PHYSICAL REVIEW E VOLUME 57, NUMBER 5 MAY 1998

Stark broadening along the berylliumlike sequence

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(Received 29 December 1997)

We report on Stark width measurements of $2s3s$-$2s3p$ singlet and triplet transitions along the berylliumlike sequence performed in a gas-liner pinch discharge. Simultaneously with the spectroscopic measurements we have diagnosed the plasma with Thomson scattering testing theoretical scalings of the Stark broadening with density, temperature, and spectroscopic charge number Z. The comparison of measured Stark widths with semiclassical calculations shows that the calculated temperature scaling is consistent with the experiment. However, a systematic discrepancy of measured Stark widths from theoretically predicted Z^{-2} scaling is found with increasing spectroscopic charge number Z. [S1063-651X(98)11605-7]

PACS number(s): 52.70.Kz, 32.70.Jz

I. INTRODUCTION

Reliable experimental data to study the dependence of Stark broadening on the charge number Z of the emitting ions are important to test theoretical predictions of linewidths from highly ionized atoms. Their understanding is crucial for the diagnostics of high density plasmas [1–5], and for x-ray laser [6–8] and opacity studies (radiation transport) [9–12]. In earlier investigations of the measured Stark widths along the isoelectronic lithiumlike [13,14] and boronlike [15] sequences, deviations are stated from some theoretical calculations using the electron-impact approximation [16,17]. In the case of the boronlike sequence, the comparison between experimental and theoretical data turns out to be difficult because of close-lying perturber levels. This problem does not exist for energy levels of the lithiumlike ions: measurements of Ref. [14] clearly show deviations from the Z^{-2} dependence which is predicted by some theories. The authors found that theoretical calculations of Hey and Breger [18] show the best description of the experimental data due to an improved calculation of the strong collision term. Since then, further improvements of the semiclassical estimate of strong collisions by Alexiou [19] led to an overall good agreement between semiclassical calculations and the experiment [20]. In the present study, we have investigated the scaling of the Stark broadening of the beryllium isoelectronic sequence to verify the generality of this finding: the $2s3s$-$2s3p$ singlet and triplet transitions in the berylliumlike ions N IV and O V. Including results of a former investigation of these transitions in Ne VII [21], we find a systematic deviation from semiclassical [16] and semiempirical [17] theories with increasing charge number Z. Performing semiclassical nonperturbative calculations and taking into account strong collisions of electrons more precisely [22] we find reasonable agreement for the transitions in the ion of the highest ionization state Ne VII.

In order to apply plasma spectroscopy in a wide range of plasma parameters, it is of utmost importance to test theories in an intermediate density range where an independent plasma diagnostic is available. In fact, at densities of the order of 1×10^{18} cm^{-3}, there are discrepancies between experimental results [23] and recent quantum-mechanical Stark width calculations [24] even for—from a theoretical point of view—simple resonance transitions where such calculations are expected to be most applicable. In addition, there is disagreement between some oversimplified close-coupling calculations, which show a Z^{-2} scaling, and the measurements along the lithiumlike isoelectronic sequence [14,20]. These discrepancies show that there are still open questions regarding the Stark broadening, especially the contribution of strong collisions and high-order terms. It shows that reliable data of line profiles are needed to benchmark the theoretical approximations. The gas-liner pinch device provides best conditions for Stark width measurements of transitions of highly ionized species: The ions of spectroscopic interest are imbedded in a well defined and properly (and independently) diagnosed plasma.

II. EXPERIMENTAL SETUP

The special feature of the gas-liner pinch—which is, in principle, a high-aspect ratio z pinch—is a fast electromagnetic gas inlet system injecting two different kinds of gases independently. The outstanding characteristic of the resulting plasma is that the ions of spectroscopic interest are confined in the homogeneous center of a hydrogen plasma column, and no cold boundary layers are present. Therefore, no Abel inversion for the data analysis has to be carried out. For the investigation along the berylliumlike sequence, the discharge voltage was gradually increased (27—34 kV), driving the plasma to higher temperature in order to obtain ions of high spectroscopic charge numbers.

