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Dynamics in Nuclei

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Abstract. The nucleus is a complex many-body system with some remarkable emergent collective properties of multiple nucleons acting together. Bohr and Mottelson [1] provided a description of collective motion in nuclei based on geometrical shapes with superimposed oscillations around those shapes. Later, Lie algebras and symmetries were used to describe nuclear dynamics [2] , followed by advances in the shell model approach [3] with new effective nucleon-nucleon two- and three-body interactions, and more recently with Hartree-Fock-Bogoliubov approximations within the extended generator coordinate method [4]. Yet, the underlying science question has remained the same. In nuclei, where there is explicit deformation in the ground state, "are the low-lying 0^+ states collective vibrations built on the ground state or are they minima of a coexisting shape?" Ref. [4] has shown that for a significant percentage of $K = 0^+$ excitations built on the deformed ground state (g.s.) should, in fact, be a collective vibration. The question has remained open due to sufficiently convincing experimental data with lifetimes, transfer reaction cross sections, and $E0$ transitions [5]. This paper summarizes the experimental situation regarding the lifetimes of 0^+ states.

1. Introduction

The nucleus is a complex many-body system with some remarkable emergent properties of multiple nucleons acting together to result in what can be described as superimposed oscillations of the nucleus around that shape. This resulted in the 1975 Physics Nobel Prize to Bohr, Mottelson, and Rainwater [1]. Later, Lie algebras and symmetries were highly successful in describing the observed dynamics within group theory representations [2] describing limits of nuclear collective behavior and resulting in predictions that explained the connection of the low-lying excited bands in deformed nuclei. Hence, in the ensuing four decades, many other theoretical and experimental developments have been made including the implementation of new effective nucleon-nucleon two- and three-body interactions within the shell model [3], and more recently with Hartree-Fock-Bogoliubov approximations within the extended generator coordinate method [4]. Yet, the underlying science question has remained the same. In nuclei, where there is explicit deformation in the ground state, "are the 0^+ states collective vibrations built on the ground state or are they minima of a coexisting shape?" The shapes that occur in the low-energy part of the spectra of nuclei can be described by a quadrupole ($\lambda = 2$) deformation in nature, resulting in two types of vibrations in deformed nuclei: β and γ oscillations, the latter breaking axial symmetry with a symmetry axis projection of $K^\pi = 2^+$. The γ vibration is characterized as the first $K^\pi = 2^+_1$, or 2^+_γ band. The transition probabilities across the deformed rare-earth region of nuclei is typically in the order of a few Weisskopf units $[B(E2 : 2^+_\gamma \rightarrow 0^+_{g.s.})]$ (W.u.) [6].

The story however is different for the K=0^+ excitations [4]. A significant percentage of them are collective vibrations and built on the deformed g.s. The absence of collective excitations in nuclei would uniquely distinguish nuclei in the quantum world of atoms, molecules, etc.

This question has remained mostly unresolved in nuclear physics due to the lack of sufficiently comprehensive experimental data with lifetimes, transfer reaction cross-sections, and $E0$ transitions [5].

Experiments carried out at the high precision Q3D spectrometer of the University of Munich have revolutionized nuclear structure studies by showing that there are tens of low-lying excited $K^\pi = 0^+$ states [7, 8] below the pairing gap in well-deformed nuclei. Figure 1 summarizes the results of the various Q3D experiments. There are several 0^+ states observed in the rare-earth nuclei (Sm, Gd, Dy, Er, Yb, and Hf). In the ^{154}Gd nucleus, there are sixteen 0^+ states identified, in the ^{162}Dy nucleus, there are twelve 0^+ states reported [8], while in the ^{168}Er case, there are fifteen 0^+ states identified. The origin and characterization of these states remain an open challenge, and it is the observation of so many $K^\pi = 0^+$ states that have revitalized the discussion about the viability of vibrational excitations.

