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J. HERAULT, R. BIMBOT, H. GAUVIN, R. ANNE[*], G. BASTIN[**] and
F. HUBERT[***]

Institut de Physique Nucléaire, BP 1, F-91406 Orsay Cedex, France
[*]*GANIL, BP 5027, F-14021 Caen, France*
[**]*CSNSM, BP 1, F-91406 Orsay Cedex, France*
[***]*CENBG, Le Haut Vigneau, F-33170 Gradignan, France*

Résumé : Les pouvoirs d'arrêt de 12 solides et de 10 gaz, et les fluctuations des pertes d'énergies, ont été mesurés à l'accélérateur GANIL pour les ions $^{16-17}O$, ^{40}Ar, ^{40}Ca, $^{84-86}Kr$, ^{100}Mo et $^{129-132}Xe$ dans le domaine d'énergie 24 à 95 MeV/u. Après une description rapide de la méthode expérimentale, un ensemble de résultats est présenté et discuté Il est montré, en particulier, que lorsque le projectile tend à être totalement épluché, une paramétrisation simple déduite des pouvoirs d'arrêt des ions $^{4}He^{++}$ à même vitesse devient applicable pour le calcul des pouvoirs d'arrêt des ions lourds. Simultanément l'effet solide-gaz, observé à basse énergie, tend à disparaître.
Les fluctuations des pertes d'énergie ont été comparées aux valeurs déduites du modèle de Bohr et du modèle plus complet de Titeica. Quand le projectile est totalement épluché, les valeurs théoriques restent trop petites d'un facteur 2. Pour des ions partiellement épluchés ce désaccord augmente mais il apparaît, dans la dispersion des pertes d'énergie, que la composante liée aux fluctuations des échanges de charge pourrait expliquer les observations expérimentales.

Abstract : The stopping powers of 12 solids and 10 gases and the associated energy loss straggling have been measured at GANIL for $^{16-17}O$, ^{40}Ar, ^{40}Ca, $^{84-86}Kr$, ^{100}Mo and $^{129-132}Xe$ ions in the energy domain 24 to 95 MeV/u. After a brief description of the experimental method, the set of data are presented and discussed. As far as stopping powers are concerned, a scaling law in Z_p^2 relative to the ^{4}He stopping powers at the same velocity becomes applicable when the projectile tends to be fully stripped. At the same time, the solid-gas effect, observed at low energy, vanishes. The energy loss straggling is compared to that deduced from Bohr model and some of its refinements. The theoretical value appears to be too small, by a factor 2, when the projectile is fully stripped. For partially stripped ions, the charge exchange straggling might explain the experimental observation.

1. INTRODUCTION

The study of heavy particle penetration through matter is important for nuclear physics in connection with the analysis of experiments. The penetration also provides information on the stopping process itself. Up to now, data concerning stopping power, energy loss straggling and angular straggling were very scarce in the intermediate energy domain from 20 to 100 MeV/u. This energy domain is of great interest because it corresponds to a simplification of the slowing down process when the projectile tends to be totally stripped and the relativistic effects are still minor.

This talk summarizes the results of an experimental study of heavy ions penetration undertaken at the GANIL national facility /1/. Results concerning stopping powers and energy loss straggling in solids and gases will be given. The angular straggling results have been published recently /2/.

2. EXPERIMENTAL SET-UP

2.1. Energy measurements

The energy measurements presented in this work have been performed at GANIL, using the LISE magnetic spectrometer /3/. The magnetic rigidity $(B\rho)_0$ of the incident beam is determined with a relative uncertainty of $\pm 10^{-4}$ using the beam monochromator situated at the exit of the machine.

The incoming beam is focused onto the target T using four quadrupoles lenses q_1 to q_4 (see Figure 1). Beam profiles are registered by gas filled or secondary emission multiwire detectors (according to the beam intensity).

Fig. 1 : General lay-out of the LISE spectrometer. T is the target position, I the intermediate focal plane and E the final achromatic focus point. The symbols BD1-2-3 indicate the beam diagnostics.

The energy measurements are made using the first part of the spectrometer LISE, with a setting of quadrupoles Q_1, Q_2, Q_3, Q_4 and dipole D_1 which ensures a dispersive relation between the object focal plane T (target box) and the image focal plane I /3,4/.

