SHAPE COEXISTENCE AND ELECTRIC MONOPOLE TRANSITIONS

John L. Wood
School of Physics, Georgia Institute of Technology
Atlanta, Georgia 30332-0430, USA

Abstract

The evidence for a widespread association of electric monopole transitions with shape coexistence is reviewed.

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ENERGIES

ANTIBES (France) June 20 - 25, 1994

Edited by:

M. Vergnes - D. Goutte - P.H. Heenen - J. Sauvage

EDITIONS
FRONTIERES
Introduction

Shape coexistence in nuclei can be fairly judged to have advanced in status from an exotic rarity twenty years ago to a widespread feature\textsuperscript{10} of nuclear structure today. Possibly it occurs in all nuclei.

Unfortunately, it is not always easy to identify experimentally. In ideal circumstances it is clearly defined by, e.g., a rotational band with a small rotational constant and large intraband transition B(E2) values. More commonly, coexisting shapes are obscured by mixing. Mixing distorts the energy patterns of bands and results in decay patterns that conceal the characteristic cascade of E2 transitions expected for a deformed band.

However, mixing of configurations with different shapes can give rise to electric monopole (E0) transitions\textsuperscript{2-3}. There is accumulating evidence that E0 transitions widely occur in association with shape coexistence because of this mixing and constitute a signature for the occurrence of shape coexistence. This accumulating evidence is the focus of the present paper.

The association of E0 transitions with shape coexistence is particularly extensive in the neutron-deficient \( Z \sim 82 \) region. Experimental results from this region are used to illustrate the present discussion.

Shape Coexistence in the Neutron-Deficient \( Z \sim 82 \) Region

Shape coexistence has been established systematically in both doubly-even\textsuperscript{1-5} and odd-mass\textsuperscript{4,5} nuclei in the neutron-deficient Pt, Au, Hg, Tl, and Pb isotopes.

The evidence for shape coexistence in the even-Hg isotopes is the most clearcut. The systematics of the shape coexisting bands in the even-Hg isotopes are depicted in Fig. 1. The evidence in the even-Pt isotopes is more subtle. The systematics of the shape coexisting bands in the even-Pt isotopes are depicted in Fig. 2. Figures 3a,b show how the ground-state band in \( ^{194}\text{Pt} \) is identifiable as a structure which is more strongly deformed than the ground-state bands in other \( N = 106 \) isotones. However, this feature of \( ^{194}\text{Pt} \) is masked at low spin by mixing. The evidence in the even-Pb isotopes is more limited. The candidates for the \( I^\pi = 0^+, 2^+ \) members of the deformed bands in \( ^{192,194,196}\text{Pb} \) are shown in Fig. 4. Evidence for strongly-deformed bands has been reported recently.
Fig. 1. The systematics of strongly-deformed bands (filled circles) and weakly-deformed bands (open circles) in even-mass Hg isotopes. (The figure is adapted from ref.1).

Fig. 2. The systematics of strongly-deformed bands (filled circles) and weakly-deformed bands (open circles) in even-mass Pt isotopes. (The figure is taken from ref.1).
Fig. 3. Yrast band systematics in the $N = 106$ isotones illustrating the anomalous nature of $^{164}$Pt.
(a) excitation energies relative to the $8^+_1$ state (the deformed band in $^{186}$Hg is shown also).
(b) the rotational parameter $\kappa^2/2J$. (The figures are taken from ref.1).
also for $^{186,188}$Pb (ref. 9).

The evidence for shape coexistence in the Au and Tl isotopes is based on the observation of low-lying $h_{9/2}$ and $i_{13/2}$ intruder states. These states are expected to lie at high-excitation energy near closed shells where spherical nuclear shapes predominate. Their appearance at low excitation energy in the neutron-deficient Au (refs. 4,5,7,8) and Tl (refs. 4,5,9,10) isotopes is explained by invoking a larger deformation for these intruder states than for the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $h_{11/2}$ (non-intruder) states. The differences in deformation of the intruder states and non-intruder states is directly supported by lifetime data 11) for E2 transitions in the $^{185-189}$Au isotopes.

