Collisional rate coefficients for the iron ions Fe VIII, Fe IX, and Fe X†

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(Received 10 February 1975; revised manuscript received 19 May 1975)

Relative values of rate coefficients for excitation by electron collisions were determined experimentally for various transitions in Fe VIII, Fe IX, and Fe X at two plasma conditions in a small θ-pinch. Collisional ionization rates were also obtained for these ions. The maximum errors of the relative values of the excitation rate coefficients are estimated to be $\pm 30\%$ to $\pm 40\%$ and those of the ionization rates to be a factor of 1.5. Iron pentacarbonyl [$Fe(CO)_5$] was used as an impurity in hydrogen or helium gases. The electron temperature and density were obtained from the analysis of scattered laser light. They were in the range 60–150 eV and 10^{15} to 2×10^{16} cm^{-3}, although this range was not available for each ion. The excitation rate coefficients were calculated by the use of the Coulomb-Born approximation. Comparison with experiment is made within each ion and also between ionization stages. A discrepancy in previous Coulomb-Born calculations is noted for the case of Fe VIII.

I. INTRODUCTION

The availability of hot plasmas in various laboratory devices makes possible the measurement of collisional rate coefficients for highly ionized atoms. Standard techniques have been developed to interpret measured absolute intensities of ions in terms of rate coefficients for excitation, and the time histories of properly chosen lines in terms of ionization rate coefficients.[1-3] In the present investigation we studied experimentally, as well as theoretically, the ions of iron Fe VIII, Fe IX, and Fe X. The rate coefficients for these ions are of immediate astrophysical interest. They are also important for the assessment of radiative energy losses from impurities in controlled-fusion plasmas. In the past few years the spectra of these ions have been analyzed and the transition probabilities for various transitions have been theoretically calculated by various workers.[4-8]

In order to determine the absolute rate coefficients for excitation, the concentration of the ion in the ground state must be known. However, the absolute concentration of the iron ions could not be determined, as will be discussed in this article. In the following experimental section, therefore, we present only relative rate coefficients for excitation and compare them with theory where possible. The theoretical excitation rate coefficients are calculated in the Coulomb-Born and in the $\bar{g}$ approximations.

II. DESCRIPTION OF THE EXPERIMENT

A. Apparatus

The plasma was generated in a θ-pinch machine which was primarily built as a spectroscopic source. The device itself and some of the diagnostic equipment have been described already elsewhere.[9]

B. Introducing iron into the discharge tube

Iron, being a solid, presents some difficulty if one wants to add it in small quantities to the initial base gas in the discharge tube. Since the discharge tube is always maintained at relatively low pressures, i.e., below 30 μm (the initial base pressure without gas is 10^{-6} Torr), compounds of iron could be used which vaporize at these pressures. Ferrocene ($FeC_{10}H_{10}$) and iron pentacarbonyl [$Fe(CO)_5$] are two such commercially available compounds.

Ferrocene sublimates and has a vapor pressure of 250 mTorr at a temperature of 27 °C. Iron pentacarbonyl is a liquid with a vapor pressure of 20 Torr at 25 °C. The latter compound had been used already elsewhere for adding iron into the discharge tube of a θ-pinch.[10]

Since the first compound did not produce stable and reproducible plasma conditions, the second one was also used in our investigations. The vapors of iron pentacarbonyl were drawn into a bottle and mixed with a desired concentration of the base gas. This premixed bottle was used to feed the mixture into the discharge tube. A magnetic stirrer maintained a uniform mixture of gases in the bottle.

C. Discussion of the two plasma cases employed

Several plasma cases corresponding to different filling pressures of hydrogen and helium with different concentrations of iron pentacarbonyl, $Fe(CO)_5$, were examined in order to find stable plasma conditions suitable for our spectroscopic investigations. One main condition was that the intensities of the lines would not show large fluctuations from shot to shot but would be rather reproducible. From those studies the following discharge conditions were found to yield very stable and reproducible plasma conditions:

Case I: 23 mTorr H_2 with 0.15% Fe.

Case II: 20 mTorr He with 0.8% Fe.

In both cases, a reverse-bias magnetic field of − 600 G was applied to the preheated plasma. The time history of the Fe II line at 2599 Å observed in the preheater phase, and the time history of the C V line at 2271 Å during the main discharge, served as monitors of the plasma conditions from shot to shot. Both monitors viewed the plasma in the midplane of the discharge coil.