2.2. Targets

2.2.1. Solid targets

Targets of ten elements from Be to Au have been used as degraders. All these targets have been prepared from commercially available material with purity higher than 99 %. Mylar films have also been used as targets. The thickness of each sample is determined by the ratio of weight to area. The mean target thickness is thus determined with a precision of about ± 1 % /4/.

2.2.2. Gaseous targets

The measurements relative to gaseous media were performed by introducing a closed gas cell into the target box T. The nickel windows of the cell have a diameter of 8 mm and a thickness between 0.9 and 4.5 mg.cm^{-2} depending on the pressure used. The beam path length inside the gas cell is 14 cm. The cell is filled at a gas pressure of 100 to 5000 hPa which is measured with a precision better than ± 1 hPa using an absolute pressure sensor. The temperature is measured in the cell by a Pt 100 gauge with a precision better than ± 0.1°C. The uncertainty in gas thickness which arises from temperature and pressure measurements is less than ± 1 %. Eleven gases (H_2, He, N_2, Ar, Kr, Xe, CO_2, CF_4, CH_4, C_4H_{10}) commercially produced with a purity higher than 99.99 % have been used as absorbers.

3. STOPPING POWERS

3.1. Experimental

The principle of the method is to measure accurately the energy loss ΔE of ions in a target of given thickness. The measurements of incident (E_i) and degraded energy (E_f) are made using the magnetic spectrometer LISE. The stopping power (S) is derived from these measurements through the approximation

$$S(E) = - \frac{dE}{dx} \simeq \frac{\Delta E}{x} = \frac{E_i - E_f}{x} \tag{1}$$

in which E stands for the mean energy in the degrading target

$$E = \frac{E_i + E_f}{2} \tag{2}$$

The validity of approximation (1) is discussed in ref. /5/. The uncertainties in these energy measurements are discussed in refs. /4,7/. They are typically of the order of ± 2 %.

3.2. Results and discussion

The stopping powers have been measured for 11 gaseous media for the projectiles $^{17}O^{8+}$ (84 MeV/u), $^{40}Ar^{15+}$ (30 MeV/u), $^{40}Ar^{16+}$ (44 MeV/u), $^{86}Kr^{29+}$ (43 MeV/u) and $^{132}Xe^{35+}$ (27 MeV/u) /1/. Only the results for the ions ^{17}O and ^{132}Xe which are representative of the extreme behaviours of stopping powers at GANIL energies are presented here. The stopping powers of gaseous media are plotted in Figs. 2 and 3 versus the stopper atomic number Z_2 for ^{17}O and ^{132}X projectiles respectively. The values obtained for solid media with the same projectiles at the same energies /6,7/ are also plotted in these figures. These experimental values are compared with those from the simple assumption of fully stripped ions. This scaling law is derived from the standard relation used in most of the semi-empirical tabulations which consists in calculating the heavy ion stopping power S_{HI} from the ^4He one (S_{He}) at the same velocity through the effective charge parametrization :

$$\frac{S_{HI}}{\gamma^2 Z_1^2} = \frac{S_{He}}{\gamma^2_{He} Z^2_{He}} \qquad (3)$$

In eq. (3) Z_1 is the atomic number of the incident ion $\gamma_{He} = 1$ for the energies concerned here, $Z_{He} = 2$ and the parameter γ (effective charge parameter) is a function of the ion velocity, of Z_1 and of the stopping medium atomic number Z_2 /9/.

For fully stripped ions, the parameter γ is equal to unity, then equation (3) reduces to :

$$S_{HI} = \frac{S_{He} Z_1^2}{4} \qquad (4)$$

The S_{He} values are taken from Ziegler /8/ (and are also tabulated in /9/.

The solid lines drawn in Figs. 2 and 3, correspond to this fully stripped assumption (T.E.). It can be seen that it leads to a fair agreement with the experimental data obtained for ^{17}O projectile at 84 MeV/u (see Fig. 2). From this figure, if we compare the data relative to solids and gases, we can conclude that the solid-gas effect, observed at low energy /10,11/, disappears when the projectile is totally stripped.

