

On quadrupole vibrations in nearly spherical nuclei

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Abstract. A new understanding of low-lying quadrupole vibrations in nuclei is emerging through lifetime measurements performed with fast neutrons at the accelerator laboratory of the University of Kentucky in combination with high-sensitivity measurements with other probes. In the stable cadmium nuclei, which have long been considered to be the best examples of vibrational behavior, we find that many $E2$ transition probabilities are well below harmonic vibrator expectations, and the $B(E2)$ s cannot be explained with calculations incorporating configuration mixing between vibrational phonon states and intruder excitations. These data place severe limits on the collective models, and it is suggested that the low-lying levels of the Cd isotopes may not be of vibrational origin. An additional example of an apparent quadrupole vibrational nucleus, ^{62}Ni , is considered.

1. Introduction

The concepts of nuclear rotation and vibration are well established in describing the collective modes in nuclei. While there exist countless examples of nuclei displaying rotational behaviour, often observed to high angular momentum, the existence of low-energy, small-amplitude surface vibrations in nuclei appears to be on a more precarious footing [1, 2].

In even-even nuclei, the features of the harmonic quadrupole vibrator, the simplest version of the nuclear vibrational model, are easily identified. At approximately twice the excitation energy of the 2^+ first excited state (the one-phonon excitation) a 0^+ , 2^+ , 4^+ two-phonon triplet of states is predicted, and the three-phonon quintet (0^+ , 2^+ , 3^+ , 4^+ , 6^+) should occur at three times the one-phonon energy. States with these spins and parities at the requisite energies and with the expected decay patterns, which involve the destruction of a single phonon, have been interpreted as evidence for vibrational behavior.

Frequently ignored, often for the lack of detailed data, however, is that the harmonic vibrator model also predicts electromagnetic properties, *i.e.*, electric quadrupole moments and $E2$ transition probabilities. The expected pattern of decays for a harmonic quadrupole vibrator is quite straightforward [1, 2]. Simply stated, the $B(E2)$ s for the decays of the two-phonon states should be twice that of the $B(E2; 2^+ \rightarrow 0^+)$ one-phonon to ground-state decay. Transition probabilities of decays from three-phonon states are slightly more complex, and the sum of the $B(E2)$ s from each member of the quintet should be three times that of the one-phonon decay, with branchings firmly predicted from coefficients of fractional parentage. In recent years, reduced transition probabilities have been determined in a number of nuclei, which appear to be vibrational based on excitation energies, but serious failings, particularly in the stable Cd nuclei, lying in a region widely viewed as offering the best examples of vibrational behaviour, have been identified [1, 2].

2. Studies with the inelastic neutron scattering reaction

The inelastic neutron scattering (INS) reaction with γ -ray detection, *i.e.*, the $(n,n'\gamma)$ reaction, as performed at the University of Kentucky accelerator laboratory has contributed significant new information about the low-lying, low-spin states important for assessing the vibrational model. With INS we are able to obtain detailed information, such as level lifetimes and transition multipole mixing ratios, for non-yrast states, which are typically inaccessible with other nuclear probes.

The methods we have developed [3–5] for measuring γ -ray angular distributions, multipole mixing ratios, and lifetimes by the Doppler-shift attenuation method (DSAM) with the $(n,n'\gamma)$ reaction afford notable advantages over other techniques. Monoenergetic, accelerator-produced neutrons permit the population of levels close to their excitation thresholds, without the attendant complications associated with feeding from higher-lying levels and the production of undesirable γ -ray backgrounds. At low incident-neutron energies, the INS reaction is non-selective and can be treated with statistical methods; however, the angular momentum brought into the system by low-energy neutrons is limited. In addition, the energy resolution for γ -ray detection is excellent, much better than that for detecting most other forms of nuclear radiation. While we note the power of these methods for nuclear structure studies, we should also emphasize that INS is typically limited to stable nuclei, as large amounts of material and, frequently, enriched isotopic samples are required.

3. The stable cadmium nuclei as nearly spherical vibrators

In recent years, we have examined all of the stable cadmium nuclei, except ^{108}Cd , with INS in an effort to assess the extent to which these nuclei can be considered as vibrational. Most frequently, the even-even Cd nuclei have been interpreted as exhibiting a complex level structure with "intruder" states (designated 0_A^+ in figure 1) at low excitation energies, near the two-phonon vibrational triplet [6, 7]. This structure and the observed transition probabilities have generally been understood through mixing of the vibrational and intruder states, which arise from the promotion of a proton pair across the $Z = 50$ shell gap to produce a two-particle, four-hole configuration, with properties similar to the ground bands of the corresponding isotones of the "6 valence proton (or hole)" Ba and Ru nuclei [8].

