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Experimental transition probabilities in N III, N IV and N V spectra

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Abstract. We have obtained transition probabilities (Einstein's A values) of thirteen transitions in doubly (N III), six in triply (N IV) and two in four times (N V) ionized nitrogen spectra belonging to the $3s{-}3p$ and $3p{-}3d$ transitions using a relative line intensity ratio (RLIR) technique. The linear low-pressure pulsed arc was used as an optically thin plasma source operated at 51 400 K electron temperature and 2.2×10^{23} m^{-3} electron density in nitrogen plasma. Our A values are compared to recent theoretical and experimental data.

PACS. 52.70.Kz Optical (ultraviolet, visible, infrared) measurements – 32.70.Cs Oscillator strengths, lifetimes, transition moments – 32.70.Fw Absolute and relative intensities

1 Introduction

Atomic data such as transition probabilities (A) play an important role in the diagnostics and modelling of cosmic and laboratory plasmas. Various kinetic processes appearing in plasma modelling need reliable knowledge of the A values [1–4]. Furthermore, knowledge of the A values gives a possibility for determination of the coefficients (B) which characterize the absorption and stimulated emission. These processes are also important in laser physics and astrophysics. Ionized nitrogen atoms, as emitters or absorbers, are important due to their presence in the many kinds of cosmic light sources [5–8] (and references therein). The resonant spectral lines from N III, N IV and N V spectra and strong spectral lines that belong to the $3s{-}3p$ and $3p{-}3d$ transitions play also an important role in astrophysics. For example, radiation of 464.0 nm and 451.2 nm, belonging to the N III spectrum, is found in light emitted from 39 Wolf-Rayet galaxies [7]. A number of papers are dedicated to the investigations of the A values in the spectra of multiply ionized (N III, N IV and N V) nitrogen. The existing experimental and calculated A values are collected in [9–12] from more than 350 references.

Although a significant number of theoretical works relate to the N III, N IV and N V properties, only few experiments are dedicated to the transition probability determination of doubly, triply and quadruply ionized nitrogen. Existing experimental A values are obtained on the basis of lifetime measurements [13–18] and beam-foil experiments [19–22] (and references therein). To the knowledge of the authors there are no A values obtained using relative intensities of the spectral lines emitted by N IV and N V ions, and only two experiments [23,24] deal with the N III transition probabilities determination on the basis of the ratio of the spectral line intensities.

In this work we present transition probability values for some lines belonging to the N III, N IV and N V spectra that were obtained, for the first time, by using the relative line intensity ratio (RLIR) method. This approach has been applied in the cases of the Ar III, Ar IV [25], O II [26,27] and Ne II [28] transitions before. Here, we have obtained transition probabilities of 13 transitions in doubly (N III), 6 in triply (N IV) and 2 in four times (N V) ionized nitrogen spectra belonging to the $3s{-}3p$ and $3p{-}3d$ transitions. A linear low-pressure pulsed arc was used as an optically thin plasma source operated at 51 400 K electron temperature and 2.2×10^{23} m^{-3} electron density in a nitrogen discharge. Obtained A values are compared to the recent theoretical and experimental data.

2 Experiment

A linear low-pressure pulsed arc [25–29] has been used as a plasma source. This is a modification of our plasma source presented in [30–32]. A pulsed discharge was driven in a quartz discharge tube of 5 mm inner diameter and effective plasma length of 7.5 cm. The tube has end-on quartz windows. On the opposite side of the electrodes the glass tube was expanded in order to reduce erosion of the glass wall and also deposition of the electrode material onto the quartz windows. The working gas was N_2 at 66 Pa filling pressure with a constant flux of 9 ml/min. The chosen flux and pressure provide negligible self-absorption of the investigated spectral lines. Spectroscopic observations of

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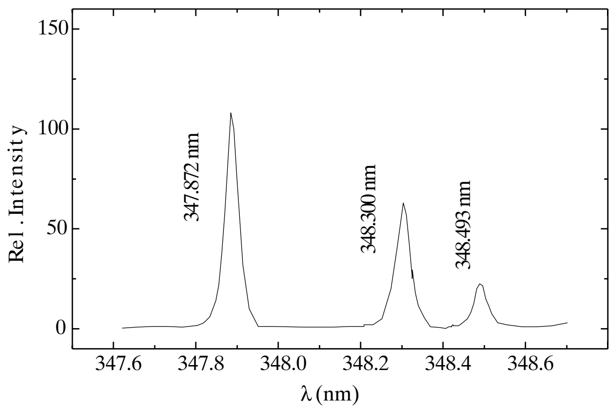

Fig. 1. Recorded spectrum at 2.5 μs after the beginning of the discharge with three N IV spectral lines in multiplet No. 1.

