

Radiative lifetimes of excited states of atoms

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A review of experimental and theoretical studies of radiative lifetimes of excited states of the hydrogen atom, of atoms of alkali metals, and atoms of the copper subgroup is presented. A complete compilation of all published values of radiative lifetimes of all excited states with a critical analysis for every atom is given. The regularities in the variation of radiative lifetimes in spectral series of excited states are brought out and constants of the power-law dependences on the effective principal quantum number are determined. A correlation between the behavior of lifetimes and the effective orbital parameter is established and it is proposed to use this correlation for the determination of the application limits of the power-law constants for evaluation of lifetimes of uninvestigated states. On the basis of a critical analysis of published sources, of the regularities in the variation of lifetimes and of a statistical treatment of values available in the literature, a table of recommended values of radiative lifetimes of excited states of all atoms of the first group is compiled.

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I. INTRODUCTION

Development of fundamental and applied studies in fields of quantum electronics, plasma physics, physics of upper levels of the atmosphere and quantum chemistry requires knowledge of values of radiation atomic constants: average lifetimes of excited states (τ_k), probabilities of spontaneous transitions (A_{ik}), oscillator strengths (f_{ki}).

The interest in the determination of radiative lifetimes connected with the necessity of the knowledge of absolute transition probabilities and also connected with needs of the physics of elementary processes with participation of excited states of atoms and ions led to the development of new effective methods of measurement of τ_k such as the delayed coincidence technique and the beam-foil technique and to the improvement of old classical Hanle and phase shift methods. On the other hand, the development of fast computers contributed to the development and application to specific atomic systems of theoretical methods of determination of radiative lifetimes. However, due to the approximate nature of calculations of atomic structures quantum mechanical methods do not always allow one to calculate radiative lifetimes of excited states with high accuracy. Especially it applies to heavy atoms which have complex electronic shells. It is necessary to note also that theoretical methods do not have reliable internal criteria of the accuracy of calculations. But

neither are experimental methods free from sources of accidental and systematic errors. Therefore, it seems necessary for a determination of the most reliable value of the radiative lifetime to compare results obtained by different experimental as well as theoretical methods.

As a result of intense development and application of different methods of determination of radiative lifetimes in the last fifteen years (Fig. 1) vast information on τ_k of excited states of atoms and ions has been accumulated. However, completeness and reliability of the data for different atoms and different excited states

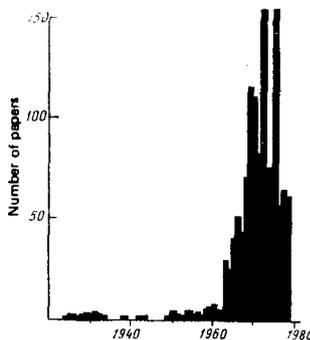


FIG. 1. Distribution of papers on determination of lifetimes of excited states of atoms according to years.

are not equal. There are atomic states which are studied in dozens of works (lower excited states of mercury, neon, helium) and there are atoms excited state lifetimes of which are almost not studied (subgroups of copper, fluorine, scandium, titanium, etc.). On the other hand, investigations made by different methods and at different times very often give data on lifetime which differ significantly. Information on radiative lifetimes is published in dozens of different journals, conference reports, preprints, etc., often hardly accessible and left out of sight of most of "consumers." However, at present there exists no complete review of all articles on determination of τ_k which would systematically discuss all excited states of atoms of all groups of the periodic system. Existing reviews are devoted to particular atoms and states which are of most interest for applications. Only for atoms of the group of lanthanides is there a complete compilation of values of radiative lifetimes published before 1978.¹⁻² A review of experimental results on determination of lifetimes of some excited states of several atoms of the third and fourth periods (NaI, MgI, AlI, FeI, NiI, ZnI) is given in Ref. 3. A complete compilation of all experimental and theoretical values of τ_k of the helium atom obtained before 1975 is published in Ref. 4. Lifetimes of autoionization states of helium are considered in Ref. 5.

Existing reviews on transition probabilities A_{ik} and oscillator strengths f_{ik} ⁶⁻⁸ are more systematic and complete. However, the reviews of Refs. 6-8 do not allow one to determine the required values of τ_k with sufficient precision due to several causes. First, they do not always have data on all possible transitions from the given excited state which are necessary for the calculation of the radiative lifetime. Second, the reviews of Refs. 6-8 are somewhat outdated: the review of Ref. 6 devoted to transition probabilities of the first ten elements includes work up to 1963, the review of Ref. 7 on the elements from 11 to 20 goes up to 1969 and the review of Ref. 8 of the transition probabilities and oscillator strengths of 70 elements was published in 1968. Because of this the main body of results contained in these reviews were obtained by imperfect, from the present-day point of view, methods which had hidden sources of possible systematic errors. As was mentioned many times in the literature, especially strong contradictions are observed between the data obtained by contemporary methods and the data of Ref. 8. For example, recent measurements of τ_k of excited states of FeI and CoI by the method of time resolved analysis with selective laser excitation⁹ gave results which differ by a factor of 3 to 20 from the values obtained from the data of Ref. 8.

Because of the aspects mentioned above it seems to us timely and necessary to write a review of all the data on radiative lifetimes of excited states of atoms with the aim: first, to make clear what has been done already and what is still necessary to do; second, to find general regularities relating lifetimes of levels of an atom and of analogous levels of atoms of the subgroup of the periodic system; third, on the basis of an analysis and a corresponding statistical study of available

data, an analysis of experimental conditions at which the data were obtained, and trends in the variation of τ_k to obtain the most probable values of radiative lifetimes which can be recommended for use. Realizing that writing a review on all atoms is difficult and time consuming we decided to write our review on groups of the periodic system of elements. Such a solution, first, hastens the publication of each separate finished part, and second, a review of work devoted to similar atoms is made easier due to generality of the experimental approach and due to common aspects of the variation of τ_k in atoms with analogous system of levels.

The present review is devoted to radiative lifetimes of excited states of atoms of the first group of the periodic system of elements. The material reviewed goes up to June 1981.

2. THEORETICAL RELATIONS

The radiative lifetime of an excited state of an atom τ_k is the time interval during which the number of atoms N_k in the excited state k is decreased due to spontaneous transitions to $1/e$ of its original value ($e = 2.71828$). The spontaneous transition of an atom from the state k to the lower state i with the emission of a photon is characterized by the atomic constant—the transition probability A_{ki} . The notion of the transition probability was introduced for the first time by Einstein¹⁰ who considered radiative decay as analogous to the process of radioactive decay. The number of spontaneous transitions per unit time for N_k atoms is $N_k A_{ki}$. And the rate of the spontaneous decay of N_k atoms from the state k to all lower states i is

$$\frac{dN_k}{dt} = -N_k \sum_i A_{ki}. \quad (1)$$

From this, by definition, the radiative lifetime τ_k is introduced as

$$\tau_k = \frac{1}{\sum_i A_{ki}}. \quad (2)$$

In the case when there is only one transition from the state k to the ground state i (resonance transition) the lifetime τ_k is uniquely related to the oscillator strength f_{ik} and to the line strength S_{ki} :

$$\tau_k = 1.499 \cdot 10^{-16} \lambda^2 \frac{q_k}{q_i} \frac{1}{f_{ik}}, \quad (3)$$

$$\tau_k = 4.935 \cdot 10^{-19} q_k \lambda^3 \frac{1}{S_{ki}}, \quad (4)$$

where q_k and q_i are statistical weights of upper and lower states and λ is the transition wavelength in angstroms.

Radiative lifetimes of excited states of atoms usually are in the range of 10^{-6} – 10^{-9} s with the exception of metastable states which can have lifetimes of the order of seconds and more and autoionization states lifetimes of which can be $\ll 10^{-9}$ s.

The relations (1), (2) are valid in the absence of absorption, stimulated emission, collision effects etc. In the experimental measurements of τ_k all these effects can be present to some extent. Therefore, in analyzing experimental results it is important to pay attention to

the experimental conditions and specific features of the method used.

3. REVIEW OF EXPERIMENTAL AND THEORETICAL VALUES OF LIFETIMES OF EXCITED STATES OF ATOMS OF THE FIRST GROUP

Here we do not pursue the aim of giving a detailed review of all existing work on the determination of τ_k of atoms of the 1st group and the methods which were used. This would take too much space and, besides that, there are many good critical reviews of the methods of radiative lifetime measurements in the literature. Therefore, we give only a complete compilation of all the experimental and theoretical results known at present with a brief comment on every atom, the cases of considerable deviation between the data obtained in different papers being considered in greater detail.

All experimental and theoretical methods of determination of τ_k known at present were used in studies of τ_k of atoms of the 1st group. In the literature there are several general reviews of experimental methods^{11,12} and also some detailed reviews of the particular most effective methods such as the delayed coincidence technique (DC),¹³ the beam-foil (beam-gas) method (BF, BG),¹⁴ the Hanle or level crossing method (H, LC),^{15,16} the phase shift technique (PS),¹⁷ and excited beams (EB). Theoretical methods (T) are considered in Ref. 18, 19. In some papers the methods of electron-optical chronography (EOC), optical double resonance (ODR) and direct oscilloscopic methods (O) were used. In the tables after the abbreviated names of the methods the letter L is added in some cases which means that the work is done by laser excitation of the state being studied.

a) Hydrogen

It is logical to begin the review of the radiative lifetimes of excited states of atoms of the 1st group with the hydrogen atom (H) as an atom with one valence electron.

The first studies of lifetimes of excited states of the hydrogen atom were done by Wien.²⁰ He studied the decay of the H_{α} , H_{β} and H_{γ} spectral lines emitted by the beam of excited hydrogen atoms moving in vacuum ("canal rays"). However, the imperfect experimental technique (vacuum of 10^{-3} Torr, beam nonuniform in atom velocities, indirect method of measurement of atom velocity, photographic method of registration) did not allow him to obtain reliable results.

The first work in which theoretical values of radiative lifetimes of excited states of the hydrogen atom were given is the monograph by Bethe²¹ devoted to the theory of one- and two-electron atoms. All later experimental measurements²²⁻²⁸ and calculations²⁹ only confirmed the values of the lifetimes given in Ref. 21 (Table I).

TABLE I. Radiative lifetimes of excited states of the hydrogen atoms.

