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Beta-gamma-gamma directional correlation in ^{103}Rh

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Abstract. β-γ-γ directional correlation studies for the cascades (i) β-rays of $E_{\max} = 0 \cdot 12$ MeV, γ-rays of 557 keV and γ-rays of 53 keV and (ii) β-rays of $E_{\max} = 0 \cdot 21$ MeV, γ-rays of 444 keV and γ-rays of 53 keV have been made. The triple correlation functions $W(\theta)$ were obtained to be $W(\theta) = 1 + (-0 \cdot 153 \pm 0 \cdot 031) P_2(\cos\theta) + (0 \cdot 004 \pm 0 \cdot 035) P_4(\cos\theta)$ for β-rays of $E_{\max}$ 0·12 MeV → 557 → 53 keV cascade and $W(\theta) = 1 + (0 \cdot 163 \pm 0 \cdot 042) P_2 (\cos\theta) + (-0 \cdot 035 \pm 0 \cdot 058) P_4(\cos\theta)$ for β rays of $E_{\max} = 0 \cdot 21$ MeV → 444 keV → 53 keV cascade.

Spins and parities of the 650, 537 and 93 keV levels of ^{103}Rh are deduced by triple angular correlation and the internal conversion coefficient studies. Multipolarities of the transitions are also determined.

Keywords. Decay ^{103}Ru; $\beta\gamma\gamma$ (θ) in ^{103}Rh; deduced spin and parity; determined multipolarities of the transitions.

1. Introduction

The excited energy levels in ^{103}Rh from the decay of ^{103}Ru have been wellestablished as given in figure 1 by many previous investigators (Lederer *et al* 1967). The spins and parities of excited states in ^{103}Rh are assigned by the directional correlation and internal conversion coefficients (ICC) have been studied by many workers (Flack and Mason 1958, Singh 1960, Manthuruthil *et al* 1968, Zoller *et al* 1969, George and Mukherji 1970, Petterson *et al* 1970, and Avignone III and Frey 1971). Recently Avignone III and Frey (1971) claimed to have conclusively assigned the parities and spins of the 93, 537 and 650 keV levels by γ-γ angular correlation and ICC studies. One of the serious difficulties pointed out by Avignone III and Frey (1971) was due to interference of the cascades from the decay of ^{106}Ru resulting from use of fission product sources. ^{106}Ru decay to ^{106}Pd *via* ^{106}Rh. Coincidence counting rate due to γ-radiations from ^{106}Rh cannot be eliminated if it is present as impurity in the coincidences of γ-rays of the interest from the decay of ^{103}Ru. But one can eliminate it (or reduce it to the extent of elimination) by β-γ-γ coincidences selecting β-radiations in a fixed energy interval. Therefore an attempt has been made to reinvestigate it by the method of β-γ-γ angular correlation, so as to either eliminate or reduce the γ cascades of ^{106}Pd.

