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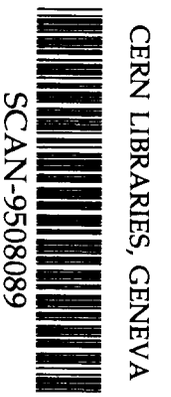

IPNO-DRE-95-04

STOPPING POWERS OF GASES FOR VERY HEAVY IONS

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Communication presented at the conference SHIM-95,
Caen, France, May 16-19, 1995

STOPPING POWERS OF GASES FOR VERY HEAVY IONS[+]

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Abstract :

The stopping powers of gases have been measured for incident 24 MeV/u ^{238}U and 29 MeV/u ^{208}Pb projectiles, using the LISE spectrometer at GANIL. The results show the persistence of the 20 % gas-solid effect observed at lower energy. The effective charges derived from these measurements depend on the atomic number of the target in a way very similar to that observed for solid degraders.

I. INTRODUCTION.

The stopping powers of solids for heavy ions can be satisfactorily reproduced over a wide range of energies (2.5-500 MeV/u) by a semi-empirical scaling based on the stopping powers of the same materials for light charged particles (protons or helium ions), and a parametrization of the heavy ion effective charge q_e, which reflects the charge state of the ion travelling through the medium [1].

However, it was shown in ref [2] that the effective charge parameter γ, ($\gamma = q_e/Z_1$) which is used for that purpose must depend on the nature of the incident ion (atomic number Z_1), on its velocity (v), but also on the nature of the target (atomic number Z_2).

When such a treatment is to be applied to gaseous stoppers, two effects must be taken into account :

