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Physics Letters B 638 (2006) 44–49
PHYSICS LETTERS B
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Enhanced density of low-lying 0^+ states: A corroboration of shape phase transitional behavior

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Received 19 January 2006; received in revised form 1 May 2006; accepted 1 May 2006

Available online 22 May 2006

Editor: D.F. Geesaman

Abstract

A (p, t) study of eight nuclei in the rare earth region identified 96 0^+ states (67 new). Their density at low energy is used to corroborate a fundamental property of quantum phase transitional behavior and to provide a new signature of nuclei near the critical point.

PACS: 21.10.Re; 24.10.Eq; 25.40.Hs; 27.70.+q

The rare earth region of nuclei is home to many well-deformed and transitional nuclei, making it an ideal region for the study of the origins of deformation and collective motion. A number of collective modes can form 0^+ states, yet the character of 0^+ states is not well understood. Recently, the nature of 0^+ excitations has attracted new attention. In a pioneering experiment [1] measuring 0^+ states in ^{158}Gd by way of the (p, t) transfer reaction, 7 new 0^+ states were discovered and 6 previously known states were confirmed below an excitation energy of 3.1 MeV. This was the first observation of such a large number of excited 0^+ states in a deformed nucleus. Following the experimental observations in ^{158}Gd, calculations [2–4] reproduced the density and distribution of these low lying 0^+ states. Similar data for a large set of nuclei, spanning this mass region and exhibiting a variety of structures, would offer a more thorough test of theory than data for a single nucleus. Therefore, we have studied a large group of nuclei spanning the rare earth region with the (p, t) reaction. These nuclei (^{152}Gd, ^{154}Gd, ^{162}Dy, ^{168}Er, ^{176}Hf, ^{180}W, ^{184}W, and ^{190}Os) range from transitional, to deformed, γ-soft, and spherical. A full presentation of the experimental results and their interpretation will be given in a forthcoming paper [5]. In this Letter we focus on one particular result of high current interest.

Much research [6–16] has recently centered on the study of zero temperature quantum phase transitions in the equilibrium structure of finite nuclei. This research has deep links to the study of phase transitions in other (finite and infinite) many-body systems. Significant results include the prediction of new critical point symmetries [6,7] that give analytic descriptions at the phase transitional point and the empirical discovery [8–10] of nuclei approximately manifesting this new class of symmetries, as well as studies of general properties of quantum phase transitions [11–13], and of empirical signatures for their appearance in nuclei [14–16].

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doi:10.1016/j.physletb.2006.05.007

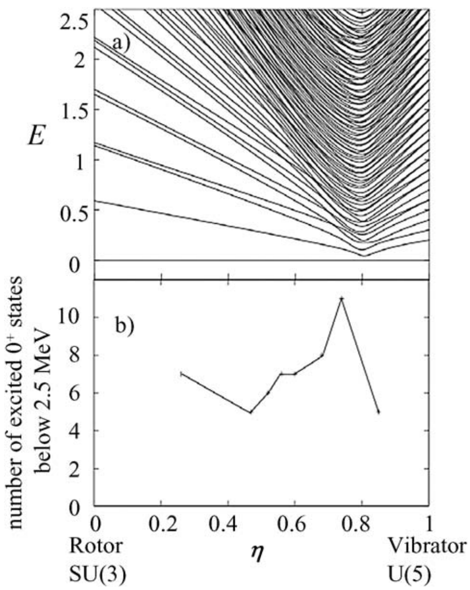

Fig. 1. (a) Behavior of calculated 0^+ states in the U(5) to SU(3) transition region as a function of the parameter η which is unity for U(5) and 0 for SU(3). The calculations are from Ref. [13] and are done for boson number 30 with χ, an internal parameter in the IBA quadrupole operator, of $-\sqrt{7}/2$. (b) Observed number of definite 0^+ states below 2.5 MeV for each nucleus studied plotted at the η value corresponding to fits [17] to their structure with the Hamiltonian of Eq. (1). The corresponding nuclei are, from left to right: ^{162}Dy, ^{168}Er, ^{180}W, ^{184}W, ^{158}Gd, ^{176}Hf, ^{154}Gd and ^{152}Gd.

