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Inelastic Neutron Scattering on ^{160}Gd

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Abstract. The nature of low-lying excitations, $K^\pi=0^+$ bands in deformed nuclei remain enigmatic in the field, especially in relationship to quadrupole vibrations. One method of characterizing these states beyond excitation energies is through measurements of absolute transition probabilities. In the rare earth region of deformation, there are five stable Gd isotopes, ^{154}Gd, ^{156}Gd, and ^{158}Gd have been studied to obtain B(E2) values, a fourth, ^{160}Gd is the focus of this work. We have examined ^{160}Gd with the $(n, n'\gamma)$ reaction and neutron energies up to 3.0 MeV to confirm known 0^+ states.

Since the work of Bohr and Mottelson [1], the lowest excited 0^+ state and the second excited 2^+ state in deformed nuclei were expected to result from quadrupole vibrations built on the deformed ground state with a projection of K = 0 and K = 2 on the symmetry axis. The γ vibration is a shape change against the axis of symmetry, and is identified by collective transitions from the $K^\pi = 2^+$ band decaying to the ground state. This vibration exhibits a systematic behavior across the region of deformed nuclei.

The β vibration, however, is a shape change along the axis of symmetry and should also be a collective $K^\pi = 0^+$ excitations. The lowest 0^+ state in deformed nuclei fail to display the systematic trends exhibited by the γ vibration. There is debate on the collectivity and even the existence of this β type of vibration in deformed nuclei. The argument is two-fold - Does the band first excited K= 0^+ band decay to the γ band or to the ground state, and is this decay collective, i.e., does it involve several nucleons or just a pair of nucleons? If the K= 0^+ band decays to the γ band, it can be viewed as an excitation built on the K= 2^+ gamma band. If it decays to the ground state, with collective transitions, then it may be viewed as a collective vibration built on the ground state.

An additional interpretation has emerged with the investigation of ^{152}Sm by P.E. Garrett *et al.* of shape coexistence [2]. What is clearly needed is more information on 0^+ states, prompting Heyde & Wood to list it as an unsolved problem in nuclear structure [3]. For these reasons, we have set out to perform a systematic study of the Gd nuclei.

There are five stable, even-even Gadolinium nuclei – ^{152}Gd (only 0.20% abundant), ^{154}Gd, ^{156}Gd, ^{158}Gd and ^{160}Gd. Suggestions have been made that the relative position of the first excited $K^\pi = 0^+$ and the $K^\pi = 2^+$ γ-band plays a key role in the vibrations [4]. While the 2^+ γ-band remains within 200 keV in excitation energy within the various isotopes, the first excited 0^+ band increases in energy

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with increasing neutron number. Another interesting evolution is the "flipping" of the order of the "β" and γ bands within the various Gd isotopes as shown in Fig. 1.

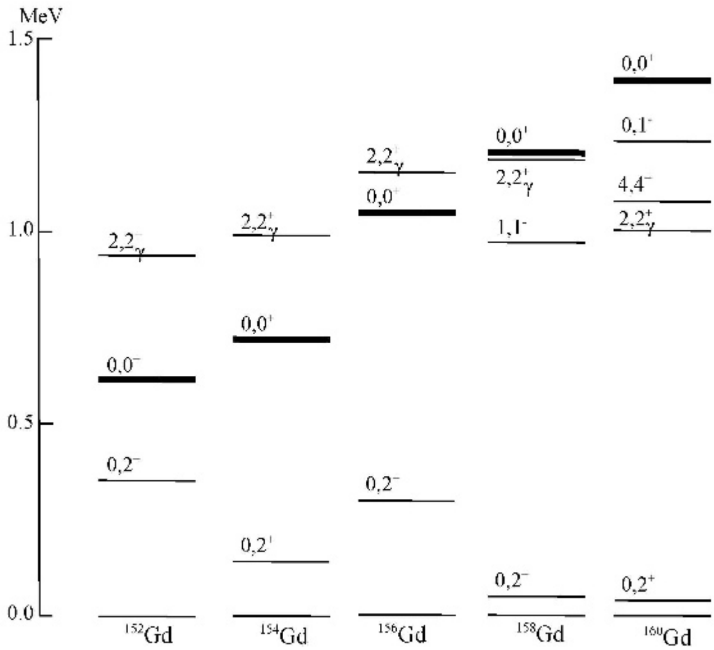

Figure 1. Level schemes for even Gd from 152 – 160, the area of interest in this study. The 0^+ states are shown in bold to guide the eye. All levels are not shown but only the ones of interest. Data is taken from Ref. [10].

Three of the stable isotopes have been studied to obtain B(E2) values: ^{154}Gd [5], ^{156}Gd [6], ^{158}Gd [7, 8]. In this work, we begin the process of confirming the 0^+ states in ^{160}Gd and measuring the lifetimes.

