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Excitation of Lanthanum and Lutetium Double-Charged Ions in Electron-Atom Collisions

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Abstract

Excitation of LaIII and LuIII in collisions of slow electrons with La and Lu atoms (excitation with simultaneous double ionization) have been studied in experiment. At exciting electron energy of 50 eV at 19 excitation cross-sections for each of LaIII and LuIII were measured. At two optical excitation functions for both of ions were recorded, in the electron energy range of 0–200 eV for LaIII and in the range of 0–250 eV for LuIII. Absolute values of excitation cross-sections for similar levels of LaIII and LuIII are compared.

Keywords: excitation, double ionization, cross-sections, double-charged ions, optical excitation functions

1. Introduction

Though experimental study of collision characteristics of double- and multi-charged ions has considerable technical difficulties, it is interesting both for fundamental science and for some applied tasks.

Firstly, after discovery of roAp-stars (i. e. rapidly oscillating cool magnetic chemically peculiar stars) by (Przybylski, 1961), intensive research of atmospheres of this class stars started. In particular, it was discovered, that abundances of some rare-earth elements (REE), determined by their single- and double-charged ions spectrum, differs by one and more decimal orders. “This strange discrepancy observed for *all four* REE cannot be explained by systematic errors of the oscillator strengths, because practically no abundance differences are observed for the first and second REE ions for several non-roAp stars…” (Ryabchikova et al., 2001, P. 986). Four REE, mentioned above, include praseodymium, neodymium, terbium and erbium. Afterwards O. Kochukov added (Kochukov, 2003) dysprosium in this list. “…analysis of the spectrum of HD 213637 revealed striking discrepancy between abundances obtained from the first and second ions of several rare-earth elements. In particular, the PrIII, NdIII, and DyIII lines indicate ≈ 1.5 dex higher abundance than determined from lines of the first ions, while for TbIII and ErIII this difference reaches 2.0 dex!” (Kochukov, 2003, P. 674).

Secondly, double-charged ions are considered as an important link of inverse population obtaining process in recombination lasers. “The latest researches of pulse lasers on mixture of tin, lead and magnesium vapors with helium shown, that main pumping process for their electron levels is recombination of double-charged metal ions, created both by electron impact and by double charge exchange on helium ions” (Ivanov, Latush, & Sem, 1990, P.108). These mechanisms play significant role in excitation of many other ion lasers on metal vapors. Along with this, it is mentioned, that “…there are few experimental data about excitation cross-sections of ion levels by electron impact, so in pumping calculations semi empirical formulas and approximations are usually used.” (Ivanov, Latush, & Sem, 1990, P.11).

Thirdly, laser generation on transitions of double- and triple-charged ions of BeIV, CIII, CIV, AlIII, SiIII, SiIV, PIII, PIV, SIII, InIII, HgIII, TlIII, BiIII (Ivanov, Latush, & Sem, 1990, Table P4.1) have been obtained long ago. Apart from the listed above, lasers on transitions of noble gases ArIII, KrIII, XeIII, along with lasers on multi-charged ion transitions from NeIV to KrV (Rocca, & Collins, 1984) have been also presented. The latter ones are of prime importance, because they allow to obtain generation of coherent radiation in the VUV spectrum range. Further development of these lasers has been related with excitation by electron beam, which allowed to create X-ray lasers. However, the development of gas lasers has been continued; for example, in the work (Zhao et al., 2011) it is reported about X-ray laser with excitation by capillary discharge, with generation on $\lambda = 69.8$ nm of

Ne-like argon ions (i.e. on ArIX), in which simultaneous generation of three lines with λ = 46.6, 68.8, 72.6 nm on transitions of triplet level system was also obtained. In the same year, generation with λ = 18.9 nm was obtained on molybdenum ion transition (Wang et al., 2011). However, these results have been obtained on the empiric base, because information about excitation cross-sections for these collisions is very scarce.