In ^{116}Cd (see figure 2), we observed an anomaly that was not apparent in the lighter Cd nuclei [8]. The 0^+ head of the intruder band decays strongly to the first excited state, while the putative 0^+ member of the 2-phonon triplet exhibits a small $B(E2)$, contrary to expectations. Configuration mixing between the intruder and multiphonon vibrational excitations *cannot* describe the observed decays of these lowest 0^+ excited states [2, 8]. In addition, the transition between the proposed 3-phonon 0^+ state to the 2^+ 2-phonon state is not observed, while the decay to the first excited state is apparent, although the $B(E2)$ could not be determined. These and other unresolved problems have fostered new, more-detailed studies of the Cd nuclei with additional probes, such as radioactive decay, Coulomb excitation, and single-nucleon transfer reactions.

A very interesting result arises from the recent detailed study of levels in ^{112}Cd populated in the decay of ^{112}In and ^{112}Ag [9] in experiments performed at TRIUMF with the powerful 8π array of 20 Compton-suppressed HPGe detectors. These data provided high sensitivities for weak γ -ray branches and intensity limits were established for unobserved transitions. In concert with DSAM lifetimes available from INS measurements [10], a search was conducted for the "missing" $E2$ decay strength from the 0^+ and 2^+ states in the three-phonon region. In short, this strength, which should be present even if extensively fragmented, was not found, even though 5 excited 0^+ states and 13 excited 2^+ states were observed and considered in the analysis. These findings thus add to our concern about the applicability of the collective phonon model.

Based on recent studies of the stable Cd nuclei with inelastic neutron scattering (performed in our laboratory), radioactive decay, Coulomb excitation, and nucleon transfer reactions, Garrett and Wood [1] arrived at the conclusion that, in spite of the (frequently misleading) energy patterns of these nuclei, serious discrepancies exist between expected and measured $B(E2)$ s. They suggest that these nuclei may be better understood as exhibiting a quasi-rotational structure.

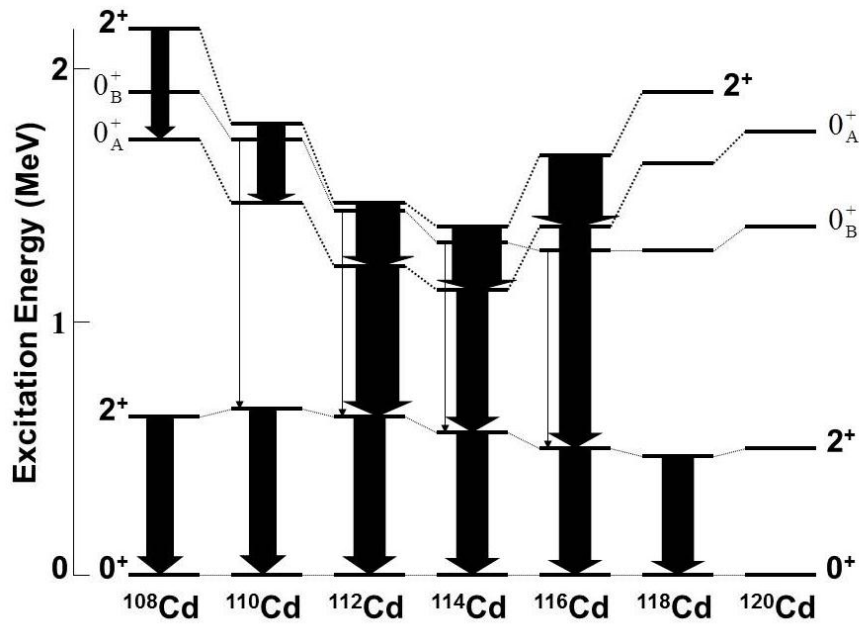


Figure 1. Systematics of 0^+ and 2^+ states in the Cd nuclei, as adopted from Ref. [8]. $E2$ transition strengths are indicated by the widths of the arrows.

