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STOPPING POWERS OF Al, Cu, Ag AND Au MEDIA
FOR 1.47 MeV/u ^{127}I , 2 MeV/u ^{32}S AND ^{79}Br IONS.

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Abstract :

The stopping powers of Al, Cu, Ag and Au solid targets for ^{32}S and ^{79}Br at $E/A = 2$ MeV/u and for ^{127}I at 1.47 MeV/u have been measured by the transmission technique using a high resolving power magnetic spectrometer and an associated position sensitive proportional gas counter as a detector system. The results are compared to the semi-empirical formula of Ziegler et al and to the tabulation of Northcliffe and Schilling. Finally, they are used to set the limits of validity of the Hubert et al formula at low incident energies.

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1. INTRODUCTION

Data relative to the stopping power and energy straggling for incident heavy ions in cold matter are still needed for the analysis of experiments in nuclear physics and in the studies devoted to improve the energy resolution of thin solid state detectors.

Concerning the stopping powers within the 2-10 MeV/u incident energy range, many experimental data are available [1-6]. However, their comparison to most of the tabulated calculations [7-11] shows significant discrepancies, and the corpus of data available for incident heavy ions such as ^{32}S , ^{79}Br or ^{127}I with energies around 2 MeV/u still needs to be completed.

In a series of experiments carried out at the Orsay-Institut de Physique Nucléaire on the MP tandem accelerator, we have undertaken the study of the slowing down of ^{32}S , ^{79}Br and ^{127}I heavy ions traversing Al, Cu, Ag and Au solid degraders of various thicknesses with $E/A \equiv 2$ MeV/u. Accurate measurements of the ion energy losses ΔE were performed using the transmission technique with the Split-Pole spectrometer [12,13]. For these measurements, the spectrometer was set at 0° relative to the beam direction

The present paper describes the experimental technique and reports on the measured stopping powers, and their comparison with the semi-empirical calculations of Ziegler et al [10], and of Northcliffe and Schilling [8]. It also compares these data with those calculated by the Hubert et al [11] semi-empirical formulae at energies below the limit of validity given by these authors (2.5 MeV/u).

2. EXPERIMENTAL SET-UP AND PROCEDURE

2.1. Ions beams and beam intensity reduction

A schematic view of the experimental set-up is shown in Fig. 1.

Beams of $^{32}\text{S}^{7+}$, $^{79}\text{Br}^{11+}$ and $^{127}\text{I}^{12+}$ heavy ions were generated with energies of 64.0, 158.0 and 186.4 MeV, respectively, corresponding to $E/A = 2.0$, 2.0 and 1.47 MeV/u. To ensure a good stability of the machine, the beam intensity was maintained at a value of at least 10 nA at the definition slits (CONTROL SLITS) located in the focal plane of the 90° analysing magnet during the course of all the experimental runs. On the other hand, the detection system could only be operated with a particle intensity less than 10^3 sec^{-1} incident on the target. A reduction of the initial beam intensity by a factor of about 10^7 was thus required. During this procedure, the beam intensity was monitored using the position sensitive detector described in § 2.3. However, as the primary beam was too intense for this counter, it was scattered using a gold target of 1 mg/cm^2 or $50 \text{ }\mu\text{g/cm}^2$ in thickness, placed at the center of the reaction chamber, and the scattered beam was recorded in the counter while approaching the spectrometer towards 0° .

The intensity reduction was made gradually by two independent means :

Firstly, a stripper consisting of a $20 \text{ }\mu\text{g/cm}^2$ thick carbon foil was placed in the beam path after the control slits. At the exit of this stripper, the beam split up into a distribution of charge states a minor component of which was selected and directed towards the target chamber by a 28° switching magnet. This procedure allowed an attenuation of the beam intensity by a factor of about 3000.

Secondly, two diaphragms, one of circular shape with an aperture of 0.1 mm diameter and the other being a $10 \text{ mm} \times 0.1 \text{ mm}$ rectangular slit, were appropriately set between the stripper and the switching magnet, at places where the beam was unfocused. The beam fraction transmitted through each diaphragm is roughly equal to the ratio of the diaphragm aperture section to that of the beam spot. Taking into account the beam spot area at each of the diaphragms (25 mm^2 and 10 mm^2 respectively), the first one reduced again the beam intensity by a factor of about 3000 and the second one by a factor of about 10.