Following the remarkable Q3D measurements, we have measured the lifetimes of the observed 0^+ states where possible. From the results of our work, we present examples of double-phonon $\gamma\gamma$, $\beta\beta$, and a $\beta\gamma$ vibration.

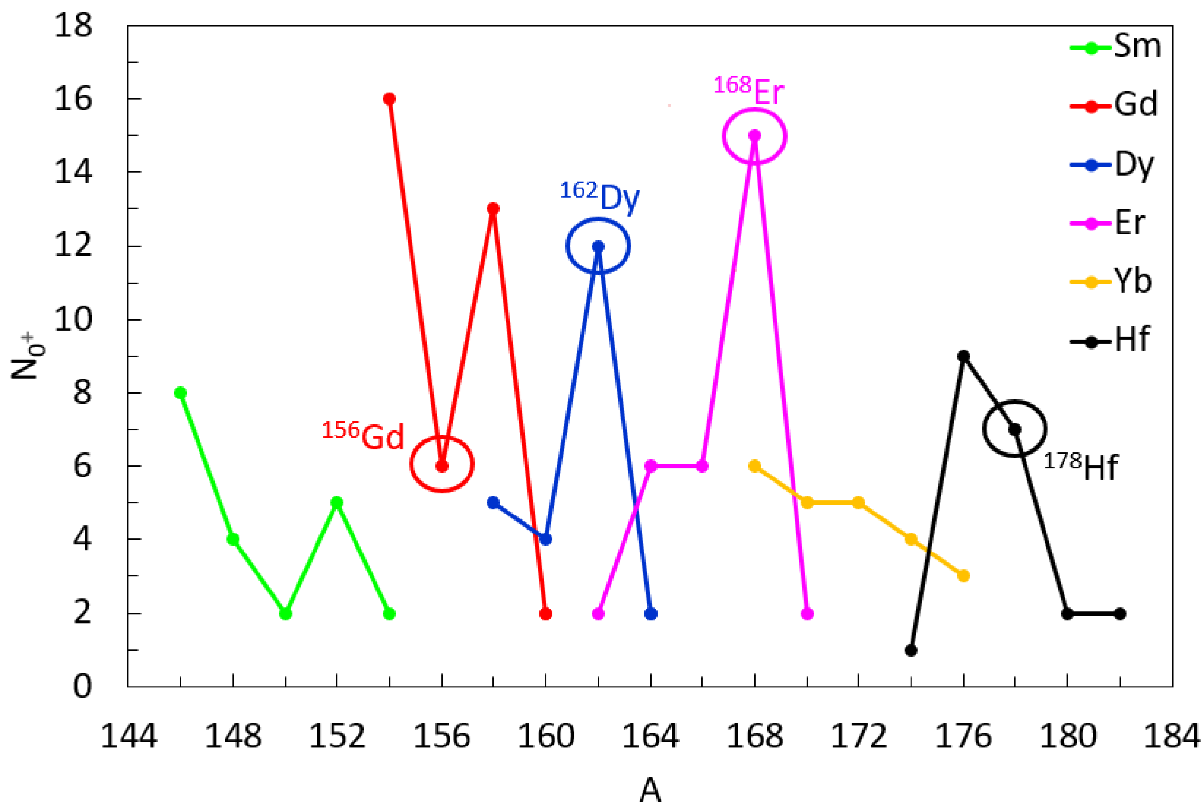

Figure 1. (Color online) The confirmed and tentative 0^+ states observed in several rare-earth nuclei (Sm, Gd, Dy, Er, Yb, & Hf).

2. Experiments

The lifetime measurements reported here include the GRID technique [9, 10]. The technique involves the measurement of γ-line widths following neutron capture. Experiments have been carried out at the Institute Laue-Langevin (ILL) neutron High Flux Reactor in Grenoble, France. They also include results from the DSAM technique [11, 12, 13] which involves the $(n, n'\gamma)$ reaction at the University of Kentucky Accelerator Laboratory (UKAL).

