The Natures of $\gamma$-Rays Emitted from $^{152}$Dy Formed through $^{124}$Sn ($^{32}$S, 4$n$) $^{152}$Dy

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Natures of $\gamma$-rays emitted from a compound nucleus of $^{152}$Dy are analyzed. Two kinds of rotational bands as paths of intra-band $E2$-transitions are assumed in the theoretical calculations. The calculated values of the angular distribution and the linear polarization show a fairly good agreement with experimental data.

§ 1. Introduction

Yrast states which decay with very large $E2$-transition probabilities are believed to originate with rotations around the axis perpendicular to the symmetry axis. A theoretical investigation based on the liquid drop model, however, showed that rotation around the symmetry axis is much favoured to oblate-shape nuclei.1) Yrast states produced by such rotation are of single particle natures and their collectivities are very small due to the MONA (Maximization of the Overlap of Nuclear wave function by Alignment) effect.2) Then, transition probabilities between yrast states are much reduced and we can expect the existence of so-called yrast isomer. The verifications of their existence were supported by many experimental and theoretical investigations, especially in the cases of nuclei with $N \approx 82$.3)

The nucleus $^{152}$Dy is one of such nuclei with $N \approx 82$. Yrast states of $^{152}$Dy were identified up to 37 and a few of them have lifetime longer than 1 ns.4,5) They can be assigned as yrast isomers. The value of moment of inertia in the yrast band is, on an average, $2\hbar^2 \approx 142 \text{ MeV}^{-1}$ which corresponds to an oblate shape with $\beta \approx -0.3$. An unusually large population is observed in $^{152}$Dy to the high spin isomers. This phenomenon is also ascribed to the small collectivity of yrast states, as follows. There are two kinds of $\gamma$-decay-paths of high spin states, statistical and of intra-band. The intra-band paths bypass the yrast line and bring the nucleus to states with lower spins before hitting the yrast line. When the intra-band paths have the small collectivity, the nucleus easily falls to...
In a previous paper we analyzed the feeding intensity to the yrast states of $^{152}$Dy whose compound states are produced with the reaction $^{124}$Sn($^{32}$S, 4$n$) $^{152}$Dy, $E_{lab}$ $\approx$ 145 MeV. The theoretical results clearly showed the smallness of the $E2$ collectivity of intra-band paths parallel to the yrast line. The experimental feeding intensities are qualitatively well explained. Theoretical energy distribution of $\gamma$-rays is also presented in the work. The distribution has two peaks at $E_{\gamma}$ $\approx$ 0.5 MeV and 0.9 MeV, which correspond to $l=1-$ statistical and intra-band stretched $E2$ transitions, respectively. The experiments, however, showed bumps of collective $E2$ situated at $E_{\gamma}$ $\approx$ 1.2 MeV. This suggests a little smaller value of moment of inertia to the stretched $E2$ intra-band paths. We have already pointed out the possibility of rotation of an oblate nucleus around the axis perpendicular to the symmetry axis in the previous paper. The rotational states produced by this rotation are expected to have larger $E2$-collectivity and smaller value of moment of inertia. They can supply paths of collective stretched $E2$-transitions.

The purpose of this paper is to report results of our deeper calculations on properties of $\gamma$-rays from $^{152}$Dy formed through $^{124}$Sn($^{32}$S, 4$n$) $^{152}$Dy, $E_{lab}$ $\approx$ 145 MeV.

§ 2. Method of calculation

The details of the theoretical basis of our calculations are found in Ref. 6). The difference from the previous work is in considering the coexistence of the two kinds of rotational bands as intra-band $E2$-paths. The relation between the yrast line and the rotational bands as intra-band $E2$ paths of $\gamma$-decays is shown schematically in Fig. 1. We have attributed the values of moments of inertia $2\mathcal{J}_{z}/\hbar^{2} = 107$ MeV$^{-1}$ and $2\mathcal{J}_{x}/\hbar^{2} = 142$ MeV$^{-1}$ to bands produced by rotations around the axis perpendicular to the symmetry axis and by those around the symmetry axis, respectively. They are the values of moments of inertia of $^{152}$Dy for each kind of rotations with an oblate deformation, $\beta \approx -0.3$.

The probability for $\gamma$-emission of multipolarity $l$ is calculated with the equation,

$$R_{l}^{-l'}dF_{\gamma} \propto C_{l}E_{\gamma}^{2l+2}[\mathcal{Q}(E,J_{z}^{\pi})/\mathcal{Q}(E,J_{x}^{\pi})]dE_{\gamma}, \quad (1)$$

where $\mathcal{Q}(\mathcal{Q}_{l})$ denotes the initial (final) level density. The values of the strengths $C_{l}$ of $\gamma$-decays are the same as those used in the previous work except for $C_{E2}^{01}$. 

yrast states with high spins via statistical transitions without sliding on the collective paths and high spin states have large side feeding populations, as is in the case of $^{152}$Dy.
The Natures of $\gamma$-Rays Emitted from $^{152}\text{Dy}$

Fig. 1. Schematic representations of the relation between the yrast line and rotational bands as paths of $\gamma$-decays by intra-band $E2$-transitions.

