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A NEW METHOD OF PLASMA DIAGNOSTICS

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Resumen

La captura electrónica por iones energéticos que atraviezan un cierto medio se caracteriza por emisiones muy peculiares. Estas emisiones se pueden emplear para diagnosticar plasmas. En este trabajo se presentan las bases teóricas para este método de diagnóstico, el cual está basado en la autoconsistencia entre las secciones eficaces de intercambio de carga y la evolución de la carga efectiva de los iones energéticos que atraviesan el medio. Se enfatiza la nécesidad de un mejor conocimiento de las secciones eficaces de intercambio de carga y de su dependencia con la temperatura del medio.

Abstract

Electron capture by energetic ions during their passagethrough a plasma produce, radiation with very peculiar signatures. These emissions may be employed for the goal of plasma diagnostics. In this paper we present a theoretical approach for such a diagnostic method, which is based on the self-consistency of charge interchange cross-sections and the evolution of the effective charge of the energetic ions in the traversed medium. It is emphasized the need of a best knowledge of charge changing cross-sections as a function of the medium temperature

1. Introduction

Among the most powerful tools for plasma diagnostics there are the several spectroscopies developed for the study of matter (in and out of) the thermodynamic equilibrium.[1] Within the frame of systems where a given population does not satisfy the SAHA law, as is the case of the interaction of energetic ions with a thermal population, we proposed in previous works[2,3] a new kind of diagnostics method, designated as "electron pick-up spectroscopy". Such a method was applied to inquire about the source of energetic ions in solar flares and cometary phenomena,[4] during acceleration of those ions. This method allows for the identification of the acceleration mechanism, abundances and charge states of the accelerated ions, the composition and density of target particles and the temperature of the medium. Obviously it may be applied to many other scenarios different from that of particle acceleration; for instance, in cosmic ray propagation through molecular clouds in the galaxy, or the passage of particle beams through matter in the laboratory, where ions may lose energy to the medium by coulomb collisions while undergoing electron-capture. There are other situations where particles do not gain or lose energy but there is enough amount of traversed matter for electron capture; this is the case of low energy cosmic rays propagation in the interstellar medium, where electron-capture signatures may be important for identifying energy and density-dependent processes.[5] Such a spectroscopy is also potentially useful for diagnostics in active experiments with particle beams, in the magnetosphere and ionosphere. Electron capture is a strong energy-dependent process, which is established or not depending on the quantity of matter passed through. The criteria for the establishment of electron capture and loss, and charge state equilibrium during an acceleration process depend on the efficiency of the acceleration mechanism.[6] The charge evolution of energetic ions in a medium gives information on whether charge interchange is established or not. A dominant tendency to electron stripping indicates an acceleration process, whereas the dominance of electron attachment indicates particle stopping. A dominant tendency to charge state equilibrium indicates that particles do not undergo any important energy change. Of course, if charge interchange is not established, particles keep their charge invariable and photons from electron capture are not produced. The efficiency of the proposed spectroscopical method depends strongly on the accuracy of charge interchange cross-sections (CICS). To inquire about the properties of the traversed medium and the behavior of energetic ion properties therein, it is necessary to know the dependence of the CICS on the temperature of the medium , the composition of target particles, and the velocity and composition of the projectile ions. Unfortunately, the relevant theoretical and experimental work concerning CICS does not consider the temperature of the medium, which is very important in finite-temperature plasmas. An attempt to undertake this fallacy deals with the introduction of the relative velocity (V_r) between projectile ions and thermal targets.[7] Furthermore, CICS depend on the evolution of the ion effective charge states, $q^*[v(T)]$. The present status de q^* is associated with experimental results of stopping power in atomic media, and it is described by semi-empirical relations[8]; some extrapolations to astrophysical contexts are done by introducing a parameterized temperature-dependent factor in those relations. However, for the goal of a self-consistent treatment of charge interchange and electron capture spectroscopy in finite temperature plasmas, the effective charge of ions must be derived on basis to the relevant CICS, with explicit dependence on the matter temperature. Such an analytical treatment will lead to a self-regulating interdependence between CICS and the effective charge.