[+] Work performed at the GANIL national facility, Caen, France

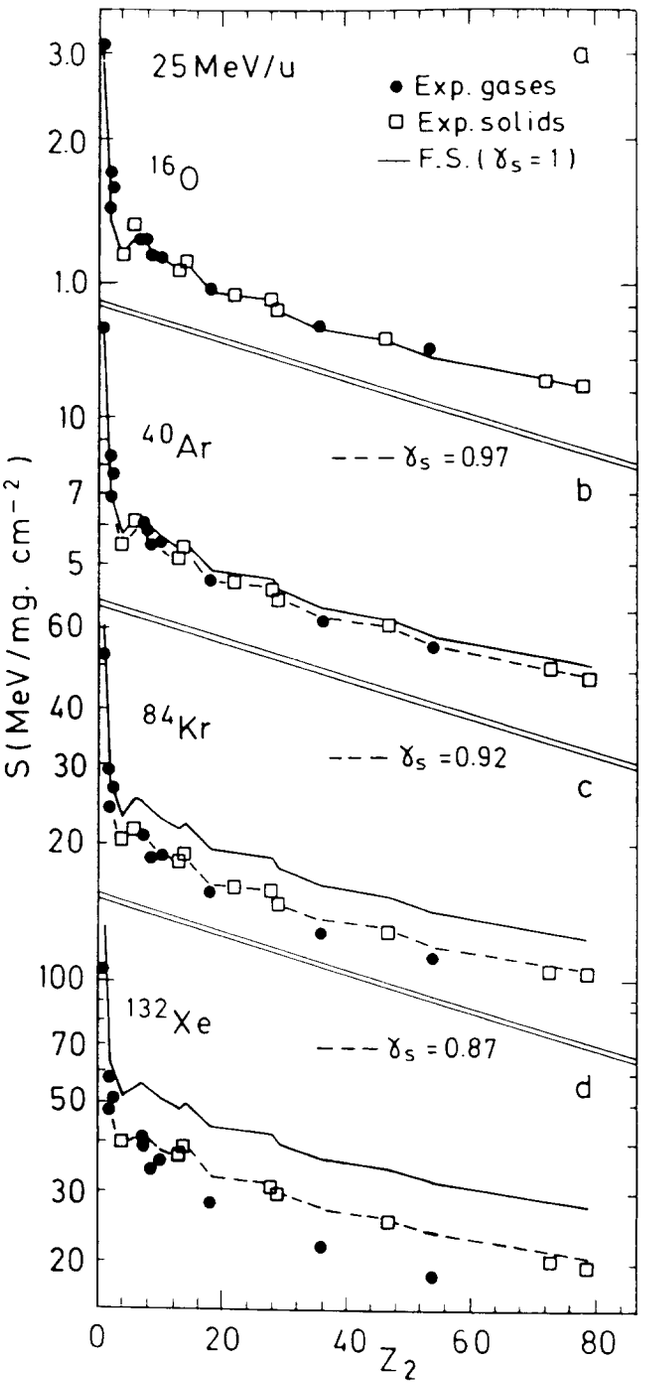

Figure 1

Vanishing of the gas-solid effect when the projectile is completely stripped. The stopping powers of gases and solids are represented by black dots and open squares, respectively. They are plotted against the atomic number Z_2 of the degrader. For compound gases, the weighted average value of Z_2 has been taken. The solid curve is calculated under the assumption of totally stripped ions. The broken lines are fits of the solid stopping powers using the indicated values of the effective charge parameter denoted here γs (from ref. [5]).

