Following Electron Impact Excitation Of Single $_{93}$np, $_{94}$pu, $_{95}$am, $_{96}$cm, $_{97}$bk, $_{98}$cf) Atoms L_i Subshell Ionization Cross Sections By Using Lotz's Equations

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***Abstract*—L shell and three L_i subshells ionization cross sections σ_L and σ_{Li} following electron impact on $_{93}$Np, $_{94}$Pu, $_{95}$Am, $_{96}$Cm, $_{97}$Bk, $_{98}$Cf atoms calculated. By using Lotz's equation in Matlab ionization cross section values obtained for 15 electron impact energy values in first ionization energy to 5.5 times ionization energy range for each atom. Lotz's parameters and special commands used for each ionization cross sections calculations. Starting all most from ionization threshold values; ionization cross sections are increasing rapidly with electron impact energy E_0. For higher E_0 values this increments getting smaller for every L_i subshells. For smaller E_0 energy close to threshold; all ionization cross sections decrease. For a fixed electron impact energy while atomic number Z value increases from 93≤Z≤98; ionization cross sections decrease with Z. Results may help to understand similar findings which obtained from other electron impact excitation of L_i subshells ionization cross sections studies for similar size single atoms.**

Keywords—L_i subshells ionization cross section calculations, Electron impact on single atoms(93≤Z≤98), Lotz's equations.

1.Introduction

Inner subshell ionization cross section studies of free atoms by electron impact are subjects of ongoing research for many years [1,2,5-13,14]. Inner shell ionization cross section information help us to understand, characterization of used target atoms in the following fields: astrophysics, plasma physics, radiation protection, energy transfer by electron impact on or in tissues study required [5,6,7,8]. In this study, L shell and Li subshells ionization cross sections σ_L and σ_{Li}(i =1,2,3) for $_{93}$Np(Neptunium, $_{94}$Pu(Plutonium), $_{95}$Am(Americium), $_{96}$Cm(Curium), $_{97}$Bk(Berkelium), and $_{98}$Cf(Californium), atoms are calculated. For each of atoms, 15 electron impact energy values E_{0i} are used. E_{0i}(i=1,.,15) values were chosen in the E_{L3i} <E_{0i}<5E_{L3i} range for each atom. E_{Li} is the binding energy of i[th] L_i(i =1,.,3) subshells. If a neutral atom A bombarded by an electron with sufficiently big E_{0i} under E_{Li}<E_{0i} conditions, firstly impacting electron emits bremsstrahlung then electron-single atom interaction occur. Target atom A becomes excited ions A^{+*} at i[th] L_i subshell. Creation of electron holes in L_i subshells depends on how big the E_{0i} compare to E_{Li} . Lotz put forward a semi-empirical formula at, for calculation of ionization cross sections for low energetic electron impact excitation of free atoms at inner shells which was based on Born Approximation(BA) [1,2,6,7,8]. Calculations for σ_L and σ_{Li} (i =1,2,3) of 93Np to 98Cf atoms carried out by using Lotz equations in Matlab program [7, 9-12].

$$\sigma_{Li} = a_i\, q_i[\ln(E_0 / E_i) / E_0E_i][1-b_i \exp(-c_i (E_0 /E_i))] \quad (1)$$

a_i, b_i, c_i constants and q_i of the i[th] subshell which are taken from Lotz [1,2]. q_i are the number of equivalent electrons at i[th] L_i subshell and E_i is the binding energy of the i[th] subshell. σ_{Li} are the ionization cross section of i[th] subshells. By using the Eq.1 and using sum of calculated σ_{Li} subshells of each atom for 15 values of E_{oi} , σ_{Ltotal} of L shell calculated.

2.Method

L shell and Li subshells ionization cross sections σ_L and σ_{Li} for $_{93}$Np, $_{94}$Pu, $_{95}$Am, $_{96}$Cm, $_{97}$Bk, $_{98}$Cf atoms are calculated. Calculations done for 15 E_{0i} values which they chosen in energy range of E_{L3i} <E_{0i}<5E_{L3i} for each atom. It means that for $_{93}$Np, used over all E_{oi}(i=1,..to,15) values fall in 17,710keV<E_{0i}<115,500keV range. E_{oi} values chosen according to the E_{L3i} of targeted atom which were taken [3]. For the 93Np to 98Cf Used ionization threshold energies given in Table.1. E_{L3i} is the outer most L subshell and E_{L1i} is the first inner L subshell following first K shell.