(a) Paths are parallel to the yrast line ($2\mathcal{A}_{\gamma}/\hbar^2 = 142 \text{ MeV}^{-1}$).

(b) Rotational bands are caused by the rotation around the axis perpendicular to the symmetry axis ($2\mathcal{A}_{\gamma}/\hbar^2 = 107 \text{ MeV}^{-1}$).

Here $C_{E1}^{y}$ and $C_{M1}^{y}$ are the strengths corresponding to the intra-band $E2$-transitions via the paths along rotational bands produced by rotation around the symmetry axis ($C_{E2}^{y}$) and the axis perpendicular to the symmetry axis ($C_{E2}^{y}$), respectively. The ratios of the above values to those in Weisskopf units are as follows:

$$C_{E1}^{y}/C_{E1}^{W} : C_{M1}^{y} : C_{E2}^{y}/C_{E2}^{W} = 50 : 25 : 1 : x : y.$$  \hspace{1cm} (2)

The value of $C_{E2}^{y}$ is much smaller than that of $C_{E2}^{y}$. Those values are not fixed and varied to give the best fit to experimental data.

The angular distribution $W(\theta)$ and polarization $P_{\gamma}(\theta)$ of $\gamma$-rays are also calculated in this work. They make information on $\gamma$-rays much richer and specially the very effective tool to determine their multipolarities. The probability of a $\gamma$-emission to the angle $\theta$ from a initial state $|J_iM_i\rangle$ to a final state $|J_fM_f\rangle$ is given by the following equation,

$$P(TL^z; J_iM_i \rightarrow J_fM_f; \theta) = \sum_{K\text{-even}} \frac{(2K+1)}{4\pi} (LM0|LM)(LK10|L1)P_{\gamma}(\cos \theta) \times \langle J_fLM_fM|J_iM_i\rangle^2 \mathcal{S}_0(TL; i \rightarrow f).$$ \hspace{1cm} (3)

Here $T$ and $L^z$ denote the character and multipolarity of the $\gamma$-radiation and $\mathcal{S}_0(TL^z; i \rightarrow f)$ the probability of $\gamma$-emission. The angular distribution $W(\theta)$ is
obtained by averaging the probabilities of every emitted $\gamma$-ray from a compound nucleus. In order to calculate $W(\theta)$ we must give initially the distribution of $Z$-component of angular momentum of entry states. They are assumed to be zero, because the energies of neutrons emitted from the initial compound state are very small. The formation cross section of the initial compound state is evaluated on the basis of the sharp cutoff model with $l_{\text{max}}=54$ (the grazing angular momentum).

After a normalization, we take the form of $W(\theta)$ as follows:

$$W(\theta) = 1.0 + \sum_{l; \text{even}} A_l P_l(\cos \theta). \quad (4)$$

The expression for the linear polarization $P_l$ is also obtained as follows:

$$P_l(TL^e; J_i, M_i \rightarrow J_f, M_f; \theta)$$

$$= \sum_k (2K+1)(LKM0|LM)(LK1-2|L-1)Re\mathcal{D}_{2,0}(\theta, \phi)$$

$$\times (J_iLM, M|J_iM_i)^{\delta(-1)^{\delta}} \mathcal{D}(TL^e, i \rightarrow f). \quad (5)$$

The final expression is

$$P_l(\theta) = \sum B_l P_l(\cos \theta, \phi=0)/W(\theta), \quad (6)$$

where the $B_l$'s are obtained by averaging the right-hand side of Eq. (5) with all cascades.

§ 3. Results and discussion

Theoretical results are plotted in Figs. 2~4. The curves in Fig. 2 present the population to the yrast states of $^{152}$Dy, corresponding to the values $x=0, 10, 200, y=0$ (Fig. 2(a)) and $x=0, y=0, 10, 200$ (Fig. 2(b)). In the case $y \neq 0$, the feeding pattern does not so depend on the value of $x$ in our detail calculations. That is due to the existence of paths of stretched collective $E2$ transitions not parallel to the yrast line and the paths, of course, do not bypass the yrast line. In this case, $y$ does not so affect the theoretical feeding pattern. As to the values of $x$ and $y$ in the following calculation, we have adopted $x=1.0$ and $y=30$, which are so...
The Natures of $\gamma$-Rays Emitted from $^{152}$Dy

adjusted as the components of the intra-band $E2$ transitions in the energy distribution of $\gamma$-rays amount about 30 $\sim$ 50\%\(^{9}\) at the corresponding bumps mentioned later. The value, $y = 30$, suggests the small collectivity of the rotation around the axis perpendicular to the symmetry axis\(^{10}\) of $^{152}$Dy ($y = 200$, in the case of $^{158}$Dy\(^6\)).