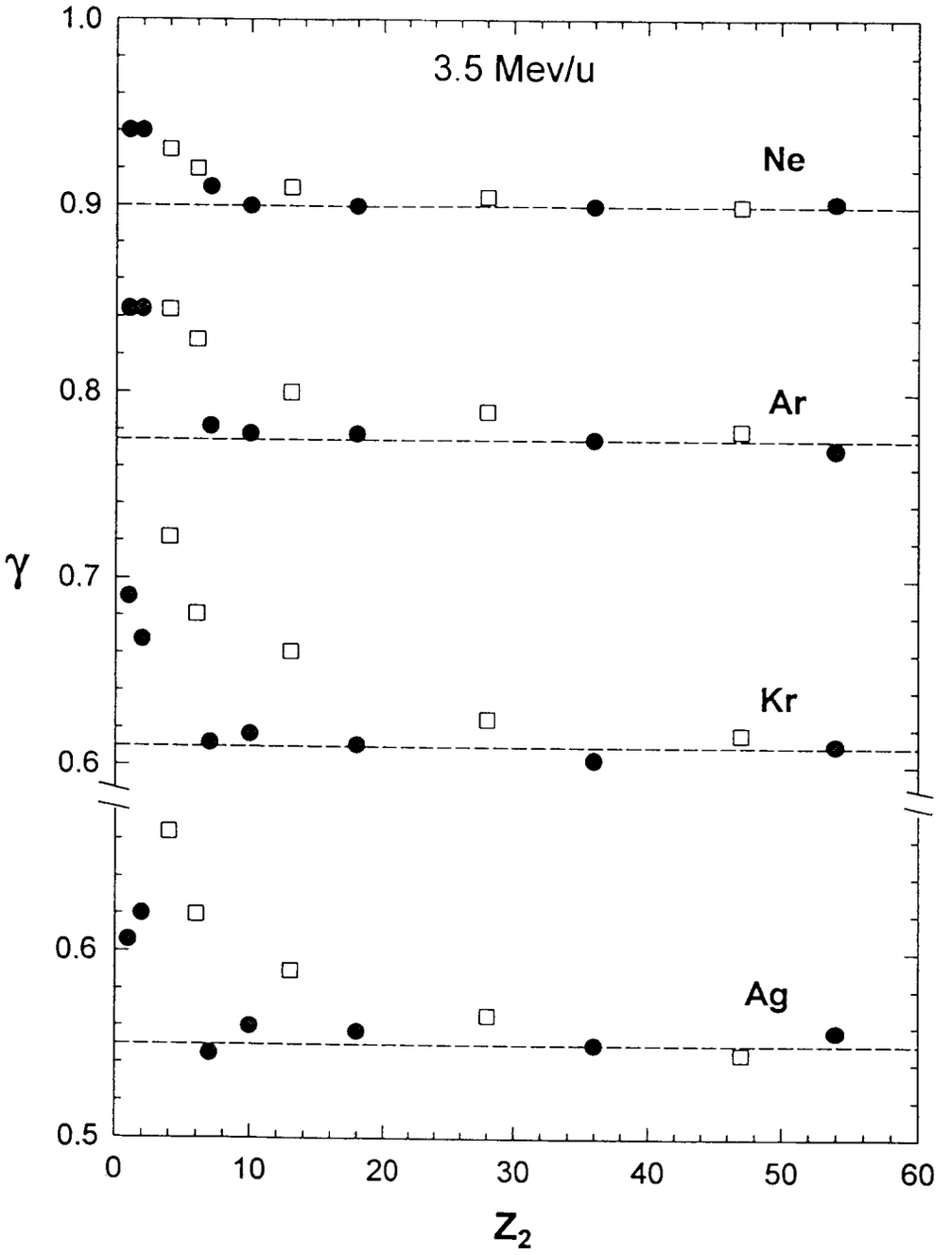

Figure 2

Variation of the effective charge parameter γ versus the degrader atomic number Z_2 for 3.5 MeV/u ions. The full dots are relative to gaseous media and the open squares to solids (from ref. [5]).

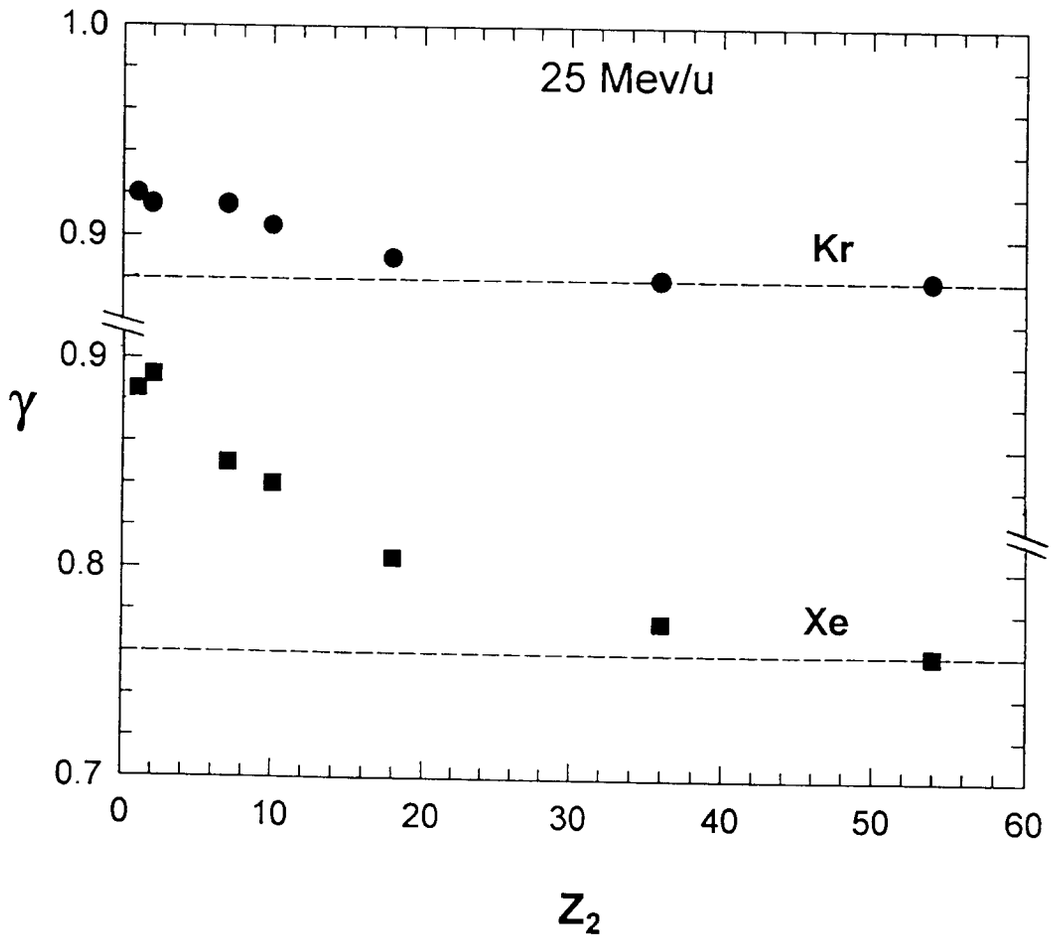

Figure 3

Variation of the effective charge parameter γ versus the degrader atomic number Z_2 for 25 MeV/u Kr and Xe ions traversing gaseous media (from ref. [6]).

