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Charge-equilibration of Fe ions accelerated in a hot plasma

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Abstract. We examine the energy-dependent rates of charge-changing processes of energetic Fe ions in the hot plasma of the solar corona. For ionization of the Fe-ion projectile in collisions with ambient protons, three different methods of estimating the corresponding ionization cross sections are presented and compared. Proton-impact ionization is found to be significant irrespective of the particular method used. Differences in the proton-impact ionization cross sections' estimates are shown to have little effect in calculating highly nonequilibrium Fe charge states during acceleration, whereas equilibrium charge states are sensitive to such differences. A parametric study of the Fe charge-equilibration comprises (i) impact of the ambient plasma density, and (ii) the energy dependence impact of the acceleration rate upon the charge-energy profiles and upon the estimated values of the density $\times$ acceleration-time product. We emphasize potential importance of careful measurements of charge-energy profiles along with ion energy spectra for determining the energy dependence of ion acceleration time and the energy dependence of the leaky-box escape time.

Key words. acceleration of particles – atomic processes – Sun: particle emission

1. Introduction

Measurements of the energy-dependent charge states of accelerated Fe ions are expected to play a key role in parametrizing sites of acceleration and equilibration processes in solar energetic particle (SEP) events. In a number of recent papers (e.g., Mazur et al. 1999), a history of SEP observational studies is given in addition to a number of relevant and recent references. We would like to recall only the main steps in the theoretical investigation of how the observed charge states of energetic ions are established during SEP events.

Luhn & Hovestadt (1987) calculated mean equilibrium charge states, $Q_{\rm eq}$, of energetic ions from carbon through silicon by averaging the cross sections of charge-changing processes over thermal electron distributions in the ion rest frame. In that study, only electron-impact ionization was taken into account and the proton-impact ionization was ignored. In application to helium and oxygen, the proton-impact ionization was incorporated into the SEP calculations by Kharchenko & Ostryakov (1987). After which study, the proton contribution to the ionization processes of solar energetic ions appears to have been ignored for more than a decade (e.g., Ruffolo 1997; Barghouty & Mewaldt 1999). Only recently this important contribution has become part of more elaborate models of SEP acceleration and charge equilibration (Kocharov et al. 2000a; Barghouty & Mewaldt 2000; Ostryakov et al. 2000), particularly in applications to solar energetic iron.

However, there are significant differences in the ionization cross sections adopted in those studies. Even though models of different research groups differ in many parameters, no systematic investigation of the parameter dependencies has been performed. For this reason, the sources of differences in the results, as well as any general regularities, are left obscured.

There is also a marked difference between results of kinetic calculations of the mean equilibrium charge states of energetic ions in a hot plasma (Luhn & Hovestadt 1987; Kocharov et al. 2000a) and a semi-empirical formula for the equilibrium charge states' dependence on energy recently proposed by Reames et al. (1999). As of yet, the source of this difference has not been fully explored.

The organization of the present paper is as follows: in Sect. 2 we present a simplified model for the investigation of the general regularities in the energy-dependent ion charge-states. The different versions of the proton-impact ionization cross sections formulations are given in

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Sect. 3. Results for the energy-dependent energetic iron charge states, employing the different versions of the ionization cross sections and for a variety of the model parameters are summarized in Sect. 4, followed by conclusions in Sect. 5.

2. The model

Energy dependent charge states of energetic ions in a hot plasma are established by the interplay between the charge-changing processes, i.e., ionization and recombination, on the one hand, and the energy-changing processes, i.e., acceleration and Coulomb losses, on the other. We begin by introducing the distribution function $N_i(E)$ for the ions of charge $Q \equiv i-1$ and kinetic energy per nucleon E, and adapt the simplest, nonequilibrium model described by the following balance equation:

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial E}\Big(\frac{\mathrm{d}E}{\mathrm{d}t}N_i\Big) + \frac{N_i}{\tau_{\rm esc}} + n\Big[(S_i+\alpha_i)N_i - S_{i-1}N_{i-1} - \alpha_{i+1}N_{i+1}\Big] = X_i\delta(t)\delta(E-E_{\rm o}), \quad (1)$$

where n is the ambient electron number density, $S_i(T,E)$ the temperature and energy dependent ionization rate coefficient for the transition from the ionization state i to the state $i+1$, and $\alpha_i(T,E)$ the recombination rate coefficient from the ionization state i to $i-1$ (S_i and α_i are in units of $\mathrm{cm^3\,s^{-1}}$). The source term in the right-hand side of Eq. (1) describes the injection of ions at the energy $E_{\rm o}$. We adopt $E_{\rm o} = 20$ keV/n and a thermal charge distribution, X_i, for the injected Fe ions corresponding to the temperature $T = 1.26\times10^6$ K.

