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Irradiation by swift heavy ions: Influence of the non-equilibrium projectile charge state for near surface experiments

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Abstract

When dealing with surface and/or thin film modifications of materials under irradiation by swift heavy ions, special attention should be given to the choice the incident projectile charge state delivered by the accelerator. This charge state should be of the order of the effective charge defined in the electronic energy loss theory. Under some hypothesis, this effective charge is assumed to be equivalent to the mean charge state deduced from measurements of ion charge state distribution. To reach such a charge state, it is necessary to introduce before the irradiated sample a thin stripper foil of carbon, the thickness of which is in between ~5 and ~1500 μg/cm^2 for beam energies ranging between 1 and 44 MeV/u, respectively.

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1. Introduction

This note concentrates on a specific attention needed when studying surface and near surface material modifications irradiated by swift heavy ions where the energy loss is dominated by electronic collisions. To get detailed know-how concerning matter transformation in this specific case, including models to predict the response of different materials, it is necessary to know the value of the electronic energy loss (S_e) that depends on the ion charge state in the matter, directly determined by its velocity (v_p) [1–6]. However, in most of the accelerators, the delivered ion species is at a lower charge state than the one corresponding to v_p, leading to smaller values of S_e [7–9] than calculated [2–5] and acting directly upon the experimental observations [10–12]. In the first part of this paper, we will present a short recall about the evolution of the electronic energy loss on a large range of ion velocity, by introducing the concept of the effective charge (Z_p^*) [6,13–17] resulting from the screening of the nucleus charge (Z_p) by the remaining projectile electrons. In the second part, this effective charge will be compared to ion charge states delivered by different accelerators. In the third part, it will be shown that this effective charge agrees with the mean equilibrium charge state of swift heavy ions passing through a solid target. This equilibrium charge state is deduced from measurements of charge state distributions [17–20], also described by different models [21,22]. In conclusion, a phenomenological approach will be proposed to calculate the thickness of a stripping target to reach the equilibrium charge state.

2. Electronic energy loss and charge state

In the electronic energy loss regime [1–5], three points should be emphasized concerning the slowing down of the projectile with a nucleus charge state Z_p:

(1) Its velocity (v_p) is the main parameter and not its energy (no mass input). For this reason, the projectile

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energy, E_p, will be defined in MeV per u (MeV/u), called "specific energy".

(2) The slowing down is the result of statistical collisions: for a velocity, its charge state is not sharply defined, except for very high velocity range ($v_p \gg cZ_p^{2/3}/137$, with c the light velocity), where electron capture cross-section by the projectile is negligible [21].

(3) Energy is transferred between electrons belonging either to the target (excitations and ionizations) or to the projectile. For the projectile, these collisions can induce electron stripping or capture that are in competition when $v_p \sim cZ_p^{2/3}/137$.

At high energy, i.e. $v_p \gg cZ_p^{2/3}/137$, where all the projectile electrons are stripped, the Bethe formula is applied within the Born's approximation,

$$S_e = \frac{4\pi Z_p^2 e^4}{m_e v_p^2} L \quad (1)$$

with the stopping number $L = N_t Z_t \ln\left(\frac{2m_e v_p^2}{I}\right)$ where Z_p and Z_t are the nucleus charge of projectile and target, respectively, m_e the electron mass and e its charge, v_p the incident ion velocity, N_t the atomic density of the target, and I the ionization potential. Valid only if $v_p > 1.4 \times 10^9 \times Z_p^{0.477}$ cm/s [see Fig. 7 in 20] or $E_p > Z_p$ if the velocity is converted in MeV/u unit, this formula (relation (1)) is an approximation of S_e since no relativistic effect and no mean electronic excitation have been included. A more complete development can be found in several references [2–5], but to illustrate our purpose such a simplification is sufficient. In this velocity regime, the electronic stopping power decreases with the projectile velocity.