Firstly, there is a difference in the effective charge which is systematically smaller for gases than for solids, introducing differences of 10 to 20% in the stopping powers, those of gases being smaller. This effect was first observed in ref [3]. It was confirmed and quantitatively studied in refs [4,5,6]. It is attributed to a difference in the average charge state of the ions traversing the stopping medium, due itself to a density effect which affects the collision frequency. It can be observed at low velocities (2-5 MeV/u), and vanishes at high energy when the ion tends to be fully stripped [6] (see Fig. 1).

The second effect, which was evidenced recently concerns the variation of the effective charge of a given ion at a given velocity versus the atomic number of the stopping medium. At low velocities, the systematic variation observed for the solids does not exist for gases. Only hydrogen and helium exhibit an enhanced effective charge [5] (see Fig. 2). But when the incident ion energy is increased, the appearance of such a variation has been detected for Kr and Xe projectiles at 25 MeV/u (see Fig. 3). This effect makes it difficult to predict accurately the stopping powers of gases for ions heavier than Argon in the energy region from 10 to 30 MeV/u, which has been little explored. Therefore new measurements are of interest for improving the knowledge of these stopping powers, both for practical purposes and for a better understanding of the stopping process.

II. EXPERIMENTS.

In order to clarify this point, a series of experiments has been recently initiated at GANIL, using the LISE spectrometer. Projectiles of $^{208}Pb^{56+}$ at 28.83 MeV/u and $^{238}U^{58+}$ at 24.04 MeV/u have been used. The stopping powers of seven gases (He, N_2, Ar, Kr, Xe, CF_4 and C_3F_8) were measured for uranium projectiles, and those of twelve gases (the same as above plus H_2, Ne, CH_4, C_4H_{10}, CO_2) for Pb projectiles.

Experimental set up.

The principle of these measurements is illustrated in Fig 4. The gas cell (G.C.), which has been described in ref [6], is placed between the two dipoles of the spectrometer. The first part of LISE, including the dipole **D1**, is used to drive to the cell entrance either the incident beam from GANIL (if no target is inserted at the object point **T**), or a selected

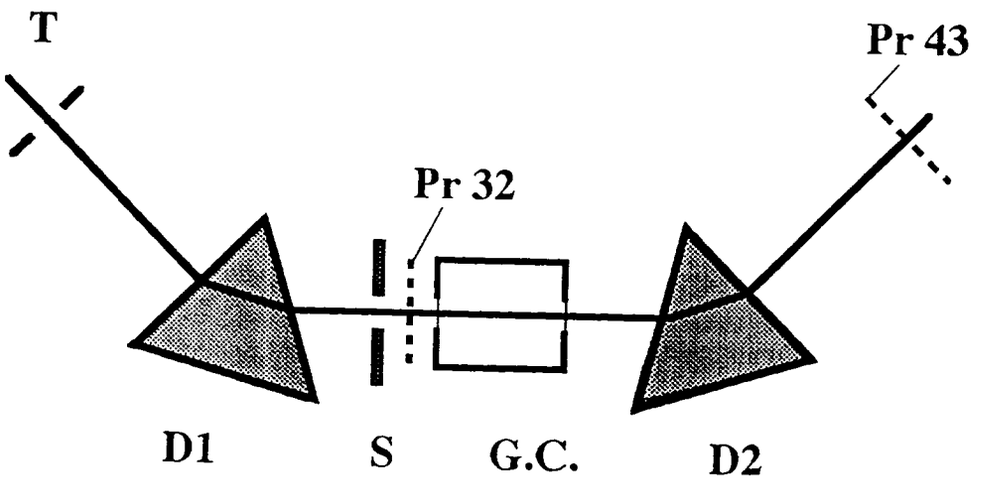

Figure 4

Experimental set-up (see text).

charge state of the degraded beam (if a target is inserted in **T**). A beam profile monitor (**Pr 32**) is used to visualise the beam which is focussed but dispersed at this point, and a slit **S** reduces when necessary its horizontal dimension to less than the diameter of the entrance window of the gas cell (usually 8 mm).

