Measurements of excitation rate coefficients for Al-like ions: Fe XIV, Ni XVI, and Cu XVII

R. U. Datla and J. R. Roberts
Atomic and Plasma Radiation Division, Center for Radiation Research, National Bureau of Standards, Gaithersburg, Maryland 20899

R. D. Durst, W. L. Hodge,* C. C. Klepper,† and W. L. Rowan
Fusion Research Center, University of Texas, Austin, Texas 78712

J. B. Mann
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 21 July 1987)

Absolute excitation rate coefficients for Fe XIV and Ni XVI ions are measured spectroscopically in the Texas Experimental Tokamak. Previous measurements for the $3d$-$3p$ transition array of Cu XVII are verified and the measurements are extended to the $3s3p^2 \rightarrow 3s^23p$ transition array of this ion. The experimental rate coefficient for the $3d$-$3p$ transition array of Fe XIV is 6.2×10^{-9} $cm^3 s^{-1}$ at an electron temperature near 160 eV and for Ni XVI and Cu XVII, the values are 4.2×10^{-9} and 3.8×10^{-9} $cm^3 s^{-1}$, respectively, at an electron temperature near 240 eV. For the $3s3p^2\,{}^2P_{3/2} \rightarrow 3s^23p\,{}^2P_{3/2}$ transition array, the experimental excitation rate coefficient for Fe XIV is 8.2×10^{-9} $cm^3 s^{-1}$ at an electron temperature near 160 eV and for Ni XVI and Cu XVII the value is 5.5×10^{-9} $cm^3 s^{-1}$ at an electron temperature near 240 eV. The uncertainty in these results is estimated to be $\pm50\%$ (one standard deviation). Computed values of absolute excitation rates in a distorted-wave approximation and Mewe's semiempirical formula are found to be in good agreement with the experimental values.

The absolute excitation rate coefficients of high-Z ions of elements such as iron, nickel, and copper are very important for plasma diagnostics and for radiative energy-loss calculations for fusion plasmas. A plasma spectroscopic technique which uses a tokamak plasma for the measurement of absolute excitation rate coefficients of ions was demonstrated in Ref. 1. Using the procedure of Ref. 1, we measured the absolute excitation rate coefficients for Fe XIV, Ni XVI, and Cu XVII ions. We improved the experimental accuracy for absolute intensity measurements of spectral lines by calibrating the 1-m grazing-incidence monochromator at the Synchrotron Ultraviolet Radiation Facility (SURF II) at the National Bureau of Standards (NBS). Also, we reestablished our previous results and extended our measurements to more transitions in Cu XVII ions. We report in this paper our experimental excitation rate coefficients and their comparison with the theoretical calculations based on distorted-wave and Gaunt factor approximation methods.

The Al-like ions, Fe XIV, Ni XVI, and Cu XVII, have the two-level ground configuration, $3s^23p\,({}^2P_{1/2,3/2})$. By designating ${}^2P_{1/2}$ as 1 and ${}^2P_{3/2}$ as 2 as in Ref. 1, the average effective excitation rate coefficient $\chi_{\text{eff}}(\overline{T}_e)$ is written as

$$\chi_{\text{eff}}(\overline{T}_e)=\chi_{2-i}(\overline{T}_e)+\frac{g_1}{g_2}\chi_{1-i}(\overline{T}e)\ , \tag{1}$$

where χ_{1-i} and χ_{2-i} are excitation rate coefficients from levels 1 and 2 to level i, respectively.

The absolute effective excitation rate coefficient $\chi_{\text{eff}}(\overline{T}e)$, to the level i, from the ground configuration of these ions is obtained from Eq. (9) given in Ref. 1, i.e.,

$$\chi_{\text{eff}}(\overline{T}_e)\simeq\frac{1}{\overline{N}_e}\frac{\lambda(i-j)}{\lambda(\text{for})}\frac{I(i-j)}{I(\text{for})}\frac{A(\text{for})\sum_{k<i}A(i-k)}{A(i-j)}\ , \tag{2}$$

where j is either of the two levels of the ground configuration designated by 1 or 2, $\lambda(i-j)$ is the wavelength, $I(i-j)$ is the measured intensity, $A(i-j)/\sum_{k<i}A(i-k)$ is the branching ratio of the transition probability of the transition (i-j), and λ(for), I(for), and A(for) are the wavelength, intensity, and transition probability, respectively, of the forbidden line between the levels 1 and 2 of the ground configuration. $\overline{N}_e$ and $\overline{T}_e$ are the electron density and electron temperature measured at the peak of the ionic radial profile in the tokamak. The assumption of statistical population between the levels of the ground configuration in deducing Eq. (2) is valid for Fe XIV, Ni XVI, and Cu XVII ions, because their forbidden transition probabilities are only 60, 191, and 330 s^{-1}, respectively, which are much smaller than the electron and ion collisional frequencies[2,3] as discussed in Ref. 1.