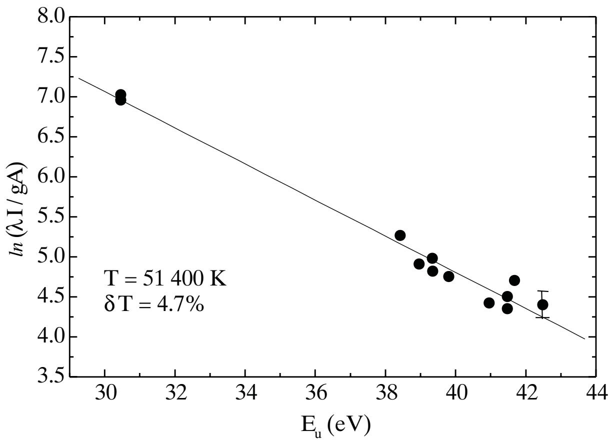

Fig. 2. Boltzmann plot on the basis of relative intensities of 12 N III spectral lines in the 2.5 μs after the beginning of the discharge.

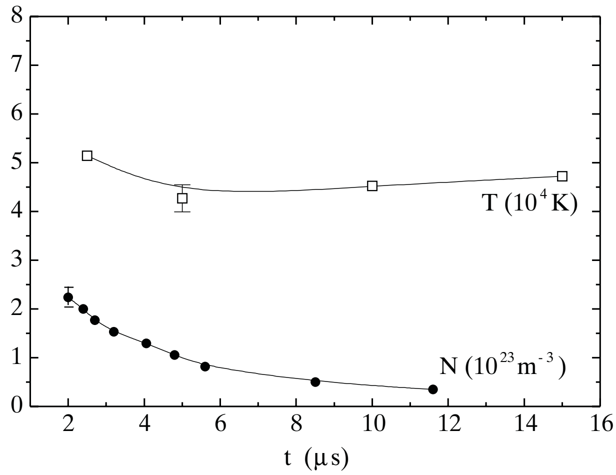

Fig. 3. Electron temperature (T, open squares) and density (N, closed circles) decay in the N_2 discharge.

isolated spectral lines were made by viewing along the axis of the discharge tube. A capacitor of 0.3 μF was charged up to 15.2 kV. The line profiles were recorded using a step-by-step technique with a photomultiplier (EMI 9789 QB) and a grating spectrograph (Zeiss PGS-2, reciprocal linear dispersion 0.73 nm/mm in the first order) system. The system was calibrated by using the EOA-101 standard lamp located at a distance of 40 cm from the spectrograph's entrance slit.

The instrumental line width of 0.008 nm was determined by narrow spectral lines emitted from the hollow cathode discharge. The spectrograph exit slit (10 μm) with the calibrated photomultiplier was micrometrically traversed along the spectral plane in small wavelength steps (0.0073 nm). The photomultiplier signal was digitized and averaged (five shots at each position) using an oscilloscope, interfaced to a computer. All spectral line profiles have been recorded with the same instrumental arrangement. A sample spectrum is shown in Figure 1.

The plasma reproducibility was monitored recording the radiation from N III, N IV and N V lines and also by the discharge current using the Rogowski coil signal (it was found that this signal is reproducible within $\pm 4\%$). From the Rogowski coil signal characteristics [33] we have found: discharge period (2.8 μs), decrement (1.59), thermal resistance (0.43 Ω), selfinductance (0.65 μH), discharge current maximum (8.5 kA) and current rise time rate (2.4×10^{10} A/s).

One can notice, (see Fig. 1) that the investigated spectral lines are well isolated while the continuum is very close to zero within the wavelengths range of interest. These facts are important for an accurate determination of the total line intensities and correspondingly, for a reliable determination of A values.

The plasma parameters were determined using standard diagnostic methods [1,4,34]. Assuming the existence of LTE (local thermodynamic equilibrium), according to the criteria from [3,35,36], the electron temperature (T) was determined from a Boltzmann plot of twelve N III lines (see Tab. 1) with an estimated error of $\pm 5\%$. Corresponding upper level energies (E_{u}) of the lines applied in the Boltzmann plot cover an interval of 12 eV.