The magnetic rigidity of the beam exiting the gas cell is measured using the second dipole **D2** and a multiwire gas proportional counter placed in the focal plane of the spectrometer (**Pr 43**). The tightness of the cell is insured by two nickel windows as thin as possible (about 2.2 mg/cm^2 in the present experiments), but able to resist to the gas pressure. As the energy loss in these windows is not negligible, it is accurately determined by a procedure which is described below and which implies measurements of the beam energy loss through the empty cell.

Experimental procedure.

The magnetic rigidity Bρ is linked to the beam energy through the relativistic equation :

$$B\rho = k\frac{A}{Q}\left[\varepsilon\left(1+\frac{\varepsilon}{2m_u}\right)\right]^{1/2} \qquad (1)$$

in which B(Tesla) is the spectrometer magnetic field

ρ(m) the curvature radius of the mean trajectory in the dipole

Q the detected ionic charge

$\varepsilon = E/A$ the beam energy per mass unit

$m_u = 931.5$ MeV the atomic mass unit

$k = (2m_u/c)^{1/2} = 0.1438$

The main difficulty in these measurements comes from the fact that the detected charge state Q is not known when the beam energy has been degraded. However, it can be determined unambiguously provided that i) the energy loss is small enough, and ii) an approximate value of the energy loss (i.e. of the involved stopping power) is known. Therefore, the following experimental procedure was used :

The energy loss in the nickel windows was estimated from their measured thickness and the tabulated stopping powers of ref [1]. It was accurately measured with the second dipole D2 associated to the beam monitor **Pr 43.** These "empty cell" measurements were

used as references. They were redone each time the gas was changed in the cell, in order to check the stability of the incident beam energy and of the spectrometer magnetic elements.

For each gas, except for hydrogen and helium, the beam energy loss was measured at three different pressures, corresponding to energy losses of about 5 %, 10 %, and 15 % of the incident energy. For each of these pressures three measurements, in which different charge states of the beam were detected, were performed. The mechanical resistance of the windows limited the maximum pressure inside the cell to one bar, and consequently, only energy losses of about 5 % could be measured for hydrogen and helium.

The precise energy losses in the gases were derived from these measurements by subtracting the energy loss in the Ni windows. This last value was slightly different from that measured when the cell was empty, because of two main effects (difference in the slowing down of ions in the exit window due to their lower energy, difference in the thickness of both windows deformed by the gas pressure), which are analysed in ref. [6], and which were also taken into account here.

The gas degrader thickness (in $mg.cm^{-2}$) was deduced from the cell length and from precise measurements of the gas temperature and pressure.

III. RESULTS.

The energy loss measurements in the nickel windows for lead and uranium projectiles were found to be respectively equal to 1.14 ± 0.01 and 1.23 ± 0.01 MeV/u. Taking into account the window thicknesses (4.57 and 4.50 mg/cm^2), these values lead to nickel stopping powers respectively equal to 52 ± 1 and 65 ± 1 $MeV/mg.cm^{-2}$. These values are systematically lower by about 5% than those interpolated from the tables of ref. [1] at the corresponding mean energies (28.25 MeV/u for Pb and 23.42 MeV/u for U). This deviation is compatible with the uncertainties given by the authors of [1], but could be due to the fact that the charge state equilibrium is not attained at least in the first window. Indeed the equilibration thickness is expected to be of several mg/cm^2 for such projectiles at these energies [7].

