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The K_α/K_β Ratio for X-ray Transitions in Higher Energy Collision Processes

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The values of K_α/K_β ratio available from electron, proton, deuteron and alpha impact processes are surveyed and compared with Scofield's theories. The ratios determined in heavy ion collision processes are also reviewed and the effect of the multiple ionization is shown.

KEY WORDS K_α/K_β ratio/ Heavy-ion collision/ Structureless-particle impact/

I. INTRODUCTION

In the electronic and atomic collision experiments a number of parameters can be measured: total and various differential ionization cross sections (angular distribution of the emitted and scattered particles, impact parameter dependence, etc.), spectral distribution of X-rays or Auger-electrons, the width and shift of the lines in the spectra and so on (see details in good surveys, as *e.g.* refs. 1-7). Among these experimental parameters the K_α/K_β X-ray intensity ratios are relatively easily measurable. At the same time, this datum is one of the parameters which can be measured most precisely. For exampe the errors of this ratio are less by a factor of two-three than those of total ionization cross section in general because some of the main sources of errors are missing at the determination of the K_α/K_β ratio as *e.g.* the value of the beam current, the number of target atoms. However, there are experimental data for this ratio with substantial error especially if the goal of the actual study was not the determination of this parameter.

In the present survey the available evidence for the K_α/K_β ratio will be analyzed at different bombarding particles in the energy region of bombarding particles approximately above 100 keV. It is intended to show what kind of information can be acquired by the interpretation of these data.

II. STRUCTURELESS BOMBARDING PARTICLES

The number of measurements for K_α/K_β ratio at electron impact ionization is relatively low (cf. ref. 8.). At the same time, however, there are data for a wide range of the energy of the bombarding electrons. The ratio was measured in the relatively low and relatively high energy region, *i.e.* at hundred keV[9-11] and hundred MeV[12,13] energies in orders of magnitude.

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Table I. The values of K_α/K_β Ratio at Electron, Proton, Deuteron, and Alpha Particle Bombardment

Element	Weighted average of experimental data				Theoretical	
	e	p	d	α	without exch. corr.[21]	with exch. corr[22]
19 K			7,23(10)	7,09(6)	10,46	8,26
20 Ca			7,49(8)	7,31(6)	9,39	7,60
21 Sc			7,58(8)	7,33(7)	9,04	7,49
22 Ti		7,14(6)	7,89(8)	7,79(9)	8,80	7,38
23 V		7,51(4)	7,80(7)	7,73(14)	8,61	7,32
24 Cr		7,04(5)	7,74(10)	7,75(8)	8,67	7,48
25 Mn		7,50(6)	7,70(8)	7,69(8)	8,37	7,22
26 Fe	7,33(22)	7,60(8)	7,93(12)	7,78(13)	8,28	7,19
27 Co	7,44(22)	7,62(9)	7,82(8)	7,67(7)	8,21	7,16
28 Ni	7,01(21)	7,28(9)	7,52(5)	7,49(6)	8,15	7,14
29 Cn	7,17(18)	7,56(10)	7,45(6)	7,33(7)	8,22	7,25
30 Zn	7,22(36)	6,87(17)	7,28(7)	7,16(8)	8,06	7,09
31 Ga		6,46(16)		7,04(35)	7,83	6,87
32 Ge		6,77(34)	6,79(9)	6,81(6)	7,57	6,65
33 As		6,52(16)		6,58(35)	7,29	6,41
34 Se	6,26(16)	6,17(56)	6,14(4)	6,10(5)	7,02	6,16
35 Br		5,90(44)	6,04(6)	6,05(7)	6,74	5,94
37 Rb		5,64(34)		6,06(37)	6,25	5,62
38 Sr	5,55(20)	5,02(41)		5,10(9)	6,05	5,46
39 Y	5,20(14)	5,51(47)		5,46(27)	5,89	5,34
40 Zr		5,22(26)			5,76	5,22
42 Mo	5,26(16)	5,10(39)	5,14(5)	5,08(5)	5,53	5,05
46 Pd	3,77(17)	6,34(57)			5,17	4,77
47 Ag	4,84(22)	4,68(13)	4,86(10)	4,87(11)	5,09	4,69
49 In	4,55(21)	4,40(17)			4,93	4,55
50 Sn	4,41(22)	4,46(22)			4,85	4,48
51 Sb		4,42(22)			4,77	4,48
56 Ba	4,16(21)			4,55(8)	4,40	4,41
57 La	4,26(8)				4,34	4,12
58 Ce	4,02(8)				4,32	4,08
59 Pr	4,04(8)				4,28	4,05