The electron density and temperature were obtained by the light-scattering technique as functions of radius and time. In the 23-mTorr H_2 case, the temperature and density were found to be homogeneous to better than 10% after 1.4 μsec across a radius of 1 cm. In the 20-mTorr He case, on the other hand, the plasma did not settle to a steady plasma column over the confinement time of our experiment, as oscillations were observed in density until 3 μsec after the beginning of the discharge. This revealed that the radial oscillations originating from the initial implosion did not damp away until that time. The emitted line intensities, however, were quite reproducible and did not present any difficulties in the analysis.

D. Line-intensity measurements

The absolute intensities of the lines emitted were measured with a 2-m grazing-incidence monochromator (1200 lines/mm and a grazing-incidence angle of 86°) equipped with a photomultiplier and *p*-terphenyl as scintillator. The calibration was done using the branching-ratio technique as previously described.[11] However, the procedure was improved by obtaining the line-intensity ratios from plots of the corresponding line intensities vs the added impurity concentration. The uncertainty of self-absorption was thus eliminated.

Among all identified lines of the iron ions of interest, the absolute intensities were measured only for those transitions which were not blended and whose background could be measured in the vicinity of the line. It was not feasible to determine the background radiation by a measurement without added iron, since the plasma conditions were altered. For this reason, the plasma parameters (density, temperature, length of plasma column) were obtained specifically for the discharge conditions with iron pentacarbonyl added. The length of the plasma column as a function of time was obtained in each case by observing the C V 2271-Å line through equidistant holes along the side of the coil.[1] This effective length varies between 70 and 90% of the coil length.

From these line intensities it is possible to derive the absolute rate coefficients if the ground-state population of the ion is known.[1,2] In previous experiments,[1,12] the element of interest was added as an impurity to a base gas such as hydrogen. (Typically, the impurity had a partial pressure of the order of 1% of the base gas pressure.) In order to determine the number of impurity atoms in the plasma state, it was assumed that the various ions and electrons mix evenly during the compression, and the relative abundance of the elements would be the same as it was before the discharge. Since each hydrogen molecule yields two free electrons, a measurement of the total electron density would give the total ion density of the impurity element. In the previous experiments, the added impurity was a lighter element of the periodic table (e.g., He, O, N, C, Ne, etc., the heaviest being Si), and the above assumption proved to be justified. It was also found experimentally that in the case of gases not interacting with the walls of the discharge tube the intensity of the lines increased linearly with added concentration, as long as it did not become too large so as to influence the plasma conditions significantly.

However, the assumption of a constant mixing ratio was found to be not valid anymore in the case of heavier elements such as argon.[12] The heavy argon atoms did not mix evenly with the hot plasma, and the concentration of argon was less than could be expected from the filling ratio.

Therefore, the estimation of the impurity concentration assuming a constant mixing ratio cannot be used for heavy ions, although it will yield an upper limit in those cases. Some other suitable method is needed to determine the iron concentration in the plasma. This is not easy, since reliable values having an accuracy of 10% or better are desired. Hence only relative excitation rates were derived.

III. EXPERIMENTAL RESULTS

The average line intensities as measured at the time of signal peak are presented in columns 4 and 5 of Tables I, II, and III, in units of W/cm^2 sr for the observable transitions of FeVIII, Fe IX, and Fe X in the two plasma cases investigated. Each value represents an average of at least ten reproducible shots, and often such determination was repeated two or three times.

The wavelength of the line and the details of the

TABLE I. Fe VIII line intensities in W/cm^2 sr and plasma parameters.

Transition	λ (Å)	gf (present calculation)	23-mTorr H_2	20-mTorr He
$3p^6 5f\,^2F - 3p^6 3d\,^2D$	108	1.683	65	34
$3p^6 4f\,^2F - 2p^6 3d\,^2D$	131.1 [b]	4.365	155	123
$3p^5 3d^2 - 3p^6 3d$:				
$(^3F)^2D_{3/2} - ^2D_{3/2}$	167.5	4.182	398	262 [a]
$(^3P)^2P_{3/2} - ^2D_{5/2}$	168.6	3.340	314	236 [a]
$(^3P)^2P_{1/2} - ^2D_{3/2}$	168.9	1.854	236	129 [a]
$(^3F)^2F_{7/2} - ^2D_{5/2}$	185.2	3.006	525	324 [a]
$(^3F)^2F_{5/2} - ^2D_{3/2}$	186.6	2.089	338	241 [a]
l (cm)			20	18.4
N (10^{16} cm^{-3})			1.25	1.0
T (eV)			95	50
p			46%	62%
t (μsec)			1.5	1.4
T_{CV} (eV)			293	152

[a] Corrected for optical depth.
[b] Reference transition.

transition are given in columns 2 and 1. When the whole multiplet is measured, the average wavelength is quoted.