The model incorporates a regular acceleration and Coulomb energy losses,

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_a - \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\rm C}, \quad (2)$$

described, respectively, by the first and second terms of Eq. (2). We assume a power-law dependence of the acceleration rate on energy,

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_a = \frac{E_1}{\tau_1}\left(\frac{E}{E_1}\right)^S, \quad (3)$$

where $E_1 = 1\,\mathrm{MeV/nucleon}$ and τ_1 is the characteristic acceleration time for the 1 MeV/n ion. The Coulomb energy losses suffered by the energetic ion with charge Q and mass number A in the hot hydrogen plasma are described by the well-known formula (e.g., Akhiezer 1974):

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\rm C} = \frac{4\pi e^4 n\Lambda}{m_{\rm e}V}\frac{Q^2}{A}G(\zeta) \approx 6.6\times10^{-4}\,\frac{Q^2}{A}\,\frac{n}{10^8\ \mathrm{cm^{-3}}} \times\Big(\frac{E}{1\ \mathrm{MeV\,n^{-1}}}\Big)^{-1/2} G(\zeta)\frac{\mathrm{MeV}}{\mathrm{nucleon}}\,\mathrm{s^{-1}}, \quad (4)$$

where we have adopted the Coulomb logarithm value $\Lambda = 20$. The function $G(\zeta)$ can be expressed in terms of the error function as

$$G(\zeta) = \frac{2}{\sqrt{\pi}}\int_0^\zeta \exp\left(-y^2\right)\,\mathrm{d}y - \frac{2}{\sqrt{\pi}}\zeta\exp\left(-\zeta^2\right),$$
$$\zeta = V/v_{\rm T}, \qquad v_T = \sqrt{2k_{\rm B}T/m_{\rm e}}.$$

In the present paper we are primarily interested in the mean charge of the accelerated ion as a function of energy, i.e., $\langle Q\rangle(E)$. For simplicity, the acceleration is considered in the escape-time approximation with a characteristic time ($\tau_{\rm esc}$) taken to be independent of both Z and A numbers of the ion. The acceleration is assumed regular and the Coulomb energy loss < rate of acceleration for all ions, so that the accelerated ions are not allowed to revert back to their lower, pre-acceleration energies. Under these conditions, the value of $\tau_{\rm esc}$ will not affect the deduced energy dependence of $\langle Q\rangle(E)$.

The ion recombination rate comprises two terms, radiative as well as dielectronic recombinations. The relative contribution of each process and the total recombination rate depend on both the ambient plasma temperature as well as the Fe projectile energy. At low energies, the recombination rate depends only on the temperature. The energy dependence becomes critical if the Fe energy exceeds ∼100 keV/n. Luhn & Hovestadt (1987), for example, show how those rates can be estimated for various ions. Here, and for applications to Fe ions, the recombination rates used are given by Kocharov et al. (2000a).

The electron ionization cross section comprises the direct ionization part and the excitation autoionization part, $\sigma_{\rm c}$ and $\sigma_{\rm a}$, respectively. The rate coefficient is obtained by integrating the total cross section, $\sigma_{\rm e} = \sigma_{\rm c} + \sigma_{\rm a}$, assuming a flux of ambient particles in the rest frame of the Fe projectile, i.e.,

$$S_{\rm e}(\alpha) = \int_0^\infty \sigma_{\rm e}(v)vf(v)\,\mathrm{d}v, \quad (5)$$

where $f(v)$ is the electron velocity distribution in the rest frame of the Fe ion moving with velocity V with respect to the plasma. The resultant ionization rates were recently summarized by Kocharov et al. (2000a). The Fe projectile can also lose electrons in collisions with ambient (thermal) protons. In this case, velocity of the thermal particles is always negligible compared to the energetic Fe ions, so that the proton ionization rate is simply the product of the Fe velocity and the proton-impact cross section, i.e., $S_{\rm p} \to V\sigma_{\rm p}(V)$. Below, we discuss three different versions of the theoretical cross section $\sigma_{\rm p}$. Experimental data for proton-impact ionization of Fe ions, as well as for many other ions, remain scarce.