Excitation of double-charged ions in electron-atom collisions (excitation with simultaneous double ionization) is a complex and underexplored process. In the earlier experimental works, accomplished in 1970s, inelastic collisions of electrons with noble gases were studied (e. g., (Samoilov, Starikova, & Smirnov, 1977)). A little later experiments with metals: yttrium (Kuchenev & Smirnov, 1982), ytterbium (Smirnov, 1996) were started. The author hasn't found any theoretical works about excitation of double-charged ions in electron-atom collisions.

In this work double-charged lanthanum and lutetium ions chosen as subjects of study. This choice is determined by a significant similarity in electron shells of lanthanum and lutetium atoms. If we exclude from consideration the profound electron shells with principal quantum numbers n < 4, ground states of atoms considered may be represented as follows: LaI – $(\ldots 4s^24p^64d^{10}5s^25p^6)\ 5d6s^2\ {}^2D_{3/2}$; LuI – $(\ldots 4s^24p^64d^{10}4f^{14}5s^25p^6)\ 5d6s^2\ {}^2D_{3/2}$. Thus, the main difference between electron shells of these atoms is presence of deep-lying fully populated shell $4f^{14}$ in lutetium atom, while outer shells in lanthanum and lutetium atoms are identical. On this base lanthanum and lutetium atoms inserted not in rare earth elements, but in platinum-group elements (El'iashevich, 1953; Radtsig & Smirnov, 1986). It should be noted, that $5d6s^2$ electrons are outer also in cerium and gadolinium atoms, but in these elements they are preceded by an incomplete $4f$-shell. In cerium atom it contain one $4f$-electron (the ground level $4f5d6s^2\ {}^1G^\circ_4$), and in gadolinium atom it contain seven electrons (the ground level $4f^7({}^8S^\circ_{7/2})5d6s^2\ {}^9D^\circ_2$).

After removal of two outer electrons from lanthanum and lutetium atoms double-charged ions of lanthanum (the ground level $5p^65d\ {}^2D_{3/2}$) and lutetium (the ground level $4f^{14}({}^1S)6s\ {}^2S_{1/2}$) are formed. After excitation of valence electrons of these ions ($5d$ and $6s$ correspondingly) one-electron spectra appear, which are similar to the spectra of alkaline metal atoms. All experimentally discovered excited levels of LaIII (41 levels) and LuIII (27 levels) correspond to one-electron excitation, in which $5p^6$ shell in LaIII (Kramida et al., 2014) and $4f^{14}$ shell in LuIII (Ralchenko et al., 2010) stays unchanged. Naturally, as a result, all known levels of both ions are doublets and their sets are the same for LaIII and LuIII.

Just recently, V. A. Zilitis calculated energies of S, P° (Zilitis, 2011) and D, F° (Zilitis, 2012) Rydberg levels for ten Cs-like ions, including LaIII. Comparison of calculated values with experimental ones for BaII has shown good compliance; for other nine Cs-like ions, including LaIII, experimental data about levels, studied in (Zilitis, 2011, 2012), are absent. Similar calculations for LuIII haven't been carried out until now.

Atomic constants for double-charged lanthanum and lutetium ions haven't been deeply studied in experiments. However, they are very interesting for astrophysical applications, so several theoretic works have been performed. Radiative atomic constants – oscillator strengths gf and transition probabilities gA – were calculated for LaIII and LuIII by Hartree-Fock's relativistic method in the detailed work (Biemont et al., 1999). For LuIII the gf and gA values were obtained for 87 spectral lines in the wavelength range λ = 67–953 nm. They were compared with gA calculated values for 65 spectral lines from the work (Migdalek, 1982). For LaIII more numerous results have been obtained: gf and gA values have been calculated for 164 spectral lines in the wavelength range λ = 74–992 nm. Comparison could be done only for 17 gA values, calculated in the work (Migdalek, & Wyrozumska, 1987). Both for LuIII and for LaIII accordance with gA theoretical values have been satisfactory.