60 Nd	4, 14(10)			4, 31(11)	4, 24	3, 99
64 Gd	3, 88(9)				4, 12	3, 89
66 Dy	3, 79(8)				4, 08	3, 87
67 Ho	3, 92(8)			3, 97(24)	4, 06	3, 85
68 Er	3, 94(10)				4, 04	3, 83
69 Tm				3, 65(19)	4, 02	3, 81
70 Yb	3, 70(8)				4, 00	3, 80
71 Lu				3, 73(12)	3, 97	3, 77
73 Ta		3, 89(30)		3, 97(31)	3, 92	3, 73
74 W				3, 52(17)	3, 89	3, 71
78 Pt				3, 77(30)	3, 82	3, 62
79 Au	3, 57(22)	3, 94(22)		3, 57(22)	3, 80	3, 51
82 Pb		3, 57(8)		3, 71(18)	3, 70	3, 54
83 Bi	3, 30(25)			3, 68(30)	3, 69	3, 52

Values for electron are calculated used the data of refs. 9–13.
Values for proton are calculated used the data of refs. 14–20.
Values for deuteron are calculated used the data of refs. 23.
Values for alpha particles are calculated used the data of refs. 23–26.
In brackets the errors calculated on the basis of experimental errors given in original papers.

As regards the data at proton bombardment, somewhat more measurements have been carried out than those at electrons, especially in the MeV region.[14–20]

In the case of both electron and proton bombardment no dependence on bombarding energy has been found. That is why weighted averages of the data for the same element measured at different bombarding energies (and by different authors) have been calculated separately for electrons and protons (cf. Table I). These weighted average values of K_α/K_β are plotted in Fig. 1 and compared with Scofield's calculation without[21] and with[22] taking into consideration the exchange correction.

On the basis of the table and figure it can be stated that there is no significant difference in K_α/K_β ratios measured at electron and proton impact. On the other hand, the data both at electron and proton bombardment are in fairly good agreement with the theoretical values calculated with taking into account the exchange correction.[22] At the much deviating point in the case of Pd there is very probably some systematic error as it is at our earlier datum for Pd.[10] (This latter datum is not indicated in Fig. 1 because we have realized the reason of the systematic error in the mean-time.) Here, however, the direction of the deviation is just the opposite as it was at our value.

The deuterons and alpha particles are not particles without any structure. However, according to the experimental evidence even in the cases of deuteron and alpha bombardment only small differences seem to be among the values of K_α/K_β ratio determined at electron (and proton) impact (cf. Table I). Here again, for alphas[23–26] and for

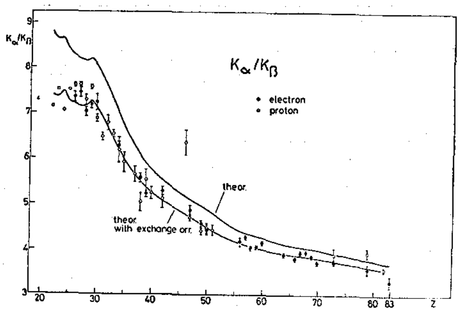

Fig. 1. The K_α/K_β ratios for electron and proton impact as a function of the atomic number of the target. The points in the figure are the weighted average of the experimental values at different impact energies and from different authors. For sources of the experimental data see the text and Table I. The theoretical curves with and without exchange corrections are drawn according to refs. 22. and 21, respectively.

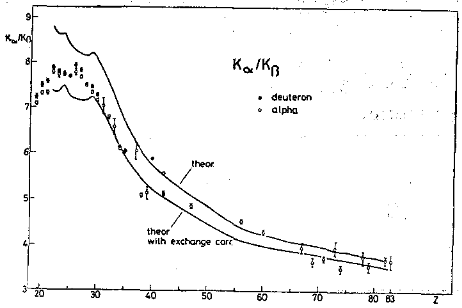

Fig. 2. The K_α/K_β ratios for deuteron and alpha particles as a function of the atomic number of the target. The points in the figure are weighted average of the experimental values at different impact energies and from different authors (for alphas). For sources of the experimental data see the text and Table I. The theoretical curves with and without exchange correction are drawn according to refs. 22. and 21, respectively.

deuterons[23] separately the weighted averages of the values obtained at different bombarding energies (and by different authors) were calculated for the individual elements. Thus, the K_α/K_β ratios from deuteron and alpha bombardment are also in more or less good agreement with the exchange corrected calculated ones (cf. Table I and Fig. 2). This agreement, however, is not so good as that for electrons and protons, and the deviations are first of all in the region of the atomic number from 22 to 29 and at $Z=56$ as well as at $Z=60$. This is probably due to the simultaneous K and M-shell ionization (see ref. 23 and later in this paper).