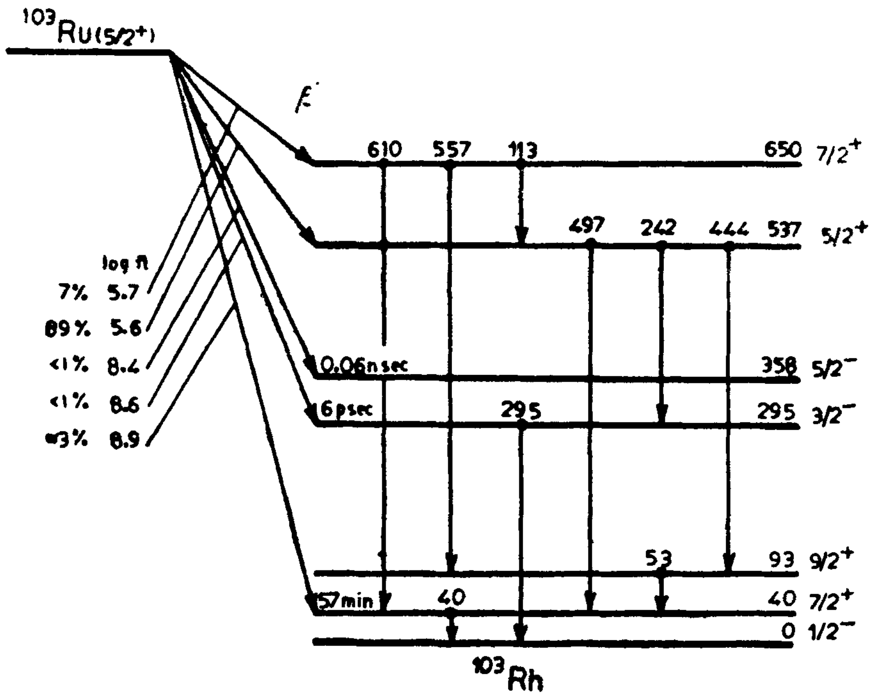

Figure 1. Decay scheme of ^{103}Rh proposed on the grounds of this and earlier work.

2. Experimental set-up and results

Two NaI(Tl) detectors and one plastic scintillator are used. NaI(Tl) detectors are 3·8 cm in dia and 3·8 cm in length and the plastic scintillator was 3·0 cm in dia and 0·4 cm in length. These detectors are optically coupled with RCA 6810A photomultiplier tubes. Conventional slow-fast coincidence circuits have been used for making a gate of coincidences of β- and γ-rays. This gate is used as one of the inputs of the mixture type coincidence unit of the resolving time of the order of 5×10^{-8} sec. The second input to this unit is from the third γ-ray spectrometer which is movable.

The detectors are mounted in the plane of the table such that two of the detectors, the plastic scintillator in vacuum and one NaI(Tl) detector are perpendicular to each other and placed at distances 3·5 cm and 6 cm respectively from the source (also in vacuum) while the third movable detector NaI(Tl) is placed 6 cm from the source. The source in the form of $RuCl_3$ in HCl was obtained from BARC, Bombay. Few drops of the source were dried on cellotape mounted on perspex stand. The source on cellotape along with the stand is kept in vacuum chamber.

The β ray spectrometer is used as an integral spectrometer for selecting β-rays between 50 keV and 1 MeV energies and the γ ray spectrometer (fixed) is used as differential spectrometer for scanning the spectrum in the region of γ-ray photopeaks of 444 keV and 557 keV in one volt channel width (1 volt = 14·2 keV). These two spectrometers are used for coincidences of $\beta\gamma$ rays using slow-fast coincidence set-up and the output of this forms a gate of $\beta\gamma$ coincidences for one of the inputs of second coincidence unit (mixture type) and the second input of this is from the other γ-ray spectrometer selecting the γ-rays in the photopeaks of

53 keV in 7 volt channel/width (1 volt = 3·6 keV). The triple coincidence spectrum along with the single spectrum is shown in figure 2. The photopeaks due to 444 keV and 557 keV γ-rays are clearly indicated.

Coincidence counting rate (output of slow-fast coincidence set-up) from β-γ coincidence gate selecting either γ-ray in the photopeak at 444 keV or 557 keV is practically the same changing with the position of γ-ray detector. Thus β-γ angular correlation is isotropic.

Angular correlation studies for the cascade of β rays of E_{max} 0·12 MeV, γ-rays of 557 keV and γ-rays of 53 keV are done by selecting 557 keV above 497 keV (using the spectrometer in the integral position above 35 volts pulse height as shown in figure 2) and 53 keV at the photopeaks in 7 volt channel width as mentioned above. The angular correlation function obtained by the method of least square fit (without applying solid angle correction which is included in the theoretical consideration) is as follows:

$$W(\theta) = 1 + (-0{\cdot}153 \pm 0{\cdot}031) P_2(\cos\theta) + (0{\cdot}004 \pm 0{\cdot}035) P_4(\cos\theta).$$

