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Multiple Scattering of Nitrogen Ions on Metal Foils

Masakatsu SAKISAKA*, Minoru TAKASAKI**, and Tetsuo YAMAZAKI***

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Multiple scattering of 4 MeV nitrogen ions on aluminium, copper, silver, and gold foils were experimentally studied. The observed angular distributions of scattered ions were compared with Meyer's theory and a fairly good agreement was found.

INTRODUCTION

In 1962, several workers of the Department of Nuclear Engineering planned to accelerate heavy ions by using the 105 cm cyclotron in the Institute for Chemical Research, Kyoto University. Two years later, carbon and nitrogen ions of 9.8 and 12 MeV in energy, respectively, were obtained by the 3rd-subharmonic mode of acceleration and were extracted to the beam duct successfully.[1] This was the first attempt of MeV heavy ions in Japan and the co-operative efforts of Dr. Uemura and other cyclotron staffs were really appreciable. Many new experiments using heavy ions became able, one of which was multiple scattering†.

In 1969, a 4 MV van de Graaff machine was newly built at the Uji campus of our university, and using this equipment the studies of multiple scattering of protons and nitrogen ions were continued until recently. Some of the results have been reported elsewhere,[2,3] but in this memorial report for Prof. Uemura, the experiment concerning heavy ions is presented.

Multiple scattering is a phenomenon of many and successive collisions of incident ion with medium atoms when it passes through a thin foil. Since the ion is affected by a screened coulomb force in each collision, it makes a zig-zag path and consequently the outgoing ions form a gaussian-like angular distribution, the observation of which leads to the important knowledges of ion-atom interaction potential and procedure of summing up scatterings.

The theoretical treatments for multiple scattering have been carried out by several workers. Williams[4] first considered it statistically. An advanced calculation using Born approximation has been done by Molière,[5] where an appropriate expression of interaction potential and, therefore, a cutoff of differential scattering cross section are elaborately introduced. The treatment by the second Born approximation has been shown by Nigam, Sundaresan and Wu[6] (NSW). These advanced theories are mathematically valid when the mean number of collisions in the foil, denoted as Ω_0, is larger

* 向坂正勝: Department of Nuclear Engineering, Faculty of Engineering, Kyoto University.
** 高崎 稔: At present, Institute for High Energy Physics, Tsukuba, Ibaragi.
*** 山崎鉄夫: At present, Electrotechnical Laboratory, Tanashi, Tokyo.

† This is the master thesis of Yamazaki in 1968 and the experiment was done by counting the scattered ions recorded on nuclear emulsions.

than 20. The case of small Ω_0 is called plural scattering, which has been computed by Keil *et al.*[7] according to the similar procedure of Molière. On the other hand, Meyer[8] has derived a new angular distribution function by applying the classical scattering cross section of Lindhard, Nielsen, and Scharff[9] (LNS). His theory is available especially for collisions of heavy ions with target atoms.

The experiments of multiple scattering have been mainly compared with the theories of Molière, Keil *et al.* and NSW, because in these the Born approximation is extended to the collisions having large values of Born parameter. Overall agreements with Molière's theory and with Keil's treatment are reported for multiple and plural scatterings, respectively. Meyer's theory has been applied by some workers[10,11] in the ion energy range of less than 1 MeV and a fairly good accordance is found also.

Previously, we have observed the multiple scattering of MeV protons and nitrogen ions on copper,[2] and quite recently the accumulated data for aluminium, copper, silver, and gold foils[3] have been presented. These results are consistent with the treatments of Molière and Keil *et al.* but the precise comparison with Meyer's theory has not been done. In this paper, therefore, we pick up the data of 4 MeV nitrogen ions and apply them to his theory.