The low-lying structure of ^{160}Gd has been studied using γ-rays spectroscopy following inelastic neutron scattering, $(n, n'\gamma)$. The advantages of using neutrons comes from their lack of charge and thus no Coulomb barrier to overcome and the reaction is usually non-selective in the sense that both collective and single particle states are excited. The experiment was performed at The University of Kentucky 7 MV Van de Graaff accelerator facility. Nearly monoenergetic neutrons were produced using the ^{3}H(p, n) reaction. The energy spread of the neutrons striking the sample was approximately 60 keV. The scattering sample was 29.46 g of Gd_2O_3 enriched to 98.12% ^{160}Gd. The excitation function was performed with a HPGe detector having relative efficiency of $\leq$ 50% and energy resolution (FWHM) of approximately 2.0 keV at 1332 keV. Time of flight gating and Compton suppression with an annular BGO shield were used to reduce extraneous background events. The excitation experiment used neutron energy steps of ~100 keV from E_n = 1.5 – 2.8 MeV.

The detector was shielded with several different types of material in order to reduce background and to prevent neutron damage to the detector. Lead rings were place around the detector to reduce the background γ-rays observed. Boron-loaded polyethylene reduced the number of scattered neutrons and γ rays reaching the detector. Copper plates with a 7.5-cm wide diameter hole were placed between the tritium cell and the detector for fast neutron shielding. A tungsten wedge was positioned at the front of the assembly to prevent neutrons from striking the detector by preventing the detector from a direct viewing of the neutron source. The reduce the number of background events due to Compton scattering, an annular bismuth germanate (BGO) scintillation detector connected to six photomultiplier tubes was placed around the HPGe detector. The BGO and HPGe detectors were operated in anti-coincidence mode to achieve Compton suppression. More details about the experimental setup can be found in Ref. [9].

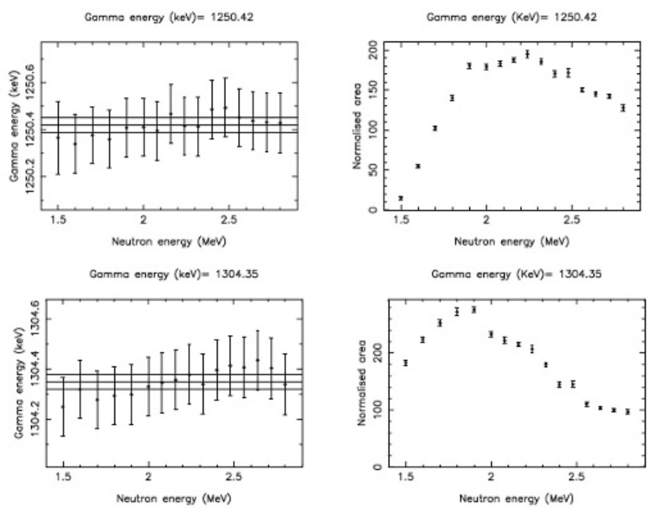

Figure 2. Preliminary excitation functions for E_γ = 1250.4 keV (top) and E_γ = 1304.3 keV (bottom). Excitation functions show two panels of information on the left, γ-ray energy vs. neutron energy is plotted to confirm the identification of the correct peak in the γ-ray spectrum. On the right, the normalized area vs. neutron energy is given. These plots allow the confirmation of levels placed in the level scheme.

Excitation functions are shown in Fig. 2 in two panels. On the left, γ-ray energy vs. neutron energy is plotted to confirm the identification of the correct peak. On the right, the normalized area vs. neutron energy is given. These plots allow the confirmation of levels placed in the level scheme [10]. The E_γ = 1250.4 keV is decays from E_L = 1325.7 $\rightarrow$ 75.3 keV, $(0^+) \rightarrow 2_g^+$, however, it is inconsistent with placement from the questioned 0^+ level at 1325.73 keV because the γ ray threshold is too high. Therefore, this work does not support the current placement of this γ ray but further analysis is needed to provide insight of the correct placement. The second excitation function is for the $0^+ \rightarrow 2_g^+$, E_L = 1379.6 $\rightarrow$ 75.3 keV is consistent with the energy and 0^+ spin assignment.

Using the excitation functions, the level scheme will be confirmed. Angular distributions were measured at 1.5, 2.0 and 2.8 MeV allowing for lifetime measurements via the Doppler-shift attenuation method (DSAM) from $10^{-14} - 10^{-12}$ s lifetime region.

The $(n, n'\gamma)$ excitation function begins to unravel the structure of the ^{160}Gd and has already revealed the mislabeling of a 0^+ state. The next step is to complete the analysis of lifetime measurements and angular distributions to further explore the nature of 0^+ states.

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