2. Method

For a quantitative evaluation of photon flux from electron capture, to be used with the aim of diagnostics, it is necessary a statistical evaluation of the number of interactions leading to photon emission by electron capture. Hence, it is necessary to know the occurrence probability of capture events (σ_c) Since the attachment of electrons by the ions depends on their total charge, the cross-section for electron loss (σ_l) need also to be determined. The number of capture and loss interactions is given by t/t_c and t/t_l

respectively, where $t_c = \lambda_c/V_r$ and $t_l = \lambda_l/V_r$ with $\lambda_c = 1/N\sigma_c$, $\lambda_l = 1/N\sigma_l$, and N_t = number density of targets. The time (t) is related to the acceleration or deceleration efficiencies in cases of acceleration or stopping power respectively. When the particle flight through a medium is free of particle energy changes, (t) is related to the scale length of the traversed medium. Hence, depending on whether (t/t_c) and (t/t_l) are > 1 or < 1 it is determined whether it is established or not one or both changing processes. The method for evaluation of the emitted photon flux has already been described[2,3] and may ultimately be reduced to a evaluation of the flux by an expression of the form,

$$F(E_\nu, t) = N_p(E, Z, t)\, N_t(Z)\, V_r\, E_\nu\, \sigma_c\, t \qquad (\text{photons/cm}^2\ \text{s}) \qquad (1)$$

$E_\nu = q^* e^2/r_n - q^* e^2/r_c$, where r_n and r_c are the orbital radius of the level n and the electron capture radius respectively, e is the electron charge, $V_r = \bar{v} + \bar{v}_t$, where v is the projectile ion velocity and v_t is the most probable velocity of the isotropic targets. $N_t(\text{cm}^{-3})$ and $N_p(\text{ions/cm}^2\text{s eV})$ give the information about the target medium and the energetic projectile ions. Depending on the scenario under consideration, N_p may be a structured energy spectrum as in cosmic rays, or a mono energetic flux. It made also be an isotropic or anisotropic particle flux. V_r and σ_c contain information on both the projectile ions and the target medium. The cross-section $\sigma_c(q^*, V_r, Z, Z_t)$ and E_ν depend on the ion effective charge at a given velocity. A direct and simplest form to evaluate q^* is by *self-regulating formulation* via the cross-sections σ_c and σ_l:

$$q^* = \int_{t_o}^{t} N_t\, V_r(\sigma_l \mathcal{F} - \sigma_c)\, dt + \text{cte} \qquad (2)$$

where $\mathcal{F}$ is a number $(1 \le \mathcal{F} \le Z)$ denoting the average number of electrons that can be pulled out from the energetic ions per interaction with each target particle. t_o is the initial time in which particles begin to interact with the medium, and (t) is the time at which the effective charge is evaluated. The evaluation of eq.(2) at $t = t_o$ leads to the following result.

$$q^* = q_o + \int_{t_o}^{t} N_t\, V_r(\sigma_l \mathcal{F} - \sigma_c)\, dt \qquad (3)$$

where $q_o = q(t_o)$ is the initial charge value of the energetic ions at the beginning of the interaction with the medium. Since it can be assumed that N_t, V_r, σ_c and σ_l do not depend on the elapsed time, therefore

