Experimental study of excitation of the even ^4P and ^4D levels of the cobalt atom by electron impact

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Abstract

The excitation of even quartet levels ^4P and ^4D of the cobalt atom was experimentally studied by the method of extended crossing beams with registration of the optical signal of excited atoms. The excitation cross sections of 43 CoI spectral lines resulting as spontaneous transitions from even levels ^4P and ^4D were measured at the exciting electron energy of 50 eV. In the incident electron energy range 0-200 eV optical excitation functions (OEFs) were recorded for transitions from eight levels. The total excitation cross sections for 12 energy levels of cobalt atom are calculated.

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

1. INTRODUCTION

Cobalt, discovered in 1735 by Swedish chemist G. Brandt, now finds numerous and varied applications. It is most widely used in the composition of magnetic alloys, heat-resistant materials, varnishes and paints, wear-resistant and corrosion-resistant alloys for the chemical and metallurgical industry, etc. Its applications in aircraft turbines and rocket technology are well known.

Cobalt has proved to be a specific element in astrophysical research. In the study of roAp-star spectra it was found that the behavior of cobalt differs significantly from the behavior of its neighbors in the periodic system of elements – iron and nickel. If the content of all elements is much heavier than strontium in the atmospheres of roAp stars bigger (by 1–2 decimal orders) than their content in the atmosphere of the Sun, the situation is significantly different for the elements of the iron group. In the atmospheres of roAp stars HD 101065, HD 24712 cobalt content is ~1.0–1.5 orders of magnitude higher than in the atmosphere of the Sun [1] whereas the content of iron and nickel is less than in the Sun by almost one order of magnitude. In the spectra of roAp stars HD 122970, 10 Aql, HD 203932 there is the same excess of cobalt content over the solar one as in the previous group of stars, whereas the content of iron and nickel is less, then in the Sun half order and less [2]. The reasons for such behavior of Fe, Co, Ni are not reported in [1, 2].

Obtaining and processing of cobalt in electrometallurgy and electrotechnology, as well as its functioning in high-temperature devices is accompanied by the appearance of cobalt atoms in the volume of these devices and in the gas discharge plasma. The increasing use of mathematical modeling methods in solving plasma problems needs to provide information about parameters of the elementary processes involved in the formation of optical and kinetic characteristics of the plasma. These processes include cross sections of inelastic electron-atomic collisions, which in many cases are the main mechanism of energy transfer from the electromagnetic field of external sources to heavy particles (atoms, ions, etc.).

The most intensive study of the collisions processes between particles took place in the middle of the second half of the XX century. It was largely stimulated by the fast development of gas lasers, microelectronics, special sources of optical radiation, etc. For example, the bibliographic index of works on the physics of electronic and atomic collisions for the years 1967-1973 [3] contains more than 3,800 publications on collision topics. At the same time, almost all experiments were devoted to collisions of electrons with atoms or molecules of substances with relatively low evaporation temperatures.

However, already in the early 80's, a number of studies were conducted on electron collisions with metal atoms whose evaporation temperature was quite high: niobium (T = 2900 K; 1981) [4], molybdenum (T = 3100 K; 1981) [5], and others. These and many subsequent experiments were performed by the extended crossing beams method, the initial description of which and its potential possibilities were given in the collection of articles [6]. The current state of this method has been discussed in recent studies [7, 8]. Among the publications of other authors, can be indicated the work on the study of the excitation cross sections of the gadolinium atom (T = 1900 K; 1984) [9]. The authors of this work note that they had to overcome "huge experimental difficulties". Some difficulties also arose in studies with extended crossing beams, but they were not related to the evaporation temperature of the studied substances, but to the individual characteristics of their physical and chemical properties. After the publication of the work [6], reports of other authors on experiments with high-temperature substances have not been published until now.

The first experimental data on the excitation cross sections of the cobalt atom by electron impact were published in 1983 for odd quartets [10] and in 1984 for odd doublets and sextets [11]; later theoretical work was published [12]. In this case, the calculation in [12] is performed only for odd levels $x^4D°$, $x^4F°$, $x^4G°$, the excitation of which is studied in [10]; their excitation originate from the levels of the main term a^4F by allowed one-electron transitions 4s → 4p. Information on excitation cross sections of the CoI even quartet levels is extremely limited: only in [10] three transitions from f^4H, h^4F, f^4F levels with energy E > 47000 cm^{-1} are reported to be excited.