Two 1-m Czerny-Turner spectrometers for the visible

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TABLE I. The measured Stark width (FWHM) of the $2s3s$-$2s3p$ singlet and triplet ($J=2$–$J=1$) transitions along the berylliumlike sequence for the measured electron density and temperature. The errors denote the standard deviation of about ten measurements. A comparison with calculated values w_G, w_{DK}, and w_{HB} after [16, 17, and 18], respectively, is given.

Ion	λ (nm)	$n_e(10^{18}\ \mathrm{cm}^{-3})$	k_BT_e (eV)	w_{expt} (0.1nm)	w_{expt}/w_G	$w_{\mathrm{expt}}/w_{\mathrm{DK}}$	$w_{\mathrm{expt}}/w_{\mathrm{HB}}$
N IV $^1S_0$-$^1P_1$	638.08	0.46±0.04	7.0±2.3	1.73±0.13	0.86	1.19	1.10
		0.65±0.04	6.2±0.6	2.53±0.14	0.87	1.20	1.13
N IV $^3S_1$-$^3P_2$	347.87	0.58±0.05	7.0±2.3	0.84±0.08	1.22	1.70	1.58
		0.81±0.05	8.3±1.7	1.10±0.10	1.18	1.67	1.52
		1.06±0.12	9.0±2.4	1.11±0.11	0.93	1.31	1.17
		1.58±0.06	8.5±0.8	1.46±0.13	0.81	1.14	1.04
		1.94±0.09	8.7±0.8	1.72±0.12	0.78	1.10	1.00
O V $^1S_0$-$^1P_1$	511.42	1.08±0.10	7.8±2.5	1.85±0.42	0.98	1.27	1.14
		1.72±0.15	14.4±7.8	2.16±0.19	0.81	1.04	0.90
		2.36±0.18	18.7±7.8	2.85±0.35	0.81	1.04	0.89
	in 2. order:	1.20±0.07	9.3±1.9	2.01±0.19	1.00	1.29	1.13
Ne VII $^1S_0$-$^1P_1$	364.36	3.50±0.50	19.0±3.8	1.70±0.26	1.28	1.57	1.15
Ne VII $^3S_1$-$^3P_2$	198.20	3.00±0.40	20.5±3.5	0.45±0.07	1.53	1.91	1.29

spectral range were available. The first was used for spectroscopic investigations, and the other employed for simultaneous measurements of density and temperature via Thomson scattering [25,26]. For the spectroscopic investigation of the berylliumlike spectral line emission, a grating with 1200 lines/mm blazed at 750 nm, and a grating with 2400 lines/mm blazed at 240 nm, were employed. They give reciprocal linear dispersions of 0.02 and 0.01 nm/channel in first order, respectively. An optical multichannel analyzer (OMA-system II, EG&G model 1456-990G) mounted in the exit plane of the spectrometer is gated with a duration of 40 ns, setting the time resolution of the spectroscopic measurements. The full width at half maximum (FWHM) of the apparatus profile is three channels.

Simultaneously with the spectroscopic observations, we measured the plasma parameters by scattering of laser radiation of a ruby laser system (Korad K1 Q-Switch, $\lambda = 694.3$ nm, 1 J). The laser beam passes through the midplane of the discharge, and the scattered radiation is collected at an angle of 90°. The light is focused onto the entrance slit of the second visible spectrometer equipped with a 1200 lines/mm grating blazed at 1000 nm, and a second OMA system. We obtain a dispersion of 0.0063 nm/channel when using the grating in second order. A time resolution of 30 ns for the Thomson scattering measurements was given by the FWHM of the laser pulse.

Recently, we employed radial resolved Thomson scattering to measure the distribution of densities, temperatures, concentrations of multiply ionized species, and macroscopic plasma flow velocities on a single shot [27]. For this purpose we used an intensified charge coupled device (ICCD camera) with an apparatus profile of 2.5 pixels, giving a radial resolution of 66 μm. This setup improves earlier experimental methods [14,15] to verify the radial homogeneity of the plasma column and the concentration of the multiply ionized atoms in the central part of the plasma column. The radial resolved measurements show that for times after maximum pinch compression until 200 ns later, the highly ionized atoms are embedded in a homogeneous and resting hydrogen plasma column.

