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STATISTICAL DECAY OF GAMMA RAYS IN $(n_{th},\gamma)$ REACTIONS

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level-density formalism of Hillman and Grover \(^{10}\) in their gamma cascade calculations. The former authors calculated isomer ratios in \((\gamma, 2n)\) reactions while the latter calculated isomer ratios in four nuclei formed in an \((n, \gamma)\) reaction for neutrons between the energies of 0.1 and 2.5 MeV.

The present paper contains results of calculations of isomer ratios formed in the \((n, \gamma)\) reaction involving 25 different doubly even target nuclei. The shell-model based level densities and spin cut-off parameters obtained with and without the inclusion of pairing, as derived by Moretto were used \(^{11,12}\). Three different forms of the transition probability governing the strength of the E1 gamma transition were used. The calculations were performed using the Monte Carlo method. In one case the statistical part of the \(\gamma\)-spectrum was calculated and compared to experiment. In sect. 2 we describe the calculations, in sect. 3 the results are presented while sect. 4 contains a discussion and conclusions.

2. Calculations

2.1. MODEL

The \(\gamma\)-ray cascade following the capture of a thermal neutron is treated here by means of the statistical model. Let \(T_{\text{ir}}\) be the transition probability for the emission of a \(\gamma\)-ray of energy \(\varepsilon\) and multipolarity \(L\) from the initial angular momentum state \(J_i\) to the final state \(J_f\). The probability \(P\) of emitting a \(\gamma\)-ray of energy \(\varepsilon\) and multipolarity \(L\) according to the statistical model is given by

\[
P \sim T_{\text{ir}}(\varepsilon, L, J_i, J_f) \rho(E-\varepsilon, J_i),
\]

with \(^7\)

\[
\rho(E-\varepsilon, J) \approx \omega(E-\varepsilon) \frac{2J+1}{\sqrt{8\pi\sigma}} \exp\left(-\frac{(J+1)^2}{2\sigma^2}\right),
\]

where \(E\) is the initial excitation energy, \(\rho(E-\varepsilon, J)\) is the level density at excitation energy \(E-\varepsilon\) and angular momentum \(J\), \(\omega(E-\varepsilon)\) is the total state density at energy \(E\) and \(\sigma\) is the spin cut-off parameter. Both \(\omega(E-\varepsilon)\) and \(\sigma\) are functions of the excitation energy and shell structure of the nucleus and will be discussed below. The problem of the transition probability \(T_{\text{ir}}\) will also be discussed in the following.

Like Huizenga and Vandenbosch we assume only E1 transitions in the \(\gamma\)-cascade. The few cases in which the calculated isomer ratios are substantially smaller than the measured results (see sect. 4) could perhaps be attributed to the admixture of E2 transitions which increase the isomer ratio.

The cascade calculations were treated by means of the Monte Carlo method. Thus similar to the calculations of Sperber \(^5\) and Clarke and Gill \(^9\) the numbers and energies of the \(\gamma\)-rays in the cascade were allowed to vary and it was possible to feed the ground and isomeric state during every stage of the cascade. Sarantites \(^{13}\) made use of the Monte Carlo method in order to calculate isomer ratios in \((\alpha, xn)\) reactions.
This author calculated the angular momentum distribution of the residual nuclei following particle evaporation, by means of the Monte Carlo method. The γ-ray cascade which commences after particle evaporation is completed, was treated in the same way as in the calculations by Vandenbosch and Huizenga [1,2].

The gamma cascade was terminated at a given energy interval from which the nucleus was forced to decay either to ground or isomeric state, depending on which spin was closer to the spin of the feeding state. Thus some arbitrariness is included in our calculations by the choice of this excitation energy range, which in the present calculations was from 0.5 to 1.0 MeV. Some consequences of this assumption will be discussed below. States within this interval, which have the same spin difference with respect to ground and isomeric state populate both the ground and isomeric states with relative probabilities given by $e_i^{2L+1}$, where $e$ is the energy of the transition, $L$ the multipolarity of the transition and $i$ an index describing whether the transition is to ground or isomeric state.

