Dependence of the radiation losses of a thermonuclear plasma on the atomic number of the impurity and the temperature

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We calculate the dependence of the radiation losses of a thermonuclear plasma on the atomic number Z of the impurity and on the electron temperature T_e, and also the Z dependence of the "lethal" relative impurity concentration in a DT reactor.

Introduction. Several calculations were made of the radiation losses of a hot plasma with particular relatively light impurities (C, O, Al, Ca, etc.)[1-4], as well as order-of-estimate calculations of losses for heavy impurities[5] and an analysis of the influence of Mo and W impurities on the ignition and Lawson criteria.[6] In such calculations one usually determined the dependence of the radiation losses on T_e for a given impurity.

In this communication we present the results of a calculation of the radiation losses for impurities with a somewhat different formulation of the problem, namely, we determine the dependence of the losses on Z for $Z = 6$ to 80 and on the thermonuclear temperatures ($T_e \geqslant 10$ keV). The results of this calculation are necessary, in particular, for a judicious choice of the material for the wall and diaphragms of a thermonuclear reactor.

The model. The calculations were performed on the basis of a coronal equilibrium model, for constant and homogeneous n_e, n^*, and T_e (n_e and n^* are the concentrations of the electrons and of the impurity). The coronal model itself, as shown by comparison (see, e.g.,[3]) with the results of calculations on a more general collision-radiation model, is well applicable at low n_e, high T_e, and large Z, which are typical of the plasma of a thermonuclear reaction, and its stationary limit ($t \to \infty$) is ensured by satisfying the Lawson criterion $n_e\tau \gtrsim 10^{14}$ cm^{-3} sec. As is well known, to calculate the radiation losses within the framework of the coronal model it suffices to know the cross sections for the ionization, photorecombination, excitation by electron impact, and bremsstrahlung.

The cross sections. At the temperatures in question, the nuclei of even the heaviest impurities are capable of retaining only $N \lesssim 10$ electrons, so that $Z \gg N$, and for each of these electrons the decisive factor is the interaction with the nucleus. We can therefore use for the cross sections of the processes indicated above, with sufficient accuracy, relatively simple and universal expressions based on various hydrogenlike approximations. The interelectron interaction is taken into account here by introducing in the hydrogenlike analytic structures the real ionization or excitation energies. It is also obvious that since $N \ll Z$ the allowance for screening in the bremsstrahlung is very greatly simplified.

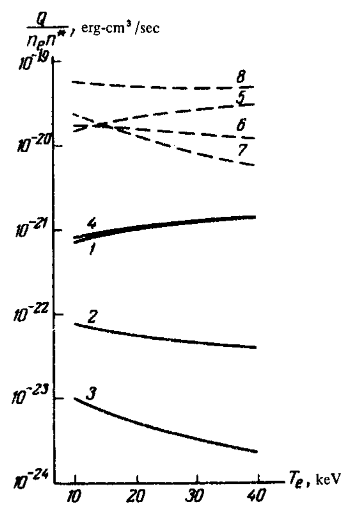

FIG. 1. Plots of Q^{br} (curves 1 and 5) Q^{rec} (2 and 6), Q^{lin} (3 and 7), and Q^{sum} (4 and 8) for carbon (solid curves 1—4) and iron (dashed curves 5 and 8) as functions of T_e.

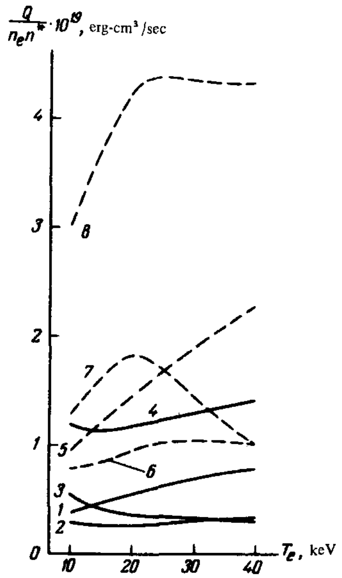

FIG. 2. The same as Fig. 1, but for molybdenum (solid curves 1—4) and for tungsten (dashed curves 5—8).