In this paper, the method of extended crossing beams is used to study the excitation of even quartet levels ^4P and ^4D located in the energy range E > 51000 cm^{-1}. In comparison with the works [10, 11], some improvements have been made in the research methodology, the most significant of which is the use of the helium intensity standard instead of the spectral band of the nitrogen molecule used before ~1984.

2. MAIN EXPERIMENTAL CONDITIONS

Since the technique and method of working with extended crossing beams in their present state has been discussed in detail in recent works [7, 8], the re-presentation of this information in this paper is unnecessary. Here we present only the main conditions for the experiment with cobalt atoms.

Cobalt with a purity of 99.99% evaporated from a graphite cup-shaped crucible as a result of heating the metal surface by an electron ray to a temperature of T = 1850 K, at which the concentration of cobalt atoms at the intersection of the electron and atomic beams was $n = 3.0 \times 10^{10}$ см$^{-3}$. Although the above temperature is almost 100° higher than the melting point of cobalt, the melting zone did not come into contact with the walls of the crucible; that allowed to exclude the formation of carbides that could get into the atomic beam. In addition, with this evaporation mode, the service life of the crucible was significantly increased. Lowering the evaporation temperature to reduce the atom concentration to $n = 2.0 \times 10^9$ см$^{-3}$, used in [13] to minimize reabsorption, was not necessary in the present work, since none of the spontaneous transitions from the levels discussed here is resonant.

The cobalt atom, like many other metal atoms, has a group of low-lying levels, which, when the metal evaporates, can be populated as a result of thermal excitation. Assuming that the population of low-lying levels of the cobalt atom in the conditions of the our experiment corresponds to the Boltzmann distribution, we obtain the following estimated values of populations (in % of the total number of atoms in the beam; the energy levels in cm^{-1} are given in brackets: $a^4F_{9/2}$ (0) – 54.3, $a^4F_{7/2}$ (816) – 23.0, $a^4F_{5/2}$ (1406) – 10.8, $a^4F_{3/2}$ (1809) – 5.3, $b^4F_{9/2}$ (3482) – 3.6, $b^4F_{7/2}$ (4142) – 1.7, $b^4F_{5/2}$ (4690) – 0.9, $b^4F_{3/2}$ (5075) – 0.4. In total, 94.3% of atoms are at the levels of the ground term a^4F, and at the levels of the low-lying metastable term b^4F – 6.6%. Since both these terms have the reverse order of levels, in both cases more than half of the total term population is accounted for by the lowest levels with J = 9/2 having the highest statistical weight within the term. The presence of such a distribution for cobalt atoms is taken into account in the theoretical work [12] (however, at a temperature T = 1950 K, at which the experiment was performed in [10, 11]).

The electron beam current density did not exceed 1.0 mA/cm^2 in the entire operating energy range 0–200 eV. The real spectral resolution of the installation was about 0.1 nm in the short-wave part of the spectrum at λ < 600 nm; at λ > 600 nm it deteriorated to ~0.2 nm due to the replacement of the diffraction grating of the monochromator.

Since the parity of the levels, the excitation of which is studied in the present work, coincides with the parity of initial levels of excitation, all measured values of the cross sections are relatively small. The measurement error of the relative values of the cross sections is 5-15% for the studied spectral lines; the absolute values of the cross sections are determined with an error of 15-25%. The conditions of experiments with cobalt and the features of the method are discussed in more detail in [13, 14].

3. RESULTS AND DISCUSSION

In the wavelength range λ = 199–800 nm, an optical spectrum is registered that occurs due to the excitation of cobalt atoms in their collisions with electrons having energy E = 50 eV. The spectral lines resulting from spontaneous transitions from even quartet levels ^4P and ^4D are located in the spectral region λ = 334–700 nm. For transitions from eight levels, the dependence of the cross sections on the energy of exciting electrons (optical excitation functions, OEFs) was recorded when the electron energy changes from 0 to 200 eV.