The experimental stopping powers of various gases for Pb and U projectiles are presented in Tables 1 and 2. The uncertainties quoted in these tables take into account all the sources of errors which have been listed and analysed in refs [6] and [8].

Gas	X mg/cm^2	E/A MeV/u	S MeV/mg.cm^{-2}
He	2.26	22.85	127 ± 13
N_2	2.91 5.90 8.7	22.91 22.39 21.87	86 ± 6 85 ± 4 86 ± 3.5
Ar	3.93 8.0 11.2	22.94 22.46 22.03	60 .0± 3.3 59.0 ± 2.5 60 ± 2
Kr	5.13 10.3 15.6	22.94 22.42 21.89	46 ± 2 47 ± 2 47.3 ± 1.4
Xe	6.05 11.8 17.8	22.94 22.39 21.86	39 ± 2 42.0 ± 1.5 42.2 ± 1.3
CF_4	3.31 7.1 10.0	22.96 22.38 22.00	69 ± 4 71 ± 3 68.6 ± 2.7
C_3F_8	6.58 9.9	22.43 21.87	73 ± 3 75.0 ± 3.5

Table 1

Stopping powers of gases for 24.04 MeV/u ^{238}U ions. The symbol X denotes the thickness of the gas degrader, ΔE is the energy loss in this degrader, E/A the mean energy per nucleon in this target and S the stopping power.

Gas	X mg/cm^2	E/A MeV/u	S MeV/mg.cm^{-2}
H_2	1.11	27.81	178 ± 9
He	2.19	27.85	83 ± 4
N_2	4.08 8.12 12.2	27.60 26.91 26.18	70.0 ± 3.5 70 ± 3 71.5 ± 2
Ne	4.24 8.5 11.1	27.65 27.03 26.67	62 ± 3 61 ± 3 60.6 ± 1.8
Ar	5.19 10.4 15.9	27.69 27.06 26.38	47.4 ± 2.4 49 ± 2 50.0 ± 1.5
Kr	7.56 15.0 22.6	27.57 26.82 26.06	39 ± 2 40.3 ± 1.6 41 ± 1
Xe	4.72 9.6 14.3	27.91 27.49 27.09	32.4 ± 2 34.0 ± 1.4 34.6 ± 1
CH_4	2.63 5.27 7.9	27.65 27.01 26.35	99 ± 5 101 ± 4 102 ± 3
C_4H_{10}	3.12 6.02 9.3	27.63 26.98 26.22	87 ± 4 90.0 ± 3.6 92 ± 3
CO_2	4.07 8.15 12.2	27.63 26.95 26.25	66 ± 3 68 ± 3 69 ± 2
CF_4	4.18 8.4 12.6	27.69 27.09 26.44	58 ± 3 59 ± 2 60.5 ± 1.8
C_3F_8	8.2 12.3	27.00 26.45	65.0 ± 2.5 61.7 ± 1.8

Table 2

Stopping powers of gases for 28.83 MeV/u ^{208}Pb ions. Same symbols as in Table 1.

IV. DISCUSSION

Firstly, it should be remarked that, for a given gas, the stopping power values measured for increasing target thicknesses are always consistent with each other. This indicates that the equilibrium charge state is not far from being attained by the projectile after the traversal of the first nickel window.

The stopping powers for 27 MeV/u lead and 22 MeV/u uranium ions have been derived from these experimental results. They are plotted in Fig. 5 versus the atomic number Z_2 of the degrader. For compound gases, a weighted average value of Z_2 has been used. For estimating the gas-solid effect, the stopping powers of several solids, derived from the tabulation [1] are also plotted in Fig. 5. The effect is clearly visible, the stopping powers of solids being systematically higher by about 20 % than those of gases.

The effective charge γ derived from these experimental values by comparison with those of alpha particles (or protons) of same velocity in the same gaseous media are plotted in Fig. 6 versus the atomic number Z_2. Both curves exhibit a variation very similar to that observed in Fig. 3 for Xe ions in gases (although the Uranium data corresponding to low Z_2 values are not very precise). These results confirm that the target atomic number Z_2 has a sizeable influence on the stopping power of gases for very heavy ions as it does for all ions in solids. This effect, which needs to be quantitatively precised by complementary measurements must be taken into account in the parametrizations leading to the elaboration of future stopping power tables.