State	Lifetime, ns	Method	Reference	State	Lifetime, ns	Method	Reference
3S	160	T	21	5d	69.5	T	29
3S	135(14)	BF	22	6d	426	T	21
3S	160	BG	23	6d	119	T	29
3S	148(11)	BF	24	7d	187	T	29
3S	159	T	29	8d	277	T	29
4S	230	T	21	9d	384	T	29
4S	186(27)	BF	22	10d	537	T	29
4S	230(17)	BF	24	11d	712	T	29
4S	227	T	29	12d	923	T	29
5S	360	T	21	4f	73	T	21
5S	378(38)	BF	24	4f	72.5	T	29
5S	352	T	29	5f	140	T	21
6S	570	T	21	5f	140	T	29
6S	534	T	29	6f	243	T	21
7S	782	T	29	6f	240	T	29
8S	1169	T	29	7f	378	T	29
9S	1511	T	29	8f	559	T	29
10S	2006	T	29	9f	791	T	29
11S	2610	T	29	10f	1079	T	29
12S	3334	T	29	11f	1426	T	29
2p	1.6	T	21	12f	1849	T	29
2p	1.600(4)	BG	23	5g	235	T	21
2p	1.60(1)	BF	26	5g	235	T	29
2p	1.592(25)	BF	27	6g	405	T	21
2p	1.6	T	29	6g	403	T	29
3p	5.4	T	21	7g	635	T	29
3p	5.4	BG	23	8g	938	T	29
3p	5.55(13)	BG	26	9g	1328	T	29
3p	5.5(2)	BF	28	10g	1810	T	29
3p	5.41(18)	BF	28	11g	2393	T	29
3p	5.8(3)	BF	24	12g	3099	T	29
3p	5.2	T	29	6h	610	T	21
4p	12.4	T	21	6h	608	T	29
4p	14.6(25)	BF	26	7h	960	T	29
4p	11.25(78)	BF	28	8h	1425	T	29
4p	12.4(6)	BF	24	9h	2047	T	29
4p	12.7	T	29	10h	2750	T	29
5p	24	T	21	11h	3634	T	29
5p	21.9(30)	BF	26	12h	4699	T	29
5p	23.8(30)	BF	24	7i	1350	T	29
5p	23.8	T	29	8i	2006	T	29
6p	41	T	21	9i	2836	T	29
6p	40.7	T	29	10i	3872	T	29
7p	64.4	T	29	11i	5118	T	29
8p	95.6	T	29	12i	6612	T	29
9p	136	T	29	8k	2083	T	29
10p	186	T	29	9k	3813	T	29
11p	247	T	29	10k	5211	T	29
12p	321	T	29	11k	6890	T	29
3d	15.6	T	21	12k	8894	T	29
3d	16.1(6)	BF	22	9l	4909	T	29
3d	15.6	BG	23	10l	6708	T	29
3d	15.8(6)	BF	24	11l	8914	T	29
3d	15.5	T	29	12l	11526	T	29
4d	36.5	T	21	10m	8419	T	29
4d	37.7(55)	BF	22	11m	11479	T	29
4d	36.9(15)	BF	24	12m	14432	T	29
4d	36	T	29	11n	13684	T	29
5d	70	T	21	12n	17772	T	29
5d	69.8(70)	BF	24	12o	21310	T	29

In the Table I (and all following tables) designations of excited states are given without multiplicity and fine structure indices (with the exception of some states of heavy atoms for which there exist results of measurements of separate components of the fine structure). The values of lifetimes are given in ns (10^{-9} s) and the error of measurement in the last digits of the result is given in brackets. Therefore, the notation 1.600(4) means $(1.6 \pm 0.004) \cdot 10^{-9}$ s. In the third column the abbreviated name of the method which was used to obtain the result is given and in the fourth column—the cited source from the list of references.

The most complete work at present is that in Ref. 29 made by the method of numerical Coulomb approximation. The comparison of the data of Ref. 29 with the data of previous theoretical and experimental work shows good agreement (see Table I). It is necessary to note the high accuracy of the values of lifetimes of the hydrogen atom levels calculated by Bethe²¹ in 1933, which is confirmed by the results of all later work.

b) Alkali metals (Li I subgroup)

The earliest measurements of radiation atomic constants of alkali metals were associated with measurements of relative and absolute oscillator strengths. The work of Rozhdestvenskii,³⁰ Prokof'ev,³¹ Filippov,³² Kvater,³³ and Penkin³⁴ carried out using the method of D. S. Rozhdestvenskii hooks at the Leningrad university has become classical by now and gave important information on the transition probabilities for the main series of spectral lines as well as on the ratios of transition probabilities of separate components of the doublets which was useful for subsequent direct measurements of radiative lifetimes.

It is convenient to separate the review of the work on the determination of radiative lifetimes of excited states of atoms of alkali metals into two parts: the ²P-states and the states not connected by direct optical transition with the ground state, because the articles concerned with each of these groups of levels have excitation and registration methods with common features.

1. ²P-states

The majority of papers on the determination of lifetimes of excited states of alkali metal atoms is devoted to the ²P-states. This is explained not only by the practical needs but also by the fact that the methods based on optical excitation (LC, ODR, PS) are most easily applied to the levels connected with the ground state. In studies of lifetimes of the ²P-states different experimental methods were used, measurements being made in vapor filled cells as well as in atomic beams. To reduce the effect of light trapping to a minimum measurements were made at very low vapor pressure and the dependence of τ_h on pressure was measured in the majority of cases. The pressure effects were investigated especially carefully in the study of ²P-states in Refs. 36, 51. The results of experimental and theoretical studies of ²P-states for the lithium subgroup are given in Table II.

Lithium. Considerably fewer papers in comparison with other alkali metals are devoted to the study of lifetimes of P-states of the lithium and potassium atoms. This is explained, apparently, by the low intensity of spectral lines and by the chemical activity of these elements. The results of Ref. 36 give larger values of τ_h of LiI than other experimental data. This can, apparently, be explained by an insufficiently precise taking into account of the velocity losses of ions of the beam in the gas target in which nitrogen and neon at a pressure of 10⁻³ Torr were used. A similar overestimate of the values in Ref. 36 is observed for the S- and D-levels of LiI (Table IV) indicating a systematic error common to all levels caused by imprecision in determination of the velocity of the ion beam.

Sodium. Approximately a third of all papers on lifetimes of excited states of alkali metals is related to studies of the P-state of sodium atoms. The 3P-state was studied in 27 papers^{19, 23-68, 158} by all the experimental and theoretical methods known at present. Many researchers tested new installations and new methods

TABLE II. Lifetimes of the ²P states of alkali metal atoms.

State	Lifetime, ns	Method	Reference	State	Lifetime, ns	Method	Reference
Lithium (Li I)							
2P	31.9(19)	BG	36	5P	345(43)	DCL	66
2P	27.2(4)	LC	37	5P	342	T	29
2P	25(1)	BF	38	5P	402.9	T	158
2P	26.2(10)	BF	39	5P	330	T	66
2P	27(3)	DL	40	6P	890(90)	DCL	66
2P	27.3	T	59	6P	837	T	29
2P	26.17	T	158	6P	991.7	T	158
2P	27.9(10)	DCL	11	6P	770	T	66
3P	235(12)	BG	36	7P	1450(100)	DCL	66
3P	182(6)	LC	42	7P	1676	T	29
3P	216	T	29	7P	2073	T	158
3P	223.3	T	158	7P	1500	T	66
4P	479(24)	BG	36	8P	3044	T	158
4P	403	T	59	8P	2600	T	66
4P	446.2	T	158	9P	4100	T	66
5P	863.5(432)	BG	36	10P	6000	T	66
5P	628	T	29	11P	8600	T	66
5P	706.2	T	158	12P	12000	T	66
6P	940	T	39	13P	15000	T	66
6P	1058	T	158	17P	11400+5000 -1400	DCL	66
7P	1359	T	39	18P	13900+8000 -2900	DCL	66
7P	1528	T	158				
8P	2176	T	158	Potassium (K I)			
Sodium (Na I)							
3P	15.9(4)	PS	43	4P _{3/2}	26.0(5)	LC	70
3P	15.9(4)	LC	11	4P _{3/2}	28(2)	LC	31
3P	15.9	PS	43	4P _{3/2}	27.8(5)	PS	48
3P	15.9(4)	LC	46	4P _{3/2}	27.6(8)	DC	72
3P	16.3(5)	O	47	4P _{3/2}	26.3(10)	H	166
3P _{3/2}	14.0(2)	PS	16	4P _{1/2}	27.8(8)	DC	72
3P	16.1(3)	LC	49	4P _{1/2}	25.0(3)	H	166
3P	16.1(7)	PS	50	4P _{1/2}	27.3(3)	H	167
3P	16.2	DC	51	4P	26.6	T	29
3P	16.3(4)	DC	52	5P _{3/2}	140.8(10)	LC	70
3P	16.1(10)	DC	53	5P _{3/2}	120(4)	LC	71
3P	16.6(2)	LC	54	5P _{3/2}	133(3)	LC	73
3P	16.0(3)	LC	55	5P	121	T	29
3P	15.9(4)	PS	56	6P _{3/2}	310(15)	LC	73
3P	16.6(4)	LC	57	6P	299	T	29
3P _{3/2}	16.11(5)	LC	58	7P	572	T	29
3P	16.5(5)	LC	59	8P	957	T	29
3P	15.6	BF	60	Rubidium (Rb I)			
3P	17(2)	BF	61	5P _{3/2}	28.2(9)	LC	71
3P	17.3(10)	DC	62	5P _{3/2}	27.0(5)	PS	48
3P	16.0	DC	63	5P _{3/2}	27.1(14)	LC	75
3P _{3/2}	16.4(6)	BF	64	5P _{3/2}	25.5(5)	LC	88
3P _{1/2}	16.1(2)	BF	65	5P _{3/2}	25.8(8)	LC	76
3P _{1/2}	16.30(16)	H	66	5P _{3/2}	27.0(5)	LC	77
3P	16.0(2)	T	29	5P _{3/2}	26.0(18)	H	78
3P	16.5	T	108	5P _{1/2}	30(3)	LC	75
3P	18.17	T	66	5P _{1/2}	28.3(11)	LC	77
4P	17	LC	67	5P _{1/2}	29.4(7)	LC	77
4P _{3/2}	90	LC	68	5P	26.5	T	29
4P	95(4)	DCL	69	6P _{3/2}	100	LC	81
4P	125(12)	T	29	6P _{3/2}	114(6)	LC	81
4P	102	T	158	6P _{3/2}	118(4)	LC	88
4P	100	T	66	6P _{3/2}	109(7)	LC	79
Rubidium (Rb I)							
6P _{3/2}	111(3)	LC	76	6P _{3/2}	29.7(2)	LC	89
6P _{3/2}	112(8)	LC	83	6P _{3/2}	30.8(15)	PS	91
6P _{3/2}	97(3)	LC	85	6P _{3/2}	32.7(15)	LC	98
6P _{1/2}	131(5)	LC	79	6P _{3/2}	31(1)	LC	92
6P _{1/2}	114(13)	LC	82	6P _{3/2}	34	LC	93
6P	99.3	T	29	6P _{3/2}	35.0(15)	PS	91
7P _{3/2}	240(20)	LC	84	6P	30.7	T	29
7P _{3/2}	239(10)	LC	76	7P _{3/2}	160	LC	91
7P	221	T	29	7P _{3/2}	118	LC	93
8P _{3/2}	400(80)	LC	86	7P _{3/2}	122(2)	DC	88
8P	404	T	39	7P _{3/2}	111(6)	LC	92
9P	659	T	29	7P _{3/2}	135(1)	LC	90
10P	1190	T	86	7P _{3/2}	134.5(25)	LC	98
11P	1710	T	86	7P _{3/2}	135(4)	LC	97
12P _{3/2}	1550(200)	DCL	87	7P _{3/2}	156(4)	DCL	97
12P	2400	T	88	7P _{3/2}	134(3)	DCL	98
13P	3230	T	86	7P _{3/2}	135(3)	DCL	98
14P _{3/2}	2800(400)	DCL	87	7P _{3/2}	136(4)	DCL	100
14P	4230	T	86	7P _{3/2}	155(5)	LC	79
15P	5410	T	86	7P _{3/2}	158(5)	DCL	97
16P	6800	T	86	7P _{3/2}	158(5)	DCL	98
17P _{3/2}	6400(1300)	DCL	87	7P _{3/2}	158(3)	DCL	97
17P	8410	T	86	7P _{3/2}	165(6)	DCL	100
18P	10200	T	86	7P	113	T	29
19P	12300	T	86	8P _{3/2}	240(20)	LC	101
20P	14700	T	86	8P _{3/2}	310(15)	LC	98
21P	18000	T	86	8P _{3/2}	300(15)	LC	98
22P _{3/2}	14000(5000)	DCL	87	8P _{3/2}	274(12)	DCL	98
22P	21100	T	86	8P _{3/2}	330(30)	LC	102
23P	24500	T	86	8P _{3/2}	330(30)	LC	102
24P	28300	T	86	8P _{3/2}	307(14)	DCL	98
25P	32500	T	86	8P	265	T	29
26P	37000	T	86	9P _{3/2}	390(30)	LC	66
27P	41900	T	86	9P _{3/2}	502(22)	DCL	98
28P	47200	T	86	9P _{3/2}	575(35)	DCL	98
Cesium (Cs I)							
6P _{3/2}	30.5(7)	PS	48	9P	498	T	29
6P _{3/2}	28(2)	LC	88	10P	826	T	39
6P _{3/2}	29.4(26)	LC	89	10P _{3/2}	900(40)	DCL	103
				10P _{1/2}	920(50)	DCL	103

