STUDY OF PHOTON EMISSION BY ELECTRON CAPTURE DURING SOLAR NUCLEI ACCELERATION.II. DELIMITATION OF CONDITIONS FOR CHARGE TRANSFERT ESTABLISHMENT.

J. Pérez-Peraza*and M. Alvarez *
Instituto de Geofísica, UNAM, 04510, C.U. México 20, D.F.

A. Gallegos
UPICSA, 08400, México, D.F.

I. INTRODUCTION. In preceeding works 1 , 2 , we have examined the conditions for the establishment of charge transfert of solar particles during their acceleration in the dense medium of their sources: In 1 , we restricted our analysis to the case of hydrogenic projectil ions, and in 2 we studied the case of highly charged ions (effective charge = $q^* < z$ =atomic number). But in both cases, we did not take into account the charge transfer cross-section dependence on the target velocity, i.e. we ignored the effect of the finite temperature of matter. A more occurate evaluation of the charge transfer criteria developed in the previous papers needs of the results derived in SH.1.1-8. With this goal in mind let us remind that the conditions for the passage of fast ions through matter at laboratory scale and in astrophysical sources of energetic particles are to some extent of opposed nature. In the first case a monoenergetic flux of high energy particles is injected into the matter, whereby particles lose energy through energy transfert to the electrons and nuclei of the target medium. When the amount of traversed matter is greater than the mean free path for charge changing processes, the charge equilibrium is established; if the particle velocity is higher than the orbital velocities of its electrons the ion is rapidly stripped, however, as the particle velocity is degraded by collisional losses to a lower velocity than the orbital velocity of the first captured electron, the electron capture cross-section gradually dominates over the electron loss cross-section. As particles slow down and electron capture leads them toward the neutralization, they may be stopped by thermalization with a low effective charge, or even in the neutral state. On the other hand, in astrophysical sources instead of that tendency toward thermalization,particles are accelerated from thermal energies up to high energies, begining with their local charge state Q_L, which is determined by ionization equilibrium at the peculiar source temperature. In order to elucidate whether particles keep their thermal charge state during that acceleration stage or not, the conditions for the establishment of charge transfert have been investigated. The behavior of particle charge during acceleration is very important due to several implications related to the mass and charge spectra of particles, the acceleration efficiency and secondary electromagnetic radiation.

II. CRITERIA FOR THE ESTABLISHMENT OF CHARGE CHANGING PROCESSES. As we explained in 1 the criteria for establishment of charge-changing processes may be seen as an evaluation of the relative importance between the mean free path for charge transfert and the characteristic length of the acceleration step, provided that the later one be shorter than the mean free path for Coulomb inelastic collisions. In order to avoid masking the effects of concurrence between the processes of charge interchange and acceleration, on the behavior of particle charge, it is convenient for the task of simplicity to consider those acceleration mechanisms whose rates are independent of charge: stochastic acceleration (Fermi mechanism) and acceleration by secularly varying magnetic fields (Betatron mechanism),