The necessary atomic data were taken from [10]. A Boltzmann plot is presented in Figure 2. The electron temperature decay is presented in Figure 3. The electron density (N) decay was measured using a well-known single-laser interferometry [37] technique for the 632.8 nm He–Ne laser wavelength with an estimated error of $\pm 6\%$. The electron density decay is presented also in Figure 3.

Taking into account temporal dependences of T and N and the criteria for the existence of the LTE [3,35,36], we can conclude that the relevant N III energy level populations are in the state of LTE up to 15 μs, the N IV levels up to 6 μs and the N V levels up to 3 μs after the beginning of the discharge.

The measured profiles are of the Voigt type due to the convolution of the Lorentzian Stark and the Gaussian profiles caused by Doppler and instrumental broadening. For the present experimental electron density and temperature the Lorentzian fraction is dominant. Van der Waals

Table 1. Transition probability (A in 10^8 s^{-1}) values: $A_{\rm exp}$, our experimental values (with estimated accuracy); $A_{\rm N}$, NIST [10]; $A_{\rm K}$, Kurucz [11]; $A_{\rm B}$, Bell *et al.* [6]; $A_{\rm KB}$, Kastner and Bhatia [5]; $A_{\rm H}$, Hibbert [40]; $A_{\rm A}$, Allard *et al.* [12]; $A_{\rm EB}$, Ervens and Berg [23] and $A_{\rm L}$, Lang *et al.* [17]. $A_{\rm rel}$ (dimensionless) denote our experimental relative A values related to the 336.736 nm N III and 347.872 nm N IV spectral lines A values. $A_{\rm EB}^{\rm rel}$ (dimensionless) denote relative transition probabilities normalized to the N III 336.736 nm transition in [23]. Atomic data such as upper level energy ($E_{\rm u}$), wavelength (λ) and transitions are taken from [10].

Transition	λ (nm)	$E_{\rm u}$ (eV)	$A_{\rm rel}$	$A_{\rm exp}$	$A_{\rm N}$	$A_{\rm K}$	$A_{\rm B}$	$A_{\rm KB}$	$A_{\rm EB}$	$A_{\rm EB}^{\rm rel}$
N III										
$3s\ ^2{\rm S}_{1/2}$–$3p\ ^2{\rm P}^0_{3/2}$	409.736	30.461	0.705 ±18%	0.895 ± 28%	0.870 ± 10%	0.956	0.877	0.846	1.34± < 50%	0.95
$3s\ ^2{\rm S}_{1/2}$–$3p^2{\rm P}^0_{1/2}$	410.339	30.456	0.697 ±18%	0.885 ± 28%	0.867 ± 10%	0.956	0.873	0.842	1.15± < 50%	0.82
$3s\ ^4{\rm P}^0_{5/2}$–$3p\ ^4{\rm D}_{7/2}$	451.485	38.414	0.590 ±9%	0.750 ± 19%	0.680 ± 10%	0.694			0.81± < 50%	0.57
$3s\ ^4{\rm P}^0_{5/2}$–$3p\ ^4{\rm S}_{3/2}$	377.103	38.955	0.445 ±9%	0.565 ± 19%	0.559 ± 10%	0.593			0.71± < 50%	0.50
$3s\ ^4{\rm P}^0_{3/2}$–$3p\ ^4{\rm P}_{1/2}$	336.580	39.337	1.165 ±6%	1.48 ± 16%	1.52 ± 10%	1.441				
$3s\ ^4{\rm P}^0_{5/2}$–$3p\ ^4{\rm P}_{5/2}$	336.736	39.349	1.000 ±3%	1.27 ± 13%	1.27 ± 10%	1.205			1.41± < 50%	1.00
$3s\ ^2{\rm P}^0_{3/2}$–$3p\ ^2{\rm D}_{5/2}$	420.007	39.805	0.913 ±8%	1.16 ± 18%	1.12 ± 10%	1.007			1.10± < 50%	0.78
$3p\ ^4{\rm D}_{5/2}$–$3d\ ^4{\rm F}^0_{7/2}$	486.127	40.952	0.394 ±10%	0.500 ± 20%	0.532 ± 10%	0.546				
$3p\ ^2{\rm P}^0_{1/2}$–$3d\ ^2{\rm D}^0_{3/2}$	393.450	41.475	0.551 ±11%	0.700 ± 21%	0.749 ± 10%	0.796				
$3p\ ^2{\rm P}_{3/2}$–$3d\ ^2{\rm D}^0_{5/2}$	393.851	41.479	0.650 ±11%	0.825 ± 21%	0.896 ± 10%	0.964				
$3p\ ^4{\rm S}_{3/2}$–$3d\ ^4{\rm P}^0_{5/2}$	454.633	41.682	0.638 ±12%	0.810 ± 22%	0.542 ± 10%	0.934				
$3p\ ^2{\rm P}_{3/2}$–$3d\ ^2{\rm P}^0_{3/2}$	298.364	42.486	0.842 ±12%	1.07 ± 22%	0.824 ± 10%	1.162				
$4d\ ^2{\rm D}_{5/2}$–$5f\ ^2{\rm F}^0_{7/2}$	400.358	42.493	1.024 ±13%	1.30 ± 23%	1.88 ± 25%	2.123				
N IV										
							$A_{\rm H}$	$A_{\rm A}$	$A_{\rm L}$	
$3s\ ^3{\rm S}_1$–$3p\ ^3{\rm P}^0_0$	348.493	50.331	1.000 ±3%	1.06 ± 13%	1.06 ± 10%	1.090	1.07	1.054	0.23 ± 38%	
$3s\ ^3{\rm S}_1$–$3p\ ^3{\rm P}^0_1$	348.300	50.333	1.000 ±3%	1.06 ± 13%	1.06 ± 10%	1.074	1.07	1.061	0.23 ± 38%	
$3s\ ^3{\rm S}_1$–$3p\ ^3{\rm P}^0_2$	347.872	50.338	1.000 ±3%	1.06 ± 13%	1.06 ± 10%	1.072	1.07	1.065	0.23 ± 38%	
$3p\ ^1{\rm P}^0_1$–$3d\ ^1{\rm D}_2$	405.776	53.206	0.774 ±11%	0.820 ± 21%	0.662 ± 10%	0.663		0.666	0.85 ± 24%	
$3s\ ^3{\rm P}^0_2$–$3p\ ^3{\rm P}_2$	346.336	61.295	1.009 ±20%	1.07 ± 30%	1.02 ± 10%	1.052		1.034		
$3s\ ^1{\rm P}^0_1$–$3p\ ^1{\rm D}_2$	374.754	61.952	0.972 ±20%	1.03 ± 30%	0.992 ± 10%	0.921		0.912		
N V										
$3s\ ^2{\rm S}_{1/2}$–$3p\ ^2{\rm P}^0_{1/2}$	461.997	59.232		0.410 ± 6%	0.410 ± 3%	0.4079				
$3s\ ^2{\rm S}_{1/2}$–$3p\ ^2{\rm P}^0_{3/2}$	460.374	59.242		0.414 ± 6%	0.414 ± 3%	0.4098				

