



EXCITATION OF THE EVEN LEVELS OF NICKEL ATOM BELONGING TO THE $3d^8 4s 4d$ CONFIGURATION

Yu. M. Smirnov

National Research University «MPEI»
Krasnokazarmennaia str., 14, 111250 Moscow
RUSSIA

Abstract: Excitation of high-lying odd levels of nickel atom related to the $3d^8 4s 4d$ configuration, was studied by the method of extended crossing beams with the registration of optical radiation of the excited atoms. At the exciting electron energy of 50 eV were measured 38 excitation cross sections of spectral lines arising owing to spontaneous transitions from the levels of $3d^8 4s 4d$ configuration on the lower-lying odd levels. Three optical excitation functions (OEFs) in the 0–200 eV electron energy range are recorded. 13 total excitation cross sections of nickel atom energy levels are calculated.

Keywords: nickel atom, excitation cross-section, even configuration, energy level, spectral line.

I. Introduction

In the Mendeleev's periodic table of elements, nickel is one of the elements with a partially closed $3d$ sub-shell and is the last element in the intermediate iron group. In the fourth period, its analog is palladium, and in the fifth – platinum. In the term structure of these three elements there is a significant similarity: all low-lying levels having energy $E < 25000 \text{ cm}^{-1}$ in the nickel atom, $E < 34000 \text{ cm}^{-1}$ in palladium and $E < 30000 \text{ cm}^{-1}$ in platinum are even and belong to the configurations of $3d^8 4s^2$, $3d^9 4s$ and $3d^{10}$ for nickel; $4d^8 5s^2$, $4d^9 5s$, and $4d^{10}$ for palladium; $5d^8 6s^2$, $5d^9 6s$ and $5d^{10}$ for platinum. At the same time, nickel and platinum have all levels of these configurations located below the lowest odd levels, and the palladium atom of the seven levels of $4d^8 5s^2$ configuration has only four levels located above the lowest odd level of PdI ($E = 34068 \text{ cm}^{-1}$).

However, there are some differences: the nickel atom ground level is $3d^8(^3F)4s^2\ ^3F_4$, the palladium atom $4d^{10}\ ^1S_0$, and the platinum atom $5d^9 6s\ ^3D_3$. In this case, the nickel atom on the ground term $3d^8(^3F)4s^2\ ^3F$ is partially superimposed with term $3d^9(^2D)4s\ ^3D$, and the singlet term $3d^{10}\ ^1S$ is significantly higher ($E = 14728 \text{ cm}^{-1}$). In the palladium atom, on the contrary, the ground term $4d^{10}\ ^1S$ is isolated and separated from the nearest excited level $4d^9(^2D_{5/2})5s\ [5/2]_3$ by the energy interval $\Delta E = 6564 \text{ cm}^{-1}$. Finally, the platinum atom ground term $5d^9 6s\ ^3D$ has a very significant J -splitting ($\Delta E > 10000 \text{ cm}^{-1}$) and it is superimposed by singlet terms $5d^{10}\ ^1S$ and $5d^9 6s\ ^1D$, the second of which has an energy of only $E = 775 \text{ cm}^{-1}$. Such a difference in the location of low-lying levels entails differences in the structure of the spectra of these atoms.

The study of atomic characteristics of familiar atoms, such as nickel, palladium, platinum, is of interest both for solving applied problems and for fundamental science. In particular, an important task is to find regularities in the behavior of the excitation cross sections. Since the theoretical predictions of such regularities are very few, the empirical approach based on the analysis of experimental results is mainly used. There is a gradual accumulation of relevant data, which are also necessary in solving practical problems of plasma physics. By now, the results of studying the excitation of the palladium atom [1] and the platinum atom [2–4], as well as the odd triplet levels of the nickel atom [5, 6] have been published. In addition, the excitation of even ^3F -levels of the nickel atom [7] and the excitation of even configurations containing nine d -electrons [8] are investigated.