The electron density and temperature at the time (t) of peak intensity of each ion are given at the bottom of each table. The relative concentration p of each ion at this time was obtained from a computer solution of the coupled rate equations governing the successive ionization stages.[3] The experimentally determined electron density and temperature were used as input.

The effect of self-absorption on the resonance lines was corrected for theoretically, by using the procedures described in detail in Refs. 13 and 14. For this correction the temperature of the ions must be known, as well as the density of the

TABLE II. Fe IX line intensities in W/cm^2 sr and plasma parameters.

Transition	λ (Å)	gf	23-mTorr H_2	20-mTorr He
$3p^5 4s\,^3P_1 - 3p^6\,^1S_0$	105.21	0.148 (Ref. 7)	100	65
$3p^5 4f - 3p^5 3d$:				
$^3D - ^3P$	111.9	3.79 (Ref. 7)	52	
$^3G - ^3F$	114	9.00 (Ref. 7)	100	50.5
$^1F_3 - ^1D_2$	115.4	1.97 (Ref. 7)	41	
$^1G_4 - ^3D_3$	116.8	2.87 (Ref. 7)	39	
$3p^5 3d - 3p^6$:				
$^1P_1 - ^1S_0$	171.1 [b]	3.72 (Refs. 8, 15)	2745 [a]	1394 [a]
$^3D_1 - ^1S_0$	217.1	0.006 (Ref. 15)	423	144
l (cm)			20	18.4
N (10^{16} cm^{-16})			1.2	1.0
T (eV)			95	50
p			37%	50%
t (μsec)			1.6	1.5
T_{CV} (eV)			293	152

[a] Corrected for optical depth.
[b] Reference transition.

ions in the ground state. A direct measurement of this temperature was not possible, because the ions formed in the main discharge did not have strong lines in the visible-wavelength region whose Doppler broadening could be easily measured. Observations on other impurity ions in θ-pinches, on the other hand, show that heavy ions usually have temperatures of similar magnitude; we used, therefore, the Doppler temperature of C V in the calculation of the optical depth. This assumption is supported by the observation that line profiles of the Fe X line at 365.6 Å obtained end-on, for example, did not indicate any broadening beyond the instrumental profile, even for a slit width of 30 μm corresponding to 0.12 Å. Also, the ion temperature of oxygen ions observed end-on agreed with the temperature of the C V ions measured side-on in the midplane of the coil.

The ground-state population of Fe VIII is estimated from the measured emission coefficient ϵ of the $3d$-$4f$ transition. This line is selected since its oscillator strength is so low that the line is certainly optically thin. In order to obtain the population of the lower level, the theoretical (Coulomb-Born) excitation rate coefficient was used. Since the populations of the excited states are small compared to the population of the ground state, one can safely assume that practically all ions are in the ground state, and one obtains the corresponding population of the ground states of Fe IX and Fe X from the relative concentrations p as quoted in Tables I–III. The corrections to the intensities calculated according to Ref. 14 were found to be only a few percent for the plasma case I, whereas in case II they were 40% for the Fe IX line at 171.4 Å and 19% for the Fe X line at 174.6 Å; this larger correction is due to the higher iron density and lower ion temperature. Higher iron ion temperatures would reduce these corrections.

Emission lines yield the ionization rate coefficients through a comparison of observed time histories with computed ones. The coupled rate equations were solved using the analytic form of Ref. 3 for the ionization rate coefficients, taking into account also the ionization from the next inner subshell of each ion. In the case of Fe VIII, ionization from the $3p$ subshell is two times the

TABLE III. Fe X line intensities in W/cm^2 sr and plasma parameters.

Transition	λ (Å)	gf (Refs. 7, 8)	23-mTorr H_2	20-mTorr He
$3p^4 4s$-$3p^5$:				
$^2D_{5/2}$-$^2P_{3/2}$	94.0	0.37	99	56
$^2P_{3/2}$-$^2P_{3/2}$	96.1	0.47	109	76
$^4P_{3/2}$-$^2P_{3/2}$	97.1	0.2	61	34
$3p^4 4f$-$3p^4 3d$:				
$(^3P)^4F_{9/2}$-$(^3P)^4D_{7/2}$	100.0	3.88	95	
$(^3P)^4G$-$(^3P)^4F$ } $(^1D)^2H_{11/2}$-$(^1D)^2G_{9/2}$ }	102.0	17.77	160	
$(^3P)^2G_{9/2}$-$(^3P)^4F_{7/2}$	101.4	1.38	22	
$(^1S)^2F_{5/2}$-$(^1S)^2D_{3/2}$	102.8	1.96	7.2	
$(^1D)^2G_{7/2}$-$(^1D)^2F_{5/2}$	104.3	1.86	23	
$3p^4 4p$-$3p^4 3d$:				
$(^1D)^2F_{7/2}$-$(^1D)^2G_{9/2}$	139.9	0.52	147	113
$3p^4 3d$-$3p^5$:				
$(^3P)^2D_{5/2}$-$^2P_{3/2}$	174.6[b]	6.51	2047[a]	1074[a]
$(^3P)^2P_{3/2}$-$^2P_{3/2}$	177.2	3.21	1660	633[a]
$(^1D)^2S_{1/2}$-$^2P_{1/2}$	190.02	0.26	445	154
$3s3p^6$-$3p^5$:				
$^2S_{1/2}$-$^2P_{1/2}$	365.6	0.33 (Ref. 16)	65	23
l (cm)			20	18.4
N (10^{16} cm^{-3})			1.2	1.4
T (eV)			142	95
p			41%	55%
t (μsec)			1.9	2.1
$T_{\text{C V}}$ (eV)			293	152