We thank the GANIL crew for their cooperation, Anne Lorieux who participated in one experiment, and Evelyne Davanture for her help in preparing the manuscript.

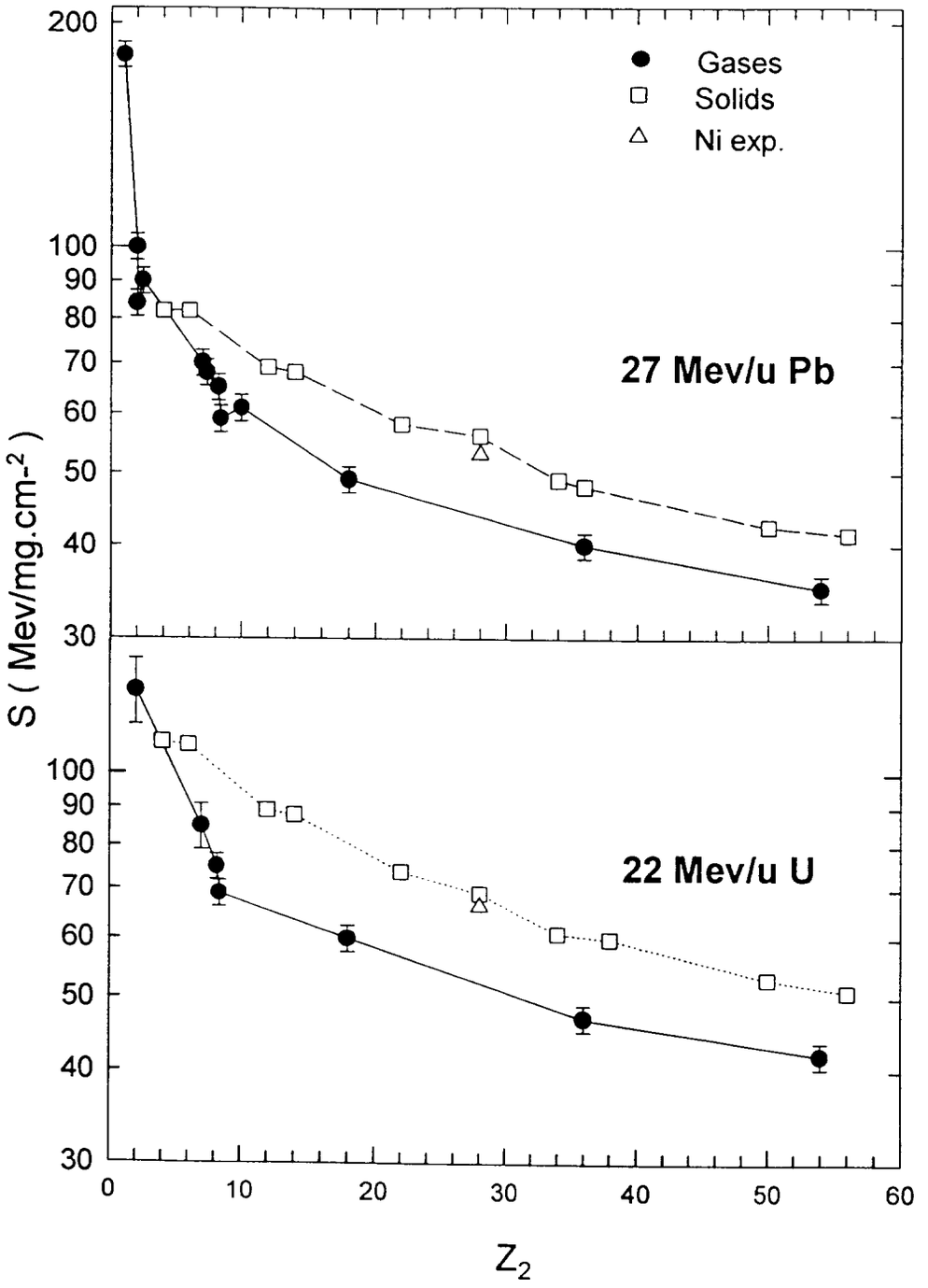

Figure 5

Gas-solid effect for 27 MeV/u Pb and 22 MeV/u U ions. The black dots are experimental gas stopping powers from this work, the open squares are solid stopping powers from ref. [1] and the triangles represent the experimental Ni stopping powers derived from the present work.

