Adv. Space Res. Vol.2, No.11, pp.197-200, 1983
Printed in Great Britain. All rights reserved.

0273-1177/83/110197-04$3.00/0

PARTICLE CHARGE INTERCHANGE DURING ACCELERATION IN FLARE REGIONS

J. Perez-Peraza, J. Martinell and A. Villareal

Instituto de Geofisica, U.N.A.M., 04510-C.U., Mexico 20, D.F.

ABSTRACT

We have examined the conditions for the establishment of charge equilibrium of solar particles during their acceleration. We derive criteria for charge interchange with the atomic and ionized hydrogen at the particles'sources, for two different acceleration mechanisms. It is found that charge interchange is established whenever a particle event is produced. The implications related to mass and charge spectra of particles are discussed. The measured charge state of solar particles cannot in general be directly used for diagnosis of the source temperature, so we suggest another alternative based on the emitted radiation from electron capture.

INTRODUCTION

It is usually assumed that the charge state of solar nuclei corresponds to the ionization equilibrium of the solar corona at $T \sim 1.6 \times 10^6$ °K [1]. This entails that charge equilibrium of particles with the source matter is not established during the acceleration process, or subsequent propagation, but that the particles keep their charge states from the source. This is claimed on the basis of two main observational features: (1) C and O are in a very high ionization state even at very low energy, and that according to indirect results [2], [3], Fe is almost completely stripped at energies as low as 0.2 and 2 MeV/n, (2) the measured mean charge states do not vary through a wide energy range and are invariant from event to event. It must be noted that observational results are still of limited reliability because the limited charge resolution does not allow for individual charge state separation and unambiguos identification by atomic number. Nevertheless, in relation to (1), it may be argued that if charge equilibrium is established, the charge values predicted by a semi-empirical expression of the form $q^* = Z[1-\xi \exp(-a\beta)]$ with $\xi = 1$ are much lower than the measured values (Z and β are the atomic number and velocity of particles in units of the light velocity and $a = 130/Z^{0.66}$). However, if instead of $\xi = 1$, we consider the fact that the target medium has a finite temperature, then $\xi = \exp[-a(3kT/m_ec^2)^{1/2}]$ (where k and m_ec^2 are the Boltzman constant and electron rest energy). So, even in the idealized assumption of $\beta = 0$, particles can be ionized due to the impact of the thermal electrons. In addition, this effective charge at the level of the thermal velocity of nuclei must be normalized to the local charge determined from ionization equilibrium at the temperature of the source. It follows, that the effective charge of low energy nuclei in astrophysical conditions is much higher than at the experimental scale where temperature is neglected. In contrast to (2), it should be mentioned that the measured charge states of Fe in the range (10-150) KeV/n for the event of 14 May 1974 are Fe^{+11} to Fe^{+13} [4], whereas at higher energies charge states up to Fe^{+18} are present [5]: this may be interpreted in terms of establishment of charge equilibrium. On the other hand, it is difficult to concede the invariance from event to event of the acceleration region location to a coronal site of $T \sim 1.5 \times 10^6$ °K given the high dispersion of flare occurence over the two other dimensions (heliolatitude-heliolongitude). As a matter of fact, the mean charge state of Fe at $E \sim 0.2$ MeV/n for different events differs from 11, [4] to 26, [2], and similarly at $E \sim 2$ MeV/n for different events [6], [3]. Therefore, these ambiguities lead us to investigate the conditions for establishment of charge equilibrium, to determine whether particles keep their local charge state during acceleration or not. This may be reduced to evaluate the relative importance between the characteristic lengths of the acceleration step and the mean free path for charge-changing