Collision constants (excitation cross-sections) for discussed ions haven't been studied before, neither experimentally, nor theoretically. In this work it has been done by the method of extended crossing beams.

2. Main Experimental Conditions

Main features of the method of extended crossing beams and its specific implementation have been repeatedly discussed (Kuchenev, Samsonova, & Smirnov, 1990; Smirnov, 1994; Kuchenev, & Smirnov, 1994). It's unnecessary to repeat this information here. Only the main conditions of the experiment with lanthanum and lutetium should be mentioned.

Both metals investigated have been evaporated from bowl-shaped tantalum crucibles. The necessary power for melting and evaporating of the studied metal, have been applied directly to the metal surface by a melting electron beam. It allow to significantly increase the crucible working life, because its temperature was essentially lower, than the temperature of the central part of the melting zone. The latter factor is especially important in case of lanthanum, because pressure of its saturated vapor at melting temperature is only $p_{sat} = 4 \times 10^{-8}$ Pa and for obtaining sufficiently dense atom beam it's necessary to overheat melting zone by 800–900° above the melting point. Lutetium has $p_{sat} \approx 1$ Pa at the melting temperature.

High-purity metals have been used in the experiment. The total content of REE (Sm, Nd, Pr) impurities in lanthanum was about 0.05%; in addition, Cu (< 0.01%), Fe (< 0.01%), Ca (0.004%) have also been controlled. The total content of REE (Er, Tm, Yb) impurities in lutetium was less than 0.1%; contents of Cu, Fe, Ta, Ca were less than 0.02% of each element.

In the main operation mode during lanthanum evaporation, its surface temperature reaches $T = 1950$ K, while atom concentration in the beam-crossing area was only $n = 6.5 \times 10^9$ cm^{-3}. In case of lutetium, it were $T = 2050$ K, $n = 1.6 \times 10^{10}$ cm^{-3}. As most of metal atoms, lanthanum and lutetium have low-lying excited levels. Most of these levels are metastable, because their parity is identical to the ground level parity. In the evaporation process these levels are populated due to thermal excitation and this population stays unchanged during their flight from crucible to atom collector.

Estimations, based on the Boltzmann distribution gives the following values of thermal level populations for a lanthanum atom (in % from total concentration of atoms in the beam; within brackets indicated level energy in cm^{-1}): $a^2D_{3/2}$ (0) – 43.7; $a^2D_{5/2}$ (1053) – 30.3; $a^4F_{3/2}$ (2668) – 6.16; $a^4F_{5/2}$ (3010) – 7.17; $a^4F_{7/2}$ (3495) – 6.69; $a^4F_{9/2}$ (4122) – 5.28; $a^2F_{5/2}$ (7012) – 0.38; $a^2F_{7/2}$ (8052) – 0.24. Thus, on the levels of ground term $5d6s^2\ a^2D$ there are 74.0% atoms in the beam, while the total population of quartet levels of $5d^26s\ a^4F$ term is 25.3%, and for a higher-lying doublet term $5d^26s\ a^2F$ it was only 0.62%. In case of the lutetium atom the situation is significantly simpler: $5d6s^2\ ^2D_{3/2}$ (0) – 72.2; $5d6s^2\ ^2D_{5/2}$ (1993) – 25.9. Population of the lowest odd $6s^26p\ ^2P°_{1/2}$ level with energy $E = 4136$ cm^{-1} is 1.9%. Thus, on the levels of ground term $5d(^2D)6s^2\ ^2D$ of the lutetium atom stay totally 98.1% from all beam atoms. Presence of metal atom distribution by several low-lying levels have been considered in some theoretical works (e. g. (Peterkop, 1983; Peterkop, 1985a; Peterkop, 1985b) during comparison of calculated cross-sections with experimental ones.

