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Sum peak method applied to the study of decay of Ir-192

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Abstract. The electron capture probabilities to 690·70 and 580·37 keV levels and the K-conversion coefficients of 205·9 and 316·5 keV transitions in the decay of Ir-192 have been determined from the measurement of gamma-ray intensities in conjunction with an analysis of the KX-ray-γ-ray sum peaks observed with a co-axial HPGe detector. The K-capture probability to 690·70 keV level was determined by an approach which is independent of K-shell fluorescence yield and absolute detection efficiency for KX-rays. The K-shell fluorescence yields of the daughter products, namely, Os and Pt of Ir-192 have also been determined by the same technique and were found to be $0{\cdot}964 \pm 0{\cdot}077$ and $0{\cdot}969 \pm 0{\cdot}068$ respectively.

Keywords. Decay of Ir-192; K-capture probabilities; K-conversion coefficients; fluorescence yield.

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1. Introduction

Bambynek *et al* (1977) have reviewed experimental data on electron capture probabilities and discussed several methods from which the K-capture probability P_K to a level can be deduced. One group of methods yields ratios of capture probabilities from different shells. There are yet other methods in which the product $P_K W_K$ is determined, where W_K is the K-shell fluorescence yield of the daughter product. Absolute measurements of internal conversion coefficients of gamma rays are of great importance in nuclear spectroscopy work. They yield valuable information on nuclear structure. They are also used for the identification of the multipolarities. In general, conversion coefficients are measured (i) from the relative gamma ray intensities and conversion electron intensities and (ii) relative to the theoretical K-conversion coefficient of a gamma ray of known multipolarity. These can also be measured using the same source in well calibrated beta and gamma ray spectrometers. Such a set-up involves two sets of spectrometers and moreover it is a time-consuming technique.

The sum technique proposed by Dasmahapatra and Mukherjee (1974) and used by other workers [Singh and Sahota (1983), Singh *et al* (1985), Singh *et al* (1990) and Chandrasekhar Rao *et al* (1990)] is followed in the present measurements. As a primary condition for the measurement of P_K by the sum peak method, the decay scheme of Ir-192 (shown in figure 1) is well established (Eid and Stewart 1985; Yoshizawa *et al* 1980; Shirley and Dariki 1983). The intensity under the KX-ray γ-ray sum peak is the consequence of simultaneous detection of cascading γ-ray photons

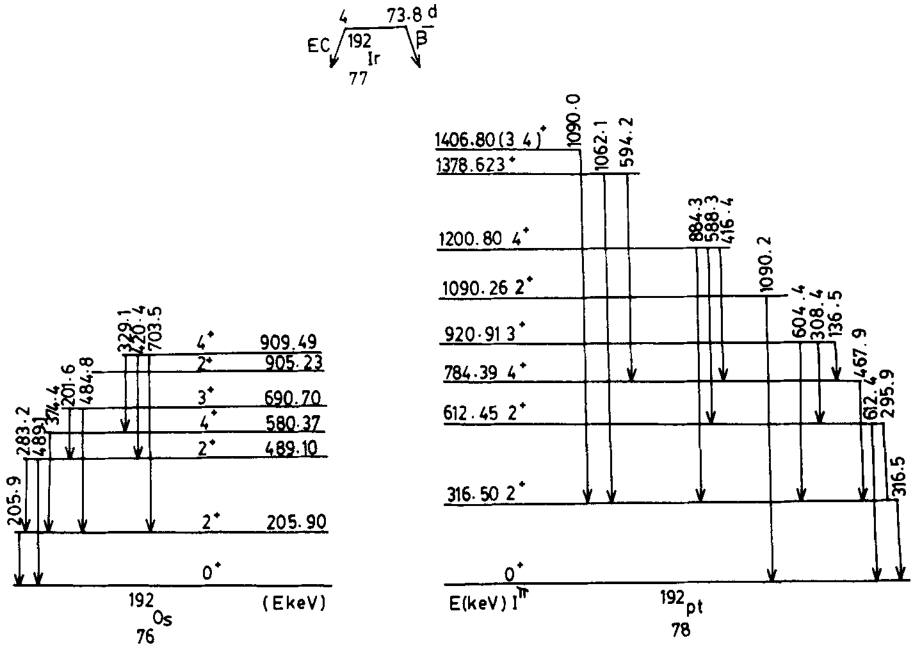

Figure 1. Decay scheme of ^{192}Ir.