MEYER'S EXPRESSION FOR MULTIPLE SCATTERING

Using a classical concept, Lindhard, Nielsen, and Scharff[9] (LNS) have derived a differential scattering cross section for a projectile of mass m_1 and charge z_1e incident upon a target atom of mass m_2 and charge z_2e, under an interaction potential of

$$V(r)=\frac{z_1z_2e^2}{r}\varphi\left(\frac{r}{a}\right), \tag{1}$$

where r is the interparticle distance, $\varphi(r/a)$ the Thomas-Fermi function and a the screening radius given by

$$a=\frac{0.8853a_0}{(z_1{}^{2/3}+z_2{}^{2/3})^{1/2}}, \tag{2}$$

a_0 being the first Bohr radius of hydrogen atom. Applying the LNS cross section, Meyer[8] has shown a reduced and spatial angular distribution due to multiple scattering. This is

$$F(\theta)=\frac{\varepsilon^2}{8\pi}\left(\frac{m_1+m_2}{m_2}\right)^2\left[f_1(\tau,\theta)-\frac{a^2}{r_0^2}f_2(\tau,\theta)\right], \tag{3}$$

where the total scattering angle θ, energy ε and foil thickness τ are given in dimensionless units. They are expressed as

$$\varepsilon=\frac{a}{b}=\frac{a}{z_1z_2e^2}E_{\mathrm{cm}}, \tag{4}$$

$$\theta=\frac{\varepsilon}{2}\frac{m_1+m_2}{m_2}\theta_{\mathrm{lab}}, \tag{5}$$

$$\tau=\pi a^2Nt, \tag{6}$$

$$n=\pi r_0^2 Nt, \qquad r_0=1/(2N^{1/3}), \tag{7}$$

here E_{cm} is the projectile energy in center of mass system, θ_{lab} the laboratory angle of outgoing projectile, N the target atoms per unit volume of foil (cm^{-3}), t the foil thickness (cm). The distribution function $f_1(\tau, \theta)$ and the correction term $f_2(\tau, \theta)$ are tabulated in his paper for discrete τ values. The notation n represents the mean number of collisions in the foil.

EXPERIMENTAL

The experimental arrangements are similar to those reported previously,[2] but the outline is briefly discribed in this paper.

Nitrogen ions (N^{2+}) of about 4.5 MeV in energy were produced by using the van de Graaff accelerator and an analyzing magnet. The longitudinal slits each having knife edges collimated the ion beam into about 0.3 mm × 0.3 mm in size. When a medium foil was placed just behind the last slit, the ions were multiply scattered in the foil and formed a gaussian-like angular distribution after passing through it.

Two solid state detectors, one of which was a fixed monitor (M) and the other a movable detector (D), were arranged on the symmetry axis of distribution and detected the scattered ions. Therefore, the count ratio D/M as a function of the detector position directly gave the spatial-angle distribution.

The energy spread of incident ions was maintained within about 5 keV. The accuracy of foil thickness and counting errors were less than 5 and 2%, respectively.

RESULTS AND DISCUSSION

The experimental data have been treated according to the method of Meyer describ-

Table I. Multiple Scattering Data for 4 MeV Nitrogen Ions.

Target	Al	Cu	Ag	Au
ρt ($\mu g \cdot cm^{-2}$)	118	290	283	606
E_{lab} (MeV)	4.18	4.40	4.47	4.37
E_{cm} (MeV)	2.75	3.60	3.96	4.08
a (10^{-9} cm)	1.55	1.29	1.15	0.997
b* (10^{-12} cm)	4.74	8.12	11.9	19.5
r_0 (10^{-8} cm)	1.27	1.14	1.29	1.29
ε	326	159	96.5	51.1
n	1340	1120	825	968
τ	19.8	14.5	6.57	5.78
$F(0)$ cal.	1025	245	228	67
$F(0)$ exp.	1180	215	185	60
deviation (%)	+15	−11	−19	−10
$\theta_{1/2}$ exp.	3.2	2.7	1.3	1.2

* b is the distance of closest approach.

ed before and the results for aluminium, copper, silver, and gold foils are listed in the table. Here ρt is the foil thickness in units of $\mu g \cdot cm^{-2}$ and E_{lab} is given by $(E_i+E_f)/2$ where E_i and E_f are the energies of incident and outgoing ions in laboratory system, respectively. The maximum amplitude of distribution at $\theta=0$ or $\theta_{lab}=0$ is denoted as $F(0)$, the deviation of which is defined as $100\times(F(0)_{exp}-F(0)_{cal})/F(0)_{cal}$. The notation $\theta_{1/2}$ in the last column is the half width at half maximum of spectrum (HWHM).

