Comparison of Energy Losses of Protons and Deuterons of Exactly the Same Velocity

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Energy losses of protons and deuterons of exactly the same velocity, of which the approximate energies are 7.27 MeV and 14.52 MeV, have been compared in the identical aluminium absorbers. The absolute values of the energy losses have been measured with a broad range magnetic spectrograph. Within the experimental uncertainty of about 0.5 percent, the energy losses of protons and deuterons have been found to be the same as theory predicts that they should be. The stopping powers for protons in aluminium have also been determined and compared with the tabulated values of Bichsel and of Sternheimer and with the experimental results of Andersen *et al.*. The present results have been found to be somewhat lower than Bichsel's values and significantly lower than the experimental values of Andersen *et al.*. Sternheimer's values agree best with the present results within the experimental errors.

I INTRODUCTION

According to the Bethe theory[1] of stopping power for heavy charged particles in matter, it is expected that the energy losses for protons and deuterons with the same velocity are just the same.

From 1948 to 1949, there were some discussions on this problem. Wilcox[2] investigated the energy losses of protons from 30 KeV to 400 KeV and deuterons from 30 KeV to 650 KeV in aluminium and gold. The results of Wilcox showed that energy losses of deuterons in gold were higher by about 8.5 percent than protons with the same velocity. He also reported that in aluminium, although somewhat obscure, the same tendency was observed. However, Hall and Warshaw[3], working with the same apparatus as Wilcox at the same laboratory, reported that in gold the energy losses of protons and deuterons never differed by more than 3 percent. They concluded that the results of Wilcox might be in error due to the local non-uniformity of the sample foils. At the same time, they reported that the energy losses in aluminium were lower by about 25 percent than those obtained by Wilcox. Huus and Madsen[4] measured the energy loss of 365 KeV protons in gold and obtained the value which was higher by about 20 percent than the result of Wilcox. From this result, they concluded that the

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results of Wilcox might be within the experimental uncertainties.

These authors did not state anything about the experimental uncertainties of their own experiments. In their experiments very thin absorbers were used due to the rather low energy. So local non-uniformity of the sample foils should affect the experimental results. Taking account of the above situations and of the fact that their results differed by more than 20 percent on the same conditions, it is hardly considered that their experiments had accuracies better than 10 percent. Therefore, from the experimental point of view, the prediction of the theory was never verified with accuracy better than about 10 percent.

In 1953, Bethe and Ashkin[1], in their review article, invoked that the energy loss depends only on velocity within one percent.

Recently, Andersen *et al.*[5] investigated the stopping power of aluminium for protons and deuterons in the energy range from 5 to 12 MeV with the stated error of 0.3 percent. They presented their results in the form of Bichsel's X-variable[6] as a function of the reduced energy $E \cdot M_p/M$, where E is the particle energy, M is the particle mass and M_p is the proton mass respectively. That is, the data for deuterons were treated as data for protons which have the same velocity as deuterons. They noticed that the proton and deuteron points do not fall together as theory predicts that they should. The deviation is about one percent for the reduced energy around 5 MeV as seen in Fig. 4 in their paper which represents the X-variable plot. They concluded, however, that the deviation may be attributed to the independent energy calibrations for protons and deuterons and that the deviation is not significant.

Nowadays, it is not a very difficult thing to compare experimentally the energy losses of protons and deuterons of exactly the same velocity in the identical sample to within 0.5 percent or less.

In the experiment of Wilcox the energy range was too low for the Bethe theory to be exactly valid, although theoretically the energy loss will depend on velocity in complicated ways. In order to check the Bethe theory, it is desirable to perform the experiment in higher energy range.

In the present study, energy losses of protons and deuterons with exactly the same velocity, of which the approximate energies are 7.27 MeV and 14.52 MeV, were measured in the identical aluminium foils by using a broad range magnetic spectrograph and compared with each other.

II EXPERIMENTAL PROCEDURES

In this work, protons and deuterons were obtained from the Kyoto University Cyclotron.

The experimental set up is shown in Fig. 1. The method of measuring the absolute energy loss of the particles when they pass through sample foils with the broad range magnetic spectrograph is an improved method over the one used in the previous experiment for alpha particles[7].

