Molybdenum atoms yield in pulse ultraviolet laser photolysis of Mo(CO)\textsubscript{6}

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Abstract. Atomic resonance absorption spectroscopy has been used to study the yield of molybdenum atoms in the process of ultraviolet laser pulse photo-dissociation of Mo(CO)\textsubscript{6} vapor. Molybdenum atoms in a ground state were formed by the quenching of the electronically excited Mo atoms generated during photolysis and were detected using the resonance absorption at a wavelength of 386.41 nm. The effective quenching rates were measured in the presence of various bath gases.

1. Introduction

The substantial progress in laser technique leads to extensive development of the investigations of photo-dissociation of metal carbonyls in gas phase under ultraviolet (UV) radiation. One point of interest is the generation of atomic vapor and following nanoparticle growth [1,2]. Here we focus on the molybdenum atoms producing by laser pulse photo-dissociation of vapor of molybdenum hexacarbonyl (Mo(CO)\textsubscript{6}). From the first studies of photolysis of Mo(CO)\textsubscript{6} it was revealed that this process is accompanied by the unsaturated species formation. Time-resolved infrared-absorption spectroscopy has been used to characterize the CO and Mo(CO)\textsubscript{1−5} photo-fragments formed in the single-photon gas-phase photolysis of Mo(CO)\textsubscript{6} at low laser fluencies (typically 1−5 mJ/cm\textsuperscript{2}) [3−5]. By the following time evolution the unsaturated metal carbonyl fragments Mo(CO)\textsubscript{1−5} are formed and degree of unsaturation increases with increasing photolysis photon energy. These observations are in contrast to the results where single-photon photolysis leads to the loss of a single CO ligand [6]. However, at higher laser fluences the multi-photon mechanism of Mo(CO)\textsubscript{6} photo-dissociation could be the case [7−10].

In theory, a multiphoton absorption is not a threshold process with respect to the incident radiation flux. However, a threshold condition is imposed by the comparison of the total probability of the production of atoms and the sensitivity of the experimental equipment. The probability of the multiphoton process is sufficiently high if the incident flux provides the absorption of the second photon over the lifetime of the transient state resulting from the absorption of the first photon. At a radiation wavelength of 266 nm, lifetime of the transient state \( \delta t = h/\delta E \) is about \( 10^{-16} \) s. For a laser pulse duration of about \( 10^{-8} \) s, the number of photons per pulse must be about \( 10^8 \) at an area of about the absorption cross section of the Mo(CO)\textsubscript{6} molecule, which is about \( 2 \times 10^{-17} \) cm\textsuperscript{2} [10] at the wavelength of 266 nm. With a photon energy of \( 7.48 \times 10^{-19} \) J at a wavelength of 266 nm, the necessary energy density in the laser pulse for the multiphoton absorption with a probability of about unity is \( 3 \times 10^6 \) J/cm\textsuperscript{2},
which is impossible for nanosecond lasers. However, at laser fluencies of nanosecond lasers above 5 mJ/cm$^2$, multiphoton photo-dissociation of Mo(CO)$_6$ could be observed because of the sequential mechanism of elimination of CO ligands in which the second and subsequent photons are absorbed by the Mo(CO)$_{1-5}$ photoproducts of the single photon dissociation [7, 8, 10].

In work by Tyndall and Jackson [7] the photo dissociation of Mo(CO)$_6$ has been examined at 248 nm by quadrupole mass spectrometer and emission spectroscopy. The authors pointed out that a single-photon dissociation of Mo(CO)$_6$ produces a distribution of Mo(CO)$_{3-5}$ photoproducts. At 248 nm, the absorption cross section of Mo(CO)$_5$ and Mo(CO)$_4$ were estimated as $1.4 \times 10^{-16}$ and $5 \times 10^{-17}$ cm$^2$ respectively. Authors [7] found that these large cross sections lead to substantial secondary photo-dissociation produces Mo(CO)$_{1-3}$ and Mo atoms, with the dominant two-photon absorption product being Mo(CO)$_3$. From the proposed energy diagram of photo-dissociation of Mo(CO)$_6$ authors concluded that the $\alpha^7S_3$ ground state of atomic Mo is formed predominately via a two-photon sequential process and the different exited states of atomic Mo observed in their study are formed via an overall three-photon mechanism. The population distribution of the atoms over the excited states in the energy range from 25000 to 35000 cm$^{-1}$ was found to be Boltzmann with a characteristic temperature of 11000±2500 K. Additionally, it was observed that the yield of photoproducts increased with laser fluence rise.