3. Proton-impact ionization cross section

All three theoretical cross-sections' estimates are taken to be sum over partial cross sections corresponding to different electron subshells,

$$\sigma_{\rm p}(E) \ = \ \sum_j \sigma_{{\rm p}j}\left(u, I_j\right), \qquad (6)$$

$$u \ = \ \left(\frac{V}{v_j}\right)^2 = \frac{m_{\rm e}E}{M_{\rm p}I_j}, \qquad (7)$$

where j is the index of the subshell with the ionization potential I_j, v_j the orbital electron velocity, and V the relative speed of the Fe ion and proton. If the speed of the projectile is $\gg$ the orbital velocities of the electrons in the ionized atom/ion, no difference exists between impact ionization by protons and by electrons at the same velocity (e.g., McDaniel 1989). Hence, the cross sections coincide at equal and large enough relative velocities:

$$\sigma_{{\rm p}j}(u, I_j) = \sigma_{{\rm e}j}(u_{\rm e}, I_j) \qquad \text{if} \qquad u = u_{\rm e} \gg 1, \qquad (8)$$

where

$$u_{\rm e} = \frac{E_{\rm e}}{I_j}, \qquad (9)$$

$E_{\rm e}$ is the projectile electron kinetic energy, and $\sigma_{{\rm e}j}$ the partial electron-impact ionization cross section for subshell j. The standard expressions for these cross sections are given by Arnaud & Raymond (1992):

$$\sigma_{{\rm e}j}(u_{\rm e}) = \frac{1}{I_j^2 u_{\rm e}}\left[A_j\left(1-\frac{1}{u_{\rm e}}\right) + B_j\left(1-\frac{1}{u_{\rm e}}\right)^2 + C_j\ln(u_{\rm e}) + D_j\frac{\ln(u_{\rm e})}{u_{\rm e}}\right]\cdot \qquad (10)$$

The set of the coefficients I_j, A_j, B_j, C_j, and D_j is given in Table 1A of Arnaud & Raymond (1992). There is an ambiguity, however, in the description of the threshold behavior of the proton-impact cross sections, i.e., in the lowest energy at which the cross sections become appreciable. Different versions of estimating theoretically $\sigma_{\rm p}(E)$, illustrated in Fig. 1 for the single ionization of the ions Fe^{+10} and Fe^{+19}, are briefly discussed below.

3.1. The Bohr cross section

The Bohr's (1948) cross section for the single ionization of an ion/atom by fast, fully stripped ions (e.g., protons) can be cast into a very compact form (Knudsen et al. 1984). In particular, for highly ionized Fe ions, i.e., $Q > +8$, for which the ionization potentials are always high $I_j \geq 16 I_{\rm o}$, the formula (Kocharov et al. 2000a) reads:

$$\sigma_{{\rm p}j} = A_{\rm norm} n_j \frac{\sigma_{\rm o}}{I_j^2 u}\Big[1 - \frac{1}{4u} + \delta\ln(4u)\Big]. \qquad (11)$$

In Eq. (11), $\sigma_{\rm o} = 4\pi a_{\rm o}^2 I_{\rm o}^2 = \pi e^4 = 6.56\times10^{-14}$ cm^2 eV^2, $I_{\rm o} = 13.6$ eV, $a_{\rm o} = 5.292\times10^{-9}$ cm is the Bohr radius, n_j the number of electrons in the subshell j, and

$$\delta = \frac{C_j}{A_j + B_j - C_j\ln 4}, \ A_{\rm norm} = \frac{A_j + B_j - C_j\ln 4}{\sigma_{\rm o} n_j}, \qquad (12)$$

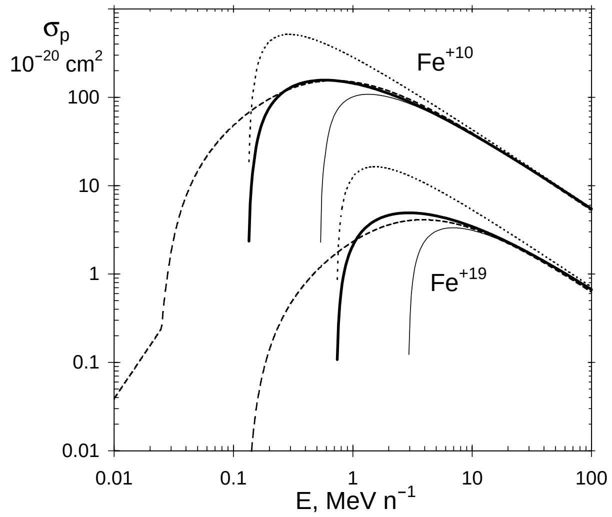

Fig. 1. Cross sections of proton-impact ionization of Fe ions calculated using $\sigma_{\rm B}$ (dotted curves), $\sigma_{\rm BEM}$ (dashed curves), and $\sigma_{\rm BGR}$ (heavy solid curves). The light solid curves depict the electron-impact ionization cross section $\sigma_{\rm e}$.

where coefficients I_j, A_j, B_j, and C_j are the same as given by Arnaud & Raymond (1992) (note that the partial cross section $\sigma_{{\rm p}j} \to 0$ for $u < 1/4$).