The measurement results with the addition of the necessary spectroscopic information are presented in the Table 1. The wavelengths λ, transitions, the values of the internal quantum number of the lower J_{low} and upper J_{up} levels, the energies of the lower E_{low} and upper E_{up} levels, the values of the excitation cross sections at the exciting electron energy of 50 eV Q_{50} and the OEF maximum Q_{max}, the position of the maximum $E(Q_{max})$ are given here. The numbers in the OEF column correspond to the numbers of the curves in Fig. 1. The wavelengths (rounded to thousandth parts of a nanometer) and the characteristics of the levels are given in the Table 1 according to work [15], in which earlier information on energy levels of CoI was significantly revised. It presents 64 new levels of the cobalt atom and simultaneously annuls 22 previously known levels, as well as revised energy values and partially revises interpretation for 300 levels. On the basis of new data set in [15] the refined classification for 2442 spectral lines of CoI is presented.

Table 1. Excitation cross-sections of the cobalt atom.

λ (nm)	Transition	J_{low}–J_{up}	E_{low} (cm^{-1})	E_{up} (cm^{-1})	Q_{30} (10^{-18} cm^2)	Q_{max} (10^{-18} cm^2)	$E(Q_{max})$ (eV)	OEF
334.255	$3d^7(^4F)4s4p(^3P^\circ)z^6F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	3/2-1/2	25041	54949	0.053	-	-	-
334.952	$3d^7(^4F)4s4p(^3P^\circ)z^6F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	9/2-7/2	23855	53702	0.10	0.10	22	8
335.154	$3d^7(^4F)4s4p(^3P^\circ)z^6F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	5/2-5/2	24733	54561	0.14	-	-	-
335.684	$3d^7(^4F)4s4p(^3P^\circ)z^6F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	5/2-3/2	24733	54514	0.11	0.13	22	7
337.620	$3d^7(^4F)4s4p(^3P^\circ)z^6F^\circ\text{-}3d^74s(^5F)4d\ f^4P$	7/2-5/2	24326	53936	0.15	0.17	30	3
394.268	$3d^7(^4F)4s4p(^3P^\circ)z^4F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	9/2-7/2	28345	53702	0.16	0.16	22	8
397.354	$3d^7(^4F)4s4p(^3P^\circ)z^4F^\circ\text{-}3d^74s(^5F)4d\ f^4P$	7/2-5/2	28777	53936	0.20	0.22	30	3
398.545	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^74s(^5F)4d\ f^4P$	1/2-1/2	30742	55826	0.065	0.069	60	2
401.092	$3d^7(^4F)4s4p(^3P^\circ)z^4F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	7/2-7/2	28777	53702	0.10	0.10	22	8
405.694	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^74s(^5F)4d\ f^4P$	7/2-5/2	24294	53936	0.24	0.27	30	2
406.953	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^74s(^5F)4d\ f^4D$	5/2-3/2	29948	54514	0.069	0.083	22	7
433.755	$3d^7(^4F)4s4p(^3P^\circ)z^4F^\circ\text{-}3d^8(^3F)4d\ e^4D$	5/2-3/2	29216	52264	0.091	-	-	-
440.267	$3d^7(^4F)4s4p(^3P^\circ)z^4F^\circ\text{-}3d^8(^3F)4d\ e^4D$	9/2-7/2	28345	51052	0.18	0.18	55	6
452.679	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^8(^3F)4d\ e^4P$	5/2-3/2	29948	52033	0.064	-	-	-
457.937	$3d^7(^4F)4s4p(^3P^\circ)z^2F^\circ\text{-}3d^74s(^5F)4d\ f^4D$	7/2-7/2	31871	53702	0.13	0.13	22	8
458.940	$3d^7(^4F)4s4p(^3P^\circ)z^4G^\circ\text{-}3d^8(^3F)4d\ e^4D$	9/2-7/2	29269	51052	0.039	0.040	55	6
459.463	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^8(^3F)4d\ e^4D$	7/2-7/2	29294	51052	0.23	0.23	55	6
459.690	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^8(^3F)4d\ e^4P$	7/2-5/2	29294	51042	0.28	0.28	60-70	1
462.577	$3d^7(^4F)4s4p(^3P^\circ)z^4D^\circ\text{-}3d^8(^3F)4d\ e^4D$	5/2-5/2	29948	51560	0.24	0.25	60	5
469.746	$3d^8(^3F)4p\ y^4D^\circ\text{-}3d^74s(^5F)4d\ f^4P$	5/2-5/2	32654	53936	0.015	0.017	30	3

