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by

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ABSTRACT

The stopping of Ag ions recoiling through Aℓ, Ti, V, Fe, Ni, Zn, Zr and Pd was measured at various recoil energies with a method based on the Doppler shift of gamma rays. The dependence of the electronic stopping cross section on the stopper atomic number and on recoil velocity is compared to the semi-empirical predictions of Ziegler et al.

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KEY WORDS: Energy loss of heavy ions,
Z_2 dependence of S_e.

INTRODUCTION

At low recoil velocities, the mean energy loss through inelastic ion-atom collisions is sensitive to the atomic structure of the stopping medium and recoiling ion, resulting in the oscillatory dependence of the electronic stopping cross section with the projectile (Z_1) and target (Z_2) atomic numbers. The oscillations with respect to Z_2, observed in the stopping of alpha particles, are well described by calculations based on Hartree-Fock-Slater atomic charge densities for free atoms[1)], but for heavier projectiles, the changes in target wave functions during collisions may be too large to be neglected, as in those approaches. In addition, at low velocities the charge fluctuation and the atomic structure of the recoiling ion, which give rise to the Z_1 oscillations, increase the uncertainties in the scaling of stopping powers of heavy ions obtained with proton or alpha particle stopping cross sections. This problematic low velocity - heavy ion combination is of great importance for the Doppler Shift Attenuation measurements (DSAM) of nuclear lifetimes. Most of the uncertainties in the lifetimes obtained with this method are due to the unreliable estimates of stopping cross sections.

In this article we report the measurements of stopping powers for ^{107}Ag ions recoiling into metal foils of Aℓ, Ti, V, Fe, Ni, Zn, Zr and Pd, in the energy range of ∿50-200 keV/amu. The mean recoil velocity is determined from the Doppler shift in the energy of the gamma rays emitted by the recoiling nucleus. This method, variations of which have been previously described[2,3)], is applicable to the same region at which DSA measurements are often performed.

EXPERIMENTAL

Beams of $\sim 30-60$ MeV ^{16}O ions from the 8UD-Pelletron tandem of the University of São Paulo were used to produce Coulomb excited ^{107}Ag nuclei which recoiled through a metal foil (Fig. 1). Since the mean life of the (423 keV, $5/2^-$, 40 ps) excited state is long compared to the transit time (0.2 ps), almost all gamma rays are emitted after the ions leave the foil. Standard backscattered particle-gamma ray coincidence selects Ag ions recoiling into a narrow cone centered around the beam direction. The Doppler shifted gamma line, observed at 0°, is used to measure the mean energy (E_f) of the ions emerging from the foil.

Targets of enriched ^{107}Ag 0.5 mg/cm^2 thick were vacuum evaporated onto the stopper foils. Except in the case of Ni (0.5 mg/cm^2 electrodeposited commercial foil) the other foils were rolled to a thickness of about 0.5 - 1.0 mg/cm^2. The foil thicknesses were measured with an accuracy of 3 - 5% by weighing the ~ 1 cm^2 foil sample in a microbalance. The areas of the trapezoidal foil samples were measured with a vernier calipers and the errors in these values give the main contribution to the uncertainties in the thickness of the foils. The uniformity of a rolled foil, checked with an alpha particle gauge was found to be better than 2%. The mean thickness obtained with the dE/dx values from Ziegler's table[4,5] agree with that measured

with a microbalance to within 1% .

Gamma ray spectra were accumulated during 3 - 6 hours, with about 20 nA of beam current, using a Ge(Li) detector of 10% efficiency and about 4 keV resolution for the Co lines. The 165 and 302 keV gamma rays from the decay of Coulomb excited ^{181}Ta of the beam stopper and the 569 keV line from a ^{207}Bi source were introduced in the spectra as random coincidences and used for calibration purposes.

For each foil the energy loss measurements were performed at four bombarding energies ($\sim$ 33., 42., 49., and 56 MeV) corresponding to $\sim$ 12, 15, 18 and 22 MeV of initial recoil energies. Exceptions are Ti (46 and 54 MeV), and Ni (46 MeV); in the latter case, results from an earlier measurement[3] were also included in this analysis. A representative gamma ray coincidence spectrum is shown in Fig. 2 .