In the present work, the excitation of even levels of the nickel atom related to the $3d^8 4s 4d$ configuration is researched. The method of extended crossing beams is used, the detailed description of which is contained in recent works [9, 10]. Therefore, we indicate here only the basic conditions for experiments with nickel.

Similar to [6–10], this study will use the method of extended crossing beams to study the excitation of singlet and triplet FeI levels in collisions of electrons with iron atoms. Thanks to a stable measurement technique and experimental conditions, the scale of absolute values is uniform across all studies [6–10].

II. Main Experimental Conditions

Nickel grade N-10 class V-4 with a basic metal content of 99.99% and an admixture of cobalt not more than 0.003% evaporated from a graphite cup-shaped crucible placed on a water-cooled stand. Electron-ray heating was used, at which the necessary power was supplied directly to the surface of the evaporated metal. The use of

a crucible of the Knudsen cell type is not possible, since the molten nickel intensively dissolves refractory metals from which such a cell could be made.

The melting point of nickel $T_{\text{melt}} = 1726$ K, with a saturated vapor pressure of $p_{\text{sat}} = 3 \times 10^{-3}$ Torr. In the main part of the experiment, the melting zone temperature was $T = 1750$ K; the concentration of atoms in the zone of intersection of the atomic and electron beams reached $n = 1.0 \times 10^{10} \text{ cm}^{-3}$. The intensity of all spectral lines studied in this paper was rather low, so that the reduction of the concentration of atoms to eliminate reabsorption was not necessary. The electron beam current density did not exceed 1.0 mA/cm^2 in the entire operating energy range 0-200 eV. The effective spectral resolution of the device was about 0.1 nm.

As indicated in the Introduction, the Nickel atom has a group of low-lying levels related to the terms $3d^8(^3F)4s^2$ ^3F and $3d^9(^2D)4s$ ^3D . When the metal evaporates, these levels can be populated by thermal excitation. Being metastable, such excited atoms overcome the distance from the crucible to the zone of collision with electrons (about 300 mm) almost completely preserving the state of excitation. Consequently, collisions of the electrons occur with the atoms of the beam, located on the ground level, $3d^8(^3F)4s^2$ $^3F_4$ and other levels of the ground term, and several metastable levels in terms $3d^9(^2D)4s$ ^3D , ^1D . Assuming that the distribution of atoms on these levels is Boltzman, we obtain the following values of populations (in % of the number of atoms in the beam; in parentheses are the energy levels in cm^{-1}): $3d^8(^3F)4s^2$ $^3F_4(0) - 42.1$; $3d^9(^2D)4s$ $^3D_3(204) - 27.5$; $3d^9(^2D)4s$ $^3D_2(879) - 11.2$; $3d^8(^3F)4s^2$ $^3F_3(1332) - 10.8$; $3d^9(^2D)4s$ $^3D_1(1713) - 3.36$; $3d^8(^3F)4s^2$ $^3F_2(2216) - 3.66$; $3d^9(^2D)4s$ $^1D_2(3409) - 1.38$. Thus, the total population of ^3F term is 56.6%, and ^3D term - 42.0%. The above distribution should be taken into account when comparing the experimental data on the cross sections with the theoretical (as the latter appear), just as it was done when calculating the excitation cross sections of samarium [11], vanadium [12] and a number of other atoms. As for the real plasma of various devices, it usually has a distribution of atoms in the levels close to that in the conditions of our experiment.

The relative values of the cross sections were measured with an error of 8-12% (depending on the line intensity and its location in the spectrum); the error of the absolute values of the cross sections is 25-30%.