*On leave for the INAOE, Tonanzintla,A.P.51, 72000-Puebla which rates in the non-relativistic range may be expressed as $(dE/dt)=\alpha E^{n}$, with $n = 1/2$, $\alpha = \alpha_f(2\mu C^2)^{0.5}$ and $n = 1$, $\alpha = 2\alpha_b$ for the Fermi and Betatron mechanisms respectively, $E = \mu v^2/2$, μ = atomic mass unit and α_f, α_b the hydromagnetic acceleration efficiencies. Using $(d/dt) = v(d/dx)$ the above rate becomes $v^{2(1-n)}dv = (\alpha/2)(\mu/2)^{n-1}dx$. Now let define a cross-velocity v_c where both cross-sections for electron capture and loss are equated. So, integrating the acceleration rate from v to v_c in the domain of electron capture $(v \leq v_c)$ through the thickness L of the traveled matter, and from v_c to v in the domain of electron loss, and introducing the condition of establishment of charge transfert, that the corresponding mean free rath (λ) must be shorter than the amount of traversed matter $(\lambda = 1/n\sigma < L)$, where n and σ are the number density and the corresponding cross-section, we obtain the following expressions $\alpha<2(v_c^{3-2n}-v^{3-2n})n\sigma/(3-2n)\ (\mu/2)^{n-1}$ and $\alpha<2(v^{3-2n}-v_c^{3-2n})\ n\sigma/(3-2n)\ (\mu/2)^{n-1}$ for the establishment of capture and loss at $v<v_c$ and $v>v_c$ respectively, when an acceleration process of efficiency α is modulating the velocity of the traversing particle through the source matter. However, such an acceleration efficiency must overcome the deceleration efficiency from the rate of inelastic losses in order to produce suprathermal particles. That is, the condition $\alpha/\alpha_c>1$ must be satisfied, where α_c is the threshold value of the acceleration efficiency above the which the acceleration dominates energy losses. Values of $\alpha_c(n)$ were given in [1] as $\alpha_c=3.38 \times 10^{-13}nq^{0.5}/A$ and $\alpha_c=4.5 \times 10^{9}nq^{0.16}/T^{0.27}A^{0.78}$ for the Fermi and Betatron processes in atomic H, and $\alpha_c=3.89 \times 10^{-7}n^{0.98}q^{1.92}/T^{0.96}A^{0.88}$ and $\alpha_c=0.28n^{0.97}q^{1.87}/T^{1.45}A^{0.67}$ in plasmas. So, our criteria are reduced to 4 evaluations of $(\alpha_f/(2\mu c^2)^{0.5}\alpha_c)>1$, two for electron capture (in atomic and ionized H) and two for electron loss, and similarly other 4 evaluations with $(\alpha_b/2\alpha_c)>1$. On the next figures we have omitted the subfixes f and b, but indicated the considered acceleration mechanism. It must be emphasized that these criteria become independent of number density but strongly dependent on cross-sections and the cross-velocity v_c. Values of v_c for the particular case of targets at rest (T≡0) were given in [2]. Here we use the σ values of SH1.1-8 and so the corresponding v_c values were numerically obtained. For the evolution of the charge q appearing in the σ and v_c values, we normalized to the thermal Q_L values as explained in SH1.1-8, when charge equilibrium was found. In the case that the shortness of the characteristic acceleration step only allows for electron capture but not electron loss, we arbitrarely employed in the normalization $q_c^* = Q_L \exp\{-130(\beta-\beta_{th})^{0.33}/Z^{0.66}\}$, whereas in the opposite case we used $q_\ell^* = Z\{1-\xi \exp(-130\beta^{0.33}/Z^{0.66})\}$ where β and β_{th} are the projectil velocity and its thermal velocity respectively and ξ as given in SH1.1-8. The results discused below may be considered as a lower limit in the amount of electron capture and loss, because the main considered target is H. If heavier elements are considered, electron capture becomes much more important, because the employed cross-sections scale as $Z_t Q_L^5$ for Coulomb capture and $\sim Z_t$ for radiative capture; so in evaluating election pick-up with heavy targets we multiplied σ_{crl} and σ_{cr} in SH1.1-8 by Z_t.

III. RESULTS AND CONCLUSIONS. We explored the conditions for establishment of charge transfert during acceleration of nuclei up to Fe, for typical conditions of solar flare regions T = 5 x 10^3 - 2.5 x 10^8°K. Our results show that such conditions are widely assorted, depending on the acceleration mechanism, the kind of projectil ions and their velocity, the target elements, the source temperature and consecuently on the degree of ionization of matter and the local charge state of the accelerated ions.

Nevertheless, in spite of that assorted behavior, there are some general tendencies that can be sumarized as follows. In atomic H electron capture is systematically established from thermal energies up to high energies, whathever the element and for both acceleration process. For a given element and fixed T, the probability and energy domain of electron capture and loss with Fermi are higher than with Betatron acceleration. For a given acceleration process the heavier the ion the higher the probability and the wider the energy range for electron capture and loss. For a given acceleration mechanism and fixed element the importance and energy domain of capture and loss increase with T: for those reasons, the energy range of charge equilibrium (illustrated with solid lines on the next figs.) is wider with Fermi and increases with temperature and atomic number of projectils. For the same reasons, electron loss is smaller while the lighter the element, the lower the temperature and the Betatron process, such that there are conditions for which electron loss is not allowed at low energies, but only electron capture is established. Consecuently, the energy domain for pure electron capture (illustrated with crosses) is wider the lighter, the element, the lower T and with the Betatron mechanism. On the other hand, at high energies electron capture is not allowed and only electron loss is established (illustrated with small squares) up to high energies, while the heavier the element and the higher the temperature. These results, illustrated through figures (1)-(4) show higher importance of electron capture than that found in [1], [2], because the increase of the cross-section with T in atomic matter described in SH1.1-8. Obviously, the employement of the conventional effective charge expression for charge equilibrium is not adequate when only electron capture is established and particles tend to neutralization, or when pure electron loss is established and particles strip faster. In ionized H electron capture is only established with Fermi acceleration for $T>2x10^8$°K and $Z>10$ provided they are at thermal hydrogenic state ($Q_L=Z$). Under these conditions the heavier the ion the higher the probability and energy domain for electron capture. Electron loss is more important with Fermi than with Betatron and the higher the temperature the higher the probability and the wider the energy domain. At low energies electron loss is more important while the lighter the element and at high energies electron loss becomes more important while the heavier the element as can be understood from the q-dependence of cross-sections in SH1.1-8. We have illustrated these effects on Figs. (5)-(7). An interesting effect that appears with the consideration of the target temperature, in contraposition of the conventional picture described in panel-1 of SH1.1-8, is that in low-T plasmas ($T>T_i$) and low velocities ($v<v_c$), σ_{pc} may become higher than σ_{cri} because the shift to low velocities of the σ_{pc}-pick and the decrease of σ_{cri} with the increase of relative velocity v_R. On the other hand, although σ_{cri} decreases with T roughly as v_R^{-2}, however the reason for which electron capture is established only at high T ($>2x10^8$°K) and that electron loss at low velocities increases with T, is due to the fact that v_c increases with T, in such a way that at high T in our criteria expressions we have, for instance in the Fermi case, that $(v_c^2-v^2)$ increases faster with T than the decrease of σ_{cri}. Finally, in Fig. 8, we have illustrated the energy domain of charge equilibrium in ionized matter for different ions, when instead of H we consider heavy targets: beyond the end of those curves, at higher energies, only electron loss is established. These cases are very importants in evaluating photon emission from electron capture, since our criteria for charge-transfert establishment are density-independent, and so, only σ and v_c determine the electron capture domain.

