line of quantum efficiency = 1 to the lower value with decreasing incident energy. We can estimate the quantum efficiency of detector for the He particles as a function of energy from the ratio of the experimental value to the theoretical one. The estimated values of the quantum efficiency for both He and D particles are shown as a function of the kinetic energy in Fig. 4, where the ratios of a constant level at energies of 3.0, 2.0 and 1.5 keV are reduced to be unity, discussed below.

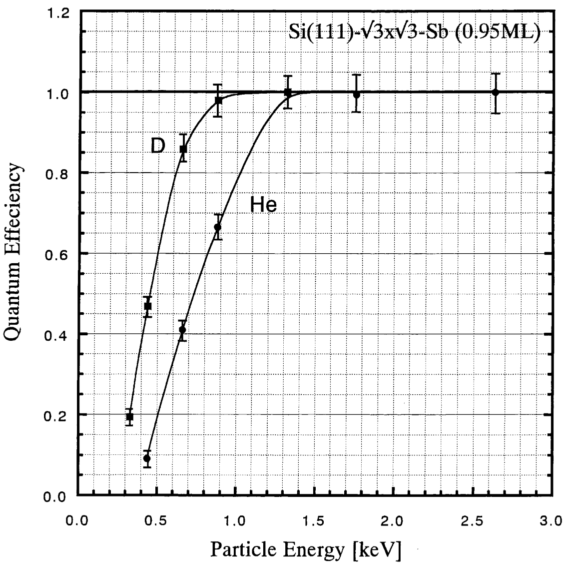

Fig. 4. Quantum efficiencies of MCP (detector) for He and D particles as a function of their kinetic energy.

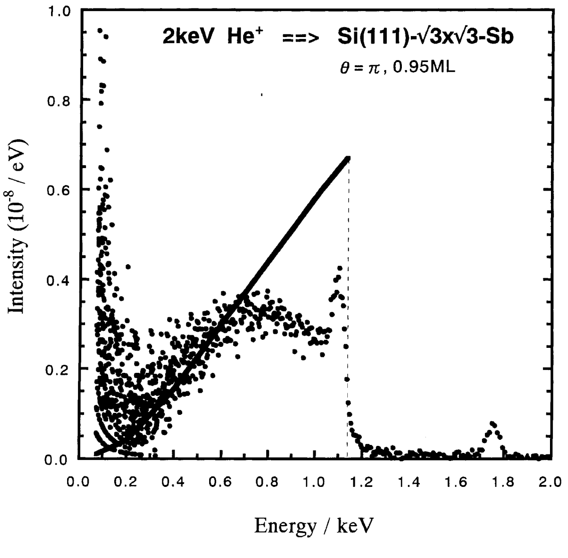

Fig. 5. Experimental backscattering energy spectrum of 2 keV He^+ ions from the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$-Sb surface at the scattering angle of π. The solid line represents the theoretical one calculated on one large angle deflection model.

Using the quantum efficiencies estimated, the energy spectrum of 2 keV He^+ ions from the Si(1 1 1)-$\sqrt{3} \times \sqrt{3}$-

Sb surface was calculated from the TOF spectrum. In Fig. 5, the experimental energy spectrum is compared with the theoretical calculation for the Si non-crystalline substrate, as discussed later.

4. Discussion

It is seen from Fig. 3 that the ratios of the experimental scattering intensities at the incident energies of 3.0, 2.0 and 1.5 keV to the theoretical ones are a constant larger than unity. Since the ratio should be, in general, unity, this fact is concluded to suggest that the elastic scattering cross section assumed is underestimated, which is responsible for the expression of the screening function or the screening distance in the screened Coulomb potential. The value of the screening distance somewhat larger than the Firsov expression $0.8853\ a_0/(Z_1^{2/3}+Z_1^{2/3})^{1/2}$, where a_0 is the Bohr radius and Z_1 and Z_2 are the atomic numbers for the projectile ion and the target atom, leads to agreement of the experimental value with the theoretical one. This correction of the screening distance is concluded to indicate that the screening effect for the He–Sb collision is weaker than the Thomas–Fermi approximation. A more detailed discussion will be done elsewhere [6].

