Chapter 6

DEcAY OF $^{84m}$Rb AND $^{86m}$Rb

1. Introduction

The disintegration characteristics of $^{84m}$Rb were first studied by Flamersfeld\(^1\) who reported a 20 min half-life. Caird and Mitchell\(^2\) studied the $\gamma$-radiations from $^{84m}$Rb and reported a cascade consisting of two unresolved $\gamma$-rays of nearly equal energy around 239 keV, and a cross-over transition of 463 keV. Dogget\(^3\) reported the energy of these $\gamma$-rays as 216 and 466 keV by studying the conversion electron spectra of $^{84m}$Rb. A systematic study of the decay of $^{84m}$Rb was made by Cohen\(^4\) who reported $\gamma$-rays of energy (relative intensity) $216 \pm 3$ (115), $250 \pm 3$ (200), and $464 \pm 3$ (102) keV. Cohen suggested the spins and parities of the excited states in $^{84}$Rb on the basis of angular correlation studies.

The existence of the 1 min isomeric state in $^{86}$Rb was first reported by Flamersfeld\(^5\) in 1951. Schwartz et al.\(^6\) studied the decay of $^{86m}$Rb with the help of scintillation spectrometers and observed a single $\gamma$-ray of 560 keV energy. Measurement was repeated by Okada\(^7\) who obtained a similar result. Schmidt-Ott\(^8\) employed a Ge(Li) detector to study the decay of $^{86m}$Rb. He reported a single $\gamma$-ray of energy $(556.03 \pm 0.25)$ keV and assigned an E4 multipolarity to it on the basis of the measured conversion coefficient.
In the present study, the $\gamma$-rays emitted by $^{84m}$Rb and $^{86m}$Rb have been measured, and their precise energies and relative intensities have been obtained using a high resolution Ge(Li) spectrometer. The total conversion coefficient of one of the isomeric transitions in $^{84}$Rb has been deduced by analyzing the measured $\gamma$-ray intensities. The $\gamma$-rays from $^{84m}$Rb and $^{86m}$Rb were simultaneously studied by Kneissl et al.\textsuperscript{9} using a Ge(Li) spectrometer. Their study was aimed at measuring the isomeric cross section ratio. The energies and the relative intensities of the $\gamma$-rays reported by Kneissl et al.\textsuperscript{9} are in good agreement with those obtained in this work. The proposed levels of $^{84}$Rb and $^{86}$Rb are consistent with the results reported by Bucurescu et al.\textsuperscript{10}, who studied the levels in $^{84}$Rb and $^{86}$Rb through $(d, \alpha)$ reaction on $^{86}$Sr and $^{88}$Sr, respectively.

2. Source preparation

Radioactive samples of $^{84m}$Rb and $^{86m}$Rb were produced through $(n, 2n)$ reaction on $^{85}$Rb and $^{87}$Rb, respectively, by 14 MeV neutrons. Rubidium nitrate of very high grade purity was used as target material. Long-lived activities of $^{84}$Rb ($T_{1/2} = 33$ d) and $^{86}$Rb ($T_{1/2} = 18.7$ d) were simultaneously produced through the $(n, 2n)$ reaction. The interference due to the radiations from these ($^{84}$Rb and $^{86}$Rb) activities was avoided by using a fresh target sample in each of the bombardments and by
keeping the duration of irradiation short (≈ 30 min). Detectable amounts of activities due to $^{82,84}{\text{Br}}$ ($T_{1/2} = 35.3\ h$, 31.8 min) and $^{85,87}{\text{Kr}}$ ($T_{1/2} = 4.4\ h$, 76 min) were produced through (n, α) and (n, p) reactions, respectively, on $^{85,87}{\text{Rb}}$. The cross sections for these reactions are of the order of only a few millibarns whereas that for the (n, 2n) reaction is ≈ 1.5 barns. The observed γ-rays due to $^{82}\text{Br}$, $^{84}\text{Br}$, $^{85}\text{Kr}$ and $^{87}\text{Kr}$ activities had negligible intensities compared to those from $^{84m}\text{Rb}$ and $^{86m}\text{Rb}$.

