TWO ELECTRON ONE PHOTON RER TRANSITIONS AS THE ORIGIN OF LOW ENERGY SATELLITES IN K_β X-RAY SPECTRA

By S. N. Soni

X-ray Laboratory, Department of Physics, University of Jodhpur*

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The two low energy satellites β_0 and β_s reported in K-X-ray emission spectra of elements with $Z = 33$ to 47 have been assigned to suitable two electron one photon RER transitions. The satellite β_s in the range $Z = 33$ to 35 and the satellite β_0 in the range $Z = 38$ to 47 are assigned to a common transition, namely $KN_2 \rightarrow M_1N_1$. The line β_s in the range $Z = 33$–35 has, therefore, been suggested for renaming as β_0. The line reported as β_0 in the range $Z = 33$–-37 has been assigned to the transition $KN_1 \rightarrow M_1N_2$ and has therefore been tentatively renamed as β_0'. Finally, the satellite reported as β_s in the range $Z = 37$–44 has been assigned to the $KN_{4,5} \rightarrow M_2M_4$ transition.

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1. *Introduction*

The occurrence of satellites (weak lines) on the high and low energy sides of strong diagram lines in X-ray spectra is very well known. The high energy satellites have been shown [1–4] to result mostly from single electronic transitions in atoms with more than one vacancies in the inner shells. However, the origin of low energy satellites has not been uniquely established. Recently, many sharp peaks and edge type structures have been observed on the low energy side of $K\alpha_{1,2}$ lines in the X-ray spectra of ^{13}Al and ^{14}Si excited by Cr—K-radiations [5], as well as 30 MeV oxygen ions [6]. Following Bloch [7], Åberg and Utriainen [5] have suggested that these low energy structures could be due to the Radiative Auger Effect (RAE) in which a photon is emitted simultaneously with an inner or outer shell electron. McWherter et al. [8] proposed the theory of multiple volume plasmon excitation for the origin of such low energy structures. However, this theory was shown by Jamison et al. [9] to be inconsistent with the intensities of these peaks observed with hydrogen ion bombardment [10]. They suggested the sequence $(1s)^{-1}(2p)^{-n} \rightarrow (2s)^{-2}(2p)^{-n+1}$, $n = 1-4$ for the origin of these low energy peaks. This simultaneous rearrangement of

* Address: X-Ray Laboratory, Department of Physics, University of Jodhpur, Jodhpur — 342001, India.

two vacancies in the atom resulting in the emission of a single photon was named [9] as Radiative Electron Rearrangement (RER). The theories of RER and RAE were later confirmed by Jamison et al. [11] who undertook a detailed study of the $K\alpha$ spectra of ^{12}Mg, ^{13}Al and ^{14}Si. Good agreement was found between the calculated and observed data on energy as well as the intensity of such transitions. The studies of $K\beta$ spectra of ^{18}Ar [12] and ^{19}K [13] have also yielded similar results.

A survey of available literature on X-ray satellites reported by earlier workers shows that out of the prominent low energy satellites β_0, β_s, $\beta_0(\eta)$ and β' reported in $K\beta$ spectra [14, 15], the first two have not been assigned to any specific transition. It was therefore thought worthwhile to find out if any two electron one photon RER or RAE transitions could be assigned to these satellites. In this paper, the results of the studies on RER transitions are reported.

2. *Results*

(a) The satellite β_0

The satellite β_0 has been reported by Hulubei et al. [16] in the K-emission spectra of elements ^{33}As to ^{47}Ag, except ^{43}Tc and ^{46}Pd. On calculating the energy of each of the allowed transitions between all possible doubly ionized states, it was found that no single transition can be suitably assigned to this satellite for all the elements in which it has been reported. However, the line reported to be β_0 for the elements ^{33}As to ^{37}Rb could be assigned to the transition

$$KN_1 \rightarrow M_1N_2 \tag{1}$$

while that reported for the elements ^{38}Sr to ^{47}Ag could be assigned to the transition