Under carrying out experiments for both elements the current density of electron beam haven't exceed 1.0 mA/cm^2 in the electron energy working range: 0–200 eV for lanthanum and 0–250 eV for lutetium. The equipment effective spectral resolution was about 0.1 nm in short-wavelength part of spectrum at $\lambda < 600$ nm; change of monochromator diffraction grating when working in longer wavelengths with $\lambda > 600$ nm resulted in deterioration of spectral resolution up to 0.2 nm, but for LaIII and LuIII in this part of spectrum only two lines were registered.

The measurement accuracy of cross-sections relative values was in the range of 5–15%, depending on intensity and spectral position of the line. The general trend is that with increasing of the wavelength the signal-to-noise ratio deteriorates due to increasing of influence of the continuous spectral background from the melted metal surface. In spite of presence of diaphragms, this radiation in some measure is scattered by equipment elements and gets to the radiation receiver photocathode. For lanthanum and lutetium the role of this radiation is approximately the same, because evaporation conditions for both metals are about the same. Cross-sections absolute values were defined with the accuracy from ±17 to ±27%; the scale of absolute values was established by the helium standard.

3. Results and Discussion

Lanthanum and lutetium spectra, resulted owing to atom bombardment by electron beam with energy of 50 eV, have been registered in wavelength range of λ = 190–850 nm. Appearance of LaIV and LuIV spectra at this exciting electron energy is impossible, because their threshold energies are $E_{\text{thr}} = 55.4$ and 52.4 eV for LaIV and LuIV correspondingly. Besides, appearance of LaO and LuO oxides spectral bands, which were reported in the work (Meggers, Corliss, & Scribner, 1975, pp. 130, 138), at our experiment conditions is also impossible. Thus, all objects, registered in our work, belong to lanthanum and lutetium atom and their single and double-charged ions spectra. LaIII and LuIII spectral lines were detected in the range of λ = 221–620 nm.

19 excitation cross-sections of LaIII and 19 excitation cross-sections of LuIII measured at the exciting electron energy of 50 eV. At two optical excitation functions (OEF) for each ion have been recorded in the electron energy range from excitation threshold up to 200 eV for LaIII and up to 250 eV for LuIII. Measurement results with added spectral reference data are presented in Table 1, 3 (for lines with OEFs recorded) and in Table 2, 4 (for these lines the reliable detection of OEFs was impossible).

In Table 1–4 are shown wavelengths, transitions, internal quantum numbers for lower J_{low} and upper J_{up} levels, energies of lower E_{low} and upper E_{up} levels (counted from ground levels of corresponding double-charged ions), excitation cross-sections at electron energy of 50 eV Q_{50}. Besides, in Table 1, 3 cross-sections $Q_{\max}$ at OEF maximum and maximum position $E(Q_{\max})$ are also shown. Numbers in the OEF column in Table 1, 3 correspond with curve numbers in Fig. 1 and 2 for LaIII and LuIII respectively. The reference data are presented according to the compilations (Kramida et al., 2014; Ralchenko et al., 2010).

Table 1. Excitation cross-sections of LaIII (with OEFs recorded)

λ, nm	Transition	J_{low}–J_{up}	E_{low}, cm^{-1}	E_{up}, cm^{-1}	Q_{50}, 10^{-18} cm^2	Q_{max}, 10^{-18} cm^2	$E(Q_{max})$, eV	OEF
221.607	$5p^65d^2D$–$5p^66p^2P°$	3/2–3/2	0	45110	0.23	0.24	60	*2*
229.774	$5p^65d^2D$–$5p^66p^2P°$	5/2–3/2	1603	45110	1.98	2.06	60	*2*
237.937	$5p^65d^2D$–$5p^66p^2P°$	3/2–1/2	0	42015	1.35	1.38	60	*1*
317.169	$5p^66s^2S$–$5p^66p^2P°$	1/2–3/2	13591	45110	1.47	1.53	60	*2*
351.716	$5p^66s^2S$–$5p^66p^2P°$	1/2–1/2	13591	42015	0.74	0.76	60	*1*