In figure 3, i.e. for the data relative to the ^{132}Xe projectile at 25 MeV/u, it can be seen that the fully stripped assumption leads to values about 20 % higher than the experimental ones for solid targets. This observation is consistent with the fact that the Xe ions outgoing the target are only partially stripped. Moreover, one can remark that the stopping powers of gaseous media are smaller than those measured in solid media. This solid gas effect is of the order of 20 %, in quantitative agreement with the results obtained at lower energies /10,11/.
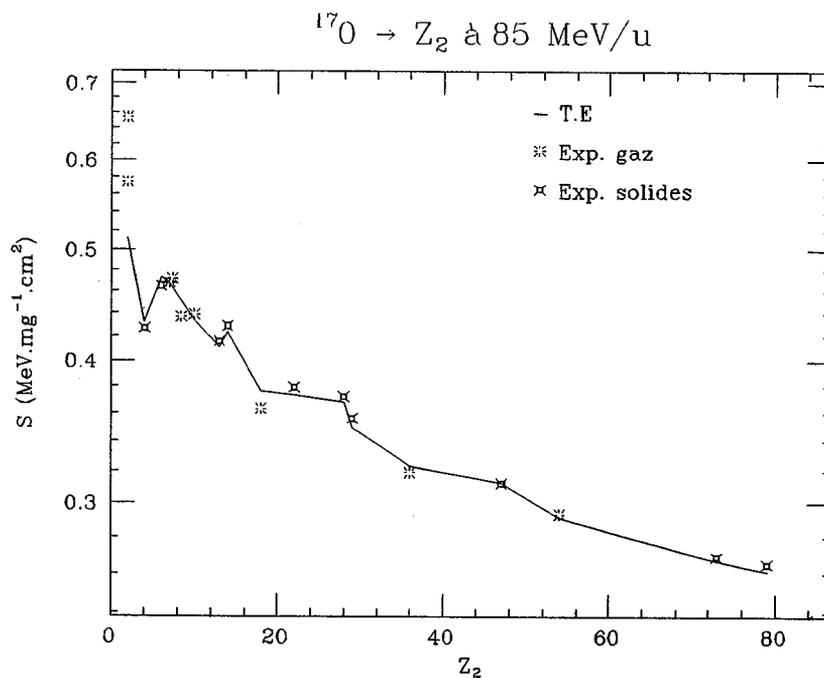
$$^{17}O \rightarrow Z_2 \text{ à } 85 \text{ MeV/u}$$

Fig. 2 : Stopping powers of solid and gaseous media (atomic number Z_2) for ^{17}O ions at 85 MeV/u. The solid line corresponds to the fully stripped assumption (T.E.).

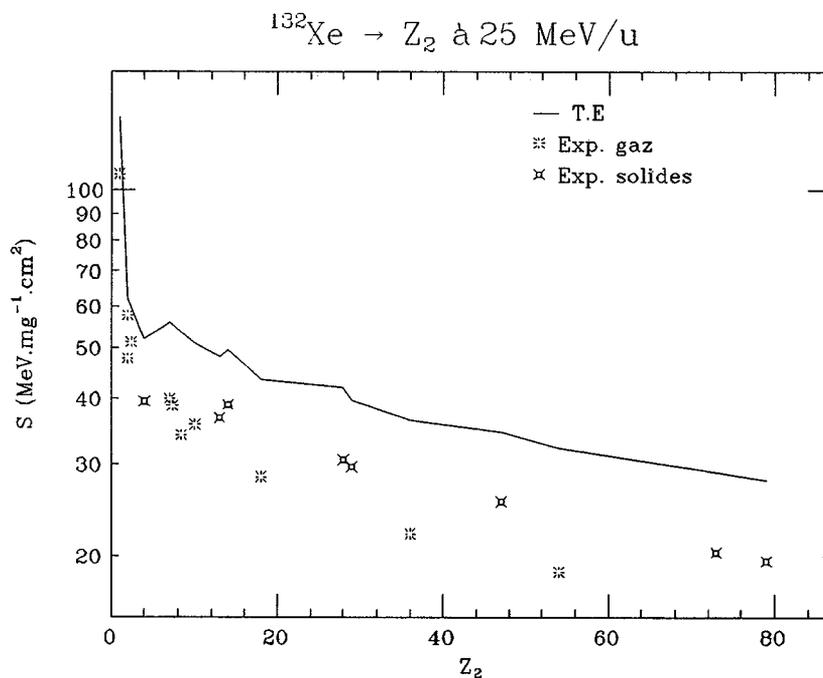$$^{132}Xe \rightarrow Z_2 \text{ à } 25 \text{ MeV/u}$$

Fig. 3 : Same as Fig. 2 for ^{132}Xe ions at 25 MeV/u.