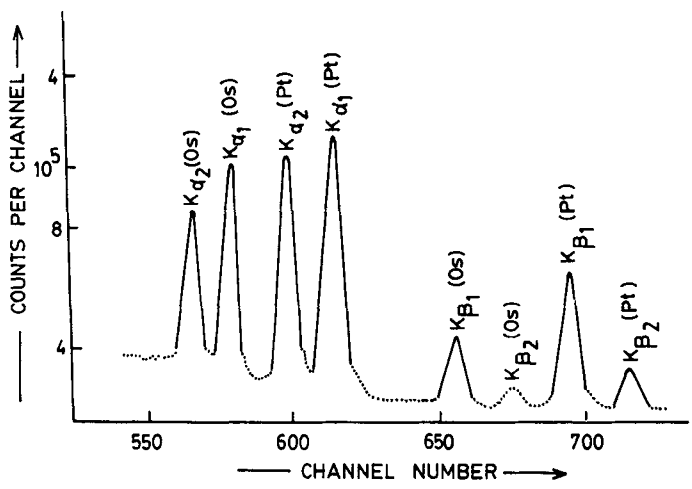

Figure 2. Part of gamma ray spectrum taken with 0·55 CC vertical HPGe detector.

and KX-ray photons emitted following K-capture to a level and K-conversion of the coincident transitions.

2. Experimental set-up

The radioactive isotope Ir-192 was obtained from the Isotope Division, Bhabha Atomic Research Centre, Bombay as sodium iridate in dilute hydrochloric acid. A very weak point source was formed by drying radioactive solution onto a perspex sheet under an infrared lamp. The source strength was adjusted so as to give a count rate of the order of 1000 counts at the experimental position. The source strength was kept low in order to avoid interference of accidental sum coincidences. The energy and intensity measurements were carried out using (i) a vertical HPGe detector (active area 78·57 mm^2 and sensitive depth 7 mm) having energy resolution of 169 eV at 5·9 keV X-rays of 55 Fe and (ii) a co-axial HPGe detector (96·0 cc) having energy resolution of 1000 eV at 122 keV γ-rays of Co-57. For intensity measurements the point source was placed at a distance of 25 cm from the detector window while for sum coincidence measurements, the weak point source was placed at the face of the 96.0 cc co-axial HPGe detector. The single's spectra recorded with 4096 channel analyser are shown in figures 2 and 3.