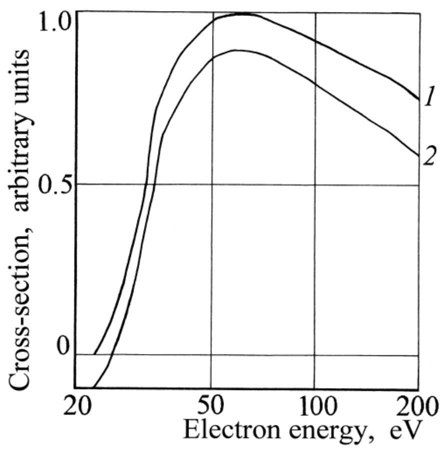

Figure 1. Optical excitation functions of La III

Table 2. Excitation cross-sections of LaIII (without OEFs)

λ, nm	Transition	J_{low}–J_{up}	E_{low}, cm^{-1}	E_{up}, cm^{-1}	Q_{50}, 10^{-18} cm^2
247.660	$5p^66p^2P°$–$5p^66d^2D$	1/2–3/2	42015	82380	1.02
247.866	$5p^66p^2P°$–$5p^67s^2S$	1/2–1/2	42015	82347	0.69
265.150	$5p^66p^2P°$–$5p^66d^2D$	3/2–5/2	45110	82814	1.37
268.234	$5p^66p^2P°$–$5p^66d^2D$	3/2–3/2	45110	82380	0.19
268.475	$5p^66p^2P°$–$5p^67s^2S$	3/2–1/2	45110	82347	1.15
289.788	$5p^65f^2F°$–$5p^66g^2G$	7/2–9/2	92534	126953	0.12
290.457	$5p^65f^2F°$–$5p^66g^2G$	5/2–7/2	92454	126952	0.15
448.298	$5p^65f^2F°$–$5p^65g^2G$	5/2–7/2	92454	114754	0.29
449.906	$5p^65f^2F°$–$5p^65g^2G$	7/2–9/2	92534	114755	0.36
549.190	$5p^65f^2F°$–$5p^67d^2D$	7/2–5/2	92534	110738	0.12
552.954	$5p^65f^2F°$–$5p^67d^2D$	5/2–3/2	92454	110534	0.10
577.814	$5p^67p^2P°$–$5p^67d^2D$	1/2–3/2	93232	110534	0.41
588.863	$5p^67p^2P°$–$5p^68s^2S$	1/2–1/2	93232	110209	0.26
614.199	$5p^67p^2P°$–$5p^67d^2D$	3/2–5/2	94461	110738	0.42

Partial state diagrams with transitions studied are shown in Fig. 3, 4 for LaIII and LuIII correspondingly. Terms with $E > 80000$ cm^{-1} are shown without splitting by J, because for these terms this splitting is small. Common characteristics of the terms are shown below X axis. The principal quantum numbers n are shown in fields of figures to the left of terms; to the right of terms J values are shown.

Table 3. Excitation cross-sections of LuIII (with OEFs recorded)

λ, nm	Transition	J_{low}–J_{up}	E_{low} cm^{-1}	E_{up}, cm^{-1}	Q_{50}, 10^{-18} cm^2	Q_{max}, 10^{-18} cm^2	$E(Q_{max})$, eV	OEF
223.618	$4f^{14}6s\ ^2S$ –$4f^{14}6p\ ^2P°$	1/2–3/2	0	44705	23.9	38.7	125	2
260.335	$4f^{14}6s\ ^2S$ –$4f^{14}6p\ ^2P°$	1/2–1/2	0	38400	9.47	15.3	125	1
277.254	$4f^{14}5d\ ^2D$ –$4f^{14}6p\ ^2P°$	5/2–3/2	8647	44705	8.71	14.1	125	2
305.787	$4f^{14}5d\ ^2D$ –$4f^{14}6p\ ^2P°$	3/2–1/2	5707	38400	4.44	7.17	125	1

