DSAM LIFETIMES AND NUCLEAR STOPPING (*)

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ABSTRACT — The use of the Doppler Shift Attenuation Method (D.S.A.M.) in nuclear lifetime measurements is briefly described for the typical L.F.E.N. experimental conditions.

The method was used in the measurement of two well known lifetimes in ^{28}Si ($\sim$ 60 and $\sim$ 700 fs, for the levels at $E_x = 4.62$ and 1.78 MeV, respectively) by means of the ^{27}Al (p, γ) ^{28}Si reaction, as a test to experimental conditions and data analysis.

From these results, at low recoil energy (v/c $\sim 0.2\,\%$), conclusions are drawn about the validity of the Thomas-Fermi potential describing the ion-atom interaction. An empiric scale factor for the calculated nuclear stopping, $f_n = 0.7$, is extracted in this case.

1 — INTRODUCTION

Lifetimes are amongst the most important quantities to be measured in experiments. They provide prime information about the structure of nuclei.

The Doppler Shift Attenuation Method (DSAM) is a nuclear lifetime measurement technique based upon the apparent energy variation of a γ-ray emitted by a nucleus in motion with respect to an observer. If Θ_1 is the angle between the velocity of the emitting nucleus and the axis of the detector, the energy of the observed γ-ray is:

$$E_1 = E_0 \left(1 + \frac{v}{c} \cos \Theta_1\right), \tag{1}$$

E_0 being the unshifted γ-ray energy, v the speed of the emitting nucleus and c the speed of light. If the experiment is conducted in

(*) Results presented at the Conference of the Portuguese Physics Society (Lisbon, February, 1978).

such a way that γ-rays are detected at two different angles, namely Θ_1 and Θ_2, the observed energy shift between the two peaks will be:

$$\Delta E = E_0 \frac{v}{c} (\cos \Theta_1 - \cos \Theta_2). \tag{2}$$

If the emitting nucleus is moving inside matter, instead of recoiling freely in vacuum, it will be slowed down by the collisions that take place and its velocity is a function of time. The mean value of the energy shift then corresponds to an integration over all decay times:

$$\overline{\Delta E} = \frac{E_0}{c} (\cos \Theta_1 - \cos \Theta_2) \int_0^\infty v(t) \frac{e^{-t/\tau}}{\tau} dt, \tag{3}$$

τ being the lifetime of the nuclear excited state.

Defining:

$$F(\tau) = \frac{1}{v_0 \tau} \int_0^\infty v(t) e^{-t/\tau} dt \tag{4}$$

we obtain:

$$\overline{\Delta E} = E_0 \frac{v_0}{c} F(\tau) [\cos \Theta_1 - \cos \Theta_2], \tag{5}$$

v_0 being the initial speed of the nucleus. In practice an experimental value is obtained,

$$F = \frac{E_1 - E_2}{\Delta E_{max}} \tag{6}$$

ΔE_{max} corresponding to the vacuum shift, and the lifetime is extracted from a calculated F (τ) curve [1]

The calculation of an F (τ) curve is a complex task in physical terms. In the slowing down process two types of collisions are usually considered. The collisions of the recoiling ion with the electrons of the medium are supposed inelastic, slowing down the ion basically without changing its direction of motion. The collisions with the atoms of the medium are assumed to be elastic and therefore associated with considerable deviation from the initial trajectory. The description of this process is usually made in terms of a screened Coulomb field, such as the Thomas-Fermi potential, which was treated in detail by Lindhard, Scharff and Schiøtt [2].

Assuming this description of the slowin down process, a method was devised by Blaugrund [3] to obtain the F (τ) curves relating the mean energy shifts with the lifetime of the nuclear states. For that, one considers both electronic and nuclear stopping mechanisms in the medium. Thus, the total stopping power can be written:

$$\frac{dE}{dx} = f_e \left(\frac{dE}{dx}\right)_e + f_n \left(\frac{dE}{dx}\right)_n \tag{7}$$

f_e and f_n being empiric correction factors. Each term is dominant at characteristic ranges of the ion energy, depending on the recoiling ion and the stopping material. Broadly, the nuclear term is important at low ion energies, decreasing rapidly as the energy increases; on the contrary, the electronic term dominates at higher recoil energies.