The details of our experiment on the Texas Experimental Tokamak (TEXT) are described in Ref. 1. Only the differences are noted here. A 1-m grazing-incidence monochromator equipped with a 1200-line/mm gold-

TABLE I. Absolute excitation rate coefficients.

Ion and transition	λ (Å)	A (s^{-1})	$\frac{I(i-j)}{I(\text{for})}$	χ_{eff} (experiment) ($cm^3 s^{-1}$)	χ (Theory $cm^3 s^{-1}$) Distorted-wave method	Gaunt factor approximation
Fe XIV				$\bar{T}_e = 159$ eV	$\bar{T}_e = 159$ eV	
$3p\ ^2P_{1/2}-3p\ ^2P_{3/2}$	5302.9	60		$N_e = 2.9\times10^{13}$ cm^{-3}		
$3p\ ^2P_{3/2}-3d\ ^2D_{5/2}$	219.1	3.99×10^{10}	7.2×10^4	6.2×10^{-9}	5.76×10^{-9}	6.77×10^{-9}
$3p\ ^2P_{3/2}-3d\ ^2D_{3/2}$	220.1	0.78×10^{10}				
$3s^23p\ ^2P_{3/2}-3s3p^2\ ^2P_{3/2}$	264.8	3.44×10^{10}	6.44×10^4	8.2×10^{-9}	7.45×10^{-9}	8.3×10^{-9}
Ni XVI				$\bar{T}_e = 237$ eV	$\bar{T}_e = 237$ eV	
$3p\ ^2P_{1/2}-3p\ ^2P_{3/2}$	3601.1	191		$\bar{N}_e = 2.8\times10^{13}$ cm^{-3}		
$3p\ ^2P_{3/2}-3d\ ^2D_{5/2}$	194.0	4.55×10^{10}	1.12×10^4	4.2×10^{-9}	4.38×10^{-9}	5.09×10^{-9}
$3p\ ^2P_{3/2}-3d\ ^2D_{3/2}$	195.2[a]	0.94×10^{10}				
$3s3p\ ^2P_{3/2}-3s3p^2\ ^2P_{3/2}$	232.5	4.12×10^{10}	1.0×10^4	5.5×10^{-9}	5.61×10^{-9}	6.22×10^{-9}
Cu XVII				$\bar{T}_e = 237$ eV	$\bar{T}_e = 237$ eV	
$3p\ ^2P_{1/2}-3p\ ^2P_{3/2}$	3007.6	330		$\bar{N}_e = 3.5\times10^{13}$ cm^{-3}		
$3p\ ^2P_{3/2}-3d\ ^2D_{5/2}$	183.5	4.92×10^{10}	6.61×10^4	3.8×10^{-9}	3.92×10^{-9}	4.56×10^{-9}
$3p\ ^2P_{3/2}-3d\ ^2D_{3/2}$	184.9	1.05×10^{10}				
$3s\ ^23p\ ^2P_{3/2}-3s3p^2\ ^2P_{3/2}$	218.7	4.35×10^{10}	6.63×10^4	5.5×10^{-9}	4.83×10^{-9}	5.41×10^{-9}

[a]Predicted from interpolation within the isoelectronic sequence.

coated grating is used for absolute intensity measurements of spectral lines below 30 nm. The detector at the exit slit of this instrument is a photomultiplier with a sodium-salicylate-coated quartz window in front to act as a scintillator for the radiation. This instrument was radiometrically calibrated at NBS using SURF II.[4] It is also calibrated *in situ* using the TEXT plasma by employing the branching ratio technique as described in Ref. 1. A careful evaluation of the solid angle of acceptance for the grazing-incidence spectrometer on TEXT is necessary to convert the irradiance calibration of SURF II into a radiance calibration for a comparison with the branching ratio technique.[1] It is found that the two calibrations are in agreement within 25% at the calibration wavelengths of the branching ratio technique. In the present experimental analysis, the radiance calibration deduced from SURF II data is used because it gives a continuous distribution with respect to wavelength rather than the discrete distribution from the branching ratio technique.

A grazing-incidence time-resolving spectrograph[5] (GRITS) is used to determine the spatial location of the ions in the plasma because the forbidden lines of Fe XIV and Ni XVI are not intense enough to be detected by the airpath Czerny-Turner monochromator arrangement as described in Ref. 1. The results of a similar scan using the scanning mirror and the airpath Czerny-Turner monochromator arrangement to obtain the Cu XVII ion distribution agreed with the results of the GRITS instrument well within the measurement uncertainties. The measurements of electron-density and electron-temperature spatial profiles of the plasma were previously described in Ref. 1.