RESULTS AND DISCUSSION

Conditions for the establishment of charge interchange during acceleration are widely assorted depending on the acceleration mechanism, the kind of element, the temperature and, consequently, the degree of ionization of the target hydrogen and the local charge state of the accelerated ions. It is precisely this assorted behavior of the particle charge that allows for a wide variety of selectivity effects on solar particle composition from event to event, and that we will discuss elsewhere. Here we will limit to present our results concerning charge-changing processes in the acceleration region: whatever the source parameters ($T=5000-2.5\mathrm{x}10^{8}$ °K and $N \leq 10^{15}\,\mathrm{cm}^{-3}$), electron capture in the domain $v<v_C$ and electron loss in the domain $v>v_C$ are systematically established for both acceleration processes in atomic and ionized hydrogen, with the preservation of electron capture by C and lighter elements in ionized hydrogen at $1.6\mathrm{x}10^{4}<T\leq 10^{5}$ °K. Thus, solid lines in Figs. (2) and (3) indicate that only one charge-changing process is established: electron capture for $v<v_C$ and electron loss for $v>v_C$. Also, for all conditions within the domain $v<v_C$, the probability and energy range for capture increase with atomic number. At low temperatures, the probability and energy range for electron loss in the domain $v>v_C$ increase the heavier the ions. Electron loss in the domain $v<v_C$ is generally established in atomic hydrogen but not at all in ionized hydrogen. Electron capture in the domain $v>v_C$ is generally established in atomic hydrogen whereas in ionized hydrogen capture occurs preferentially for heavier nuclei and only at $T \geq 10^{7}$ °K. On figs (2) and (3) it is illustrated with point-dashed and dashed lines the range of electron loss establishment in the domain of electron capture and the range of capture establishment in the domain of electron loss, respectively. These ranges where both charge-interchange processes occur simultaneously determine the domain of charge-equilibrium. It follows that outside of that domain, i.e., where only one charge-changing process is allowed during acceleration, the well known semi-empirical expressions of effective charge during deceleration of monoenergetic ions in atomic matter do not apply: other descriptions of effective charge must be found for the low and high energy range where charge equilibrium is not established. In fact, low energy ions gain charge while increasing their energy, so that eventually they can be lost from the accelerated flux if they reach their atomic state. On the other hand, at high energies where only electron loss is generally established, particles strip faster than they do with the effective charge predicted from charge-equilibrium: since in a wide temperature range of ionized hydrogen sources ($\sim 2\mathrm{x}10^{4}-10^{7}$ °K) charge equilibrium is not established, we claim this is the reason why in addition to the arguments mentioned in the introduction, solar particles of $v>v_C$ are measured in a higher stripped state than predicted from charge equilibrium of ions undergoing deceleration through atomic matter. Therefore, according to the energy range in consideration, three different expressions of effective charge modulated by the presence of thermal electrons of finite temperature ($\xi \neq 1$) and normalized to the local charge state, Q_L, need to be employed in

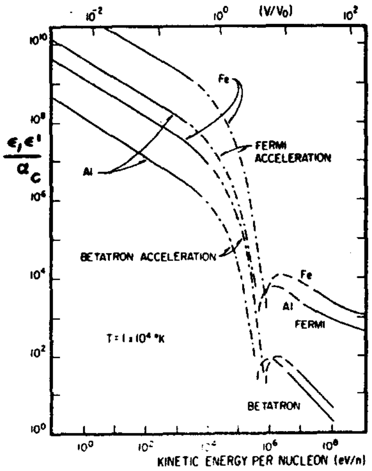

Fig.2.- Energy domain v s. relative importance of electron capture and loss (solid lines at low and high energies respectively) and charge equilibrium (dashed and point-dashed lines) of Fe and Al in atomic hydrogen.

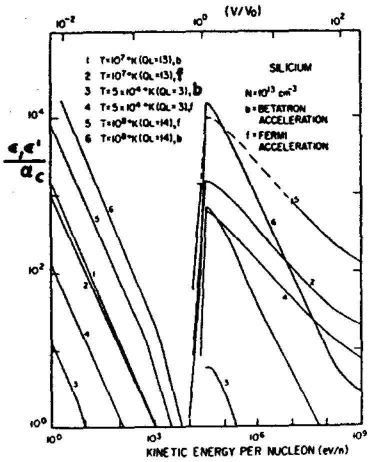

Fig.3.- Energy domain v s, relative importance of electron capture and loss (solid lines at low and high energies respectively) and charge equilibrium (dashed lines) of Silicium in ionized hydrogen.

processes.