It follows from the analysis of these two extreme and of intermediate situations encountered with other ions and energies /1/, that the solid-gas effect is really linked to the ion charge state.

We have shown its persistence when the projectile is partially stripped and its vanishing when the ion is fully stripped. This observation is in agreement with the Bohr model /12/ which predicts a higher effective charge in solids than in gases due to a higher frequence of collisions.

4. ENERGY LOSS STRAGGLING

4.1. Main contributions to the straggling at intermediate energy

The energy loss straggling in this velocity regime comes from two different contributions. The first one results from the statistical nature of the slowing down process by electronic collisions and the second from the statistical fluctuations of the ion charge state. At high energy, the first contribution can be expressed by the Bohr formula /13/ :

$$\Omega^2_B = 4\P Z_1^2 Z_2 N\Delta X \qquad (5)$$

Here Z_1 and Z_2 denote the nuclear charge of the projectile and target atoms, respectively and $N\Delta X$ the number of target atoms per unit area.

With decreasing projectile energy, the assumption of free target electrons can no longer be valid, and refinement concerning the electron binding energies have to be included in the Bohr theory. Titeica /14/ worked out a more complete formulation which can be expressed /1/ by :

$$\Omega^2_{Ti} = \Omega^2_B + \frac{4}{3} E_{cin} S_B \Delta X \qquad (6)$$

Here E_{cin} denotes the average electron kinetic energy in the stopping material and S_B the stopping power of Bloch /15/ which may be replaced by a stopping power value derived from experiment or tables.

The formula (5) is derived from the assumption of a constant charge Z_1 of the moving ion. When the ion is partially stripped, an effective charge γZ_1 must be used. However, the ion charge state fluctuates statistically. This phenomenon generates the second contribution to the energy loss straggling, Ω^2_C.

This term can be calculated analytically /16/ if only two charge states are present (with a significant probability) during the ion passage through matter.

As the collisional and charge exchange energy loss distributions are independant (and approximatively gaussian) the total straggling is found by adding their

variances :

$$\Omega^2 = \Omega^2_{Ti} + \Omega^2_C \tag{7}$$

4.2. Experimental results and discussion

The full width at half maximum (FWHM) of the beam energy distribution (denoted δE) resulting from the absorber traversal is obtained from the difference

$$\delta E^2 = \delta E^2_{total} - \delta E^2_{beam} \tag{8}$$

Where δE_{total} and δE_{beam} are respectively the FWHM measured on the beam profiles with and without absorber. Note that, for gaseous media, the term $\delta_{E~beam}^2$ takes into account the additional straggling in Ni windows.

The experimental results have been directly compared to the theory by plotting the ratio of the experimental straggling δE to the calculated collisional (δE_{Ti} or δE_B) as a function of the fraction of ion energy lost in the absorber. The results for ^{16}O projectiles at 49.6 MeV/u are shown in figure 4. One can remark
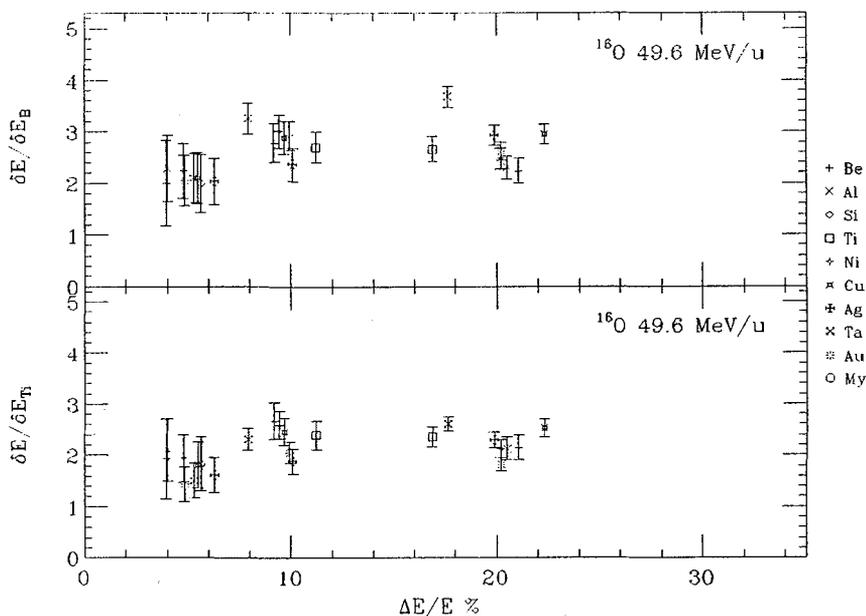