[a] Corrected for optical depth.
[b] Reference transition.

ionization from the outer $3d$ shell. In Fe IX and FeX, the inner $3s$ subshell contributes 20% and 16% of the outer $3p$ shell contribution, respectively, to the total calculated ionization. In the computations, the theoretical rate coefficient was varied by a factor R until observed and computed time histories agreed. This factor $R = I_{\text{ex}}/I_{\text{theory}}$ is given in Table IV for the 23-mTorr case only, since this plasma was more homogeneous, with fewer and smaller radial oscillations in density and temperature. A variation of R by 15% caused a noticeable difference between computed and observed time histories.

TABLE IV. Ratio R of experimental to theoretical ionization rate coefficients.

Ion	T_e (eV) range	T_e (eV) at ion peak	R 23-mTorr H_2 case
Fe VIII	60–150	110	0.48
Fe IX	70–150	125	0.62
Fe X	90–150	142	0.54

IV. CALCULATION OF COLLISIONAL EXCITATION CROSS SECTIONS AND EXCITATION RATES

The relative rate coefficients of excitation obtained from our measurements of resonance lines of Fe VIII, Fe IX, and Fe X are compared with theoretical values in Table V.

For Fe VIII, all excitation cross sections were calculated in the LS coupling scheme without regard to any possible mixing of levels.

For Fe IX and FeX, we took into account the effects of mixing on the excitation cross sections Q by using the f values of Fawcett *et al.*,[7,8] Cowan,[15] and Garstang,[16] in the formula

$$Q(\alpha J \rightarrow \alpha' J') = (8\pi/\sqrt{3})(E\Delta E)^{-1} f(\alpha J, \alpha' J')\, \bar{g}\, \pi a_0^2 ,$$

where E and ΔE are the electron energy and the excitation energy (in rydbergs), respectively, and $\bar{g}$ is the effective Gaunt factor which depends on E. Values of $\bar{g}$ were taken either from Van Regemorter[17] (the results are referred to as $\bar{g}$ approximation) or from our Coulomb-Born (CB) calculations.

Besides the excitation rate coefficients given in Table V, we have calculated cross sections and rate coefficients for 28 other transitions in Fe VIII, Fe IX, and Fe X. Details and results of this calculation are given in Ref. 18.

The comparison of our collision strengths with

TABLE V. Relative rate coefficients of excitation.

