Bull. Inst. Chem. Res., Kyoto Univ., Vol. 55, No. 1, 1977

# Stopping Powers of Al, Ni, Cu, Ag, and Ta for 8.78 MeV Alpha Particles

Ryutaro ISHIWARI, Naoko SHIOMI, Tamiko KINOSHITA, and Fumiko YASUE*

*Received January 31, 1977*

The stopping powers of Al, Ni, Cu, Ag, and Ta have been measured by using the absorber wheel technique and a silicon detector. In order to examine the possible nonuniformity of the sample foil, the alpha particle beam was made scan in two directions, *i.e.* parallel and perpendicular to the rolling direction of the foil. The agreement between the measurements of two directions was proved to be satisfactory. The present results were devided by 4 and reduced to 2.0 MeV and compared with the proton data from the table of Bichsel. It turned out that the data for alpha particles are by 1.4～3.4 percent higher than those for protons.

## I. INTRODUCTION

In a previous work,[1] in which the possible effect of the geometrical condition on stopping power measurements was investigated, the energy losses of 8.78 MeV alpha particles from $Po^{212}$ in several metallic elements have been measured. In this experiment, in order to spare the time of experiment two foils with slightly different thicknesses were used for each sample element. Therefore, the resultant stopping power obtained in the previous experiment might contain the systematic error arising from the difference of the thicknesses of two foils used as the samples.

The present paper reports the new measurements of the stopping powers of Al, Ni, Cu, Ag, and Ta for 8.78 MeV alpha particles from $Po^{212}$ with more careful precautions.

## II. EXPERIMENTAL PROCEDURE

The experimental procedure is quite the same as described in the previous paper.[1] The absorber wheel technique was used to measure the energy loss of alpha particles in the sample foils. The sample foil was fitted to one of the two windows of the absorber wheel and the other window was left empty. This wheel was rotated in front of the silicon detector. Thus, the pulse heights with and without the absorber foil were measured simultaneously in one exposure. The so-called poor geometry was employed in the present measurements (see Fig. 2 of ref. 1). The pulse height spectrum was calibrated with a precision pulser. The energy of $Po^{212}$ alpha particles was taken as $8.78437 \pm 0.00007$ MeV.[2] The ionization defect of the silicon detector for 8 MeV alpha particles was taken as 13 keV from the work of Lindhard *et al.*[3]

In our absorber wheel technique, the alpha particle beam does not scan all over the area of the sample foil but it scans only $1.5 \times 20$ mm$^2$ area across the sample foil

* 石割隆太郎，塩見直子，木下民子，安江富美子：Department of Physics, Faculty of Science, Nara Women's University, Nara.

when the absorber wheel rotates. In order to examine the possible systematic error due to the nonuniformity of the sample foil, the alpha particle beam was made scan the sample foil in two ways, *i.e.* parallel and perpendicular to the rolling direction of the foil.

The measurements were made five times for each direction and the average values were obtained.

Thickness, purity, and supplier of each smaple foil are as follows:

Aluminium

Thickness: 2.6742±0.0040 mg/cm². Stated purity: 99.8 percent. Supplier: Toyo Aluminium Co., Ltd.

Nickel

Thickness: 3.3774±0.0051 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Copper

Thickness: 3.6871±0.0055 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Silver

Thickness: 4.3987±0.0066 mg/cm². Stated purity: 99.9 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

Tantalum

Thickness: 7.2907±0.0109 mg/cm². Stated purity: 99.99 percent. Supplier: Fukuda Metal Foil and Powder MFG Co., Ltd.

## III. RESULTS

A typical pulse height spectrum is shown in Fig. 1. It was very difficult to remove completely the low energy tail of the peaks. For the peak without the absorber the difference between the mode and the mean was from 0.090 to 0.113 percent of the integral pulse height. These values are not so bad as compared

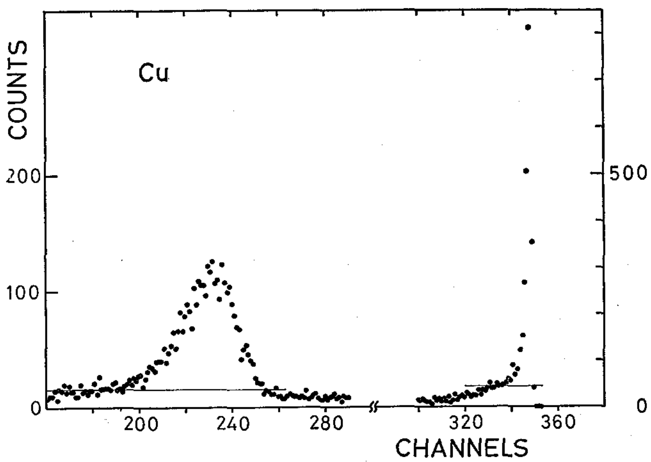


Fig. 1 Typical pulse height spectrum.

with the value 0.07 percent quoted by Hanke and Bichsel.[4]

As in the previous work,[1] the peak position was determined after subtracting the background for each peak. The Background subtraction was made in such a way that the integrated number of counts for the peak with the absorber became equal to that for the peak without the absorber within the limit of the statistical fluctuation.

