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EVOLUTION OF EFFECTIVE CHARGE OF ACCELERATED IONS

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Abstract Semi-empirical relations for effective charge $\bar{q}_{eff}(v)$ of energetic ions, derived from Stopping Power data cannot be extrapolated to scenarios where ions undergo an acceleration process while interacting with finite temperature matter, because the nature of acceleration rates is completely different from Stopping Power rates. We derive here a theoretical expression for $\bar{q}_{ef}$ during acceleration with explicit temperature dependence.

Introduction Charge states of energetic ions and their evolution during the passage of ions through matter is a very important factor for the study of particle interaction with matter and E.M. fields. At laboratory scale the study of Stopping power of ions in different materials is strongly dependent on the accurate knowledge of equilibrium charge states. In Cosmic Ray Physics it is also very important to determine Stopping Powers in different contexts: evaluation of radiation fluxes from the interaction of particles with matter and magnetic fields, production of secondary nuclei by spallation, modulation of low energy ions in the frontier of the heliosphere and magnetosphere, and whenever magnetic fields are present because the ions magnetic rigidity depends on the charge carried on by ions. It is of particular importance the behavior of charge states during the generation of energetic ions in their sources in connection with the energy and charge spectra: the relative chemical abundance of the accelerated ions are highly dependent on the charge states during their acceleration and escape from the source, and so it is the emitted radiation when the accelerated ions capture electrons of the medium (Pérez-Peraza et al, 1989). The present knowledge of Effective Charge (or mean equilibrium charge states) is associated with experimental results of Stopping Power of ions in solids and atomic gaseous media, which can be adequately described within the frame of the classical Thomas-Fermi atomic model: since at relatively low energies ($\leqslant$ 50 MeV/n) the actual charge carried on the ions is generally a fraction of the nuclear charge, it is defined an effective charge $\bar{q}_{eff} = \gamma Z$.

In order to compare different ionic species on the same basis, the correlationship of $\bar{q}_{eff}$ to the ion velocity is made in terms of fractional effective charges $\gamma = \bar{q}_{ef}/Z$ and reduced velocities $V_r = \beta/cv_o Z^{\omega}$, where β is the ion velocity in terms of the light velocity c, and $v_o = e^2/\hbar$. In the process of fitting Sopping Power data, several semi-empirical relations of ion velocity and charge have been developed in the form of parametrized smooth functions, which general form is $\gamma = 1 - \xi \exp(-CV_r)$ (e.g., Betz, 1972). ξ depends slightly on Z and is related to ionization potentials; in solid and atomic gases $\xi = 1$ at $v \gtrsim v_o$. C ranges from ~ 0.7 for solids to ~ 0.98 for atomic gases. ω in solids is a decreasing function of Z, and for gases ranges from ~ 0.4-0.7, when $\omega = 2/3$, V_r is related to the Thomas-Fermi velocity; in this case, for C=0.93 the previous relation it is written as $\bar{q}_{eff} = Z[1 - \exp(-127\beta/Z^{2/3})]$. Similar expressions are usually employed with C=0.91 (Barkas, 1963), C=0.95 (Pierce and Blann, 1968), all of them obtained from Stopping Power data in heavy ion targets of very high density ($n \gtrsim 10^{16}$ cm^{-3}). This kind of semi-empirical relation do not consider the temperature of the medium (T) and refer to experiments of ion deceleration toward stopping in solids and atomic gases. For astrophysical applications of particle transport in ionized or atomic hydrogen, it is usually extrapolated that kind of expression by introducing T as $\xi = \exp[-a(3kT/Mc^2)^{1/2}]$ where $a = 127/Z^{2/3}$ and $M = m_e$ the electron mass in ionized medium and $M = \mu A$ in atomic media, so that the expression is used as $\gamma = 1 - \xi \exp(-a\beta)$. Such an expression shows that ions strip faster at low energy as T increases. (Pérez-Peraza et al, 1983). When ions instead of being stopped, they are undergoing an acceleration process while interacting with the local matter, as is the case in Cosmic Ray sources, these kind of expressions are not at all valid. In fact, because the energy gain rate is off different nature to the Stopping Power rate, the evolution of particle charge as a function of energy must be derived taking into account the acceleration rate. Since there is not data of particle charge evolution in finite temperature matter during an acceleration process, we proceed here to derive an expression in terms of theoretical charge-changing cross sections extrapolated to finite temperature matter and a specific acceleration rate, namely that of the Fermi process.

