Proceedings of the Eleventh International Symposium

Capture Gamma-Ray Spectroscopy and Related Topics

2 – 6 September, 2002

Průhonice near Prague, Czech Republic

Editors: J. Kvasil, P. Cejnar & M. Krtička

Institute of Particle and Nuclear Physics, Charles University, Prague
Czech Republic

World Scientific
New Jersey • London • Singapore • Hong Kong
MICROSCOPIC STUDY OF $^{156}$Gd

GABRIELA POPA
Department of Physics, Rochester Institute of Technology,
Rochester, NY 14623-5612, USA E-mail: gpopa@rochester.rr.com

JORGE G. HIRSCH
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México,
Apartado Postal 70-543 México 04510 DF, México
E-mail: hirsch@nuclecu.unam.mx

JERRY P. DRAAYER
Department of Physics and Astronomy, Louisiana State University,
Baton Rouge, Louisiana 70803, U.S.A.
E-mail: draayer@lsu.edu

ANI APRAHAMIAN AND R. C. DE HAAN
University of Notre Dame, Notre Dame, IN 46556, U.S.A.
E-mail: aapraham@darwin.helios.nd.edu

A pseudo-SU(3) shell model study of low-lying rotational bands in $^{156}$Gd is reported. Symmetry breaking terms that are included in the Hamiltonian induce representation mixing and this in turn yields theoretical predictions for inter-band as well as intra-band B(E2) transition strengths that can be compared with the available experimental data.

1. Introduction
The pseudo-SU(3) model\textsuperscript{1} has been used to describe normal parity bands in heavy deformed nuclei. The scheme takes full advantage of the existence of pseudo-spin symmetry, which refers to the fact that single-particle orbitals with $j = l - 1/2$ and $j = (l - 2) + 1/2$ in the $\eta$ shell lie close in energy. and can therefore be labeled as pseudo-spin doublets with quantum numbers $\tilde{j} = j$, $\tilde{\eta} = \eta - 1$ and $\tilde{l} = l - 1$.

The simplest version of the model has been used to give a detailed description of various rotational bands as well as B(E2) and B(M1) transition strengths in even-mass rare earth isotopes ($^{156,158,160}$Gd, $^{160,162,164}$Dy, $^{166}$Er) and in various odd-mass nuclei ($^{158}$Er, $^{160}$Er, $^{162}$Er, $^{164}$Er, $^{166}$Er). Some recent results for the $^{156}$Gd isotope that were obtained using a more robust version of the pseudo-SU(3) formalism with an improved treatment of the nuclear potential energy surface in ways not yet available. In the present analysis, some nuclei exhibit symmetry breaking, and the details of the nuclear potential energy surface is a combination of the available information on B(E2) and B(M1) transition strengths that can be compared with the available experimental data.
and in various odd-mass nuclei (\(^{159}\text{ Tb}, \,^{159,163}\text{ Dy}, \,^{159}\text{ Eu}, \,^{161}\text{ Tb}, \,^{161}\text{ Tm}, \,^{165}\text{ Er}\))\(^{2}\).

In the present contribution we review some recent results for the \(^{156}\text{ Gd}\) isotope that were obtained using a more robust version of the pseudo-SU(3) formalism with an eye towards offering a quantitative description of excited 0\(^{+}\) bands and their coupling to the ground state band.

As a result of representation mixing induced by the symmetry breaking single-particle and pairing terms in the Hamiltonian, the eigenstates are a combination of coupled irreps that support inter- as well a intra-band B(E2) transitions. The latter is of interest as it allows one to address the issue of shape coexistence and electromagnetic transitions, including monopole links, between the excited and the ground-state band. This, in turn, allows one to probe the elusive landscape of the nuclear potential energy surface in ways heretofore not possible.

2. Model space and Hamiltonian

The pseudo-orbital and pseudo-spin angular momenta are assigned according to occupied single-particle states in the normal-parity sector of the full model space. The building blocks of the model are the pseudo-SU(3) proto and neutron configuratons with pseudo-spin zero (0) and one-half (1/2) for an even and odd number of nucleons, respectively. Many-particle states are built as pseudo-SU(3) coupled states with a well-defined particle number and good total angular momentum.

Nucleons occupying the intruder orbits are considered implicitly through the use of effective charges. The explicit inclusion of unique-parity configurations remains an open challenge – one that is currently under investigation, but whose solution is not yet available. To determine occupancies the normal- and unique-parity sectors, a deformed Nilsson single-particle scheme is employed, filling levels from the bottom up. A simple algorithm allows one to extract from this the most important SU(3) irreps which turn are coupled to final SU(3) irreps that have good total angular momentum. Details can be found in previous publications\(^{3,4}\).

The Hamiltonian includes realistic single-particle energies for the protons and neutrons, the quadrupole-quadrupole and pairing interactions with strengths taken from systematics, and four ‘rotor-like’ terms that diagonal in the SU(3) basis with strengths determined through a least-squares fit to experimental data. The parameters as determined by analysis are consistent with those used in a description of the neighboring even-even and odd-A nuclei\(^{2,3}\).
3. Results

The experimental and calculated energies of the lowest three energy bands (0\(^+\) ground state, first 2\(^+\) excited state, and first 0\(^+\) excited state) of \(^{156}\)Gd are compared in Fig. 1. As can be seen, the calculated results are in good agreement with experiment.