Figure 3 shows the energy distributions of $\gamma$-rays. In each case, the main component in the high energy region is the $E1$ transition. It is remarkable that the $l = 1$ transitions are dominant even in low energy region and give a bump at $E_{\gamma} \approx 0.5$ MeV. The stretched $\Delta J = 1$ transitions are the main component at this bump. The bumps corresponding to the intra-band $E2$ radiation are seen at $E_{\gamma} \approx 0.9$ and 1.3 MeV. The former comes from transitions via paths parallel to the yrast line (Fig. 1(a)) and the latter from those via paths not parallel to the yrast line (Fig. 1(b)). As to bumps of the stretched $E2$ transitions, one was experimentally found at $E_{\gamma} \approx 1.2$ MeV,\(^{7}\) which seems to correspond to the bump at $E_{\gamma} \approx 1.3$ MeV above mentioned. In Ref. 9\) they suggested an existence of a bump of the stretched $E2$ transition at $E_{\gamma} \approx 0.4$ $\sim$ 0.8 MeV. This bump was not observed in the experiment analyzed in this work.\(^{7}\) This may come from the difference of the reactions used to excite the $^{152}$Dy nucleus.\(^9\) Contrary to the experiment, the theoretical result shows the bump at $E_{\gamma} \approx 0.9$ MeV. The origin of the discrepancy is an open problem. There is a possibility that the two bumps are smeared out

![Fig. 3](https://example.com/fig3.png)

**Fig. 3.** Theoretical energy distributions of emitted $\gamma$-rays. The arrows at $E_{\gamma} = 0.9$ and 1.3 MeV indicate the positions of bumps corresponding to the intra-band $E2$ paths in Figs. 1(a) and (b), respectively.

![Fig. 4](https://example.com/fig4.png)

**Fig. 4.** (a) Angular distribution coefficient $A_2$ and (b) linear polarization $P_r$ of $\gamma$-rays. The circles denote the experimental data.\(^{7}\) The solid lines show the results of the calculations with $x = 1.0$ and $y = 30$ in Eq. 2. The dashed line in (b) presents the results in which the collective $M1$ transition is additionally considered with $C^{M1}/C_{M1} \approx 1.3$. 

and only one bump was observed in the experiment.

Figure 4(a) shows the calculated values of the coefficient $A_2$ in Eq. (4). The experimental values of $A_2$ are also plotted in the same figure. The theoretical result has reproduced well the experimental trend. A bump seen at $E_\gamma \approx 1.3$ MeV in the theoretical result originates from the stretched $E2$ transitions. A bump seen in the experimental data in this energy region corresponds to this one and there is no discrepancy between the experimental and the theoretical results. In addition, the value of $A_2$ trends to decrease with decreasing $E_\gamma$ in the region, $0 \leq E_\gamma \leq 0.9$ MeV, in both experimental and theoretical cases. The experimental value, however, keeps the sign positive, suggesting the existence of a stretched $E2$ component in the region, $E_\gamma \approx 0.5 \sim 1.0$ MeV. It is not sure whether the component originates from the rotation about the symmetry axis. According to our calculation, the bumps of such a component are situated at $E_\gamma \approx 0.9$ MeV and the component itself is not large in lower energy region.

In Fig. 4(b) the experimental\cite{5} (circles) and theoretical (solid line) results of the linear polarization $P_\gamma$ are plotted. The experimental trend is reproduced fairly well. Vivien et al.\cite{4} suggested the existence of a stretched $M1$ component at $E_\gamma \approx 0.25$ MeV. Then, we have introduced the collective $M1$ transition, and a better agreement is obtained in the region $E_\gamma \approx 1.0$ MeV as presented with the dotted line in Fig. 4(b). The strength $C_{M1}^{\text{col}}$ has been arbitrarily chosen as $C_{M1}^{\text{col}} / C_{M1} \approx 1.3$. The collective $M1$ transition additionally considered gives, however, hardly any influence on the calculated result of $P_\gamma$ in the higher energy region and on that of $A_2$ as seen in Fig. 4.

In conclusion, we have succeeded in explaining qualitatively the natures of $\gamma$-rays emitted from $^{152}$Dy formed through $^{124}$Sn($^{32}$S, 4$n$)$^{152}$Dy. It is very effective to consider intra-band $E2$ paths not parallel to the yrast line which originates rotation around the axis perpendicular to the symmetry axis. However, some discrepancies are seen between the experimental data and the theoretical results especially in the angular distribution of $\gamma$-rays with low energies $E_\gamma \leq 0.8$ MeV. The introductions of the intra-band $E2$ ($\Delta I = 1$) transition and $K$-quantum number into theoretical calculations may be ones of clues to this problem. In the calculations, the reduction of $B(E2)$-values is took into account through geometrical reduction factors. The analysis is now in preparation.

References

The Natures of $\gamma$-Rays Emitted from $^{152}$Dy