2.1. GRID

The GRID technique was used to measure the level lifetimes in ^{162}Dy and ^{156}Gd [6, 14] at the High Flux Reactor at the Institut Laue-Langevin (ILL) in Grenoble, France. The GRID technique [10, 15] is based on precisely measuring the width of a decaying gamma-ray using perfect crystals. The initial recoiling velocity of the nucleus results in a broadening of the width of a given gamma-ray emitted in flight. Knowing the slowing down process from simulations, the nuclear level lifetimes are extracted. The recoiling velocities are typically in the 10^{-4}c to 10^{-6}c range which results in a few eV broadening of that γ-ray. This precise measurements of the energy or wavelength of the γ rays are possible with Si or Ge perfect crystal diffraction.

2.2. $n, n'\gamma$

Level lifetimes for ^{162}Dy [16] and ^{168}Er [17] nuclei have been measured with inelastic neutron scattering at the University of Kentucky Accelerator Laboratory (UKAL). Measurements include γ-ray excitation functions and angular distributions. The emitted γ rays are usually measured with a $\leq$50% efficient HPGe detector suppressed by a BGO shield [11].

3. Results

3.1. ^{156}Gd

The rare-earth deformed region includes the Gd isotopes. The $R_{4^+/2^+}$ ratio is 3.24 in the ^{156}Gd nucleus. The spectra in the low-lying part of the excitation spectra of this nucleus is well known up to an excitation energy of 2.35 MeV. In this range of energy, there are six excited $K^\pi = 0^+$ bands, where four of them are below the 2 MeV pairing gap. The low-lying level scheme of ^{156}Gd is shown in fig. 2.

Two of the $K^\pi = 0^+$ bands in this nucleus are connected to the ground state band. Transitions from the one $K^\pi = 0^+_2$ band at 1049.5 keV are more collective than the ones from the other $K^\pi = 0^+_3$ band at 1168.2 keV. Plotting the moments of inertia for the various $K^\pi = 0^+$, the $K^\pi = 2^+$, and the $K^\pi = 4^+$ bands are very informative. It appears that all the bands except the $K^\pi = 0^+_3$ band at 1168.2 keV have nearly identical moments of inertia with the ground state band. This is evidence of collectivity built on the ground state for all of the bands except the $K^\pi = 0^+_3$ band [17]. The transition probabilities calculated for transitions from the $K^\pi = 2^+$ band to the ground state band also support the assignment of this individual band as the γ band. The $K^\pi = 0^+_4$ and the $K^\pi = 4^+_1$ bands that are at 1715.1 keV and 1510.6 keV, respectively, show strong connections to the $K^\pi = 2^+$ γ band. This is evidence of a second set of two-phonon $\gamma\gamma$ vibrational excitations although the anharmonicities are very different when compared with the data for the ^{166}Er nucleus.

3.2. ^{162}Dy

Similarly, our new measurements of lifetimes in the ^{162}Dy nucleus allow us to say that the K^π=0^+ excitation at 1400.2 keV is, in fact, the β vibrational excitation. The earlier assumption that this band is perhaps the two-phonon $\gamma\gamma$ vibration is disputed. The new measurements point to significant collectivity above the pairing gaps. Specifically, a 4^+ state at 2180.6 keV with B($E2$)=8.4 W.u. to the K^π=2^+ γ band showing fragmentation of the K^π=4^+ strength to