TABLE III. Radiative lifetimes of the 2P states of Na I.

State	Theory			Experiment ⁴³⁻⁶⁸		
	Ref. 158	Ref. 29	Ref. 66	$\frac{198-68}{60}, \%$	$\frac{1}{n} \sum_{i=1}^n \tau_i$	Number of papers
	Variational Hartree-Fok method ¹⁵⁸	Numerical Coulomb approximation	Coulomb approximation based on SMEOP			
	1977	1977	1980		1962-1977	
3P	18.17	16.5	17	9	16.06	25
4P	116.5	102	100	16	103.3	3
5P	402.9	342	330	22	345	1
6P	991.7	837	770	29	890	1
7P	2073	1676	1500	38	1450	1

Note. SMEOP—semieprirical method based on the effective orbital parameters.

using the value of the lifetime of this level as the standard. The results of all experimental work⁴³⁻⁶⁸ agree within experimental errors. The results of three theoretical determinations^{29, 66, 158} differ and are larger than the average value of all the experimental results (Table III).

As can be seen from Table III, the theoretical results obtained by the method of the Coulomb approximation^{29, 66} are close to the experimental values while the variation method¹⁵⁸ gives values which deviate from the experimental data, the deviation increasing as the principal quantum number increases. The mean value obtained from 25 experimental determinations of τ_k of the 3P-state of NaI must be considered as one of the most reliable values of the lifetime of an excited state of an atom. Such a good agreement of experimental results obtained in the period from 1962 to 1978 at different laboratories allows one to conclude that all the present-day experimental methods of determination of radiative lifetimes of excited states, in principle, do not have sources of large systematic errors. The difference between some results for levels with large principal quantum numbers can be explained by accidental errors or by uncontrolled experimental conditions. Thus, experimentally measured values of τ_k of 17P and 18P states of NaI (see Table II) are three times smaller than the calculated theoretically values⁶⁹ (48.4 and 58.4 μ s correspondingly). Such disagreement was explained by the authors of Ref. 69 by the influence on the lifetimes of upper excited states of the thermal radiation corresponding to room temperature. The thermal radiation field causes the stimulated emission from the excited state under investigation of transitions with $h\nu \ll kT$ which leads to a redistribution of the population and a decrease of the measured lifetime τ^* in relation to the theoretically calculated value of τ_k at $T=0$ K. The experimentally observed τ^* is related to τ_k by⁶⁹

$$\frac{1}{\tau^*} = \frac{1}{\tau_k} + \frac{1}{\tau_k^T} \quad (5)$$

The addition τ_k^T corresponding to the influence of the thermal radiation is connected with the transition probability A_{ki} by the relation

$$\frac{1}{\tau_k^T} = \sum_i A_{ki}^T(\bar{n}_i) \quad (6)$$

where

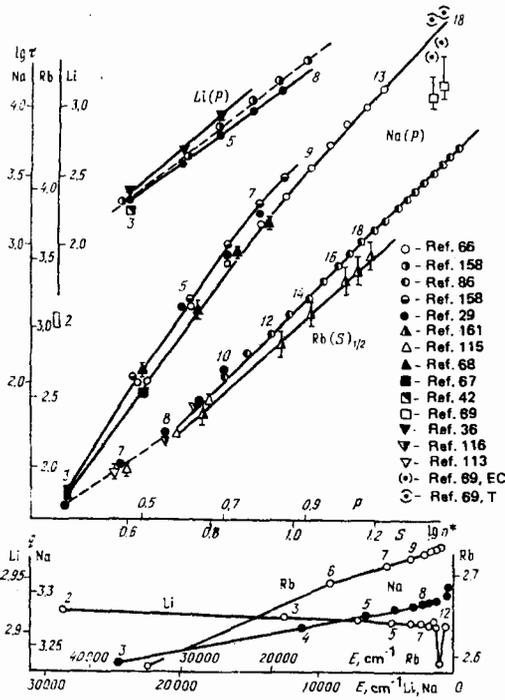


FIG. 2. Plots of the dependence of the radiative lifetime on the effective principal quantum number $\tau(n^*)$ and of the effective orbital parameter on the energy $q(E)$. EC—experimental values corrected for the thermal radiation effect, T—values calculated theoretically.

$$A_{ki}^* = A_{ki} \quad \text{for } k > i, \\ A_{ki}^* = g_i A_{ki} / g_k \quad \text{for } k < i; \quad \bar{n} = (\exp^{h\nu/kT} - 1)^{-1}.$$

The estimates of τ_k^T for 17P- and 18P-states of NaI made by the authors of Ref. 69 gave values of 22.7 and 25.6 μ s respectively. The determined values of τ_k^T and the observed values of τ^* (Table II) allow one to determine the experimental values of τ_k corrected for the effect of thermal radiation which were equal to 23 and 30 μ s correspondingly, i.e., closer to the theoretical values, but the disagreement was still present. The plots of the dependences of τ_k on the effective principal quantum number n^* and of the effective orbital parameter q on the state energy E are given in Fig. 2. Such dependences help in the analysis of the regularities in the variation of radiative lifetimes in the spectral series (see section 4 for more details). It can be seen from the plot of $\tau_k(n^*)$ for NaI that the theoretically calculated values of τ_k for the 17P- and 18P-states correspond to the extrapolated values of τ_k for the lower states while τ_k^{exp} and τ_k^T are beyond the extrapolation limits which indicates the possible presence of one more effect⁶⁹ causing a decrease of the measured lifetime. The presence of hidden sources of systematic errors in some experimental and theoretical papers is indicated by the shift of plots with respect to each other in Fig. 2 which can be especially well seen in the case of LiI and RbI.

Rubidium. P-states are studied most completely in rubidium (up to $n=18$). Large doublet splitting made it possible to measure τ_k directly using the weak doublet

components. The lifetimes of $(5, 6)P_{3/2}$ -states were $\sim 10\%$ shorter than τ_k of $(5, 6)P_{1/2}$ -states. The results of the theoretical calculation of Ref. 29 are closer to τ_k of $P_{3/2}$ -states. The large (up to 40%) systematic deviation of the results of experimental determination of τ_k of the $(12, 14, 17, 22)P_{3/2}$ -states⁸⁷ from the results of the theoretical calculations by the method of the Coulomb approximation⁸⁶ is noticeable. The DC method with laser excitation of atoms in a cell filled with vapor was used in the work of Ref. 87. Radiative lifetimes were obtained by extrapolation to zero pressure of the dependence of the effective lifetimes on the rubidium vapor pressure, with the influence of the polarization of radiation, the departure of excited atoms from the observation volume, the linewidth of the laser radiation and the power of the exciting pulse being taken into account. The authors of Ref. 87 comparing their results with the data obtained from the values of oscillator strengths¹⁰⁴ and noting considerable disagreement suppose that more accurate calculations taking into account spin-orbit interaction will give results which are in better agreement with experiment. However, in our opinion the underestimated values of lifetimes⁸⁷ could result from a rapid redistribution of the population of high Rydberg states caused by the thermal radiation field.⁶⁹ The conjecture concerning the underestimated values of experimental data⁸⁷ is supported by the good agreement of the theoretical calculation data⁸⁶ with the extrapolation of all experimental and theoretical lifetime values for the lower $(5-9)P$ -states of RbI (Figs. 4, 5), and the validity of the extrapolation to $n = 12-22$ is supported by the plot of the dependence of q on E (see Section 4).