$$q^* = q_o + N_t V_r t (\sigma_l \mathcal{F} - \sigma_c) \qquad (4)$$

it follows from (1) and (4) that a good knowledge of CICS is required. At present experimental work concerns mainly the study of CICS in atomic matter. These studies are very fractioned, for a limited range of ion velocity, limited range of energetic species and charge states (mainly hydrogenic ions) and limited range of target species (mainly neutral hydrogen). There is not a global study of CICS for all particle velocity, all nuclear species and ionization states of energetic ions and targets, and for any temperature of the traversed medium. Consequently, theory is also very limited and fractioned and does not consider explicitly the matter temperature.[9-12] We have attempted to build a kind of unified and global description of CICS covering all the features mentioned above: we proceeded to make a kind of "collage" of theoretical CICS to enlarge their range of validity, as is shown in fig. 1 for hydrogenic iron ions through neutral hydrogen, where σ_{cc} = coulomb capture cross-section, σ_l = electron cross-section, σ_{cr} = radiative capture cross-section, v_o = Bohr velocity and v = projectile ion velocity. Due to the lack of knowledge of adequate temperature-dependent interaction potentials, we introduced the temperature through the thermal velocity of target in V_r. In ionized matter ($\geq 2\times10^4$ K) and at energies $\geq$ 10 MeV/n in atomic matter, the radiative capture cross-section was employed.[13] Figs. 2 and 3 illustrated the temperature dependent CICS, where q_o was taken as the ionization equilibrium state at the corresponding temperature.[14] Finally, in fig. 4 it is illustrated the potentiality of the spectroscopical method for whatever the place where particles are being accelerated while undergoing electron capture. Though the employed parameters an acceleration mechanisms have been chosen only with a paradigmatic goal, they could be associated with a laboratory plasma device where some kind of instabilities make create the accelerating electric fields, such that some form of Fermi acceleration or direct electric field acceleration may be produced therein. It can be appreciated, for instance, that the intensity, energy band and tame scale of the emitted photon flux depend on the kind of acceleration mechanism, the kind of target and projectile ion, and the temperature of the medium. As previously stated[2] the charge state evolution of the energetic ions can be inferred from the emitted radiation. Since σ_c scales as $Z^5 Z_t^5$, this diagnostic method becomes more powerful with heavy or ultra-heavy nuclei interacting with molecular, atomic, plasma or dust of high atomic number.

3. Conclusions

The knowledge of charge evolution of energetic ions as a function of velocity and time is very important in many contexts. The conventional description of effective charge by means of parameterized semi-empirical relations is not adequate in finite-temperature matter. We present here a *self-regulating method* to evaluated the effective charge of ions on basis to CICS. The fundamental importance of this interdependence between q* and CICS has been illustrated within the frame of a new spectroscopical theory. In