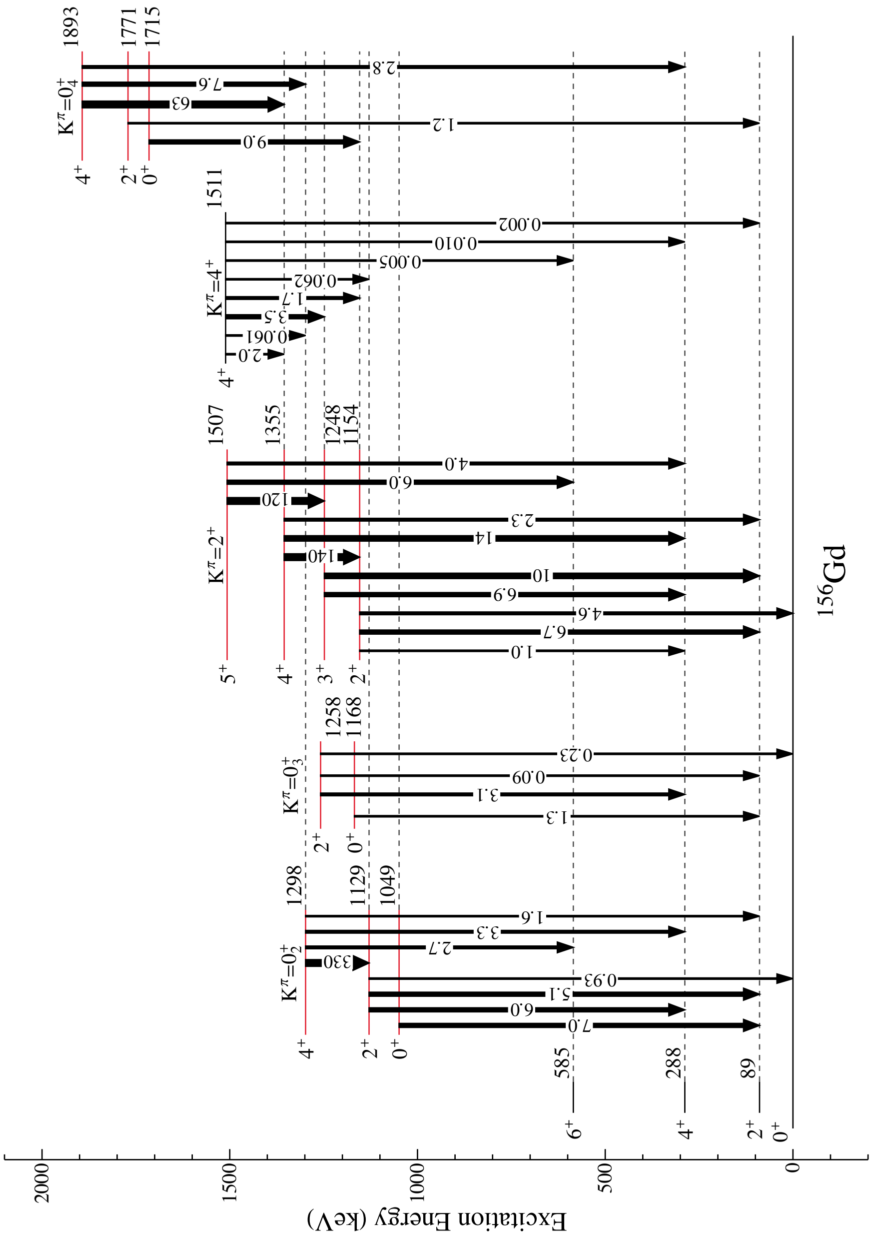

Figure 2. The ^{156}Gd level scheme with levels with new lifetimes measurements. The GRID values are displayed with the use of a ratio of $0.6 \times \tau_{\max}$ of the GRID range. This is described in the text. The level with $K^{\pi} = 4^{+}$, $J^{\pi} = 4^{+}$ was measured earlier by coulomb excitation. We display widths of transitions in proportion the transition probability values in W.U.

Table 1. Ratios of B($E2$) values and Energies in comparison to theoretical values. There are two values if fragmentation is observed and measured.