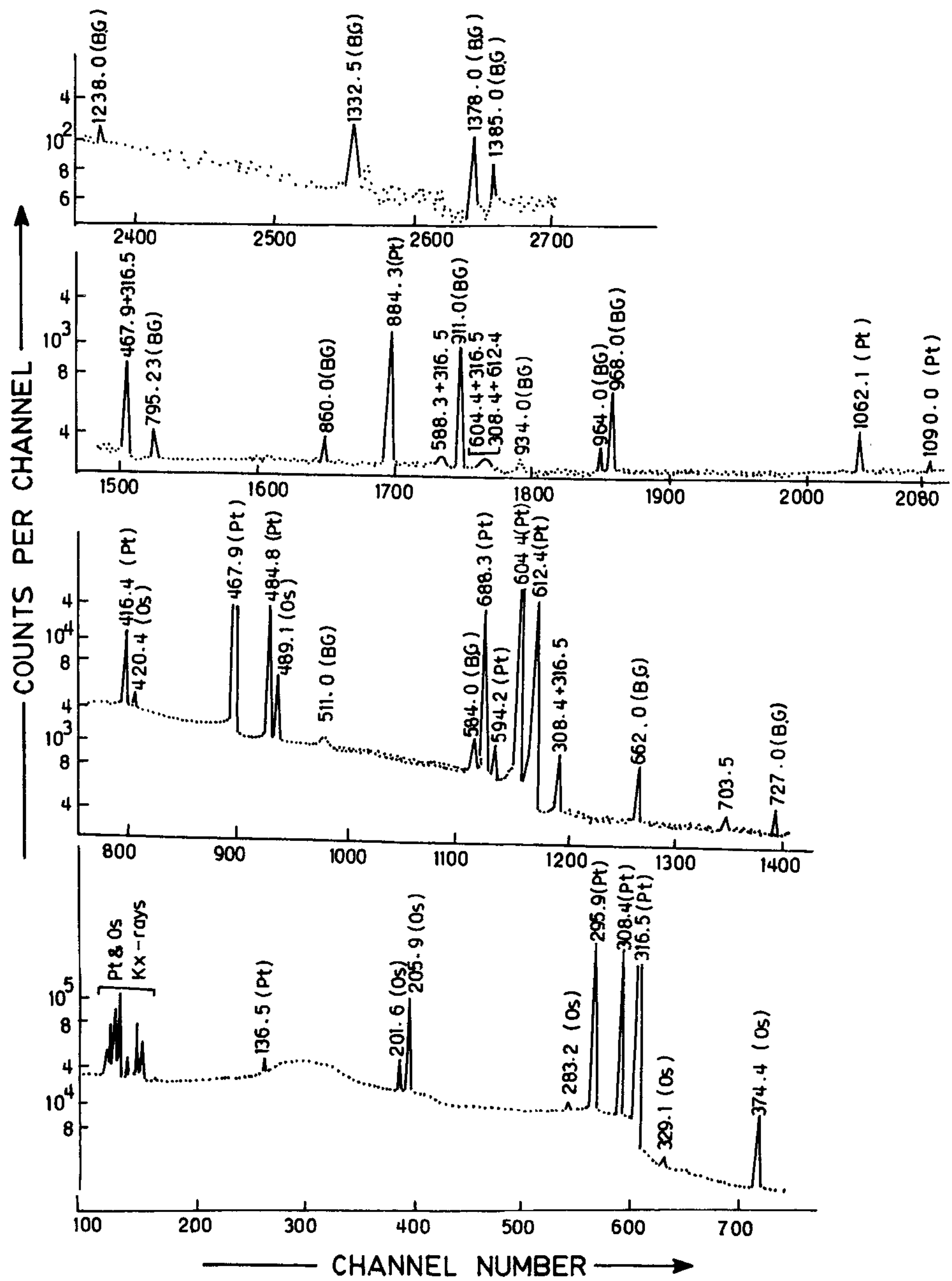

Figure 3. Gamma ray spectrum taken with 96·0 CC HPGe detector.

3. Measurements and results

3.1 *Relative intensity measurements*

The relative intensities of the gamma-rays were obtained by dividing the area under the photopeak with corresponding relative full energy photopeak detection efficiency of the detector obtained in the present work. The efficiency of the detector at intermediate energies was obtained by putting the regression coefficients and energy in keV in a polynomial used for fitting procedure. The KX-ray and γ-ray intensities obtained are shown in table 1. The areas of various gamma-rays were corrected for summing loss or gain. These correction factors were calculated using computer program KORSUM, developed by Debertin and Schotzig (1979). The magnitudes of correction factors obtained for various transitions are shown in the last column of table 1.

Table 1. Relative X and gamma ray intensities in the decay of ^{192}Ir.

Energy (keV)	Relative intensities: Present work	Iwata *et al* (1984)	Yoshizawa *et al* (1980)	Summing correction (%)
61·5 $K_{\alpha 2}$(Os)	1·40(4)			
63·0 $K_{\alpha 1}$(Os)	2·39(8)			
65·1 $K_{\alpha 2}$(Pt)	3·08(10)			
66·8 $K_{\alpha 1}$(Pt)	5·58(19)			
71·3 $K_{\beta 1}$(Os)	0·82(3)			
73·4 $K_{\beta 2}$(Os)	0·210(5)			
75·4 $K_{\beta 1}$(Pt)	1·890(65)			
77·9 $K_{\beta 2}$(Pt)	0·490(18)			
136·5	0·260(8)	—	0·35(6)	0·41
201·6	0·57(2)	—	0·57(4)	0·28
205·9	3·98(6)	—	4·01(6)	0·21
283·2	0·303(9)	0·303(22)	0·304(22)	0·41
295·9	34·52(60)	34·62(17)	34·69(17)	0·42
308·4	35·77(62)	35·84(18)	35·87(19)	0·38
316·5	100(1)	100	100	0·28
329·1	0·033(5)	—	—	0·12
374·4	0·888(17)	0·861(8)	0·860(9)	0·20
416·4	0·776(15)	0·800(10)	0·797(11)	0·41
420·4	0·072(5)	—	0·078(9)	0·28
467·9	56·97(99)	57·50(23)	57·76(25)	0·11
484·8	3·818(67)	3·810(18)	3·828(18)	0·19
489·1	0·516(11)	0·525(9)	0·527(9)	0·10
588·3	5·395(95)	5·398(21)	5·42(2)	0·39
594·2	0·059(4)	—	0·052(3)	0·40
604·4	9·87(17)	9·75(4)	9·79(4)	0·38
612·4	6·25(11)	6·33(25)	6·37(3)	—
703·5	0·006(2)	—	—	—
884·3	0·346(8)	0·342(24)	0·344(3)	0·95
1062·1	0·062(3)	0·063(1)	0·063(1)	0·11
1090·0	0·0020(6)	—	—	0·21