Table.1 93Np to 98Cf atoms L subshell ionization threshold energies in eV [3].

Atom No	E_{oL1}	E_{oL2}	E_{oL3}
93Np .	22427	21600	17610
94Pu.	23104	22266	18057
95Am.	23808	22952	18510
96Cm.	24526	23651	19870
97Bk.	25256	24371	19435
98Cf.	26010	25108	19907

Calculations carried out by using written commands for Lotz's Eq.1 in Matlab for each atom [1,2,9 -14]. The values of a_i, b_i, c_i parameters and q_i are given in the same order for L_i subshells as:
For a_i equal to (4, 2, 2)$10^{-14}cm^2(eV)^2$; for b_i equal to 0.5, 0.92, 0,92; for c_i equal to 0.6, 0.19, 0.19, and for q_i equal to 2, 2, 4, values used[1-2, 9-12]. . By using the Eq.1 and using sum of calculated σ_{Li} subshells of each atom for 15 values of E_{0i} , σ_{Ltotal} of L shell calculated.

3.Results

Results, for $_{93}$Np(Neptunium, $_{94}$Pu(Plutonium), $_{95}$Am(Americium), 96Cm(Curium), 97Bk(Berkelium), to $_{98}$Cf(Californium), atoms for 15 E_{oi} are given in Table.2 to 8 and Figs. 1 to 7 under the name of each atom. Each table contains L subshell ionization cross section results of one atom. All the Table captions are the same except the chemical symbol of elements which used for targeted atoms. Z dependency of ionization cross sections for a fixed E_{0i} =40keV impact given in Table 8 and also in Fig.7. İonization cross section values are given in 10^2 b(barn) units in tables and in all figures.

Table.2 L subshell ionization cross section of $_{93}$ Np in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
17,71	-0,2675	-0,1645	0,0045	-0,4275
22,65	0,0093	0,0332	0,1834	0,2259
27,55	0,1686	0,1496	0,3037	0,6219
33,5	0,3121	0,2379	0,4071	0,9571
40,722	0,3709	0,304	0,4949	1,1698
48,126	0,4221	0,3459	0,5584	1,3264
55,53	0,4526	0,3727	0,6042	1,4295
62,934	0,4706	0,3898	0,6376	1,498
70,338	0,4805	0,4006	0,6619	1,543
77,742	0,4849	0,4069	0,6795	1,5713
85,146	0,4855	0,4101	0,6918	1,5874
92,646	0,4834	0,4109	0,7001	1,5944
100146	0,4794	0,4099	0,7049	1,5942
107,646	0,4741	0,4076	0,7072	1,5889
115,5	0,4675	0,4042	0,7072	1,5789

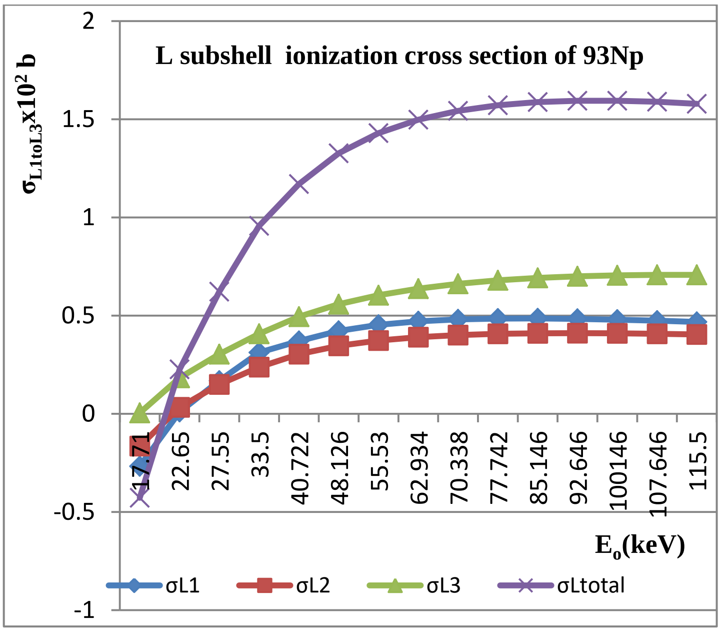

Figure.1 L subshell ionization cross section of $_{93}$ Np in 10^2 b.