The actual path lengths of alpha particles in the sample foils were corrected for the multiple scattering using the elementary theory of multiple scattering.[5] The correction was taken as $\langle\Theta^2\rangle/4$, where $\langle\Theta^2\rangle$ is the mean square emergence angle of alpha particles from the foil.

Table I lists the results. The symbol $\Delta E$ denotes the energy loss of alpha particles in the sample foil, $\Delta t$ denotes the actual path length of alpha particles in the foil, $\Delta E/\Delta t$ corresponds to the stopping power, $-\mathrm{d}E/\mathrm{d}x$, at the average energy defined as

$$\bar{E} = E_0 - \Delta E/2$$

where $E_0$ is the incident alpha energy.

The symbol $\bar{E}_p$ denotes the proton energy which has the same velocity as an alpha particle of energy $\bar{E}$. The value of $\Delta E/\Delta t$ was devided by 4 and reduced to the proton energy of 2 MeV. The reduction was made by multiplying $(\ln v^2/v^2)_{2.0}/(\ln v^2/v^2)$.

In Table II, the stopping power values measured with parallel and perpendicular scanning directions are compared. The measurements of two directions agree well with each other except for Al. In the case of Al, the difference are statistically significant. However, if we take the average value of the two values, it becomes $113.65 \pm 0.39$ and the fractional standard error is only 0.34 percent. In the fourth row, the average values of parallel and perpendicular measurements are shown. The error attached to the average value is the propagation error except the case of Al.

In the fifth row the previous results[1] are shown. The agreements between previous and new data are satisfactory.

In Table III, the present results are compared with Bichsel's table.[6] The present results are higher than Bichsel's value by 1.4∼3.4 percent. The stopping power values given by Bichsel for 2.0 MeV protons are the extrapolations of the data of Andersen *et al.*[7∼10] Therefore, the apparent face of Table III nearly agrees with Table I in the paper of Andersen *et al.*[11] which compares the stopping powers for protons of 2.0 MeV with those for alpha particles of the same velocity. This fact indicates that the present results accord well with the data obtained by Confort *et al.*[12] for $Po^{212}$ alpha particles.

However, there is a fact that the data of Andersen *et al.*[7∼10] for 7.0 MeV protons are higher by 1.5∼3 percent than our previous proton data.[13,14]

Although our recent study[15] of stopping powers of various elements for 6.75 MeV protons shows evidences that our previous values for 7 MeV protons[13,14] might be some 1 percent too low, there remains yet a question that the data of Ander-

Table I. Results

| Element | Direction | $\Delta E$ (keV) | $\Delta t$ (mg/cm$^2$) | $1/4\times(\Delta E/\Delta S)$ (keV/mg cm$^{-2}$) | $\bar{E}_p$ (MeV) | $1/4\times(\Delta E/\Delta S)_{2.0}$ (keV/mg cm$^{-2}$) |
|---|---|---|---|---|---|---|
| | Parallel | 1185.79 | | 110.84 | 2.05908 | 114.03 |
| | | ±1.73 | | ±0.23 | | ±0.24 |
| Al | | | 2.6744 | | | |
| | | | ±0.0040 | | | |
| | Perpendicular | 1177.15 | | 110.04 | | 113.26 |
| | | ±1.51 | | ±0.22 | 2.06022 | ±0.22 |
| | Parallel | 1147.22 | | 84.90 | 2.06436 | 87.56 |
| | | ±2.35 | | ±0.22 | | ±0.22 |
| Ni | | | 3.3780 | | | |
| | | | ±0.0051 | | | |
| | Perpendicular | 1149.98 | | 85.11 | | 87.75 |
| | | ±2.03 | | ±0.20 | 2.06391 | ±0.20 |
| | Parallel | 1185.95 | | 80.40 | 2.05998 | 82.74 |
| | | ±2.10 | | ±0.19 | | ±0.19 |
| Cu | | | 3.6879 | | | |
| | | | ±0.0055 | | | |
| | Perpendicular | 1188.39 | | 80.56 | 2.05802 | 82.84 |
| | | ±3.59 | | ±0.27 | | ±0.28 |
| | Parallel | 1125.91 | | 63.97 | 2.06715 | 66.06 |
| | | ±1.78 | | ±0.14 | | ±0.15 |
| Ag | | | 4.4003 | | | |
| | | | ±0.0066 | | | |
| | Perpendicular | 1123.81 | | 63.85 | 2.06741 | 65.94 |
| | | ±2.12 | | ±0.15 | | ±0.16 |
| | Parallel | 1461.02 | | 50.06 | 2.02525 | 50.67 |
| | | ±4.17 | | ±0.16 | | ±0.16 |
| Ta | | | 7.2967 | | | |
| | | | ±0.0110 | | | |
| | Perpendicular | 1454.21 | | 49.82 | 2.02590 | 50.45 |
| | | ±2.30 | | ±0.11 | | ±0.11 |