III. HEAVY IONS

The situation in connection with the K_α/K_β ratios determined in heavy ion collision processes seems to be more complicated than in the case of lighter projectiles. It is first of all due to the multiple ionization processes and so the Scofield theories cannot be used here.

The most important data on the published works dealing with the determination of K_α/K_β ratio at heavy ion impact are summarized in Table II. On the basis of the experimental values of these works for K_α/K_β ratios first of all it can be stated that those depend not only on the atomic number of the target atom, but also on the energy and atomic number of the projectile in general, deviating from the findings for electrons and protons and mostly also for deuterons and alpha particles. In the case of ^{16}O and ^{18}O, the projectile isotope dependence of K_α/K_β ratios were also studied but practically no effect has been found.[34] Watson and Li[42] measured the K_α/K_β ratio for fission fragments as projectiles, too.

If the K_α/K_β ratio values are plotted as a function of the projectile energy, the

Table II. The Main Parameters in the Published Measurements for K_α/K_β Ratio at Heavy Ion Impct

Bombarding particles	Bombarding energy (MeV/amu)	Target (Z)	Reference
$_6C$	2.35−8.33 (at four values)	19−47 (for 17 elements)	Li and Watson 1974 [23]
	0.4−2.4 (at 11 values)	28−51 (for four elements)	Gray *et al.* 1976 [27]
$_7N$	5.0	24−82 (for 9 elements)	Awaya *et al.* 1976 [25]
	0.4−2.4 (at 11 values)	28−51 (for four elements)	Gray *et al.* 1976 [27]
	0.5−2.57 (at 12 values)	20−30 (for 10 elements)	McDaniel *et al.* 1977 [28]
	0.5−2.57 (at 12 values)	32−47 (for 5 elements)	Tricomi *et al.* 1977 [29]
	0.2	22−32 (for 8 elements)	Mukoyama *et al.* 1978 [30,31]
$_8O$	0.9−1.2	Cu	Richard *et al.* 1970 [14]
	1.88	Fe	Burch *et al.* 1971 [32]
	5.0−10.0 (at 5 values)	Fe	Saltmarsh *et al.* 1972 [33]
	0.4−2.4 (at 11 values)	28−51 (for four elements)	Gray *et al.* 1976 [27]
	0.87−3.0 (at∼15 values)	19−32 (for 9 elements)	Knaf *et al.* 1977 [34]
$_{16}S$	0.3−3.0 (at 13 values)	25−32 (for 5 elements)	Tserruya *et al* 1976 [35]

following general picture is obtained. It should be noted here that it was rather difficult to select elements at which a some way complete series of data is available (cf. the series of data in Figs. 3 and 4). Values at either low or high energy are missing. Especially few measurements have been carried out at targets of higher atomic number. For relatively low atomic number of the target and projectile, the ratios - except the values at the lowest measured energies - are lower than the Scofield value[22] for K-shell single ionization (Figs. 3a and 3b). In the case of Ni *e.g.* data for three different neighboring projectiles (C, N, O) are available (Fig. 3a). Here and also for Cr a more or less definite dependence of the actual value of the ratio and a minimum value of that can be observed. Qualitatively similar trend was found by Tserruya *et al.*[35] for Ni at S impact, as well (see Fig. 3a). For relatively high atomic number of the target and the projectile however, the ratios are lower than the Scofield values[22] at the lowest meas-

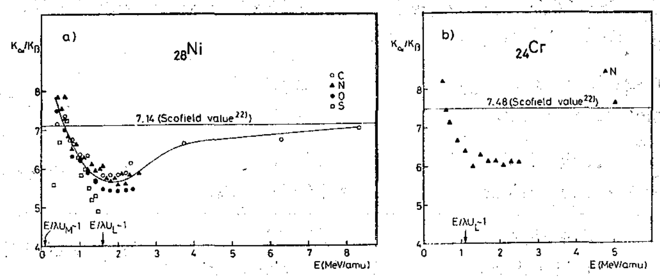

Fig. 3. The K_α/K_β ratio as a function of the projectile energy (MeV/amu) at different bombarding ions for Ni (a) and Cr (b) targets. Concerning the meaning of E/λ U_L and E/λU_M see the text. The experimental data are taken from ref. 23, 25, 27, 28, 35. The line in a) is drawn only to guide the eyes.