Cesium. Experimental studies of τ_k of P -states of CsI were carried out using all the basic present-day methods and, as in the case of $3P$ NaI, the results obtained by all methods are in good agreement. The difference between τ_k of $P_{3/2}$ and τ_k of $P_{1/2}$ of CsI is substantially larger than for RbI and attains values of 15-20% (τ_k of $P_{1/2} > \tau_k$ of $P_{3/2}$). The results of a theoretical calculation²⁹ are closer to the values of τ_k of $P_{3/2}$.

2. Levels not connected with the ground state by optical transitions

In contrast to 2P -state the lifetimes of the 2S -, 2D - and 2F -excited states of alkali metal atoms were practically not studied until recently. Before 1975 there were three experimental papers on lithium and three papers on cesium which were devoted to average lifetimes of levels not connected optically with the ground state. Two papers dealt with sodium and one with rubidium. This was caused by the fact that classical methods (ODR, PS, H) based on optical excitation were not applicable to levels not connected with the ground state and only after the development of new methods (DC, BF) and especially after appearance of frequency tuned lasers the number of papers on τ_k of S -, D - and F -states began to increase. However, many levels have not been sufficiently well studied as yet. Results of experimental and theoretical studies of radiative lifetimes

of excited states not connected with the ground state by optical transitions are given in Table IV.

Lithium. Noticeable (up to 20%) disagreement between the data³⁶ on τ_k of 2S - and 2D -levels of LiI and other experimental^{106,107} and theoretical^{29,158} data is caused, evidently, by the same methodological difficulties characteristic of the BG method which were discussed above [see lithium, section b), 1)].

Sodium. The 2S - and 2F -states of NaI are sufficiently well studied experimentally by the delayed coincidence technique with the stepwise excitation of the studied level by two synchronized lasers with tunable wavelength.^{108,109,111,112} One of the lasers excited sodium atoms from the ground $3S$ - into the $3P$ -state and the second laser, synchronized with the first by common pumping, excited atoms from the $3P$ -states into the studied S -, D - or F -states. In these papers for the first time all the advantages of pulsed pumping by two synchronized lasers allowing one to excite selectively practically any level were demonstrated. It eliminates the influence of

TABLE IV. Radiative lifetimes of S -, D -, F -, G -, H -, and I -states of alkali metal atoms.

State	Lifetime, ns	Method	Reference	State	Lifetime, ns	Method	Reference
Lithium (Li I)							
3S	25.5(13)	BG	38	5S	80.57	T	158
3S	30.3	T	29	5S	80	T	66
3S	30.6	T	158	6S	152	T	29
4S	55.8(28)	BG	36	6S	152.4	T	158
4S	48(2)	BF	38	6S	160	T	66
4S	56.6	T	29	7S	269(10)	DCL	108
4S	56.47	T	158	7S	276(14)	DCL	109
5S	113(6)	BG	36	7S	263	T	29
5S	103	T	29	7S	262.42	T	258
5S	102.9	T	158	7S	280	T	66
6S	190(10)	BG	36	8S	393(20)	DCL	108
6S	173	T	29	8S	465(40)	DCL	109
6S	173.3	T	158	8S	422	T	29
7S	220(12)	BG	36	8S	418.5	T	158
7S	273	T	29	8S	450	T	66
7S	272.4	T	158	9S	618	DCL	108
8S	405.7	T	158	9S	713(76)	DCL	109
3D	14.0(7)	BG	36	9S	635	T	29
3D	15.0(1)	BF	38	9S	690	T	66
3D	16.7(10)	O	105	10S	1024(49)	DCL	109
3D	14.60(13)	BGL	106	10S	913	T	66
3D	14.7	T	29	10S	1000	T	29
3D	14.86	T	158	10S	900	T	66
3D	14.5(7)	DCL	107	11S	1270(130)	DCL	109
4D	39.2(20)	BG	36	11S	1263	T	29
4D	33(1)	BF	38	11S	1400	T	66
4D	42.3(15)	O	105	11S	1250	T	66
4D	39.4	T	29	12S	1690	T	29
4D	34.14	T	158	12S	1900	T	66
4D	31(1)	DCL	107	13S	2270(170)	DCL	109
5D	72.0(36)	BG	36	13S	2300	T	66
5D	56(2)	BF	38	13S	2180	T	66
5D	63.7	T	29	3D	19.9	T	29
5D	65.23	T	158	3D	20.45	T	158
6D	106(5)	BG	36	3D	21	T	66
6D	108	T	29	4D	53.5(30)	DCL	108
6D	111.1	T	158	4D	51.3	O	210
7D	139.5(70)	BG	36	4D	57	DCL	111
7D	170	T	29	4D	52.4	T	29
7D	169.7	T	158	4D	54.81	T	158
8D	251.3	T	158	4D	55	T	66
4F	72.4	T	29	5D	120(14)	DCL	109
4F	72.46	T	158	5D	108	T	29
5F	140	T	29	5D	113.5	T	158
5F	140.2	T	158	5D	110	T	66
6F	239	T	29	6D	176(10)	DCL	108
6F	240.4	T	158	6D	206(24)	DCL	109
7F	376	T	29	6D	191	T	29
5G	235	T	29	6D	202.2	T	158
6G	403	T	29	6D	200	T	66
7G	636	T	29	7D	279(15)	DCL	108
				7D	324(32)	DCL	109
				7D	308	T	29
				7D	326.6	T	158
				7D	320	T	66
Sodium (Na I)							
4S	39.5	T	29	8D	449(50)	DCL	108
4S	39.87	T	108	8D	502(39)	DCL	109
4S	37	T	66	8D	463	T	29
5S	71(5)	DCL	108	8D	492.7	T	158
5S	80.3	T	29				

sults of the DCL method^{99, 116, 122, 124} for the S- and D-levels give 15–30% lower values than corresponding data of other methods and of theoretical calculations. The value of τ_k of $9D_{5/2}$ obtained in Ref. 125 is an obvious mistake which follows from comparison with the data of other work and also from an analysis of the dependence $q(E)$ for nD - series of CsI (see Section 4).

In the studies of lifetimes of the S-state of CsI¹²² it was found that the experimentally observed decay time of the excited state after the end of the excitation pulse depends upon the intensity of the laser pulse. When the laser beam was focused inside the volume of the cesium vapor the decay curve became shorter and, vice versa, on defocusing the decay time approached the radiative lifetime of the state being studied. The decrease of the observed lifetime in the DCL method, apparently, is caused by the appearance of collective spontaneous emission (superemission) from the state being studied which caused the appearance of the additional "fast" exponent and the distortion of the decay curve.¹²⁷ The region of the fast decay appears after the time t_D .¹²⁷

$$t_D \sim \frac{8\pi}{Nl\lambda^3 A} \quad (7)$$

where N is the concentration of the excited atoms, l is the length of the excitation volume, λ is the wavelength of the transition studied, A is the transition probability.

The amplitude of the "fast" exponent is proportional to the square of the concentration of the atoms excited to the studied level.¹²⁷ The degree of distortion of the decay curve depends on many factors and, primarily, on the concentration of the excited atoms, i.e., on the power of the exciting pulse. To exclude the influence of the effects connected with high power pumping on the values of lifetimes of excited states obtained by DCL method it is, apparently, necessary to study each time the dependence of the observed lifetime on the power of the exciting laser pulse; however, in the work on the determination of lifetimes of S-, D-, and F-states of CsI and RbI carried out by the DCL method such dependences are not given. The difference in the data on τ_k of RbI and CsI obtained by the DCL method and the data obtained by other experimental methods and by theoretical calculations show that the application of so precise and universal method as the DCL method requires great care and, as in other experimental methods, careful taking into account of all experimental conditions.

3. Autoionization states

The study of autoionization states of atoms and ions is one of important problems of present-day atomic physics. The data on autoionization states are of great significance for the development of an understanding of the intraatomic processes taking place when several electrons are excited. Moreover, the constants of autoionization states are also of practical importance because the existing experimental and theoretical studies show the significant role played by these states in processes with participation of excited atoms and ions, in particular, in the processes using selective photoionization of atoms by laser radiation, which are used for detection of single atoms and for isotope separation.

TABLE V. Radiative lifetimes of autoionization states of alkali metal atoms.

State	Lifetime, ns	Method	Reference	State	Lifetime, ns	Method	Reference
Lithium (Li I)							
1s 2s 3s 4S	9.7(7)	BF	129	1s 2p 3p 4P	0.8(3)	BF	169
1s 2s 3s 4S	6.72(2)	T	108	1s 2p 3p 4P	30(3)	T	170
1s 2s 3s 4S	7.7(10)	BF	169	1s 2p 4p 4P	7.1(30)	BF	133
1s 2s 4s 4S	10.4(20)	BF	133	1s 2p 4p 4P	3.5(10)	BF	169
1s 2s 4s 4S	15.4(5)	BF	169	1s 2p 5p 4P	42(4)	T	170
1s 2s 2p 4P _{3/2}	5800(1200)	EB	128	1s 2p 3d 4D	2.3(4)	BF	130
1s 2s 2p 4P _{3/2}	460(100)	BF	128	1s 2p 3d 4D	3.0(8)	BF	132
1s 2s 2p 4P _{3/2}	140(70)	BF	128	1s 2p 3d 4D	4.47(6)	T	168
1s 2s 3p 4P	270(30)	T	170	1s 2p 3d 4D	1.5(4)	BF	180
1s 2s 4p 4P	300(30)	T	170	1s 2p 4d 4D	2.3(5)	BF	133
1s 2s 5p 4P	500(30)	T	170	1s 2p 4d 4D	1.11(15)	BF	169
1s 2s 3d 4D	5.5(4)	BF	129	1s 2p 5d 4D	2.5(10)	BF	168
1s 2s 3d 4D	4.3(12)	BF	130	1s 2p 4f 4F	23.0(7)	T	168
1s 2s 3d 4D	4.15(4)	T	168	1s 2p(3P) 3d 2D	1.45(10)	BF	133
1s 2s 3d 4D	4.3(1)	BF	169	1s 2p(3P) 4d 2D	0.24(10)	BF	133
1s 2s 4d 4D	5.9(10)	BF	133	1s 2p'(P) 3d 2D	0.063(50)	BF	133
1s 2s 4d 4D	9.6(6)	BF	169	1s 2p ² 2D	0.177	T	131
1s 2s 4f 4F	60.6 (23)	T	168	1s 2p ² 2P	0.015(10)	BF	135
1s 2p 3s 4P ₀	11.8(2)	BF	130	1s 2p ² 2P	0.054	T	131
1s 2p 3s 4P ₀	12.4(5)	BF	128	1s 2p ² 2P	0.041	T	136
1s 2p ² 4P	6.4(3)	BF	130	1s(2s 2p' P) 2P	0.00075(10)	BF	137
1s 2p ² 4P	5.8(7)	BF	131	Potassium (K I)			
1s 2p ² 4P	7(2)	BF	131	3p ³ 4s 3d 4F	90000(20000)	EB	138
1s 2p ² 4P	6.5(3)	BF	132	Rubidium (Rb I)			
1s 2p ² 4P	5.76(5)	T	168	4p ³ 5s 4d 4F	75000(20000)	EB	138
1s 2p 3p 4P	2.9(3)	BF	132				