The accelerated particles from the cyclotron were focused with a pair of quadrupole magnets on the object slit S_1 for the sector type analyzing magnet.

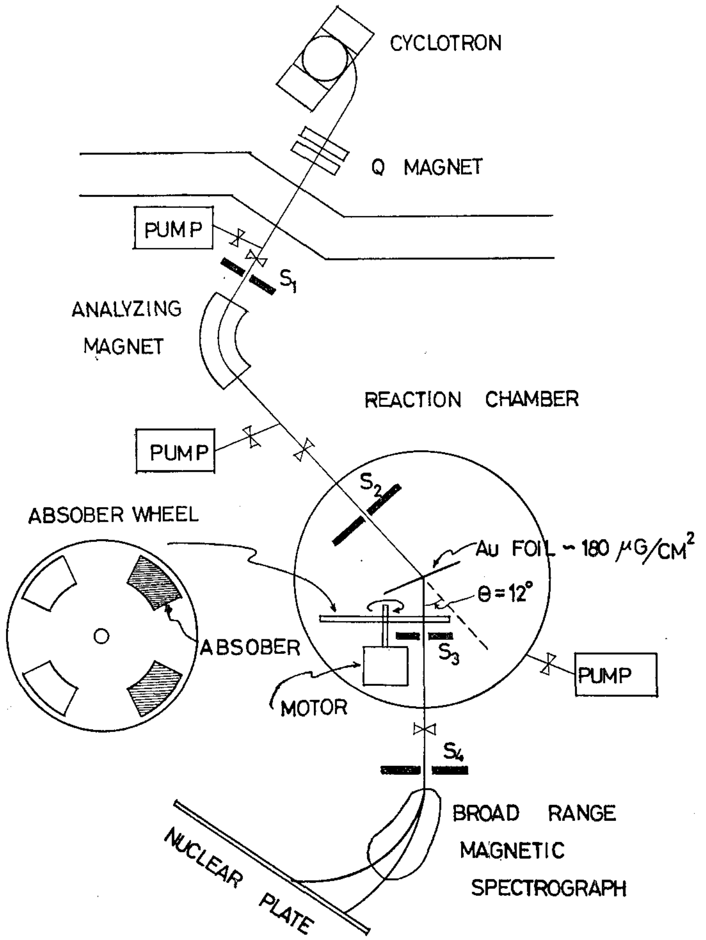

Fig. 1. The experimental set up for the absolute measurement of the energy loss of the particles from the cyclotron by using the broad range magnetic spectrograph.

The momentum of the accelerated particles were determined to within 0.1 percent by the analyzing magnet. The beam was then admitted into the reaction chamber through the slit S_2, the height of which was 0.393 mm and the width was 0.735 mm. Thus, the very sharply defined beam was scattered by a thin gold foil of about 180 $\mu g/cm^2$ thick at the centre of the reaction chamber. The scattered particles at an angle of 12 degrees were used for the absorption measurement. The reason for using the scattered beam was to control the beam intensity. The sample foils were inserted into the scattered beam and the lines with and without the absorber foil were recorded by the nuclear plate* mounted along the focal plane of the broad range magnetic spectrograph. The momentum resolution of the spectrograph was set to be less than 0.1 percent all over the focal plane. Thus, from the shift of the peak position on the nuclear plate with a sample absorber from that without the sample absorber, the energy loss of the particles

* Sakura NRE-1, 100μ, Konishiroku Photo Industries Co. Ltd.

was absolutely determined.

The most important technical point in such an experiment is to keep the incident particle energy as constant as possible during two exposures with and without the absorber. If there were any drift of the incident energy during two exposures, it would affect directly the measured energy loss. In order to keep the analyzed beam energy constant, first of all a high merit of performance of the stabilizer of the analyzing magnetic field is required. In the present experiment, the magnetic field of the analyzing magnet was stabilized by a current stabilizer and was measured by the method of nuclear magnetic resonance immediately before and after each exposure. During the time of exposure from 3 to 5 minutes, the magnetic field was kept constant better than 5 parts in 10^5.

