# Experimental lifetimes of some levels belonging to the $3p^5nd$ ($n=4,5,6,7$) configurations of Ar I

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Lifetimes of twenty-three nonresonant levels belonging to the $3p^5nd$ ($n=4,5,6,7$) configurations of Ar I have been measured. The single-photon delayed-coincidence method has been used to obtain the lifetime values given in the present work. As far as we know, no previous experimental results exist for sixteen of these levels. The experimental error was in the range from 1 to 10%. Our results have been compared with other experimental values and with our calculations performed in $jK$ coupling and Coulomb approximation and with the intermediate-coupling results given in the literature.

## INTRODUCTION

The shortage of experimental information about the lifetimes of $nd$ ($n=4,5,6,7$) levels of Ar I led us to carry out an experimental study on the lifetimes of these levels. Lifetimes of twenty-three nonresonant levels belonging to the configurations mentioned above have been measured. The wavelengths of the radiative transitions used for this experiment ranged from 4767 to 7372 Å.

Regarding the theoretical values for the lifetimes of the $nd$ levels, there are also a few published data. For instance, for the lifetimes of $6d$ and $7d$ levels, no previous theoretical calculations have been found in the literature. We have compared the experimental results with our calculations performed in $jK$ coupling and Coulomb approximation. In the cases when it was possible, comparison was also made with the theoretical values of Gruzdev and Loginov.[1] These calculations were performed in intermediate coupling (IC) and using Hartree-Fock (HF) functions to determine the radial part of the transition probabilities.

## EXPERIMENTAL METHOD

Lifetimes have been measured by the single-photon delayed-coincidence method described in detail by different authors.[2,3] The monochromator used to select the desired wavelength was a 0.25-m Jarrell-Ash with a resolution of about 5 Å. The levels were excited by means of an electron pulsed beam of suitable energy and 0.7-mA peak current. The repetition rate was 10 and 50 kHz depending on the selected time range of the time-to-amplitude converter. The electron pulse duration was 200 ns. The measurements were performed at gas pressures from 1 to 30 mtorr, and a continous gas flow was maintained during each measurement. For all the measured levels, no change in the lifetime values with pressure was observed. The energy of the electron beam used for the excitation ranged from a value close to the threshold level up to 40 eV above it. When there was an Ar II line in the neighborhood of the line of interest, the energy was kept below the ionization limit (16 eV). Photons were detected with an EMI 9816 B (S-20 response) photomultiplier cooled with dry ice. The decay curves were always observed in two time ranges, 900 and 3500 ns, and agreement was found between the results from both ranges, within the experimental error.

The measurements conditions, together with the fact that the levels under study are highly excited, allowed us to obtain decay curves which in our range of electron energy and pressure can be fitted to a single exponential function. Exceptions were the $5d(\frac{1}{2})_0$ and $5d'(\frac{3}{2})_2$ levels, where two exponential terms were needed. These results contrast to those of previous decay measurements of levels belonging to the $3p^54p$ configuration of Ar I where a greater amount of cascade population was observed.[3]

## RESULTS AND DISCUSSION

Lifetimes have been grouped in three tables according to the configurations to which they belong.

TABLE I. Lifetimes of some levels belonging to the $3p^5 4d$ configuration of Ar I.

| Level *jK* Notations | Level Paschen Notations | λ(Å) | Experimental lifetimes (ns) This work | Theoretical lifetimes (ns) Present work (*jK*) | Ref. 1 $\tau_{rv}$ [a] | Ref. 1 $\tau_{MC}$ [b] |
|---|---|---|---|---|---|---|
| $4d(\frac{1}{2})_0$ | $4d_6$ | 6938 | 120±10 | 124 | 474 | 368 |
| $4d(\frac{7}{2})_4$ | $4d'_4$ | 7372 | 226±20 | 230 | 436 | 460 |
| $4d(\frac{7}{2})_3$ | $4d_4$ | 7353 | 285±15 | 297 | 404 | 408 |
| $4d(\frac{3}{2})_2$ | $4d_3$ | 6753 | 147±7 | 384 | 424 | 372 |
| $4d'(\frac{5}{2})_3$ | $4s_1'''$ | 6605 | 310±10 | 317 | 374 | 367 |
| $4d'(\frac{3}{2})_2$ | $4s_1''$ | 6538<br>6059 | 223±13 | 259 | 393 | 392 |

[a] $\tau_{rv}$ have been calculated from the geometrical mean of the line strengths in the length and velocity approximation in single configuration approximation.
[b] $\tau_{MC}$ have been calculated from the multiple configuration approximation.

Both Paschen and *jK*-coupling notations have been used for all the levels shown.

In Table I, lifetimes of six $4d$ levels are shown. Our experimental results seem to be the first ones in the literature. So, comparisons are possible only with the IC calculations of Ref. 1 and with our calculations in *jK* coupling and Coulomb approximation using the energy level given by C. Moore.[4] Considering *jK* calculations, there is agreement for most of the levels. The differences between our experimental results and the *jK* calculations are less than 4% for four levels, and 14% for the $4d'(\frac{3}{2})_2$ level, for the $4d(\frac{3}{2})_2$ level there exists a remarkable discrepancy, which is also seen for the $5d(\frac{3}{2})_2$ level, as can be seen in Table II. The computed values of Ref. 1 are higher than the present experimental values.