One facet which emerges from collective model calculations in spherical-deformed transition regions is a predicted minimum in the energy of the first excited 0^+ state in the transition region. This is, in fact, a well-known phenomenon and has been discussed and reproduced with models such as the IBA [17,19,20]. As the transition region is approached, for example, as a function of neutron number, the lowest 0^+ excitation comes down sharply, actually crossing below the quasi-γ-excitation. Once a stable equilibrium deformation is established, the first 0^+ excitation quickly moves back up in energy.

Recently, detailed studies of the behavior of all 0^+ states in first order phase transitions were performed [13] using the Ising-type IBA Hamiltonian [21] of the consistent Q formalism (CQF) [22] in which the competition of spherical and deformed degrees of freedom is primarily expressed in terms of a parameter η, which varies from 0 (rotor) to 1 (vibrator) and where the transition point occurs for large boson number at $\eta \sim 0.8$, almost independent of χ. The results of the calculations of Ref. [13] for a vibrator to axial rotor transition region are shown in Fig. 1(a). They show not only a rapid descent of the first excited 0^+ state, but a descent in energy and a compression of *all* excited 0^+ states. Fig. 1(a) implies that the energy density of low-lying 0^+ states should maximize near the transition region. (Similar results apply for higher spin states.) Note that the calculations in Ref. [13] and Fig. 1(a) are done with very high boson numbers ($N = 30$). This is done on purpose to enhance the visibility of the phase transitional effects. The increased level density persists, however, for lower and more realistic values of N.

The prediction of increased level density is fundamental to the nature of a first order vibrator to axial rotor transition region. It arises due to the phase coexistence of two families of levels at low energy and the fact that the potential well effectively broadens at the transition point due to the degeneracy of spherical and deformed coexisting minima with a relatively small barrier between them. The high density of states also facilitates mixing of the coexisting states as seen by the multiple avoided crossings in Fig. 1(a). Although the prediction of a compression of 0^+ states is an inevitable consequence of a first order phase transition, it has never been tested empirically (except for the observed lowering of the first excited 0^+ state). Such a test is critical to our understanding and validation of phase transitional behavior.

It is therefore the purpose of this Letter to show that the extensive data we have obtained on 0^+ states provides a confirmation of this prediction of phase transitional behavior. Key to this is the study of a variety of nuclei spanning a significant mass region of heavy nuclei that contains vibrational, transitional, and deformed structures. These nuclei were chosen to contain examples with neutron numbers ($N = 88$–114) ranging across much of a major shell, and to include a number of well deformed nuclei to test whether the ^{158}Gd case was unique or typical. These nuclei have $R_{4/2} = E(4_1^+)/E(2_1^+)$ values of ~ 2, ~ 3, and near the rotor value of 3.33. It would be interesting to study an example with an $R_{4/2}$ intermediate between the vibrator and transitional regions (e.g., with $R_{4/2} \sim 2.5$) but no suitable case was available for this study.

This series of (p, t) experiments was performed at the MLL (Maier–Leibnitz Laboratory of LMU Munich and TU Munich) MP tandem accelerator laboratory using the Q3D magnetic spectrograph [23] and procedures similar to those of Ref. [24], a high resolution (p, t) study of actinide nuclei. A beam of 25 MeV unpolarized protons was incident on isotopically enriched targets, and outgoing tritons were measured at angles of 5, 17.5, and 30 degrees with respect to the beam axis. The spectrograph is an ideal instrument for the measurement of transfer reactions. The energy resolution is 4–6 keV FWHM for 15–20 MeV tritons. With the high resolution 1 m long focal plane detector [25,26] only two magnetic settings are necessary to cover an excitation energy range from 0–3 MeV. Very clean cross section measurements down to a few μb/sr (approximately 0.1% of the ground state cross sections) were possible with little or no background, particularly at 5 degrees. Typical spectra obtained at 5 degrees from ^{178}Hf(p, t)^{176}Hf and ^{156}Gd(p, t)^{154}Gd are shown in Fig. 2 (top). Energy calibrations were obtained using known levels, and peaks arising from target impurities were identified from their Q values.

Spin-parity values of 0^+ states can be easily assigned since the angular distribution for $L = 0$ transfer uniquely peaks strongly at forward angles. (Note that the population of 1^+ states with $L = 0$ is forbidden in a one step process as the transferred dineutron is in an $S = 0$ state and two-step processes do not yield the forward peak. Transfers with $L > 1$ (e.g., to 2^+ and 4^+ states) likewise do not give a forward angle peak.) In assigning L transfer values, we compared relative cross sections at 5 and 17.5 degrees to those calculated by the distorted