As shown in Fig. 1, the Bohr cross section exhibits the highest attainable value among the three partial cross sections' estimates. We employed the Bohr cross section to estimate proton-impact ionization of the carbon ions C^{+1}, C^{+2}, and C^{+3}, and compared the results to experimental data by Sant'Anna et al. (1998) and Goffe et al. (1979). The comparison indicates that the Bohr cross section tends to overestimate the measured maximum cross section by a factor of 1.5–2.

3.2. The BEM cross section

Among the simple, semiclassical approximations describing ionization, the binary-encounter model (BEM) is one of the more successful schemes (Gryzinski 1965; McGuire & Richard 1973; Peter & Meyer-ter-Vehn 1991). Following Gryzinski (1965), the cross section for a single proton-impact ionization from a total of n_j electrons in the jth subshell of the projectile ion is given by:

$$\sigma_{{\rm p}j} = n_j \frac{\sigma_{\rm o}}{I_j^2 u} F(u), \qquad (13)$$

where

$$F(u) \ = \ \alpha^{3/2}\left[\alpha + 2\delta(1+\beta)\ln\left(2.7+\sqrt{u}\right)\right] \times(1-\beta)(1-\beta^{1+u}) \quad \text{at} \quad u > 0.0425,$$

$$F(u) \ = \ \frac{4}{15}u^3 \qquad \text{at} \quad u < 0.0425;$$

$$\alpha = u(1+u)^{-1}; \qquad \beta = \left[4(u+\sqrt{u})\right]^{-1}; \qquad \delta = C_j/(\sigma_{\rm o} n_j).$$

Dietrich et al. (1992) compared charge-state measurements of fast Ar and Xe ions passing through a plasma target to the results of Monte Carlo calculations incorporating the BEM cross section. It was found that for Ar and Xe the ionization cross sections calculated in the binary encounter model were too small compared to the measured total electron-loss cross sections. A comparison with experimental data for the electron loss of heavy ions showed that the BEM cross sections have the correct energy and charge-state dependences, but, on average, tend to underestimate the data by about a factor of 2.5.

3.3. The BGR cross section

Barghouty (2000) described a simple procedure to estimate proton-impact ionization cross sections over the energy range up to tens of MeV/n. The procedure connects, in the first Born approximation, the partial proton-impact cross section $\sigma_{\mathrm{p}j}$ to the known electron-impact cross section $\sigma_{\mathrm{e}j}$ using the Bates-Griffing relation (BGR). The resultant cross section takes the form:

$$\sigma_{\mathrm{p}j}(u, I_j) = \frac{(1+4u)^3}{4u(16u^2+4u-2)}\,\sigma_{\mathrm{e}j}(u_{\mathrm{e}}, I_j), \tag{14}$$

where u_{e} is related to u as:

$$u_{\mathrm{e}} = \left(1+\frac{1}{4u}\right)^2 u. \tag{15}$$

The electron-impact cross section $\sigma_{\mathrm{e}j}$ is given by Eq. (10). The threshold behavior of this cross section is similar to that of the Bohr cross section, whereas the maximum value is close to the value of the BEM cross section.

In what follows we use the designations σ_{B}, σ_{BEM}, and σ_{BGR} for the three versions of the proton-impact ionization cross sections: The Bohr cross section given by Eq. (11), the cross section resulting from the binary-encounter model, given by Eq. (13), and for the cross section based on the Bates-Griffing relation, given by Eq. (14), respectively. If analogy with the C, Ar, and Xe ions is valid, one may expect that experimental cross sections for the Fe ions will be about halfway the values σ_{B} and $\sigma_{\mathrm{BEM(BGR)}}$.