In the study of Nakai and co-authors [10] neutral molybdenum atoms and dimers were produced by UV multiphoton dissociation of Mo(CO)$_6$ at high laser fluencies up to 104 mJ/cm$^2$ by using 355 nm irradiation from pulse Nd:Yag laser. The emission from Mo atoms and dimers was measured by a time resolved UV-visible emission spectroscopy. The atomic emission was found to consist of two components, an early component with a time profile similar to the photolysis pulse, and a late component with a peak at around 300 ns after the photolysis. Authors suggested that the late emission was caused by Mo produced in a neutralization process of ionic species. A plausible mechanism involving electron-ion recombination was proposed for the late emission.

Thus, the published results show that molybdenum atoms can be produced due to the photo-dissociation of Mo(CO)$_6$ at relatively low energy densities of the unfocused UV laser beam. An increase in the atomic yield with an increase in the energy density of the laser pulses is an important result of the previous works. The goal of this study is the measurements of Mo atoms concentration in the ground state formed in the photo-dissociation of Mo(CO)$_6$ at wavelength of 266 nm and the determination of the quenching rates of excited states of Mo atoms in different bath gases.

2. Experimental

The experiments have been carried out at room temperature in a quartz cell with sizes of 18×5×6 mm that is preliminary evacuated to a pressure of $10^{-3}$ mbar. The evacuation and filling of the quartz reaction cell was realized by a flange connection on the bottom of the cell. The saturated vapor of Mo(CO)$_6$ was injected in the quartz cell from initially evacuated glass tube with Mo(CO)$_6$ powder. The pressure of Mo(CO)$_6$ saturated vapor was determined by the room temperature measurements. The high purity bath gases He, Ar, N$_2$, CO, CO$_2$, CH$_4$ were added manometrically. Thus the mixture of around 150 µbar of Mo(CO)$_6$ + 1 bar of bath gases was prepared in the cell. Figure 1 demonstrates the scheme of the experimental setup. For the photo-dissociation of Mo(CO)$_6$ a fourth harmonic of Nd:YAG laser SOLAR LQ-129 with a wavelength of 266 nm and a pulse duration of 12 ns has been applied. The laser energy passed through the empty cell was measured using an Ophir PE25S calibrated energy meter. The laser pulse energy density in the experiments was in the range from 20 to 170 mJ/cm$^2$.

The measurement of Mo atoms concentration by the method atomic resonance absorption spectroscopy (ARAS) in photolysis of Mo(CO)$_6$ was the same as it was applied for the study of
Fe atoms in [11]. The atomic absorption is described using the Lambert-Beer law (1):

\[ J = J_0 e^{-k_\nu l}, \]  

where \( J \), \( J_0 \) are the passed and incident light intensity, \( l \) is the optical path length, \( k_\nu \) is the absorption coefficient, which depends on the concentration of absorbing atoms, properties of the atom and its spectral line, and the physical conditions for the absorption of radiation with frequency \( \nu \). Atomic absorption corresponds to the atomic transitions from lower to higher energy states, so that absorption depends on the populations of the lower energy levels. Maximum absorption at temperature \( T \) which is significantly lower than \( E/k_B \) (\( E \) is the energy of the excited level and \( k_B \) is the Boltzmann constant) is observed for the lines that correspond to transitions from the lower unexcited level (resonance lines). The dependence of the absorption coefficient for the resonance lines on the concentration of absorbing atoms is given by the equation (2) [12]:

\[ k_\nu = 2e^2 f N_0/mc\Delta\nu, \]

where \( N_0 \) is the concentration of atoms at the ground level, absorbing radiation at frequency \( \nu \), \( f \) is the oscillator strength (probability of electronic transition from the ground level to the excited level), \( \Delta\nu \) is the width of the spectral line related to the broadening of energy levels, \( c \) is the speed of light, \( m \) is the electron mass, and \( e \) is the electron charge. For successful measurement of the atomic absorption the following conditions must be satisfied [13]:

- the wavelength of the absorption line corresponding to the maximum absorption of atomic vapor under study must coincide with the wavelength of the selective radiation source;
- the half width of the absorption line of atomic vapor must be significantly greater than the half width of excitation radiation of the selective source.