There is direct evidence of shape coexistence in $^{185}$Hg from optical hyperfine spectroscopy 12) which establishes an extremely large isomer shift for the mean-square charge radius of the ground state (which is deduced to be strongly deformed) and an $I^e = 13/2^+$ isomer (which is deduced to be weakly deformed). This result is a dramatic confirmation of the observation by Bonn et al. 13) of a sudden change in mean-square charge radii of the ground states of the neutron-deficient Hg isotopes between $^{187}$Hg and $^{185}$Hg and its interpretation 13) as a sudden onset of deformation. (It was the work of Bonn et al. which first indicated the presence of low-lying shape coexistence in this region.)

**Electric Monopole Transitions in the Neutron-Deficient Z – 82 Region**

Electric monopole transitions are a widespread feature of neutron-deficient Pt, Au, Hg, and Pb isotopes (to date, no E0 transitions have been observed in the Tl isotopes). The most dramatic examples of E0 transitions are in $^{184}$Pt and $^{185}$Pt. The low-lying band structure and associated E0 transitions observed 14) in $^{184}$Pt are shown in Fig. 5. Examples of $\gamma$-ray-gated $\gamma$ spectra and $\gamma$-ray-gated conversion-electron spectra supporting the E0 transitions shown in Fig. 5 are presented in Figs. 6a, b, and c. The low-lying levels associated with some of the E0 transitions observed 15) in $^{185}$Pt are shown in Fig. 7. Examples of $\gamma$-ray-gated conversion-electron spectra supporting some of the E0 transitions shown in Fig. 7 are presented in Fig. 8. It should be noted that six transitions in $^{185}$Pt have no observable 15) $\gamma$-decay strength (five of these six transitions are shown in Figs. 8a-d); further the 530 keV transition between the $3^+$ states at 940 and 1470 keV in
Fig. 4. Electromagnetic decay data for low-spin candidates of the deformed bands in $^{192-196}\text{Pb}$. (The figure is taken from ref.\textsuperscript{13}).

Fig. 5. The low-lying band structure and associated $E0$ transitions in $^{184}\text{Pt}$. (The figure is taken from ref.\textsuperscript{14}).
Fig. 6. Gamma-ray-gated $\gamma$ spectra and conversion-electron spectra supporting E0 transitions in $^{194}$Pt between: (a) the $2^+_1$ and $2^+_2$ states; (b) the $2^+_4$ and $2^+_2$ states; and (c) the $3^+_2$ and $3^+_1$ states. The $3^+_2 \rightarrow 3^+_1$ transition is pure E0 within the statistics of the data. (The figures are taken from ref. 14).
Fig. 7. The low-lying levels and pure E0 transitions in $^{185}$Pt. (The figure is taken from ref. 15).
Fig. 8. Gamma-ray gated $\gamma$ spectra and conversion-electron spectra supporting pure E0 transitions in $^{188}\text{Pt}$. (The figure is taken from ref.15).
Fig. 9. (a) The band structures in $^{185,187}$Au associated with E0 transitions. (b) Gamma-ray gated $\gamma$ spectrum and conversion-electron spectrum supporting an $11/2^- \rightarrow 11/2^-$ E0 transition in $^{185}$Au. (The figures are taken from ref. 17).

Fig. 10. The connection between the E0 transitions in $^{185,187}$Au and the E0 transitions in the neighboring even mass Pt and Hg isotopes for: (a) the $h_{9/2}$ particle states; (b) the $h_{11/2}$ hole states. (The figures are taken from ref. 17).
$^{184}$Pt has no observable $\gamma$-decay strength (see Fig. 6c). (An essentially identical pattern of E0 transitions to that seen$^{14}$ in $^{184}$Pt is evident$^{16}$ also in $^{186}$Pt.)

In $^{185,187}$Au a systematic pattern of E0 transitions is observed$^{17,18}$ in association with the $h_{11/2}$ states and the $h_{9/2}$ intruder states. This is depicted in Figs. 9a. The connection between the states in $^{185,187}$Au shown in Figs. 9a and coexisting states in $^{184,186}$Pt and $^{186,188}$Hg is shown in Figs. 10a,b. The implication of Figs. 10a,b is that in $^{185,187}$Au there are four different coexisting structures: two associated with the $h_{11/2}$ proton hole structure and two associated with the $h_{9/2}$ proton particle (intruder) structure.