4. Results of calculations

In the first set of calculations we have deduced the equilibrium charge state distributions, $N_i^{\mathrm{eq}}(E)$, of Fe ions at different energies for the three different versions of the proton-impact ionization cross sections discussed in Sect. 3. Those distributions represent solutions of Eq. (1) when all the terms of the equation except the square-bracketed one are neglected. The mean equilibrium charge of Fe ions, $Q_{\mathrm{eq}}(E)$, can be calculated by averaging the ionic charge $Q = i - 1$ over the distribution $N_i^{\mathrm{eq}}(E)$. The result is shown in Fig. 2. It is seen that the sharpness of the steps in the curve essentially depends on the version of the proton cross-section used.

Rather than solve the complex system of charge-changing reactions, often in astrophysical applications a

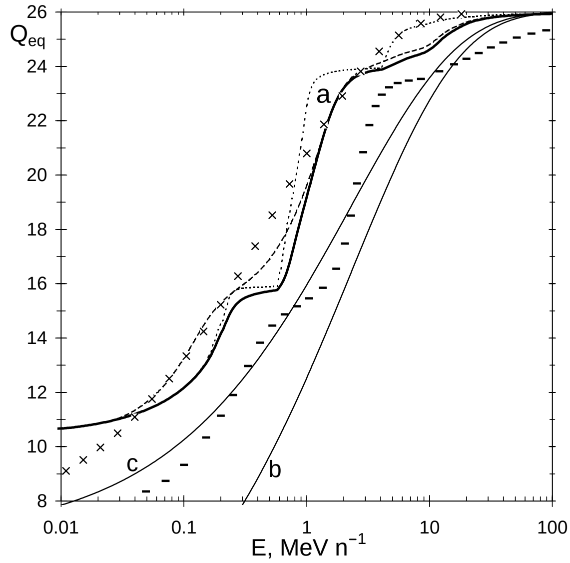

Fig. 2. The equilibrium mean charge of energetic Fe ions calculated when both electron and proton-impact ionization are included (three upper curves labeled "a"). The employed versions of the proton-impact ionization cross section are σ_{B} (dotted curve), σ_{BEM} (dashed curve), and σ_{BGR} (heavy solid curve). For comparison we show the equilibrium charge for the cold neutral gas ("b", Eq. (16)) and the equilibrium charge estimated using semi-empirical formulas Eq. (17) ("c") and Eq. (18) (crosses). An additional calculation (minus signs) is explained in text.

simple, semi-empirical expression (Barkas 1963; Betz et al. 1966) for the mean charge dependence on energy is used,

$$\langle Q\rangle/Z = 1 - \exp\left[-V/\left(v_0 Z^{2/3}\right)\right], \tag{16}$$

where V and Z are the speed and nuclear charge of the projectile and $v_0 = e^2/\hbar$ is the Bohr velocity. The exponent in Eq. (16), which is based on the Thomas-Fermi model of the ion, assumes that a fast heavy ion penetrating through rarefied gases retains all of its electrons with orbital velocities exceeding the velocity of the ion[1]. Expression (16) seems to describe fairly reasonably the equilibrium charge state of an ion as a function of energy as it traverses neutral, dense solids and gases (Pierce & Blann 1968; Betz 1972).

In contrast to applications to cold neutral gases, however, the simple relation between mean charge and velocity in Eq. (16) fails in applications to plasmas. Studies of fast ions in plasmas indicate significantly higher ionization of the projectile than that of the same projectile species in a cold neutral target (Nardi & Zinamon 1982; Peter & Meyer-ter-Vahn 1986). For this reason, kinetic calculations need to be performed and verified against

[1] Expression (16), in the low-V limit, can be arrived at by simply estimating the total number of electrons in the heavy ion as $Z-Q = 2(4\pi/3)^2(pr)^3/(2\pi\hbar)^3$, where r is the ion radius and p the momentum of the outer electron. Writing $p^2/(2m_{\mathrm{e}}) = Qe^2/r$ and equating the electron speed to that of the ion, i.e., $p/m_{\mathrm{e}} \to V$, for $Q \ll Z$ one gets $Q/Z \approx V/(v_0 Z^{2/3})$.

experimental data (e.g., Dietrich et al. 1992; Peter & Meyer-ter-Vahn 1991). A similar kinetic approach is adapted in this work for energetic Fe ions in the plasma of the solar corona. With this first-principles approach, both equilibrium and nonequilibrium charge states can be calculated.