The Thomson scattering measurements [27] were performed at various times during the discharge. Each Thomson scattering spectrum recorded with the ICCD consists of 578 radial channels, and we averaged 20 channels in order to improve the signal-to-noise ratio. This procedure resulted in 26 spectra which were fitted with the theoretical form factor of Evans [28], giving the plasma parameters at corresponding radial channels [29]. The shapes of the spectra clearly show that ion temperatures are equal to electron temperatures: The high density plasma is thermalized in a few nanoseconds due to high electron-ion collision frequency. Furthermore, analysis of the width of the impurity peak on the spectrum indicates that the temperature of the highly ionized atoms is also equal to electron temperature. The bulk velocity determined from the Doppler shift of the spectra shows the plasma dynamics: During the whole time of the discharge the central ($r<2$ mm) part of the plasma is at rest, so that there is no macroscopic Doppler shift. Consequently, an additional broadening mechanism of the spectral lines can be excluded. Only at late times ($t>200$ ns after maximum pinch compression) did we observe a decompression velocity of 2×10^6 cm/s of the outer regions of the plasma (6 mm $<r<10$ mm). Therefore, we excluded spectroscopic measurements performed at these times. In this way we ensure that only plasma conditions were analyzed, where multiply ionized ions are at rest and are still located on the axis. Furthermore, we kept the amount of impurity ions low (1–2 % of the electron density), and found that the plasma formation is reproducible.

III. STARK WIDTH MEASUREMENTS

The measured Stark widths of various $2s3s$-$2s3p$ singlet and triplet lines along the isoelectronic sequence of the berylliumlike ions N IV, O V, and Ne VII are compiled in Table I for the measured densities and temperatures from Thomson

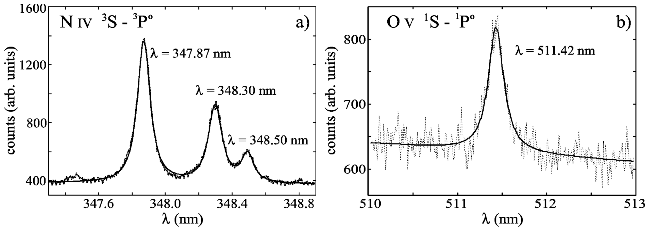

FIG. 1. Example of spectra of the $2s3s$-$2s3p$ ^3S-^3P triplet line of N IV (a) and ^1S-^1P singlet line of O V (b) along with least-squares fits. The apparatus and the Doppler profile calculated for the measured temperatures are taken into account by the fitted Voigt profiles.

scattering. The N IV singlet and triplet lines were measured in first and third orders, respectively, using optical filters to suppress contributions of lower orders. An example of the recorded spectra of the triplet lines of N IV is given in Fig. 1(a) along with the best fit. All measured spectral lines were fitted by a least-squares method, with a Voigt profile taking into account the measured apparatus profile, a Doppler profile calculated for the measured temperature, and a Lorentz profile. The width of the Lorentz contribution and the intensities of the individual multiplet components were varied independently by the fitting procedure. The optical thickness of the triplet lines can be calculated from the experimental spectra by comparing the intensity ratios of the multiplet components with theoretical ratios (5:3:1) which are obtained assuming LS coupling [30]. In addition, the comparison of the Stark widths within the multiplets is a more sensitive method in order to find spectral line profile distortions by radiation transport [31]: The experimental Stark widths of the three components are equal, i.e., their ratio is 1.00 ± 0.06, strongly indicating that self-absorption is absent. In addition, the measured intensity ratio of the two strongest triplet components $[\mathrm{I}(J=2\text{–}J=1)/\mathrm{I}(J=1\text{–}J=1)]$ is $(5.1 \pm 0.2){:}3$, e.g., it agrees to within 2% with the theoretical ratio (5:3) over the whole density range. In addition, the experimental intensity ratio of the two weaker components $[(3.0 \pm 0.4){:}1]$ is equal to the theoretical ratio (3:1). These observations clearly show that the density of the impurity ions indeed was chosen to be low enough and, as a consequence, the spectral lines are emitted optically thin.