Fig. 4 : Ratio of the experimental energy straggling δE (FWHM) for ^{16}O projectile at 49.6 MeV/u to the calculated collisional δE_B or δE_{Ti} versus the relative energy lost in the absorber. δE_B refers to the Bohr's theory and δE_{Ti} to the Titeica formulation. Symbols of the different absorbers are given on the right side.

that the collision straggling is not sufficient to explain the experimental values. In this case, the charge exchange straggling cannot be involved because

the projectile is totally stripped /7/. Moreover, it appears from these comparisons that the Titeica formula slightly reduces both the disagreement between theory and experiment and the dispersion of the points. This effect is especially obvious for heavy targets.

These discrepancies are not due to target inhomogeneities as can be seen in Fig. 5 in which identical ratio $\delta E/\delta E_{Ti}$ are observed for 44 MeV/u ^{40}Ar ions in gaseous and solid media.

The energy loss straggling has been measured for various ions and energies, and increasing values of the ratio $\delta E/\delta E_{Ti}$ have been found when the ion is heavier and less energetic (see Fig. 6), i.e. less ionised. In order to evaluate the
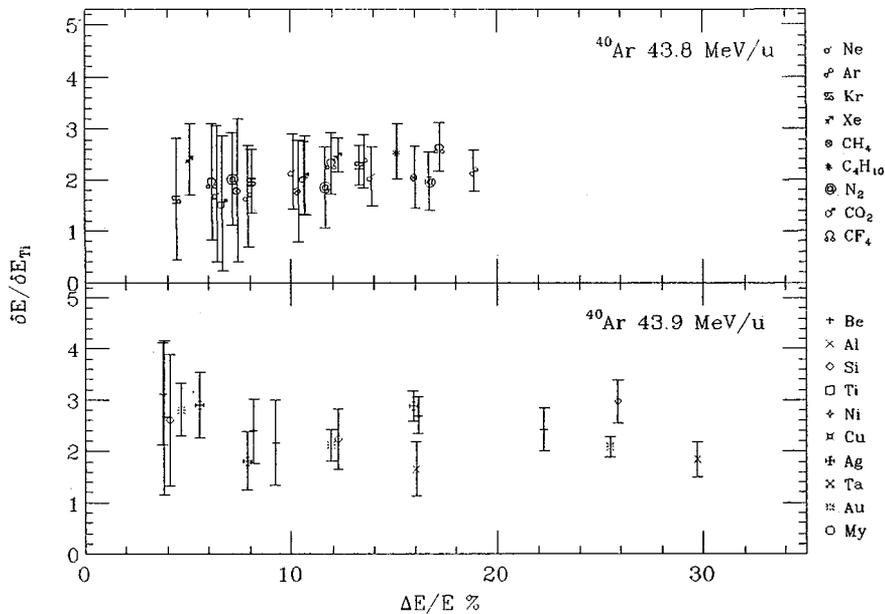

Fig. 5 : Ratio of the experimental energy straggling δE for ^{40}Ar ions at 43.8 MeV/u to the calculated collisional δE_{Ti} from the Titeica formulation versus the relative energy lost in the absorber. Upper part is relative to gaseous media and lower part to solid media.