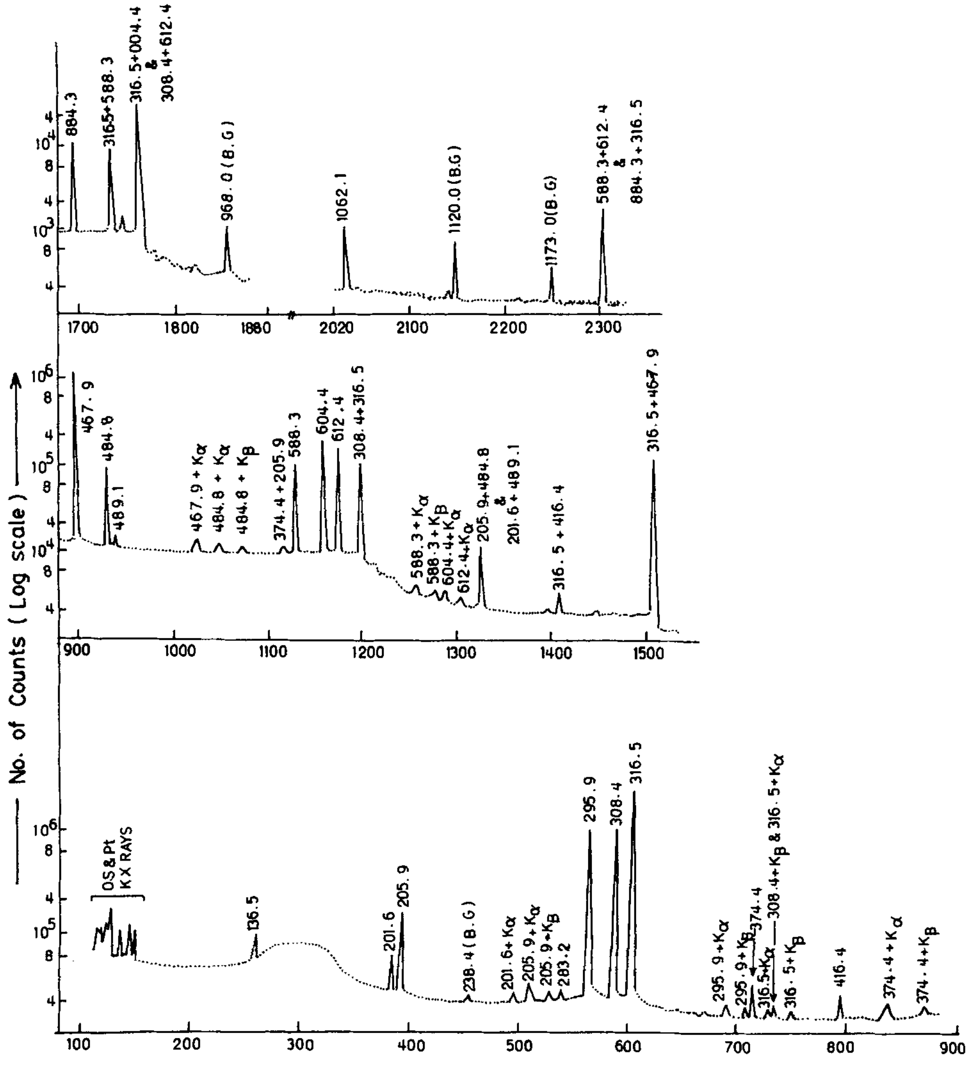

Figure 4. Sum spectrum taken with 96·0 CC HPGe detector (only peaks of interest are shown).

3.2 *Determination of K-capture probabilities*

The relative K-capture probabilities to 690·70 and 580·37 keV levels have been determined by the analysis of sum peaks. The γ-ray spectrum taken in the close geometry set-up is shown in figure 4.