The optical thickness of a radiative transition is proportional to the population of the lower level and the absorption oscillator strength. Since for the other spectral lines investigated in the present study, the same low amount of test gas was used, and the population of lower levels in the singlet system can expected to be even lower than in the triplet system, we conclude that for all present spectral lines radiation transport effects are negligible.

In the case of O V the triplet lines overlap with several O IV lines and, therefore, only the singlet line was measured. In addition to measurements in first order, we performed additional measurements in second order to increase the resolution and to decrease the relative contribution of the apparatus profile to the total linewidth. The Stark widths agree within the error bars of about 10%. In second order the apparatus profile convoluted with the Doppler profile computed at respective temperatures amounts to 15% to the total width. An example of the O V singlet line is given in Fig. 1(b).

Measurements of the F VI multiplet lines were also attempted, but suffered under poor intensity; the singlet line was even undetectable. The triplet line was obtained for one density value, and the intensity ratio of the triplet components did not agree with the theoretical ratio. Furthermore, at wavelength positions near to the triplet lines unidentified lines occurred, so that the deviation from the intensity ratio can be explained most probably by underlying transition lines giving contributions to the triplet components. Therefore, we decided to exclude the measurements of the F VI lines.

IV. RESULTS AND DISCUSSION

In Table I, we compare measured Stark widths of the $2s3s$-$2s3p$ transitions with calculated widths following three theoretical approaches evaluated at the measured densities and temperatures of the experiment. The symbol w_G represents the electron-impact width calculated after Eq. (526) from Griem [16], w_{DK} is evaluated after a modified semiempirical approach of Dimitrijević and Konjević [17], and w_{HB} was calculated using a code of Hey and Breger [18]. The data for the energy levels were taken from Ref. [32]. The theoretical values of Ref. [18] are also electron-impact widths, but the calculations allow for more perturbing levels than the other two approximations. In addition, Hey and Breger [18] chose other cutoff parameters, thereby considering the contribution of strong collisions more carefully. The detailed calculation procedure and some applied improvements were discussed in Ref. [14].

The theoretical values of Ref. [16] show fairly good agreement, but overestimate the experimental data for the ions N IV and O V by about 15% at higher densities. For the highly charged ion Ne VII, this behavior is reversed, and the calculation gives widths which are up to 50% too low. The semiempirical values after Ref. [17] underestimate the widths for all ions and all densities. The best agreement for all experimental data can be found with calculations using the code of Ref. [18]. Nevertheless, these theoretical values of the N IV triplet transition deviate from experimental data at lower densities. These data points are measured at late times after maximum pinch compression ($t \approx 150$ ns) at temperatures which are lower than those at the highest densities, so that the deviation might be due to an underestimation of the temperature effect of this theory (see Fig. 2). For Ne VII detailed semiclassical nonperturbative calculations were performed by Ref. [19], and show good agreement with experimental data when taking into account electron quadrupole broadening [21]. Unfortunately, such calculations were not done for the lower ionized species measured in the present investigation, so that the dependence of Stark widths on Z cannot be given for this theory.