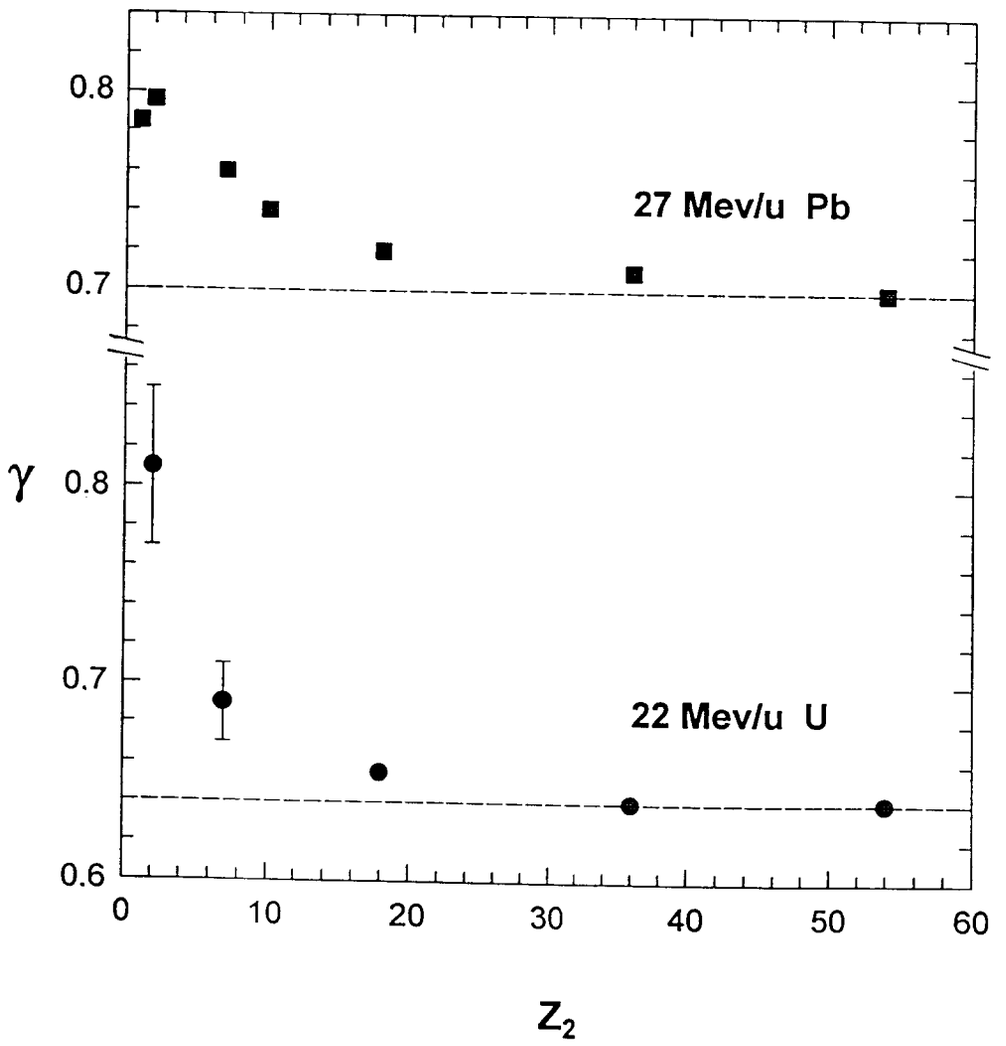

Figure 6

Same as fig 3 for 27 MeV/u Pb and 22 MeV/u U ions.

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