Theory The condition for particles undergo a given kind of interaction with matter while traversing through a medium is $\lambda = vt_{in} \leq L = vt_f$, where t_{in} is the mean interaction time and t_f is the mean flight time in the region of thickness L; λ is related to the cross section $\lambda = \mu A/\sigma$ where A is the atomic mass and μ is the atomic mass unit, and L is related to the density of the medium $L = \rho vt_f$. So the condition $\lambda \leq L$ depends strongly on the matter density and/or the flight time. Now, if together with the interaction process there is another process taking place on ions, hence L must be related to such a process. In laboratory together with charge-changing interactions it is generally the stopping power of the matter that is taking place on ions. But if instead of deceleration there is an acceleration process, t_f becomes the time for a ion to gain velocity from v to $v + \Delta v$. It has been shown by Pérez-Peraza et al (1985) that L is related to a given acceleration mechanism of rate $(dE/dt) = \alpha E^{\eta}$ by $L = 2(v^{3-2\eta} - v^{3-2\eta})/\alpha(3-2\eta)(\mu/2)^{\eta-1}$ for $v \leq v_c$ and $L = 2(v^{3-2\eta} - v_c^{3-2\eta})/\alpha(3-2\eta)(\mu/2)^{\eta-1}$ for $v^c > v_c$. where v_c is is the velocity where both the electron capture and the electron loss cross sections are equated ($\sigma_c = \sigma_\ell$) and $\eta = \frac{1}{2}$ corresponds to the non-relativistic Fermi acceleration rate. The criteria for determination of values of the acceleration efficiency (α) was discussed by Pérez-Peraza et al, (1988). Criteria for the establishment of charge-changing processes during acceleration were delimited by Pérez-Peraza et al, (1985) to three cases, charge equilibrium $(L/\lambda_c, L/\lambda_\ell) > 1$, or pure electron capture $(L/\lambda_c > 1; L/\lambda_\ell < 1)$ or pure electron loss $(L/\lambda_c < 1; L/\lambda_\ell > 1)$. To estimate how the ion charge is modified in a limited time lapse (acceleration time from E to $E + \Delta E$) and limited space (the cross section) let us argue on the following terms: the accelerated ion while moving in the source is seeing a flux nv_R of targets (free or bounded electrons), where v_R is the relative velocity between the projectile ion and the targets. From that flux, only a fraction $(nv_R\sigma_c)$ may be captured by the ion, and another fraction of target electrons $(nv_R\sigma_\ell)$ is able to pull out electrons from the ion. So, the mean number of electrons that are captured or lost in an acceleration step are $(nv_R\sigma_c t_a)$ and $(nv_R\sigma_\ell t_a F)$ respectively, where $t_a = L/v_R$ is the mean acceleration time for particles to go from v to $v + \Delta v$, and F is a number (between 1 and Z) denoting the average amount of electrons that can be pulled out by each target particle per interaction with the ion. Therefore, the mean equilibrium charge carried on by the ions depends on the number of capture and loss interactions that the ion undergoes along its path. The number of collisions along the path L (for ions to gain energy from E to $E + \Delta E$) is given by $X_c = L/\lambda_c$ and $X_\ell = L/\lambda_\ell$, where $\lambda_c = 1/n\sigma_c$ and $\lambda_\ell = 1/n\sigma_\ell$ respectively. Hence the evolution of charge as a function of the ion energy is $q_{eff} = n\int_E^{E'} v_R(F\sigma_\ell t_a X_\ell - \sigma_c t_a X_c)$, where $E' = E + \Delta E$, that can be numerically evaluated by the following expression

$$\bar{q}_{eff}(E) = q_o(E,Z) + n\bar{v}_R(E')[F\bar{\sigma}_\ell \bar{t}_a (\bar{L}/\lambda_\ell) - \bar{\sigma}_c \bar{t}_a (\bar{L}/\lambda_c)] \qquad (1)$$

where $q_o(E,Z)$ is the initial charge before each acceleration step , so that at the beginning of the process corresponds to the local thermal charge defined by thermodynamic equilibrium according to the source temperature (T). It can be seen in (1) that depending on whether the ratios (L/λ_ℓ) and (L/λ_c) are > 1 or < 1, it is determined whether it is established or not one or both charge-changing interactions; i.e. the interaction processes are established when $t_c < t_a$ and $t_\ell < t_a$, where $t_c = (\sigma_c/\P v_R)^{1/2}$ and $t_\ell = (\sigma_\ell/\P v_R)^{1/2}$. When it is not acting an acceleration process, like in the previously mentioned experiments, t_a is replaced by t_d ~~and t_ℓ~~ , and L by the range $R = \int_{E'}^{E} E/(dE/dx)$ for particles to be decelerated from E' to E. The T-dependence in (1) is introduced through σ_c and σ_ℓ as explained by Pérez-Peraza et al, (1985) by means of the thermal velocity of the targets within the relative velocity v_R.

