Role of fast ions in the emission from a hot plasma

V. A. Abramov, V. G. Gontis, and V. S. Lisitsa
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 2 March 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 8, 375–377 (20 April 1983)

Impurity radiative loss can be a direct energy-loss mechanism for plasma ions, equally important as the corresponding mechanism for electrons. Under certain conditions the energy loss due to the excitation of impurities can also amount to a substantial fraction of the energy loss of fast heavy particles in a plasma.

PACS numbers: 52.20.Hv

Essentially all the published calculations of the radiative energy loss from fusion plasmas containing impurities (see Refs. 1–3, for example) consider only the excitation of multiply charged impurity ions by electrons (we will be concerned here with only the loss due to the line emission). The heavy particles (protons, for example) have implicitly been assumed unimportant in establishing the ionizational equilibrium and in the excitation of ions. This assumption is correct for the ionization of multiply charged ions and for the excitation of transitions involving a change in the principal quantum number ($\Delta n \neq 0$), but precisely the opposite situation may hold for transitions with $\Delta n = 0$, which frequently play a governing role in the total emission. Estimates of the cross sections for the excitation of $\Delta n = 0$ transitions by heavy particles show that (for example) the rate at which protons excite the 2*s*-2*p* transition in the lithiumlike iron ion Fe XXIV becomes comparable to the rate of excitation by electrons at only $T_i = T_e = 2$ keV, and as the temperature is raised further the rate of excitation by protons increases further, while the rate of excitation by electrons falls off. Under coronal-equilibrium conditions this increase in the rate of excitation of impurity ions by heavy particles is offset to some extent by the decrease with increasing T_e in the fraction of complex ions which undergo transitions with $\Delta n = 0$ (ion "burnup"). We might note, however, that even under the conditions of the coronal model the incorporation of the excitation of iron ions by heavy particles leads to a 30% increase in the radiative energy loss in the region $T_i \simeq 2$ keV. These effects are even more apparent for large-*Z* elements, for which the burnup of the complex ions occurs at higher temperatures, so that in a fusion plasma there is a temperature interval in which this effect can be seen quite clearly.

It is obvious that the excitation by protons (or deuterons) may be most apparent under conditions such that, for some reason or other, the ionizational equilibrium is strongly shifted toward ions with a low charge, i.e., upon a deviation from the coronal equilibrium. In tokamaks, some possible reasons for deviations from the coronal equilibrium are, for example, the diffusion of impurities or a charge exchange of impurities with hydrogen atoms (of the residual gas or introduced into the plasma during the injection of neutral beams for plasma heating).

The distortion of the ionization equilibrium has recently been studied in detail, both theoretically and experimentally.[4–7] It has been demonstrated that the radiative

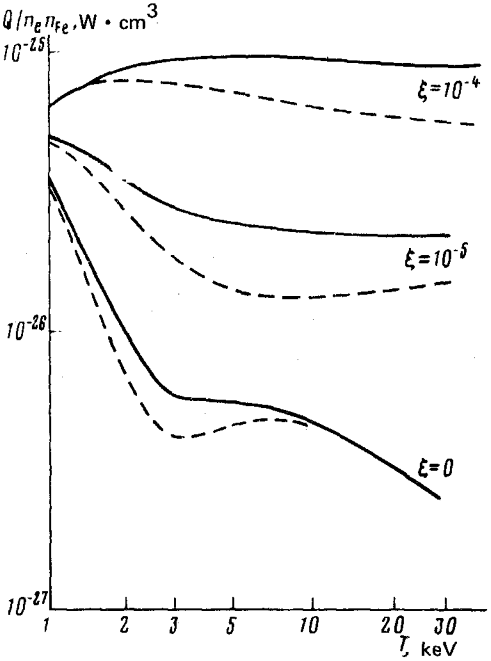

FIG. 1. Temperature dependence of the radiative energy loss per electron per iron atom. Dashed curves—Heavy particles ignored; solid curves—with heavy particles. Here $\xi = n_0/n_e$, where n_0 is the density of neutral hydrogen atoms.

energy loss may increase sharply during injection,but only if excitation by electrons is taken into account. The incorporation of excitation by protons may intensify this effect substantially. In this letter we report calculations of the radiative loss of a plasma with an iron impurity; the shift of the ionization equilibrium due to charge exchange and the excitation of transitions with $\Delta n = 0$ is taken into account. We use an approximate expression for the cross section for excitation by heavy particles found from an interpolation between results obtained in the dipole approximation[8] and results obtained in the rectilinear-trajectory approximation.[9] Figure 1 shows the temperature dependence of the radiative energy loss (per electron per impurity atom) for various number densities of the neutrals. The proton contribution is by no means small in comparison with that of electrons.