REFERENCES

[1] Pérez-Peraza, J., et al., Adv. Space Res. 2, 197, 1983.
[2] Pérez-Peraza, J., et al., 18th Int. Cosmic Ray Conf. 9, 309, 1983.

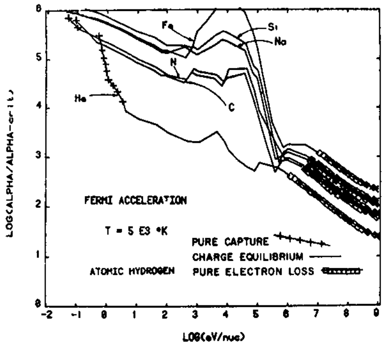

FIG. 1

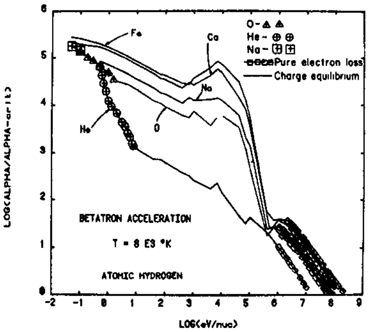

FIG. 2

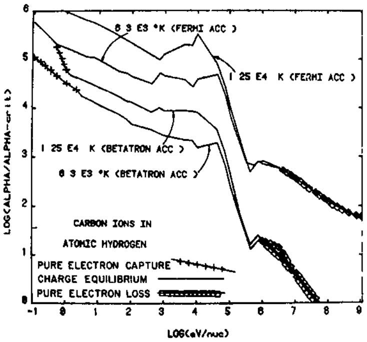

FIG. 3

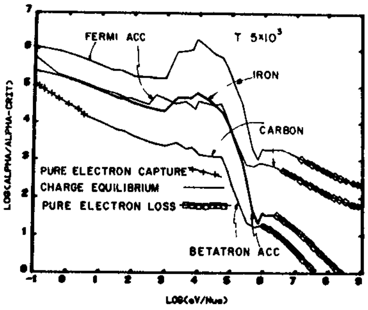

FIG. 4

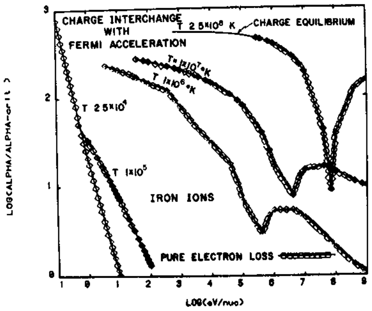

FIG. 5

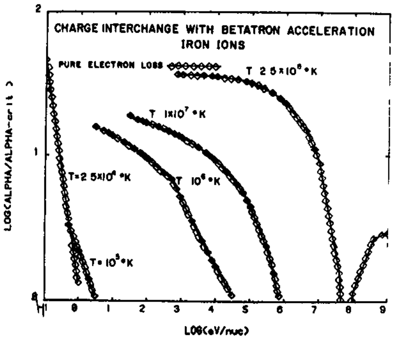

FIG. 6

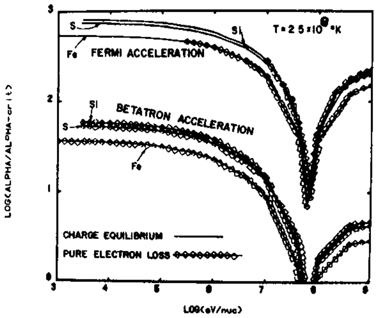

FIG. 7

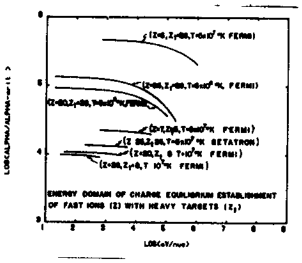

FIG. 8