The studies of lifetimes of autoionization states are only at a beginning stage; there are very few data on τ_k of particular states and there are no systematic studies. However, we found it useful to give in Table V experimental and theoretical values available at present of lifetimes of autoionization states of alkali metal atoms.

c) Copper, silver, gold

The studies of lifetimes of excited states of atoms of the copper subgroup (CuI, AgI, AuI) in contrast to those of alkali metal atoms did not attract sufficient attention until recently. Before 1975 there were only a few experimental investigations made by level crossing and phase shift methods in which the authors studied lifetimes of the resonant 2P -levels. This can be explained by known difficulties in obtaining atomic vapors of these elements and by the lack of demand for the radiation constants of excited states of these atoms. However, rapid development of quantum electronics and thermo-nuclear studies during recent years required data on oscillator strengths, transition probabilities and lifetimes of the atoms of Ib-subgroup and, first of all, of the atoms and ions of the isoelectronic series of CuI. This caused the recent appearance of theoretical¹⁴⁰ and experimental^{139, 171, 172} work in which, besides τ_k of resonance states, lifetimes of higher excited states of CuI were studied. All results available at present in the literature of direct determination of τ_k of CuI, AgI and AuI are given in Table I.

An analysis of Table IV shows that the lifetimes of the atoms of the copper subgroup have not been studied in sufficient detail. A sufficient amount of noncontradictory data is available only for the $4p^2P_{3/2}$ -level of CuI; the experimental data for other levels of CuI^{139, 145, 164, 171} differ between themselves and disagree with the data of the theoretical calculations.¹⁴⁰ Especially strong contradiction is between the experimental^{139, 164} and theoretical¹⁴⁰ data on τ_k of the $6P$, and $7P$, states. In the

TABLE VI. Radiative lifetimes of excited states of Cu I, Ag I, and Au I.

State	Lifetime, ns	Method	Reference	State	Lifetime, ns	Method	Reference
Copper (Cu I)							
3d ¹⁰ 5s ² S _{1/2}	21.0(42)	EOC	139	4p ² P _{3/2} ^o	5.97	T	140
5s ² S _{1/2}	23.5	T	140	4p ² P _{3/2}	7.0(9)	DC	171
6s ² S _{1/2}	86.0(71)	EOC	139	5p ² P _{1/2}	38.8	T	140
6s ² S _{1/2}	52.8	T	140	5p ² P _{1/2} ^o a/a	12(2)	BF	145
6s ² S _{1/2}	49.3(25)	DC	171	5p ² P _{3/2}	34(5)	EOC	139
7s ² S _{1/2}	101	T	140	5p ² P _{3/2}	38.8	T	140
7s ² S _{1/2}	86.1(83)	DC	171	5p ² P _{3/2}	27.9(42)	DC	171
8s ² S _{1/2}	181	T	140	6p ² P _{1/2}	185	T	140
9s ² S _{1/2}	306	T	140	6p ² P _{1/2}	23(5)	DC	184
4p ² P _{1/2} ^o	7.1(6)	EOC	139	6p ² P _{3/2}	19.1(30)	EOC	139
4p ² P _{1/2}	6.11	T	140	6p ² P _{3/2}	353	T	140
4p ² P _{3/2} ^o	7.0(9)	DC	171	6p ² P _{3/2}	6.2(6)	DC	164
4p ² P _{3/2}	7.0(2)	LC	141	7p ² P _{1/2}	338	T	140
4p ² P _{3/2} ^o	7.2(3)	PS	142	7p ² P _{1/2}	5.8(6)	DC	161
4p ² P _{3/2}	7.4(7)	BF	143	7p ² P _{3/2}	118	T	110
4p ² P _{3/2} ^o	7.24(15)	LC	144	7p ² P _{3/2}	17.0(45)	DC	164
4p ² P _{3/2}	7.0(7)	PS	145	8p ² P _{1/2}	165	T	140
4p ² P _{3/2} ^o	7.2(10)	EOC	139	8p ² P _{1/2}	320(10)	LC	144
8p ² P _{3/2}	220	T	140	4p ² D _{3/2}	361(54)	LC	144
9p ² P _{1/2}	343	T	140	4p ² D _{3/2}	370(28)	DC	171
9p ² P _{3/2}	407	T	140	4p ² F _{7/2}	424(40)	DC	171
4d ² D _{3/2} ^o a/a	11(2)	BF	145	4d ² F _{9/2}	377(28)	DC	171
4d ² D _{3/2}	66.2(34)	EOC	139	4d ² G _{9/2}	61(9)	DC	171
4d ² D _{3/2}	12.2	T	140	4d ² G _{9/2}	4.8(6)	BF	145
4d ² D _{3/2}	14.5(6)	DC	171	4d ² G _{7/2}	97.9(57)	DC	171
4d ² D _{3/2}	45.0(42)	EOC	139	4d ² G _{7/2}	98.9(38)	DC	171
4d ² D _{5/2}	12.3	T	140	Silver (Ag I)			
4d ² D _{5/2}	14.2(13)	DC	171	5p ² P _{3/2}	6.3(6)	LC	147
5d ² D _{3/2}	54.8(51)	EOC	139	5p ² P _{3/2}	6.5(6)	DC	148
5d ² D _{3/2}	26.8	T	140	5p ² P _{3/2}	7.3(4)	()	149
5d ² D _{3/2}	30.9(17)	DC	171	5p ² P _{1/2}	7.5(7)	DC	171
5d ² D _{3/2}	47.2(43)	EOC	139	5p ² P _{1/2}	7.5(7)	DC	174
5d ² D _{3/2}	27.4	T	140	7s ² S _{1/2}	41.5(32)	DC	175
5d ² D _{3/2}	29.8(27)	DC	171	8s ² S _{1/2}	139(13)	DC	175
6d ² D _{3/2}	51.4	T	140	5d ² D _{3/2}	12.9(8)	DC	175
6d ² D _{3/2}	71.5(91)	EOC	139	5d ² D _{3/2}	13.4(12)	DC	175
6d ² D _{3/2}	52.7	T	140	6d ² D _{3/2}	30.2(33)	DC	175
6d ² D _{3/2}	55.6(35)	DC	171	7d ² D _{3/2}	61.6(56)	DC	175
7d ² D _{3/2}	88.3	T	140	7d ² D _{3/2}	60.6(43)	DC	175
7d ² D _{3/2}	87.9	T	140	8d ² D _{3/2}	106(7)	DC	175
8d ² D _{3/2}	137	T	140	5p ² P _{3/2} ^o	3.0(2)	DC	175
8d ² D _{3/2}	137	T	140	6s ² S _{1/2}	5.1(9)	DC	175
4f ² F _{5/2}	70.2	T	140	5p ² P _{1/2} ^o	3.9(10)	DC	175
4f ² F _{5/2}	70.4	T	140	Gold (Au I)			
5f ² F _{5/2}	136	T	140	5d ¹⁰ 6p ² P _{3/2} ^o	4.6	LC	150
5f ² F _{5/2}	136	T	140	5d ¹⁰ 6p ² P _{3/2}	4.6(3)	LC	151
3d ¹⁰ 4p ² P _{1/2} ^o	10.7(4)	LC	141	5d ¹⁰ 6p ² P _{1/2}	7.4(7)	DC	171
4p ² P _{3/2} ^o	13.2(6)	DC	171	5d ¹⁰ 6p ² P _{3/2}	5.6(8)	DC	174
4p ² P _{3/2}	19(2)	LC	144				
4p ² P _{3/2} ^o	20.0(23)	DC	171				
4p ² P _{3/2}	318(16)	ODR	146				

method of the numerical Coulomb approximation used in Ref. 140 the applicability of the single-configuration approximation to the studied states was assumed. The single-configuration approximation can be too crude in the case of perturbed states. As is known,¹⁷² the series of the terms 3d¹⁰n²P_j^o of CuI is perturbed, the states 6P_j, 7P_j, and 8P_j, for which strong disagreement between theoretical and experimental values of τ_k is observed (see Table VI), being especially strongly perturbed. It is known¹⁶⁰ that for the one-electron approximation to be applicable it is necessary that the orbital parameter q should vary monotonically with an increase of the excitation energy. The dependence q(n*) for the n²P_j^o-series of CuI is given in Fig. 3 (the plot 3). The strongly expressed nonmonotonic character of this dependence indicates the presence of a considerable perturbation of 6²P_j, 7²P_j, and 8²P_j states. For strongly perturbed states 6²P_j and 7²P_j, the one-electron approximation is not valid and the method of the Coulomb approximation for the calculation of τ_k is not applicable. This can explain the strong disagreement between experimental and theoretical values of τ_k of these states. The states 4²P_j and 5²P_j are also

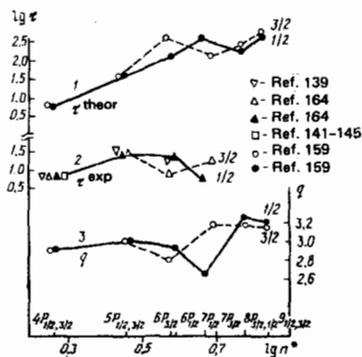


FIG. 3. Plots of the dependences of the radiative lifetime τ and of the effective orbital parameter q on the effective principal quantum number n* for the n²P_j states of Cu I.

perturbed, however their perturbation is weak and the single-configuration approximation satisfactorily describes them and, therefore, the theoretical results¹⁴⁰ for these states differ but little (in comparison with 6²P_j and 7²P_j) from the experimental data (see Table VI).