The following special improvement was made in the present experiment as compared with the previous work[7]. The sample foils were fitted on sector windows of the absorber wheel of which one sector window was left empty and the wheel was rotated at 24 r.p.m. in the reaction chamber as shown in Fig. 1. With this device, beams with and without the absorber were admitted alternatively into the broad range spectrograph so that the scattered particles with and without the absorber were recorded on the nuclear plate simultaneously in one exposure. The time of one exposure was from 3 to 5 minutes. By rotating the sample foil, the beam passes through the area of the foil so that the effect of local non-uniformity of the sample foil if any was minimized.

In order to obtain the sharpest peak, the gold scatterer was mounted in such a way that the normal to the scatterer-surface was at an angle of 6 degrees (one half the scattering angle) with respect to the incident beam in the scattering plane.

The slit S_3 was 0.7 mm in height 0.7 mm in width and was placed immediately behind the absorber sample in order to keep the ion optical conditions constant in both cases when the sample foil was inserted into the beam and removed from the beam. The distance from the centre of the scatterer to the absorber sample was 5.2 cm and the distance from the centre to the entrance slit S_4 of the spectrograph was 61.8 cm.

The relation between the distance along the nuclear plate and the radius of the particle trajectory in the spectrograph was calibrated by alpha particles from a Th (C+C′) source. The energy values of the alpha particles were taken from the table of Wapstra *et al*[8]*. The calibration of the magnetic field by thorium alpha rays were performed at the field strengths of 6869.26 gauss and 7601.93 gauss. While the present energy loss measurement were made for protons at 6150.97 gauss and 6608.03 gauss and for deuterons at 12295.84 gauss and 12650.96 gauss respectively. These values of the magnetic field fall on the completely linear portion of the excitation curve of the magnet. Therefore, it is believed that the effect of the fringing field does not play an important role for the measurements at different magnetic field strengths.

The magnetic field of the broad range spectrograph was stabilized by the

* These energy values are in good agreement with the more recent determination by Ritz (*Helv. Phys. Acta*, 34, 240 (1961)).

method of nuclear magnetic resonance.

The nuclear plates were after exposure processed by usual temperature development and were scanned with microscopes with 21 cm long stage. The field of view of the microscope was chosen as 400 microns.

Aluminium foils of two different thicknesses, approximately 17 microns and 37.5 microns, were used. Both foils were rolled ones with the stated purity of 99.8 percent and 2 cm by 2 cm square samples were cut from 20 cm by 20 cm square sheets. The weights of the foils were measured with a microbalance with the sensitivity of 1 μg, and the measurements were repeated five times for each foil and the average values were determined. The areas of the foils were measured with a microscope with a micrometer stage which can read to 1 micron. The area measurements were also repeated three times for each foil and the average values were obtained.

The Kyoto University Cyclotron can accelerate deuterons and molecular hydrogen ions up to about 14.5 MeV. In order to convert molecular hydrogen ions into protons, a thin aluminium foil of about 6.8 microns, the stripper, was inserted to the molecular beam before the object slit S_1 of the analyzing magnet. Because the insertion of the stripper into the beam is accompanied by certain reduction of the velocity of protons, for the deuteron beam a foil of about 15.5 microns thick was inserted to make the velocity of deuterons nearly equal to that of protons.

In the present study, it was attempted to compare the energy losses of protons and deuterons with exactly the same velocity in the identical sample absorber. Such a condition was realized by setting the analyzing magnetic fields in the following way. The equations of motion for protons and deuterons in the analyzing magnetic fields are

$$m_p v_p = eH_p \rho,$$

and

$$m_d v_d = eH_d \rho,$$

where m_p and m_d are masses of proton and deuteron with velocities v_p and v_d, H_p and H_d are the magnetic fields for protons and deuterons. The radius of curvature of particles, ρ, is a constant proper to the apparatus.

Hence on the condition

$$v_p = v_d$$

one obtains

$$H_d/H_p = m_d/m_p = m_{0d}/m_{0p},$$

where m_{0p} and m_{0d} are the rest masses of proton and deuteron. Thus, the velocities of protons and deuterons were made equal to the limit of the stability of the analyzing magnetic field.

Exposures were made twice for both protons and deuterons.