Reames et al. (1999) have recently proposed a semi-empirical formula for the equilibrium charge states of energetic ions in a hot plasma. The formula is essentially a slight modification of the neutral-matter relation (Eq. (16)),

$$\langle Q\rangle/Z = 1 - \exp\left[-125(\beta + \beta_{\rm th})/Z^{2/3}\right], \quad (17)$$

where $\beta = V/c$ and $\beta_{\rm th}^2 = 2k_{\rm B}T/(m_{\rm e}c^2)$. The modification attempted to account for the fact that an ionizing collision between the incoming ion and an electron of the plasma will depend upon the relative speed of the two, and this relative speed, in turn, depends on the plasma temperature. Despite this correction, the modified formula by Reames et al. (1999) compares rather poorly to our equilibrium results, using any set of the cross sections' estimates (curve "c" vs. curves "a" in Fig. 2).

A most likely reason for this marked discrepancy is that in expression (17) there was no correction made to account for the difference in cross sections of charge changing processes in neutral gases and those in plasmas. In particular, recombination cross sections in neutral gasses are typically very high (e.g., Table IV by Betz 1972). As an illustration of the recombination rate effect, we have calculated equilibrium charge states of Fe ions – with kinetic approach using $\sigma_{\rm p} = \sigma_{\rm BEM}$ – but with recombination rate artificially enhanced by a factor of 10 (minus signs in Fig. 2).

One can attempt to improve on Eq. (17) by accounting for some of the salient peculiarities of charge-changing cross sections in plasmas. At relatively low recombination rate and high contribution of protons to the ionization, the threshold velocity for ionization becomes close to 1/2 of the orbital electron velocity ($u = (V/v_j)^2 = 1/4$ in Sect. 3.1). Based on this, one can argue that Fe ion retains all its electrons with orbital velocity greater than twice the ion velocity. Hence, Eq. (17) may be substituted with

$$\langle Q\rangle/Z = 1 - \exp\left[-125(2\beta + \beta_{\rm th})/Z^{2/3}\right]. \quad (18)$$

This charge-energy dependence (crosses in Fig. 2) can be seen to roughly approximate the results of kinetic calculations[2]. However, a semi-empirical formula cannot be reliably established before a comprehensive comparison with experimental data is made. Unfortunately, there are serious obstacles for direct experimental determination of the equilibrium charge states of Fe ions in hot plasmas, making reliance on kinetic calculations unavoidable.

[2] A formula close to Eq. (18) but without correction to the plasma temperature, was previously suggested by Tatischeff et al. (1998), basing on kinetic calculations for C, N, O, and Ne.

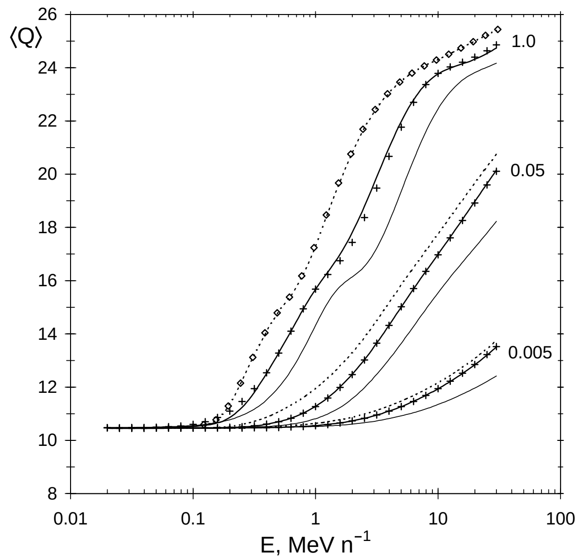

Fig. 3. The nonequilibrium mean charge of energetic Fe ions for different values of the density × acceleration-time product at $S = 0$. The parameter $n \times \tau_1$ is shown next to the curves in units of 10^{10} cm^{-3} s. The employed versions of the proton-impact ionization cross section are $\sigma_{\rm B}$ (dotted curves), $\sigma_{\rm BEM}$ (plus signs), and $\sigma_{\rm BGR}$ (heavy solid curves). For comparison we show the charge calculated with only electron-impact ionization included (light solid curves). The upper series in the figure illustrates also a coincidence of the mean charge inside the acceleration region (the dotted curve) and the mean charge of escaping particles (diamond signs). For the calculation of escaping particles we adopted $\tau_{\rm esc} = 2\,(E/1~{\rm MeV\,n^{-1}})\,\tau_1$, whereas all the curves are calculated assuming infinitely large $\tau_{\rm esc}$.