3.2.1 *K-capture probability to 690·70 keV level*: It is evident from the decay scheme (figure 1) that KX-rays in cascade with the 484·8 keV gamma-ray arise following the (i) K-capture to the 690·70 keV level and (ii) K-conversion of 205·9 keV transition. The area under sum peak (484·8 + K_α) keV can be written as

$$N_{484\cdot 8+K_\alpha} = W_K \frac{I_{K2}}{I_{K_\alpha}+I_{K_\beta}} \varepsilon_{K_\alpha} \left[P_K(690\cdot 37) + \frac{\alpha_K^{205\cdot 9}}{1+\alpha_T^{205\cdot 9}} \right] N_{484\cdot 8} \tag{1}$$

where W_K, I_{K_α}, I_{K_β} and ε_{K_α} are K-shell fluorescence yield, intensities of the KX-rays and absolute photopeak efficiency of the detector of KX-rays respectively. Similarly, by taking into account all effects, the area under the sum peak (201·6 + K_α) keV can be written as

$$N_{201\cdot 6+K_\alpha} = \frac{I_{K_\alpha}}{I_{K_\alpha}+I_{K_\beta}} W_K \varepsilon_{K_\alpha} \left[P_K(690\cdot 70) + \frac{I_{489\cdot 1}}{T_{489\cdot 1}} \frac{\alpha_K^{489\cdot 1}}{1+\alpha_T^{489\cdot 1}} + \frac{I_{283\cdot 2}}{T_{489\cdot 1}} \times \left(\frac{\alpha_K^{283\cdot 2}}{1+\alpha_T^{283\cdot 2}} + \frac{\alpha_K^{205\cdot 9}}{1+\alpha_T^{205\cdot 9}} \right) \right] N_{201\cdot 6}, \tag{2}$$

where $T_{489\cdot 1} = I_{489\cdot 1} + I_{283\cdot 2}$ while all the other terms have their usual meanings. Since the transitions 484·8 and 201·6 keV depopulate the same level, the equations giving the areas under sum peaks (484·8 + K_α) and (201·6 + K_α) keV involve K-capture probability to the same level. Their division with each other will lead to the cancellation of some unwanted factors like efficiency of the detector, ε_{K_α} K-shell fluorescence yield, W_K and fraction of KX-ray photons. In this way the measurement of $P_K(690\cdot 70)$ will be independent of these factors. The final form of the equation may be written as

$$\frac{N_{484\cdot 8+K_\alpha}}{N_{201\cdot 6+K_\alpha}} = \frac{\left[P_K(690\cdot 7) + \frac{\alpha_K^{205\cdot 9}}{1+\alpha_T^{205\cdot 9}} \right] N_{484\cdot 8}}{\left[P_K(690\cdot 7) + \frac{I_{489\cdot 1}}{T_{489\cdot 1}} \frac{\alpha_K^{489\cdot 1}}{1+\alpha_T^{489\cdot 1}} + \frac{I_{283\cdot 2}}{T_{489\cdot 1}} \left(\frac{\alpha_K^{283\cdot 2}}{1+\alpha_T^{283\cdot 2}} + \frac{\alpha_K^{205\cdot 9}}{1+\alpha_T^{205\cdot 9}} \right) \right] N_{201\cdot 6}}. \tag{3}$$

The LHS of the above equation involves the ratio of sum peak areas while the product on RHS involves the ratio of peak areas corresponding to the energies 484·8 and 201·6 keV besides K-conversion coefficients, total conversion coefficients and gamma ray branching ratios. By taking relative gamma ray intensities from the present work and conversion coefficients from Shirley and Dariki (1983) the above equation was solved for $P_K(690\cdot 70)$. The value of K-capture to 690·70 keV level obtained is shown in table 2.

Table 2. Relative K-capture probabilities to the excited states of ^{192}Ir.