III. Results and Discussion

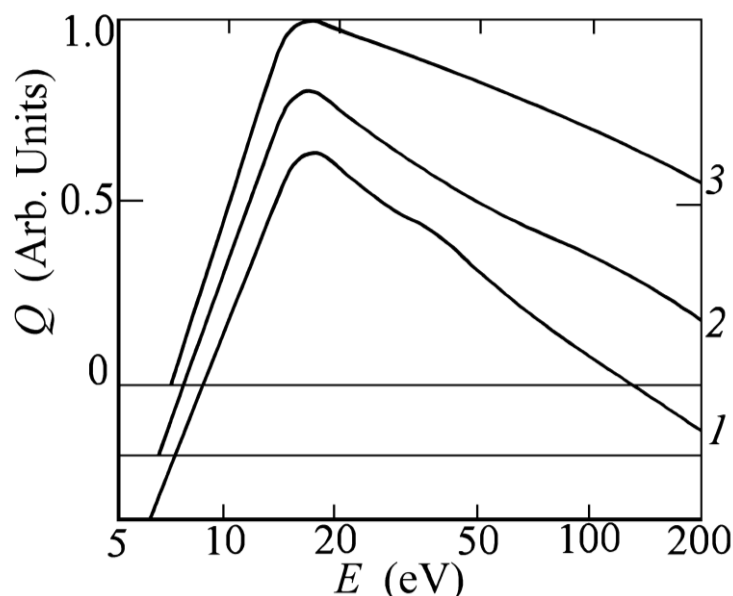
The emission optical spectrum was registered in the wavelength range 220-622 nm at the energy of incident electrons $E = 50$ eV. Over 250 spectral lines are identified as belonging to the NiI spectrum. The spontaneous transitions presented in this paper occur due to the excitation of even levels related to the $3d^8(^3F)4s4d$ configuration. All terms related to this configuration are located quite high on the energy scale in the range $E = 56600$ - 59300 cm^{-1} . Since the parity of the excited levels coincides with the parity of the initial levels at excitation, the absolute values of the excitation cross sections are relatively small: all Q_{50} , with one exception, are in the range of 10^{-18} - 10^{-19} cm^2 . Therefore, it was possible to reliably record the dependence of the cross sections on the energy of the incident electrons (optical excitation functions, OEFs) only for transitions from three levels.

The measurement results with addition of the reference spectroscopic data are presented in the table 1 (for transitions with registered OEFs) and in table 2 (for transitions, for which sufficiently reliable recording of OEFs was impossible). In tables 1, 2 are the wavelengths λ ; transitions; values of the internal quantum number of the lower J_{low} and upper J_{up} levels; energy of the lower E_{low} and upper E_{up} levels; values of cross sections Q_{50} at the energy of incident electrons 50 eV. Also in table 1 are the values of cross sections in the maximum OEF Q_{max} , the position of the maximum $E(Q_{\text{max}})$, as well as the number of OEF according to the numbering of curves in Fig. 1. The format of Fig. 1 is usual for atomic OEF: the scale on the abscissa axis is logarithmic, on the

Table 1: Excitation Cross-Sections of the Nickel Atom Spectral Lines (with OEFs Recorded)

λ (nm)	Transition	$J_{\text{low}}-J_{\text{up}}$	E_{low} (cm^{-1})	E_{up} (cm^{-1})	Q_{50} (10^{-18} cm^2)	Q_{max} (10^{-18} cm^2)	$E(Q_{\text{max}})$ (eV)	OEF
332.739	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [5/2]$	3-2	26665	56710	0.21	0.32	17	1
347.926	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [11/2]$	4-5	28068	56801	0.39	0.57	16	2
353.762	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [11/2]$	5-5	28542	56801	0.13	0.19	16	2
360.685	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [11/2]$	4-5	29084	56801	0.36	0.52	16	2
369.691	$3d^9(^2D)4p \rightarrow 3d^9(^2D)4s(^4F_{9/2})4d [5/2]$	3-2	29668	56710	0.17	0.26	17	1
386.306	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [11/2]$	5-5	30922	56801	0.21	0.30	16	2
419.552	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [11/2]$	4-5	32973	56801	0.41	0.59	16	2
420.171	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [9/2]$	4-4	32973	56766	0.52	0.62	16	3
423.637	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [5/2]$	3-2	33112	56710	0.36	0.55	17	1
430.728	$3d^8(^3F)4s4p(^3P^\circ) \rightarrow 3d^8(^3F)4s(^4F_{9/2})4d [5/2]$	3-2	33500	56710	0.29	0.44	17	1