The angular correlation studies for the second cascade of β-rays of E_{max} of 0·210 MeV, γ-rays of 444 keV and γ-rays of 53 keV are made by selecting the 444 keV energy at the photopeak (using the spectrometer as differential with setting at 28 volt pulse height in 7-volt channel width) and 53 keV at the photopeak. The Compton contribution of triple $\beta \rightarrow 557 \rightarrow 53$ keV cascade at the photopeak of 444 keV (as shown in figure 2) has been taken by keeping the position of movable detector at 112·5° with respect to the first detector. The Compton contribution at the other angle was calculated using the above experimental correlation function for this cascade. The Compton contribution is subtracted from the counting rates of second cascade of $\beta \rightarrow 444 \rightarrow 53$ keV and angular correlation function is obtained. The angular correlation function (without applying the solid angle correction which is included in the theoretical consideration) is as follows:

$$W(\theta) = 1 + (0{\cdot}163 \pm 0{\cdot}042) P_2(\cos\theta) + (-0{\cdot}035 \pm 0{\cdot}058) P_4(\cos\theta).$$

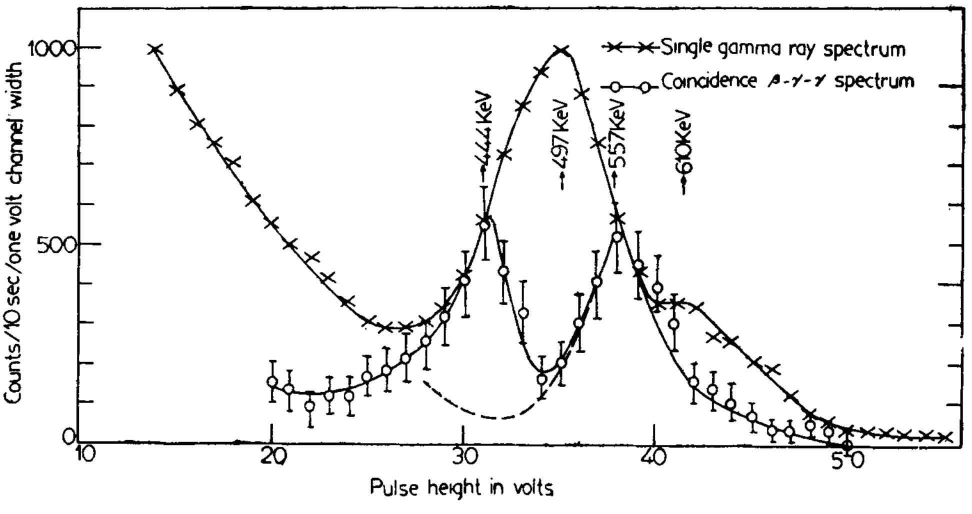

Figure 2. β-γ-γ coincidence spectrum along with single spectrum.

3. Theoretical consideration

The triple β (particle) $\rightarrow \gamma \rightarrow \gamma$ correlation function $W(\theta)$ has been given by Ferguson (1965) for the cascade $a\ (l_1)\ b\ (L_2)\ c\ (L_3)\ d$. a, b, c, d are the spin quantum numbers, l_1 is the angular momentum and l'_1 is the higher angular momentum carried away by β particles. L_2 and L_3 are the multipolarities of the second and third γ transitions with mixture of L'_2 and L'_3 respectively. The function $W(\theta)$ is

$$W(\theta) = (1/4\pi)^{3/2} \Sigma\, (-1)^{a+d} (-1)^{l_1 - l'_1 + k_1}\, Z_1\, (l_1 b_1 L'_1 b\,;\ a k_1)$$

$$G\gamma \begin{Bmatrix} c & L_2 & b \\ c & L'_2 & b \\ k_3 & k_2 & k_1 \end{Bmatrix} Z_1\, (L_3 c L'_3\, c\,;\ d k_3)\, \delta_1^{r_1}\, \delta_2^{r_2}\, \delta_3^{r_3}$$

$$\times\ Q_{k_1}\, Q_{k_2}\, Q_{k_3}\ a^t k_1 k_2 k_3 k\ P_k\ (\cos\,\theta)$$

with the summation over

$$L_2,\ L'_2,\ L_3,\ L'_3,\ k_1,\ k_2,\ k_3,\ k.$$

δ_1, δ_2 and δ_3 are the multipole mixing ratios. $W(\theta)$ can be written in terms of the experimental A_2 and A_4. Q_{k_1}, Q_{k_2} and Q_{k_3} are attenuation factors depending upon the solid angle and energy of the γ-rays. This solid angle correction is considered in the theoretical calculation of A_2 and A_4 rather than applying in the experimental results.