Table.3 L subshell ionization cross section of $_{94}$Pu in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
18,2	-0,2552	-0,1575	0,006	-0,4067
23,5	0,0151	0,0354	0,1818	0,2323
28,1	0,1522	0,1355	0,286	0,5737
34,5	0,2695	0,2236	0,3892	0,8823
40,5	0,3371	0,276	0,4586	1,0717
48,126	0,3903	0,3192	0,5227	1,2322
55,53	0,4214	0,346	0,5676	1,335
62,934	0,4401	0,3634	0,6005	1,404
70,338	0,4508	0,3746	0,6248	1,4502
77,742	0,456	0,3815	0,6424	1,4799
85,146	0,4576	0,3852	0,655	1,4978
92,646	0,4564	0,3866	0,6638	1,5068
100,146	0,4534	0,3863	0,6692	1,5089
107,646	0,4489	0,3847	0,6721	1,5057
115,5	0,4433	0,3819	0,6729	1,4981

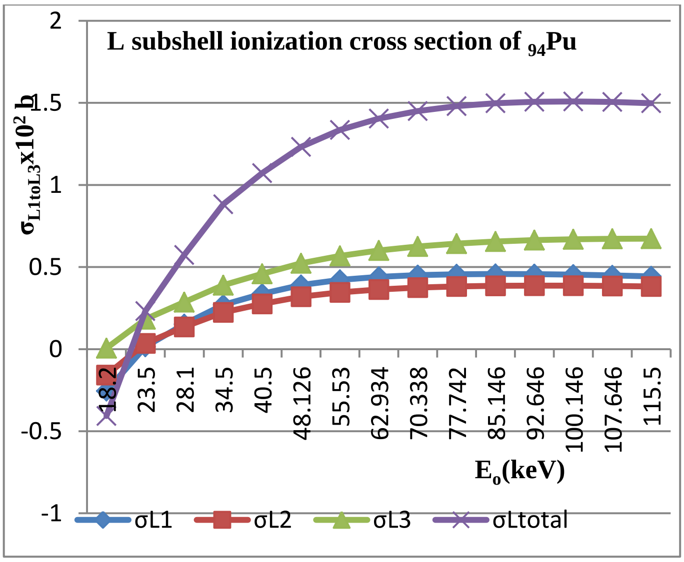

Figure.2 L subshell ionization cross section of $_{94}$Pu in 10^2 b.

Table.4 L subshell ionization cross section of $_{95}$ Am in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
18,65	-0,247	-0,1532	0,0055	-0,3947
24	0,0067	0,0277	0,1708	0,2052
29,5	0,1549	0,1361	0,2844	0,5754
35	0,2467	0,2048	0,3658	0,8173
40,5	0,3069	0,2513	0,4268	0,985
48,126	0,3601	0,2941	0,4893	1,1435
55,53	0,3915	0,3209	0,5332	1,2456
62,934	0,4108	0,3385	0,5657	1,315
70,338	0,4223	0,3501	0,5898	1,3622
77,742	0,4284	0,3573	0,6076	1,3933
85,146	0,4307	0,3616	0,6204	1,4127
92,646	0,4305	0,3636	0,6295	1,4236
100,146	0,4283	0,3638	0,6355	1,4276
107,646	0,4247	0,3628	0,6389	1,4264
115,146	0,4199	0,3607	0,6403	1,4209