Table II. Comparison of Stopping Powers Measured with Parallel and Perpendicular Scanning Directions

| Direction | Stopping Powers (keV/mg cm$^{-2}$) Al | Ni | Cu | Ag | Ta |
|---|---|---|---|---|---|
| Parallel | 114.03 | 87.56 | 82.74 | 66.06 | 50.67 |
| | ±0.24 | ±0.22 | ±0.19 | ±0.15 | ±0.16 |
| Perpendicular | 113.26 | 87.75 | 82.84 | 65.94 | 50.45 |
| | ±0.22 | ±0.20 | ±0.28 | ±0.16 | ±0.11 |
| difference | 0.77 | 0.19 | 0.10 | 0.12 | 0.22 |
| | ±0.33 | ±0.30 | ±0.39 | ±0.22 | ±0.19 |
| Average value | 113.65 | 87.66 | 82.79 | 66.00 | 50.56 |
| | ±0.39 | ±0.15 | ±0.17 | ±0.11 | ±0.10 |
| Previous value | 112.93 | — | 82.98 | 66.19 | 50.82 |
| | ±0.20 | | ±0.51 | ±0.32 | ±0.38 |

Table III. Comparison of Present Results with Bichsels Table (keV/mgcm$^{-2}$)

| | Al | Ni | Cu | Ag | Ta |
|---|---|---|---|---|---|
| Present results | 113.65 | 87.66 | 82.79 | 66.00 | 50.56 |
| Bichsel | 110.67 | 86.45 | 81.09 | 63.74 | 49.27 |
| Difference (%) | +2.62 | +1.38 | +2.05 | +3.42 | +2.55 |

sen *et al.* for protons might be still some 1 percent too high.

At any rate, the fact that the stopping power for alpha particles devided by 4 is surely higher than those for protons of the same velocity has been confirmed by the present experiment.

We want to withhold the further discussion of $Z_1^3$ effect and the comparison of the experimental data with theories[16~19] until the stopping power data for protons are certainly established.

## ACKNOWLEDGMENTS

The authors would like to thank Professor T. Yanabu and the members of the Cyclotron Laboratory of Kyoto University for the use of the scattering chamber for the present experiment. One of the authors (R.I.) expresses his heartfelt gratitude to the late Professor Yoshiaki Uemura for the continuous encouragement and support to our stopping power works.

## REFERENCES

(1) R. Ishiwari, N. Shiomi, T. Katayama-Kinoshita, and F. Sawada-Yasue, *J. Phys. Soc. Japan,* **39** 557 (1975).
(2) A. Ritz, B. Grenberg, and D. J. Gorman, "Atomic Masses and Fundamental Constants, Vol. 4 ed, J. H. Sanders, and A. H. Wapstra, Plenum Pub., New York (1972) p. 1.
(3) J. Lindhard, V. Nielsen, M. Scharf, and P. V. Thomsen, *K. Danske Vidensk. Selsk. mat.-fys. Medd.,* **33** (1963) No. 10.
(4) C. C. Hanke and H. Bichsel, *K. Danske Vidensk. Selsk. mat.-fys. Medd.,* **38** (1970) No. 3.
(5) H. A. Bethe and J. Ashkin, "Experimental Nuclear Physics," Vol. 1 ed, E. Segrè, Wiley, New York (1953) p. 166.
(6) H. Bichsel, "American Institute of Physics Handbook," McGraw-Hill, New York (1972) 3rd ed, 8–142.
(7) H. H. Andersen, C. C. Hanke, H. Sørensen, and P. Vajda, *Phys. Rev.,* **153** 338 (1967).
(8) H. H. Andersen, C. C. Hanke, H. Simonsen, H. Sørensen, and P. Vajda, *Phys. Rev.,* **175** 389 (1968).
(9) H. H. Andersen, H. Simonsen, H. Sørensen, and P. Vajda, *Phys. Rev.,* **186** 372 (1969).
(10) H. Sørensen and H. H. Andersen, *Phys Rev.,* **B8** 1854 (1973).
(11) H. H. Andersen, H. Simonsen, and H. Sørensen, *Nuclear Phys.,* **A125** 171 (1969).
(12) J. R. Comfort, J. F. Decker, E. T. Lynk, M. O. Scully, and A. R. Quinton, *Phys. Rev.,* **150** 249 (1966).
(13) R. Ishiwari, N. Shiomi, S. Shirai, T. Ohata, and Y. Uemura, *Bull. Inst. Chem. Res., Kyoto Univ.,* **49** 390 (1971).
(14) R. Ishiwari, N. Shiomi, S. Shirai, and the late Yoshiaki Uemura, *Bull. Inst. Chem. Res., Kyoto Univ.,* **52** 19 (1974).
(15) Our new experiment. To be soon published elsewhere.

(16) J. C. Ashley, R. H. Ritchie, and W. Brandt, *Phys. Rev.*, **B5** 2393 (1972).
(17) J. D. Jackson and R. L. McCarthy, *Phys. Rev.*, **B6** 4131 (1972).
(18) J. C. Ashley, R. H. Ritchie, and W. Brandt, *Phys. Rev.*, **A8** 2402 (1973).
(19) J. C. Ashley, *Phys. Rev.*, **B9** 334 (1974).