$$KN_2 \rightarrow M_1N_1. \tag{2}$$

Both these transitions are allowed according to the Heisenberg selection rules [17]. Various quantum mechanical parameters for the initial and final states of these transitions are shown in columns 2–5 of Table I. The consideration of configuration interaction makes these transitions more allowed. The states M_1N_2 ^1P and ^3P can interact with $N_1N_{2,3}$ ^1P and ^3P states respectively, transitions from KN_1 ^1S and ^3S states to which are dipole allowed one electron transitions in doubly ionised atoms. Similarly the interaction M_1N_1 $^1S+N_{2,3}^2$ ^1S enhances the intensity of the $KN_2 \rightarrow M_1N_1$ transition as $KN_2 \rightarrow N_{2,3}^2$ is a dipole allowed transition. However, in calculating the energies of the transitions (1) and (2), the level shifting due to the configuration interaction has been neglected assuming it to be small because of the large difference in energy values of interacting partners.

The energies of the transitions (1) and (2) have been calculated by Wentzel's $(Z+1)$ approximation method using the formulas

$$\Delta E = [(E_K)_Z+(E_{N_1})_{Z+1}]-[(E_{M_1})_Z+(E_{N_2})_{Z+1})$$

and

$$\Delta E = [(E_K)_Z+(E_{N_2})_{Z+1}]-[(E_{M_1})_Z+(E_{N_1})_{Z+1}]$$

TABLE I

Quantum states of two electron one photon RER transitions

Transition	$KN_2 \to M_1N_1$		$KN_1 \to M_1N_2$		$KN_{4,5} \to M_2M_4$	
Particulars	Initial state	Final state	Initial state	Final state	Initial state	Final state
States of holes	$1s_{1/2}$, $4p_{1/2}$	$3s_{1/2}$, $4s_{1/2}$	$1s_{1/2}$, $4s_{1/2}$	$3s_{1/2}$, $4p_{1/2}$	$1s_{1/2}$,$4d_{3/2,5/2}$	$3p_{1/2}$, $3d_{3/2}$
l-values	0 1	0 0	0 0	0 1	0 2	1 2
j-values	1/2 1/2	1/2 1/2	1/2 1/2	1/2 1/2	1/2 3/2, 5/2	1/2 3/2
Σl	1	0	0	1	2	3
Parity	Odd	Even	Even	Odd	Even	Odd
Quantum states ($L-S$ coupling)	$1P$ & $3P$	$1S$ & $3S$	$1S$ & $3S$	$1P$ & $3P$	$1D$ & $3D$	$1P$, $1D$, $1F$, $3P$, $3D$ & $3F$
J-values ($j-j$ coupling)	0 & 1	0 & 1	0 & 1	0 & 1	1 & 2 or 2 & 3	1 & 2

respectively, where the symbol $(E_K)_Z$ denotes the energy of the excited state K of the atom having atomic number Z. Similar meanings are carried by other symbols. The values of these singly ionised states of atoms have been taken from the tables of Bearden and Burr [18]. The observed values of wavelengths of this satellite, their corresponding computed

TABLE II

Energy and wavelength of satellite $K\beta_0$

Z	Observed values for the Satellite $K\beta_0$: Wavelength	Observed values for the Satellite $K\beta_0$: Energy (keV)[a]	Calculated energy of the proposed transition (keV)
	Transition: $KN_1 \to M_1N_2$		
33	1058.9	11.684	11.679
34	993.8	12.449	12.448
35	934.8	13.235	13.231
36	881.4	14.037	14.051
37	831.8	14.874	14.877
	Transition: $KN_2 \to M_1N_1$		
38	786.5	15.731	15.727
39	744.2	16.625	16.622
40	705.1	17.547	17.543
41	669.2	18.488	18.490
42	635.62	19.465	19.466
44	575.4	21.502	21.499
45	548.16	22.570	22.557
47	499.7	24.759	24.756
	Satellite $K\beta_0(\eta)$ Transition: $KN_2 \to M_1N_1$		
32	1133.7	10.913	10.911

Values in x.u. have been converted to keV units by the conversion factor 12372.2 x.u. KeV.

energies and the calculated energies of these transitions are shown in Table II. The excellent agreement between the third and the fourth columns of this table establishes the validity of the proposed transition assignments. It may be pointed out here that the satellite $\beta_0(\eta)$ reported [14] at $\lambda = 1133.7$ x.u. in the K-emission spectrum of ^{32}Ge can also be assigned to the transition $KN_2 \rightarrow M_1N_1$ (see Table II).