Level energy	Peaks used	Sum peak area	Experimental P_K Present work	Experimental P_K Dasmahapatra (1975)	Theory
580·37	$374{\cdot}4 + K_\alpha$	6455(547)	0·84(8)		0·81
	$374{\cdot}4 + K_\beta$	1830(422)	0·81(12)		
	374·4	139067(691)			
		Wt. Av. $P_K(580) = 0{\cdot}83(7)$			
690·70	$484{\cdot}8 + K_\alpha$	6593(398)			
	$201{\cdot}6 + K_\alpha$	5110(600)	0·74(9)	0·70(6)	0·77
	484·8	213845(957)			
	201·6	122811(1038)			

3.2.2 *Determination of K-capture probability to the 580·37 keV level*: The K-capture probability to the 580·37 keV level was determined from the $(374 + K_\alpha)$ and $(374 + K_\beta)$ sum peaks. The 374·4 keV gamma ray is in cascade with KX-rays arising from (i) K-capture to 580·37 keV level and (ii) K-conversion of 205·9 keV gamma transition. Thus the area under the $(374{\cdot}4 + K_\alpha)$ keV sum peak is written as

$$N_{374{\cdot}4+K_\alpha} = f_{K_\alpha} W_K \left[P_K(580{\cdot}37) + \frac{\alpha_K^{205{\cdot}9}}{1 + \alpha_T^{205{\cdot}9}} \right] N_{374{\cdot}4} \tag{4}$$

where

$$f_K = \frac{I_{K_\alpha}}{I_{K_\alpha} + I_{K_\beta}} K$$

$N_{374{\cdot}4}$ = area under the peak 374·4 keV corrected for summing.

Similarly equation for $(374{\cdot}4 + K_\beta)$ keV was written by replacing f_{K_α} by f_{K_β}. The above equation was solved for $P_K(580{\cdot}37)$. The value of W_K was taken from Lederer and Shirley (1978). The efficiencies ε_{K_α} and ε_{K_β} of the detector for KX-rays were obtained from the equations that give rise to the areas under the $(484{\cdot}8 + K_\alpha)$ and $(484{\cdot}8 + K_\beta)$ keV sum peaks respectively. Present value of $P_K(690{\cdot}70)$ was used to determine P_K to 580·37 keV level. Notice that $P_K(690{\cdot}70)$ was determined independent of absolute detection efficiency and K-shell fluorescence yield. The values of absolute detection efficiencies of the detector for KX-rays were found to be

$$\varepsilon_{K_\alpha} = 0{\cdot}0635 \quad 0{\cdot}0029$$

and

$$\varepsilon_{K_\beta} = 0{\cdot}0759 \quad 0{\cdot}0058.$$

3.3 *Determination of K-shell fluorescence yield* (W_K)

The methods of determining W_K vary according to the ionization process, the target material, the decay scheme of the radionuclide, the detector and the requirements of necessary corrections.

The number of sum peaks arising due to r–r and r-KX-ray coincidences has been observed in gamma ray spectra of Ir-192 taken in the close geometry set-up. Of the number of sum peaks observed in the spectra some are used to determine K-shell fluorescence yield and others have been used to measure K-conversion coefficients.

From the decay scheme (figure 1) equation for the area under the sum peak (374·4 + 205·9) keV can be written as

$$N_{374\cdot4+205\cdot9} = \left[\frac{1}{1+\alpha_T^{205\cdot9}}\right]\varepsilon_{205\cdot9}^{\text{abs.}} N_{374\cdot4}. \tag{5}$$

Combining 4 and 5 we get

$$N_{374\cdot4+K_\alpha} = \frac{I_{K_\alpha}}{I_{K_\alpha}+I_{K_\beta}} W_K \left(\frac{\varepsilon_{K_\alpha}}{\varepsilon_{205\cdot9}}\right)^{\text{abs}} \left[P_K(580\cdot37) + \frac{\alpha_K^{205\cdot9}}{1+\alpha_T^{205\cdot9}}\right] N_{374\cdot4+205\cdot9}(1+\alpha_T^{205\cdot9}). \tag{6}$$

For the determination of W_K from the above equation theoretical value of $Pk(580\cdot37)$ obtained from the expression given by Behrens and Janecke (1969) was used. The K-shell and total conversion coefficients have been taken from Shirley and Dariki (1983) and $\varepsilon_{K_\alpha}/\varepsilon_{205\cdot9}$ have been taken from the relative efficiency curve. The main advantage of putting an equation in the form given above is that the determination of absolute detector efficiency for KX-rays is not required. Similar equation was written for the area under the sum peak (374·4 + K_β) keV and K-shell fluorescence yield WK for Os-192 was determined. The weighted average of the value is shown in tables 3 and 4. The determination of K-shell fluorescence yield W_K of Pt-192 by this method is rather simple. Sum peak (604·4 + K_α) keV has been chosen for the determination of W_K(Pt). The KX-rays that are in coincidence with the 604·4 keV transition is created following K-conversion of 316·5 keV transition. The final form of the equation for area under the sum peak (604·4 + K_α) keV is written as

$$N_{604\cdot4+K_\alpha} = \frac{I_{K_\alpha}}{I_{K_\alpha}+I_{K_\beta}}\left(\frac{\varepsilon_{K_\alpha}}{\varepsilon_{316\cdot5}}\right) W_K \alpha_K^{316\cdot5} N_{604\cdot4+316\cdot5}. \tag{7}$$

Again this equation is independent of total conversion coefficient α_T and absolute detection efficiency of the detector for X-rays. The contribution of (612·4 + 308·4) keV sum peak was subtracted from the total sum peak area by the knowledge of known branchings.