Figure 1: Optical excitation functions of the nickel atom

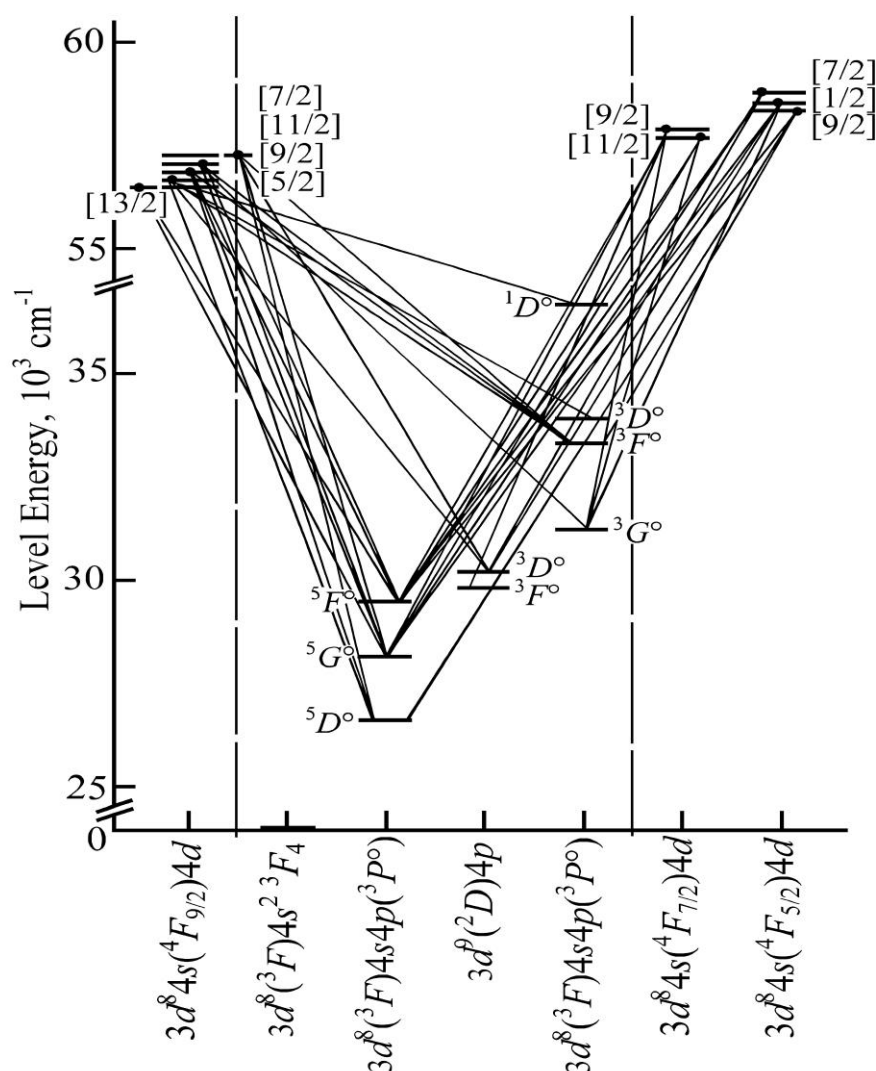


ordinate axis is linear with an individual level of zero reference for each curve. All curves are normalized to at the energy of incident electrons 50 eV. Also in table 1 are the values of cross sections in the maximum OEF Q_{max} , the position of the maximum $E(Q_{max})$, as well as the number of OEF according to the numbering of curves in Fig. 1. The format of Fig. 1 is usual for atomic OEF: the scale on the abscissa axis is logarithmic, on the ordinate axis is linear with an individual level of zero reference for each curve. All curves are normalized to unity in the maximum. Reference data on wavelengths, transitions and energy levels are given according to [13]. In contrast to the lower levels nominated in the symbolism of the *LS*-coupling, for the upper levels of the designations used *J_CK*- coupling, more than adequate for the levels of the $3d^8(^3F)4s4d$ configuration.