Finally, attenuated direct beams of $^{32}\text{S}^{8+}$, $^{79}\text{Br}^{19+}$ and $^{127}\text{I}^{25+}$ were selected and used in the experiments.

2.2. Targets

Al, Cu, Ag and Au targets of various thicknesses were prepared by vacuum evaporation at the Orsay-Institut de Physique Nucléaire. Prior to their use in the heavy ion experiments, their thicknesses were determined accurately and their nonuniformities carefully studied by using alpha particles from a ThC radioactive source, and a set-up which had been constructed previously for this purpose [14]. A systematic mapping of the target area was performed by determining the thickness x of each foil at several points through measurements of the energy loss of alpha particles. The macroscopic nonuniformity y of each foil was evaluated by the relation :

$$y = (x_{\max} - x_{\min}) / \bar{x} \quad (1)$$

where $x_{\max}$, $x_{\min}$ and $\bar{x}$ are the measured maximum, minimum and mean foil thicknesses, respectively. Then, target foils having a macroscopic nonuniformity less than 2 % were selected and used in the heavy ion slowing down experiments during which their uniformity was checked again.

At a microscopic level, the good degree of uniformity of the target foils was confirmed by the satisfactory fits of the energy loss straggling measured for alpha particles by curves obtained from the Bohr and the Bethe-Livingston theories [15,16], as can be observed in Fig. 2 for 8.78 MeV α particles crossing Au foils.

In the heavy ion experiments, for each run, four targets of the same material were fixed onto a mounting system with five target positions, one position being kept free for recording the direct incident beam profile. In this way, the target thickness was easily varied without breaking the vacuum within the chamber ($\cong 10^{-7}$ Torr).

2.3. Detection system and procedure : determination of the heavy ion energy losses

As stated above, the degraded ions were momentum analyzed with an Enge split-pole magnetic spectrograph at 0° relative to the beam, and detected with a system located in its focal plane. This detection system was 50 cm long and composed of three compartments, (i) a position-sensitive proportional counter similar to the one described in reference [17], (ii) a proportional counter acting as a ΔE counter and (iii) a 5 mm thick plastic scintillator. The useful length of the counter was sufficient to record almost the whole charge state distribution of the beam exiting the target (see for example, in fig 3, the charge state distribution of ^{127}I ions after the traversal of a $300 \mu\text{g}/\text{cm}^2$ -thick Au foil).

For each distribution, the individual charge states Q were unambiguously identified using an approximated value of the stopping power. Then, the energy of the outgoing ions was accurately determined from the knowledge of Q and the measurement of the associated magnetic rigidity. Indeed, for an ion deflected by the magnetic field of the spectrometer (whose intensity is denoted by B) according to a bending radius ρ , the magnetic rigidity $B\rho$ is given by the (non relativistic) relation :

$$B\rho = P/Qe = k \sqrt{EA} / Q \quad (2)$$

where P , Q and e are the ion momentum, its charge state and the electronic charge unit, respectively, and where E and A are the energy and atomic mass of the ion. The constant k is equal to 0.1438 if B is expressed in Tesla, ρ in m, and E in MeV.

In principle, the curvature radius ρ of the trajectory leading to a given point (of the PSD coordinate) could be calculated from the characteristics of the magnet. However, in order to get a better accuracy in the measurements, calibration curves, $\rho = f(u)$, such that reported in Fig. 4 were established at the beginning of each run and for each ion of known energy. For that purpose, the beam profiles obtained without any target were recorded for a series of B values.

For this calibration, and for the energy loss measurements, the mean position u , and full width at half maximum Δu of the peaks in the position spectrum were determined using an

automatic analysis and assuming a Gaussian shape, which led to the identity $\Delta x = 2.35 \sigma$ (σ being the corresponding standard deviation).

For each given incident beam of known energy E_i entering the target under study, the degraded energy E_f of each outgoing charge state Q was thus determined by using eq (2), in which the value of $\bar{\rho}$ was determined from that of u through the calibration curve, and in which the magnetic field B was measured with a NMR probe.. The incident beam energy loss in the traversed foil was then simply derived as :

$$\Delta E = E_i - E_f \quad (3)$$

2.4. Stopping power determination and results

For each incident beam and target of thickness x , the stopping power $S = dE/dx$ was determined using the approximate relation [1] :

$$S(E) \equiv \Delta E/x \quad (4)$$

the value

$$E = \frac{E_i + E_f}{2} \quad (5)$$

being the beam average energy in the target.