Table 3. K-shell flourescence yields of Os and Pt elements.

Peaks used (keV)	Peak Area	Fluorescence yield (W_K) Present work	Lederer and Shirley (1978)
374·4 + K_α	6455(547)	0·966(82)Os	
374·4 + K_β	1830(422)	0·955(220)(Os)	
374·4 + 205·9	1631(341)		
	W.Av(Os)	0·964(77)	0·961
604·4 + K_α	5150(278)	0·969(68)(Pt)	0·963
604·4 + 316·5	148330(317)		

Table 4. Absolute K-conversion coefficients.

Peaks used area	Peak	Transition energy (keV)	Conversion coefficients (K) Present work	Shirley and Dariki (1980)	Mukherjee and Dasmahapatra (1974)
$467{\cdot}9 + 316{\cdot}5$	818285(938)	316·5	0·050(3)		
$467{\cdot}9 + K_\beta$	9312(316)				
$467{\cdot}9 + K_\alpha$	29144(433)		0·055(3)		
	Weighted Av.	316·5	0·053(2)	0·054	0·051(3)
$374{\cdot}4 + K_\alpha$	6455(547)				
$374{\cdot}4 + 205{\cdot}9$	1631(341)	205·9	0·149(7)	0·145(8)	
374·4	139067(691)				

3.4 *Determination of absolute K-conversion coefficients*

For a radioactive decay having many gamma rays, the conversion coefficients are generally measured relative to the theoretical K-conversion coefficient (α_K) of a gamma ray of known multipolarity. Hultberg and Stockendal (1959) and Mukherjee (1960) measured the absolute conversion coefficients using the same source in a well calibrated beta and gamma ray spectrometers. But the method is time-consuming and involves expensive instruments of two types. In the present study we have used a technique given by Mukherjee and Dasmahapatra (1974) for the measurement of absolute K-conversion coefficient of gamma rays. This method is less time-consuming and inexpensive. This method is also suitable for short-lived radioisotopes. The simplicity of the method tempted us to measure absolute K-conversion coefficients of the 205·9 and 316·5 keV transitions that are involved in the electron capture and β-decay of Ir-192 respectively. Both these transitions are of 2^+–O^+ type and their theoretical conversion coefficients are well-known.

3.4.1 *K-conversion coefficient of 316·5 keV transition*: Although we observe a number of ($KX + \gamma$-ray) sum peaks due to complex decay scheme of ^{192}Ir, only two sum peaks ($467{\cdot}9 + K_\alpha$) keV and ($467{\cdot}9 + K_\beta$) keV have been found to be suitable for the measurement of α_K of the 316·5 keV transition. From the decay scheme of Ir-192 (figure 1) it is observed that the sum peak ($467{\cdot}9 + K_\alpha$) keV arises mainly due to the summing of the 467·9 keV gamma rays with the KX-rays following the K-conversion of the 316·5 keV transition in cascade. The contribution from the other gamma rays in the cascade (136·5, 316·5, 416·4 and 594·2 keV) can be neglected by considering the intensities of these transitions relative to that of the 316·5 keV transition.

Under this approximation the area under the sum peak ($467{\cdot}9 + K_\alpha$) keV can be expressed as

$$N_{467\cdot9+K_\alpha} = \frac{I_{K_\alpha}}{I_{K_\alpha} + I_{K_\beta}} W_K \varepsilon_{K_\alpha} \left[\frac{\alpha_K^{316\cdot5}}{1 + \alpha_T^{316\cdot5}} \right] N_{467\cdot9}. \tag{8}$$

Also,

$$N_{467\cdot9+316\cdot5} = \left[\frac{1}{1 + \alpha_T^{316\cdot5}} \right] \varepsilon_{316\cdot5} N_{467\cdot9} \tag{9}$$