Results To calibrate equation (1) to the semi-empirical relation, we assume $T \equiv 0$ ($v \neq 0$), t_a is replaced by t_d ~~and t_ℓ~~ and L by the range R. Evaluations of γ are shown in Figs. 1 and 2, for several stopped ions in a medium of $n = 10^{16}$ cm^{-3} atoms of oxygen, which is the typical target medium stopping power data. The solid curve represents the semi-empirical relation of Fe ions. In Fig. 1 the contribution of electron capture was neglected and it can be appreciated that ions strip slightly faster than in Fig. 2 where both charge changing processes are considered (charge equilibrium). Concerning cross-sections there is a very complex problem at this regard: they are highly dependent on the ion velocity domain, on Z and $\bar{q}_{eff}$ of ion projectiles, on the Z_t and $\bar{Z}_{eff}$ of the target medium (ionization degree of the medium) and on the target velocities v_t (T of the medium). Experimental data exist only for some projectile ions, some atomic targets, in a limited velocity domain and for $v_t \approx 0$. Theoretical cross-sections for ionized medium are very rare. For a global description of cross-sections through the entire velocity domain in targets of low average $\bar{Z}_{eff}$ (~ atomic media) and high average $\bar{Z}_{eff}$ (~ ionized media) a combination of different experimental and theoretical cross-sections must be done (Pérez-Peraza et al, 1985). However there is a high degree of uncertainty around cross-sections since they are generally given as approximate expressions $\sigma \approx \pi a_o^2 f(v, Z, \bar{q}_{eff}, Z_t, \bar{Z}_{eff})$. We have found that for calibration of (1) at T = 0 (Figs. 1 and 2) and stabilization of (1) in finite-temperature atomic matter, the $\bar{q}_{eff}$-dependence of σ_ℓ must be decreased by a factor $\sigma_\ell (26/Z)\bar{q}_{eff}^{-1.8009}$ whereas in ionized matter the factor is $\sigma_\ell \bar{q}_{eff}^{-1.5}$ for $T \leq 10^5$ K and $\sigma_\ell \bar{q}_{eff}$ for $T > 10^5$ K. In Fig. 3 it is shown the evolution of (1) for iron ions during a Fermi acceleration process, in a medium of hydrogen, for different T values: $T = 10^5$ K, $n = 10^{12}$ cm^{-3} with Fe^5, $T = 5 \times 10^5$ K, $n = 10^{11}$ cm^{-3} with Fe^8 and $T = 10^6$ K, $n = 10^{10}$ cm^{-3} with Fe^{10}. It can be seen that at low velocities the higher the temperature the higher is the equilibrium charge state, because the initial local charge state is higher, but as ions gain energy the tendency reverses