[2] and resonance [2] broadening were estimated to be smaller by more than one order of magnitude in comparison to Stark, Doppler and instrumental broadening. The standard deconvolution procedure [38] was computerized using a least-squares algorithm. The total line intensity (I) corresponds to the area under the line profile. Great care was taken to minimize the influence of self-absorption. The opacity was checked by measuring relative line intensity ratios within low-lying multiplets in the N III, N IV and N V spectra during the plasma decay. The obtained values were compared to calculated ratios of the products of the spontaneous emission probabilities (A) and the corresponding statistical weights (g) of the upper levels of the lines. The necessary atomic data were taken from [10]. It turns out that the experimental relative line intensity ratios are constant during the whole plasma decay period (within ±12%) proving the absence of the self-absorption for the applied discharge conditions (see Fig. 4). On the other hand, the Stark width values of the investigated spectral lines agree (within ±25% in average) with existing theoretical width values [39] indicating the absence of the self-absorption.

3 Transition probability measurements

Transition probabilities of spontaneous emission of some transitions in N III, N IV and N V spectra have been obtained using the RLIR technique. The total line intensities (I) have been measured with high accuracy (3–5%) using the step-by-step technique (described above) for the recorded line profiles. In the case when the plasma remains at LTE the well-known formula [1,3]

$$(I_1/I_2)_{\rm EXP} = (A_1 g_1 \lambda_2 / A_2 g_2 \lambda_1)\exp(\Delta E_{21}/kT) \qquad (1)$$

can be used for a comparison between measured relative line intensity ratios and corresponding calculated values assuming validity of the Boltzmann distribution for the population of the excited levels in the emitters. In equation (1) I, λ, A, ΔE_{21} and g denote measured relative line intensity, wavelength of the transition, transition probability of the spontaneous emission, difference between excitation energies from the ground energy level of two related transitions and corresponding statistical weight, respectively. T is the electron temperature of the plasma in LTE