Ion and Transition	Expt.	$\bar{g}$ approx.	Coulomb-Born approx.	Seaton-Burgess approx.	Expt.	$\bar{g}$ approx.	Coulomb-Born approx.	Seaton-Burgess approx.
Fe VIII		$T_1 = 95$ eV				$T_2 = 50$ eV		
$3p^6 3d \rightarrow 3p^6 5f$	0.36	0.265	0.296	0.206	0.23	0.218	0.25	0.17
$3p^6 3d \rightarrow 3p^6 4f$	1	1	1	1	1	1	1	1
		(6.12×10^{-10} cm^3/sec)	(6.7×10^{-10} cm^3/sec	(8.2×10^{-10} cm^3/sec)		(3.44×10^{-10} cm^3/sec)	(3.35×10^{-10} cm^3/sec)	(4.14×10^{-10} cm^3/sec)
$3p^6 3d\ ^2D$–$3p^5 3d^2\ ^2D_{3/2}$	3.64	1.79	3.73		3.05	2.18	4.82	
$3p^6 3d\ ^2D$–$3p^5 3d^2\ ^2P$	4.86	2.17	4.56		4.14	2.56	5.87	
$3p^6 3d\ ^2D$–$3p^5 3d^2\ ^2F$	8.05	2.45	5.4		6.76	3.02	7.5	
Fe IX		$T_1 = 95$ eV				$T_2 = 50$ eV		
$3p^6\ ^1S_0$–$3p^5 4s\ ^3P_1$	0.023	0.0146	0.0034		0.029	0.0098	0.0019	
$3p^6\ ^1S_0$–$3p^5 3d\ ^1P_1$	1	1	1		1	1	1	
		(90×10^{-10} cm^3/sec)	(218×10^{-10} cm^3/sec)			(59.9×10^{-10} cm^3/sec)	(143×10^{-10} cm^3/sec)	
$3p^6\ ^1S_0$–$3p^5 3d\ ^3D_1$	0.2	0.0026	0.0028		0.131	0.0028	0.0032	
Fe X		$T_1 = 142$ eV				$T_2 = 95$ eV		
$3p^5\ ^2P$–$3p^4 4s\ ^2D_{5/2}$	0.026	0.017	0.004		0.028	0.0154	0.003	
$3p^5\ ^2P$–$3p^4 4s\ ^2P_{3/2}$	0.032	0.024	0.006		0.042	0.023	0.005	
$3p^5\ ^2P$–$3p^4 4s\ ^4P_{3/2}$	0.016	0.0097	0.003		0.017	0.0089	0.002	
$3p^5\ ^2P$–$3p^4 3d\ ^2D_{5/2}$	1	1	1		1	1	1	
		(32.3×10^{-10}. cm^3/sec)	(75.6×10^{-10} cm^3/sec)			(27.3×10^{-10} cm^3/sec)	(69.3×10^{-10} cm^3/sec)	
$3p^5\ ^2P$–$3p^4 3d\ ^2P_{3/2}$	0.857	0.529	0.523		0.62	0.527	0.523	
$3p^5\ ^2P$–$3p^4 3d\ ^2S_{1/2}$	0.903	0.167	0.166		0.595	0.168	0.167	
$3p^5\ ^2P$–$3s 3p^6\ ^2S_{1/2}$	0.225	0.564	0.571		0.154	0.593	0.648	

values obtained by Czyzak and Krueger[5] shows in several cases large discrepancies, caused mainly by the difference in partial wave contributions from $l=7$ at higher energies. Our partial collision strengths change smoothly with l and do not show any conspicuous peak at $l=7$, as do the values of Czyzak and Krueger. The largest disagreement is in the case of $4p$-$5s$ at $E/\Delta E=4.0$, where our value is 7.2 times smaller. Our collision strengths for the $4p$-$5s$ and $3d$-$4f$ transitions compare much more satisfactorily with the semiclassical approximation presented in the paper of Czyzak and Krueger.

V. INTERPRETATION AND DISCUSSION

A. Excitation

Table V gives the relative rate coefficients of excitation as obtained for the resonance lines in Fe VIII, Fe IX, and Fe X. The results are given for the two plasma cases separately, under the heading of the respective electron temperature. In each ion, one transition is used as reference, and absolute theoretical rate coefficients are quoted in parentheses for these transitions. Theoretical ratios of the rate coefficients are given for the effective Gaunt factor approximation of Van Regemorter[17] ($\bar{g}$ approximation), the CB approximation, and, in the case of Fe VIII, for Seaton's and Burgess's semiclassical approximation taken from Ref. 5.

The ground states of Fe VIII and Fe X are doublet states. At the electron densities of our experiment ($\approx 10^{16}$ cm^{-3}), both levels are populated according to their statistical weights, since collisional transitions between the doublet states are much stronger than the radiative transitions. The critical electron density above which collisions take over radiative decay of the upper level is 10^{8} cm^{-3} for Fe VIII and about 10^{11} cm^{-3} for Fe X (Ref. 19). When transitions are possible to both doublet levels of the ground term from an excited state, and only one of these transitions was measured, the emission coefficient of the other component was calculated using theoretical transition probabilities; in this way, the average rate coefficient from the total ground state was obtained.

In the case of Fe VIII, the experimental values are generally within ±30% of our CB results. Using the gf values for the $3p^5 3d^2$ configuration obtained by considering term mixing,[20] the agreement of relative X-s for the $3p^6 3d$-$3p^5 3d^2$ array becomes ±20%. However, when comparison is made with the $3d$-$4f$ excitation, as is done in Table V, the relative calculated values of X for $3p^5 3d^2$ are higher by a factor of ~1.5 than measured values.