4. Analysis of the angular correlation data and discussion of the results

The spin and parity of the ground state of ^{103}Ru have been reported by earlier workers (Kuhn and Woodgate 1951, Goldhaber and Hill 1952, Mason *et al* 1959) to be $7/2^+$.

53 keV γ-ray transition from 93 keV level to 40 keV level has been considered predominantly to be M_1 transition with little mixture of E_2 ($\delta \leqslant 0{\cdot}02$) by ICC measurements. In the present analysis, 53 keV transition is taken to be a mixture of $M_1 + E_2$ with $\delta = 0{\cdot}02$.

Singh (1960) has considered 3/2, 5/2 or 7/2 as possible spin values for 537 and 650 keV levels and 5/2, 7/2 or 9/2 for 93 keV levels. These possibilities of spin assignments for 93, 537 and 650 keV levels are taken on the basis of 'log ft values' half lives of excited states and partly on the basis of conversion coefficient measurements of various transitions.

β-γ-γ angular correlation coefficients A_2 and A_4 were calculated for all the possible spin sequences as given in table 1 considering the transitions either to be pure dipole or pure quadrupole. The plots of A_2 *versus* $Q (Q = \delta^2/1 + \delta^2)$ have been made for all the cascades. One such plot is given in figure 3, when the experimental values cut the curves.

As summarized in *Nuclear Data Sheets* (1974) and based on reference therein, the 537 keV level decays to 295 keV level ($J^\pi = 3/2$) *via* 242 keV γ-ray. Since the 537 keV level must have positive parity from log ft $= 5{\cdot}7$ in ^{103}Ru decay, the 242 keV γ-ray must be E_1 or M_2 and E_3. The conversion electron studies of Petterson *et al* (1970) and also Avignone III and Frey (1971) show that the

Table 1. Spin sequence for the β-γ-γ cascade of a $\xrightarrow[\text{allowed}]{\beta\text{-transition}}$, $b \xrightarrow{\gamma_1} c \xrightarrow{\gamma_2} d$

S. No.	Spin value for *b*	Spin value for *c*	Multipolarity of gamma-transition from *b* to *c*	Triple angular correlation Coefficient	
1.	5/2	9/2	quadrupole	$A_2 = 0{\cdot}1327$	$A_4 = 0{\cdot}0001$
2.	7/2	9/2	dipole	$A_2 = -0{\cdot}0874$	$A_4 = 0{\cdot}0000$
	7/2	9/2	quadrupole	$A_2 = 0{\cdot}0059$	$A_4 = 0{\cdot}0001$
3.	3/2	5/2	dipole	$A_2 = -0{\cdot}0346$	$A_4 = 0{\cdot}0000$
	3/2	5/2	quadrupole	$A_2 = 0{\cdot}0181$	$A_4 = 0{\cdot}0000$
4.	5/2	5/2	dipole	$A_2 = 0{\cdot}0410$	$A_4 = 0{\cdot}0000$
	5/2	5/2	quadrupole	$A_2 = -0{\cdot}0177$	$A_4 = 0{\cdot}0000$
5.	7/2	5/2	dipole	$A_2 = -0{\cdot}0302$	$A_4 = 0{\cdot}0000$
	7/2	5/2	quadrupole	$A_2 = 0{\cdot}0074$	$A_4 = 0{\cdot}0000$
6.	3/2	7/2	quadrupole	$A_2 = -0{\cdot}1606$	$A_4 = 0{\cdot}0001$
7.	5/2	7/2	dipole	$A_2 = 0{\cdot}1303$	$A_4 = 0{\cdot}0000$
	5/2	7/2	quadrupole	$A_2 = -0{\cdot}0287$	$A_4 = 0{\cdot}0000$
8.	7/2	7/2	dipole	$A_2 = -0{\cdot}1508$	$A_4 = 0{\cdot}0000$
	7/2	7/2	quadrupole	$A_2 = 0{\cdot}0977$	$A_4 = -0{\cdot}001$