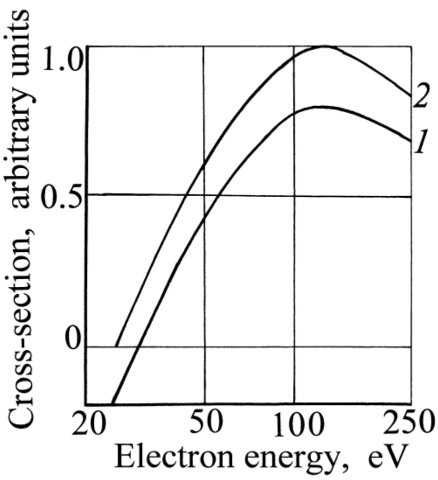

Figure 2. Optical excitation functions of Lu III

As noted in the Introduction, structures of outer electron shells of lanthanum and lutetium double-charged ions are significantly similar. This similarity can be substantially seen in Fig. 3, 4. Though LaIII has $5p^6 5d\ ^2D_{3/2}$ as the ground state, and LuIII has $4f^{14}(^1S)6s\ ^2S_{1/2}$, this difference doesn't affect the level set and possible transition between levels for these ions. Some visible differences between Fig. 3 and 4 (e.g., on LaIII diagram absent $5p^6 6f\ ^2F°_J$ levels which take place in case LuIII), are caused by secondary factors.

Table 4. Excitation cross-sections of LuIII (without OEFs)

λ, nm	Transition	J_{low}–J_{up}	E_{low}, cm^{-1}	E_{up}, cm^{-1}	Q_{50}, 10^{-18} cm^2
206.535	$4f^{14}6p\ ^2P°$–$4f^{14}6d\ ^2D$	3/2–5/2	44705	93107	5.70
207.056	$4f^{14}6p\ ^2P°$–$4f^{14}7s\ ^2S$	1/2–1/2	38400	86681	4.98
209.945	$4f^{14}6p\ ^2P°$–$4f^{14}6d\ ^2D$	3/2–3/2	44705	92321	0.83
238.159	$4f^{14}6p\ ^2P°$–$4f^{14}7s\ ^2S$	3/2–1/2	44705	86681	7.08
272.165	$4f^{14}6d\ ^2D$ –$4f^{14}6f^2F°$	3/2–5/2	92321	129053	0.96
280.091	$4f^{14}6d\ ^2D$ –$4f^{14}6f^2F°$	5/2–7/2	93107	128799	1.33
425.144	$4f^{14}5f^2F°$–$4f^{14}5g\ ^2G$	5/2–7/2	105590	129105	0.79
427.190	$4f^{14}5f^2F°$–$4f^{14}5g\ ^2G$	7/2–9/2	105704	129106	0.85
449.001	$4f^{14}7p\ ^2P°$–$4f^{14}7d\ ^2D$	1/2–3/2	100357	122622	0.73
495.643	$4f^{14}7p\ ^2P°$–$4f^{14}7d\ ^2D$	3/2–5/2	102810	122981	1.02
514.587	$4f^{14}7p\ ^2P°$–$4f^{14}8s\ ^2S$	1/2–1/2	100357	119784	0.59
578.647	$4f^{14}5f^2F°$–$4f^{14}7d\ ^2D$	7/2–5/2	105704	122981	0.24
586.971	$4f^{14}5f^2F°$–$4f^{14}7d\ ^2D$	5/2–3/2	105590	122622	0.17
588.976	$4f^{14}7p\ ^2P°$–$4f^{14}8s\ ^2S$	3/2–1/2	102810	119784	0.22
619.806	$4f^{14}7s\ ^2S$–$4f^{14}7p\ ^2P°$	1/2–3/2	86681	102810	1.65