To investigate scalings of the Stark broadening, we accept the theoretically predicted [33,16], and in a number of experiments confirmed, linear density dependence of the Stark width [34]. We linearly scaled the measured widths to a density of $n_e = 1 \times 10^{18}$ cm^{-3}. In Fig. 2, the scaled widths are shown vs temperature together with the theoretical widths. The error bars denote the standard deviation of about ten measurements. In addition, an experimental value of the N IV

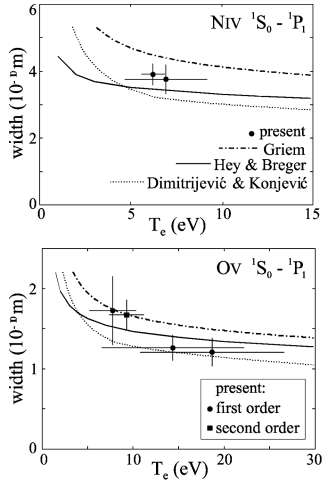

FIG. 2. The temperature dependence of the measured Stark width (FWHM) linearly scaled to a density of $n_e = 1\times10^{18}$ cm^{-3} along with the theoretical calculations of Griem [16], Hey and Breger [18], and Dimitrijević and Konjević [17]. Within the uncertainty of the experiment, the experimental data follow the electron broadening predictions of theories quite well.

triplet line measured in Ref. [35] in a linear-pinch discharge plasma using a scanning procedure is given. In that work the density—measured by employing single-wavelength laser interferometry—is one order of magnitude lower than in the present investigation. This data point compares well to the present study, indicating that the linear scaling is a good approximation.

From Fig. 2, we find that the present experimental results cannot distinguish between the temperature dependencies predicted by the theoretical approximations of Refs. [16,17] and of Hey and Breger [18], because the standard deviation of the experimental values is not small enough and the temperature range is limited to a small range. The theoretical values of Ref. [18] show a weaker temperature dependence in comparison to semiclassical [16] or semiempirical theory [17]. The latter shows nearly the same temperature dependence as Ref. [16]. A stronger $1/\sqrt{k_B T_e}$ scaling of the electron impact width is predicted, assuming the Gaunt factor $\bar{g}$ to be constant:

$$w = n_e \frac{8\pi}{3}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi k_B T_e}\right)^{1/2}\frac{\pi}{\sqrt{3}}\left[\sum_{i'} \mathbf{R}^2_{i'i}\ \bar{g}\left(\frac{E}{\Delta E_{i'i}}\right) + \sum_{f'} \mathbf{R}^2_{f'f}\ \bar{g}\left(\frac{E}{\Delta E_{f'f}}\right)\right] \qquad (4.1)$$

(see, e.g., Refs. [36] and [17]). In this formula, elastic collisions at low temperatures are taken into account by extrapolating the threshold value of the inelastic cross section below the threshold. $\mathbf{R}^2_{j'j}$ is the square of the coordinate operator matrix element summed and averaged over magnetic substates of angular momentum J' and J, respectively, and the sum is over all contributing perturbing energy levels. If the energy of perturbing electrons $E=\frac{3}{2}k_B T_e$ is lower than twice the energy difference of the perturbing level, the effective Gaunt factor proposed in Refs. [37] and [38] indeed becomes constant ($\bar{g}=0.2$). In the case of the N IV lines, this upper limit is slightly exceeded for the nearest perturber level, and for ions with higher charge number the Gaunt factor varies with temperature especially for data points measured at highest densities (and consequently higher temperatures). Here the $1/\sqrt{k_B T_e}$ temperature dependence of the width is mainly compensated for by the Gaunt factor in the term of the sum corresponding to the nearest perturber level which contributes about 50% to the total width: In Fig. 2, the Stark widths show a strong $1/\sqrt{k_B T_e}$ temperature scaling only at low temperatures; the temperature dependence becomes much weaker at higher temperatures. We conclude that the temperature scaling predicted by the three semiclassical approximations considered in this study is a reasonable approximation, and describes the experimental behavior quite well (in particular the case of O V).