A series of measurements with a self-supporting Ag target was also carried out to estimate the energy loss of the recoiling ion in the target as a function of beam energy. The unshifted energy (E_o) of the transition in ^{107}Ag was also measured using a thick Ag foil, to avoid systematic errors in the determination of centroid shifts.

Some of the measurements were repeated at one energy with a silver beam stopper, instead of tantalum. In this case, the accuracy of the energy calibration was greatly improved by using the (unshifted) 423 keV line as well as more sources - ^{133}Ba (301 and 356 keV), ^{198}Au (411 keV) and ^{207}Bi (569 keV). In these measurements, the Ge(Li) detector employed had 20% efficiency and 1.9 keV resolution for Co gamma rays.

DATA ANALYSIS

The data analysis consists in the simulation of the Doppler shifted line centroids by the Monte Carlo method. The Monte Carlo program of Dost and Rogers[6] for DSAM analysis was modified to take into account the present geometry and the target - stopper combination. The program simulates all the dominant processes occurring in the experiment, from the collision of a beam particle with a target nucleus, to the emission of a gamma ray into the counter face. The slowing down of the ions was described by modified LSS formulae[7]:

$$-\left(\frac{d\varepsilon}{d\rho}\right)_e = k\varepsilon^p \qquad d\sigma_n = n\pi a^2 \frac{f(t)}{2t^{3/2}} dt$$

where ε, ρ, t are the familiar LSS reduced variables and k, p, η are adjustable parameters. A versatile version of this program, to treat different geometries of DSAM will appear in the literature.

The nuclear stopping power for the present recoil velocities is less than 20% of the electronic contribution and thus, η was taken to be unity and the parameters p and k were varied to minimize the square differences between experimental and simulated centroid shifts. Fig. 3 shows the measured and Monte Carlo simulated centroid shifts corresponding to the best values of p and k as a function of beam energy, in the case of silver in aluminum.

The error in the electronic stopping power due to the uncertainties in the centroid determinations was obtained

from the $\chi^2(k)$ curve shown in the inset in Fig. 3. The uncertainty in the foil thickness was added in quadrature to the above error. The measured stopping powers are estimated to be accurate to within 7%. However, the results of the measurements under improved experimental conditions lead us to conclude that this uncertainty could be reduced by a factor of about two.

RESULTS AND DISCUSSION

Table I shows the experimental values of the parameters k and p expressing $-dE/dx = k(v/v_o)^{2p}$ in units of $MeV.cm^2/mg$. The dependence of the electronic stopping power with the ion velocity is compared to the LSS theory[7] and the semi-empirical results of Ziegler[5] in Fig. 4. The oscillatory dependence of the stopping cross section with the stopper atomic number ($S_e(Z_2)$), is shown in Fig. 5 for 3 different velocities, and compared to Ziegler's calculations and LSS (monotonic) predictions.

The observed oscillatory pattern is well reproduced by the calculations of Ziegler at the upper limit of the velocity range presently studied. However, as the recoil velocity decreases, the maximum at $Z_2 = 22$ seems to disappear, and that at $Z_2 = 26$ (also seen with He ions) is enhanced. Such an energy dependence is due to the fact that $S_e(Z_2)$ have different slopes for different Z_2. It is interesting to note that a similar behavior in $S_e(Z_1)$ may be inferred from the data of Brown and Moak[8] for U, I and Br ions in carbon.

The results show that the predictions of stopping powers for heavy ions from calculations based on light ion data are only qualitative estimates (at least for E/M less than 200 keV/amu). With the method described here, it is possible to measure the stopping power for an ion, under the same experimental conditions (stopper, recoil velocity) at which DSA meanlife measurements are performed, thereby reducing the uncertainties in the measured lifetimes.

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FIGURE CAPTIONS

FIG. 1 - Details of the target-foil system ($\theta_D = 0^o$ in the actual measurements).

FIG. 2 - Back-scattered ^{16}O-gamma coincidence spectrum.