The angular distributions measured are shown in Figs. 1~4 in normalized forms, together with the curves of Meyer. But in Fig. 1. the curves of Keil *et al.* and NSW are added. The present experiment includes four foils of different atomic number and the values of ε and τ change by factor 3 to 6, but the observed $F(0)$'s stay within less than 20% deviation from the calculated ones. This deviation does not mean a heavy discrepancy, because in normalizing the observed distribution of $I(\theta_{lab})$, $2\pi I(\theta_{lab})$ $\sin\theta_{lab}\,\Delta\theta_{lab}$ becomes zero at $\theta_{lab}=0$ and maximum near HWHM angle — the deviation of $F(0)$ has a small contribution in normalization. In practice the spatial-angle distributions have been often compared by taking $F(0)_{exp}=F(0)_{cal}=1$. Therefore, it can be said that our data are fairly well reproduced by Meyer's treatment.

Andersen and Bottiger[10] have observed multiple scattering of various heavy ions ($z_1=2, 3, 7, 18$) on carbon foil in the energy range of 200–1000 keV. Bernhard *et al.*[11] have investigated lithium ion scattering on carbon and aluminium films, where the

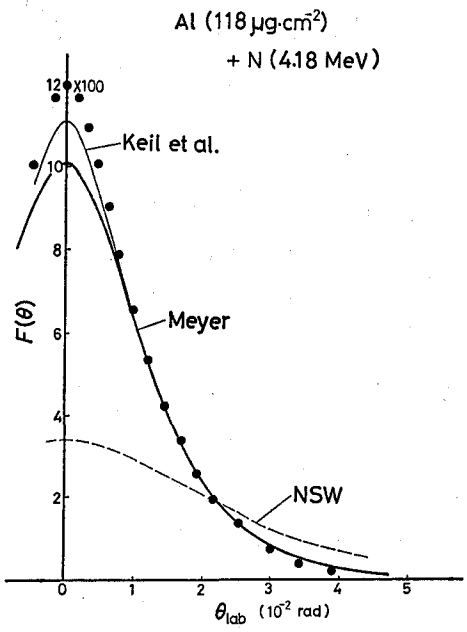

Fig. 1. Reduced spatial-angle multiple scattering distribution of nitrogen ions on aluminium.
Solid circles are experimental. Heavy and thin solid lines are drawn according to Meyer and Keil *et al.*, respectively. Thin broken line is from NSW by taking the potential parameter μ as 1.8, where $V(r)=\frac{z_1 z_2 e^2}{r}\times\exp(-\mu r/a)$.

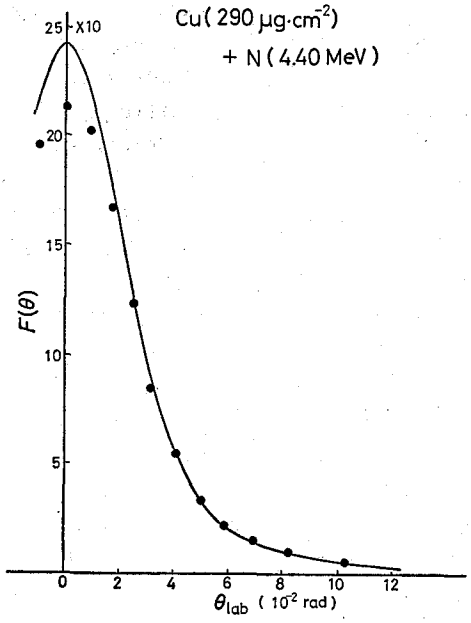

Fig. 2. Angular distribution of nitrogen ions on copper.
Heavy solid lines in Figs. 2~4 are from Meyer's theory.