It can be seen further that the values for the excitation rate coefficient given by the $\bar{g}$ approximation are close to the CB calculations for $\Delta n \neq 0$ transitions, and are a factor $\gtrsim 2$ too low in $\Delta n = 0$ transitions, as was observed before.[11, 12, 21]

The ground state for Fe IX is $3p^6\,{}^1S_0$. The reference transition is between this ground state and the level $3p^5 3d\,{}^1P_1$. Only three transitions to the ground state are measured. By comparing the measured and theoretical ratios, we see that the transition $3p^6\,{}^1S_0$-$3p^5 3d\,{}^3D_1$ is on the average 55 times more frequent than expected from CB values. It is seen from Ref. 15 that there is negligible mixing of ${}^1P_1$ and ${}^3D_1$ terms in this $3p^5 3d$ configuration, and additional CB calculations with exchange showed that the rates change at most by 20% due to exchange. There could be a population mechanism of the ${}^3D_1$ state by a collisional coupling with other fine-structure states and (or) by the process of exchange collisions between singlets and triplets. The discrepancy may also be due to the process of cascading from higher levels and the uncertainty of the gf value.

The excitation rate to $3p^5 4s\,{}^3P_1$ is 6.5 times higher at 95 eV and 15 times higher at 50 eV than expected from theory, as seen from Table V. However, the cascading contribution from $3p^5 4p\,{}^1S$ to $3p^5 4s\,{}^3P_1$ as calculated by the CB approximation was equal in magnitude to direct excitation at both temperatures. Similarly, the cascading contribution from $3s3p^6 4s$ to $3p^5 4s\,{}^3P_1$ was found to be 1.7 times higher at 95 eV and 1.5 times higher at 50 eV than the direct excitation. Hence, after including the cascading, the experimental value is 2 times higher at 95 eV and 4 times higher at 50 eV than expected theoretically. The remaining discrepancy could be due to exchange collisions from the ground state which are not considered in our theoretical calculations.

In the case of Fe X, we find that the levels of the $3p^4 4s$ configuration are excited five to six times more frequently than expected from the CB calculations. One of the three observed transitions, $3p^5\,{}^2P_{3/2}$-$3p^4 4s\,{}^4P_{3/2}$, is an intercombination line, and for the calculation of the rate coefficient the process of exchange could again be important. The cascading contributions from the $3p^4 4p$ and $3s3p^5 4s$ configurations to $3p^4 4s$ levels were considered in LS coupling by taking the proper branching ratios. The contribution from the $3p^4 4p$ to ${}^2P_{3/2}$ and ${}^2D_{5/2}$ levels of $3p^4 4s$ was found to be about equal in magnitude to the direct excitation. The contribution from $3s3p^5 4s$ to these levels was found to be negligibly small. Hence this discrepancy between the experiment and theory would still be by factors of 3 to 5.

Still discussing Table V, the better agreement between the experimental ratios and the values obtained from the $\bar{g}$ approximation should be viewed only as a coincidence. It is also interesting to note that for this excitation to the $3p^4 4s$ states, the values from the $\bar{g}$ approximation are about four to five times higher than the CB values. Therefore in this $\Delta n = 1$ case, CB values are smaller than the values obtained from the $\bar{g}$ approximation.

The excitations to the $3s3p^6\,{}^2S_{1/2}$ and $3p^4 3d\,{}^2S_{1/2}$ levels from the ground state $3p^5\,{}^2P$, are not at all in agreement with theory. At the higher temperature $3p^4 3d\,{}^2S_{1/2}$ is 5.4 times more excited than expected, whereas $3s3p^6\,{}^2S_{1/2}$ is 2.6 times less excited. The factors at the lower temperature are 3.6 for $3p^4 3d\,{}^2S_{1/2}$ excitation, and 4.2 for $3s3p^6\,{}^2S_{1/2}$ excitation, and the deviations are in the same direction as noted at the higher temperature. These discrepancies may be partly due to configuration interaction, which is neglected in the evaluation of the gf values. This has been recently verified by Mason.[22] Also, there are several other multiplet levels in the $3p^4 3d$ configuration, and all these may be coupled collisionally. The process of exchange could also be important.

The excitation from the ground state $3p^5\,{}^2P$ to $3p^4 3d\,{}^2P_{3/2}$ is in agreement with theory to within ±30–40%, when both plasma cases are averaged.

In Table VI a comparison is made between the experimental ratios and the similar ratios obtained from the analysis of the solar EUV spectrum by Malinovsky and Heroux.[23] Interestingly enough, the solar data give ratios which are within ±35% of our experimental ratios, excepting the $3p^6\,{}^1S$-$3p^5 4s\,{}^3P_1$ excitation in FeIX and the $3p^5\,{}^2P$-$3p^4 3d\,{}^2S_{1/2}$ excitation in FeX, where the experimental values are factors of 2 and 2 to 3 higher,

TABLE VI. Comparison of relative photon fluxes between the present experiment and solar observations.