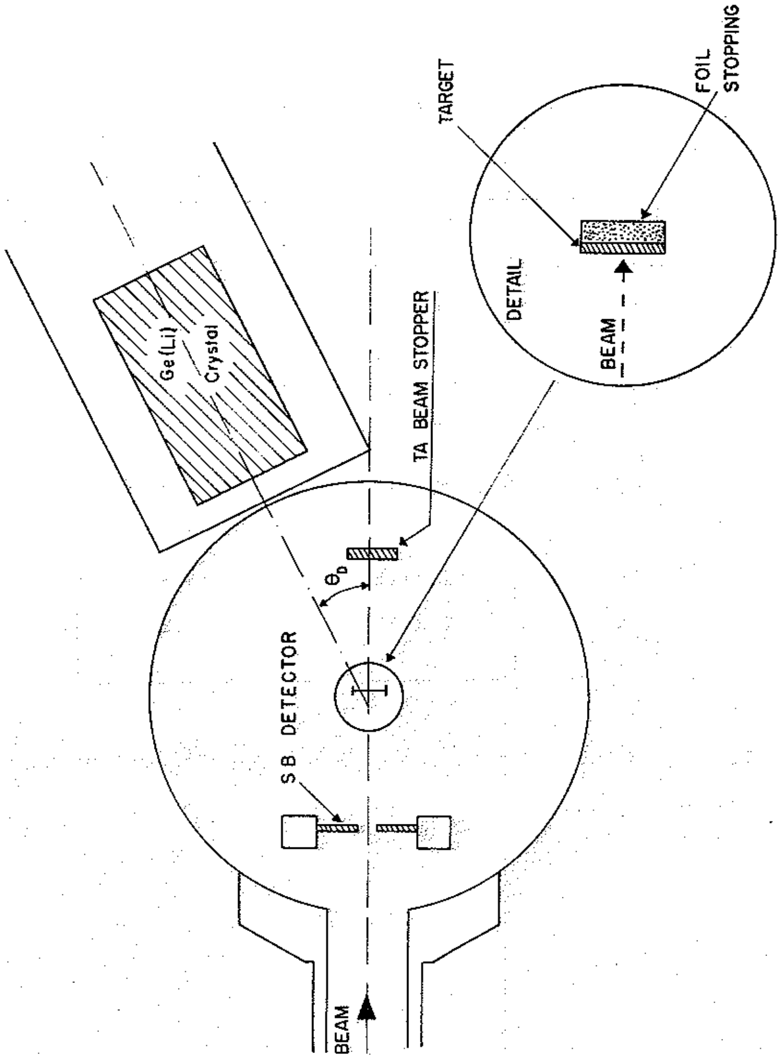
FIG. 3 - Measured and Monte-Carlo simulated centroid shifts as a function of beam energy.

FIG. 4 - Dependence of the electronic stopping power on the ion velocity.