Atomic absorption is almost impossible when the first condition is not satisfied. The sensitivity of the measurements is substantially decreased when the second condition is not satisfied. In this case, only a small fraction of the broadband of incident radiation intensity is absorbed and the absorbed energy is in any case significantly less than the total energy of the radiation source. When a broad absorption line interacts with a narrow emission line of the radiation source, the incident energy is absorbed over the entire bandwidth of the radiation.
Figure 2. Absorption of Mo atoms at the wavelength of 386.41 nm measured after the pulsed photo-dissociation of Mo(CO)$_6$ in nitrogen.

source and the maximum absorption is reached. In addition, the spectral slit width of the monochromator must be relatively small to provide the measurement of a narrow emission line.

In the experiments, a commercial hollow cathode lamp served as the radiation source (figure 1) with the line spectrum of atomic molybdenum. The lamp was boosted with respect to current from 20 to 500 mA over a time interval of 1 ms to increase the measured signal. The synchronization was tuned in such a way that the measurements of atomic absorption were performed at a constant intensity of the boosted radiation source. The lamp radiation was collected by a lens with a focal length of 45 mm and transmitted through an aperture to the cell in which the Mo(CO)$_6$ photo-dissociation takes place. Then, the beam passed through the cell was focused by a lens on the entrance slit of an Acton SpectraPro 150 monochromator equipped with a diffraction grating (1200 grooves/mm) with the maximum reflectance at a wavelength of 300 nm. The monochromator was calibrated using a quartz mercury lamp. The resonance line of Mo with wavelength $\lambda = 386.41$ nm was chosen for the ARAS measurements. The widths of the entrance and exit slits of the monochromator (150 $\mu$m) provided acceptable signal to noise ratio at a spectral resolution of 1.1 nm. The absorption signal was measured in the presence of the lamp radiation background using a Hamamatsu H6780-04 photomultiplier module and a LeCroy WavePro7K digital oscilloscope with a band pass of 1 GHz. The time resolution of the system was measured to be less than 15 ns using a Stanford Research Systems DG 535 pulsed generator and a fast photodiode emitted at a wavelength of 845 nm with radiation spectral width of 50 nm and rise time of emission of 2 ns. figure 2 demonstrates a typical ARAS signal appeared due to Mo atoms absorption.

Reliable calibration is an important condition for the quantitative ARAS measurements of the atomic concentrations. A reference source of Mo atoms with the known concentration is unavailable at room temperatures. Therefore, the experimental concentrations of Mo atoms are calculated from the measured absorption using Eqs. (1) and (2) taking into account oscillator strength $f = 1.4 \times 10^{-1}$ for resonance line 386.41 nm [14]. In accordance with the Lambert-Beer
law, absorbance \( A \) is proportional to the number of absorbing particles \( N_0 \):

\[
A = \ln \frac{J_0}{J} = aN_0l.
\] (3)

Here, \( a \) is a constant coefficient for the given atoms, spectral line, and experimental conditions and \( l \) is the thickness of the absorbing layer. Note that the law is satisfied at moderate optical thicknesses and at a highly uniform distribution of atomic concentration along the absorption path. For the calculation of the absolute concentration of Mo atoms, the knowledge about real bandwidths of incident radiation and absorption in the investigated volume is necessary (see Eq. (2)). Natural broadening determined by the lifetime of the excited state of Mo atom at resonant transition \( \lambda = 386.41 \) nm is about \( 5 \times 10^{-6} \) nm. The observed spectral bandwidth is significantly wider. The Doppler width of the spectral line determined by the thermal motion of atoms in the cell in wavelength units is given by [15]:

\[
\Delta \lambda_D = 7.2 \times 10^{-7} \lambda \sqrt{\frac{T}{M_{Mo}}},
\] (4)

For the spectral line of Mo \( (M_{Mo} = 96) \) with a wavelength of 386.41 nm and temperature \( T = 300 \) K, the Doppler width \( (5 \times 10^{-4} \) nm) is larger than the natural width by almost two orders of magnitude. However, the broadening of resonance line in the reaction cell proceeds predominantly due to the Lorentz effect upon the collisions of molybdenum atoms with bath gas molecules at a relatively low temperature and atmospheric pressure. The line shape determined by the Lorentz effect is similar to the line shape under natural broadening. The half width is calculated as [15]:

\[
\Delta \lambda = \frac{\lambda^2}{c} V n \sigma = 2 \frac{\lambda^2}{c} N_a P \pi (d_{Mo} + d_g)^2 \sqrt{\frac{2}{\pi RT}} \left( \frac{1}{M_g} + \frac{1}{M_{Mo}} \right),
\] (5)

where \( \sigma \) is the effective cross section of the atom-molecule collisions leading to the broadening; \( n \) is the concentration of the diluting gas; \( V \) is the mean relative velocity of collisions; \( c \) is the speed of light; \( d_{Mo} \) and \( d_g \) are the collisional diameters of molybdenum atoms and bath gas molecules, which are determined using the Lennard-Jones potential [16, 17]; \( N_a \) is the Avogadro number; \( P \) is the gas pressure; \( M_{Mo} \) and \( M_g \) are atomic weights of the gas molecule and molybdenum atom, respectively; and \( R \) is the gas constant.

For Mo atoms spectral line at a wavelength of 386.41 nm, temperature \( T = 300 \) K, and argon pressure of 1 bar, the collisional broadening \( (6 \times 10^{-3} \) nm) is an order of magnitude larger than the Doppler broadening \( (5 \times 10^{-4} \) nm). In the radiation source (hollow cathode lamp) at an internal argon pressure of 10 mbar at a temperature of 800 K, the collisional broadening for the same spectral line of molibdenum \( (4 \times 10^{-5} \) nm) is significantly less than the Doppler broadening \( (8 \times 10^{-4} \) nm). Thus, the comparison of the Doppler broadening in the source \( (8 \times 10^{-4} \) nm) and the collisional broadening in the cell \( (6 \times 10^{-3} \) nm), with disregard of spectral shifts due to collisions, shows that the Walsh conditions are satisfied. Therefore, the experimental measured absorbance can be supposed to be proportional to Mo atom concentration.

3. Kinetics of Mo atoms yield

As was mentioned, the dominant products of the multiphoton dissociation of Mo(CO)\(_6\) are Mo atoms in electronically excited states [7,9,10]. Therefore, the most probable reactions leading to an increase in the atomic concentration in the ground state involve the quenching of the electronically excited states of Mo atoms. The most probable photo-dissociation process is the absorption of the first photon by the Mo(CO)\(_6\) molecule and the absorption of the second and
third photons by instantaneously formed products of the primary decomposition—Mo(CO)$_{1−5}$, which leads to detachment of the CO ligands [7]. The absorption of the second and third photons is possible because the absorption cross sections of the Mo(CO)$_{1−5}$ are comparable with the absorption cross section of parent Mo(CO)$_{6}$ molecule. According to energy diagram presented in [10] the energy of the third absorbed photon at a wavelength of 266 nm is always greater than the energy necessary for the photo-dissociation of Mo(CO)$_{6}$ up to Mo atom and six CO molecules. This energy excess leads to the population of various electronically excited states of Mo atoms. Einstein coefficients $A_{ki}$, which characterize the rate of spontaneous transitions for most electronically excited states of Mo atoms with energy less than 4.5 eV range from $1 \times 10^{7}$ to $2 \times 10^{8}$ 1/s [14]. On the other hand, the collision frequency of Mo atoms and bath gas molecules under the above conditions ($T = 300$ K and $P = 1$ bar) is $(1-5) \times 10^{10}$ 1/s. If the quenching probability due to the collisions with the bath gas molecules is $10^{-2}–10^{-3}$, the spontaneous emission from the electronically excited states of Mo atoms can be comparable with collision quenching. Assuming that the experimental increase in the absorbance of the Mo atoms in the ground state is described using reaction of collision quenching with the bath gases $M$, where $M$ = He, Ar, CO, N$_2$, CO$_2$, CH$_4$, one can analyze the kinetic characteristics of the relaxation of excited atoms Mo$^*$ and, in particular, determine the effective quenching rate using reaction:

$$Mo^* + M \rightarrow Mo + M.$$  

(6)

To study the kinetics of yield of Mo atoms formed in the Mo(CO)$_{6}$ photo-dissociation, the time dependences of the experimental absorption signals (figure 2) were converted into the concentration of Mo atoms using expressions (1), (2), and (5). In accordance with the above assumption, an increase in the concentration of Mo atoms in the ground state is described using second order reaction (6). In this case, the rate of production of Mo atoms is determined from equation

$$d[Mo^*]/dt = -K_1 [Mo^*][Mo]$$  

(7)

and by relationship

$$[Mo^*](t) = [Mo^*]_0 - [Mo^*],$$  

(8)