Now going to very low velocity $v_p \ll cZ_p^{2/3}/137$ [1], the electronic energy loss increases with the projectile velocity.

The link, between these two opposite evolutions of electronic energy loss with ion velocity, is achieved in a regime called the "Bragg peak". When the projectile velocity decreases from the high energy regime, the charge state of the projectile becomes smaller than Z_p due to electron capture and becomes in the material an *effective charge* (Z_p^*), that diminishes when the projectile velocity decreases. A first approach was proposed by Northcliffe [13], based on the Bohr concept [6]:

$$Z_p^* = Z_p \times (1 - \exp(-137 v_p/c/Z_p^{2/3})). \quad (2)$$

Knowing the evolution of Z_p^* (Fig. 1 (right)), the electronic energy loss (S_e) is calculated in a carbon target (Fig. 1 (left)), using SRIM2003 code [2,4], in which a more detailed evolution of Z_p^* have been introduced [16].

3. Ion charge state extracted from different accelerators

After ionization of atoms in a source, the ions are extracted towards the different stage of the acceleration system. In most cases, the outgoing ions from the accelerator present a lower charge state than the effective charge as seen in the following examples.

In a single stage Van de Graaff of 4 MeV, an accelerated He^{1+} at 4 MeV (=1 MeV/u) is one charge state below its effective charge.

A MP tandem Van de Graaff at 12 MV delivers an iodine (mass = 127) beam at 150 MeV (1.18 MeV/u) with a charge 12+ [11] (I^{12+}), given by a stripping foil standing at the terminal voltage. This charge state is nearly two times lower than the effective charge (Fig. 1 (right)).

At GANIL accelerator [23], a lead beam is delivered with a charge 55+ at energy of 6032 MeV (29 MeV/u), that is around 80% less than the effective charge [20].

Now GANIL injectors [24] deliver a beam with specific energies of 1 MeV/u for C^{4+} and 0.65 MeV/u for Pb^{32+}. In these two cases (Fig. 5 (left)) the delivered charge is larger than the effective charge as calculated using the Northcliffe's formula (Fig. 1 (right)).

These examples show that the accelerated beam delivers ions with a charge state that does not correspond to the effective one. Since S_e varies with the square of the projectile charge (relation (1)) the experimental electronic energy loss [7–9] does not match to the calculated one [2–5]. Using

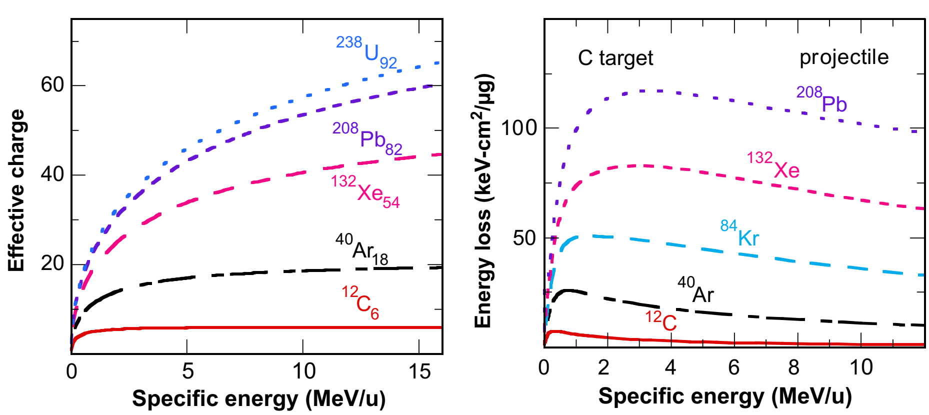

Fig. 1. Right: Effective charge for incident ion ${}^{A}P_{Z_p}$ versus specific energy [13], where Z_p is the nucleus charge and A its mass. Left: Electronic energy loss versus beam specific energy of different projectiles in carbon target. The electronic energy loss is bigger than the nuclear energy loss for ion energies larger than ~1 keV/u.