Alternatively, calculations may also be made to obtain the theoretical spectrum of the emitted γ-rays, for an assumed value of τ, and then one compares this spectrum with the experimental one. This process is usually carried out by means of Monte-Carlo techniques [4].

However, the theoretical description of the slowing down process is far from perfect, and it is necessary to test it experimentally [5]. A direct way of doing it, is, of course, the measurement of the stopping power itself. This measurement is however difficult and, besides, it must be stressed that the decomposition of the stopping power in nuclear and electronic parts is somewhat artificial.

An elegant test, though indirect in nature, is the measurement of a well known nuclear lifetime, which has already been the object of much experimental concern. In brief, this test may be used to obtain estimates of the empiric scale factors of equation (7). It can also be used to draw conclusions about the ion-atom interaction potential and to enable us to distinguish between different theoretical descriptions.

2 — EXPERIMENTAL METHOD

The lifetimes of the levels at $E_x = 1.78$ and 4.62 MeV in ^{28}Si have been selected to test the slowing down theory. The adopted values of these lifetimes are 680 ± 30 and 59 ± 6 fs, respectively [6]. Both lifetimes have been measured several times by many authors, with different experimental conditions and even (the first one) by several independent techniques.

The proton resonance capture in ^{27}Al was chosen to populate the levels in question, for many reasons. Namely, it is very easy to use this reaction with the L. F. E. N. 2 MV Van de Graaff accelerator, it has been widely studied and it originates a beam of ^{28}Si ions with a very well and uniquely defined velocity. Two different resonances were used (and therefore ions with two different initial energies were obtained) to populate each of the excited levels in a very simple way. The chosen resonances were those at $E_p = 923$ and 1800 keV for the level at $E_x = 1.78$ MeV and $E_p = 767$ and 1588 keV for the level at $E_x = 4.62$ MeV.

Fig. 1 shows the curves for the electronic and nuclear stopping powers, assuming that the Thomas-Fermi potential describes the ion-atom interaction, for ^{28}Si ions recoiling in ^{27}Al. Also depicted are the ion energies during the recoil, up to a time corresponding to three lifetimes (for each case).

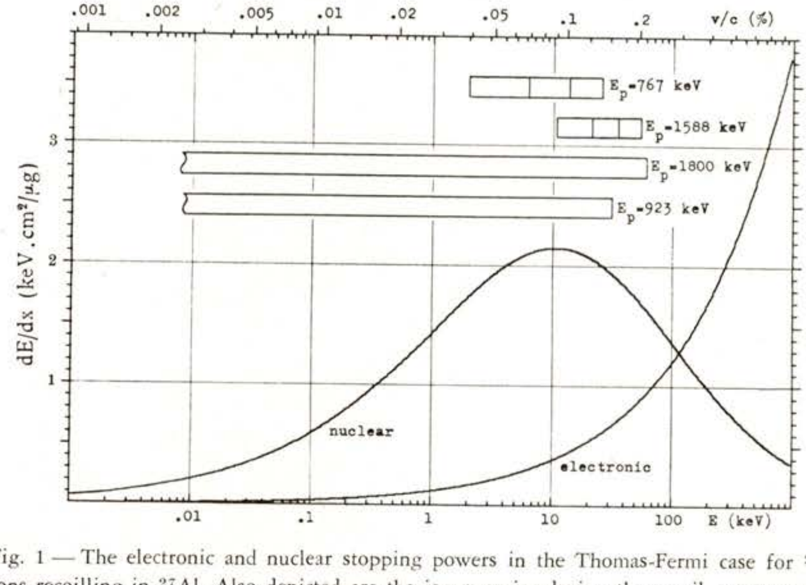

Fig. 1 — The electronic and nuclear stopping powers in the Thomas-Fermi case for ^{28}Si ions recoilling in ^{27}Al. Also depicted are the ion energies during the recoil, up to a time corresponding to three lifetimes.