2.2. LEVEL DENSITIES

The level densities and spin cut-off parameters were obtained using the Nilsson model. The Nilsson level scheme was employed with the parameters $\varepsilon_2$, $\varepsilon_4$, $\chi$ and $\mu$ recommended for the various mass regions studied here [4]. Values of the level densities and spin cut-off parameters were calculated using both a BCS Hamiltonian [ref. 12] and a Hamiltonian which does not include pairing [11]. Using the Nilsson model enables the inclusion of shell effects in the level density and spin cut-off parameter values. The influence of shell effects on the spin cut-off parameter $\sigma$, and the difference between the calculations with and without BCS theory with respect to the spin cut-off are illustrated in fig. 1. $\tilde{\sigma}$ is the spin cut-off parameter as derived on the basis of the uniform model of single-particle levels (with no shell effects included) and is given by $\tilde{\sigma}^2 = 0.0888 A t$, where $t$ is the nuclear temperature [11]. $(\sigma/\tilde{\sigma})^2$

Fig. 1. Ratios between spin cut-off parameters calculated from the shell model and from the uniform model. On the right pairing is included, on the left it is excluded.
of $^{113}\text{Sn}$ is observed to be lower than $(\sigma/\bar{\sigma})^2$ of $^{137}\text{Ce}$ and $^{109}\text{Pd}$ as a result of the 50 proton shell in $^{113}\text{Sn}$. The $(\sigma/\bar{\sigma})^2$ values obtained with the pairing Hamiltonian are, as expected, lower than those obtained without pairing.

2.3. GAMMA RAY TRANSITION PROBABILITY

The form of the transition probability in eq. (1) is very uncertain and the isomer ratio calculations described here were performed using different assumptions regarding the value of $T_{it}$.

The general form for the probability of an electric transition of multipole order $L$ and energy $\epsilon$ can be written

$$T_{it} \sim \epsilon^{2L+1} \langle \psi_f | e^{-1} Y_{LM} | \psi_i \rangle^2,$$

where $\psi_i$ and $\psi_f$ are the initial and final nuclear wave functions.

The transition probability of a single proton from a state of angular momentum $J_i$ to a state of angular momentum $J_f$, assuming that the particle is coupled to a passive core of zero spin, was derived by Moszkowski \cite{15} and is given by

$$T_{it} \sim \epsilon^{2L+1} S(J_i, L, J_f).$$

The effect of the $S$-term is to favour transition to $J_f = J_i + 1$ over the transition $J_f = J_i - 1$.

Sperber \cite{16} calculated the $E1$ transition in the more general case in which the spin of the passive core is given by $S_f$ and the total initial and final angular momenta are given by $J_i$ and $J_f$ respectively. If $J_i$ and $J_f$ are the initial and final angular momentum of the proton making the transition and $l_i$ and $l_f$ the corresponding orbital momentum,

$$T_{it} \sim \frac{\epsilon^2}{2J_i+1} \sum_{l_i,l_f} \langle l_i S_f J_f J_i | l_f S_f J_f J_i \rangle^2.$$  

This formula illustrates the complexity of the problem in the case of a general single particle transition. Sperber \cite{16} has pointed out that in the limiting case in which $J_i$ and $J_f$ are much larger than $l_i$, $T_{it}$ can be approximated by, $T_{it} \sim \epsilon^2(2J_i + 1)(2J_f + 1)$. This approximation has also been shown to be quite good for lower values of $J_i$ and $J_f$ [ref. \cite{17}].

In the statistical region strong configuration mixing occurs and the $E1$ transitions are expected to involve more than one particle. The difficulty of solving this problem is apparent and has yet to be performed. The general form of $T_{it}$ can be written as $\epsilon^3$ multiplied by a sum of matrix elements which depend on the nuclear wave functions. By making the extremely simplifying assumption that the second term does not depend on energy and angular momentum we obtain that the transition probability is given by $T_{it} \sim \epsilon^3$. Thus, similar to Huizenga and Vandenbosch \cite{1, 2} the isomer ratios were calculated using $T_{it} \sim \epsilon^3$. A basic shortcoming of this assumption is that we ignore the limitations imposed by the electromagnetic sum rules.
Isomer ratios were also calculated using the form of \( T_{\alpha \beta} \) given in eq. (3). The general trend of the result using this formula is expected to be similar to \( T_{\alpha \beta} \sim e^2(2J_f + 1) \) since the effect of both is to increase the probability of high spin states.

The ratio of the E1 to the E2 transition probability for a nucleus of \( A \approx 100 \) for a gamma ray of 1 MeV is of the order of \( 10^5 \) [ref. 15)]. Hence E2 transitions were neglected in our calculations, especially since none of the nuclei treated here are deformed.