(i) β-rays of E_{max} 0·12 meV → γ-rays of 557 keV → γ-rays of 53 keV	A_2 Expt $= -0{\cdot}153 \pm 0{\cdot}031$ A_4 Expt $= 0{\cdot}004 \pm 0{\cdot}035$
(ii) β rays of E_{max} 0·21 MeV → γ rays of 444 keV → γ-rays of 53 keV	A_2 Expt $= 0{\cdot}163 \pm 0{\cdot}042$, A_4 Expt $= -0{\cdot}035 \pm 0{\cdot}058$

γ_1 is 557 or 444-keV gamma-transition and γ_2 is 53 keV gamma-transition which is taken to be a mixture of $M_1 + E_2$ with the mixing ratio $\delta = 0{\cdot}02$ spin values *a* and *d* are fixed and are taken to be 5/2 and 7/2 respectively. The different spin assignments to *b* and *c* are possible for the two levels i.e. (i) 650 keV and (ii) 537 keV. The values of angular correlation coefficients A_2 and A_4 are calculated by taking gamma-ray transtion to be pure dipole or quadrupole.

242 keV γ-ray is E_1 in character. Furthermore, Petterson *et al* (1970) also showed that the 497 keV γ-ray between the 537 keV level is mostly M_1. Therefore, it is reasonable to conclude that 537 keV level has $J^\pi = 5/2^+$. This spin value can be assigned by present β-γ-γ angular correlation studies but in that 9/2 or 7/2 are to be considered for 93 keV level (as given in tables 1 and 2). From table 2 it is further noticed that if 9/2 is taken for 93 keV level, then 444 keV transition is pure quadrupole and if 7/2 is taken, then 444 keV transition is either almost pure dipole or the mixture of quadrupole and dipole. Avignone III and Frey (1971) reported by ICC studies that 444 keV transition is pure quadrupole. In that case one can reasonably assign 9/2 for 93 keV level with 5/2 for 537 keV level by the present studies.

As given in table 2, 5/2 is not possible for 650 keV level taking 9/2 for 93 keV level. But 7/2 can be assigned for 650 keV level with the certain mixture

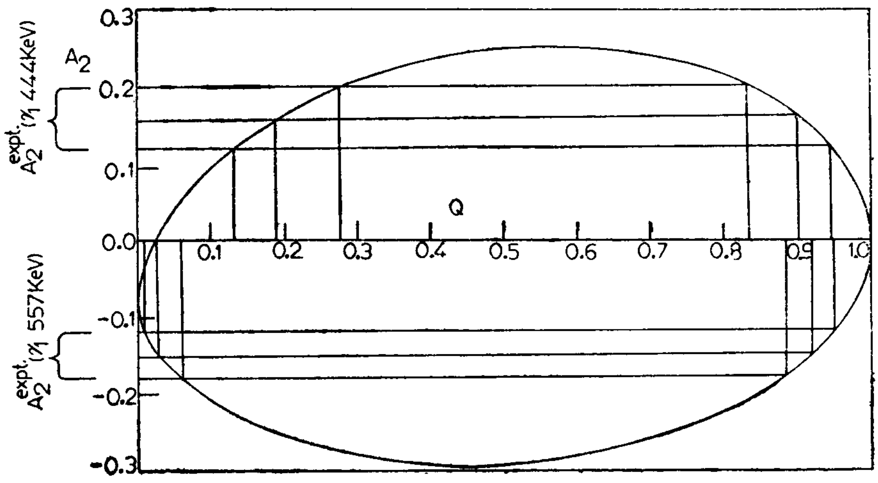

Figure 3. Theoretical plot of A_2 versus Q in 557 or 444 keV for the cascade.

$$5/2 \xrightarrow[\text{allowed}]{\beta\text{-ray}} 7/2 \xrightarrow[(M_1 + E_2)]{(557 \text{ or } 444 \text{ KeV})} 9/2 \xrightarrow[M_1 \text{ with } E_2\ (\delta = 0{\cdot}02)]{53 \text{ KeV}} 7/2$$