FIG 1

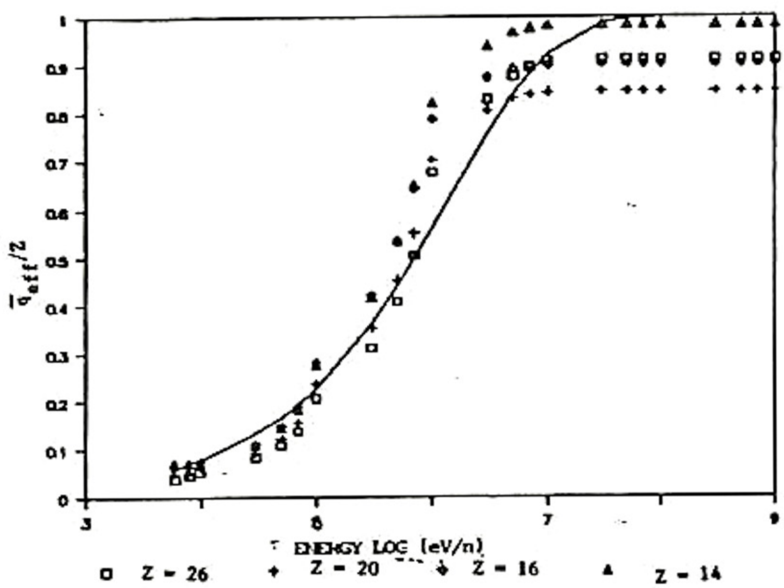
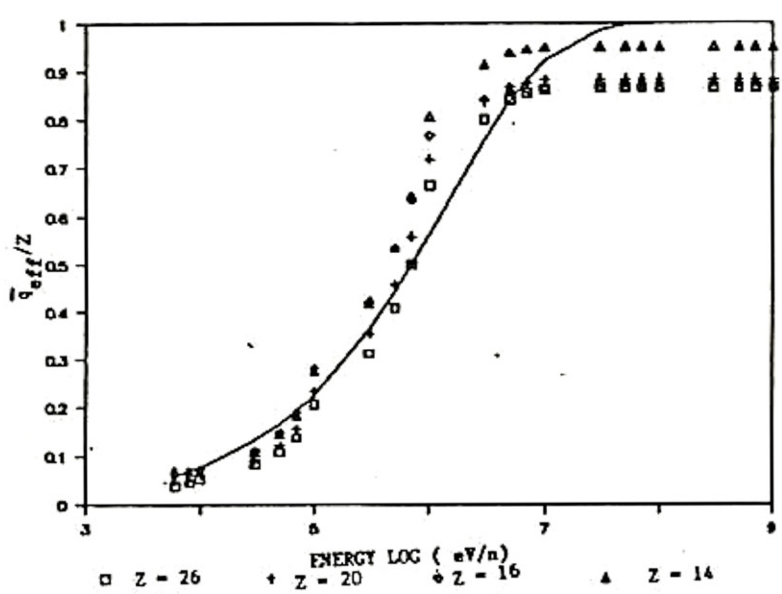


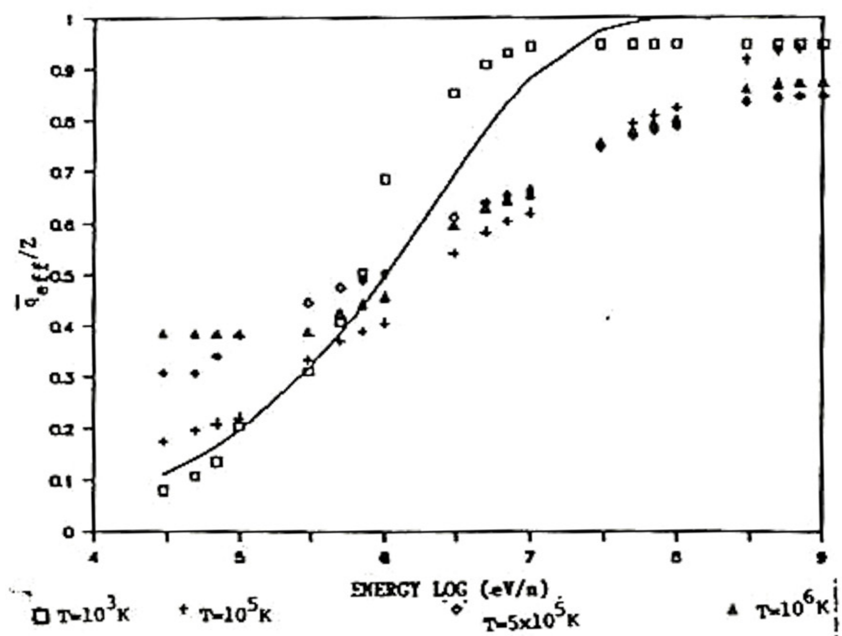
FIG 2



because the decrease of σ_ℓ with the increase of v_R. Also, it is shown in Fig. 3 the behavior of our predictions for charge evolution during stopping of iron ions at $n = 10^{13}$ cm^{-3} and T = 10 ' K together with the corresponding semi-empirical relation (solid curve). Taking in account the uncertainties on the cross-sections, our theoretical curve is close to the semi-empirical one, though the difference is higher than in the previous figures because the introduction of temperature.

<u>Conclusions</u> We have derived on theoretical grounds an expression for the effective charge (or fractional effective charges $= \gamma$), that in spite of its dependence on the accuracy of the employed cross-sections of charge-changing processes is of general validity, in the sense that it can be applied during an acceleration process as well as during stopping of ions while traversing a medium, depending on whether L is the acceleration length step or the stopping range, and whether the elemental time scale is $t_a = L/v_R$ or $t_\lambda = \lambda_R/v_R$ ($\lambda = \lambda_c + \lambda_\ell$).

FIG 3



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