Ion	Transition	Solar EUV spectrum (Ref. 23)	Present expt.	
Fe VIII			95 eV	50 eV
	$3d\,{}^2D$-$4f\,{}^2F$	1	1	1
	$3p^6 3d\,{}^2D$-$3p^5 3d^2\,{}^2D_{3/2}$	2.66	3.6	3.05
	-$3p^5 3d^2\,{}^2P$	4.5	4.89	4.16
	-$3p^5 3d^2\,{}^2F$	8.75	8.05	6.7
Fe IX			95 eV	50 eV
	$3p^6\,{}^1S$-$3p^5 3d\,{}^1P$	1	1	1
	-$3p^5 4s\,{}^3P_1$	0.012	0.029	0.023
Fe X			142 eV	95 eV
	$3p^5\,{}^2P$-$3p^4 4s\,{}^2D_{5/2}$	0.033	0.026	0.028
	-$3p^4 4s\,{}^2P_{3/2}$	0.0335	0.032	0.042
	-$3p^4 4s\,{}^4P_{3/2}$	0.015	0.016	0.017
	-$3p^4 3d\,{}^2D_{5/2}$	1	1	1
	-$3p^4 3d\,{}^2P_{3/2}$	0.58	0.86	0.62
	-$3p^4 3d\,{}^2S_{1/2}$	0.34	0.9	0.6

respectively. The lack of statistical population of the fine-structure states of the ground term in Fe X in the solar corona cannot explain this particular deviation. In fact, the general agreement seen in Table VI shows that the intensity ratios are relatively insensitive to density effects. Our experimental results in the case of Fe X are consistent with the report of Malinovsky and Heroux [23]: Both components of the transition $3p^5\,{}^2P$-$3p^4 3d\,{}^2S$ are found to be stronger by a factor of 3 in comparison to their expected intensity. Also, the lines of the multiplet $3p^5\,{}^2P$-$3p^4 4s\,{}^2D$ and $3p^5\,{}^2P$-$3p^4 4s\,{}^2P$ are reported to have high intensities. It seems that the latter deviation is a general trend for these high-Z iron ions, as such a disagreement was also reported in the case of FeXIV.[24]

The experimental ratios for all the ions show an increase of population with temperature for the lower-lying levels, e.g., $3p^5 3d^2\,{}^2F$, $3p^5 3d\,{}^3D_1$, and $3s3p^6\,{}^2S_{1/2}$, when compared with high levels. This may be due partly to a real effect, e.g., cascading.

The error estimated in the absolute calibration of the grazing-incidence spectrometer was 25% in the wavelength region 90–150 Å, 30% in the wavelength region 150–210 Å, and 40% for wavelengths lying above 300 Å. However, the error in the relative calibration of the instrument was less (10%, 15%, and 25% in the regions specified above). The estimated deviation on each experimental ratio in Table V is thus between 20 and 30%.

B. Ionization

The experimental values are compared with the semiempirical formula of Ref. 3, taking into account, of course, also ionization from the next inner subshell. This formula agrees to about 10% with proposed rate coefficients of Lotz.[25]

The effect of autoionization has been discussed by several authors for various iron ions.[26–28] Bely[27] concluded that the effect is considerable for FeXV and FeXVI (factors of 3 and 6 times the direct ionization), but that it would be very small for lower-Z ions like FeIX and FeX. The total rate given by Bely[27] for Fe IX is 7% lower, and for Fe X 4.5% lower than our calculated value used in Table IV. Jordan[28] noted that the autoionization process is most important for isoelectronic sequences where there are many electrons in the outer shell, e.g., the NaI, MgI, CaI, and KI sequences. Fe VIII is a potassium-like ion, except that the outermost electron is in the $3d$ subshell, unlike KI, where it is in the $4s$ subshell. A theoretical estimate of autoionization is not available for this ion from any of the references above; however, from our experimental result we can conclude that autoionization will not contribute significantly to the total ionization of Fe VIII. As can be seen from Table IV, the experimental rate coefficients obtained for Fe VIII, Fe IX, and Fe X are 48%, 62%, and 54% of our theoretical rates, respectively. The overall accuracies of our experimental values are estimated to be a factor of 1.5 or better.

In Ref. 3 it was found for Li-like and Be-like ions, and in Ref. 12 for Na-like Ar VIII, that the experimental ionization rate coefficients were also only 60% of the theoretical values, consistent with the present results. However, the theoretical ionization rate coefficients obtained recently by Summers[29] in the ECIP approximation for Li-like and Be-like ions are also about 50% of the values obtained from the empirical formula of Ref. 3. This indicates that the Lotz's empirical ionization cross sections may be overestimated by a factor of 2.