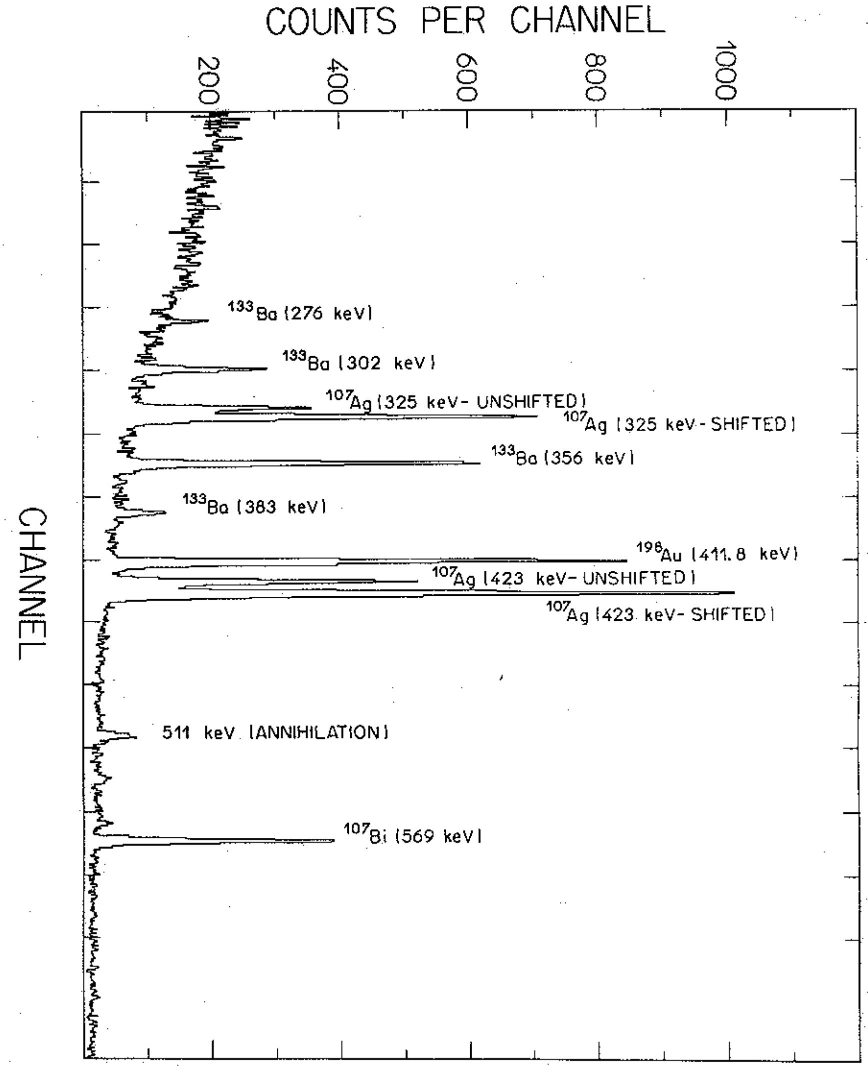
FIG. 5 - Stopping cross-section as a function of stopper atomic number (Z_2).

stopper	k	p
Aℓ	8.3(6)	0.7
Ti	3.5(2)	0.9
V	8.6(7)	0.5
Fe	12.0(8)	0.4
Ni	5.8(5)	0.6
Zn	4.3(3)	0.7
Zr	3.7(2)	0.8
Pd	2.2(2)	0.8

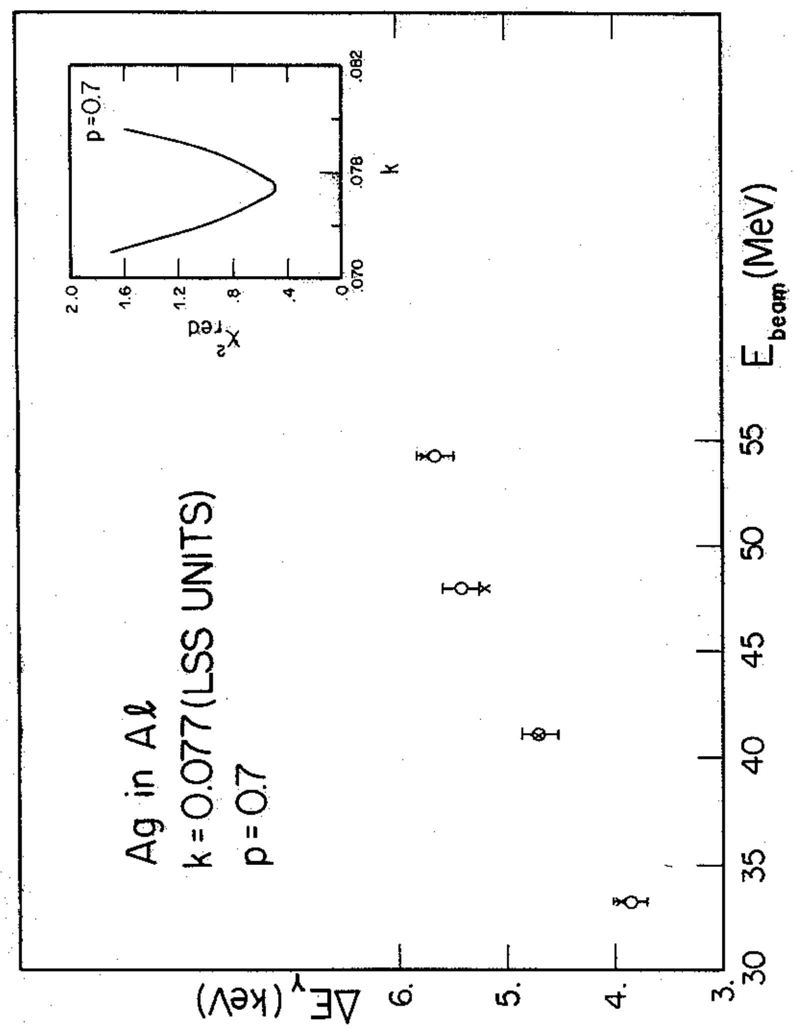
TABLE 1 - Values of k and p $\left[-\frac{dE}{dx} = k\left(\frac{V}{V_o}\right)^{2p}\ \mathrm{MeV\ cm^2/mg}\right]$.



