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Lifetime measurements near the first order phase transition

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1. Experiment Summary

We propose to investigate the deformation crossing near the first order shape-phase transition in Gd isotopes by measuring lifetimes of low-lying excited states in ^{150}Gd using the recoil-distance Doppler shift method and the fast-timing technique. In order to populate the excited states in the ^{150}Gd residual nucleus, we plan to use the reaction ^{140}Ce(^{13}C,3nγ)^{150}Gd for the study of 2_1^+ and 2_2^+ states and the study of β-decay of ^{150}Tb populated in the ^{147}Sm(^{6}Li,3nγ)^{150}Tb reaction for measuring the 0_2^+ state lifetime. The incident energy for the ^{13}C will be 61 MeV and for the ^{6}Li about 32 MeV. The Bucharest mixed detector array of HPGe and $LaBr_3$:(Ce) will be used for detection of the gamma rays which will allow the extraction of the measured lifetimes. In order to use these quantities to study the deformation changes in the vicinity of the phase transition, we employ the model-independent quadrupole shape invariant *q2*, which provides a measure of the deformation of a given nucleus. This shape invariant can be obtained by using experimental B(E2) values for the ground state band and first excited 0^+ band. The measurement of electromagnetic transition rates also represents a crucial test for different theoretical models which address this transitional region of the nuclear chart.

2. Introduction

The analysis of nuclear properties in systems near the phase transitional points is today an important topic of research [1-5]. Especially around the first order phase transition the characteristic feature of shape coexistence was recognized. Already a well-established phenomenon in many regions of the nuclear chart, most of the studies concentrated on the existence of deformed states in spherical nuclei [6,7] and superdeformed states in nuclei with moderate deformation [8]. Recently, the existence of weakly deformed excited states in a deformed nucleus was also recognized [9].

An important point in understanding the first order phase transition is the coexistence of different shapes in the two lowest 0^+ states. This problem was addressed in Ref. [10] where the deformation of these states in the Gd isotopic chain was studied using the quadrupole shape invariants, which are directly related to the squared β deformation. The most important thing about these quantities is that they can be obtained from experimental B(E2) values of the low-lying states. Therefore, an accurate knowledge of the lifetime in this region is very important and could establish another signature for the presence of phase transitions.

The quadrupole shape invariants were introduced by Kumar [11] and are defined as the expectation value in a given nuclear eigenstate of second order moments of the E2 transition operator coupled to spin J=0. For the n-th 0^+ state, the second order quadrupole invariant is:

$$q_2(0_n^+) = e^2\langle 0_n^+|(Q\cdot Q)|0_n^+\rangle, \qquad (1)$$

where Q is the quadrupole operator. It can be shown [12] that the quadrupole shape invariant is the total absolute E2 strength from that state:

$$q_2(0_n^+) = \sum_{j=1}^{\infty} B(E2; 0_n^+ \rightarrow 2_j^+)\ . \qquad (2)$$

Although the sum in Eq.(2) goes to infinity, in practice the convergence of this sum is very rapid and only the knowledge of the first two or three matrix elements are required.

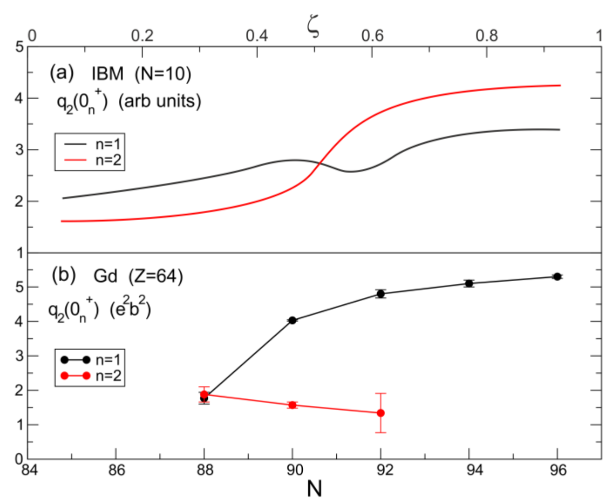

Fig1. Values of the $q_2(0_1^+)$ and $q_2(0_2^+)$ quadrupole shape invariants calculated within the Interacting Boson Model, on the U(5)-SU(3) leg of the symmetry triangle for N_B=10 bosons. (b) Plots of the experimental invariants as a function of neutron number N.