Fig. 1

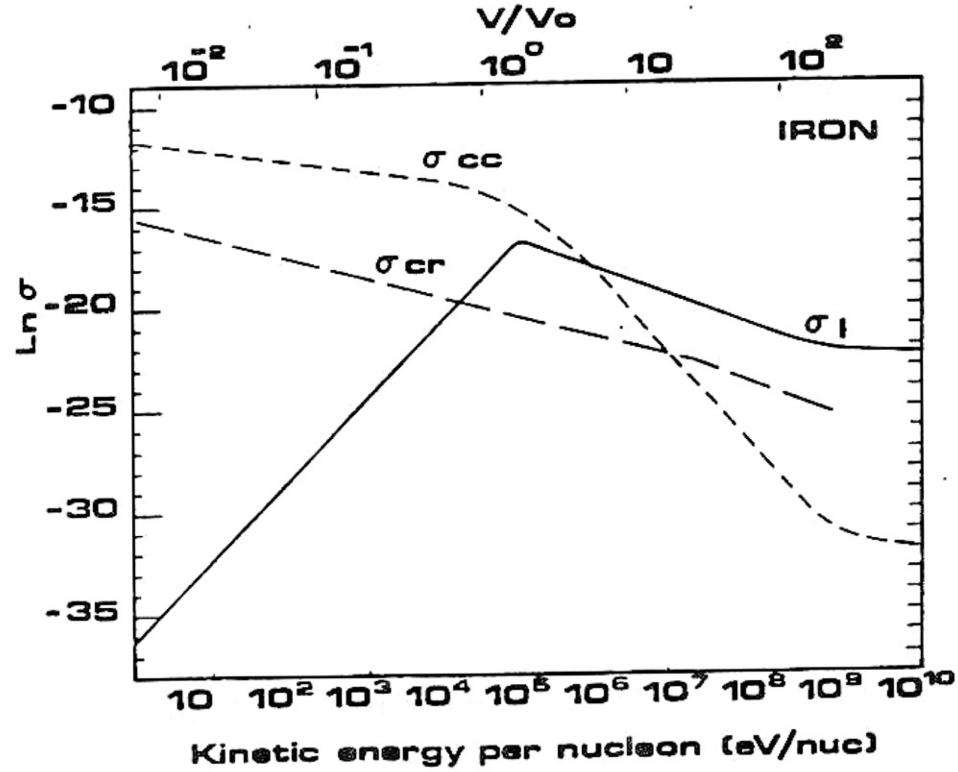

V/Vo
10^{-2}
10^{-1}
10^{0}
10
10^{2}
-10
-15
-20
-25
-30
-35
Ln σ
IRON
σ cc
σ cr
σ I
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Kinetic energy per nucleon (eV/nuc)