The relative uncertainty in the determination of $S(E)$ can be derived from eq. 4 :

$$\frac{\delta S}{S} = \frac{\delta(\Delta E)}{\Delta E} + \frac{\delta(x)}{x} \quad (6)$$

The relative uncertainties in x were directly deduced from the foil thickness measurements while those in ΔE were derived from eq. (2). The detailed development of eq. (6) can be found in Refs. [18,19]. Finally, one gets the following expression of the uncertainty :

$$\frac{\delta S}{S} = 4 \frac{E}{\Delta E} \frac{\delta B}{B} + 2 \frac{\delta \rho}{\rho} + \frac{\delta x}{x} \quad (7)$$

As $\delta B/B$ and $\delta \rho/\rho$ are of the order of $\pm 10^{-4}$, the overall relative uncertainty in each measured $S(E)$ can be estimated to less than $\pm 3 \%$.

The measured stopping powers are given in Tables 1-3 and plotted in Fig. 5-8.

3. DISCUSSION

3.1. Comparison with other experimental data and calculated curves.

In figs 5,6, the present experimental results are compared with data from previous studies (refs. [20-26]), indicated by open symbols. The following remarks can be made regarding this comparison :

A fair agreement is observed between the present results and the previous ones whenever they exist in the same energy range and for the same couple projectile-target (i.e. for I+Al, and I+Ag). The present data are also consistent with the previous ones when they extend them to higher energies (Br+Al, Ag, Au). Note that this comparison is less precise for the data concerning I+Au, because of the scatter of both the previous and present experimental points. Finally, for the couples S+Al, Br+Cu, and I+Cu, the results from this work are the only data available.

The results obtained with the Ag targets may also be compared with the stopping powers of xenon for various ions, measured in ref. [27]. This comparison is interesting because the Xe atomic number and mass are not far from the Ag ones, and because an anomaly had been observed for these gaseous targets. The corresponding results are recalled in fig. 7. The anomaly consisted in the presence of high stopping power values (relative to the Northcliffe and Schilling calculations) in the energy region around 2 MeV/u, especially for Cu and Kr

projectiles. For Ag targets, no anomaly is observed (see fig. 6a) even for bromine ions which are very close to krypton.

In figs 5 and 6, the experimental data are also compared with the calculated curves from Northcliffe and Schilling [7], and from Ziegler [8]. It should be noted first that the curves from the two parameterizations are generally in good agreement with each other (within 5%). Most of the experimental results agree also with the calculated values. However, a deviation of about 10% is observed for the stopping powers of Br in Al, the experimental stopping powers being higher than the calculated ones. This deviation confirms the observations made previously at slightly higher energies, for Kr ions in Al [1,2].

3.2 Application of the parametrization of Hubert et al.

In this section, the experimental data are compared with the values calculated using the semi-empirical method of Hubert et al [11]. This method is based on a Q^2 scaling of the heavy ion stopping powers relative to those of ^4He nuclei or protons. The effective charge used for heavy ions is parametrized according to equations which are given in ref [11], and which result from a fit of all existing experimental stopping powers in the range 2.5 to 100 MeV per nucleon. Therefore, the parametrization is given to be valid only in this energy range. It is however interesting to try and apply it to energies below 2.5 MeV/u, in order to test the real limits of its validity.

The calculated curves are shown in figs 8 and 9. At energies close to 2 MeV/u, a fair agreement is observed with experimental data whenever they exist, i.e. for S and Br projectiles and for all targets. This agreement is still observed at lower energies for the lightest targets (Al, Cu), but significant deviations (20%) appear around 1 MeV/u for the heaviest ones (Ag, Au). Therefore, the Hubert et al parametrization seems to remain applicable at energies

between 1.5 and 2.5 MeV/u, at least for projectiles lighter than Iodine and targets lighter than Silver, with an accuracy better than 10%.