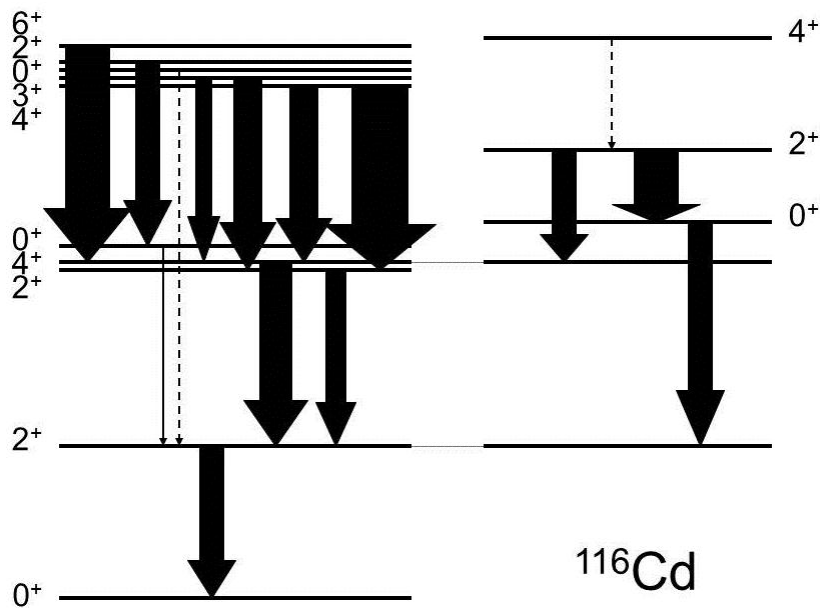


Figure 2. Schematic representation of levels in ^{116}Cd observed with the $(n,n'\gamma)$ reaction. The suggested phonon multiplets are on the left, and the intruder band is on the right. The arrow widths are proportional to the measured $B(E2)$ values. Dashed arrows indicate observed transitions for which the level lifetimes and, therefore, the transition rates have not been determined. See Ref. [8] for greater detail.

4. Vibrational structure of ^{62}Ni

Chakraborty *et al.* [11] have used the $(n,n'\gamma)$ reaction to examine the multiphonon structure of ^{62}Ni , which lies at the middle of the $N = 28$ to 40 subshell formed by the valence neutrons in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbitals and has a low-lying structure that is vibrational in appearance (see figure 3). While ^{62}Ni is not as collective as the stable Cd nuclei, an advantage of studying this nucleus is that shell model calculations can be performed for comparison with the measured data. The results of these calculations indicate a similarity with the findings in the Cd region, *i.e.*, while two-phonon states are in reasonable agreement with vibrational expectations, candidates for three-phonon states are sparse when the transition rate data are considered. A detailed examination of the states predicted by the shell model in the three-phonon region yields no good candidates for three-phonon states, because there is little total $E2$ strength for decays from states in the three-phonon region to members of the two-phonon triplet [11]. In essence, we arrive at the same conclusion as that reached by Green [9] in ^{112}Cd ; fragmentation of the three-phonon strength is not the answer to the lack of $E2$ strength in decays from 3-phonon to 2-phonon states.

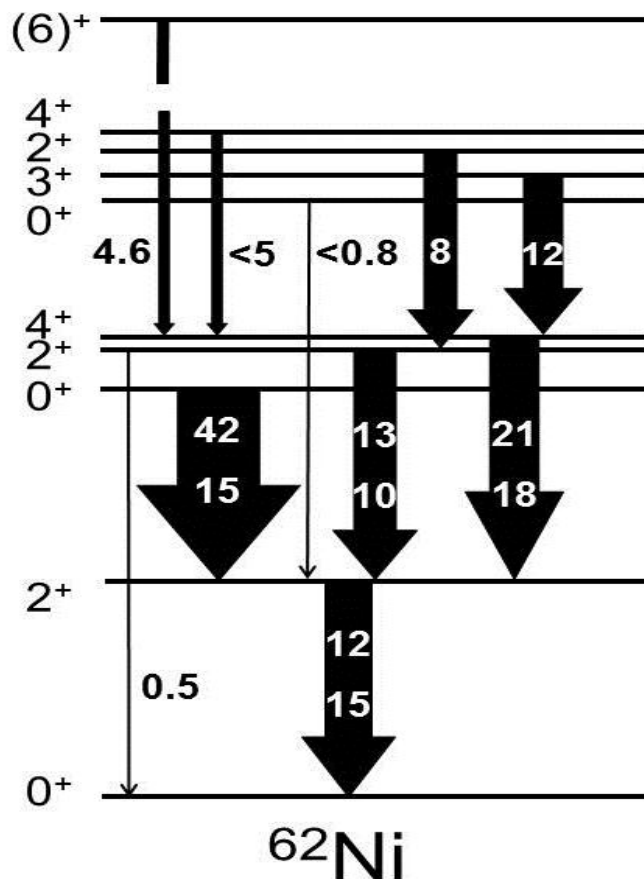


Figure 3. Level scheme of ^{62}Ni from the $(n,n'\gamma)$ reaction [11]. Experimentally determined $B(E2)$ s in W.u. (upper values on the transition arrows) and the results of shell model calculations (lower values on the arrows) for one-phonon and two-phonon states are shown. The uncertainty of the transition rate for the decay of the first excited 0^+ state is large, $B(E2;0^+ \rightarrow 2^+) = 42 \pm 23$ W.u. Only the experimental values are shown for the three-phonon candidates.

5. Conclusions

Examples of nuclei which appear to be nearly spherical vibrators by considering only the level energies are presented; however, when $E2$ transition probabilities are examined, the vibrational phonon picture fails to account for the observed decays. This failure becomes apparent for the three-phonon states and, frequently, even for the two-phonon excitations. Fragmentation of the $E2$ strength among other states of the same spin-parity does not appear to address this dilemma, and one must question whether robust examples of a nearly spherical quadrupole vibrator exist.

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