Ratios	^{156}Gd	^{162}Dy	^{168}Er	Theory
$E(4^+_{\gamma\gamma})/E(2^+_\gamma)$	1.31	1.73; 2.5	2.5	2.0
$E(0^+_{\gamma\gamma})/E(2^+_\gamma)$	1.49	1.6		2.0
$E(2^+_{\beta\gamma})/E(2^+_\gamma)$		2.5		≈ 2.0
$B(E2{:}4^+_{\gamma\gamma} \to 2^+_\gamma)/B(E2{:}2^+_\gamma \to 0^+_{g.s})$	0.39	14±9; 1.8		2.78
$B(E2{:}0^+_{\gamma\gamma} \to 2^+_\gamma)/B(E2{:}2^+_\gamma \to 0^+_{g.s})$	1.96			5.0
$B(E2{:}2^+_{\beta\gamma} \to 2^+_\gamma)/B(E2{:}2^+_\gamma \to 0^+_{g.s})$		1.1		1.43

the $K^\pi=2^+$ band. This is similar to the case in ^{166}Er [18]. Also, a state at 2231.0 keV has a B($E2$)=5.1 W.u transition to the same $K^\pi=2^+$ band, indicating that it may be the first example of a two phonon $\beta\gamma$ vibration. Fig. 3 shows the part of the level scheme of interest.

3.3. ^{168}*Er*

The lifetimes and the associated B($E2$) values are shown in Fig. 4. In this nucleus, we report on the collectivity of the third excited 0^+ state. There is once again, a strong similarity between the ^{166}Er case and the ^{168}Er nucleus. It is once again, the fourth 0^+_4 state that carries the collectivity. The theoretical predictions from Ref. [4] indicate that the collectivity to the ground state should be at the at 1.818 MeV which corresponds to the third excited $K^+=0^+$ state [17].

4. Discussion

The lifetimes of various deformed nuclei have been measured and interesting characteristics emerge for the 0^+ bands. In the ^{156}Gd, there are two $K^\pi = 0^+$ bands low in the excitation spectrum of the nucleus. The 0^+ band at 1049.5 keV is more collective than the $K^\pi = 0^+$ band at 1715.1 keV. This latter band is connected to the γ band or the first excited $K^\pi = 2^+$ band. In the ^{162}Dy nucleus, we find the fragmented strength of two-phonon $\gamma\gamma$ vibration and for the first time, a two-phonon $\beta\gamma$ vibration. In the ^{168}Er nucleus, there are several 0^+ states the one with the greater transition probabilities connecting to the ground state is the third excited $K^\pi = 0^+$ band. We present the information on single and double-phonon excitations in Table 1 in comparison with theory.

In this paper, we show an extensive set of lifetime measurements that complement transfer reaction data. In order to develop a comprehensive understanding of collectivity across this region of deformation, additional measurements of $E0$ transitions are required. Only then, do we hope to develop a consistent picture that can help us differentiate between collectivity and coexistence in nuclei.