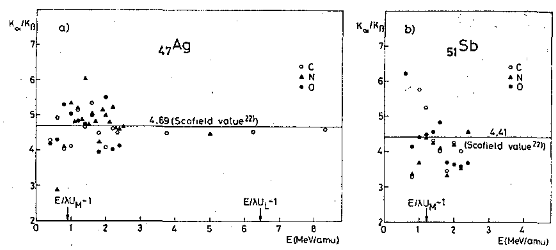

Fig. 4. The K_α/K_β ratio as a function of the projectile energy (MeV/amu) at different bombarding ions for Ag (a) and Sb (b) targets. Concerning the meaning of E/λ U_L and E/λU_M see the text. The experimental data are taken from ref. 23, 25, 27, 29.

ured energies, then there is a region where the experimental values are higher than that one, and finally they are lower again (Figs. 4a and 4b).

The above behavior is qualitatively understandable as follows. The K_α/K_β ratio depends sensitively on the number of L and M shell vacancies simultaneously produced with a K vacancy because K_α X-rays originate from 2p-1s and K_β X-rays predominantly from 3p-1s transitions. So a minimum for the K_α/K_β ratios is expected at the energy value corresponding to $E/\lambda U_L \sim 1$, (here E is the projectile energy, λ is the ratio of projectile mass to the electron mass, and U_L is the average binding energy for L electrons in the target atom) where the probability for L-shell ionization simultaneously with the production of a K vacancy has a maximum.

Similarly, a maximum for the K_α/K_β ratio is expected at the energy value which correspond to $E/\lambda U_M \sim 1$, where U_M is the average binding energy for M electrons. The principles of this interpretation is given in refs. 23, 33, and 31. In the last work the first evidence was published for the increase of K_α/K_β ratio above the single ionization value at relatively low bombarding energy corresponding to $E/\lambda U_M \sim 1$. The performance of exact calculations is rather difficult (cf. 23, 32, 31) but on the basis of these measurements and interpretation valuable information can be obtained on the multiple ionization process, namely on the simultaneous K-shell and L- as well as M-shell ionization, on the number of electrons (or vacancies) in the L- or M-shell in this multiple ionization, etc. Such type of valuable information can be obtained especially if the shifts of K_α and K_β

line are also measured and interpreted together with the K_α/K_β ratios.

The above findings can be summarized as an evidence of the validity of the BEA model *i.e.* the direct Coulomb excitation mechanism for this phenomenon. Some departures from this picture at higher atomic number projectiles (cf. *e.g.* the case of $_{16}S$ projectile in Fig. 3a) might be expectable and due to the departure of the phenomenon from the rough BEA model.

IV. CONCLUSIONS

The K_α/K_β ratio is one of the experimental parameters in atomic collision processes which is relatively simply and fairly accurately measurable. Some other data like $K_{\alpha_1}/K_{\alpha_2}$, $K_{\alpha_1'}/K_{\alpha_2'}$ etc. also can be measured similarly (see *e.g.* in ref. 26) and also those for higher shells, carrying similar information as K_α/K_β (cf. ref. 36).

The atomic number dependence of the K_α/K_β ratio if fairly well described for light particle bombardments (electron, proton, and mostly deuteron alpha particle) by the exchange corrected Scofield theory.[22] May I mention here that also at photon and low energy electron generated X-rays (*e.g.* refs. 37-39) the K_α/K_β values are in good agreement with the above theory. At electron capture radioactive decay,[40,41] however, there is a definite departure from the Scofield theory[22] in the same region of the atomic numbers as that for deuteron and alpha impact excitation.

At heavy ion collisions we have the qualitative interpretation of the experimental data on the basis of the multiple ionization processes. As it was mentioned in Section III, more experimental values are necessary for K_α/K_β ratios especially at low and high bombarding energies, at targets with higher atomic numbers and finally with heavier projectile ions.

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