Table 2: Excitation Cross-Sections of the Nickel Atom Spectral Lines (without OEFs Recorded)

λ (nm)	Transition	$J_{low}-J_{up}$	E_{low} (cm ⁻¹)	E_{up} (cm ⁻¹)	Q_{50} (10 ⁻¹⁸ cm ²)
320.214	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5D^o-3d^84s(^4F_{9/2})4d [9/2]$	4-5	25753	56973	0.37
321.406	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5D^o-3d^84s(^4F_{9/2})4d [7/2]$	4-4	25753	56857	0.42
328.442	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5D^o-3d^84s(^4F_{9/2})4d [7/2]$	3-3	26665	57103	0.28
330.495	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{7/2})4d [9/2]$	5-5	27580	57829	0.29
331.232	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{7/2})4d [11/2]$	5-6	27580	57762	0.42
332.667	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{5/2})4d [7/2]$	3-3	28578	58629	0.26
335.911	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{7/2})4d [9/2]$	4-5	28068	57829	0.49
337.555	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{5/2})4d [7/2]$	2-3	29013	58629	0.28
337.632	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{7/2})4d [11/2]$	4-5	28068	57677	0.36
339.618	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{5/2})4d [9/2]$	4-5	29084	58520	0.29
340.116	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{9/2})4d [9/2]$	5-5	27580	56973	0.48
342.134	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{7/2})4d [11/2]$	5-6	28542	57762	0.44
344.204	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{9/2})4d [13/2]$	5-6	27580	56624	0.59
344.256	$3d^8(^3D)4p \rightarrow ^3F^o-3d^84s(^4F_{5/2})4d [9/2]$	4-5	29480	58520	0.15
344.304	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5G^o-3d^84s(^4F_{9/2})4d [7/2]$	4-3	28068	57103	0.21
347.789	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{7/2})4d [9/2]$	4-5	29084	57829	0.16
349.634	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{7/2})4d [11/2]$	4-5	29084	57677	0.47
351.162	$3d^8(^3D)4p \rightarrow ^3F^o-3d^84s(^4F_{7/2})4d [9/2]$	3-4	29320	57789	} 0.31
351.192	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{5/2})4d [7/2]$	2-3	30163	58629	
351.621	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{9/2})4d [9/2]$	5-5	28542	56973	0.67
352.654	$3d^8(^3D)4p \rightarrow ^3F^o-3d^84s(^4F_{7/2})4d [9/2]$	4-5	29480	57829	0.37
355.992	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^5F^o-3d^84s(^4F_{9/2})4d [13/2]$	5-6	28542	56624	0.33
362.990	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^3G^o-3d^84s(^4F_{5/2})4d [9/2]$	4-5	30979	58520	0.19
364.394	$3d^8(^3D)4p \rightarrow ^3D^o-3d^84s(^4F_{9/2})4d [7/2]$	3-3	29668	57103	0.07
371.550	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^3G^o-3d^84s(^4F_{7/2})4d [9/2]$	5-5	30922	57829	0.11
372.482	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^3G^o-3d^84s(^4F_{7/2})4d [11/2]$	5-6	30922	57762	0.12
414.296	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^3F^o-3d^84s(^4F_{9/2})4d [7/2]$	4-3	32973	57103	0.17
416.696	$3d^8(^3F)4s4p(^3P^o) \rightarrow ^3F^o-3d^84s(^4F_{9/2})4d [7/2]$	3-3	33112	57103	0.18

Figure 2: Partial state diagram of the nickel atom with the transitions recorded



The partial state diagram of the nickel atom with the transitions studied is presented in Fig. 2. Notations for configurations are placed under the x-axis and for terms on the drawing. Vertical dashed lines divide states of different parity. All high-lying terms nominated in the $J_c K$ -coupling are doublets with small splitting by J ; in most cases, the distance between the levels is several cm^{-1} and cannot be displayed in the figure without significant distortion of the scale. In order to avoid over-complication of the figure, the lower triplet and quintet terms are also shown without splitting in the same way. Thus, the combination of level pairs in the Fig. 2 do not correspond to individual transitions, and to multiplets.