484.932	$3d^8(^3F)4p\ y^4F^\circ$-$3d^74s(^5F)4d\ f^4D$	5/2-5/2	33945	54561	0.098	-	-	-
507.741	$3d^7(^4F)4s4p(^3P^\circ)z^2F^\circ$-$3d^8(^3F)4d\ e^4D$	7/2-5/2	31871	51560	0.045	0.047	60	5
515.885	$3d^8(^3F)4p\ y^4D^\circ$-$3d^8(^3F)4d\ e^4P$	5/2-3/2	32654	52033	0.051	-	-	-
521.475	$3d^7(^4F)4s4p(^3P^\circ)z^2F^\circ$-$3d^8(^3F)4d\ e^4P$	7/2-5/2	31871	51042	0.077	0.078	60-70	1
525.762	$3d^8(^3F)4p\ y^4D^\circ$-$3d^8(^3F)4d\ e^4P$	7/2-5/2	32027	51042	0.45	0.46	60-70	1
528.779	$3d^8(^3F)4p\ y^4D^\circ$-$3d^8(^3F)4d\ e^4D$	5/2-5/2	32654	51560	0.11	0.11	60	5
529.227	$3d^8(^3F)4p\ y^4D^\circ$-$3d^8(^3F)4d\ e^4D$	3/2-1/2	33150	52040	0.17	0.22	90	4
548.966	$3d^8(^3F)4p\ y^4F^\circ$-$3d^8(^3F)4d\ e^4D$	9/2-7/2	32841	51052	0.18	0.18	55	6
549.756	$3d^8(^3F)4p\ y^2F^\circ$-$3d^74s(^5F)4d\ f^4D$	5/2-3/2	36329	54514	0.028	0.034	22	7
552.718	$3d^8(^3F)4p\ y^4F^\circ$-$3d^8(^3F)4d\ e^4P$	5/2-3/2	33945	52033	0.020	-	-	-
560.235	$3d^8(^3F)4p\ y^4F^\circ$-$3d^8(^3F)4d\ e^4D$	3/2-1/2	34196	52040	0.18	0.23	90	4
565.180	$3d^7(^4F)4s4p(^3P^\circ)z^2D^\circ$-$3d^8(^3F)4d\ e^4D$	3/2-1/2	34352	52040	0.021	0.027	90	4
567.544	$3d^8(^3F)4p\ y^4F^\circ$-$3d^8(^3F)4d\ e^4D$	5/2-5/2	33945	51560	0.035	0.036	60	5
568.473	$3d^8(^3F)4p\ y^4G^\circ$-$3d^8(^3F)4d\ e^4D$	7/2-7/2	33466	51052	0.033	0.033	55	6
636.625	$3d^8(^3F)4p\ y^2F^\circ$-$3d^8(^3F)4d\ e^4P$	5/2-3/2	36329	52033	0.032	-	-	-
640.749	$3d^8(^3F)4p\ y^2F^\circ$-$3d^8(^3F)4d\ e^4D$	7/2-7/2	35450	51052	0.041	0.042	55	6
646.305	$3d^8(^3F)4p\ y^2D^\circ$-$3d^8(^3F)4d\ e^4D$	5/2-5/2	36092	51560	0.12	0.12	60	5
670.390	$3d^7(^4F)4s4p(^1P^\circ)x^4D^\circ$-$3d^74s(^5F)4d\ f^4D$	7/2-5/2	39649	54561	0.14	-	-	-
678.928	$3d^7(^4F)4s4p(^1P^\circ)x^4D^\circ$-$3d^74s(^5F)4d\ f^4P$	1/2-1/2	41101	55826	0.13	0.14	60	2
699.721	$3d^7(^4F)4s4p(^1P^\circ)x^4D^\circ$-$3d^74s(^5F)4d\ f^4P$	7/2-5/2	39649	53936	0.17	0.19	30	3

A partial state diagram of the cobalt atom with the transitions studied is shown in Fig. 2. Vertical dashed lines divide states of different parity. To simplify the figure, most of the terms are shown in blocks without splitting on J. In the cases when the term is presented in the Table 1 by only one level (all such cases refer only to the lower terms), position of this level is shown in Fig. 2. The peculiarity of the structure of the energy levels of the cobalt atom is that it has no low-lying odd levels: in the energy range E = 0–23611 cm^{-1}, all levels of the cobalt atom are even. Above is the energy region E = 28470–44782 cm^{-1}, within which all levels are odd. Since the states whose excitation is investigated in this paper are even, a strict forbiddenness on combining states of the same parity forbids the appearance in the CoI spectrum of transitions to low-lying levels, which are therefore not shown in Fig. 1.