III RESULTS AND DISCUSSIONS

As already mentioned, the magnetic field of the analyzing magnet was measured immediately before and after each exposure by the method of proton resonance. The average value of the resonance frequency throughout the measurements were

$$f_d = 42.01035 \pm 0.00084 \text{ Mc/sec},$$

$$f_p = 21.01518 \pm 0.00030 \text{ Mc/sec},$$

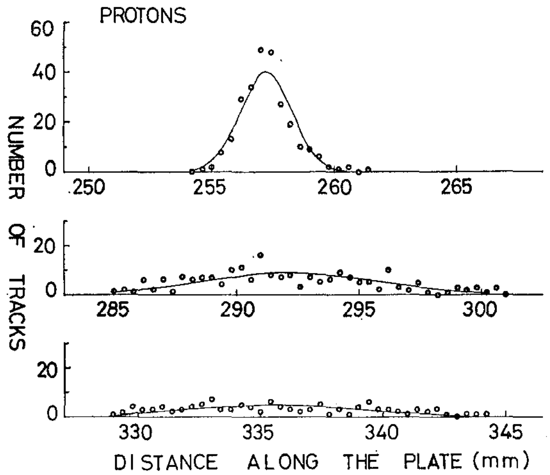

Fig. 2. The typical histogram for protons. The solid curves show the fitting by normal distribution.

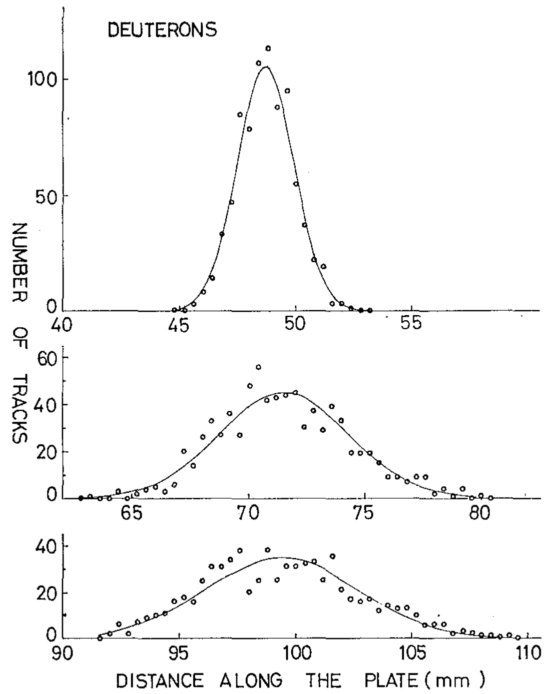

Fig. 3. The typical histogram for deuterons. The solid curves show the fitting by normal distribution.

where f_p and f_d are the frequency for protons and deuterons. Since the magnetic field is proportional to the frequency, the ratio of the magnetic fields was

$$H_d/H_p = f_d/f_p = 1.999048 \pm 0.000049$$

in the present work. While from the mass data[9]

$$m_{0d}/m_{0p} = 1.99900762 \pm 0.00000061.$$

Thus the velocities of protons and deuterons were equal on the average to within 0.002 percent.

Typical histograms for protons and deuterons are shown in Fig. 2 and Fig. 3. The abscissa is the distance along the nuclear plate. In the case of protons, the peaks with absorbers are somewhat obscure because of higher dispersion than deuterons and shortage of exposure time. The peaks, however, can be fitted fairly well with normal distribution. Therefore, mean values could be satisfactorily determined from these peaks.

The kinetic energy was calculated by the well known formula

$$E = m_0c^2\left\{\sqrt{\left(\frac{eH\rho}{m_0c}\right)^2+1}-1\right\}$$

where m_0 is the rest mass of the particle, c is the light velocity, e is the elementary charge, and $H\rho$ is the measured magnetic rigidity. Physical constants[10] of 1965 were used in the calculation. The rest mass of deuteron was obtained from the mass table of König *et al.*[9].

The energy values of each peak for protons and deuterons are shown in Table I and Table II respectively.

Table I. The energy values and the energy losses for protons.

Run		Absorber thickness (micron) 0	17	37.5
1	E(KeV)	7271.88±0.91	7075.91±1.43	6826.67±2.00
	ΔE(KeV)		195.97±1.70	445.21±2.20
2	E(KeV)	7267.67±1.32	7068.80±1.96	6818.38±2.49
	ΔE(KeV)		198.87±2.36	449.29±2.81

Table II. The energy values and the energy losses for deuterons.