The beam energy stability was improved to maximum possible (about 500 eV) and the spectrum stability warranted by a digital stabilization unit. Spectra calibrations were of 400-500 eV / channel. The Ge(Li) detector resolution was 2.5 keV at $E_\gamma = 1.33$ MeV.

Targets were of pure aluminium, deposited onto gold or tantalum thick backings. Targets with different thicknesses were used for the resonance at $E_p = 1588$ keV. For the other resonances, the targets were thick enough to guarantee that the recoiling ion was brought into rest inside them.

3 — RESULTS AND DISCUSSION

Fig. 2 presents the experimental spectra obtained (after background extraction) for the 2.84 MeV γ-ray ($E_x = 4.62 \rightarrow 1.78$ MeV transition) at the $E_p = 767$ keV resonance, and for the three measured angles.

Table 1 displays the experimental results. The $F(\tau)$ values presented are already corrected for the finite size of the detector and for the internal side-feeding due to the $E_p = 1588$ keV resonance decay scheme.

From the $F(\tau)$ analysis it is quite clear that the Thomas-Fermi potential does not describe correctly the slowing down mechanism. Assuming as correct the theoretical value for the electronic stopping power ($f_e = 1.0$), f_n was varied down to 0.6. The best set of values was found to be that corresponding to an empiric factor $f_n = 0.7$.

On the other hand the Monte-Carlo analysis of the $E_p = 767$ keV resonance ($v_0/c = 0.140\,\%$) quite corroborates this fact. Again, the value $f_n = 0.7$ appears to be the correct on. The analysis of the $E_p = 1588$ keV resonance ($v_0/c = 0.202\,\%$) was not attempted, as it is much more difficult to interpret than in the 767 keV case, due to the internal side feeding of the $E_x = 4.62$ MeV level. Also, the lifetime of the first excited state in ^{28}Si does nct seem amenable to a Monte-Claro analysis, as its value is considerably higher than characteristic slowing down time (of the order of 120 fs), resulting in an appreciable fraction of γ-emissions proceeding with the excited nuclei at rest.

We can thus conclude that the commonly accepted theory, which is based upon the Thomas Fermi statistical model of the atom, seriously overestimates nuclear stopping at low recoil energies. For the ion-stopper combination and initial recoil velocity used in this experiment, the theoretical estimates must be corrected by an empiric factor $f_n = 0.7$. This indicates that the interaction potential actually gives rise to cross-sections that are correpondingly smaller than the

Thomas-Fermi ones, for this energy range, therefore encouraging the consideration of other theoretical descriptions conducing to lower stopping power values.