![Energy spectra of \(^{156}\)Gd.](image)

Likewise, the B(E2) transitions probabilities given in Table (1) are also in good agreement with the experimental data taken from \(^5\) (marked with *) and \(^6\). The values for the intra-band transitions are very collective, with intensities a few \(e^2t^2\). As expected, inter-band transition strength are a factor 100 weaker, but non-zero due to the irrep mixing.

4. Conclusions

This study demonstrates that a relatively few pseudo-SU(3) irreps with maximum deformation suffices to obtain good agreement with known experimental results for energies as well as intra- and inter-band B(E2) transition strengths between low-lying bands in rare earth and actinide nuclei. The results exhibits the power of the pseudo-SU(3) scheme for probing the true nature of deformation in rare-earth and actinide nuclei.
Table 1. Experimental and calculated B(E2) transition probabilities in $^{156}$Gd.

<table>
<thead>
<tr>
<th>$J_{K_i}$</th>
<th>$J_{K_f}^f$</th>
<th>Exp</th>
<th>Th</th>
<th>$J_{K_i}$</th>
<th>$J_{K_f}^f$</th>
<th>Exp</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_2$</td>
<td>$2^+_g$</td>
<td>6.65 ± 0.12</td>
<td>4.66</td>
<td>$0^+_2$</td>
<td>$2^+_g$</td>
<td>0.014 ± 0.005</td>
<td>0.065</td>
</tr>
<tr>
<td>$2^+_2$</td>
<td>$4^+_g$</td>
<td>3.36 ± 0.04</td>
<td>2.39</td>
<td>$2^+_2$</td>
<td>$2^+_g$</td>
<td>0.025 ± 0.006</td>
<td>0.0053</td>
</tr>
<tr>
<td>$4^+_2$</td>
<td>$6^+_g$</td>
<td>2.12 ± 0.06</td>
<td>2.09</td>
<td>$2^+_2$</td>
<td>$4^+_g$</td>
<td>0.0039 ± 0.0008</td>
<td>0.0163</td>
</tr>
<tr>
<td>$6^+_2$</td>
<td>$8^+_g$</td>
<td>2.09 ± 0.11</td>
<td>1.94</td>
<td>$2^+_2$</td>
<td>$3^+_g$</td>
<td>0.053 ± 0.011</td>
<td>0.0165</td>
</tr>
<tr>
<td>$0^+_0$</td>
<td>$2^+_0$</td>
<td>2.247</td>
<td></td>
<td>$2^+_0$</td>
<td>$4^+_g$</td>
<td>0.025 ± 0.006</td>
<td>0.0545</td>
</tr>
<tr>
<td>$2^+_0$</td>
<td>$4^+_0$</td>
<td>2.91 ± 1.12</td>
<td>2.109</td>
<td>$4^+_2$</td>
<td>$4^+_g$</td>
<td>0.057 ± 0.016</td>
<td>0.00026</td>
</tr>
<tr>
<td>$4^+_0$</td>
<td>$6^+_0$</td>
<td>1.984</td>
<td></td>
<td>$4^+_2$</td>
<td>$5^+_g$</td>
<td>0.013 ± 0.02</td>
<td>0.0097</td>
</tr>
<tr>
<td>$6^+_0$</td>
<td>$8^+_0$</td>
<td>1.853</td>
<td></td>
<td>$5^+_2$</td>
<td>$6^+_g$</td>
<td>0.018 ± 0.005</td>
<td>0.0384</td>
</tr>
<tr>
<td>$2^+_1$</td>
<td>$3^+_2$</td>
<td>0.157</td>
<td></td>
<td>$0^+_1$</td>
<td>$2^+_g$</td>
<td>0.038 ± 0.017</td>
<td>0.00011</td>
</tr>
<tr>
<td>$2^+_3$</td>
<td>$4^+_2$</td>
<td>1.754</td>
<td></td>
<td>$2^+_2$</td>
<td>$2^+_g$</td>
<td>0.021 ± 0.007</td>
<td>0.082</td>
</tr>
<tr>
<td>$3^+_3$</td>
<td>$5^+_2$</td>
<td>2.60 ± 1.98</td>
<td>1.685</td>
<td>$2^+_2$</td>
<td>$4^+_g$</td>
<td>0.023 ± 0.008</td>
<td>0.0095</td>
</tr>
<tr>
<td>$4^+_3$</td>
<td>$5^+_2$</td>
<td>0.037</td>
<td></td>
<td>$2^+_2$</td>
<td>$4^+_g$</td>
<td>0.028 ± 0.010</td>
<td>0.015</td>
</tr>
<tr>
<td>$4^+_4$</td>
<td>$6^+_2$</td>
<td>1.743</td>
<td></td>
<td>$4^+_2$</td>
<td>$4^+_g$</td>
<td>0.0137 ± 0.053</td>
<td>0.034</td>
</tr>
<tr>
<td>$6^+_4$</td>
<td>$7^+_2$</td>
<td>0.004</td>
<td></td>
<td>$4^+_2$</td>
<td>$6^+_g$</td>
<td>0.016 ± 0.006</td>
<td>0.0066</td>
</tr>
<tr>
<td>$6^+_5$</td>
<td>$8^+_2$</td>
<td>1.635</td>
<td></td>
<td>$4^+_0$</td>
<td>$6^+_g$</td>
<td>0.013 ± 0.005</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Acknowledgments

This work was supported in part by Conacyt (México) and the U.S. National Science Foundation.

References

6. R. C. De Hann and A. Aprahamian, U. Notre Dame internal report.