VI. SUMMARY

Excitation rate coefficients for Fe VIII, Fe IX, and Fe X ions have been calculated theoretically using the Coulomb-Born (CB) approximation, and relative rates were obtained experimentally from the absolute intensities of lines emitted by these ions in well-diagnosed plasmas. The maximum error in each experimental ratio is 30%–40%. A discrepancy with CB calculations of Czyzak and Krueger[5] in Fe VIII is most likely due to numerical problems in their computer code. From the time history of Fe VIII, Fe IX, and Fe X, ionization rate coefficients were deduced and found to be 50–60% smaller than the theoretical estimates based on the formula of Kunze[3] and the results of Bely.[27]

ACKNOWLEDGMENTS

The authors would like to express their appreciation to H. R. Griem for valuable discussions, and R. D. Cowan and H. E. Mason for private communications.

†This work was supported by the National Science Foundation, the National Aeronautics and Space Administration, and the U. S. Atomic Energy Commission.

*The material in this article is part of a thesis submitted in partial fulfillment of the requirements for the Ph.D. degree at the University of Maryland.

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[1]H.-J. Kunze, Space Sci. Rev. 13, 565 (1972).

[2]A. H. Gabriel and C. Jordan, *Case Studies in Atomic Collision Physics 2* (North-Holland, Amsterdam, 1972), Chap. 4.

[3]H.-J. Kunze, Phys. Rev. A 2, 937 (1971).

[4]A. H. Gabriel, B. C. Fawcett, and C. Jordan, Proc. Phys. Soc. Lond. 87, 825 (1966).

[5]S. J. Czyzak and T. K. Krueger, Astrophys. J. 144, 381 (1966).

[6]E. Alexander, U. Feldman, and B. S. Fraenkel, J. Opt. Soc. Am. 55, 650 (1965).

[7]B. C. Fawcett, R. D. Cowan, E. Y. Kononov, and R. W. Hayes, J. Phys. B 5, 1255 (1972).

[8]B. C. Fawcett, N. J. Peacock, and R. D. Cowan, J. Phys. B 1, 295 (1968).

[9]A. W. DeSilva and H.-J. Kunze, J. Appl. Phys. 39, 2458 (1968).

[10]L. House, W. A. Deutschmann, and G. A. Sawyer, Astrophys. J. 140, 814 (1964).

[11]W. D. Johnston III and H.-J. Kunze, Phys. Rev. A 4, 962 (1971).

[12]R. U. Datla, H.-J. Kunze, and D. Petrini, Phys. Rev. A 6, 38 (1972).

[13]H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).

[14]R. C. Elton and W. W. Köppendörfer, Phys. Rev. 160, 194 (1967).

[15]R. D. Cowan, J. Opt. Soc. Am. 58, 924 (1968).

[16]R. H. Garstang, Ann. Astrophys. 3, 109 (1962).

[17]H. Van Regemorter, Astrophys. J. 136, 906 (1962).

[18]R. U. Datla, M. Blaha, and H.-J. Kunze, University of Maryland Technical Report No. 75-076, 1975 (unpublished). See also National Auxiliary Publications Service document No. 02648 for 15 pages of supplementary material. Order from ASIS/NAPS, c/o Microfiche Publications, 305 E. 46th St., New York, N. Y. 10017.

[19]A. H. Gabriel, B. C. Fawcett, and C. Jordan, Nature 206, 392 (1965).

[20]R. D. Cowan (private communication, 1974).

[21]H.-J. Kunze and W. D. Johnston III, Phys. Rev. A 3, 1384 (1971).

[22]H. E. Mason (private communication, 1974).

[23]M. Malinovsky and L. Heroux, Astrophys. J. 181, 1009 (1973).

[24]M. Blaha, Sol. Phys. 17, 99 (1971).

[25]W. Lotz, Astrophys. J. Suppl. Ser. 14, 207 (1967); Report No. IPP 1/62, Institut für Plasmaphysik, Garching bei München, 1967 (unpublished).

[26]L. Goldberg, A. K. Dupree, and J. W. Allen, Ann. Astrophys. 28, 589 (1965).

[27]O. Bely, Ann. Astrophys. 30, 953 (1967).

[28]C. Jordan, Mon. Not. R. Astron. Soc. 142, 501 (1969).

[29]H. P. Summers, Mon. Not. R. Astron. Soc. 169, 663 (1974); Internal Memo No. 367, Appleton Lab., England, 1974 (unpublished).