Combining these two equations we get

$$N_{467\cdot9+K_\alpha} = W_K\left[\frac{I_{K_\alpha}}{I_{K_\alpha}+I_{K_\beta}}\right]\left[\frac{\varepsilon_{K_\alpha}}{\varepsilon_{316\cdot5}}\right]^{\text{abs.}}\alpha_K^{316\cdot5}N_{316\cdot5+467\cdot9} \tag{10}$$

where $\varepsilon_{K_\alpha}/\varepsilon_{316\cdot5}$ is the ratio of efficiencies for KX-rays and 316·5 keV photons respectively and has been taken from the relative efficiency curve. The value of ε_{K_α} was also taken from the present work while the value of W_K was taken from Lederer and Shirley (1978). In this way the value of α_K (316·5) was determined by making use of merely summing phenomenon. Similar type of equation was written for the area under the sum peak $(467\cdot9+K_\beta)$ keV by replacing a factor f_{K_α} by f_{K_β}. Only the sum peak $467\cdot9+K_\beta$ keV was well resolved and it was easy to evaluate the area under this peak precisely. So, the resulting equation for the area under the $467\cdot9+K_\beta$ keV peak will be

$$N_{467\cdot9+K_\beta} = W_K\left[\frac{I_{K_\beta}}{I_{K_\alpha}+I_{K_\beta}}\right]\left[\frac{\varepsilon_{K_\beta}}{\varepsilon_{316\cdot5}}\right]\alpha_K^{316\cdot5}N_{316\cdot5+467\cdot9}. \tag{11}$$

The results obtained are shown in table 4. The weighted average value of α_K (316·5) agrees well with Shirley and Dariki (1983).

3.4.2 *Absolute K-conversion coefficient of 205.9 keV transition*: From the decay scheme of Ir-192 it is clear that sum peak $(374\cdot4+K_\alpha)$ keV arises due to the coincidence summing of 374·4 keV gamma rays with the KX-rays emitted in the following processes.

(i) K-conversion of 205·9 keV transition, (ii) K-conversion of 329·1 keV transition, (iii) K-capture to the 909·49 keV level which is linked by 329·1 keV transition and (iv) K-capture to the 580·37 keV level.

The contribution to the sum peak area $(374\cdot4+K_\alpha)$ keV due to second and third processes is negligible because of the low value of relative intensity of 329·1 keV γ-ray and K-capture probability to the 909·49 keV level. So the main contribution to the sum peak is due to the first and fourth processes. By taking all effects into account except those having negligible contribution, the equation for area under the $(374\cdot4+K_\alpha)$ keV sum peak may be written in the following form:

$$N_{374\cdot4+K_\alpha} = \left[\frac{I_{K_\alpha}}{I_{K_\alpha}+I_{K_\beta}}\right]W_K\left[\left(\frac{\varepsilon_{K_\alpha}}{\varepsilon_{205\cdot9}}\right)\alpha_K^{205\cdot9}N_{374\cdot4+205\cdot9} + P_K(580\cdot37)\varepsilon_{K_\alpha}N_{374\cdot4}\right]. \tag{12}$$

By using theoretical value of P_K (580·37) from the relation given by Behrens and Janecke (1969) the value of $\alpha_K^{205\cdot9}$ was determined and is shown in table 4. The uncertainty in the value of α_K (205·9) depends mainly on the statistics under the sum peak.

4. Discussion

The present study indicates the possibility of measurements of K-capture probability to different excited states, K-shell fluorescence yield of daughter atoms and the absolute K-conversion coefficients of gamma-rays from the study of a single gamma-ray spectrum. Since experimental and theoretical values of K-capture probabilities are in good agreement with each other, the technique of measuring the P_K values from the analysis of KX-ray-γ-ray sum peaks is justified. A clear advantage of this method is the determination of the α_K from the ratios of the sum peak areas and the efficiencies and thus the accuracy in the measurement of the α_K can be improved with good statistics. This method is also suitable for determining K-conversion coefficients of the transitions involved in the electron capture decay of the radioisotope by just taking a few more factors into account. The method, however, is limited to the transitions having appreciable conversion probability and hence cannot be applied to the measurement of the α_K of the weak transitions. Moreover, accuracy of the results depends on the resolution of the detection system. This method is particularly advantageous for the short-lived isotopes, when a long time scanning of the conversion electron spectra becomes difficult.

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