CHARGE INTERCHANGE DURING ACCELERATION

Particle acceleration processes whose rates are independent of mass A and charge q may be expressed in the non-relativistic range as $(dE/dt)=\alpha E^n$ (energy/sec. nucleon), where $n=\frac{1}{2}$ with $\alpha = \alpha_f(2\mu c^2)^{0.5}$ and $n = 1$ with $\alpha = 2\alpha_b$ correspond to the Fermi and Betatron processes respectively; α_f and α_b are the hydromagnetic acceleration efficiencies, μc^2 is the atomic mass unit and $E = \mu v^2/2$ is the kinetic energy per nucleon. Using $(d/dt)= v(d/dx)$ the above rate becomes $v^{2(1-n)}dv= (\alpha/2)(\mu/2)^{n-1}\,dx$. In the energy range where electron loss is dominant ($v > v_c$), this equation must be integrated from v_c to v through the traveled thickness of matter L, whereas in the range where electron capture is dominant ($v<v_c$) the integration must be from v to v_c, where v_c is the velocity where the cross sections for electron capture and loss equate. Since the condition for the charge-changing processes requires that the amount of traversed matter be larger than the mean free path of the charge interchange process in consideration ($L>\lambda=1/N\sigma$) where N is the number density and σ the corresponding cross section, we obtain the following conditions for the establishment of electron loss and capture respectively

$$\alpha < 2(v^{3-2n} - v_c^{3-2n})N\sigma/(3-2n)(\mu/2)^{n-1} = \varepsilon \qquad (1)$$

$$\alpha < 2(v_c^{3-2n} - v^{3-2n})N\sigma/(3-2n)(\mu/2)^{n-1} = \varepsilon' \qquad (2)$$

Now, since solar particles are more likely generated in sources of $T\leq 10^7$°K, and are distributed in the range ($\sim 10^4-2\times 10^{10}$) eV/n, it must be assumed that they are generally accelerated with a rate higher than the rate of Coulomb losses $[(dE/dt)_a > (dE/dt)_L]$,otherwise particles would concentrate at low energies, most of them below the observational domain. To quantify Coulomb losses relative to acceleration efficiency, one usually defines a critical acceleration efficiency α_c determined as the thereshold value of α for which $(dE/dt)_a$ and $(dE/dt)_L$ are tangentially equated, so that particles overcome the Coulomb barrier only when $\alpha>\alpha_c$. Therefore, the criteria described by eqs. (1) and (2) reduce to the restrictions $\varepsilon/\alpha_c>1$ and $\varepsilon'/\alpha_c>1$. The rates of Coulomb losses in ionized and atomic hydrogen with explicit temperature dependence have been previously discussed [7], so for a source of atomic hydrogen we find $\alpha_c(n=\frac{1}{2})=3.38\times 10^{-13}N(q^{0.5}/A)$ and $\alpha_c(n=1)=4.5\times 10^{9}(N/T^{0.27})(q^{0.16}/A^{0.78})$ for the Fermi and Betatron mecanisms respectively, whereas in ionized hydrogen we obtain $\alpha_c(n=\frac{1}{2})=3.89\times 10^{-7}(N^{0.98}/T^{0.96})(q^{1.92}/A^{0.88})$ and $\alpha_c(n=1)=0.28\,(N^{0.97}/T^{1.45})(q^{1.87}/A^{0.67})$. With regard to the employed cross-sections in atomic sources the expressions given in [8] for electron capture and loss at low velocities (when particles are highly charged) have been aplied. At higher velocities (hydrogenic ions) we have used the expression given in [8] for electron capture, whereas for electron loss we used the Bohr formula [9]. In ionized hydrogen and at E>9Mev/n in atomic hydrogen, we used the radiative electron capture cross section [10]. For the electron loss cross-sections in ionized hydrogen we have employed the same cross-sections as in atomic hydrogen, since the electronic screening of the target nuclei is negligible relative to the ionization potentials of electrons in the projectil. In fig. 1 we have illustrated these cross-sections for Fe^{+26}. The crossing velocity v_c, where the capture and loss cross sections of fast protons in atomic hydrogen equate, occur at $v=v_o$ (where v_o is the Bohr velocity), whereas for heavy nuclei we found that $v_c=1.27\,Z^{0.43}\,v_o$. In ionized hydrogen $v_c=0.1\,q^{0.6}\,v_o$ for all elements. Introduction of adequate cross-sections and crossing velocities in eqs. (1) and (2) allows us to determine whether the accelerated ions by the Fermi and Betatron processes undergo electron loss or not in atomic and ionized hydrogen for both ranges: ($v<v_c$) where electron capture predominates and ($v>v_c$)where electron loss is dominant. Similarly, we determined whether particles undergo electron capture or not in both ranges, for both acceleration processes and in both media. The charge state q of local matter has been taken from conventional ionization equilibrium calculations [11]