The task of calculating the transition probability was also attempted using the collective model, by making use of the inverse cross section for the E1 transition, i.e., the giant dipole resonance cross section. Using the principle of detailed balance, the transition probability, \( P \), that the nucleus by emitting an E1 photon of energy \( \varepsilon \) makes a transition to a final state of spin \( J_f \), from initial spin state \( J_i \) and initial excitation energy \( E \) is

\[
P \sim k^2 \sigma(\varepsilon) \rho(E - \varepsilon, J_i) \sim e^2 \left( \frac{(\varepsilon^2 - \varepsilon_0^2)^2}{\varepsilon_0^2 \Gamma^2} + 1 \right)^{-1} \rho(E - \varepsilon, J_i),
\]

where \( \sigma(\varepsilon) \) is the photonuclear cross section, while \( k \) is the wave number, and \( \varepsilon_0 \) as a function of \( A \) were obtained from Fuller and Hayward 18). A similar method was used by Starfelt 19), for calculating the shape of the neutron capture \( \gamma \)-ray spectrum. The advantage of the collective approach is that "sum rules" are obeyed in contrast to the single-particle model. On the other hand experimental data on the photonuclear absorption cross section at \( \gamma \)-energies below 7 MeV are very scarce.

3. Results

The experimental and calculated isomer ratios defined as the yield of the high spin state divided by the total yield of the high and low spin state are listed in table 1. The experimental data are taken from the compilation of Bishop et al. 4) and from the more recent experimental data of Mannhart and Vonach 20). The results of the latter authors were used in table 1 whenever possible. In the other cases whenever estimated errors were given we retained only the results which were given with the errors.

Four different sets of calculated isomer ratios are compared to the experimental results. The first three columns were obtained using level densities derived for an unpaired system of nucleons. Each column involves a different assumption for the transition probability. The fourth column was obtained using level densities derived for a paired system of nucleons. The isomer ratio values obtained in this case are extremely small due to the low absolute values of the level densities. The low level density values cause a large number of direct transitions to the low spin state and prevent the spreading of the spin population to large angular momentum values. This result might indicate that either the absolute values of the level densities for the paired nucleon system are too low or that the dependence of the matrix element upon energy and angular momentum is not well understood.
Table 1

Experimental and calculated isomer ratios for thermal neutron capture in level-even targets

<table>
<thead>
<tr>
<th>Nuclei formed in $n,\beta$ capture</th>
<th>Spins of isomer and ground state</th>
<th>Experimental isomer ratio (%)</th>
<th>Calculated isomer ratio non-paired nucleon system $\alpha(c)\epsilon^2$</th>
<th>Calculated isomer ratio paired nucleon system $\alpha(c)\epsilon^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{69}$Zn</td>
<td>$\frac{3}{2}$, $\frac{5}{2}$</td>
<td>8.2±0.4</td>
<td>14.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$^{71}$Zn</td>
<td>$\frac{5}{2}$, $\frac{7}{2}$</td>
<td>9.3±0.8</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{73}$Ge</td>
<td>$\frac{5}{2}$, $\frac{7}{2}$</td>
<td>31.9±1.8</td>
<td>11</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{77}$Ge</td>
<td>$\frac{5}{2}$, $\frac{7}{2}$</td>
<td>33.9±2</td>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{77}$Se</td>
<td>$\frac{3}{2}$, $\frac{5}{2}$</td>
<td>21.0±3</td>
<td>18</td>
<td>1.2</td>
</tr>
<tr>
<td>$^{81}$Se</td>
<td>$\frac{5}{2}$, $\frac{7}{2}$</td>
<td>11.4±0.7</td>
<td>20</td>
<td>0.9</td>
</tr>
<tr>
<td>$^{83}$Ce</td>
<td>$\frac{5}{2}$, $\frac{7}{2}$</td>
<td>12.9±0.8</td>
<td>7.3</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>$\frac{3}{2}$, $\frac{5}{2}$</td>
<td>40.0±20</td>
<td>12.4</td>
<td>1.9</td>
</tr>
<tr>
<td>$^{85}$Sr</td>
<td>$\frac{7}{2}$, $\frac{9}{2}$</td>
<td>37.4±3.0</td>
<td>25.4</td>
<td>3.0</td>
</tr>
<tr>
<td>$^{109}$Pd</td>
<td>$\frac{3}{2}$, $\frac{5}{2}$</td>
<td>2.2±0.4</td>
<td>0.5</td>
<td>8.4</td>
</tr>
<tr>
<td>$^{111}$Pd</td>
<td>$\frac{3}{2}$, $\frac{5}{2}$</td>
<td>1.1±0.1</td>
<td>6.8</td>
<td>0</td>
</tr>
<tr>
<td>$^{115}$Cd</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>12.0</td>
<td>30</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{113}$Sn</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>40.0±10</td>
<td>27</td>
<td>3.0</td>
</tr>
<tr>
<td>$^{121}$Sn</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>0.7±0.7</td>
<td>3.7</td>
<td>0</td>
</tr>
<tr>
<td>$^{123}$Sn</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>0.6±0.6</td>
<td>3.1</td>
<td>0</td>
</tr>
<tr>
<td>$^{125}$Sn</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>2.0±1.3</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{121}$Te</td>
<td>$\frac{3}{2}$, $\frac{3}{2}$</td>
<td>14±4</td>
<td>26</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{127}$Te</td>
<td>$\frac{3}{2}$, $\frac{3}{2}$</td>
<td>13±2</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>$^{139}$Te</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>7.4±1.5</td>
<td>3.0</td>
<td>15</td>
</tr>
<tr>
<td>$^{131}$Te</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>10±3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{133}$Ba</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>5</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>$^{135}$Ce</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>13.1±1</td>
<td>22</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{151}$Os</td>
<td>$\frac{1}{2}$, $\frac{3}{2}$</td>
<td>31.0±1</td>
<td>27</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{197}$Pt</td>
<td>$\frac{3}{2}$, $\frac{3}{2}$</td>
<td>6.5±1.3</td>
<td>4.5</td>
<td>0</td>
</tr>
<tr>
<td>$^{197}$Hg</td>
<td>$\frac{3}{2}$, $\frac{3}{2}$</td>
<td>4.4±0.8</td>
<td>6.0</td>
<td>0</td>
</tr>
</tbody>
</table>