Summaries of E0 transitions in association with shape coexistence in the $Z \sim 82$ region and other regions can be found in refs.$^{19,20}$

The Origin of E0 Transition Strength

The E0 strength parameter, $\rho$, is defined by

$$\rho_{\gamma} = \langle f | \sum_j e_j r_j^2 | i \rangle / e R^2,$$

where the sum is over nucleons, $e_j$ is the effective monopole charge of the jth nucleon, $e$ is the unit of electric charge, and $R^2 = (1.2 A^{1/3} \text{ fm})^2$ is the mean-square nuclear radius. Rates of E0 transitions are given by

$$\frac{1}{\tau(E0)} = \rho_{\gamma}^2 \sum_j \Omega_j(Z,E),$$

where $\tau(E0)$ is the lifetime for E0 decay and $\Omega_j(Z,E)$ is the electronic factor which depends on the nuclear charge, $Z$, and the transition energy, $E$, and $k$ labels the various processes by which the E0 transition occurs: $K$, $L_1$, $L_2$, $M_1$, ..., shell internal conversion and internal pair formation.

The strength of E0 transitions is greatest when the states $|i\rangle$ and $|f\rangle$ are linear combinations of two configurations, $|1\rangle$ and $|2\rangle$, such that the mean-square radii of $|1\rangle$ and $|2\rangle$ are very different. Thus (defining $\sum_j e_j r_j^2 = m(E0)$, $<f|m(E0)|i\rangle = M_{i\gamma}(E0)$),
$|i\rangle = \alpha |1\rangle + \beta |2\rangle$, $|f\rangle = -\beta |1\rangle + \alpha |2\rangle$,

and

$$M_{\gamma}(E0) = \alpha \beta <2|m(E0)|2\rangle - \langle 1|m(E0)|1\rangle + \alpha^2 <2|m(E0)|1\rangle - \beta^2 \langle 1|m(E0)|2\rangle$$

This reduces, in practice, to

$$M_{\gamma}(E0) = \alpha \beta \Delta <r^2>,$$

i.e., $M_{\gamma}(E0)$ is proportional to the mixing of the configurations ($\alpha$ and $\beta$) and the difference in their mean-square radii. This is a completely general result and is not dependent on any specific nuclear model. Evidently, $M_{\gamma}(E0)$ will be large whenever the initial and final states involve mixed configurations with very different mean-square radii such as would occur when shape coexistence is present. Caution is needed, however, because configurations with very different mean-square radii can occur with near-degenerate energies as a result of the spin-orbit depression of high-$j$ orbits and as a result of deformed mean-field effects.

A single-particle unit of strength for $\rho^2$ of 0.5 $\text{A}^{-2/3}$ has been given by Bohr and Mottelson$^{21}$.

A Brief Survey of E0 Strength

The E0 strength of transitions is conventionally quoted as $\rho^2 \times 10^3$. Of greatest interest are answers to the questions: What are the strongest and weakest E0 transitions and where do they occur?

The weakest E0 known is from the decay of the "fission" isomer in $^{238}\text{U}$. This is shown in Fig. 11. The next weakest E0 transition known is in $^{58}\text{Ni}$. This is dramatized by the fact that $^{58}\text{Ni}$ also possesses a strong E0 transition. These details for $^{58}\text{Ni}$ are shown in Fig. 12. The behavior of $^{238}\text{U}$ reveals that shape coexistence alone does not generate E0 strength (mixing also is necessary). The behavior of $^{58}\text{Ni}$ contrasts a mixing of neutron configurations from the same shell (similar mean-square radii) and a mixing of proton configurations from different shells: the $0^+$ state at 3531 keV in $^{58}\text{Ni}$ involves a proton pair excitation across the $Z = 28$ shell. The weakness of the E0 transition
Fig. 11. Electromagnetic decay data for the fission isomer in $^{238}$U. (The figure is taken from ref.1).}

Fig. 12. Electric monopole transitions in $^{58,60,62}$Ni. The E0 transition between the $0_2^+$ and $0_1^+$ states in $^{58}$Ni is second in slowness only to the E0 decay of the fission isomer in $^{238}$U. The E0 transition between the $0_3^+$ and $0_1^+$ states in $^{58}$Ni is one of the fastest known. The E0 data are from ref.22 and the proton-pair excitation ($\Pi 2p$-$2h$) identifications are from ref.23.
Fig. 13. Electromagnetic decay data for $N = 58$ isotones. The E0 transition between the $0_3^+$ and $0_2^+$ states in $^{56}$Sr is the fastest known for $A > 56$. The numbers in circles are in-band/out-of-band $B(E2)$ ratios. The data are taken from refs.\textsuperscript{25,26,27} and Nuclear Data Sheets.