As is known,^{153,156} the dependences τ_k(n*) and q(E) correlate between themselves both in the case of those series where the one-electron approximation is applicable as well as in the case of perturbed states. Here in the case of strong perturbation a correlation in the dependences τ_k^{exp}(n*) and q(n*) for the 3d¹⁰n²P_j^o states of CuI is also observed (see Fig. 3, plots 2 and 3). Note that the dependence τ_k^{theor}(n*) does not correlate with the dependence q(n*) which is one more indication that the calculated data¹⁴⁰ for n²P_j-states of CuI are not correct.

An analysis of the values of τ_k for the nD_j-states of CuI using the dependences Δn(n*) allows us to conclude (see Section 4, Fig. 7) that the experimental data¹³⁹ have accidental errors which is also supported by the good agreement of the recent experimental results with the theoretical results¹⁴⁰ for the same states.

Data on τ_k of the upper excited states of AgI and AuI are absent in the literature. Because of this and because of the wide spread of the data from different determinations of τ_k of CuI it seems necessary to carry out new experimental and theoretical studies of lifetimes of excited states of atoms and ions of the copper subgroup.

4. REGULARITIES IN THE RADIATIVE LIFETIMES OF EXCITED STATES OF ATOMS OF THE FIRST GROUP

Regularities in the radiative lifetimes of excited states of a single spectral series (here and subsequently a spectral series is understood to be a set of excited states with the same orbital and spin angular momenta) of atoms and ions heavier than hydrogen have recently attracted considerable attention of researchers who carry out calculations or experimental studies of lifetimes.^{68,153-156} The regularities in the variation of lifetimes of excited states as a function of the principal

and azimuthal quantum numbers that have been determined and also the regularities in the variation of τ_k of analogous states of atoms of the same subgroup and of ions of isoelectronic series allow us to understand better the physics of excited states. Moreover, the constants of power-law dependences $\tau_k(n^*)$ for particular series together with dependences $q(E)$ allow us to evaluate reliably lifetimes of states which for some reason have remained unstudied.^{153,156}

The power-law dependence of the variation of radiative lifetimes of excited states of the hydrogen atom follows from quantum mechanics. As was shown by H. Bethe as early as in 1933 in the first edition of the monograph of Ref. 152 the radiative lifetimes of excited states of the hydrogen atom increase with an increase of the principal quantum number in the case when the azimuthal quantum number l is constant as well as in the case of averaging over l . At constant l for hydrogen we have

$$\tau_{n,l} \sim n^3, \quad (7)$$

and the average lifetime of the n -th state is

$$\tau_n = \left(\sum_l \frac{2l+1}{n^3} \frac{1}{\tau_{n,l}} \right)^{-1} \sim n^{4.5}. \quad (8)$$

In 1975 it was shown simultaneously and independently in three articles¹⁵³⁻¹⁵⁵ that for some series of heavy atoms (Ne I, Hg I, and Na I) the power-law variation of lifetime with n is also valid:

$$\tau_k = \tau_0 n^\alpha, \quad (9)$$

where τ_0 and α are constants for a given series, the index α being able to attain the value of six.¹⁵⁴ It was shown later^{155,156} that a greater number of series of heavy atoms have dependences

$$\tau_k = \tau_0 n^{*\alpha}, \quad (10)$$

where n^* is the effective quantum number, α is close, though not equal, to 3 (see Table VIII). This is reasonable because the dependence on n^* is more "hydrogen-like." The constants τ_0 and α were determined for a large number of series of heavy atoms.¹⁵⁶ However, for the hydrogen atom the dependences (8) and (9) are still not determined (the constants τ_0 are not determined and it is not shown how closely is $\alpha=3$). Moreover, in order to understand the regularities in radiative lifetimes of complex atoms it is necessary to determine all the laws governing radiative lifetimes in the simplest hydrogen atom.

Using all the data available in the literature on the experimental and theoretical determination of radiative lifetimes of excited states of the hydrogen atom, we plotted the dependences of lifetimes on the principal quantum number for all the series (Fig. 4) and analyzed their behavior by the least square fit method in order to determine τ_0 and α . The analysis of the data has shown that in contradiction to the notion established in the literature^{152,157} that the radiative lifetimes of all the series of the hydrogen atom vary as n^3 , the S-series has a different dependence (see Fig. 4). The lifetimes of the levels of the S-series vary with the principal quantum

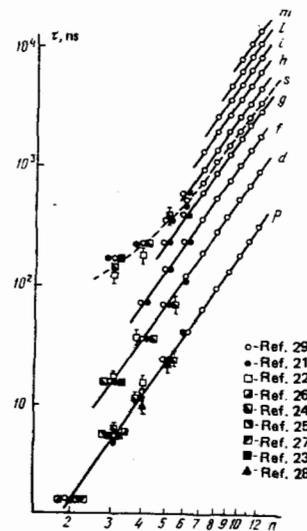


FIG. 4. Plot of the dependence of the radiative lifetimes τ on the principal quantum number n of excited states of the hydrogen atom.

number according to complex curve with a varying slope coefficient α (from 1.42 for $n=3, 4$ to 2.81 for $n=11, 12$).

The lifetimes of the S-states of the hydrogen atom behave as the lifetimes of complex atoms.^{152,156} The "perturbation" influences S-states up to $n=12$ while other excited states of the hydrogen atom with the quantum number l not equal to 0 are not influenced by the "perturbation." The perturbation of the series of excited states in complex atoms is caused by the interaction of the electron in the excited level with the field of electrons of the atomic shell. This type of perturbation is absent in hydrogen, therefore, the nature of the "anomalous" behavior of lifetimes of the S-states is apparently a manifestation of the specific features of the interaction of an S-electron with a nucleus.

All other series of the hydrogen atom follow the power dependence (9) with constants τ_0 and α given in Table VII (at a confidence level of 0.95).

In testing the relation (8) by the substitution of the data on τ_k from Refs. 21-29 it was found that the power index is equal to 4.50 (5) only for $n \geq 9$, for n from 3 to 8 the power index is changing from 4.15 for $n=5$ to 4.75 for $n=3$.

TABLE VII. Values of the constants τ_0 and α for the spectral series of the hydrogen atom.

Series	p	d	f	g	h
τ_{ns}	0.209(1)	0.627(2)	1.235(1)	2.068(1)	3.113(1)
α	2.948(8)	2.932(6)	2.941(2)	2.942(1)	2.945(1)
Series	l	k	l	m	
τ_{ns}	4.372(5)	5.766(18)	7.212(14)	9.313(82)	
α	2.946(2)	2.954(6)	2.968(6)	2.956(11)	

The dependence (10) can be used by means of an extrapolation for the evaluation of lifetimes of levels which are not present in the literature.^{66, 153, 156} However, for the validity of extrapolation it is necessary to have a criterion of the validity of the dependence (10) in the region of the levels of interest. As has been shown in Ref. 160 the power dependence is valid for all the series of the hydrogen atom except S-series, therefore, it is possible to suppose that for series of other atoms and ions for which the one-electron approximation is applicable the relation (10) is valid. As was shown in Ref. 160, the behavior of the effective orbital parameter q as a function of the state energy E is the criterion for the applicability of the one-electron approximation. The parameter q is related to the state energy E by the relation¹⁶⁰

$$q = Z^* \sqrt{\frac{2}{|E|}} - 2p - 1, \quad (11)$$

where Z^* is the effective charge which is equal to one for the neutral atom, E is the experimental value of the energy of the given state in atomic units, p is the radial quantum number.

For the validity of the one-electron approximation (i.e., for the series to be "hydrogen-like") the orbital parameter for a given series must increase linearly with increasing n , if there are electrons with the same orbital angular momentum in the atomic shell, or decrease linearly, if there are no such electrons.¹⁵³ As was shown in Ref. 156, there exists a correlation between the behavior of q and τ_n . In the case where one-electron approximation is valid a power-law dependence for the lifetimes is observed and vice versa. The existence of such a correlation provides the possibility of using the dependence of q on E for a justification of the extrapolation of the power-law dependence of τ_n on n^* to levels which cannot be studied experimentally at present and for evaluation of the values of τ_n of these levels. Such evaluation obtained by the extrapolation of the dependence $\tau_n(n^*)$ plotted using reliable data on τ_n for the lower states well studied by different methods can be in many cases more reliable than single experimental and theoretical determinations (see, for example, Fig. 2).

To illustrate the correlation of the dependences $\tau_n(n^*)$ and $q(E)$ in the spectral series of atoms of the 1st group and to obtain the values of the parameters of the dependences $\tau_n(n^*)$ (constants α and τ_0) in order to use them for evaluation of lifetimes of states that have not been studied we used all the data on τ_n for series of excited states to plot $1g\tau_n$ and $1gn^*$ similar to the plots in Figs. 2, 5, 6. The dependences of q on E for corresponding series were also plotted there. Analysis of the plotted dependences showed that for all studied series of atoms of the 1st group a correlation between the plots of $\tau(n^*)$ and $q(E)$ was present. Where the plot $q(E)$ showed the existence of a "hydrogen-like" series of states, the power-law dependence (10) for τ_n was observed and vice versa (see Figs. 2, 5, 6). The dependences $\tau_n(n^*)$ for "hydrogen-like" series were approximated by the power-law dependence (10) using the least square fit

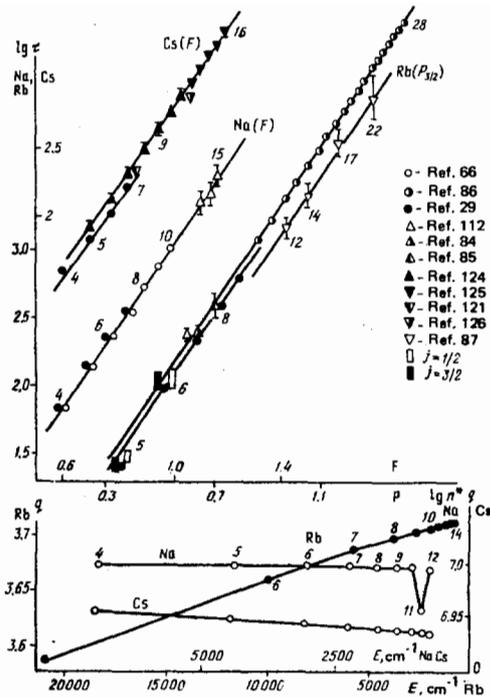


FIG. 5. Plots of the dependences $\tau(n^*)$ and $q(E)$ for the F states of Na I and Cs I and for the P states of Rb I.

method, and the constants α and τ_0 given in Table VIII were determined.