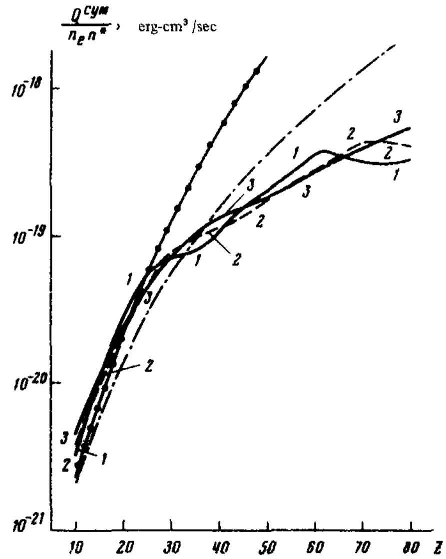

FIG. 3. Dependence of $Q^{\rm sum}$ on Z: 1) $T_e = 10$ keV, 2) $T_e = 20$ keV, 3) $T_e = 40$ keV; dash-dot line—two-term formula of[13], line with points—three term formula of[2], both for $T_e = 10$ keV.

To be specific: the ionization cross sections were calculated in analogy with[7]; the photorecombination rates were taken in the Kramers approximation with due allowance for the number of free places in the outer shell and for capture on excited levels[1]; the excitation rates of the transitions with $\Delta n \neq 0$ were taken in accordance with[8] with additional correction of the asymptotic behavior at the "Born" temperatures; for the transitions with $\Delta n = 0$ we used the expressions from[5]. The ionization and excitation energies were calculated by isoelectronic extrapolation of the type of[9] from the data of[10], but the relativistic effects were taken into account more fully than in[9]. The oscillator strengths were calculated from the Bates and Damaard tables[11] with partial monitoring against the more exact data of[12].

Radiation losses. Figures 1—3 show the results of calculation of the radiation power loss to bremsstrahlung and to recombination and line radiation (and their sum) per impurity particle and per electron. The curves are nonmonotonic as a result of passage through helium- and neonlike shells. The weak dependence of the *summary* losses $Q^{\rm sum}$ on T_e is attributed to the presence in these losses of terms that increase with T_e as well as decreasing terms. As to the line radiation ($Q^{\rm lin}$), we note that the predominance of transitions with $\Delta n = 0$, and accordingly the practical independence of $Q^{\rm lin}$ of Z and T_e, which was indicated in[5], no longer holds at the high T_e considered here, even in the case of tungsten.

As seen from Fig. 3, at relatively small Z (when stripping of the impurity is practically complete, the function $Q^{\rm sum}(z)$ is approximated satisfactorily by the three-term formula of[2], which takes the bremsstrahlung and recombination radiation into account in the bare-nucleus approximation ($Q^{\rm br} \propto Z^2 T_e^{1/2}$, $Q^{\rm rec} \propto Z^4 T_e^{-1/2}$) and the line radiation in the approximation $T_e \gg Z^2\,{\rm Ry}$, when the relative concentration of the hydrogenlike ions is already small ($Q^{\rm lin} \propto Z^6 T_e^{-3/2}$). The two-term formula of[13] (Fig. 3) corresponds to the 100%-stripping approximation. Its order-of-magnitude accuracy is due to partial mutual cancellation of the neglect of $Q^{\rm lin}$ and the overestimate of $Q^{\rm rec}$.

"Lethal" concentrations. We use our results to ascertain the Z-dependence of "lethal" relative concentration of the impurity $c(Z) = n^*/n_e$, defined as the concentration at which the summary radiation losses exceed the thermonuclear energy yield of the DT reaction (in α particles) at *any* temperature. It is assumed here that $T_e = T_i$ and that n_e is fixed (i.e., does not depend on n^*). The results of the calculation of $c(Z)$ for $6 \leq Z \leq 80$ is well approximated by the formula $c(z) = 2.34 Z^{-1.60}$. For the Mo and W considered in[6], it yields $c(42) = 0.6\%$ and $c(74) = 0.2\%$; the corresponding values in[6] are 0.8 and 0.2%.

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