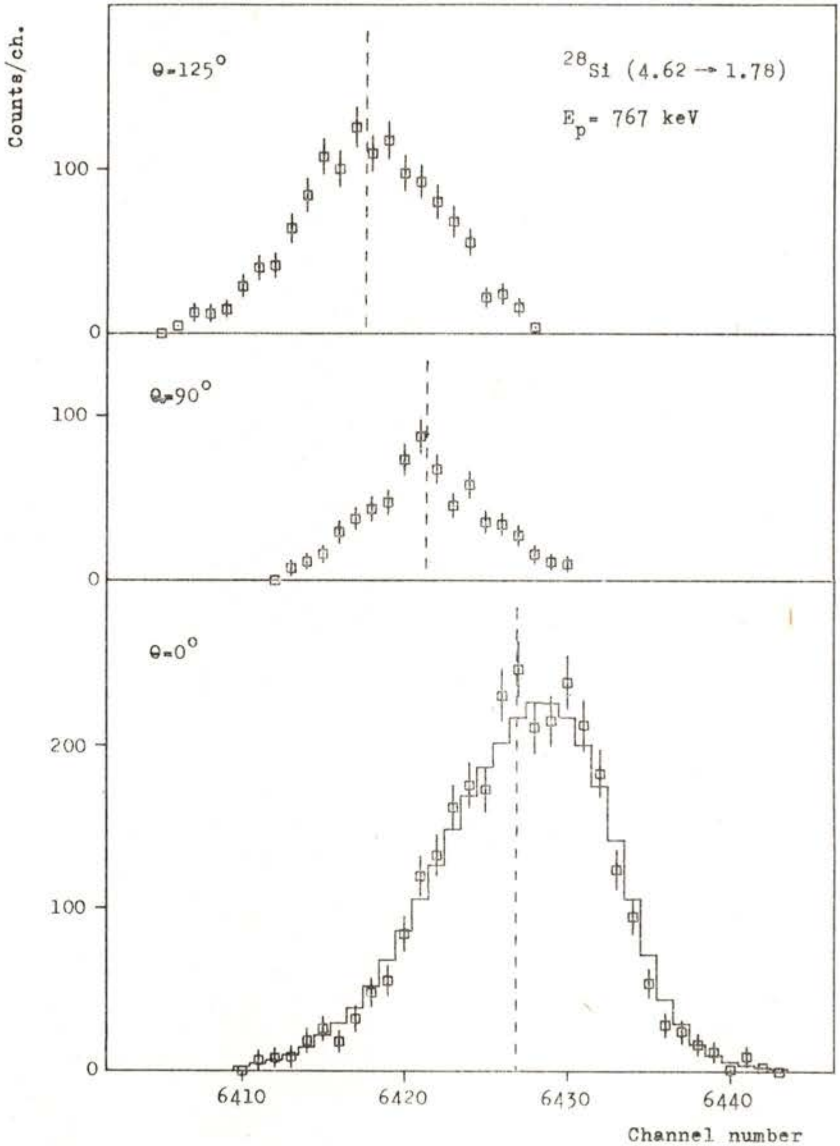

Fig. 2 — Experimental spectra obtained (after backgroud extraction) for the 2.84 MeV γ-ray ($E_x = 4.62 \rightarrow 1.78$ MeV transition) at the $E_p = 767$ keV resonance, for the three measured angles. Superimposed on the 0^0 peak is the calculated Monte-Carlo lineshape.

TABLE 1

Lifetime values (fs)

v_0/c (%)		0.155	0.216	0.140	0.202	
Target ($\mu g/cm^2$)		100	100	50	50	10 *a)*
F (τ) analysis	F (τ)	0.13 ± 0.01	0.17 ± 0.01	0.65 ± 0.02	0.74 ± 0.02	0.67 ± 0.01
	$f_n = 1.0$	490 ± 50	500 ± 30	41 ± 3	43 ± 4	48 ± 2
	$f_n = 0.7$	660 ± 70	670 ± 40	56 ± 4	57 ± 6	58 ± 2
Monte-Carlo analysis	$f_n = 1.0$			46 ± 3		
	$f_n = 0.7$			61 ± 4		
adopted value ref. [6]		680 ± 30		59 ± 6		

a) The recoiling ions travelled about 8 $\mu g/cm^2$ in aluminium before entering the tantalum backing.

Further elucidation of these questions shall be conducted in two main directions: (i) a systematic study of different ion-stopper combinations, and (ii) a wider choice of inital recoil velocities, covering the whole range of possible (and interesting) measurements.

The active collaboration of J. D. Cunha during experiments and in the early part of this work is gratefully ackowledged.

REFERENCES

[1] J. M. G. CARAÇA, «Vidas Médias Nucleares», LFEN-B N.º 6 (1976),

[2] J. LINDHARD, M. SCHARFF and H. E. SCHIφTT, «Range concepts and heavy ion ranges», *Mat. Fys. Medd. Dan. Vid. Selsk.* **33**, n.º 14 (1963).

[3] A. E. BLAUGRUND, «Notes on Doppler shift lifetime measurements», *Nucl. Phys.* **88** (1966) 501.

[4] W. M. CURRIE, «A Monte-Carlo programme for Doppler shift analysis», *Nucl. Instr. and Meth.* **73** (1969) 173.

[5] Many references exist in the literature on this subject. See, for instance, *Nucl. Instr. and Meth.* **132** (1976) *and* M. TOULEMONDE and F. HAAS, *Phys. Rev.* **C15** (1977) 49 and further references therein.

[6] P. M. ENDT and C. VAN DER LEUN, *Nucl. Phys.* **A214** (1973) 1.