The values of the lifetimes of the lower S-states of alkali metal atoms published in the literature do not follow the power-law dependence (10). The constants α and τ_0 for NaI given in Table VIII were obtained from

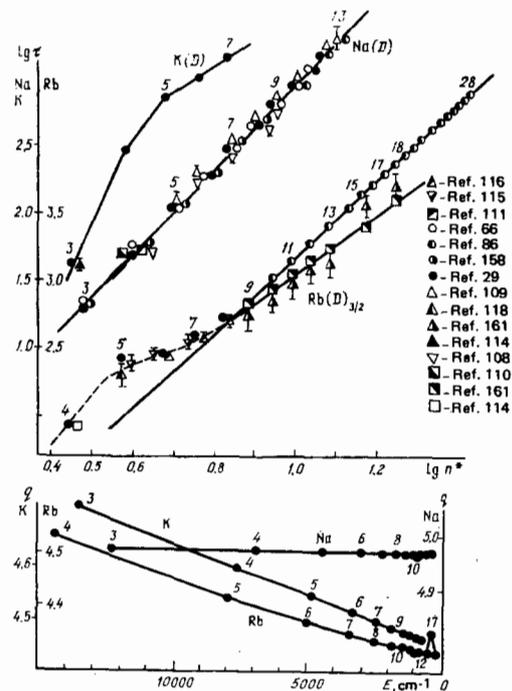


FIG. 6. Plots of the dependences $\tau(n^*)$ and $q(E)$ for the D states of Na I, K I, and Rb I.

TABLE VIII. Values of the constants α and τ_0 for the spectral series of alkali metal atoms.

Atom	Constants	S	P	D	F	G
LiI	α			2.96(11)	2.94(3)	2.95(9)
	τ, ns			0.74(16)	1.22(5)	2.00(8)
NdI	α	2.89(3)		3.06(8)	2.93(7)	2.94(4)
	τ, ns	1.80(7)		0.94(4)	1.20(4)	2.05(8)
KI	α		3.06(4)		2.70(5)	2.92(7)
	τ, ns		3.47(11)		1.48(5)	2.09(4)
RbI	α	2.95	3.03(9)		2.88(7)	2.90(6)
	τ, ns	1.44	2.57(7)		0.97(6)	2.15(8)
CsI	α	2.60(11)	3.13(6)		2.76(4)	2.85(4)
	τ, ns	3.11(13)	2.47(5)		1.01(6)	2.33(6)

the experimental and theoretical values of lifetimes of the S-states beginning from $n=7$. The plot of the dependence of τ_k on n^* for RbI is represented by the smooth curve with a changing slope and only for τ_k^{theor} beginning from $n=20$ does the power-law dependence with $\alpha=2.95$ and $\tau_0=1.44$ hold. For the S-states of CsI the constants α and τ_0 were obtained from the experimental values of τ_k beginning from $n=8$.

The power-law dependence on n^* is observed for the experimental and theoretical values of τ_k of the P-states of LiI (see Fig. 2) available in the literature, but the results of different articles give dependences with substantially different τ_0 and α [$\alpha_{\text{theor}}=2.12(9)$, $\alpha_{\text{exp}}=2.75(6)$]. The value $\alpha=2.75$ seems to us to be preferable for the series for which the one-electron approximation is valid, however new theoretical and experimental studies of τ_k of this series are needed to obtain more precise values of the constants. For τ_k of the P-states of Na I a power-law dependence is not observed even for high values of n (see Fig. 2). The constants τ_0 and α for KI were obtained using experimental and theoretical values of τ_k , and for RbI and CsI only theoretical values of τ_k were used. The experimental results, especially for CsI, have a very large spread. The data⁸⁷ for the (12, 14, 17, 22)P-states of Rb I (see Fig. 5), apparently, have a systematic error caused by the influence of thermal radiation on the higher levels.

The plots of dependences of τ_k on n^* for the D states of alkali metal atoms are surprisingly different (see Fig. 6). The power-law dependences (10) are observed only for Li I and Na I, the constants given in Table VIII being obtained from theoretical results for LiI and from experimental and theoretical results for Na I. The dependence (10) is especially well followed for the D-states of Na I (see Fig. 6). The lifetimes of the D states of KI, Rb I, Cs I change in dependence on n^* according to complex curves showing the presence of a strong perturbation.

The radiative lifetimes of the F and G states of all the atoms of the Li I subgroup exhibit a power-law dependence on the effective principal quantum number. For Rb I and Cs I the dependence (10) is observed beginning from the 5F and 6F states respectively, and for Li I, KI and Na I all the F and G states follow power-law dependences, the F states of Na I following a power-

law dependence especially well (see Fig. 5). The constants α and τ_0 of the F series of Rb I are obtained from the theoretical values of τ_k . The constants for the G series of Cs I were obtained from the experimental values of τ_k for the $F_{7/2}$ states. The constants α and τ_0 for the G states given in Table VIII were obtained from the theoretical values of τ_k .

The power-law dependences (10) are not valid for the S series of Li I and KI, P series of Na I, D series of KI, Rb I, Cs I. The dependences $q(E)$ for the same series show the existence of a perturbation of these series and a deviation from "hydrogen-likeness."

As is known,^{172, 173} the S and P electrons are bound much more strongly in all alkali metal atoms than in a hydrogen atom (strongly penetrating orbits), and the bond strength decreases from Li to Cs. Therefore, the power-law dependences for τ_k in the S and P series are observed only for the upper states and for heavy atoms. For D electrons the bond strength increases from Li to Cs and the effect of penetrating orbits disturbs the "hydrogen-likeness" of the D series of K, Rb and Cs. Therefore, the power-law dependence $\tau_k(n^*)$ for the D states is observed only for Li I and Na I.

The F and G electrons in all alkali metal atoms are bound practically in the same manner as in a hydrogen atom and lifetimes τ_k for these states follow quite well the power-law dependence (10) with the power index α close to that of hydrogen.

An analysis of the $q(E)$ dependences of all the series of alkali metal atoms has shown that the dependences $\tau_k(n^*)$ must have peculiarities for particular values of n (τ_k of these states must go off the plot of $\tau_k(n^*)$, provided that the data of Ref. 159 on the energies of the states are correct). Such peculiarities should be observed for the following states: 10S, 11P, 11D of Li I; 13S, 14D, 11F of Na I; 13S of K I; 17D of Rb I. Unfortunately, data on τ_k exist only for 13S of Na I and 17D of Rb I. For τ_k of 13S of Na I the peculiarity (τ_k is less than the value determined from the extrapolation) is observed for the theoretically obtained value of τ_k .⁶⁶ The calculated⁸⁷ value of τ_k of 17D of Rb I does not give a noticeable peculiarity on the plot (see Fig. 6), which indicates, probably, insufficient sensitivity of the method used to specific properties of particular states.

The possibility of deviation from a power-law dependence (10) for particular states requires the use of the constants given in Table VIII for evaluations of τ_k of unstudied states only in conjunction with dependences (11) for the same states.

For atoms of the Cu I subgroup the laws of the variation of τ_k can be seen only for the S, P and D states of copper. The dependences of τ_k on n^* plotted by us for these series are shown in Fig. 3 and Fig. 7. The dependences $\tau_k(n^*)$ for the P₁ series of CuI were discussed above. The plots of dependences $\tau_k(n^*)$ for the S and D series of Cu I are given in Fig. 7. Plot 3 constructed according to the data of Ref. 139 is characteristic for the perturbed series (see Fig. 3) while the data of other theoretical¹⁴⁰ and experimental^{145, 171} studies are well approximated by a linear dependence

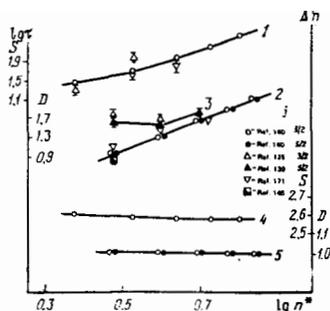


FIG. 7. Plots of the dependences of the radiative lifetime τ and quantum defect Δn on the effective principal quantum number for S and D states of Cu I.

(plot 2). It is known¹⁶² that the plot of the dependence of the quantum defect Δn on the principal quantum number for a perturbed series must have a nonmonotonic character. The plots of $\Delta n(n^*)$ for S and D series of CuI (plots 4 and 5) which do not have extrema are shown in Fig. 7. The plots of $\Delta n(n^*)$ are characteristic for unperturbed series for which the plots of $\tau_k(n^*)$ must resemble the plots 1 and 2. This is observed for all available data on τ_k except the data of Ref. 139 which are apparently incorrect. The plots in Fig. 7 show that the dependences $\Delta n(n^*)$ may be used for proving the correctness of the extrapolation of the dependence (10).

In the monograph of Ref. 152 it is noted that lifetimes of all sublevels nl of the quantum state n in the hydrogen atom (excluding the S state) vary smoothly with the orbital quantum numbers of these levels. In fact, it can be seen from Fig. 4 that at fixed n the lifetime of levels with different l grows with increase of l according to some well defined law. It was found from an analysis of the variation of radiative lifetimes of excited states of the hydrogen atom that radiative lifetimes τ_k are inversely proportional to the energy differences ΔE between neighboring states:

$$\tau_{n,l} = A (\Delta E)^{-\beta}, \quad (12)$$

where A and β are characteristic constants for the series of excited states with the same n .