The quadrupole shape invariants can be calculated within the framework of any theoretical model. The authors of Ref. [10] have chosen the Interacting Boson Model (IBM) [13] to illustrate the deformation of first and second excited 0^+ states. The results are presented in Fig.1 (a). It was found that by using the quadrupole moment of the IBM, quadrupole shape invariants corresponding to the ground state and first excited 0^+ state cross in the vicinity of N=90, very close to the critical point symmetry. Such a finding should be verified by the experimental data. However, the lifetimes of the low-lying states have been measured up to this point only for ^{152}Gd-^{156}Gd and are presented in Fig. 1 (b). This means that the crossing point is established experimentally only above N=88, which is the intersection point. To verify the results of the IBM calculations reliable data in ^{150}Gd (N=86, $R_{4/2}$=2.02) should be measured.

3. Experiment Description

Since the present experiment implies the use of two methods, the task will be divided into two parts. We propose to start the experiment with the measurement of lifetimes for states in the ground-state band of ^{150}Gd using the recoil distance Doppler shift (RDDS) technique [14] with the Koln-Bucharest Plunger device coupled to the present γ-spectrometer. To maximize the prompt population of states in ^{150}Gd we plan to use the ^{140}Ce (^{13}C, 3nγ)^{150}Gd at a beam energy of 61 MeV. The *3n* channel is the dominant one in this reaction with an appreciable cross section. A partial level scheme of ^{150}Gd is given in Fig. 2. Since it is very difficult to produce self-supporting Ce targets, a ^{140}Ce layer will be evaporated on a Au or Ta foil which will face the beam. Assuming a 0.5 mg/cm^2 ^{140}Ce target, a 5 pnA ^{13}C beam and production cross section of 400 mb, we will produce 2.7 x 10^4 ^{150}Gd nuclei per second. The crucial part of this part of the experiment will be the population of the 2_2^+ state. We expect a population of 1% for this state, and taking into account the 1% efficiency of the Ge detectors, we can observe 65 useful γ-γ coincidences for the $4_2^+ \rightarrow 2_2^+ \rightarrow 2_1^+$ cascade per hour or 1560 per day.

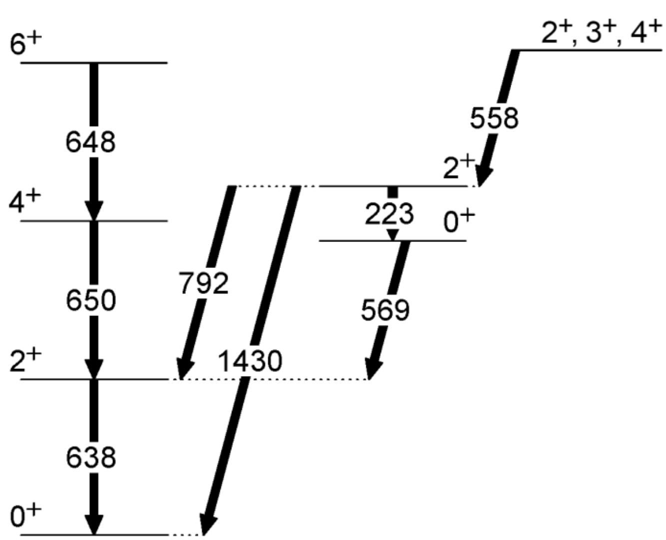

Fig. 2. Partial level scheme of ^{150}Gd for the states and transitions of interest for this proposal.