A significant majority of transitions presented in the Table 1 and Fig. 2, occurs within the quartet term system; only five of the most short-wavelength transitions end in the most low-lying sextet term $3d^7(^4F)4s4p(^3P^\circ)\ z^6F^\circ$. And besides eight intercombination transitions end in a doublet terms z^2D° and z^2F° related to the $3d^7(^4F)4s4p(^3P^\circ)$ configuration and y^2D° and y^2F° related to the $3d^8(^3F)4p$ configuration. Unfortunately, the work [15] does not contain information on component composition of levels, i.e. about mixing configurations of the cobalt atom states. According to the earlier compilation [16], almost all lower levels presented in the Table 1, do not belong to the number of strongly mixed, whereas for the upper levels (even quartets) studied in the presented work, there are no data on the configuration composition.

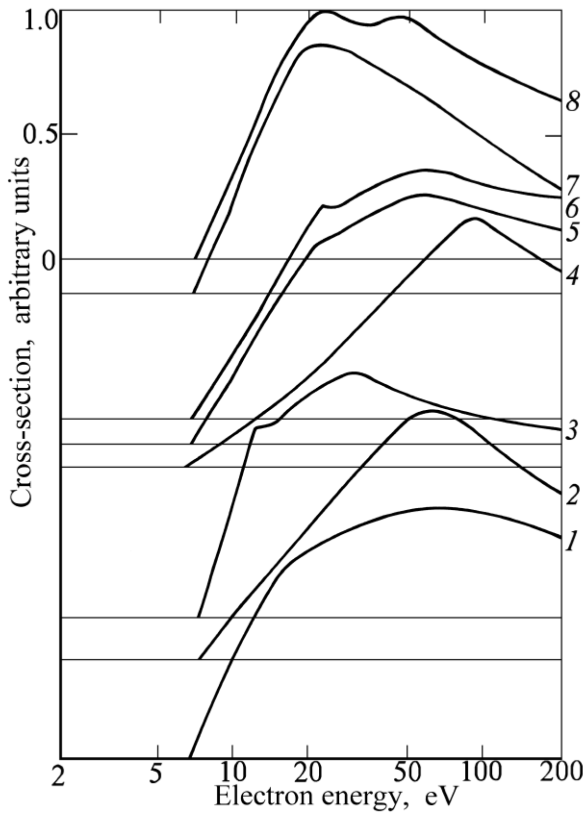

Figure 1. Optical excitation functions of the cobalt atom.

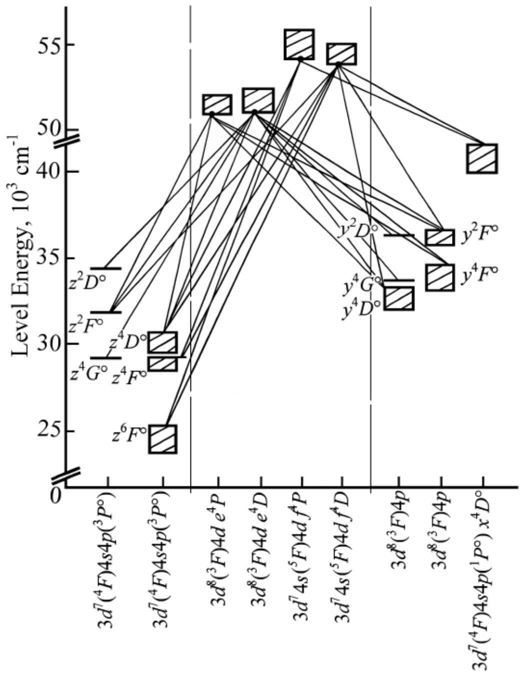

Figure 2. Partial state diagram of the cobalt atom with transitions recorded.