influence of charge exchange straggling in these measurements, we have performed the Efken et al /16/ calculation, for ^{86}Kr projectile at an energy of 43 MeV/u on a 18 mg.cm^{-2} Be target. According to these authors, the charge exchange straggling δE_C can be calculated if only two charge states (q_1, q_2) are present with a significant probability. Its expression is given by :

$$\delta E_C = 2.355 \left(\frac{S}{\gamma Z_1}\right) (q_1{}^2 - q_2{}^2) \left(2 \frac{F_{q_1} F_{q_2}}{\sigma_{q_1 \to q_2} + \sigma_{q_2 \to q_1}} X\right)^{1/2} \qquad (9)$$

Where S is the stopping power, γZ_1 the effective charge of the projectile, F_{q1}, F_{q2} the fraction of the charge states q_1 and q_2, $\sigma_{q_1 \to q_2}$ and $\sigma_{q_2 \to q_1}$ the charge exchange cross-section, X thickness of targets.

In the present case, the terms F_{36} and F_{35} are respectively equal to 0.75 and 0.25 /1/. The capture cross-section $\sigma_{36 \to 35}$ has been extracted from the Rozet et al values /17/. The electron loss cross section has been deduced from the capture one by assuming charge equilibrium. This leads to

$$\sigma_{36 \to 35} = 0.4 \ 10^{-21} \ cm^2$$
$$\sigma_{35 \to 36} = 1.2 \ 10^{-21} \ cm^2$$

and to a δE_C value of 16.5 MeV. The experimental value is $\delta E = 14 \pm 3$ MeV. The collisional straggling $\delta E_{Ti} = 3.2$ MeV, which must be added quadratically is negligible.

Therefore, we observe a good agreement between the charge exchange straggling deduced from Efken et al /16/ and the experimental measurements. This phenomenon may be invoqued to explain the increasing ratio $\delta E / \delta E_{Ti}$ from 2.1 for ^{16}O to 5 for ^{132}Xe (Fig. 6). Nevertheless, in the case of totally stripped ions the observed ratio of the order of two is still unexplained.
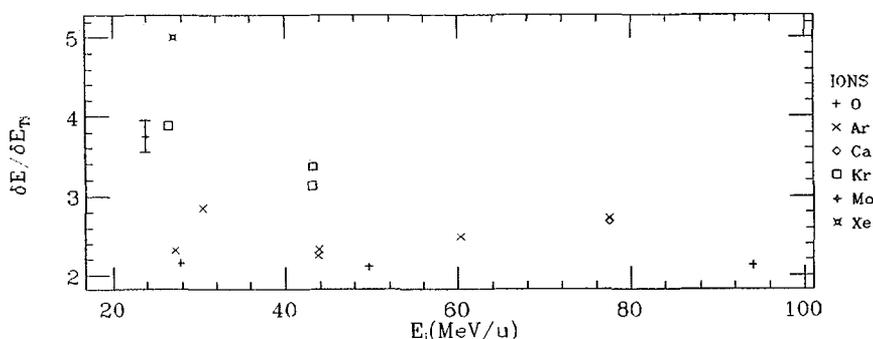

Fig. 6 : Evolution of the ratio $\delta E / \delta E_{Ti}$ with the incident energy of the projectiles (symbols are given on the right side).

5. CONCLUSION

This general experimental study of heavy particle penetration through matter have permitted to measure several essential parameters, namely stopping power, energy straggling and angular straggling.

It has evidenced the vanishing of the gas-solid effect when the projectile is totally stripped. The energy straggling measurements have shown that the calculated collision straggling cannot explain the experimental values by itself even when the projectile is totally stripped. For partially stripped ions, the

charge exchange effect seems to be able to account for most of the energy loss straggling. Finally the angular straggling measurements, which have not been presented here, have permitted to extend the scaling law established by Sigmund et al /18/ over five orders of magnitude /2/.

These series of measurements constitute a set of parameters which permits to determine the average energy loss, energy loss straggling and angular straggling for heavy ions beams after their passage through matter over a wide range of energies. These predictions have a direct application for the conception and analysis of experiments using heavy ions beams in the intermediate energy domain (20 to 100 MeV/u). They are also useful for testing stopping theories and models.

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