To calculate nonequilibrium charge state distributions, we integrate Eq. (1) using a Monte Carlo code. We start with the case of a constant acceleration rate, i.e., $S = 0$ in Eq. (3), and employ, for parameterization purposes, the product of acceleration time, τ_1, and the ambient electron/proton density, n, measured in units 10^{10} cm^{-3} s (parameters appearing next to the curves in Fig. 3). Using the Monte Carlo code we can compute the charge-energy distribution of escaping ions, as a time integral of the "leaky-box" term $N_i/\tau_{\rm esc}$ in Eq. (1), as well as the charge-energy distribution of Fe ions inside the acceleration region, as a time integral of N_i. However, one can see that in the case of a regular acceleration dominating over the Coulomb deceleration with $\tau_{\rm esc}$ independent of Q, both calculations give the same mean charge $\langle Q\rangle$ (upper curve and points in Fig. 3 for $\langle Q\rangle$ inside and outside the acceleration region, respectively). For this reason, the rest of profiles are shown for the ion distributions N_i inside the acceleration region. Nonequilibrium mean charge states are calculated for the three different versions of the proton-impact ionization cross sections. For comparison we also show results with only electron-impact ionization included in the calculations. It is seen that the differences among the versions of the proton-impact cross sections are not all that consequential under the assumed strong nonequilibrium conditions (i.e., $n \times \tau_1 < 10^9$ s cm^{-3}), whereas inclusion of the proton-impact ionization for any version is important.

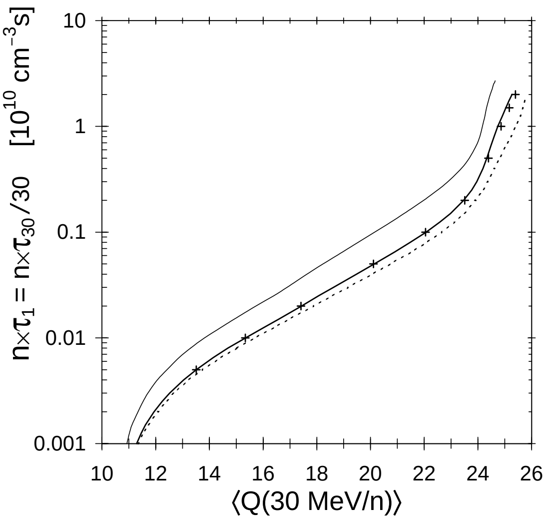

Fig. 4. The density $\times$ acceleration-time product as a function of the mean charge for 30 MeV/n Fe ions at $S = 0$. The employed versions of the proton-impact ionization cross section are σ_{B} (dotted curves), σ_{BEM} (plus signs), and σ_{BGR} (heavy solid curves). For comparison, we show the values calculated with only electron-impact ionization included (light solid curve).

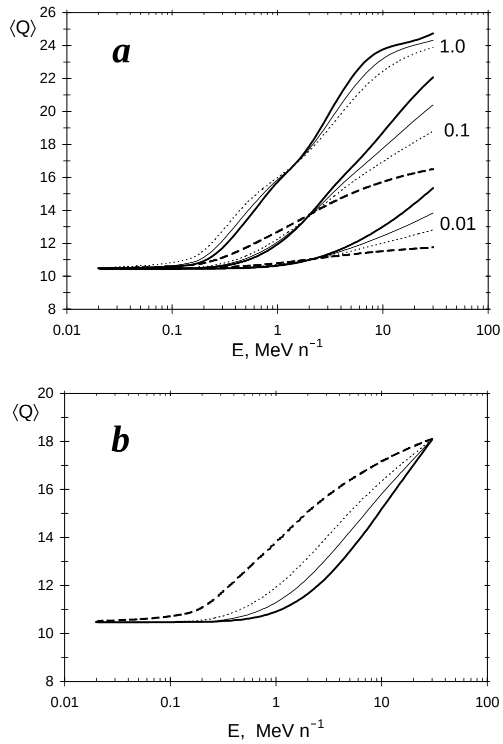

Fig. 5. The nonequilibrium mean charge of energetic Fe ions for different dependencies of the acceleration rate on energy (parameter S in Eq. (3)). Employed values of S are 0 (heavy solid curves), 0.25 (light solid curves), 0.5 (dotted curves), and 1 (dashed curves). The proton-impact cross section used is $\sigma_{\mathrm{p}} = \sigma_{\mathrm{BGR}}$. **a)** Results of calculations at fixed values of the density times acceleration-time product, $n \times \tau_1$ (shown next to the curves in units of 10^{10} cm^{-3} s). **b)** Results of calculations at fixed value of the mean charge of 30 MeV/n Fe ions; parameter $n \times \tau_1/(10^{10}$ cm^{-3} s$) = 0.025$, 0.045, 0.075, 0.2 for $S = 0$, 0.25, 0.5, 1, respectively.