(b) The satellite β_s

This satellite was reported by Hulubei et al. [16] in the K-spectra of elements ^{33}As to ^{35}Br, ^{37}Rb to ^{41}Nb and of ^{44}Ru. Similar to the satellite β_0, no single transition could be assigned to this satellite in the entire range $Z = 33$ to 44. However, the line β_s in the range $Z = 33$ to 35 can be assigned to the transition

$$KN_2 \rightarrow M_1N_1 \tag{3}$$

that is the same as that assigned to β_0 in the range $Z = 38$ to 47. In the rest of the elements, namely ^{37}Rb to ^{44}Ru, the line reported as β_s can be assigned to the transition

$$KN_{4,5} \rightarrow M_2M_4. \tag{4}$$

The degree to which this transition is allowed can be judged by various quantum mechanical parameters of the initial and final states given in columns 6 and 7 of Table I and the Heisenberg selection rules [17]. The interactions $M_2M_4\ {}^1P + N_{2,3}N_{4,5}\ {}^1P$, $M_2M_4\ {}^1D + N_{2,3}N_{4,5}\ {}^1D$, $M_2M_4\ {}^1F + N_{2,3}N_{4,5}\ {}^1F$, $M_2M_4\ {}^3P + N_{2,3}N_{4,5}\ {}^3P$, $M_2M_4\ {}^3D + N_{2,3}N_{4,5}\ {}^3D$ and $M_2M_4\ {}^3F + N_{2,3}N_{4,5}\ {}^3F$ also help in making the state M_2M_4 an allowed state in the transition (4) because of the allowedness of $K\ N_{4,5} \rightarrow N_{2,3}N_{4,5}$ one electron jump in doubly ionized atoms. However, the effect of the configuration interaction in calculating the energy of the transition has been neglected for the same reasons as mentioned in Section 2(a). The

TABLE III

Energy and wavelength of satellite $K\beta_s$

Z	Observed values of the satellite $K\beta_s$		Calculated energy of the proposed transition
	Wavelength (x.u.)	Energy (keV)[a]	(keV)
	Transition: $KN_2 \rightarrow M_1N_1$		
33	1061.9	11.651	11.647
34	997.5	12.403	12.404
35	938.4	13.184	13.204
	Transition: $KN_{4,5} \rightarrow M_2M_4$		
37	834.8	14.821	14.818
38	789.5	15.671	15.665
39	747.7	16.547	16.543
40	709.0	17.450	17.447
41	672.7	18.392	18.378
44	579.6	21.346	21.326

[a] Values in x.u. have been converted to keV units by the conversion factor 12372.2 x.u. keV.

observed data of the satellite β_s and the calculated energy values of the two transitions are given in Table III. Although the method of calculation for the transition (3) was same as that mentioned in Section 2(a), the value of the transition (4) has been calculated by the formula

$$\Delta E = [(E_K)_Z + (E_{N_{4.5}})_{Z+1}] - [(E_{M_2})_Z + (E_{M_{4.5}})_{Z1}],$$

where the symbols have their usual meaning and the energy values of singly ionised states of atoms have been taken from the tables of Bearden and Burr [18]. The excellent agreement between the observed and calculated energies suggests that the proposed transition assignments are appropriate.

3. Conclusion

Suitable two electron one photon transitions of the RER type have been assigned to the low energy satellites β_0 and β_s reported in the K—X-ray emission spectra of the elements ^{33}As to ^{47}Ag. The transition $KN_2 \rightarrow M_1N_1$ has been assigned to the satellite β_s in the range $Z = 33$–35 and also to the satellite β_0 in the range $Z = 38$–47. It is, therefore, suggested that the satellite β_s in the range $Z = 33$–35 should be reidentified as β_0. Further, the satellite reported as β_0 in the range $Z = 33$ to 37 has been assigned to $KN_1 \rightarrow M_1N_2$. This satellite in this range should therefore be given a new name. A tentative name β_0' is hereby proposed. This line in the spectra of elements with $Z > 37$ should be looked for experimentally. Finally, the satellite reported as β_s in the range $Z = 37$–44 has been assigned to the transition $KN_{4,5} \rightarrow M_2M_4$.

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