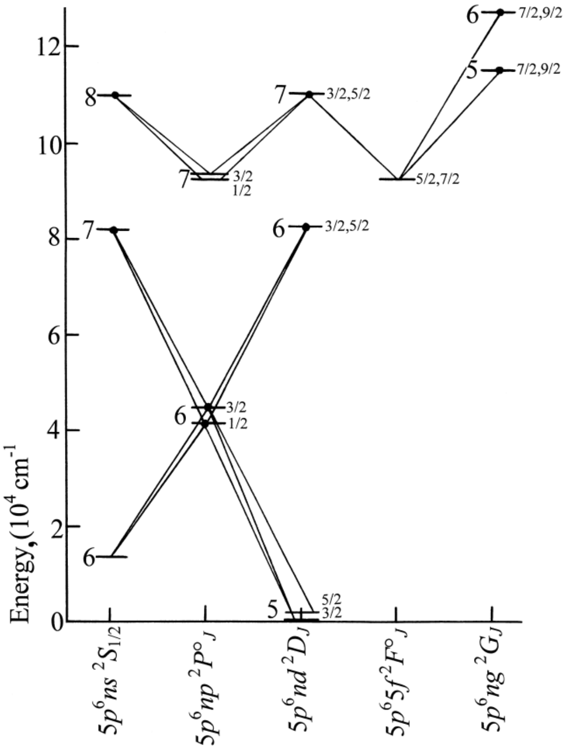

Figure 3. Partial state diagram of La III

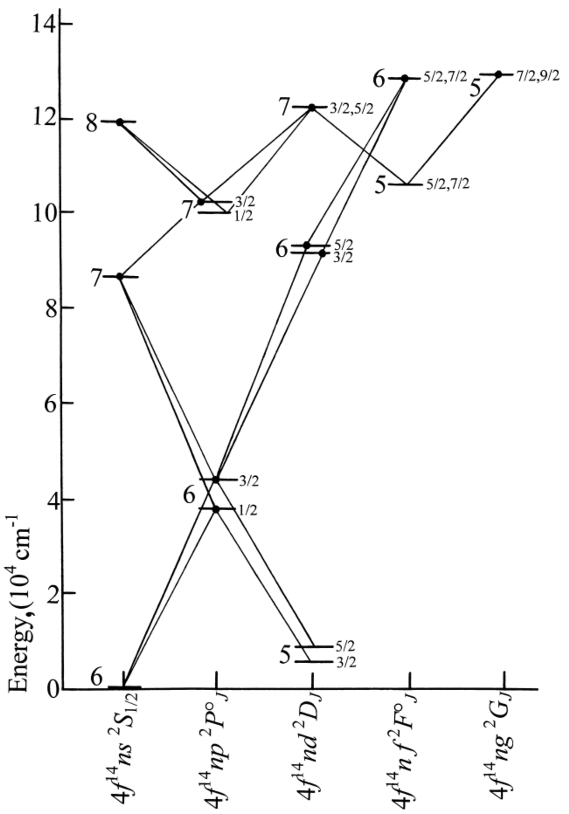

Figure 4. Partial state diagram of Lu III

In experiments with crossing beams, population of the studied k level in the stationary excitation mode was realized by two processes: 1) direct excitation by electron impact from initial state (states) of excited particles; 2) cascade excitation by spontaneous transitions from higher-lying levels l. De-excitation of k level was realized by spontaneous radiative transitions to lower levels i, in most cases branching took place, i.e. competition for these transitions.