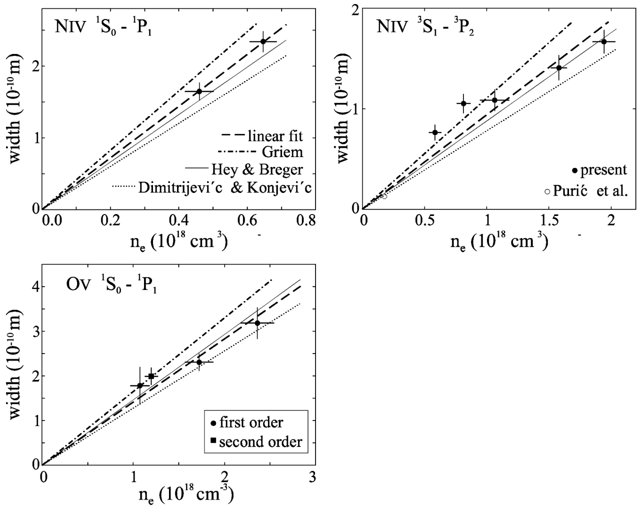

FIG. 3. Experimental Stark widths scaled to $T_e = 10$ eV using the temperature scaling of Dimitrijević and Konjević [17] or Griem [16]. The experimental values are increasing linearly with density. The linear fits of the Stark widths of N IV and O V lines are in good agreement with calculations after Hey and Breger [18]. Measurements after Purić *et al.* [35] for the N IV triplet line also agree with the present results.

In order to compare experimental results independently from temperature, the Stark widths were scaled to $k_B T_e = 10$ eV, employing the theoretical temperature scaling of Ref. [17]. These Stark widths are shown in Fig. 3 along with the three mentioned theoretical approaches calculated at corresponding electron densities. In addition, the temperature-scaled widths were fitted with a linear function that was constrained to pass through the origin. Within the error bars we find good agreement for both singlet and triplet N IV lines and the O V singlet line with theoretical values of Ref. [18]. The value of Ref. [35] is in good agreement with the fit through the present experimental data. In Fig. 3, it becomes obvious that semiclassical calculations after Ref. [16] overestimate experimental Stark widths, and semiempirical values underestimate them.

In order to study the Z dependence of the Stark width, the results of the different ion species are plotted in Fig. 4 vs their respective charge number. The widths in angular frequency units are taken from the fit at a density of $n_e = 1\times10^{18}$ cm^{-3} and a temperature of $k_B T_e = 10$ eV. In addition, the experimental data of Refs. [39] and [35], and the theo-

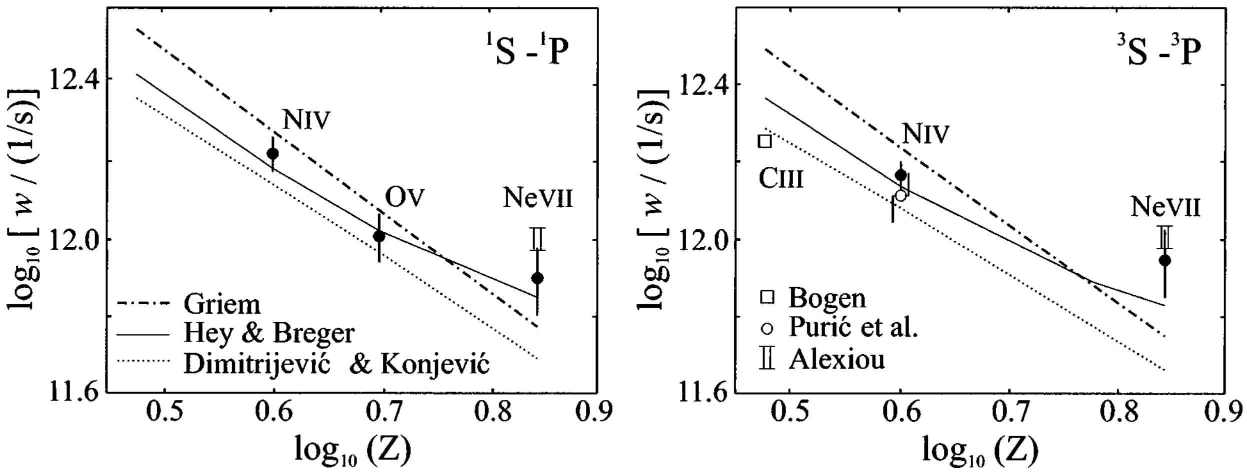

FIG. 4. The fitted experimental Stark width (in frequency units) in the (a) singlet and (b) triplet system plotted over the spectroscopic charge number Z on a logarithmic scale. The density and temperature are $n_e = 1 \times 10^{18}$ cm^{-3} and $k_B T_e = 10$ eV, respectively. The error bars of the Stark widths include the experimental errors of electron density and temperature. A systematic discrepancy of experiment and theory with increasing spectroscopic charge number becomes obvious.