3. Measurements and results

3.1. HALF-LIFE

The decay of the irradiated sample was followed under an end-window GM counter. The analysis of the decay data showed the existence of activities with half-lives of $20.0 \pm 0.5\ min$ and $\approx 1\ min$. In another experiment, the sample was irradiated for 1 min and the decay of γ activity was followed using a NaI(Tl) detector and a single channel analyzer. The half-life of the short-lived component was confirmed to be $61 \pm 1\ sec$. The 20 min half-life was assigned to $^{84m}\text{Rb}$ and the 61 sec activity was attributed to $^{86m}\text{Rb}$ on the basis of the earlier reports. Indications of long-lived activities discussed in Sec. 2, were also obtained when the sample was irradiated for a longer duration.
(1 h) and the decay was followed in a low-background GM counter assembly.

3.2. GAMMA RAYS

The γ-ray spectra were studied using a Ge(Li) spectrometer. The sensitive volume of the detector was 4 cm² area x 5.0 mm depletion depth. The resolution (FWHM) of the system was 3.0 keV at the 662 keV full-energy peak of ¹³⁷Cs. A 0.5 gm sample of rubidium nitrate, packed in a thin polyethylene bag was irradiated with an average flux of 5 x 10⁹ neutrons/sec-cm² for 30 min. The counting started about 1 min after the irradiation. To identify the origin of the γ-rays, the decay of each full-energy peak intensity was followed. The procedure adopted was the following: After irradiation, the sample was rigidly mounted on the detector. The γ spectrum was recorded for 40 min and printed out. After 50 min, the sample was counted for another 40 min and printed out. This procedure continued till the activity decayed almost to the background. The result obtained is shown in fig. 1. The peaks at 216.3, 248.2 and 464.5 keV decayed with 20 min half-life and therefore, were assigned to ⁸⁴mRb. The 556.1 keV peak decayed almost to the background level in the first 40 min run. Its decay was studied in a separate run when the sample was irradiated for 1 min and spectra were taken for successive intervals of 1 min. Its half-life was found to be 61 sec and therefore, its origin was taken to be ⁸⁶mRb.
Fig. 1. The γ-ray spectrum of the neutron irradiated rubidium nitrate. The data were collected for successive intervals of 40 min starting 5 min after the irradiation.

Fig. 2. The γ-ray spectrum of irradiated RbNO₃. The counting time was 1 hour starting after a waiting period of 15 hours. The γ spectrum of ¹³³Ba was recorded simultaneously to facilitate the energy determination.
The 511 keV peak was found to decay faster than $^{84m}$Rb and slower than $^{86m}$Rb. It was concluded that the contribution to its intensity came from both short-lived and long-lived impurity activities. The 402.9 keV peak decayed with 76 min half-life and therefore, it was assigned to $^{87}$Kr. To study the long-lived activities, $\gamma$-ray spectrum of the same sample was recorded 15 hours after the irradiation, and is shown in fig. 2. A single peak at 511 keV is observed which is attributable to the positron annihilation photon in the decay of $^{84g}$Rb. To check if a part of the 511 keV $\gamma$-ray intensity was due to positron emission decay of $^{84m}$Rb, the decay of $\gamma$-rays in the energy range 500-1000 keV was followed. No $\gamma$-ray with 20 min half-life was detected. Therefore, the scope of present investigation was limited only to the 0-600 keV energy range.

In the determination of the energy and relative intensity of the $\gamma$-rays, care was taken to account for the effect of counting rate on the peak position. The $\gamma$-ray spectra of the irradiated sample were recorded along with the calibrating sources. A $\gamma$ spectrum of the standard source only was recorded with identical gain settings to facilitate the identification of its peaks in the composite spectrum. Fig. 3 shows a typical $\gamma$ spectrum of $^{84m,86m}$Rb and $^{133}$Ba recorded simultaneously, for the energy determination. Currently reported $\gamma$-ray energies of $^{133}$Ba (ref.12) and $^{152}$Eu (ref.13) were taken as standards for calibration. The centroids of full-energy peaks were taken as peak positions.
TABLE I

Energies (in keV) and relative intensities of $\gamma$-rays from $^{84m}$Rb and $^{86m}$Rb