Figure 3. Approximation of the initial fragment of an increase in the concentration of Mo atoms using an exponential function (9) for the experimental parameters of figure 2.
Figure 4. The effective quenching rates of the excited Mo atoms after the photo-dissociation of Mo(CO)\(_6\) in various bath gases at the pressure of 1 bar: 1—He, 2—CH\(_4\), 3—CO, 4—N\(_2\), 5—Ar, 6—Ar (0.4 bar), 7—CO\(_2\); dashed lines represent the range of radiative quenching rate constant \(\gamma\) for different excited states of Mo atoms.

where [\(Mo^*\)] and [\(Mo^*\)]\(_0\) are current and initial concentrations of Mo atoms in the electronically excited states with allowance for expression [\(Mo^*\)]\(_0\) = [\(Mo\)]\(_\text{max}\), [\(Mo\)]\(_\text{max}\) and [\(Mo\)](\(t\)) are maximum and current concentrations of Mo atoms in the ground state. Thus, the experimental ARAS signals are approximated using the exponential decay (9):

\[
[Mo]\ (t) = [Mo]_{\text{max}} \left(1 - \exp\left(-K_1 [M_g] \, t\right)\right),
\]

where [\(M_g\)] is the concentration of quenching molecules of bath gas, \(K_1\) is the reaction rate constant, and \(t\) is the time. The product \(K_1[M_g]\) represents an effective quenching rate of the excited Mo atoms. Figure 3 shows an example of the approximation of the initial stage of the experimentally measured Mo atom concentration using function (9).

Note, that assuming the quenching of excited Mo atoms by spontaneous emission \(Mo^* \rightarrow Mo + h\nu\) (first order reaction) the same exponential time behavior of ground state Mo atoms concentration could be observed with the radiative quenching rate constant value \(\gamma\) equal to Einstein coefficient of given transition \(A_{ki}\):

\[
[Mo]\ (t) = [Mo]_{\text{max}} \left(1 - \exp\left(-\gamma \, t\right)\right).
\]

4. Results and discussion

Figure 4 presents the effective quenching rates of excited Mo atoms in dependence on bath gas molecular mass. Symbols demonstrate the measurement results in different bath gases: He, Ar, CO, N\(_2\), CO\(_2\), CH\(_4\). The deviation of experimental points caused by the different laser energies density ranged from 20 up to 170 mJ/cm\(^2\) applied for activation of the gas mixtures. The dashed lines demonstrate the range of radiative quenching rate constants \(\gamma\) of various excited states of Mo atoms extracted from Einstein coefficients \(A_{ki}\), for the states with energy less than 4.5 eV [14]. It is seen that measured effective quenching rates are within the range of the values.
Figure 5. The effective quenching rates of the excited Mo atoms after the photo-dissociation of Mo(CO)$_6$ versus laser energy density at the pressure of 1 bar: 1—He, 2—CH$_4$, 3—CO, 4—N$_2$, 5—Ar, 6—Ar (0.4 bar), 7—CO$_2$; dash-dot line represents the mean value of effective quenching rate of the excited Mo atoms in CO and arrows represent the trends of changing of effective quenching rates with laser energy density in noble gases and in molecular gases.

of $\gamma$ for different electronically excited states of Mo atoms. Some weak influence of the kind of the bath gas on the results obtained could be noticed. The effective quenching rates of the excited Mo atoms in noble gases are somewhat different from that for molecular gases, especially for CO. If the quenching rates in the presence of molecular gases (except CO) demonstrate the same values of about $10^8$ 1/s with little deviation, the quenching rates in the presence of noble gases He and Argon (at two different values of pressure) show a larger deviation within one order of magnitude in dependence on laser energy density. The case of CO as a bath gas will be discussed below. Thus, some influence of bath gas on the effective quenching rates of excited Mo atoms was found. It means that the some input of collision quenching also could be the case.