The situation is much improved using level densities for an unpaired system of nucleons. In particular the agreement between calculations and experiment is best if $T_{\epsilon}$ is proportional to $\epsilon^3$. The isomer ratios obtained taking $T_{\epsilon} \sim \alpha(c)\epsilon^2$ are consistently lower than for $\epsilon^3$ since the latter expression contains a stronger energy dependence than the former. Thus, a smaller number of gamma rays are emitted in the cascade when the form $\alpha(c)\epsilon^2$ is used compared to $\epsilon^3$ hence, the population of the high spin or isomer state of the nucleus is also lower. The effect of the geometrical factor $S$ can be seen in the third column. The isomer ratios are observed to increase considerably compared to the first column. This result is as discussed above due to the $S$-term which causes the transitions to higher spin states to be more probable than to the lower spin states.
The general agreement between the calculated results for $T_{1/2} \sim e^3$ and the experimental data seems satisfactory. For 16 of the 25 cases in table I the agreement is better than 30%. Several discrepancies are however apparent. The calculated isomer ratios for $^{81}$Se, $^{121}$Sn and $^{123}$Sn are considerably higher than the experimental values. A possible explanation in the case of $^{81}$Se is that a $\frac{3}{2}$ level lies directly above the $\frac{1}{2}$ level thus causing an increase in the ground state yield. A similar argument could be invoked for the existence of a $\frac{3}{2}$ state in $^{121}$Sn and $^{123}$Sn. Similarly the low calculated isomer ratio in $^{77}$Ge could be explained by an additional low-lying $\frac{1}{2}$ level. The effect of the low-lying discrete levels on the isomer ratio has been pointed out on previously by Ligget and Sperber.

The calculated isomer ratios for the heavy nuclei of $^{191}$Os, $^{197}$Pt and $^{197}$Hg are considerably lower than the experimental values. This discrepancy can in part be explained by the presence of E2 transitions in the cascade. Such transitions were not accounted for in our calculations, and their effect would be to increase the high spin isomer yield. Sperber and Mandler treated quadrupole admixture as a free parameter and found that quadrupole admixture of varying degrees were needed for all but six nuclei in table I. Thus, a possible explanation for the large discrepancies in $^{191}$Os, $^{197}$Pt and $^{197}$Hg and perhaps in $^{77}$Ge and $^{113}$Sn is the admixture of quadrupole radiation.

The isomer ratio calculations of Bishop et al. were carried out using the level density parameter of $a = 10$ for $69 \leq A \leq 85$, $a = 15$ for $109 \leq A \leq 139$ and $a = 20$ for the heavy nuclei. In the region $69 \leq A \leq 85$ the results of our calculations are essentially similar to those of Bishop et al. In the region of the heavy nuclei ($191 \leq A \leq 197$) our calculations give higher isomer ratios than Bishop et al., however they are still lower than the experimental values.

