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ISOMERIC STATE AND ROTATIONAL BAND IN $^{158}$Ho

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Résumé. — Le noyau impair- impair $^{158}$Ho a été étudié au moyen des réactions $^{159}$Tb($\alpha$, 5n)$^{158}$Ho et $^{160}$Dy(p, 3n)$^{158}$Ho. Un état isomérique de période $T_{1/2} = (29 \pm 3)$ ns a été mis en évidence. Une bande de rotation a été développée jusqu’au spin 16$^-$. 

Abstract. — The odd-odd $^{158}$Ho nucleus is studied by means of the reactions $^{159}$Tb($\alpha$, 5n)$^{158}$Ho and $^{160}$Dy(p, 3n)$^{158}$Ho. The lifetime of an isomeric state is measured as $T_{1/2} = (29 \pm 3)$ ns. A rotational band is developed up to spin 16$^-$. 

1. Introduction. — In the framework of a systematic study of the spectroscopy of neutron-deficient holmium isotopes, the level scheme of the odd-odd nucleus $^{158}$Ho has been investigated.

A previous investigation by Stenström and Jung [1] determined the genetic relationships and half-lives of $^{158}$Ho isotopes. Recently Abdurazakov et al. [2] and Harmatz and Handley [3] have investigated the decay scheme of the nucleus $^{158}$Er $\rightarrow$ $^{158}$Ho. As a result of their investigations the ground state of $^{158}$Ho is found to have spin and parity 5$^+$ corresponding to 67 protons and 91 neutrons with a $p$ 7/2$^- [523] \uparrow n$ 3/2$^- [521] \uparrow$ configuration. An isomeric state ($T_{1/2} = 27$ min.) in $^{158}$Ho with energy 67.3 keV is known which has been interpreted as having spin and parity 2$^-$ and which corresponds to possible configurations:

\begin{align*}
p 1/2^+ [411] & \downarrow n 5/2^- [523] \downarrow \text{ Ref. [2]} \\
p 7/2^+ [404] & \downarrow n 3/2^- [521] \uparrow \text{ Ref. [3]} \\
p 7/2^- [523] & \uparrow n 3/2^- [402] \downarrow
\end{align*}

It is the purpose of this letter to discuss the above possibilities and compare them with our data which concern the levels of $^{158}$Ho studied by in-beam spectroscopic methods in the reactions ($\alpha$, xny) and (p, xny).

2. Experimental procedure and results. — The in-beam experiments were carried out at the Grenoble cyclotron. For the $^{159}$Tb($\alpha$, 5n) reaction, a monoisotopic terbium foil target of 5 mg/cm$^2$ was used. The $^{160}$Dy(p, 3n) reaction was performed with a 5.5 mg/cm$^2$ 85 % enriched $^{160}$Dy$_2$O$_3$ target. The study of excitation functions suggested that alpha and proton particle energies of approximately 63 MeV and 43 MeV respectively were the most favourable for the production of $^{158}$Ho. Gamma lines belonging to $^{158}$Ho $2^-$ $\rightarrow$ 5$^+$. 

$^{158}$Ho $6^-$ $\rightarrow$ 5$^-$.

$^{158}$Dy $7^-$ $\rightarrow$ 6$^-$.

$^{158}$Ho $8^-$ $\rightarrow$ 7$^-$.

$^{158}$Ho $5^-$ $\rightarrow$ 5$^+.

$^{158}$Ho $9^-$ $\rightarrow$ 8$^-.

$^{158}$Ho $10^-$ $\rightarrow$ 9$^-.

$^{158}$Ho $7^-$ $\rightarrow$ 5$^-.

$^{158}$Ho $11^-$ $\rightarrow$ 10$^-.

$^{158}$Ho $8^-$ $\rightarrow$ 6$^-.

$^{158}$Dy $12^-$ $\rightarrow$ 11$^-.

$^{158}$Ho $13^-$ $\rightarrow$ 12$^-.

$^{158}$Ho $9^-$ $\rightarrow$ 7$^-.

$^{158}$Ho $14^-$ $\rightarrow$ 13$^-.

$^{158}$Ho $15^-$ $\rightarrow$ 14$^-.

$^{158}$Dy $10^-$ $\rightarrow$ 8$^-.

$^{158}$Ho $11^-$ $\rightarrow$ 9$^-.

$^{158}$Dy $12^-$ $\rightarrow$ 10$^-.

$^{158}$Ho $13^-$ $\rightarrow$ 11$^-.

$^{158}$Ho $14^-$ $\rightarrow$ 12$^-.

$^{158}$Ho $15^-$ $\rightarrow$ 13$^-.

$^{158}$Ho $16^-$ $\rightarrow$ 14$^-.$
\(^{157}\text{Ho}\) and \(^{159}\text{Ho}\) and their daughter products were observed in the spectrum due to the \((\alpha, 6n)\) and \((\alpha, 4n)\) reactions.