Figure 4 illustrates how the mean charge of 30 MeV/n Fe ions, $\langle Q(30\ \mathrm{MeV/n})\rangle$, is related to the theoretical parameter $n \times \tau_{30}$, where τ_{30} is the characteristic acceleration time at 30 MeV/n; $\tau_{30} = 30\,\tau_1$ if $S = 0$. It can be seen that over a wide range of $\langle Q(30\ \mathrm{MeV/n})\rangle$ the differences among the three versions of the proton-impact cross sections have little affect on estimates of the density $\times$ acceleration-time product.

In the final set of simulations, we study the energy dependence effect of the acceleration rate (S in Eq. (3)) on the charge-energy profiles using the proton-impact cross section $\sigma_{\mathrm{p}} = \sigma_{\mathrm{BGR}}$. Panel "*a*" of Fig. 5 shows the charge-energy profiles for S varying from zero to unity in the two lower members of the curves, and from 0–0.5 in the upper one. In panel "*b*", values of the parameter $n \times \tau_1$ have been adjusted to get the same value of the mean charge at 30 MeV/n, $\langle Q\rangle = 18$, for different dependencies of the acceleration rate on energy, $S = 0$, 0.25, 0.5, 1. The values of the parameter $n \times \tau_1$ are very different for different S, because τ_1 is the characteristic acceleration time at 1 MeV/n, not representative for 30 MeV/n. However, the product of the density n and the time of ion acceleration from 0.1 MeV/n to 30 MeV/n, $n \times t_{(0.1-30\,\mathrm{MeV/n})}$, is close to 8×10^9 cm^{-3} s in all cases: $n \times t_{(0.1-30\,\mathrm{MeV/n})}/(10^{10}$ cm^{-3} s$) = 0.75$, 0.76, 0.79 for $S = 0$, 0.25, 0.5, respectively.

5. Conclusion

We have considered a systematic of kinetic calculations for equilibrium and nonequilibrium charge states of accelerated Fe ions in the hot plasma of the solar corona. Large uncertainties exist in the proton-impact ionization cross sections' estimates (Fig. 1). Those uncertainties can affect the mean equilibrium charge (Fig. 2), but their effect on our nonequilibrium calculations is shown to be small (e.g., Fig. 3, $n \times \tau_1 \ll 10^{10}$ cm^{-3} s). This is because the high-energy structure of the ionization cross sections becomes important when the ion charge is below the equilibrium value Q_{eq}, and the fact that the high-energy asymptotes coincide for all three versions of the cross sections' estimates used. As a result, theoretical estimates of the parameter $n \times t$ are largely independent of the uncertainties in the cross sections' estimates (Fig. 4). We also find that estimates of $n \times t$ are not sensitive to the energy dependence of the acceleration rate.

Based on our nonequilibrium kinetic calculations, we find the effect of proton-impact ionization on Fe charge states to be significant without regard to the particular version of the ionization cross section adopted. Inclusion of the proton-impact ionization reduces the estimated values of the $n \times t$ by a factor of $\sim$2$-$3 as compared with results of only electron-impact ionization included. Differences in the versions of the proton-impact ionization cross sections seem to have little effect on highly nonequilibrium Fe charge states during acceleration. In contrast, equilibrium charge states are found to be quite sensitive to the choice of the cross sections' estimates. In application to the energy dependent charge states of solar energetic ions, we estimate that uncertainties in the theoretical parameter $n \times t$ due to differences in the proton-impact ionization cross sections' estimates are $\sim$20%. Further experimental studies of proton-impact ionization of Fe ions are important for more realistic modeling of the plasma ionization processes in the solar corona.

Modeling of the particle acceleration is frequently performed in the escape-time approximation (e.g., Kocharov et al. 2000b). A shape of the accelerated ion energy spectrum is ruled by both the energy dependence of acceleration time (acceleration rate) and the energy dependence of the leaky-box escape time. As one can learn from Fig. 5b, experimental measurements of the charge-energy profile possess a potentiality to deduce the energy dependence of acceleration time independently of the energy dependence of the escape time. Simultaneous use of the observed charge-energy profiles and energy spectra could enable one to decouple in empirical manner the ion acceleration time and the escape time. Such a determination of energy dependencies of the two characteristic times might provide a test/clue for theoretical acceleration models developed so far and expected in future.

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