Here, we discuss the energy spectrum of 2 keV He^+ ions scattered from the Si(1 1 1) substrate at the angle of π, shown in Fig. 5. Based on the large angle single deflection model [3], the energy spectrum is expressed by

$$F(E,\pi) = I(E)\ \frac{\sigma(E_1,\pi)}{kS(E_0)+S_{(E)}}\,\mathrm{d}\Omega, \tag{1}$$

where $I(E)$ is the intensity of particles at the energy of E emerging from the surface after scattered at the energy of E_1 inside the target $(E < E_1)$, $\sigma(E_1,\pi)$ the scattering cross-section, $\mathrm{d}\Omega$ the solid angle, $\mathrm{S}(E_0)$ and $S(E)$ the stopping cross-sections of target atoms for projectiles at energies of incidence and emergence and k is the scattering factor of projectile-Si head-on collision. The scattering energy E_1 is connected to the energies of E_0 and E as follows:

$$\int_{E_0}^{E_1} \frac{\mathrm{d}(E')}{N_0 S(E')} = \int_{kE_1}^{E} \frac{\mathrm{d}(E')}{N_0 S(E')}, \tag{2}$$

where N_0 is the number density of target atoms.

The value of $I(E)$ may be estimated on the assumption that the intensity of incident beam decays only when the particles in the beam suffer the scattering over the critical angle θ_c on the paths of incidence and emergence due to one single collision. In such a case, $I(E)$ is given by the following equation:

$$\begin{aligned} I(E) = {} & I_0 \exp\left(-\int_{E_0}^{E_1} \sigma_c(E')\frac{\mathrm{d}(E')}{S(E')}\right) \\ & \times \exp\left(-\int_{kE_1}^{\mathrm{E}_2} \sigma_c(\mathrm{E}')\frac{\mathrm{d}(E')}{S(E')}\right) \end{aligned} \tag{3}$$

with

$$\sigma_c(E) = \int_{\theta_c}^{\pi} \mathrm{d}\sigma(E,\theta), \tag{4}$$

where $\mathrm{d}\sigma$ (E,θ) is the differential cross-section at energy E and at angle θ. According to the Thomas–Fermi model [5], the differential cross-section at angle of π is given by the following equation:

$$\sigma_c(E,\theta) = \frac{a^2}{8}\cdot\frac{f(\varepsilon)}{\varepsilon} \tag{5}$$

with

$$\begin{aligned} & \varepsilon = \frac{Ea}{Z_1 Z_2 \mathrm{e}^2}\,\frac{M_2}{(M_1+M_2)} \quad \text{and} \\ & f(\varepsilon) = 1.309\varepsilon^{1/3}\left[1+(2.618\varepsilon^{4/3})^{2/3}\right]^{-3/2}. \end{aligned} \tag{6}$$

When it is assumed that $(f\varepsilon) = 0.43$ in the calculation of σ_c *(E)* and the stopping cross-section of Si for He is proportional to $E^{1/6}$ in this energy region, we can calculate analytically the backscattering energy spectrum for a parameter of θ_c. One of the best-fitted energy spectra is shown by solid line in Fig. 5, where the low energy tail above 200 eV in the spectrum is only fitted, because the high-energy part coming out form the near surface includes the crystalline effects such as channelling and blocking and the yields below 200 eV are attributed to imperfect subtraction of the background in the TOF spectrum. For best fitting the critical angle θ_c is found to be 25°. Similar calculation was done for the backscattering energy spectrum of 1 keV D_1^+ ion beam, which was compared with that of 2 keV D_2^+ ion beam. In this case the critical angle θ_c for best fitting was found to be 4°. The difference between the critical angles θ_c for He and D is quite reasonable in a qualitative point of view. Finally it is noted that the large angle single deflection model is applicable to calculation of the energy spectrum of light ions scattered to the large angle from solid targets in the sub-keV regime.

5. Summary

The intensity of He and D particles reflected from the Si(1 1 1)-$\sqrt{3}\times\sqrt{3}$-Sb surface at an angle of π and in the sub-keV regime has been measured by means of the CAICISS system. The quantum efficiency of MCP for the particle detector in the CAICISS system has been determined as a function of their kinetic energy from comparison of the experimental intensity from the Sb atoms in the sub-monolayer regime with the theoretical one calculated using the elastic scattering cross-section derived from the Thomas–Fermi model of the screened Coulomb potential.

The backscattering energy spectrum of He particles from the Si(1 1 1) substrate on incidence of 2 keV He^+ ions has been calculated from the TOF spectrum by use of the quantum efficiencies determined and compared with the theoretical one calculated on large angle single deflection model.

Finally, it is to note that the use of MCP for the detector provides with a direct measurement of the integrated energy spectrum of charge-exchanged neutral particles of H, D and He emitted from the core plasma in the fusion devices, by means of the time of flight technique. The low energy limit to the sensitivity of MCP is expected to be 150 eV for D particles in the present study.

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