Fig. 14. Electromagnetic decay data for $N = 60$ isotones, cf. Fig. 13. The figure is adapted from ref.\textsuperscript{1)} with additional data from ref.\textsuperscript{26} and Nuclear Data Sheets.
Fig. 15. Electromagnetic decay data for $^{110,112,114}\text{Cd}$, cf. Fig. 13. The data are taken from refs.$^{128,29}$ and Nuclear Data Sheets. (See also Fig. 3.1.7 in ref.$^1$).

Fig. 16. Electromagnetic decay data for $^{114-120}\text{Sn}$, cf. Fig. 13. The data are taken from refs.$^{130}$ and Nuclear Data Sheets.
Fig. 17. Electromagnetic decay data for $N = 88$ isotones, cf. Fig. 13. The data are taken from ref.\textsuperscript{31} and Nuclear Data Sheets.

Fig. 18. Electromagnetic decay data for $N = 90$ isotones, cf. Fig. 13. The data are taken from ref.\textsuperscript{32} and Nuclear Data Sheets.
involving the neutron configurations is in part due to the very small neutron monopole effective charge. This translates into a very small core polarizability in \( ^{58}\text{Ni} \). Core polarizability increases with mass. Thus, the \( \rho^2 (0^+_2 \rightarrow 0^+_1) \) observed\(^{24}\) in \( ^{206}\text{Pb} \) is 150 times larger than \( \rho^2 (0^+_2 \rightarrow 0^+_1) \) in \(^{58}\text{Ni} \).

The strongest E0 transitions are observed between 0\(^+\) states in the lightest nuclei. Typical \( \rho^2 \times 10^3 \) values\(^{25}\) are in the range 150 - 500. In part, these large values reflect the presence of multiparticle-multihole configurations at low energy in light nuclei (see, e.g., ref.\(^1\)). For nuclei with \( A > 56 \), the strongest E0 transitions are observed in the vicinities of: \(^{98,100}\text{Zr} \) (cf. Figs. 13,14), \(^{114}\text{Cd} \), \(^{116}\text{Sn} \) (cf. Figs. 15,16), and \(^{152,154}\text{Gd} \) (cf. Figs. 17,18). These nuclei all lie in regions of well-established shape coexistence\(^1\).

Unfortunately, lifetime data (of 0\(^+\) states) in the vicinity of \( ^{184}\text{Pt} \) are very limited. There are very recent measurements\(^{33}\) for \(^{186,188}\text{Hg} \). These indicate little mixing in \( ^{188}\text{Hg} \) and (at least) moderate mixing in \( ^{186}\text{Hg} \), with \( \rho^2 \times 10^3 \) values of 7.7 and \( \geq 32 \), respectively, for the \( 0^+_2 \rightarrow 0^+_1 \) transitions.

Of particular interest are a number of regions where \( \rho^2 (0^+_3 \rightarrow 0^+_2) \gg \rho (0^+_3 \rightarrow 0^+_1) \) (cf. Figs. 13,15-18) suggesting that 0\(^+_2 \) and 0\(^+_3 \) states are mixed configurations with very different mean-square charge radii. All of these regions exhibit shape coexistence.

There is a serious lack of information on \( \rho^2 \) values in deformed nuclei. A major effort is needed to systematize \( \rho^2 \) values in deformed nuclei.

This work is based on an extensive collaboration with E. F. Zganjar (Louisiana State University) and K. Heyde (Rijksuniversiteit, Gent). Support of the present work has been in part by U. S. Department of Energy Grant DE-FG05-87ER 40330 and in part by NATO Grant RG-92/0011/R.

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