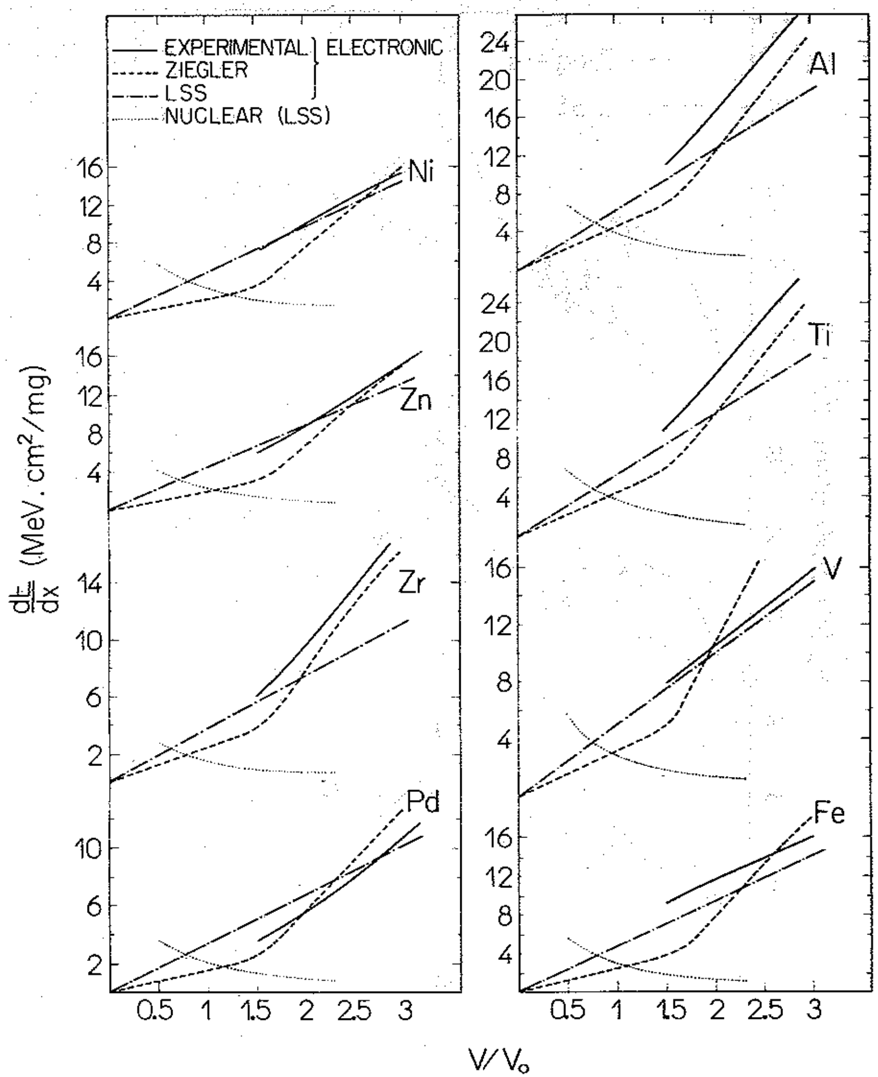
TARGET
FOIL
STOPPING
DETAIL
BEAM
Ge(Li)
Crystal
TA BEAM STOPPER
θ_D
SB DETECTOR
SB
BEAM