Table 2. Multipolarity mixing ratio in 444 and 557 keV transition

Spin sequence $b \xrightarrow{\gamma_1} c \xrightarrow{\gamma_2} d$	δ^2 in 444-keV transition $\beta \to 444$ keV $\to$ 53 keV angular correlation results
$5/2 \to 9/2 \to 7/2$	Possible (table 1)
$7/2 \to 9/2 \to 7/2$	$0{\cdot}149 \leqslant \delta_1^2 \leqslant 0{\cdot}379$ $5{\cdot}060 \leqslant \delta^2_2 \leqslant 10{\cdot}0$
$3/2 \to 7/2 \to 7/2$	Not possible
$5/2 \to 7/2 \to 7/2$	$0 \leqslant \delta^2_1 \leqslant 0{\cdot}010$ $9{\cdot}52 \leqslant \delta_2^2 \leqslant 24{\cdot}0$
$7/2 \to 7/2 \to 7/2$	$1{\cdot}150 \leqslant \delta_1^2$ $\delta_2^2 \leqslant \infty$
3/2 $5/2 \to 5/2 \to 7/2$ 7/2	Not possible
Spin sequence	δ^2 in 557 keV transition
$b \xrightarrow{\gamma_1} c \xrightarrow{\gamma_2} d$	β-557-keV-53 keV angular correlation results
$5/2 \to 9/2 \to 7/2$	Not possible
$7/2 \to 9/2 \to 7/2$	$0{\cdot}010 \leqslant \delta_1^2 \leqslant 0{\cdot}063$ $7{\cdot}695 \leqslant \delta_1^2 \leqslant 19{\cdot}0$
$3/2 \to 7/2 \to 7/2$	Possible (table 1)
$5/2 \to 7/2 \to 7/2$	$0{\cdot}15 \leqslant \delta_1^2 \leqslant 0{\cdot}25$ $10{\cdot}11 \leqslant \delta_1^2 \leqslant 39{\cdot}0$
$7/2 \to 7/2 \to 7/2$	$0{\cdot}0049 \leqslant \delta_2^2 \leqslant 0{\cdot}031$ $0{\cdot}626 \leqslant \delta_2^2 \leqslant 1{\cdot}857$
3/2 $5/2 \to 5/2 \to 7/2$ 7/2	Not possible

of dipole and quadrupole (*i.e.*, ' δ ' to be 0·1 to 0·25 or 2·77 to 4·36). If 557 keV transition is taken predominantly dipole in character, the present value of ' δ ' (between 0·1 to 0·25) and the value of ' δ ' deduced by Avignone III and Frey (1971), *i.e.*, $-0{\cdot}32 \pm 0{\cdot}03$ are approximately to be of the same order in magnitude. The sign of ' δ ' also agrees if we follow the same sign convention [Avignone III and Frey (1971) have taken the sign convention of Krane and Steffen (1970)]. Therefore spin values of 9/2, 5/2 and 7/2 are assigned to the 93, 537 and 650 keV excited energy levels in ^{103}Rh respectively by the present analysis.

Complete absence of β-transition to 93 keV indicates that 9/2 is preferred for 93-keV level.

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References

Avignone III F T and Frey G D 1971 *Phys. Rev.* C **4** 912
Flack F C and Mason P 1958 *Proc. Phys. Soc.* (*London*) **71** 247
Fergusen A J 1965 *Angular Correlation Method in Gamma-ray Spectroscopy* (North Holland Pub. Co.)
George M C and Mukerji A 1970 *Can. J. Phys.* **48** 2699
Goldhaber M and Hill R D 1952 *Rev. Mod. Phys.* **24** 179
Krane K S and Steffen R M 1970 *Phys. Rev.* C **2** 724
Kuhn H and Woodgate G K, 1951 *Proc. Phys. Soc.* (*London*) **64** 1090
Lederer C M, Hollander J M and Perlman I, 1967 *Table of the Isotopes*, (Wiley) p. 241
Manthuruthil J C, Hennecke H J and Cothern C R 1968 *Phys. Rev.* **165** 1363
Mason P, Flack F C and Perry G, 1959 *Proc. Phys. Soc.* (*London*) **73** 138
Nuclear Data Sheets 1974 **13** 337
Petterson H, Antman S and Grunditz Y 1970 *Z. Phys.* 233 260; **239** 485
Singh B P 1960 *Nucl Phys.* **21** 450
Zoller W H, Macias E S, Perkal M B and Walters W B 1969 *Nucl. Phys.* **A130** 293