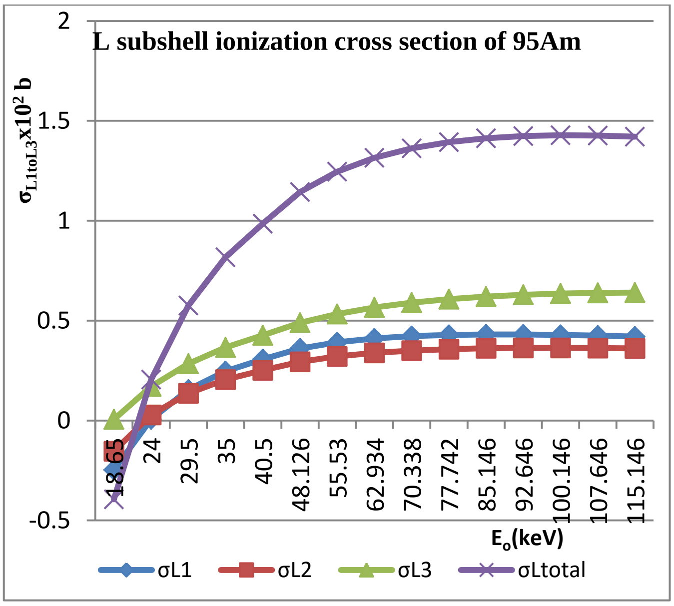

Figure.3 L subshell ionization cross section of $_{95}$ Am in 10^2 b.

Table.5 L subshell ionization cross section of $_{96}$ Cm in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
19,1	-0,2394	-0,1492	0,0047	-0,3839
24,6	0,0024	0,0231	0,1627	0,1882
30	0,1385	0,1224	0,2672	0,5181
35	0,2191	0,1826	0,3378	0,7395
40,5	0,2788	0,2285	0,3971	0,9044
48,126	0,3318	0,2708	0,4581	1,0607
55,53	0,3636	0,2975	0,5011	1,1622
62,934	0,3834	0,3152	0,5331	1,2317
70,338	0,3955	0,3271	0,5569	1,2795
77,742	0,4023	0,3347	0,5746	1,3116
85,146	0,4055	0,3394	0,5877	1,3326
92,646	0,4061	0,3419	0,5971	1,3451
100,146	0,4045	0,3427	0,6035	1,3507
107,646	0,4017	0,3422	0,6074	1,3513
115,146	0,3977	0,3407	0,6094	1,3478

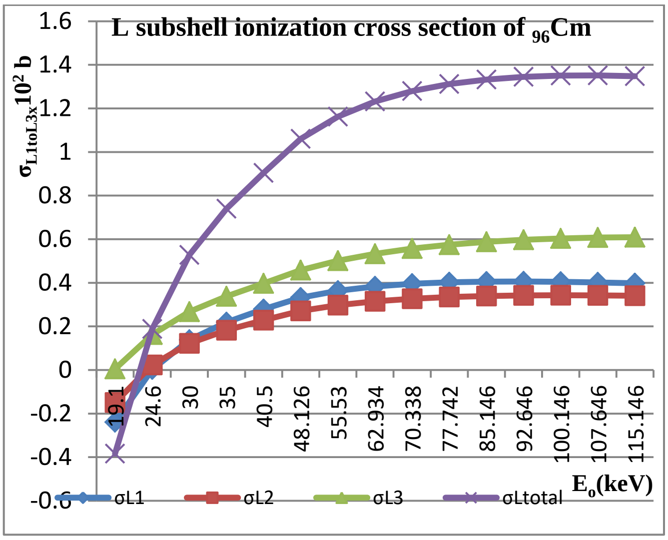

Figure.4 L subshell ionization cross section of $_{96}$ Cm in 10^2 b.

Table.6 L subshell ionization cross section of $_{97}$ Bk in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
19,35	-0,2331	-0,1462	0,0034	-0,3759
24,5	-0,0233	0,0032	0,1396	0,1195
30,5	0,1234	0,1087	0,2508	0,4829
35,5	0,1999	0,1667	0,3176	0,6842
40,5	0,2527	0,2071	0,3694	0,8292
48,126	0,3056	0,2489	0,4288	0,9833
55,53	0,3375	0,2754	0,4708	1,0837
62,934	0,3578	0,2933	0,5023	1,1534
70,338	0,3704	0,3054	0,5259	1,2017
77,742	0,3779	0,3135	0,5437	1,2351
85,146	0,3817	0,3185	0,5569	1,2571
92,646	0,3829	0,3214	0,5666	1,2709
100,146	0,3822	0,3226	0,5733	1,2781
107,646	0,3801	0,3226	0,5776	1,2803
115,5	0,3768	0,3216	0,5801	1,2785