Fig. 2

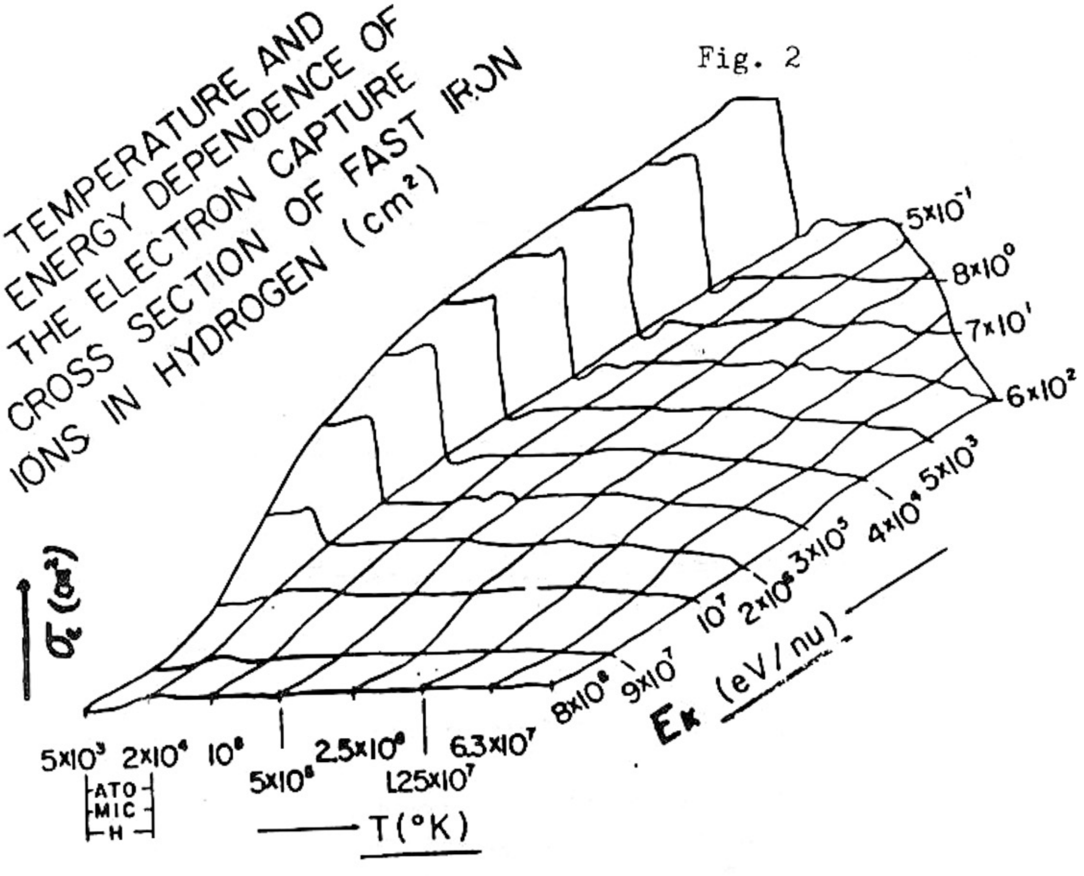
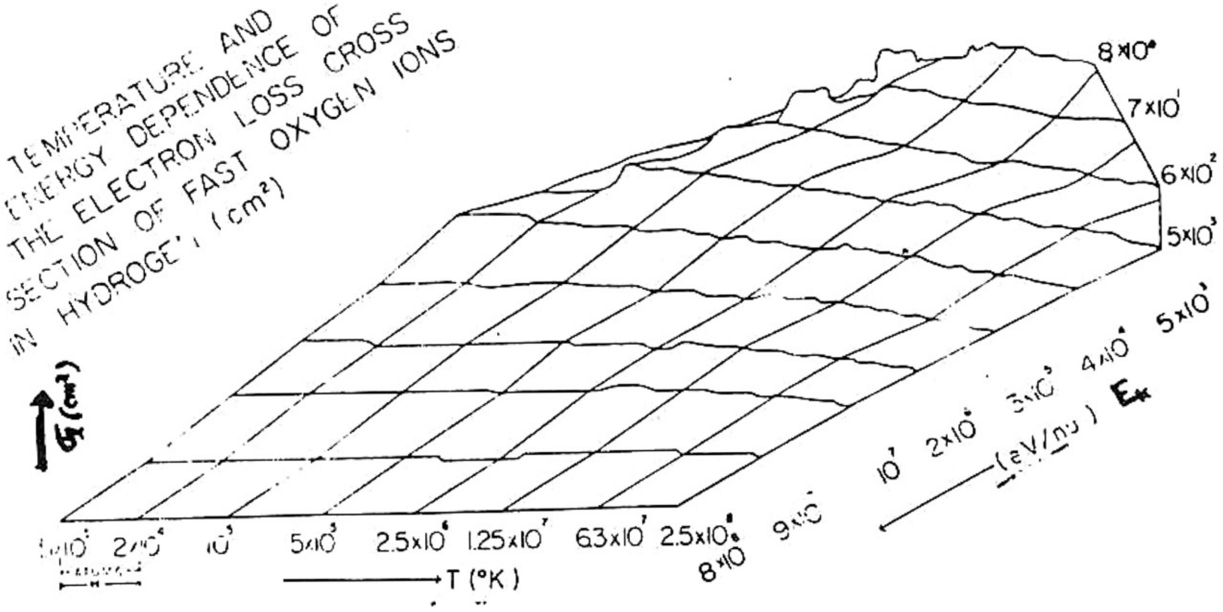

TEMPERATURE AND ENERGY DEPENDENCE OF THE ELECTRON CAPTURE CROSS SECTION OF FAST IRON IONS IN HYDROGEN (cm²)
σ_e (cm²)
5x10⁻¹
8x10⁰
7x10¹
6x10²
5x10³
4x10⁴
3x10⁵
2x10⁶
10⁷
9x10⁷
8x10⁸
Ek (eV/nu)
5x10³
2x10⁴
10⁵
5x10⁵
2.5x10⁶
1.25x10⁷
6.3x10⁷
ATOMIC H
T(°K)