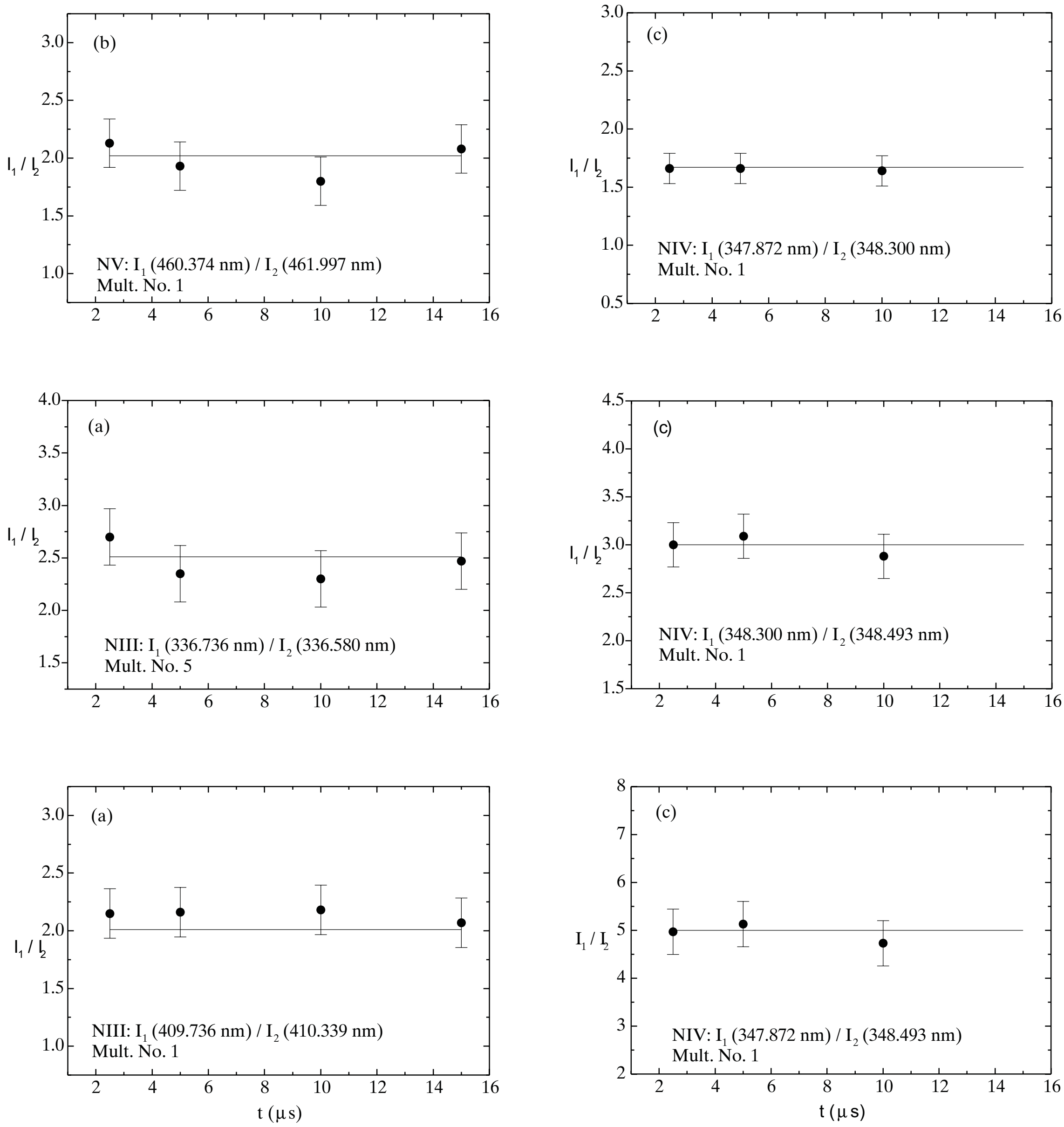

Fig. 4. Relative line intensity ratios (I_1/I_2) during the plasma decay in N III (a), N IV (c) and N V (b) spectra. Our experimental values (full circles, 8−12% accuracy) and ratios obtained using tabulated [10] transition probabilities (NIST, horizontal lines).

and k is the Boltzmann constant. In the case when compared spectral lines belong to the same multiplet, equation (1) can be rewritten in the form

$$(I_1/I_2)_{\mathrm{EXP}} = A_1 g_1/A_2 g_2 \qquad (2)$$

because of the very small difference between excitation energies and wavelengths related to the compared lines. Equation (2) gives the possibility to check the existing A values associated with the transitions within a multiplet.