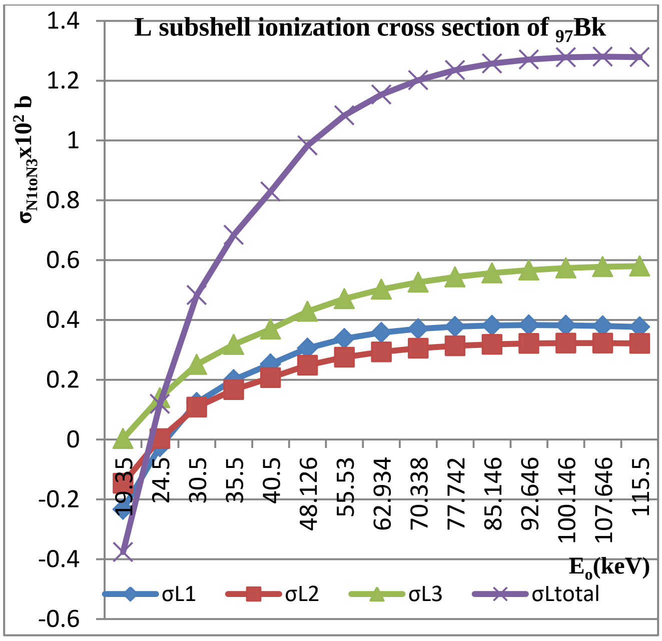

Figure.5 L subshell ionization cross section of $_{97}$ Bk in 10^2 b.

Table.7 L subshell ionization cross section of $_{98}$ Cf in 10^2 b.

E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
20,1	-0,2207	-0,1387	0,006	-0,3534
25,25	-0,0214	0,003	0,1363	0,1179
30,5	0,1005	0,0914	0,2283	0,4202
35,5	0,1758	0,1474	0,2932	0,6164
41	0,2324	0,1904	0,3479	0,7707
48,126	0,2807	0,2285	0,4014	0,9106
55,53	0,3128	0,2548	0,4425	1,0101
62,934	0,3334	0,2727	0,4734	1,0795
70,338	0,3465	0,285	0,4967	1,1282
77,742	0,3546	0,2932	0,5144	1,1622
85,146	0,3591	0,2987	0,5277	1,1855
92,646	0,3609	0,302	0,5376	1,2005
100146	0,3608	0,3037	0,5447	1,2092
107,646	0,3593	0,3041	0,5494	1,2128
115,5	0,3567	0,3035	0,5523	1,2125

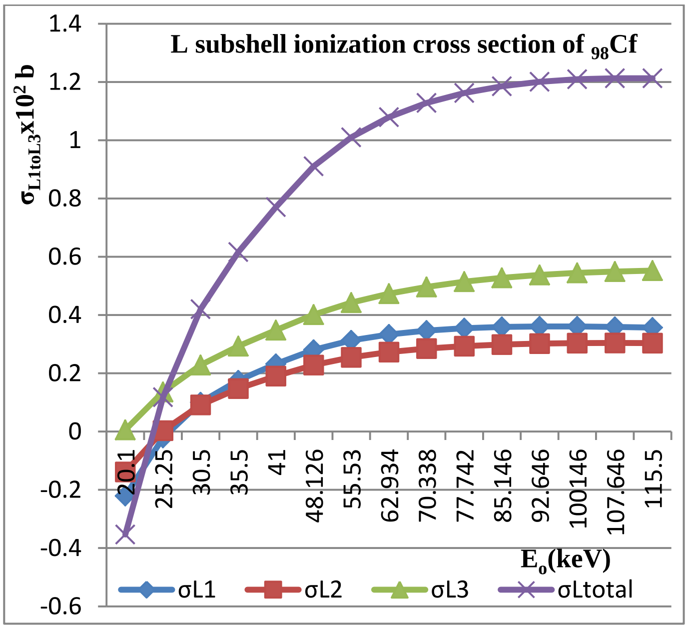

Figure.6 L subshell ionization cross section of $_{98}$ Cf in 10^2 b.