As seen in Fig. 2 and in tables 1, 2, among the studied here terms of the configuration $3d^8(^3F_{J_c})4s4d [K]$ is full only sub-configuration with $J_c = 9/2$ – five terms out of five possible. A sub-configuration with $J_c = 7/2$ is represented by only two terms with $K = 9/2, 11/2$ of five, and a sub-configuration with $J_c = 5/2$ is also represented by two terms with $K = 7/2, 9/2$ of the four known from [13]. As you can see, in the last two cases only the terms with the largest values of the K are shown. Finally, there are no all three terms with $J_c = 3/2$; the most likely reason for their absence is that the excitation values are too small, which tend to increase with increasing J .

In the study of collision processes, special conditions are created under which the excitation process of the studied level k dominates in a single collision of an electron with an atom – it is direct excitation. However, if the electron energy exceeds the threshold energy of direct excitation, excitation above the located l levels is also inevitable, followed by spontaneous transitions from l to k (cascade transitions). If the registration of optical radiation of excited atoms is used, the value measured in the experiment is the Q_{ki} – cross-section of excitation of spontaneous transition from the upper level k to the lower level i . However, the main value used in theoretical

consideration and practical calculations is the q_k – cross-section of the direct excitation of the energy level k . The relationship between these values is established by a known ratio

$$q_k = \sum_i Q_{ki} - \sum_l Q_{lk}, \quad (1)$$

where the left sum is the total excitation cross-section of level k , taking into account the contribution of both direct excitation and population by cascade transitions; the right sum is the resulting contribution of cascade transitions.

In the conditions of our experiment, cascade transitions cannot be registered for two main reasons: 1). The intensity of cascade transitions to level k in most cases is about an order of magnitude less than that of spontaneous transitions from level k . Because the measured cross-sections showed in the tables 1, 2 do not exceed 10^{-18} cm^2 , measurement of excitation cross-sections even for the most intense cascade transitions is at the ability limit of our equipment. 2). As noted earlier, all levels, the excitation of which is studied in the present work, have an energy $E \geq 56600 \text{ cm}^{-1}$, whereas the first ionization limit of the nickel atom $E_i \approx 61600 \text{ cm}^{-1}$. Thus, the cascade transitions quanta have energy no more than 5000 cm^{-1} , i.e. the corresponding lines are located in the IR part of the spectrum with a wavelength $\lambda > 2 \text{ }\mu\text{m}$, where the sensitivity of the radiation receivers is significantly lower than in the UV and visible parts of the spectrum.

The values of the total level excitation cross-sections obtained from the data of tables 1, 2, actually give a lower limit for total cross-sections. Since all allowed transitions from the $3d^8 4s 4d$ configuration levels of the nickel atom are located in the UV and visible parts of the spectrum, restrictions on the completeness of the information obtained about these transitions are imposed by only two factors: 1). It is impossible to register weak lines with intensity below the sensitivity threshold of the installation. 2). Impossibility of the studied lines registration in cases of their blending by intensive transitions from the levels of other configurations.

The contribution of unregistered transitions to full excitation cross sections can be taken into account if additional information on the transition probabilities A_{ki} is used, since $A_{ki}/A_{km} = Q_{ki}/Q_{km}$. Unfortunately, the information published so far on the transition probabilities for transitions from the $3d^8 4s 4d$ configuration levels of the nickel atom is extremely limited. In [14], A_{ki} values were determined for 76 transitions of the nickel atom, of which only four occur at the level of $3d^8(^3F_{9/2})4s4d [9/2]_5$ ($E = 56973 \text{ cm}^{-1}$) related to the $3d^8 4s 4d$ configuration. In a latest work [15] measured 371 values A_{ki} for the transitions of the NiI, however, the transitions from the levels of the $3d^8 4s 4d$ configuration are only the same four A_{ki} , as in [14]. The values of the excitation cross sections in present paper are measured for three of these four transitions. Thus, the program of branching accounting for a more accurate determination of the values of the total level cross sections considered in this work cannot be implemented now, since the necessary spectroscopic information for transitions from these levels is not available.