FIg. 3



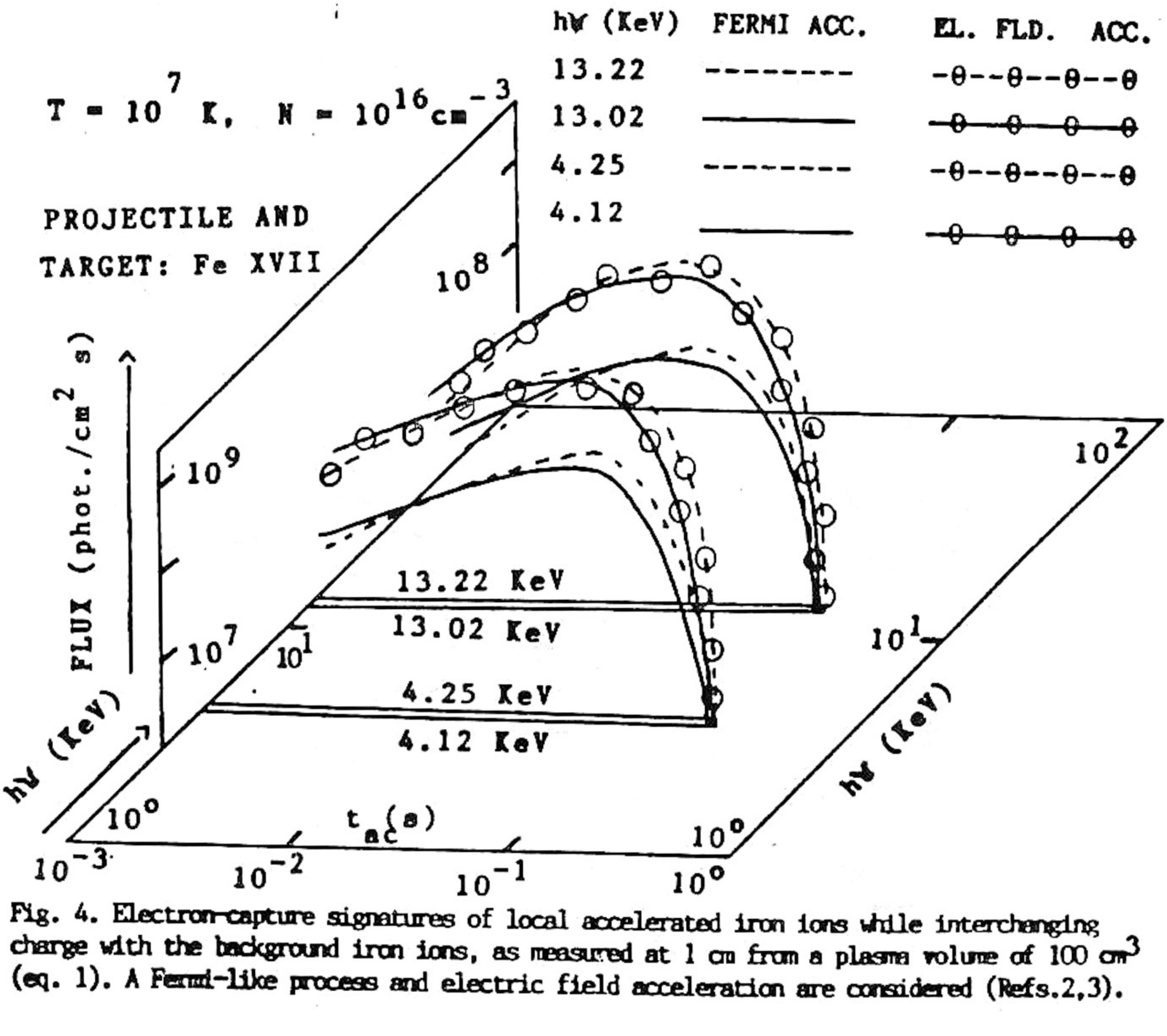


Fig. 4. Electron-capture signatures of local accelerated iron ions while interchanging charge with the background iron ions, as measured at 1 cm from a plasma volume of 100 cm^3 (eq. 1). A Fermi-like process and electric field acceleration are considered (Refs.2,3).

order to develop this as a powerful tool of plasma diagnostics, a high accurate determination of CICS is required. We conclude that a new impetus on experimental an theoretical work about CICS with explicit temperature -dependence will afford new insights in plasma physics.

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