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Present work</th>
<th>Earlier reports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_\gamma$</td>
<td>$I_\gamma$</td>
</tr>
<tr>
<td>$^{84m}$Rb</td>
<td>216.3 ± 0.2</td>
<td>93.5 ± 9.4</td>
</tr>
<tr>
<td></td>
<td>248.2 ± 0.2</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>464.5 ± 0.2</td>
<td>116 ± 12</td>
</tr>
<tr>
<td>$^{86m}$Rb</td>
<td>556.1 ± 0.2</td>
<td>100</td>
</tr>
</tbody>
</table>

a) ref. 4; b) ref. 9; c) ref. 8
Fig. 3. The $\gamma$-ray spectrum of irradiated RbNO$_3$ + $^{133}$Ba. The peaks marked with (a), (b), (c) and (d) are due to $^{133}$Ba, $^{84m}$Rb, $^{87}$Kr and $^{86m}$Rb, respectively.

Fig. 4. Proposed decay schemes of $^{84}$Rb and $^{86m}$Rb.
For the evaluation of the relative intensities of $\gamma$-rays, currently reported relative intensities of $^{133}\text{Ba}$ (ref.12), $^{152}\text{Eu}$ (ref.14), and $^{108}\text{Ag}$ (ref.15) $\gamma$-rays were used as standards. Correction for self-absorption was applied in the usual way. The coincidence summing probability was studied and accounted for in finding $\gamma$-ray relative intensities. The results of the $\gamma$-ray energy and relative intensity measurements are given in table I.

4. Decay scheme

The results obtained in the present study are summarized in the decay scheme shown in figs. 4(a) and (b). From the relative peak-heights of the three $\gamma$-rays in $^{84m}\text{Rb}$ spectrum it is evident that the 464.5 keV $\gamma$-ray is too intense to be attributed to purely coincidence summing. Earlier investigators have shown that the 216.3 and 248.2 keV $\gamma$-rays form a cascade. From the relative intensities of these two $\gamma$-rays, it is readily noticed that the 216.3 keV transition is highly converted and therefore, it must have a higher multipolarity. The half-life of the 248.2 keV $\gamma$-ray was measured to be 0.3 ns by Sethi and Mukherjee. The above experimental facts lead to the conclusion that the first excited state of $^{84}\text{Rb}$ is at 248.2 keV, and it is populated by the 216.3 keV $\gamma$-ray. Consequently, the 20 min isomeric state is shown at 464.5 keV. The observed 464.5 keV $\gamma$-ray is placed between the
isomer, and the ground state. The proposed level scheme is further supported by the reaction studies of Bucurescu et al.\textsuperscript{10}

According to the decay scheme shown in fig. 4(a), the intensities of 216.3 and 248.2 keV transitions must be equal. With the help of the measured \( \gamma \)-ray intensities and the conversion coefficients from ref.\textsuperscript{4}, the total conversion coefficient of the 216.3 keV \( \gamma \)-ray was determined to be 1.2. The relative intensities of the \( \gamma \) transitions in \(^{84}\)Rb are summarized in table II.

**TABLE II**

Approximate intensities of \( \gamma \) transitions in \(^{84}\)Rb

<table>
<thead>
<tr>
<th>Transition energy (keV)</th>
<th>Conversion coefficient ((\alpha'))</th>
<th>Inferred multipolarity</th>
<th>Transitions per 100 decays of (^{84})Rb (\text{a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>216.3</td>
<td>1.2 b)</td>
<td>(M3, E4)</td>
<td>62 ± 6</td>
</tr>
<tr>
<td>248.2</td>
<td>&lt;0.03 c)</td>
<td>(E1, M1, E2)</td>
<td>62</td>
</tr>
<tr>
<td>464.5</td>
<td>0.1 c)</td>
<td>(M4, E4)</td>
<td>38 ± 4</td>
</tr>
</tbody>
</table>

a) The values quoted include an additional error due to uncertainty in estimated conversion coefficients.

b) Obtained from the relation \(\alpha' = \frac{(1 + \alpha I_\gamma(248) - I_\gamma(216))}{I_\gamma(216)}\)

where \(\alpha'\) is the conversion coefficient of 248.2 keV \(\gamma\)-ray.

c) Taken from ref.\textsuperscript{4}. We have calculated the transition intensities and the total conversion coefficient of the 216.3 keV \(\gamma\)-ray assuming the total conversion coefficient of the 248.2 keV transition as 0.03.
5. Discussion

The theoretical values* of the conversion coefficients of the 216.3 keV $\gamma$ transition having M3 and E4 multipolarities come out to be 0.56 and 1.4, respectively. The value of 1.2 obtained in the present study, suggests an admixed [M3 (29%) + E4 (71%)] multipolarity for the observed 216.3 keV $\gamma$ transition in $^{84}\text{Rb}$.