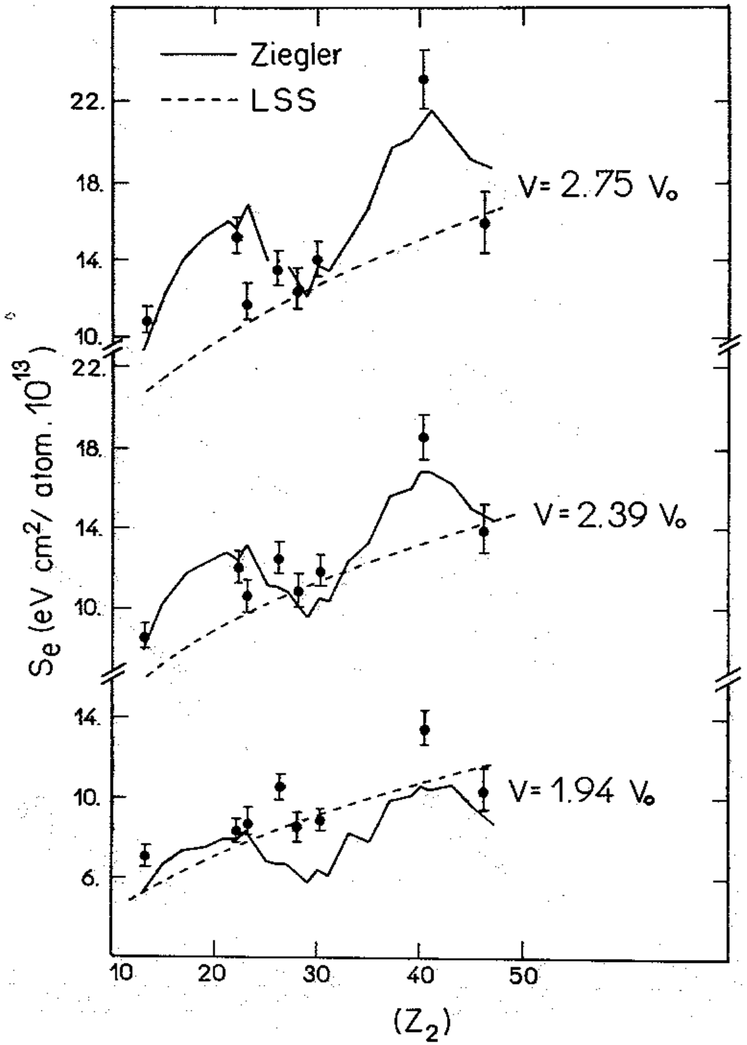
COUNTS PER CHANNEL
200
400
600
800
1000
CHANNEL
^{133}Ba (276 keV)
^{133}Ba (302 keV)
^{107}Ag (325 keV- UNSHIFTED)
^{107}Ag (325 keV - SHIFTED)
^{133}Ba (356 keV)
^{133}Ba (383 keV)
^{198}Au (411.8 keV)
^{107}Ag (423 keV- UNSHIFTED)
^{107}Ag (423 keV- SHIFTED)
511 keV (ANNIHILATION)
^{107}Bi (569 keV)



Ag in Aℓ
k = 0.077 (LSS UNITS)
p = 0.7
p = 0.7
χ^2_{red}
k
E_{beam} (MeV)
ΔE_γ (keV)



EXPERIMENTAL
ZIEGLER
LSS
ELECTRONIC
NUCLEAR (LSS)
Ni
Zn
Zr
Pd
Al
Ti
V
Fe
$\frac{dE}{dx}$ (MeV. cm^2/mg)
V/V$_o$



Ziegler
LSS
22.
18.
14.
10.
22.
18.
14.
10.
14.
10.
6.
V= 2.75 V₀
V= 2.39 V₀
V= 1.94 V₀
Se (eV cm2/ atom . 1013)
10
20
30
40
50
(Z2)