In the experiments with registration of the optical emission of excited particle, when the excitation event was detected by registration of a spontaneously emitted photon, the measured cross-section values were excitation cross-sections of spectral lines Q_{ki} and Q_{lk}, which characterized spontaneous transition probabilities for $k \rightarrow i$ and $l \rightarrow k$ transitions correspondingly. Connection between these values and direct excitation cross-section q_k for k level is established by the equation

$$Q_k = \sum_i Q_{ki} - \sum_l Q_{lk} \quad . \tag{1}$$

The first sum in this equation is the total excitation cross-section q_{tot} for k level, which takes into account both direct excitation and cascade population. The second sum is the total excitation cross-section for cascade transitions. Obtaining of the full experimental information about cascade transitions is impossible, because their number is theoretically unlimited, as a number of upper energy levels for any atom. The second significant circumstance is the fact, that at increasing of the lower level energy, the wavelength of cascade transitions goes to the IR range, where their study is significantly impeded due to the limitation of current technical possibilities of optical emission registration systems. At the same time, for double-charged ions, studied in this work, consideration of branching for most of levels, presented in Tables 1–4, is also incomplete, because at increasing of the upper level energy, the wavelength of the most intensive transitions from these levels goes to the VUV range.

Nevertheless, it is possibly to compare the relative excitation efficiencies for LaIII and LuIII, basing on fact, that most of transitions, presented in Tables 1, 2 and 3, 4, are identical. This comparison is presented in Table 5, where, except values, presented in Tables 1–4, simplified designation is used of total level excitation cross-section: $\sum_i Q_{ki} \equiv \Sigma Q_{50}$. Besides, in the last column relation of ΣQ_{50} values for lutetium and lanthanum ions are shown.

Table 5. Total cross-section ratio for excitation of LuIII and LaIII levels

Upper level	J_{up}	E_{up}(La), cm^{-1}	E_{up}(Lu), cm^{-1}	ΣQ_{50}(La), 10^{-18} cm^2	ΣQ_{50}(Lu), 10^{-18} cm^2	ΣQ(Lu)/ΣQ(La)
$4f^{14}7s\ ^2S$	1/2	82347	86681	1.84	12.06	6.55
$4f^{14}8s\ ^2S$	1/2	110209	119784	0.26	0.81	3.12
$4f^{14}6p\ ^2P°$	1/2	42015	38400	2.09	13.91	6.66
$4f^{14}6p\ ^2P°$	3/2	45110	44705	3.68	32.61	8.90
$4f^{14}6d\ ^2D$	3/2	82380	92321	1.21	0.83	0.69
$4f^{14}6d\ ^2D$	5/2	82814	93107	1.37	5.70	4.16
$4f^{14}7d\ ^2D$	3/2	110534	122622	0.51	0.90	1.76
$4f^{14}7d\ ^2D$	5/2	110738	122981	0.54	1.26	2.33
$4f^{14}5g\ ^2G$	7/2	114754	129105	0.29	0.79	2.72
$4f^{14}5g\ ^2G$	9/2	114755	129106	0.36	0.85	2.36

As can be seen from Table 5, almost for all levels studied, lutetium excitation cross-sections are greater, than lanthanum cross-sections. The only exception is $4f^{14}6d\ ^2D_{3/2}$ level, for which ΣQ(Lu)/ΣQ(La) = 0.69. In this case for LuIII doesn't have rather intensive transition $4f^{14}6p\ ^2P°_{1/2} - 4f^{14}6d\ ^2D_{3/2}$, because it lies in the VUV range (λ = 185.457 nm). LaIII has the similar transition at λ = 247.660 nm, which is simply recorded by our equipment. On the whole, from Table 5 data, it follows that ΣQ(Lu)/ΣQ(La) ratio is decreased by increasing of level energy.

4. Conclusion

Experimental study of inelastic electron-atom collisions, resulting in generation of double-charged excited ions, is of interest both of fundamental science and for some practical tasks. Development of metal vapor lasers also continues, for which the role of double and multi-charged ions is significant. Besides, such ions appear in some types of plasma-chemical reactors and in electron beam plasma installations. This work to some extent compensates the significant deficiency of data about generation processes of double-charged ions in electron-atom collisions.

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