For the study of bath gas influence on the effective quenching rates of excited Mo atoms the experimental data were presented in dependence on laser energy density applied for photo-dissociation of Mo(CO)$_6$. In figure 5 the effective quenching rates of the excited Mo atoms yielded in photo-dissociation of Mo(CO)$_6$ versus laser energy density in different bath gases (He, Ar, CH$_4$, CO, N$_2$, CO$_2$) are presented. Note that the data in Ar were measured at different pressures 1 bar and 0.4 bar. One can clearly see that all quenching rates measured in noble gases (Ar and He) do not depend nor on the kind of gas nor on the pressure. One can consider this fact as a confirmation of the domination of the spontaneous emission quenching channel. The decrease of the effective quenching rate of excited Mo atoms in noble gases (see solid arrow in figure 5) could be caused by the increase of specific input of long-life excited states among the total sum of population of excited states with increase of laser energy density. The weak increase of the effective quenching rate of excited Mo atoms in molecular gases with the laser energy density (see dashed arrow in figure 5) one can interpret as a process of laser excitation of these molecules [18] and increase of effectiveness of electron-electron exchange between $Mo^*$ atoms and laser excited molecules. The higher values of effective quenching rates of the excited Mo atoms in CO (see figures 4, 5) relatively to others bath gases can be explained by an influence
of reaction of chemical quenching:

\[
\text{Mo}^* + \text{CO} \rightarrow \text{MoCO}^* \rightarrow \text{Mo} + \text{CO}.
\]  

(11)

Here \(\text{MoCO}^*\) designates the quasi-stable excited state of \(\text{MoCO}\) radical. The quantitative investigation of this reaction is out of the frame of this study.

5. Conclusions

Atomic resonance absorption spectroscopy on the resonance line of Mo atoms was used to measure the time dependences of the concentration of the ground state molybdenum atoms yielded in UV laser photolysis of \(\text{Mo(CO)}_6\). It was demonstrated that the formation of the Mo atoms in the ground state proceeds by the quenching of the electronically excited \(\text{Mo}^*\) atoms populated due to multi-photon \(\text{Mo(CO)}_6\) photo-dissociation. It was found that the effective rate of quenching of excited \(\text{Mo}^*\) atoms is caused mainly by the spontaneous radiation. The collision quenching by various gas molecules plays a minor role and depends on the laser energy density. With the increase of laser energy density the molecular gases could absorb a portion of laser radiation which leads to some increase of the effective quenching rate of excited Mo atoms. In noble gases the effective quenching rate of the excited Mo atoms decrease with increase laser energy density in the investigated range of 20-170 mJ/cm\(^2\) was observed. The results obtained can be used for the development of the kinetic model of the growth of Mo clusters and nanoparticles in photo-dissociation of \(\text{Mo(CO)}_6\).

Acknowledgments

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References

[1] Gurentsov E V and Eremin A V 2009 Nanotechnologies in Russia 4 319
[2] Gurentsov E V and Eremin A V 2015 Tech. Phys. Lett. 41 547
[3] Ganske J and Rosenfeld N 1989 J. Phys. Chem. 93 1959
[4] Ishikawa Y, Brown C E, Hackett P A and Rayner D M 1990 J. Phys. Chem. 94 2404
[5] Buntin S A, Cavanagh R R, Richter L J and King D S 1991 J. Phys. Chem. 94 7937
[6] Geoffrey L and Wrighton M S 1979 Organometallic Photochemistry (New York: Academic)
[7] Tyndall G and Jackson R L 1991 J. Phys. Chem. 95 687
[8] Venkataratman B, Hou H, Zhang Z, Chen S, Bandukwalla G and Vernon M 1990 J. Phys. Chem. 92 5338
[9] Belyayev Yu E, Dem’yanenko A V and Puretzky A A 1992 Laser. Chem. 12 223
[10] Nakai Y, Wakabayashi T and Ishikawa Y 1998 Appl. Phys. B 66 621
[11] Gurentsov E V, Eremin A V and Priemchenko K Yu 2013 Technical Physics 58 1337
[12] Frish S E 1970 Spectroscopy of Gas Discharge Plasma: Collection of Scientific Works ed Frish S E (Leningrad: Nauka)
[13] Wahlen A 1955 Spectrochim. Acta 7 108
[14] Ralchenko Yu, Kramida A E and Reader J 2011 NIST ASD Team, NIST Atomic Spectra Database http://physics.nist.gov/asd
[15] Demtroder W 1982 Laser Spectroscopy (Berlin: Springer)
[16] Svehla R A 1962 NASA Technical report R132 (Cleveland, Ohio: Lewis Research Center)
[17] Halicioglu T and Pound G M 1975 Phys. Status Solidi A 30 619
[18] Okabe H 1978 Photochemistry of Small Molecules (New York: John Wiley)