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Measurement of Dielectronic Recombination Rates for the Iron Ions Fe IX–XI

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(Received 11 April 1978)

Iron is injected into a well-diagnosed θ-pinch plasma. The intensities of lines from various ionization stages are measured as functions of time and interpreted by means of a time-dependent corona ionization-recombination model. Effective coefficients for dielectronic recombination at electron densities $N_e \approx 3\times10^{16}$ cm^{-3} are equal to or smaller than presently accepted theoretical values for low-density plasmas. Rate coefficients for ionization tend to be smaller than theoretical values.

The distribution of (heavy) atomic ions over ionization stages remains an important quantity in astrophysics and solar physics, and has now also become very important in controlled fusion research. To calculate this distribution, one needs ionization and recombination rate coefficients for the dominant processes—usually electron-impact ionization for increases in the ionic charge and, more often than not, for decreases in the charge, "dielectronic" recombination.[1] The latter process involves radiationless capture of a plasma electron, accompanied by excitation of a bound electron, into doubly excited (autoionizing) states. These captures are followed by stabilizing radiative transitions which give rise to satellites of the resonance lines of the recombining ions. Finally, the captured electron cascades radiatively or by collisions from its normally rather highly excited state. Calculations of such complex processes are necessarily very uncertain and depend on many approximate cross sections and spontaneous transition rates that have not been tested experimentally.

To provide an experimental test of the overall dielectronic recombination process, two methods come to mind. One approach would be based on an absolute measurement of all important satellite lines in a plasma with known concentration of recombining ions and electrons. The sum of all corresponding photon emission rates could then yield the desired recombination rate. This approach has may difficulties and has not yet been successful. Our approach is a generalization of a method[2,3] for the determination of effective ionization-rate coefficients from a comparison of measured and calculated line emission from impurity ions in a transient plasma whose electron temperature and density have been measured independently.

We assume that practically all ions are in their respective ground states and consider the coupled rate equations for the corresponding densities, N_z, in a plasma of electron density N_e:

$$dN_z/dt = N_e[S_{z-1}N_{z-1} + \alpha_{z+1}N_{z+1} - (S_z + \alpha_z)N_z].$$

The ionization and recombination coefficients, S_z and α_z, are functions of electron temperature, T. The shape of these functions is assumed to be known,[1,2] as is the shape of the excitation rate coefficients $[\sim\exp(-E/kT)/E]$ which relate N_z to the observed line intensities. (Here E is the excitation energy.) By introducing temperature-

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independent multipliers of calculated S_z and α_z, and varying these while repeatedly solving the rate equations for measured time sequences of N_e and T, one then arrives at a set of effective ionization and recombination coefficients that best describes the ionization and recombination processes within the confines of this simulation procedure. We note here that this procedure also entails some smoothing of local temperature and density fluctuations to allow for the line-of-sight average of the observed intensities. Residual fluctuations in intensities correlate quantitatively with the average density,[4] but have here been smoothed out for convenience.

The experiment was performed using essentially the same θ-pinch and diagnostic apparatus as in the ionization-rate measurements.[2,3] However, there were two major improvements. First, the iron line emission is now measured side-on by connecting the grazing-incidence monochromator via an extension tube to a 1-cm hole drilled into the side of the quartz discharge tube. The line of sight is thus a diameter in the midplane in which the Thomson scattering measurements for the determination of electron temperature and density are made.

The second improvement is in the method of impurity introduction into the hydrogen plasma. Previously, iron was mixed with the hydrogen fill gas in the form of iron pentacarbonyl. Besides radiation from iron, there was therefore considerable line emission from carbon and oxygen. This not only caused problems with blends, but also cooled the plasma. Now, the iron is introduced by a laser puffing method.[5] A film of iron is deposited on a glass plate mounted near the axis of the θ pinch ~60 cm from the nearest coil and with the iron deposit facing the coil. A 2-J ruby laser is fired axially toward the plate and coil 0.2–0.6 msec, depending on the fill pressure, before the main discharge. The laser beam

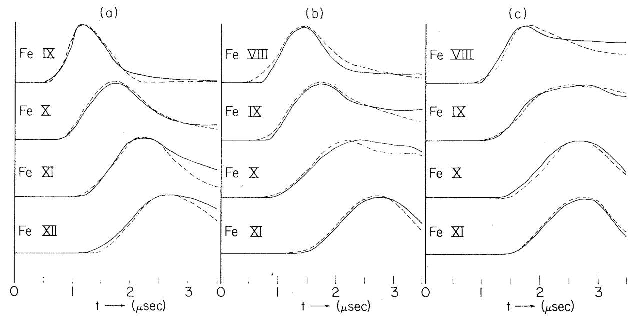

FIG. 1. Observed and calculated time histories for the iron ions indicated for various plasma conditions: (a) $T_e \approx 200$ eV, $N_e \approx 7\times10^{15}$ cm^{-3}; (b) $T_e \approx 105$ eV, $N_e \approx 3.5\times10^{16}$ cm^{-3}; (c) $T_e \approx 65$ eV, $N \approx 1.8\times10^{16}$ cm^{-3}. In cases (b) and (c), the actually observed time histories were smoothed to take out effects of rapid density fluctuations from radial oscillations fo the plasma column.

is focused on the plate and blows off ~10 mm of the $\lesssim 1$-μm-thick iron deposit. The long delays between iron injection and discharge were found necessary to give sufficient intensities. After each shot, the plate was moved laterally and could thus be used for over one hundred discharges.