The plots of dependences of lifetimes τ_k of excited states on the energy difference ΔE (cm^{-1}) between neighboring states¹⁵⁹ are presented in Fig. 8. For the series given in Fig. 8 the constant β has the following values: 1.0 (plot 1), 1.12 (plots 2, 3), 0.92 (plot 4), 0.89 (plot 5). The plots 4 and 5 in Fig. 8 show that the relation (12) is valid not only for the hydrogen atom, but also for sodium and copper atoms. It should be noted that the relation (12) together with dependences $q(E)$ and $\Delta n(n)$ may also be used to estimate lifetimes of states that have not been investigated.

5. TABLE OF RECOMMENDED VALUES OF RADIATIVE LIFETIMES OF EXCITED STATES OF ATOMS OF THE FIRST GROUP

The values of lifetimes of excited states of atoms obtained by different methods, as can be seen from the tables given above, very often differ from each other;

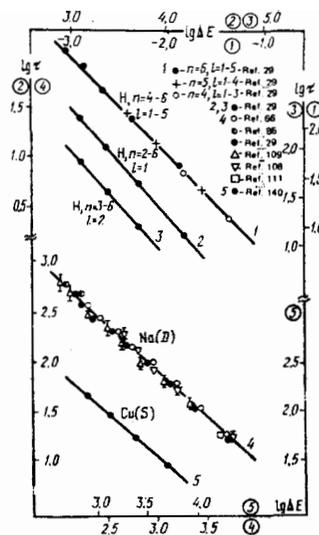


FIG. 8. Plots of the dependences of the radiative lifetime τ on the energy difference between levels ΔE for the atoms of hydrogen, sodium (D states) and copper (S states).

sometimes these differences are very substantial and may be of the order of the lifetime itself and even larger (CuI). This can be explained by the difficulty of experimental determination of lifetimes of particular states as well as by incomplete consideration of the experimental conditions, especially, when new experimental methods are used. Therefore, together with a complete systematization of the data on τ_k existing in the literature at present, we carried out a critical analysis of them, in order to recommend the most reliable data to facilitate their practical use.

The values τ^{rec} given in Table IX were calculated according to

$$\tau^{\text{rec}} = \frac{1}{n} \sum_{i=1}^n \tau_i, \quad (13)$$

where n is the number of articles taken into consideration. Papers were not considered if their results differed from the mean value by more than 2σ (σ is the mean square deviation). Experimental results without a statement of the probable error and earlier work of the same authors were also not considered. Another criterion for the rejection of the results of some articles, in addition to the mean square deviation, was their inconsistency with the dependence (10) obtained from the data of other papers the validity of which was supported by the dependence $q(E)$ (see Section 4). All other experimental and theoretical results were considered to be equally precise and distributed according to the normal distribution law about the real value. It should be noted that consideration of experimental and theoretical values together is possible only for hydrogen and the light alkali metal atoms (Li, Na, K) where splitting into fine structure components is small. As analysis of the summary tables of τ_k has shown, theoretical and experimental values of radiative lifetimes of excited states of these atoms agree within experi-

TABLE IX. Recommended values of radiative lifetimes of excited states of the atoms of the 1st group.

Atom	State	Lifetime, ns	Error	Atom	State	Lifetime, ns	Error	
H	3s	156.7	B		7P	1542		
	4s	229.1	B		3D	20.4	C	
	5s	363.3	C		4D	53.9	A	
	6s - 12s see Table I				5D	110.5	C	
	2p	1.59	A		6D	197.7	C	
	3p	5.51	A		7D	319.6	B	
	4p	12.2	B		8D	481.9	C	
	5p	23.8	A		9D	698	C	
	6p - 12p see Table I				10D	946.5	B	
	3d	15.6	A		11D	1254		
	4d	36.4	B		12D	1604	C	
	5d	69.7	A		13D	2070		
	6d - 12d, f, g, h see Table I				4F	71.6	B	
	LiI	3s	30			5F	136.6	C
		4s	56.2		B	6F	234.2	C
		5s	103			7F	371	B
		6s	173			8F	549	
		7s	272			9F	760	
8s		405		10F	1030			
2P		26.9	A	12F	1741			
3P		224		13F	2265			
3D		14.7	A	14F	2725			
4D		33.5	C	15F	3540			
LiI	5D	64		5G - 9G see Table IV				
	6D	108.3	C	10G	1785			
	7D	169		11G	2362			
	8D	251		12G	3051			
	4F - 7F see Table IV			4P	26.9	A		
	8F	551		4P _{3/2}	27.2	C		
	9F	779		4P _{1/2}	28.7	C		
	10F	1062		5P	128.7			
	11F	1406		5P _{3/2}	131.2			
	12F	1816		6P - 8P see Table II				
	5G - 7G see Table IV			9P	1511			
	8G	922		10P	2241			
	9G	1306		11P	5333			
	10G	1782		12P	6960			
	11G	2361		7s	94.5	C		
	12G	3052		8s	166			
	NaI	4s	38.7	C	9s	273		
		5s	80.2	A	10s	449		
6s		154.8	C	11s	628			
7s		267.6	A	12s	887			
8s		430.1	A	5P _{3/2}	26.7	A		
9s		662	C	5P _{1/2}	29.3	C		
10s		937.6		6P _{3/2}	111.5	A		
11s		1261		6P _{1/2}	122			
12s		1795		7P _{3/2}	236			
13s		2250		8P - 28P see Table II				
3P		16.2	C	4D _{3/2}	90			
4P		99	A	5D	249			
5P		354.9	C	6D _{3/2}	289			
6P		863	C	7D _{3/2}	379			
4F - 12F see Table IV			8D _{3/2}	515				
CsI		8s	100.3	C	8s ² S _{1/2} , 9s ² S _{1/2} see Table VI			
		9s	189.2	C	4p ³ P _{1/2}	7	B	
		10s	283		4p ² P _{3/2}	7		
	11s	417		5p ² P _{1/2}	38.8			
	6P _{3/2}	30.2	A	5p ² P _{3/2}	33.5			
	6P _{1/2}	34	A	6p ³ P _{1/2}	23			
	7P _{3/2}	135	A	6p ³ P _{3/2}	6.2			
	7P _{1/2}	157.2	A	7p ³ P _{1/2}	5.8			
	8P _{3/2}	294.6		7p ³ P _{3/2}	17			
	8P _{1/2}	318		4d ² D _{3/2}	13			
	9P _{3/2}	502		4d ² D _{5/2}	13			
	9P _{1/2}	575		5d ² D _{3/2}	28			
	6D _{3/2}	62		5d ² D _{5/2}	28			
	6D _{1/2}	58		6d ² D _{3/2}	52			
	7D _{3/2}	90		6d ² D _{5/2}	54			
	7D _{1/2}	94		7 ² D _j , 8 ² D _j see Table VI				
	8D _{3/2}	153		3d ³	4p' 2D _{3/2}	20		
	9D _{3/2} - 14D _{3/2} see Table IV				4p' 4P _{3/2}	319		
5F _{7/2} - 13F _{7/2} see Table IV			4p' 4D _{3/2}		368			
5s ² S _{1/2}	22		4d ¹⁰ 5p ² P _{3/2}		6.7			
6s ² S _{1/2}	50		AgI					
7s ² S _{1/2}	93							

mental error excluding erroneous data of some papers. In the case of RbI and CsI the difference between the experimental values of τ_k of the fine structure components is noticeable and these values differ from the theoretical values. The theoretical values, as a rule, are given for the center of gravity of the state and, as the compiled tables show, are close to the experimental τ_k values for states with a larger statistical weight. For RbI and CsI we give recommended values of τ_k for

the fine structure components and in the case when there are no experimental data we give theoretical values for the center of gravity of the state.

Besides the values of several measurements of τ_k averaged according to Eq. (13), there are included in Table IX the results of single measurements, which correspond to the dependence (10) plotted from the averaged τ_k of other states of the series and the evaluations of τ_k of unstudied states also obtained from the dependence (10). The results of single measurements and estimates of τ_k whose reliability is confirmed by the plot of the dependence $q(E)$ (see Section 4) are included in the table.

We were not able to distribute the data of the individual papers according to their statistical weights because due to difficulties of analyzing the experimental conditions of every paper it was impossible to introduce an objective scale of weights corresponding to dates or methods. The introduction of statistical weights according to the stated probable error was not legitimate because the difference between results was often considerably larger than the stated errors which indicated that the stated errors did not correspond to the real precision of the results.

The errors of the recommended values given in Table IX were calculated using the Student coefficient $t_{\alpha, n-1}$ for the confidence level $\alpha = 0.95^{163}$:

$$\Delta\tau^{rec} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^n (\tau^{rec} - \tau_i)^2 t_{\alpha, n-1}^2} \quad (14)$$

The error of recommended values calculated according to Eq. (14) is given in percent and is designated by letters: A (< 5%), B (< 10%), C (< 30%). For economy of space the recommended values of individual papers are not given in Table IX (references to the previous tables). The predicted values are estimates and are given without an indicated error.

Table IX does not include results of single measurements of τ_k if no states of a given series have several values of τ_k determined by different methods. Also, predicted values of τ_k of the states for which there are no data on energies in Ref. 159 are not included in the table.

6. CONCLUSION

The present level of fundamental and applied studies requires knowledge of the values of atomic constants including radiative lifetimes with a precision of 5-10%.¹⁶⁵ If one is to consider as real a value which is in agreement with results obtained by different experimental and theoretical methods, one should admit that the problem of the determination of real values of radiative lifetimes of excited states of atoms of the 1st group with the precision and completeness required at present is far from being solved. It should be noted that the situation is satisfactory for lifetimes of excited states of the hydrogen atom and the lower (up to $n=10$) states of alkali metal atoms (except LiI and KI). The data on radiative lifetimes of upper states of alkali metal atoms and of all excited states (except resonance

states) of the copper subgroup atoms are either not available or contradictory. The lifetimes of autoionization states have been studied in fact only for LiI.

New more precise data for lower states are also necessary which would allow one to determine and to make more accurate the constants of the power-law dependences (10) and, therefore, to evaluate the lifetimes of upper states with better precision. Reliable data on τ_k of the excited states for which the behavior of the quantum defect predicts "peculiarity" in the dependence $\tau_k(n^*)$ are very important. The stable interest in the determination of radiative lifetimes of excited states of atoms and ions observed in many countries enables one to hope that necessary data will be obtained in the very near future.

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