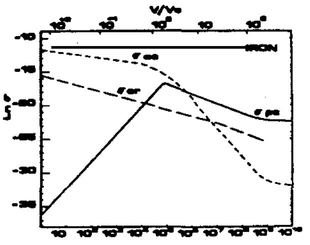

Fig.1.-Cross-sections of radiative electron capture (σ_{cr}) and Coulomb electron capture (σ_{cc}) and loss (σ_{pc}) of Fe^{+26}.The crossing-velocities V_c are defined at $\sigma_{cc}=\sigma_{pc}$ and $\sigma_{cr}=\sigma_{pc}$ in atomic and ionized hidrogen respectively. $\sigma_{cr} > \sigma_{cc}$ at 9MeV/n.

order to describe the evolution of the charge behavior as a function of particle velocity. So, our results rule out the direct measurement of particle charge states to diagnose source temperatures. We propose a more realiable method of diagnosis by analyzing the shifts toward long wave-lengths of the radiation peaks produced by electron capture of low energy heavy nuclei as they become progressively charged and more energetic during acceleration. The evolution of X-rays from radiative capture by high energy nuclei may also become an important diagnostic tool. Concerning the mass spectrum we only want to mention here that the tendency for increasing probability and energy range for electron capture at low energies for heavier ions favors the enrichment of heavy elements, because the decrease of effective charge entails a decrease of Coulomb losses (q^{*2}/A) of these ions. For the same reason, temperatures between $1.6 \times 10^4 < T \leq 10^5$ °K favor heavy nuclei enhancements, since due to the difficulty in capturing free-electrons, light elements do not undergo electron pick-up. At high energies $(v > v_C)$ and low temperatures, heavier ions have a higher probability of occurance and a higher energy range for electron loss. This fact argues in favor of the determination of the mass spectrum during the acceleration of thermal particles : if particles were previously accelerated, due to this faster stripping of high energy nuclei, they would be preferentially decelerated by Coulomb losses because their higher effective charge.

REFERENCES

(1) R.K. Sciambi, G. Glockler, C.Y. Fan and D. Hovestadt, Direct measurement of the ionization states of energetic Carbon and Oxygen emitted by the sun, Astrophys. J. 214, 316 (1977).

(2) D. Brady, J. Chan and P.B. Price, Charge states and Energy-dependent composition of solar flare particles, Phys. Rev. Letters 30, 669 (1973).

(3) J.D. Sullivan and P.B. Price, On the Charge state of low energy Fe nuclei accelerated by solar flares, Proc. 13th Int. Cosmic Ray Conf. 2, 1470 (1973).

(4) G. Glockler, R.K. Sciambi, C.Y. Fan and D. Hovestadt, A direct measurement of the charge states of energetic iron emitted by the Sun, Astrophys. J. 209, L93 (1976).

(5) L.S. Ma Sung, G. Glockler, C.Y. Fan and D. Hovestadt, Ionization states of heavy elements observed in the 14-15 May anomalous solar particle event, Proc. 16th Int. Cosmic Ray Conf. 12, 271 (1979).

(6) J.J. O'Gallagher, D. Hovestadt, B. Klecker, G. Glockler and C.Y. Fan, Time dispersion of energetic solar particles : unexpected velocity and species dependence, Astrophys. J., 109, L97 (1976).

(7) J. Pérez-Peraza and R. Lara A., The required range for the acceleration efficiency when particles undergo energy losses, Proc. 16th Int. Cosmic Ray. Conf. 12, 259 (1979).

(8) V.S. Nikolaev, Electron capture and loss by fast ions in atomic collisions, Sov. Phys. Uspekhi 8, 269 (1965).

(9) N. Bohr, Penetration of atomic particles through matter, Dan. Mat. Fys. Medd 18-8 (1948).

(10) H. Bethe and E.E. Salpeter, in Quantum Mechanics of one and two-electron atoms, Springer Verlag, pp. 320-322 (1957).

(11) N.K. Jain and V. Narain, Ionization equilibrium of some elements of astrophysical importance, Astron. Astrophys. Suppl. 31, 1 (1978).