5. Acknowledgments

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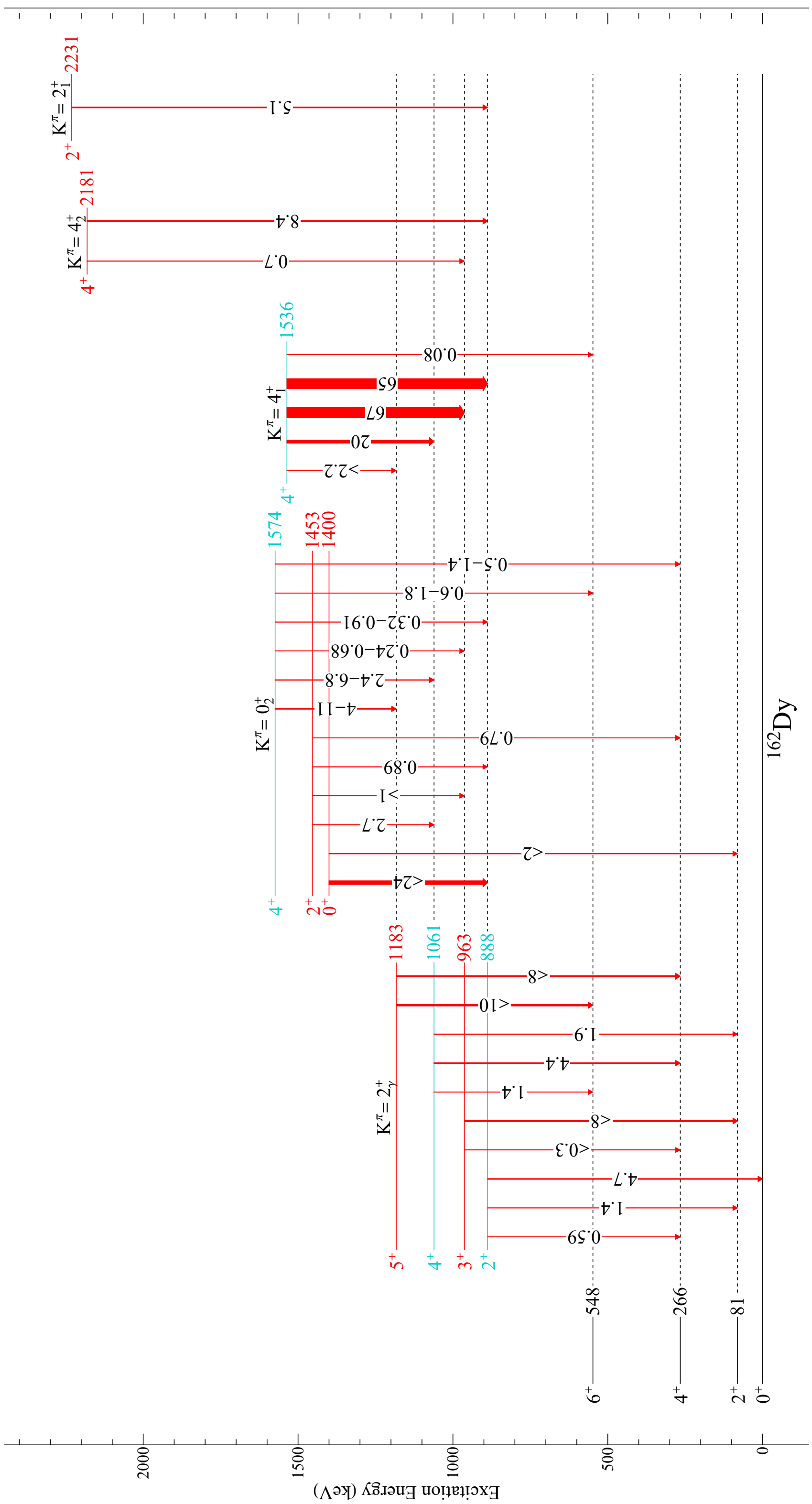

Figure 3. (Color online) Level scheme showing all observed transitions from the lowest-lying 2^+_{γ}, 0^+_2, and 4^+_1 band with all interband (K^{π}=J^+_i $\rightarrow$$K^{\pi}$=$2^+_{\gamma}$) decays. Levels with new lifetime measurements are drawn in red while those with an associated literature lifetime are drawn in turquoise (color online). The B($E2$) calculations are expressed in Weisskopf units (W.u.) and drawn in red. Intensities for transitions to the γ band are taken from [19]. Also shown is a tentative (2^+) state at 2231.0 keV with a strong decay to the 2^+_{γ} band.