As indicated above, the excitation of the even quartet levels in the conditions of our experiment takes place almost entirely from the levels of the ground term $3d^7 4s^2$ a^4F with a predominance of the contribution of the excitation from the ground level $3d^7 4s^2$ $a^4F_{9/2}$. The upper terms e^4P and e^4D, the excitation of which is investigated in this work, refer to the $3d^8(^3F)4d$ configuration, and for them the transformation $3d^7 4s^2 \rightarrow 3d^8 4d$ is a very complex restructurisation of the atomic electron shell as a result of the forbidden two-electron transition. The probability of such a process is wittingly very small, which is manifested in small values of all measured cross-sections: none of them exceeds 10^{-18} cm^2. More likely is the excitation from the initial low-lying term $3d^8(^3F)4s$ b^4F, in which the state of the subshell $3d^8$ remains unchanged and there is only the one-electron forbidden transition $4s \rightarrow 4d$. However, in our experiment, the contribution of this process seems to be small, since the population of $3d^8(^3F)4s$ b^4F levels is 14 times less than $3d^7 4s^2$ a^4F. For the higher-placed terms f^4P and f^4D relating to the $3d^7 4s(^5F)4d$ configuration, the situation is close to just considered: there is also a one-electron forbidden transition $4s \rightarrow 4d$ of one of the equivalent 4*s*-electrons, and subshell $3d^7$ and the second 4*s*-electron remain unchanged.

In the conditions of beam experiments for the study of electron-atomic collisions, the population of the considered level is determined by the contributions of two processes: direct excitation of the level *k* by an electron impact from the initial state, characterized by the q_k cross section, and population as a result of cascade transitions from the above levels. If the optical signal of excited atoms is recorded in such experiments, the result of the measurements is the excitation cross section of the spectral line Q_{ki}, corresponding to the spontaneous transition from level *k* to level *I*. The excitation of the cascade transitions from levels *l*, located above the level *k*, characterized by the cross sections Q_{lk}. The relationship between the above mentioned cross section values is established by a known ratio

$$q_k = \sum_i Q_{ki} - \sum_l Q_{lk} \ . \qquad (1)$$

In this ratio, the left sum is the total excitation cross-section of level k, taking into account both the direct excitation and the contribution of cascade transitions; the right sum is the resulting contribution of cascade transitions. Thus, the use of the ratio (1) in principle makes it possible to determine of the level excitation cross-sections based on the results of beam experiments in which the radiation of excited atoms is recorded.

However, the real possibilities of such experiments are significantly limited by the requirement to ensure the condition of single collisions between particles in the working volume. Therefore, in all the experiments carried out so far to study electron-atomic collisions, no more than tens of cross sections (in the traditional method of crossing beams) or hundreds (using extended beams) were measured, while the use of gas-discharge radiation sources makes it possible to record up to 30,000 spectral lines in spectra abundant with lines, for example, in the spectra of rare earth elements and heavy metals.

Table 2: Excitation cross-sections for energy levels of cobalt atom (E = 50 eV).

Configuration	Term	*J*	*E* (cm^{-1})	$\sum_i Q_{ki}$ (50) (10^{-18} cm^2)
$3d^8(^3F)4d$	e^4P	3/2	52033	0.135
		5/2	51042	0.81
	e^4D	1/2	52040	0.37
		3/2	52264	0.091
		5/2	51560	0.55
		7/2	51052	0.70
$3d^7 4s(^5F)4d$	f^4P	1/2	55826	0.195
		5/2	53936	0.81
	f^4D	1/2	54949	0.053
		3/2	54514	0.21
		5/2	54561	0.41
		7/2	53702	0.81

In the present work, the ratio of (1) is used to calculate total excitation cross sections of the investigated levels at an energy of exciting electrons of 50 eV. The calculation results are given in Table 2. The values of the total cross sections presented here in principle can make more accurate using branching factors obtained in spectroscopic experiments, since the ratio of the excitation cross sections of two spectral lines having a common upper level is equal to the ratio of the probabilities of spontaneous transitions from the same levels: Q_{ki}/Q_{km} = A_{ki}/A_{km}. Unfortunately, it was not possible to find publications that would determine branching factors for transitions from the levels studied in this paper. As for the cascade transitions, they cannot be investigated in this work for two main reasons: 1) all cascade transitions to the studied levels of the cobalt atom are located in the far IR part of the spectrum; 2) the excitation cross sections of these transitions are very small.

4. SUMMARY

The excitation of high even ^4P and ^4D levels of the cobalt atom by electron impact were studied for the first time. The measured values of the excitation cross sections of spectral lines do not exceed 10^{-18} см^2. The results obtained can be used to solve the problems of diagnostics of long-expanded and low-density plasma, including one in gas shells of astrophysical objects.

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