Turning to consideration of the possible excitation channels for levels of the $3d^8 4s 4d$ configuration must be taken into consideration noted in the previous section the existence of a distribution of atoms for low-lying levels associated with their thermal population. The excitation from the levels of the ground term is carried out in the process of $3d^8(^3F)4s^2\ ^3F - 3d^8(^3F)4s4d [K]$ by a one-electron forbidden transition $4s \rightarrow 4d$ ($\Delta l = +2$). The state of the $3d^8(^3F)$ shell remains unchanged. Excitation from the levels of low-lying terms $3d^9(^2D)4s\ ^3D$, ^1D is carried out by the forbidden one-electron transition $3d \rightarrow 4d$ ($\Delta l = 0$), at which the $3d$ shell is simultaneously reconstructed. Any analysis and comparison of the results obtained will be possible only after the relevant theoretical data are available.

IV. Summary

The excitation of high-lying even levels of the nickel atom related to the $3d^8 4s 4d$ configuration is studied for the first time. Despite the absence of similar theoretical data, the results can be used as reference data in the calculation of the characteristics of non-LTE plasma, including the studies of the beam plasma containing nickel atoms.

V. References

- [1] Yu. M. Smirnov, *Journal of Applied Spectroscopy*, 51 (1989), 1241–1244.
- [2] Yu. M. Smirnov, *Astronomy Reports*, 48 (2004), 29–34. DOI: 10.63-7729/04/4801-0029.
- [3] Yu. M. Smirnov, *Optics and Spectroscopy*, 96 (2004), 319–323. DOI: 0030-400X/04/9603-0319.
- [4] Yu. M. Smirnov, *High Temperature – in Russian*, 43 (2005), 510–515.
- [5] Yu. M. Smirnov, *Journal of Applied Spectroscopy – in Russian*, 76 (2009), 645–651.
- [6] Yu. M. Smirnov, *Optics and Spectroscopy*, 112 (2012), 836–843. DOI: 10.1134/S0030400X12060203.
- [7] Yu. M. Smirnov, *High Temperature*, 39 (2001), 342–346. DOI: 0018-151X/01/3903-0342.
- [8] Yu. M. Smirnov, *Optics and Spectroscopy*, 115 (2013), 787–793. DOI: 10.1134/S0030400X13110234.
- [9] Yu. M. Smirnov, *Journal of Physics B: Atomic, Molecular and Optical Physics*, 48 (2015), 165204. DOI: 10.1088/0953-4075/48/16/165204.
- [10] Yu. M. Smirnov, *Journal of Physics B: Atomic, Molecular and Optical Physics*, 49 (2016), 175204. DOI: 10.1088/0953-4075/49/17/175204.
- [11] R. K. Peterkop, *Latvian SSR Academy of Science News. Series Physical and Technical Sciences – in Russian*, No3 (1982), 3–11.
- [12] R. K. Peterkop, *Optics and Spectroscopy*, 58 (1985), 14–18.

- [13] U. Litzen, J. W. Brault, A. P. Thorne, *Physica Scripta*, 47 (1993), 628–673. DOI: 10.1088/0031-8949/47/5/004.
- [14] M. E. Wickliffe, J. E. Lawler, *The Astrophysical Journal Supplement Series*, 110 (1997), 163–166. DOI: 10.1086/312995.
- [15] M. P. Wood, J. E. Lawler, C. Sneden, J. J. Cowan, *The Astrophysical Journal Supplement Series*, 211 (2014), 20 (13 pp). DOI: 10.1088/0067-0049/211/2/20.