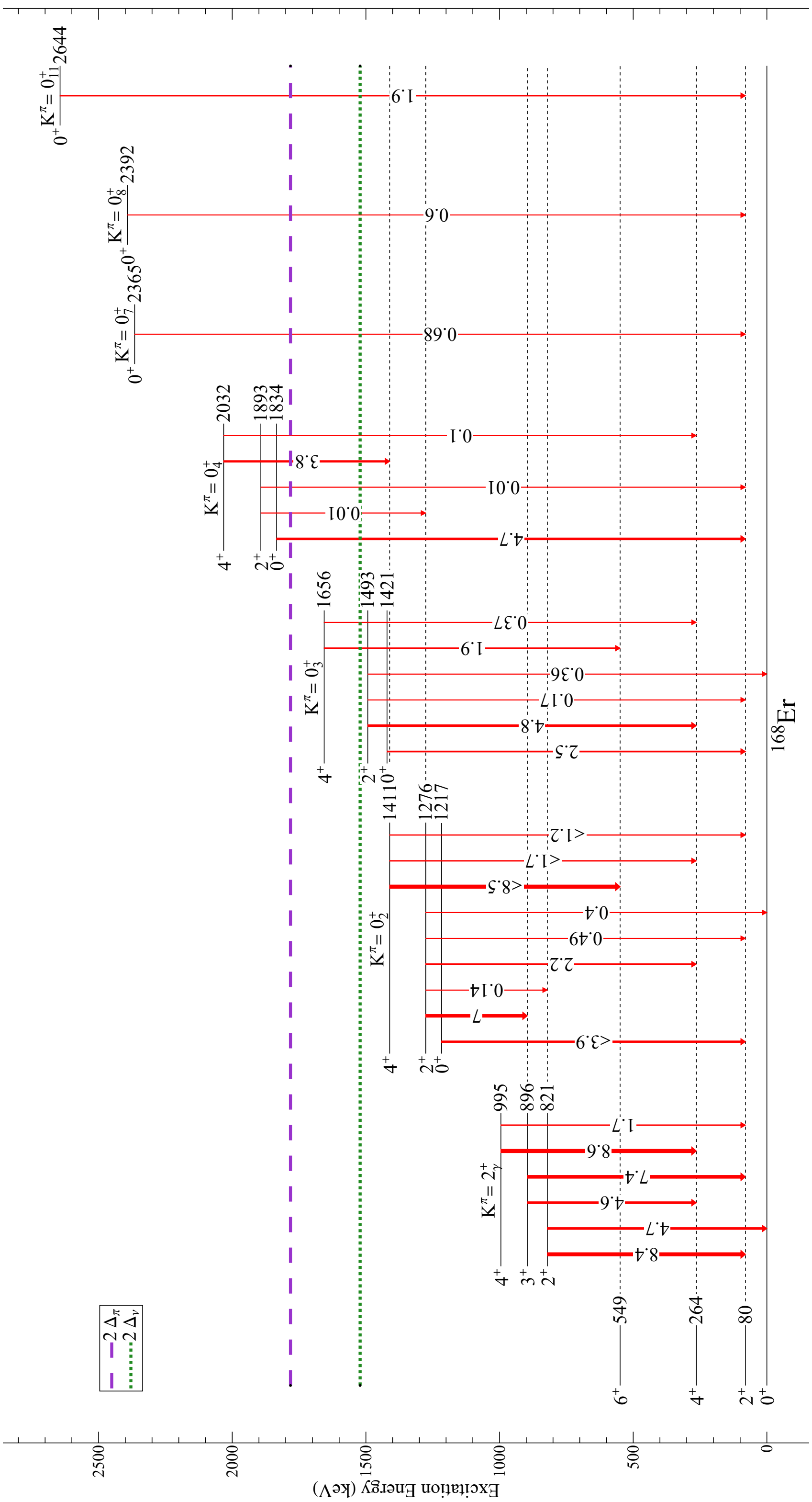

Figure 4. (Color online) Partial level scheme for the 0^+ bands identified and reported in Ref. [17] and discussed in this work. The solid arrows represent $E2$ transitions. The band labels are according to the (p, t) experiment labels [20]. The dotted horizontal lines are the two-neutron and two proton pairing gaps for ^{168}Er calculated using the formulas in Ref. [21] and masses from Ref. [22].