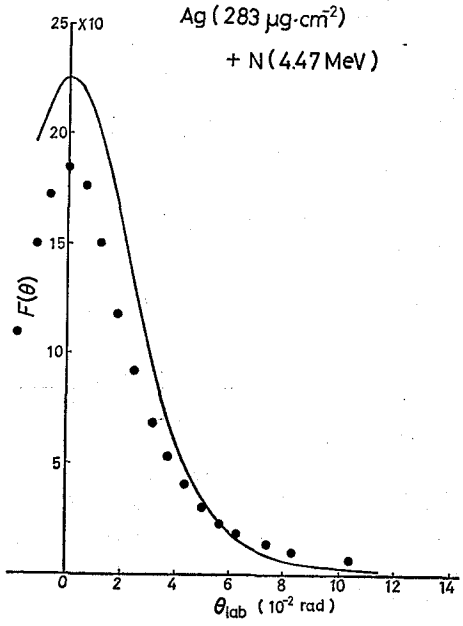

Fig. 3. Angular distribution of nitrogen ions on silver.

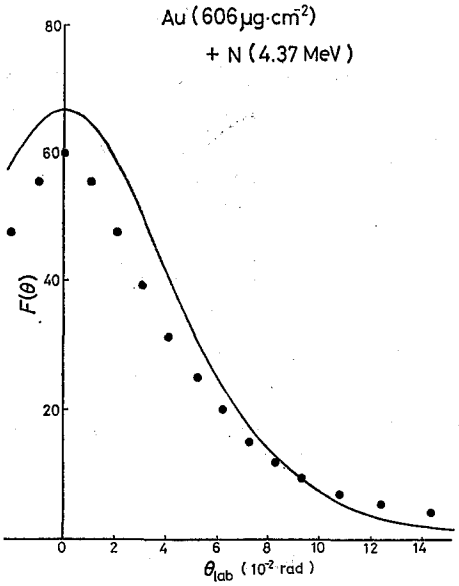

Fig. 4. Angular distribution of nitrogen ions on gold.

energy region is from 10 to 100 keV. In both cases the experiments have been well explained by Meyer's theory.

Since the second term $f_2(\tau, \theta)$ in Eq. (3) is negligible in our case, we have, with the aid of Eq. (5), a universal curve of $\theta_{1/2}$ as a function of τ. This is drawn in Fig. 5 and our observed values are plotted by heavy marks. The data from refs. 10) and 11) are also inserted for the sake of comparison. As stated above, these workers have used low z_2 foils ($z_2=6$, 13) and the energy ranges applied are less than 1 MeV, whereas our experiment has been done using low to high z_2 targets ($z_2=13$, 29, 47, 79) and the ion energies are as high as 4 MeV.

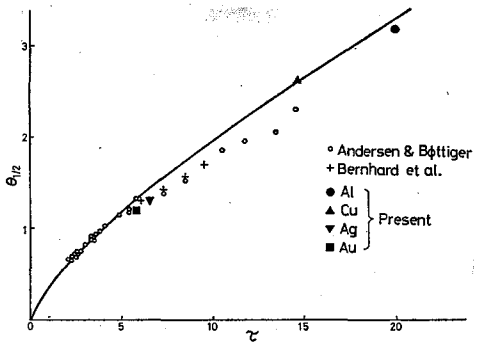

Fig. 5. Half width $\theta_{1/2}$ at half maximum of distribution as a function of foil thickness τ.

Meyer's theory has been said available for heavy ion-atom collisions of low energy range. However, since the whole observed points are distributed closely to the universal curve of Meyer, it would be concluded that his theory is fairly satisfactory in explaining

multiple scattering phenomena and that it is applicable to various ion-atom combinations in the wide region of ion energy.

In our recent paper,[3] we have compared the data of protons and nitrogen ions with the theories of Molière and Keil *et al.*, where the present four cases are included. As a result, the treatment of Molière-Keil has shown a better accordance than the present method of Meyer, as seen in Fig. 1. The theory of NSW has a heavy disagreement with the observation.

ACKNOWLEDGMENTS

In this memorial report, we heartfully appreciate his co-operative contribution of Prof. Uemura to the initiative work of heavy ion physics which was performed from 1962 to 1968 in the Institute for Chemical Research. The fruitful discussion and continuous encouragement of the members of our department should be greatly acknowledged.

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