Run		Absorber thickness (micron) 0	17	37.5
1	E(KeV)	14514.32±0.15	14316.09±0.16	14072.20±0.18
	ΔE(KeV)		198.23±0.22	442.12±0.23
2	E(KeV)	14517.58±0.16	14321.06±0.18	14070.31±0.20
	ΔE(KeV)		196.52±0.24	447.27±0.19

In Table I and Table II, errors are only statistical. As shown in the tables, the values of incident energies are rather dispersed than are expected from the stability of the analyzing magnetic field. Since the measurement of the frequency of the proton resonance device has very high accuracy, the observed dispersion of the energy values may be attributed to some random error in the course of data treatment. Most probable cause of this error might be the difficulty of reading the position of the edge of the nuclear plate with a microscope of high magnification. Any way, it is reliable that the incident energy had been kept constant better than 1 part in 10^4 from the analyzing magnet data. So that the arithmetic mean was taken for both protons and deuterons.

The average values of incident energies and energy losses are shown in Table III.

Table III. The average values of incident energies and energy losses for protons and deuterons. Figures in the parenthesis are the fractional errors. All errors are standard errors. The fractional difference for protons and deuterons for each absorber are also shown.

Particle	Incident energy (KeV)	Energy losses and Fractional error (%) 17 microns	37.5 microns
proton	7269.78±2.11	197.42±1.45 (0.73)	447.25±2.04 (0.46)
deuteron	14515.95±1.63	197.38±0.86 (0.44)	444.70±2.58 (0.58)
Difference		0.04±1.69	2.55±3.29
Fractional Difference (%)		0.020	0.50

The velocities corresponding to tabulated incident energy values are $v_p=(3.71041 \pm 0.00054)\times 10^9$ cm/sec and $v_d=(3.70835\pm 0.00021)\times 10^9$ cm/sec respectively. The fractional difference is 0.056 percent, and is larger by one order of magnitude than expected from the stability of the analyzing magnetic field. Because this difference is caused by some error of data treatment, it is believed that the actual velocities of protons and deuterons were equal to each other within 0.002 percent.

From Table III, it can be concluded that the energy losses of protons and deuterons of exactly the same velocity are equal within the experimental uncertainties of about 0.5 percent. If we consider more minutely, the reduction of velocities of protons and deuterons by passing through a foil of finite thickness are different by a factor of about two. As shown in Table III, however, the energy losses of protons and deuterons with exactly the same incident velocity are equal within the experimental uncertainty. No further consideration was made on this point.

From the accurate measurements of surface densities of the aluminium sample foils, the stopping power of aluminium for protons was obtained. Since the absorber foils have finite thicknesses, the calculated value of $\Delta E/\Delta x$ is considered to correspond, to the first approximation, to dE/dx at the average energy defined as $E_0 - \Delta E/2$, where E_0 is the incident energy. The results are shown in Table IV.

In Table IV the calculated values of Bichsel[11] and Sternheimer[12] and the experimental values of Andersen *et al.*[5] are compared with the present results.

For both thicknesses, Bichsel's values are higher than the present results.

Table IV. Stopping power of aluminium for protons.

Foil thickness (mg/cm^2)	4.5585±0.0018	10.1175±0.0023
Energy loss (KeV)	197.42 ±1.45	447.25 ±2.04
Average energy (KeV)	7171.07 ±2.23	7046.15 ±2.34
dE/dx ($KeV/mg/cm^2$)	43.41 ±0.32	44.21 ±0.20
Bichsel[a)] ($KeV/mg/cm^2$)	43.775	44.342
Andersen[b)] ($KeV/mg/cm^2$)	44.02 ±0.3 %	44.60 ±0.3 %
Sternheimer[c)] ($KeV/mg/cm^2$)	43.65	44.18

a) H. Bichsel, ref. 11.
b) H. H. Andersen *et al.*, ref. 5.
c) R. M. Sternheimer, ref. 12.

The differences, however, are less than twice of the uncertainties of the present work. Therefore, it cannot be concluded that the difference are statistically significant.

Andersen's values are higher than the present results by just twice the uncertainties of the experimental values. So that the differences are barely significant with 5 percent significance level.

Sternheimer's values agree best with the present results.

Further expriments are now under way on the other elements.

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