The excitation of impurities by heavy particles may also affect the energy loss of the fast ions which are produced in a plasma during the ionization of a neutral beam used for plasma heating. Working from the familiar expressions for the rate of energy loss in Coulomb collisions (see Ref. 10, for example) and the Born-approximation expression for the excitation cross section of $\Delta n = 0$ transitions, we can easily derive the following expression for the ratio of the energy-loss rates in these processes:

$$\eta \equiv \left(\frac{d\epsilon}{dt}\right)^{\text{Coul}} \bigg/ \left(\frac{d\epsilon}{dt}\right)^{\text{exc}} = \frac{2}{f}\frac{n_e}{n_z}\left(\frac{m_e}{M}\frac{\epsilon}{T_e}\right)^{3/2}, \tag{1}$$

where f is the oscillator strength for the given transition, n_z is the density of impurities,

n_e is the electron density, and ε and M are respectively the energy and mass of the heavy particle. In estimating η we should take into account the circumstance that n_z is the density of ions having transitions with $\Delta n = 0$ (i.e., lithiumlike and more complex ions). The values of η usually lie in the range 10–100. For the conditions in the T-11 tokamak, for example, with $3s$-$3p$ transitions with $f = 1.5$ in molybdenum ions, we have $\eta \sim 10$. The parameter η has roughly the same value when a plasma is heated to the ignition point in a tokamak reactor by deuterium ions with an energy $\varepsilon = 150$ keV in the presence of an iron impurity. The value of η may decrease substantially upon a shift of the ionizational equilibrium. Despite the relatively small rate of impurity energy loss which follows from (1), the energy loss itself may not be small, because the two types of loss vary with the energy in different ways. Solving the equation for the behavior of the energy of the particle, taking into account both mechanisms, we find the following expression for γ, the ratio of the energy loss due to Coulomb collisions and that due to excitation:

$$\gamma \equiv \frac{\Delta Q^{\text{Coul}}}{\Delta Q^{\text{exc}}} = \left[\frac{2}{3}\,\frac{\eta}{\ln\left(\frac{2}{3}\eta + 1\right)} - 1\right]^{2/3} . \tag{2}$$

It follows from (2) that, for example, at $\eta = 10$ we would have $\gamma = 1.6$, or at $\eta = 30$ we would have $\gamma = 3.3$. The role played by the excitation of impurities in the total energy loss is thus significantly more important than would follow from a simple comparison of the corresponding rates η. The physical reason lies in the different time dependences of the Coulomb loss and of the impurity-excitation loss.

This analysis shows that there exists a new mechanism for the direct energy loss of ions in a hot plasma—a mechanism which does not involve the ion energy losses due to thermal conductivity and charge exchange, which are customarily taken into consideration. It should be noted that a corresponding loss mechanism should operate for α particles, which may excite transitions with not only $\Delta n = 0$ but also $\Delta n = 1$. For α particles it may prove necessary to refine the loss calculations to take into account the circumstances that the banana trajectories of these particles also pass through the peripheral part of the plasma, where the density of ions having transitions with $\Delta n = 0$ and $\Delta n = 1$ is significantly higher than at the center of the plasma column.

[1] V. I. Gervids and V. I. Kogan, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 329 (1975) [JETP Lett. **21**, 150 (1975)].
[2] C. Breton *et al.*, Nucl. Fusion **16**, 891 (1976).
[3] R. V. Jensen *et al.*, Nucl. Fusion **17**, 1187 (1977).
[4] V. A. Krupin *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 353 (1979) [JETP Lett. **29**, 318 (1979)].
[5] V. A. Abramov *et al.*, Piz'ma Zh. Eksp. Teor. Fiz. **29**, 550 (1979) [JETP Lett. **29**, 501 (1979)].
[6] R. A. Hulse, D. E. Post, and D. R. Mikkelsen, J. Phys. B **13**, 3895 (1980).
[7] S. Suckewer, Physica Scripta **23**, 72 (1981).
[8] V. A. Bazylev and M. I. Chibisov, Usp. Fiz. Nauk **133**, 617 (1981) [Sov. Phys. Usp. **24**, 276 (1981)].; Preprint IAÉ-3125, Kurchatov Institute of Atomic Energy, Moscow, 1979.
[9] V. A. Ryabov and G. L. Yudin, Zh. Eksp. Teor. Fiz. **78**, 474 (1980) [Sov. Phys. JETP **51**, 239 (1980)].
[10] B. A. Trubnikov, in: Voprosy teorii plazmy, Vol. 1, Atomizdat, Moscow, 1963, p. 98 (Reviews of Plasma Physics, Vol. 1, Consultants Bureau, New York, 1965).

Translated by Dave Parsons
Edited by S. J. Amoretty