The final results are summarized in Table I. The wavelengths and transition probabilities of the forbidden

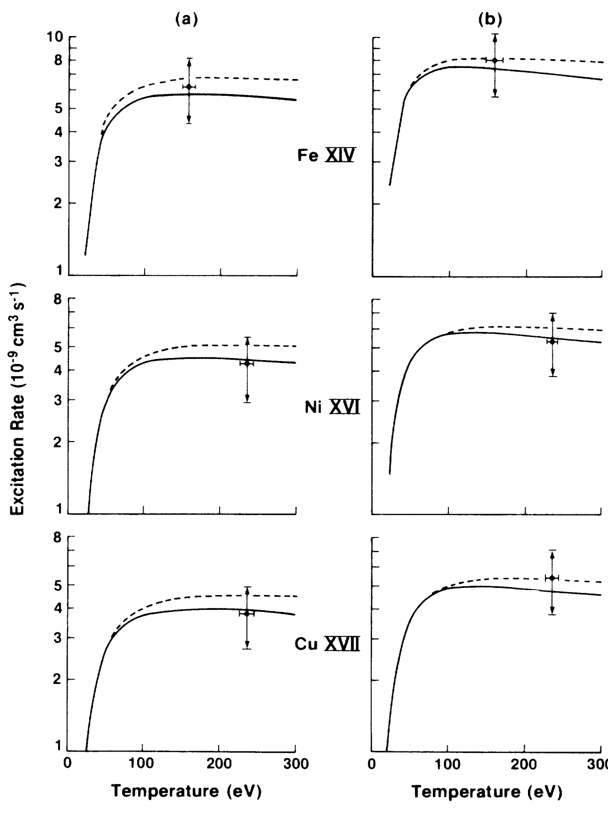

FIG. 1. Electron-impact excitation rate coefficients as a function of electron temperature. (a) $3p$-$3d$ excitation, (b) $3s^23p$-$3s3p^2$ excitation. Legend: ——, distorted wave; (— — —), Gaunt factor (Mewe); and experimental points with error bars.

lines are taken from Ref. 6. The allowed line wavelengths and identifications for Fe XIV, Ni XVI, and Cu XVII are taken from Refs. 7 and 8. The transition probabilities of allowed lines are calculated by using the atomic-structure code of Cowan with the Slater integrals multiplied by a scaling factor of 0.8.[9] The measured ratio of the absolute intensities of the allowed line and the forbidden line, for specific average electron densities, are given in column 4. The experimental excitation rate coefficients are deduced from Eq. (2) and are given in column 5. Equation (1) gives the effective theoretical excitation rates that are compared with the experimental values. Electron-temperature values at the minor radii of the peak of the ionic abundances are used in evaluating the effective theoretical excitation rate coefficients of Eq. (1). Column 6 gives the theoretical excitation rate coefficients computed using a distorted-wave method[10] and the effective Gaunt factor approximation due to Mewe[11] are listed in column 7. Figure 1 shows the temperature dependence of the theoretical rate coefficients and the experimental points with error bars for the ions and transitions listed in Table I. Both the distorted-wave method and the Gaunt factor method give results in good agreement with experiment. The vertical error bars on the experimental points represent the $\pm 30\%$ uncertainty in the average electron-density determination and the horizontal bars show the $\pm 10\%$ uncertainty in the temperature measurements. The other main source of error is the absolute radiometric calibration of the 1-m grazing-incidence spectrometer. However, the calibration is performed by using two different methods, one using the SURF II synchrotron source and the other using the *in situ* branching ratio technique. As both calibrations have a $\pm 25\%$ uncertainty and agree within 25%, the overall uncertainty in the experimental rates should be less than $\pm 50\%$. All of these are measurement uncertainties and represent one standard deviation of the mean.

The support of the TEXT professional and technical staff is greatly appreciated. We also express our appreciation for the help given by Steve Ebner and Tom Hall of SURF II and Martin Bassin of NBS. This work is supported under Contracts No. EA-77-A-01-6010 and No. DE-AC05-78ET053043 from the United States Department of Energy.

---

*Present address: Physics International Company, 2700 Merced Street, P.O. Box 1538, San Leandro, CA 94577.

†Present address: Fusion Energy Division, Oak Ridge National Laboratory, P.O. Box Y, Oak Ridge, TN 37831.

[1]R. U. Datla, J. R. Roberts, W. L. Rowan, and J. B. Mann, Phys. Rev. A **34**, 4751 (1986).

[2]M. Blaha, Astron. Astrophys. **1**, 42 (1969).

[3]O. Bely and P. Faucher, Astron. Astrophys. **6**, 88 (1970).

[4]E. B. Saloman, S. C. Ebner, and L. R. Hughey, Opt. Eng. **21**, 951 (1982).

[5]W. L. Hodge, B. C. Stratton, and H. W. Moos, Rev. Sci. Instrum. **55**, 16 (1984).

[6]V. Kaufman and J. Sugar, Phys. Chem. Ref. Data **15**, 321 (1986).

[7]R. L. Kelly and L. J. Palumbo, Naval Research Laboratory Report No. 7599, 1973 (unpublished).

[8]J. Sugar and V. Kaufman, J. Opt. Soc. Am B **3**, 704 (1986).

[9]R. D. Cowan, *The Theory of Atomic Structure and Spectra* (University of California Press, Berkeley, 1981).

[10]J. B. Mann, At. Data Nucl. Data Tables **29**, 407 (1983).

[11]R. Mewe, Astron. Astrophys. **20**, 215 (1972).