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$$E_i/A = 2 \text{ MeV/u}$$

Target Material	$\bar{x}$ (mg/cm ²)	E/A (MeV/u)	ΔE (MeV)	S(E) (MeV.cm ² /mg)
Al	0.315	1.913	5.6	17.6
	0.53	1.871	8.3	15.6
	0.70	1.835	10.6	15.1
Cu	0.55	1.895	6.7	12.1
	0.96	1.819	11.6	12.0
	1.55	1.712	18.4	11.8
Au	1.23	1.885	7.3	6.0
	2.32	1.781	14.0	6.0
	3.49	1.669	21.2	6.1

Table 1 - Measured stopping powers for incident 64 MeV (2 MeV/u) ^{32}S heavy ions. The symbols are defined in the text.

$$E_i/A = 2 \text{ MeV/u}$$

Target Material	$\bar{x}$ (mg/cm ²)	E/A (MeV/u)	ΔE (MeV)	S(E) (MeV.cm ² /mg)
Al	0.321	1.916	13.2	41.1
	0.53	1.866	21.2	40.0
	0.99	1.739	41.2	41.7
Cu	0.555	1.899	16.0	28.9
	0.96	1.821	28.2	29.3
	1.55	1.718	44.5	28.7
Au	0.88	1.877	19.5	22.1
	1.17	1.845	24.5	20.9
	1.69	1.764	37.3	22.1
Au	1.19	1.888	17.6	14.9
	2.45	1.768	36.7	15.0
	3.60	1.661	53.6	14.9

Table 2 - Same as table 1 for incident 158 MeV (2 MeV/u) ^{79}Br ions.

^{127}I

$$E_i/A = 1.467 \text{ MeV/u}$$

Target Material	$\bar{x}$ (mg/cm ²)	E/A (MeV/u)	ΔE (MeV)	S(E) (MeV.cm ² /mg)
Al	0.321	1.395	18.4	57.4
	0.53	1.353	29.1	54.9
	0.99	1.244	56.8	57.3
Cu	0.555	1.382	21.8	39.3
	0.96	1.319	37.8	39.3
	1.44	1.237	58.7	40.8
	1.55	1.197	68.8	44.3
Au	0.500	1.403	16.6	33.1
	0.88	1.354	29.0	32.8
	1.17	1.325	36.2	31.0
	1.69	1.250	55.3	32.8
Au	1.19	1.365	26.6	21.9
	2.45	1.221	62.6	25.5
	3.60	1.135	84.6	23.5

Table 3 - Same as table 1 for incident 186.4 MeV (1.467 MeV/u) ^{127}I ions.

Figure 1 - Experimental arrangement. After strong attenuation of its intensity, using a **stripper** and **two diaphragms**, the beam was directed by the **switching magnet** towards the **target** placed inside the vacuum chamber. The outgoing slowed down ions were focused by the **Split-Pole magnetic spectrometer** onto a **position sensitive** proportional gas counter located in its focal plane. In this schema, the Split-Pole is not placed at 0° relative to the incident beam direction at variance with the position adopted in the present experiments.

Figure 2 - Energy straggling results (Ω_{exp}) for 8.78 MeV α -particles from a ThC radioactive source slowed down in Au. The data are plotted against the energy loss ΔE in the target. The measured values are consistent with the Bohr (Ω_B) and the Bethe-Livingstone (Ω_{B-L}) theories, indicating a good degree of uniformity of the targets at a microscopic level.

Figure 3 - Position spectrum showing the charge state distribution resulting from the passage of the incident $^{127}\text{I}^{25+}$ ions through a 300 $\mu\text{g}/\text{cm}^2$ thick Au target.

Figure 4 - Calibration curve of the detection system giving the bending radius versus the position, $\rho = f(u)$, for a ^{79}Br heavy ion beam.

Figure 5 - Comparison of experimental stopping powers for S, Br and I ions from the present work (black dots) with the results of previous studies (open symbols), and of calculations from Northcliffe and Schilling (solid lines) and Ziegler (dotted lines).
 a) for Al targets (open circles are data from ref [20], open triangles from refs [20,21])
 b) for Cu targets (open squares are data from ref [22]).

Figure 6 - Same as figure 5

a) for Ag targets (open circles are data from ref [20], open triangles from refs [20,21], and open squares from ref [22])

b) for Au targets (open circles are data from ref [25], open triangles from refs [20,21,24,25], and open squares from ref [22,23,24])

Figure 7 - The xenon anomaly : the xenon stopping powers for Ne, Ar, Cu and Kr projectiles are compared to Northcliffe and Schilling calculations (from ref. [27]).

Figure 8 - Comparison of experimental stopping powers for S, Br and I ions from the present work (black dots) and of the results of previous studies (open symbols), with the calculations from Hubert et al [11] (solid lines).

a) for Al targets

b) for Cu targets

Figure 9 - Same as Fig.8..

a) for Ag targets

b) for Au targets