Table.8 Fixed 40keV electron impact, Z dependency of.σL_i for 93Np to 98Cf atoms in 10^2 b.

Atomic Number	E_o(keV)	σ_{L1}	σ_{L2}	σ_{L3}	σ_{Ltotal}
93	40	0,36432	0,29871	0,48613	1,14916
94	40	0,32291	0,2693	0,4529	1,04511
95	40	0,3107	0,2545	0,4321	0,99734
96	40	0,2823	0,23136	0,40206	0,91572
97	40	0,25586	0,20969	0,37411	0,83965
98	40	0,22673	0,18576	0,33942	0,75191

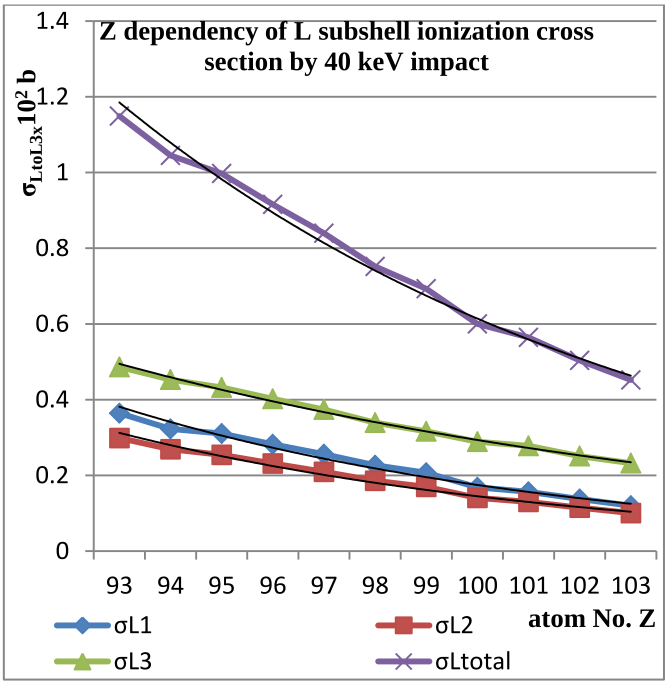

Figure.7 Fixed 40keV electron impact, Z dependency of.σL_i for 93Np to 98Cf atoms in 10^2 b.

4. Conclusions

L shell σ_L and σ_{Li} (i = 1 to 3) subshells ionization cross sections of $_{93}$Np to $_{98}$Cf by electron impact results given in Tabs.2 to 7 and in Figs.1to7. For L shell σ_L and for L_i subshells σ_{Li} increase rapidly by E_{oi} while E_{0i} increases from $E_i \leq E_{0i} \leq 5E_i$ as shown in data Tables and at graphics in Figures. These increments faster for very close to threshold energy values. Results for σ_L and σ_{Li} increase by E_{0i} for data of each atom. Variation of σ_{Li} by E_o near to E_{Li} region of L_i subshells of each atom show similarity they are related to production of characteristic x ray yield rate of that subshell. σ_{L2} always crosses σ_{L1} ones then further gets bigger up to highest electron impact energies for every atom. For a fixed E_{0i} = 40keV, while Z value increases from 93≤ Z ≤98 σ_L and σ_{Li} decrease: Variation for σ_{LTotal} is from $1,14916.10^2$ b to $0,75191.10^2$ b. σ_{Li} of three subshells also decrease similarly to each other by Z while increases from 93≤ Z ≤98. For $E_i \leq E_{0i} \leq 5E_i$ electron impact energy region results must be compared with experimental measurements and with other calculations such as Distorted wave Born approximation (DWBA) and Modified Relativistic Bethe Born Approximations (MRBEB) [4,5,6-14].

Acknowledgment

I would like to thank DUBAP of Dicle University (http://dubap.dicle.edu.tr) who allowed to use our project's computer(Reg.No:13-FF-53).

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