We monitored ratios $(I_1/I_2)_{\mathrm{EXP}}$ for spectral lines that belong to the same multiplet up to the moment when the line intensity maximum has dropped down to 20% of its maximal value. We found that the experimental ratios are constant within 8% during the plasma decay. This confirms the absence of self-absorption and offers the possibility to compare experimental and calculated transition probability values using equation (2). Using equation (2) we found satisfying agreement between measured and calculated relative line intensity ratios. Among the lines that we have investigated the above mentioned behaviors are found for the 409.736 nm and 410.339 nm lines in the $3s^2\mathrm{S}{-}3p^2\mathrm{P}^0$ and 336.736 nm and 336.580 lines in the $3s^4\mathrm{P}^0{-}3p^4\mathrm{P}$ N III transitions. In the N IV spectrum a similar behavior is shown by the 348.493 nm, 348.300 nm and 347.872 nm lines in the $3s^3\mathrm{S}{-}3p^3\mathrm{P}^0$ transitions and in the case of the N V spectrum by the 461.997 nm and 460.374 lines in the $3s^2\mathrm{S}{-}3p^2\mathrm{P}^0$ transition (see Fig. 4).

Thus, the A values of these lines [10] can be accepted as reliable atomic data. Taking into account these facts we have used the A values of the 336.736 nm N III and

347.872 nm N IV lines, presented by NIST [10], as reference values. There are two practical reasons for this choice. First, the transition probability values of these lines have not been changed for many years in the NIST (NBS) [10] tables and are quoted with a high accuracy. Second, due to high intensity, measurements related to these lines are most reliable.

4 Results

Using equation (1) we have obtained transition probability values for some transitions in N III, N IV and N V spectra relative to the selected reference A values. Wavelength value and E_{21} were taken from [10]. Our results are presented in Table 1. A_{exp} represents averaged values obtained during plasma decay in time interval for which the criteria of the existence of the LTE is fulfilled. Corresponding line intensities are measured with 3−5% accuracy. It should be pointed out that in the case of the N V $3s-3p$ transition we have confirmed the literature value of the ratio of the A values [10] within an experimental accuracy of ±6%. In same table are given also the A values of the investigated transitions presented in various theoretical and experimental data sources. The accuracy described to our experimental data contains contributions of the line intensity and electron temperature determination, uncertainties due to the optical calibration procedure and uncertainties of the selected reference A values. Our A_{rel} values provide the possibility for future comparison with absolute as well as with data presented in relative form.

5 Discussion and conclusion

By inspection of Table 1 one can notice a quite good agreement between our experimental data and existing theoretical values [5,6,10–12,40] in the case of the $3s\mathrm{S}-3p\mathrm{P}$ transitions in N III (doublet), N IV (triplet) and N V (doublet) spectra. Other investigated N III and N IV transitions are also in good agreement (within ±10% in general) with existing A values. It is worth noting that for the 454.633 nm transition in N III our result is not coherent with the value presented by NIST [10], but still is in reasonably good agreement (within ±15%) with data published by Kurucz [11]. The worst agreement in N III spectrum is in the case of the 400.358 nm transition. Our value is 31% below the one published by NIST [10] which is estimated to be of 25% accuracy. Our N III A_{rel} values agree well (within 16% in average) with experimental A_{EB} values normalized to the A value related to the reference 336.736 nm N III transition (see columns A_{rel} and $A_{\mathrm{EB}}^{\mathrm{rel}}$ in Tab. 1).

In the N IV spectrum we have agreement, with respect to theoretically obtained data, within a few percent for all transitions except for the 405.776 nm transition where the discrepancy is about 25% compared to [10–12]. But, in this case our A_{exp} agrees very well (within 4%) with experimental A_{L} value presented in [17].

Relying upon the present experimental data one can conclude that transition probability values belonging to the $3s-3p$ and $3p-3d$ transitions in N III, N IV and N V spectra are in agreement with recently calculated A values. Only one line (400.358 nm), belonging to the $4d-5f$ transition, in N III shows a significant discrepancy with respect to [10,11]. It should be pointed out that data published in [10,11], for the same transition, also show a mutual discrepancy of ∼12%.

Generally, we have found good agreement between existing calculated and our experimental A values obtained, for the first time, with RLIR technique in the case of some transitions in N III, N IV and N V spectra.

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