The experimental information consists of \(\gamma\)-ray spectra (in and out of beam), the life-time of the isomeric state measured using the cyclotron pulses and the prompt and delayed \(\gamma-\gamma\) coincidences. The results of our experiments are summarized in table I and in figures 1, 2, 3 and 4. In table I only the energies and the relative \(\gamma\)-ray intensities for the lines of \(^{158}\text{Ho}\) are tabulated. A spectrum obtained using the delayed coincidence method is presented in figure 1. In this figure the 156.9 keV \(\gamma\)-ray is taken as the gate STOP. Figure 2 gives an example of the prompt coincidences for the 115.1 keV \(\gamma\)-ray. The decay curve for the 156.9 keV line of \(^{158}\text{Ho}\) is shown in figure 3.

3. Data analysis and results. — In the course of measurement of in and out of beam gamma spectra, an intense delayed gamma line at 156.9 keV was found to decay with a half-life of \((29 \pm 3)\) ns. A comparison of this value with those assigned for the isomeric states in odd-odd holmium isotopes is given in the following table.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>(T_{1/2})</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{164}\text{Ho})</td>
<td>37.5 min.</td>
<td>139 keV</td>
</tr>
<tr>
<td>(^{162}\text{Ho})</td>
<td>68 min.</td>
<td>106 keV</td>
</tr>
<tr>
<td>(^{160}\text{Ho})</td>
<td>60 ns</td>
<td>118.1 keV</td>
</tr>
<tr>
<td>(^{158}\text{Ho})</td>
<td>29 ns</td>
<td>156.9 keV</td>
</tr>
</tbody>
</table>

Thus, while both the \(^{162}\text{Ho}\) and \(^{164}\text{Ho}\) nuclei seem to have a \(6^-\) isomeric state with the \(p \, 7/2^- [523] \oplus n \, 5/2^+ [642] \uparrow\)
configuration, the isomeric state observed at 118.1 keV in \(^{160}\text{Ho}\) apparently has not this configuration as reported by Leigh, Stephens and Diamond [5]. These authors indicated that the 6\(^-\) state should also occur in \(^{160}\text{Ho}\) and the rotational band observed is probably based on this state with the configuration 6\(^-\), \(p^7/2\) \([523]\) \(\uparrow n^3/2\) \([642]\) \(\uparrow\). This conclusion was based on the very great similarity between the sequence of \(\gamma\)-rays transitions in both \(^{162}\text{Ho}\) and \(^{160}\text{Ho}\).

Moreover the oscillations in the energy level spacings for \(^{162}\text{Ho}\) and \(^{160}\text{Ho}\) obtained by plotting

\[
\frac{(E_i - E_{i-1})}{2I} \text{ vs } f(2I)^2
\]

are in phase. The isomeric state could be a 5\(^-\) state with the configuration \(p^7/2\) \([523]\) \(\uparrow n^3/2\) \([402]\) \(\uparrow\).

With regard to the nucleus \(^{158}\text{Ho}\), it must be noted that the sequence of \(\gamma\)-transition is different from that in \(^{160}\text{Ho}\). This discrepancy may be explained by the presence of the \(p^7/2\) \([523]\) Nilsson level in the...
configuration which shows strong perturbation by Coriolis coupling. The increasing perturbation of the $p\ 7/2^-$ [523] band with decreasing mass number is indicated by the variation of the strength of fluctuations in neighbouring $^{155}$Ho and $^{159}$Ho nuclei [7]. Figure 4 shows this in a plot of $f(2 I_f^2)$ for $^{160}$Ho and $^{158}$Ho. It is clear that the perturbation in the energy level spacing of $^{158}$Ho is stronger than that in $^{160}$Ho. If we suppose that the curves $(E_i - E_{i-1})/2I$ must be in phase in both $^{160}$Ho and $^{158}$Ho, the 156.9 keV state of spin 5$^-$ must be assigned as the isomeric state in the $^{158}$Ho nucleus. The spin $I = K = 6^-$ might be attributed to the head of the rotational band.

However, two other assumptions are also possible:

1) The 6$^-$ state could be attributed as the isomeric state and considered as the head of the rotational band.

2) The isomeric state could be assigned as the 5$^-$ state by supposing a weak transition between the 6$^-$ and 5$^-$ state. We cannot see a gamma line of such low energy with our experimental arrangement; if present, it is undoubtedly highly converted and will be difficult to observe. In this case the $\gamma$-ray of 72.9 keV could represent the transition between the 7$^-$ and 6$^-$ states.

By choosing the spin and parity of the isomeric state as 5$^-$, a possible configuration for this state is $p\ 7/2^- [523] \uparrow n\ 3/2^+ [402]$. According to Gallagher-Moszkowski's rule, the 2$^-$ state of 67.3 keV in $^{158}$Ho is the lower member of the doublet. However, this situation leads to a different interpretation from that given in refs. [2, 3].

4. Conclusion. — a) The level scheme of $^{158}$Ho proposed on the basis of our experiments is shown in figure 5.

b) The rotational band observed in $^{158}$Ho is highly perturbed by Coriolis coupling. This is due to the fact that the orbits of the proton and neutron states originate from high-$j$ shells of $h_{11/2}$ and $i_{13/2}$ respectively and to the fact that with decreasing A the perturbation increases rapidly in the neighbouring odd-A nuclei.

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