Our results are in better agreement with the experimental data than those of Bishop et al. throughout the region $109 \leq A \leq 139$ with the exception of $^{113}$Sn, $^{121}$Sn and $^{123}$Sn. We note that our calculations can account for the dependence of the isomer ratio on shell effects. The isomer ratios of the Te isotopes are observed to decrease with increasing neutron number. As the neutron number increases the magic $N = 82$ shell is approached, hence the level density and spin cut-off parameter decrease. Thus with increasing neutron number the spectrum becomes harder and involves less transitions in the cascade. The isomer ratio decreases both as a result of the smaller number of transitions and the decrease in the value of the spin cut-off parameter.

A similar explanation can be given for the increase of the isomer yield of $^{133}$Ba and $^{137}$Ce with respect to Te. In these cases the addition of protons causes nuclei to move away from the magic 50-proton shell thus causing an increase in the nuclear level density and spin cut-off parameters.

The only free parameter in the present calculation involves the definition of the energy interval from which the nucleus is forced to decay to the ground or isomeric state. By changing the interval from 0.5–1.0 MeV to 0.5–1.4 MeV we obtain for isomer ratios greater than 10% changes of the order of 25%. For isomer ratios of
less than 5% the isomer ratios decrease to about 60% of their value for the 0.5–1.0 MeV interval.

The code developed here for calculating the isomer ratios was also used to obtain the shape of the gamma spectrum. These results could be compared with experimental spectra in $(n,\gamma)$ reactions. However such a comparison was done here only in the case of Cd since only for this element both gamma spectra and isomer ratio were available. For any theory to be meaningful the calculated results must agree with both the experimental isomer ratio and gamma spectrum.

In fig. 2 we compare the calculated and experimental gamma spectrum 22) for the $(n,\gamma)$ reaction in Cd. Two forms for $T_{\gamma}$ were used, $e^3$ and $\sigma(e)e^2$ and the level densities were those of an unpaired nucleon system. As in the case of the isomer ratios

![Fig. 2. Total γ-ray spectrum from neutron capture in Cd. The spectrum $N_\gamma$ is multiplied by the γ-ray energy $\gamma$. The experimental spectrum is shown together with the theoretical calculations.](image)

the $e^3$ term gives better agreement with experimental data. This might indicate that the photo-absorption cross section $\sigma(e)$ is described incorrectly in the region below 7 MeV by the Lorentzian in eq. (2). A similar calculation with $T_{\gamma} \sim e^3$ was carried out by Troubetzkoy 23) who obtained good agreement between the experimental and calculated spectra in Gd.

### 4. Discussion

We have seen here that the simple statistical model based gamma cascade calculation, which does not essentially incorporate free parameters gives in most cases satisfactory agreement with the experimental data. The results which fit best the experimental data were obtained by assuming only E1 transitions, the transition probability given by $T_{\gamma} \sim e^3$ and the shell-model based level densities, without the inclusion of pairing.
The model discussed here is however by no means complete. The main source of difficulty is that the energies and spins of the low-lying levels are unknown. As discussed above low-lying levels with spins of intermediate value between those of the ground and isomeric state could have much influence on the value of the isomer ratio. A complete knowledge of all low-lying state would also enable us to make the transition between the discrete energy level region at low excitation energy and the region at higher excitation described by the level density from the statistical model. Thus the need for defining the arbitrary energy interval from which the levels must decay to ground or isomeric state would be eliminated. At present experimental data cannot furnish us with a complete descriptions of all low-lying levels in the nuclei studied here. One must therefore resort to shell-model calculations which are not sufficiently accurate for our purpose.

Given the ideal case in which all the low-lying discrete energy levels are known we are still faced with basic physical problems. The assumption made, that the cascade is composed of E1 transitions only must be approached with great caution. Sperber 5) for example has presented several argument for the admixture of E2 transitions. This problem might in part be resolved by comparing the calculated and measured isomer ratio and γ-spectrum in the case of a nucleus whose level structure in the low-lying and statistical region are known to good accuracy.

Another problem which comes to light is the success of the form $T_{1f} \sim e^3$ used in the present calculations to describe the E1 transitions. This form refers to single nucleon transitions which is hardly the case especially in the high energy region of the statistical cascade. Finally, it is not clear why the non-paired level density formalism gives better results than the paired system although the latter has a better theoretical foundation.

Concluding, in spite of the relative success of the simple model described in this paper much has still to be resolved in connection with the statistical decay of gamma radiation. This could in principle be accomplished by studying both the isomer ratios and gamma spectra in systems in which the low-lying discrete states are known to a high degree of accuracy.

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