retical data are shown. The calculated data of Refs. [16] and [17] suggest a Z^{-2} dependence of the Stark width. It is obvious that neither the theoretical data of Ref. [18] nor the experimental data show a Z^{-2} dependence and, therefore, the experimental values deviate systematically from the theory of Refs. [16] and [17]. Although Ref. [18] deviates from the data for the Ne VII triplet line, this theory gives the best overall agreement and follows the experimental trend for higher Z ions. The experimental results clearly show deviations from a Z^{-2} dependence with an increasing charge number of the ions probably related to strong collision. This result confirms earlier findings for the lithiumlike sequence [14], and show that a general Z^{-2} scaling is not applicable.

The deviation for atoms of higher charge number Z is most likely due to an inadequacy of the respective theories: Measurements along the isoelectronic sequence of lithium-like ions made in Ref. [14] show the same discrepancy of these theories for the ions of the highest ionization stage. Performing nonperturbative calculations, Alexiou [22] found good agreement for the lithiumlike sequence. Calculations employing this modern code for Ne VII triplet and singlet lines also show good agreement, especially when taking into account electron quadrupole broadening [19]. These nonperturbative calculated values slightly overestimate the width, and they are plotted in Fig. 4 with and without taking into account the strong collision estimate.

When calculating the Stark widths of transition lines of ionized atoms with intermediate charge numbers, semiclassical and semiempirical codes [16–18] give reliable Stark widths within an accuracy of 30%. More complex calculations [22] should be applied if ions of a high ionization stage are investigated, and a higher accuracy is required.

V. SUMMARY

We have reported on measurements of $2s3s$-$2s3p$ singlet and triplet transitions in the berylliumlike ions N IV and O V from a gas-liner pinch plasma. It is well confined, reproducible, and properly diagnosed using the Thomson scattering technique. The spectral lines were recorded for a range of densities and temperatures in order to investigate the dependence of the Stark width with density and temperature.

Semiclassical calculations according to Ref. [16], and the semiempirical calculations of Ref. [17], show the same temperature dependence of the Stark width, while the calculations of Hey and Breger [18] show a slightly weaker temperature scaling. In this study we could not distinguish between these theoretical predictions. They all show agreement with the experiment within the error bars. In order to compare measured widths independently of temperature, we scaled the experimental results to $k_B T_e = 10$ eV using the theoretical temperature scaling. The experimental results are underestimated by theoretical values of Ref. [17], and overestimated by theoretical calculations according to Ref. [16]. These theories suggest a Z^{-2} scaling of the Stark width. The experimental data show a growing systematic discrepancy with these theories with increasing spectroscopic charge number Z. Using more perturber levels and an improved estimate of the strong collision term [18], the calculations follow the trend of experimental Stark width along the isoelectronic sequence of berylliumlike ions. The latter theoretical values only slightly underestimate the width for the highest spectroscopic charge number. Nonperturbative calculations of Ref. [22] are in good agreement with the present data, especially when taking into account electron quadrupole broadening, but they slightly overestimate the experimental widths. It will be interesting to compare the present experimental data and calculations with results of modern codes such as quantum mechanical close coupling calculations (which have been done for other transitions in berylliumlike ions [9] and with too few perturbing levels), or to nonperturbative semiclassical calculations [19] to clarify the contribution of strong collisions and higher order terms to the Stark width.

ACKNOWLEDGMENTS

This research was supported by Sonderforschungsbereich 191 of the DFG and the U.S. Department of Energy under Contract No. W-7405-ENG-48. The authors would like to thank H. R. Griem for helpful comments. One of us (I.A.) thanks the DAAD for support.

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