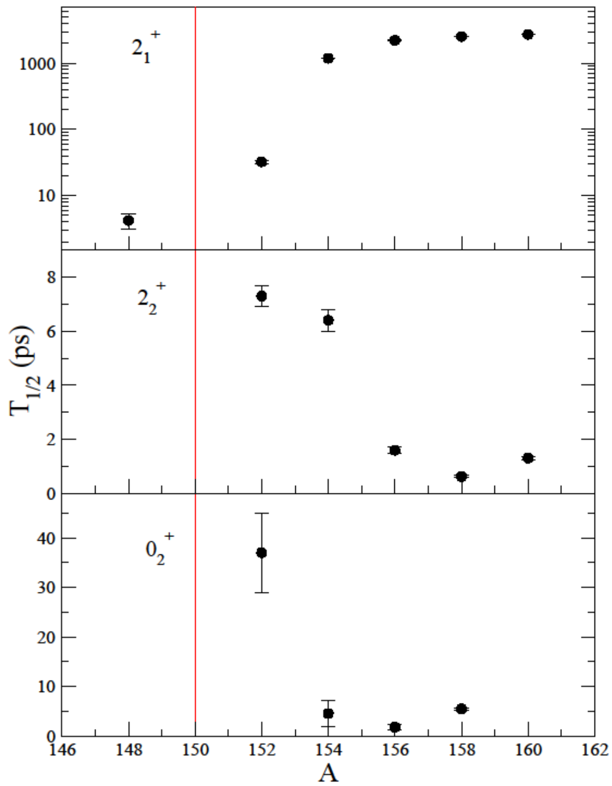

Fig. 3. Systematics of lifetimes for the 2_1^+, 2_2^+ and 0_2^+ states in Gd isotopic chain. The red line corresponds to ^{150}Gd, the nucleus of interest for this proposal.

From the systematics presented in Fig. 3, we expect the lifetime of the 2_1^+ and 2_2^+ states of about 10 ps and 8 ps, respectively. In addition, a similar experiment performed in ^{148}Gd gives a hint about the possibility of measuring lifetimes for other positive or negative states [15]. We estimate that about 7-8 additional states can also be measured and their lifetime deduced with high statistics. To obtain a high precision it is necessary to measure the intensities of the Doppler shifted and stopped components of the transitions for a sufficiently large number of target-to-stopper distances. The recoil velocity is calculated to be 2.25 μm/ps, equivalent of 0.75% *c*. With the count rates estimated above, we approximate that a measuring time of 24 hours is needed per distance. To achieve a high precision for the lifetime of the 2^+ states we propose to measure at 10 plunger distances between 5 and 100 μm. Thus we require 10 days of beam time.

In the second part of the experiment we propose to study the lifetime of the 0_2^+ state in the *β*-decay of ^{150}Tb populated in the ^{147}Sm(^{6}Li,3nγ)^{150}Tb reaction. The half-life of ^{150}Tb is about 3.5 hours, so successive runs of about 3-4 hours of activation and decay measurements are needed. The lifetime will be determined with the fast timing method described in Ref. [16]. The incident energy of the beam will be 32 MeV which will result in a cross section of about 600 mb. From Fig. 3 we expect the lifetime of this states in the range of 40 ps which can be measured from the time difference in the $LaBr_3$ detectors between transitions populating and depopulating the 0_2^+ state.

Assuming a 2 mg/cm^2 ^{147}Sm target and an intensity of 10 particle nA for the ^{6}Li beam, we estimate we will produce 3.2 x 10^5 ^{150}Tb nuclei per second. The 2_2^+ state is directly fed in the β-decay process with an intensity of 2%, and considering a branching of 2% for the population of the 0_2^+ state and using an average $LaBr_3$ efficiency of 1%, we expect a lower limit of about 45 useful coincidences per hour. Thus we request 4 days of beam time and additional 2 days for calibration purposes.

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