The principal advantage of this method is that radiative cooling is now less severe for a given iron concentration. This allowed us to increase the hydrogen fill density and therefore the electron density without lowering the electron temperature below the threshold required for measurable line emission. We found that increased electron density and decreased temperature resulted in qualitatively different time histories of the line emission (light curves).

At low densities and high temperatures, lines from the various ion species appear sequentially, and their light curves can readily be simulated by only allowing for ionization in the system of

TABLE I. Measured and calculated[a] recombination and ionization coefficients.

	$N_e=(1-3)\times10^{16}$ cm^{-3} $\alpha_{\rm expt}$	$N_e=10^{10}$ cm^{-3} $\alpha_{\rm Jacobs}$	$N_e=10^{10}$ cm^{-3} $\alpha_{\rm Burgess}$	$S_{\rm expt}$	$S_{\rm semiempirical}$
Fe IX	1.1×10^{-10}	2.7×10^{-10}	6.1×10^{-10}		2.9×10^{-10}
Fe X	1.6×10^{-10}	2.3×10^{-10}	3.5×10^{-10}	0.7×10^{-10}	1.3×10^{-10}
Fe XI	2.2×10^{-10}	2.2×10^{-10}	3.3×10^{-10}	0.4×10^{-10}	0.6×10^{-10}

[a]The calculated recomination coefficients, for $T_e=100$ eV, are from Jacobs *et al.* (Ref. 6) and Burgess (Ref. 1); the semiempirical value of the ionization rate coefficients are calculated as in Ref. 2, also for $T_e=100$ eV.

TABLE II. Measured and calculated[a] corona equilibrium temperatures in electron volts.

	Expt.	Jacobs *et al.*	Jordan
Fe IX	65	86	68
Fe X	105	108	108

[a]The calculated values are from Refs. 6 and 8, respectively.

rate equations [see Fig. 1(a)]. At higher densities and lower temperatures the light curves develop more structure, some of them acquiring plateaus [Figs. 1(b) and 1(c)] rather than rounded maxima. Which of the ion species attain such more complicated light curves depends on the actual plasma conditions [compare Figs. 1(b) and 1(c)]. Under some conditions [e.g., in cases of Figs. 1(b) and 1(c)] emission from some higher ionization stage actually declines before that from the preceding stage, as one would expect for a recombining plasma. However, this effect is usually obscured by the rapid plasma loss after ~ 3 μsec from the beginning of the discharge.

Simulation of the more complicated light curves proved impossible without allowance for recombination Fe IX, X, XI, and XII. Best-fit values for recombination and ionization coefficients (in the sense discussed above) are listed in Table I, together with theoretical values.[1,6] (Note that the theoretical recombination rate is almost entirely dielectronic, i.e., that direct radiative and three-body recombination rates are negligible.) Estimated experimental errors are ± 30%. They were determined by variation of the assumed coefficients in the rate equations and by comparison of the corresponding light curves with the observed curves. Errors from electron density and temperature measurements are smaller than those associated with the sensitivity of the light-curve fitting procedure.

In conclusion, we have measured, for the first time, dielectronic recombination coefficients and found them to be equal to or smaller than calculated values for low-density plasmas. How much of the reduction with respect to theory is due to a decrease in effective recombination rates caused by the effects of collisions[7] on the highly excited levels of the captured electron, or due to errors in the various cross sections, remains to be investigated. In any case, for plasmas in the density and temperature range covered here, both recombination and ionization rates tend to be smaller than those calculated. This explains why the plateaus in the observed light curves occur at temperatures that are very close to the calculated temperatures[6,8] which correspond to maximum abundance of the ion in question for corona ionization equilibrium. This comparison, shown in Table II, should not be considered as proof of the corresponding method for temperature determination, e.g., of the solar corona, until the possible variation of the effective recombination coefficients with density has been determined. It should also be noted that in true corona equilibrium, recombination and ionization between any two adjacent ionization stages are balancing each other, whereas in the experiment we have only a balance of ionization and recombination into an ionization stage with ionization and recombination out of this stage. In other words, instead of a plateau in Fe IX or X, all ions would show a plateau had we achieved true corona equilibrium.

This work was supported by the U. S. Department of Energy, Office of Fusion Research, and the National Aeronautics and Space Administration.

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