Earlier investigators $^{3,4}$ assigned an M4 multipolarity of the 464.5 keV transition. The Weiskopf estimate of the half-life of this transition with M4 multipolarity comes out to be an order of magnitude larger as compared to the experimental observation (see table III). The multipolarity of the corresponding transition (556.1 keV) in $^{86}\text{mRb}$ has been recently reported $^{8}$ to be E4. If we assume the multipolarity of 464.5 keV transition in $^{84}\text{mRb}$ as E4, the hindrance factor comes out to be of the order of 10, which is consistent with the systematics $^{19}$ of E4 transitions.

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* The values of $\alpha_K$, $\alpha_L$ and $\alpha_M$ were obtained from the tables of Hager and Seltzer $^{17}$ and the contribution from N and higher shells were taken from ref. $^{18}$
TABLE III

Possible multipolarities and the estimated and experimental half-lives of the isomeric transitions in $^{84m}$Rb and $^{86m}$Rb.

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Transition energy (keV)</th>
<th>Experimental partial half-life (Sec) a)</th>
<th>Weizsäcker estimate (Sec) a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>M3  M4  M5  E3  E4  E5</td>
</tr>
<tr>
<td>$^{84m}$Rb</td>
<td>216.3</td>
<td>1.9 x 10^3</td>
<td>5.7  1 x 10^7</td>
</tr>
<tr>
<td></td>
<td>464.5</td>
<td>3.1 x 10^3</td>
<td>3 x 10^4  2 x 10^10</td>
</tr>
<tr>
<td>$^{86m}$Rb</td>
<td>556.1</td>
<td>61</td>
<td>3 x 10^3  4 x 10^9</td>
</tr>
</tbody>
</table>

a) Corrected for internal conversion.

If one assumes an E4 multipolarity for the 464.5 keV transition [see fig. 4(a)], then the ground and the isomeric states have identical parities. The ground state spins of $^{86m}$Rb and $^{84m}$Rb are 2$^-$ (see ref. 20). The spin of the isomeric state in $^{86m}$Rb has been reported as 6$^-$. Cohen suggested a 3$^+$ spin parity for the 248.2 keV level. With the above spin assignment for the isomeric state, the parity of the 248.2 keV level should be odd in order to have an M3 multipolarity for the 216.3 keV transition. The assignment of 3$^-$ spin to the first excited state of $^{84}$Rb is indirectly supported by the recent experimental data on $^{87}$Rb (d, p) $^{88}$Rb by Rapport et al. who suggest a 3$^-$ spin parity.
for the first excited state in $^{88}\text{Rb}$. Consequently, the multipole order of the 248.2 keV transition may not be E1. Other possible multipolarities are M1, E2 or an admixture of the two. The $\gamma$-decay half-life of the 248.2 keV transition was observed to be $3.08 \times 10^{-10}$ sec by Sethi and Mukherjee. Assuming M1 multipolarity, the hindrance factor, according to the Weisskopf estimate, comes out, approximately, to be 20, which agrees well with the systematics of M1 transitions. The experimental value of the conversion coefficient for this transition was reported as 0.01 which is consistent with the theoretical value obtained by assuming M1 multipolarity.

According to the shell model, the 37th proton in Rb-isotopes occupies probably any one of the $2p_{3/2}$ and $1f_{5/2}$ orbitals. The 47th and 49th neutrons in $^{84}\text{Rb}$ and $^{86}\text{Rb}$ are expected to occupy $1g_{9/2}$ and $2p_{1/2}$ orbitals, respectively. The ground state spin $2^-$ may arise due to the coupling of $1f_{5/2}$ and $1g_{9/2}$ orbitals according to the Nordheim's strong rule. The spins $3^-$ and $6^-$ may arise by different coupling schemes. One of the possibilities for the $6^-$ state would be by the coupling of $2p_{3/2}$ and $1g_{9/2}$ orbitals according to Nordheim's weak rule.
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