We point out that the $4d'(\frac{3}{2})_2$ level lifetime has

TABLE II. Lifetimes of levels belonging to the $3p^5 5d$ configuration of Ar I.

| Level *jK* Notations | Level Pashen Notations | λ(Å) | Experimental lifetimes (ns) This work | Ref. 7 | Ref. 8 | Theoretical lifetimes (ns) Present work (*jK*) | Ref. 1 $\tau_{rv}$ [a] | Ref. 1 $\tau_{MC}$ [b] |
|---|---|---|---|---|---|---|---|---|
| $5d(\frac{1}{2})_0$ | $5d_6$ | 5651 | 116±8 | 110±7 | 140±14 | 127 | 1696 | 352 |
| $5d(\frac{7}{2})_4$ | $5d'_4$ | 6032 | 255±10 | 242±15 | | 218 | 1443 | 1487 |
| $5d(\frac{7}{2})_3$ | $5d_4$ | 5987 | 320±13 | | | 337 | 1284 | 1240 |
| $5d(\frac{3}{2})_2$ | $5d_3$ | 6756<br>6248<br>5559 | 205±15 | | 70±7 | 437 | 1371 | 631 |
| $5d(\frac{5}{2})_2$ | $5d_1''$ | 5999 | 330±30 | | | 582 | 1120 | 954 |
| $5d(\frac{5}{2})_3$ | $5d'_1$ | 6212 | 475±5 | | | 592 | 1050 | 848 |
| $5d'(\frac{5}{2})_2$ | $5s_1''''$ | 5739 | 227±9 | | | 235 | 1166 | 514 |
| $5d(\frac{5}{2})_3$ | $5s_1'''$ | 5572 | 247±7 | | | 275 | 1181 | 1088 |
| $5d(\frac{3}{2})_2$ | $5s_1''$ | 6216<br>5188 | 134±4 | 135±5 | | 146 | 1276 | 1221 |

[a] $\tau_{rv}$ have been calculated from the geometrical mean of the line strengths in the length and velocity approximation.
[b] $\tau_{MC}$ have been calculated from the multiple configuration approximation.

TABLE III. Lifetimes of levels belonging to the $3p^5 6d$ and $3p^5 7d$ configurations of Ar I.

| Level *jK* Notations | Pashen | λ(Å) | Experimental values (ns) This work | Ref. 7 | Theoretical values (ns) This work (*jK*) |
|---|---|---|---|---|---|
| $6d(\frac{1}{2})_0$ | $6d_6$ | 5151 | $167\pm7$ | $169\pm10$ | 162 |
| $6d(\frac{7}{2})_4$ | $6d'_4$ | 5496 | $297\pm5$ | $300\pm10$ | 267 |
| $6d(\frac{7}{2})_3$ | $6d_4$ | 5506 | $500\pm20$ | | 572 |
| $6d(\frac{5}{2})_3$ | $6d'_1$ | 5682 | $295\pm30$ | | 803 |
| $6d'(\frac{5}{2})_2$ | $6s_1''''$ | 5560<br>5128 | $295\pm12$ | | 299 |
| $6d'(\frac{3}{2})_2$ | $6s_1''$ | 4769 | $210\pm10$ | | 224 |
| $7d(\frac{7}{2})_4$ | $7d'_4$ | 5221 | $363\pm17$ | $340\pm30$ | 353 |
| $7d'(\frac{5}{2})_2$ | $7s_1''''$ | 5373 | $438\pm27$ | | 590 |

been measured by means of the $4p(\frac{1}{2})_1-4d'(\frac{3}{2})_2$ transition; the wavelength for this transition, deduced from the level energies given by C. Moore[4] and S. Bashkin and J. O. Stoner,[5] is $\lambda_{vac}=6061.05$ Å, corresponding to $\lambda_{air}=6059.37$ Å. This value is in disagreement with that given in Ref. 6 for the same transition. In order to be sure of the correct assignment of the transition, the lifetime of the level was measured by means of another transition (6538 Å) with the same upper level. The agreement between the lifetime values found with both transitions confirms the correct assignment deduced from Refs. 4 and 5.

Table II shows the lifetimes of nine levels belonging to the $3p^5 5d$ configuration measured by means of twelve transitions. Some of our results are compared with the experimental one given by B. Zurro *et al.*[7] and Yu. Malakhov and V. Potyomkin.[8] The agreement with the values of Ref. 7 is good, and for $5d(\frac{1}{2})_0$ level the difference with the value of Ref. (8) is not remarkable. The $5d(\frac{3}{2})_2$ level has been measured by means of three transitions where wavelengths were 6248, 6756, and 5559 Å. Using the first two transitions, the lifetime values obtained agree within the experimental error. For the third line, of wavelength 5559 Å, blending with the line of 5560 Å from the $6d'(\frac{5}{2})_2$ level occurs. Nevertheless, the lifetime values of both levels can be obtained by fitting the 5559–5560-Å decay curve with two exponentials. The lifetime of the $6d'(\frac{5}{2})_2$ level was known by means of the 5128-Å transition. The results agree with the independent measurements. Comparing our experimental results with *jK*-coupling calculations, differences lower than 10% are found except for the $5d(\frac{5}{2})_{2,3}$ and $5d(\frac{3}{2})_2$ levels. There is a great disagreement between the present measurements and the calculated values of Ref. 1. In our opinion more IC calculations are needed to determine the source of the discrepancy with the experimental values.

Table III shows the results for six $6d$ levels and two $7d$ levels. For three of these levels the experimental values from Ref. 7 are in good agreement with ours. As is shown in this table, there is good agreement with respect to *jK*-coupling calculations, except for the $6d(\frac{5}{2})_3$ and $7d(\frac{5}{2})_2$ levels.

We can conclude from the values of Tables I, II, and III that, in most cases, the present experimental values and the calculations in pure *jK* coupling are in agreement. Nevertheless, more calculations performed in intermediate coupling, taking into account configuration mixing, are needed for a good understanding of the *nd* configurations of Ar I.

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