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SHAPE COEXISTENCE AND ELECTRIC MONOPOLE TRANSITIONS

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Abstract

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

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Introduction

Shape coexistence in nuclei can be fairly judged to have advanced in status from an exotic rarity twenty years ago to a widespread feature¹⁾ 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^{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^{1,5)} and odd-mass^{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 ^{184}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 ^{184}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 ^{184}Pt .

(a) excitation energies relative to the 8_1^+ state (the deformed band in ^{186}Hg is shown also).

(b) the rotational parameter $K^2/2J$. (The figures are taken from ref.¹⁾).

also for $^{186,188}\text{Pb}$ (ref.⁶⁾).

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 data¹¹ for E2 transitions in the $^{185-189}\text{Au}$ isotopes.

There is direct evidence of shape coexistence in ^{185}Hg from optical hyperfine spectroscopy¹² 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 $I^\pi = 13/2^+$ 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 interpretation¹³ 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 $Z \sim 82$ 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 observed¹⁴ in ^{184}Pt are shown in Fig. 5. Examples of γ -ray-gated γ spectra and γ -ray-gated conversion-electron spectra supporting the E0 transitions shown in Fig. 5 are presented in Figs. 6 a, b, and c. The low-lying levels associated with some of the E0 transitions observed¹⁵ in ^{185}Pt are shown in Fig. 7. Examples of γ -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 observable¹⁵ γ -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.¹⁾).

Fig. 5. The low-lying band structure and associated E0 transitions in ^{184}Pt . (The figure is taken from ref.¹⁴⁾).

Fig. 6. Gamma-ray-gated γ spectra and conversion-electron spectra supporting E0 transitions in ^{184}Pt between: (a) the 2_3^+ and 2_1^+ 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 γ spectra and conversion-electron spectra supporting pure E0 transitions in ^{185}Pt . (The figure is taken from ref.¹⁵).

Fig. 9. (a) The band structures in $^{185,187}\text{Au}$ associated with $E0$ transitions. (b) Gamma-ray gated γ 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 $^{185,187}\text{Au}$ 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 γ -decay strength (see Fig. 6c). (An essentially identical pattern of E0 transitions to that seen¹⁴⁾ in ^{184}Pt is evident¹⁶⁾ also in ^{186}Pt .)

In $^{185,187}\text{Au}$ 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 $^{185,187}\text{Au}$ shown in Figs. 9a and coexisting states in $^{184,186}\text{Pt}$ and $^{186,188}\text{Hg}$ is shown in Figs. 10a,b. The implication of Figs. 10a,b is that in $^{185,187}\text{Au}$ 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, ρ , is defined by

$$\rho_v = \langle f | \sum_j e_j r_j^2 | i \rangle / eR^2,$$

where the sum is over nucleons, e_j is the effective monopole charge of the j th 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

$$\frac{1}{\tau(E0)} = \rho_v^2 \sum_k \Omega_k(Z, E),$$

where $\tau(E0)$ is the lifetime for E0 decay and $\Omega_k(Z, E)$ 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 $\sum_j e_j r_j^2 \equiv m(E0)$, $\langle f | m(E0) | i \rangle \equiv M_{if}(E0)$),

$$|i\rangle = \alpha |1\rangle + \beta |2\rangle, |f\rangle = -\beta |1\rangle + \alpha |2\rangle,$$

and

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

This reduces, in practice, to

$$M_{if}(E0) = \alpha \beta \Delta \langle r^2 \rangle,$$

i.e., $M_{if}(E0)$ is proportional to the mixing of the configurations (α and β) and the difference in their mean-square radii. This is a completely general result and is not dependent on any specific nuclear model. Evidently, $M_{if}(E0)$ 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 p^2 of $0.5 A^{-2/3}$ has been given by Bohr and Mottelson²¹⁾.

A Brief Survey of E0 Strength

The E0 strength of transitions is conventionally quoted as $p^2 \times 10^3$. 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}U . This is shown in Fig. 11. The next weakest E0 transition known is in ^{58}Ni . This is dramatized by the fact that ^{58}Ni also possesses a strong E0 transition. These details for ^{58}Ni are shown in Fig. 12. The behavior of ^{238}U reveals that shape coexistence alone does not generate E0 strength (mixing also is necessary). The behavior of ^{58}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}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 $^{58,60,62}\text{Ni}$. 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 ^{96}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.^{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.¹⁾ with additional data from ref.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.^{1,28,29} 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.^{1,30} and Nuclear Data Sheets.

Fig. 17. Electromagnetic decay data for N = 88 isotones, cf. Fig. 13. The data are taken from ref.³¹⁾ and Nuclear Data Sheets.

Fig. 18. Electromagnetic decay data for N = 90 isotones, cf. Fig. 13. The data are taken from ref.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}Ni . Core polarizability increases with mass. Thus, the $\rho^2 (0_2^+ \rightarrow 0_1^+)$ observed²⁴⁾ in ^{286}Pb is 150 times larger than $\rho^2 (0_2^+ \rightarrow 0_1^+)$ in ^{58}Ni .

The strongest E0 transitions are observed between 0^+ states in the lightest nuclei. Typical $\rho^2 \times 10^3$ values²⁵⁾ 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}Cd , ^{116}Sn (cf. Figs. 15,16), and $^{152,154}\text{Gd}$ (cf. Figs. 17,18). These nuclei all lie in regions of well-established shape coexistence¹⁾.

Unfortunately, lifetime data (of 0_2^+ states) in the vicinity of ^{184}Pt are very limited. There are very recent measurements³³⁾ for $^{186,188}\text{Hg}$. These indicate little mixing in ^{188}Hg and (at least) moderate mixing in ^{186}Hg , with $\rho^2 \times 10^3$ values of 7.7 and ≥ 32 , respectively, for the $0_2^+ \rightarrow 0_1^+$ transitions.

Of particular interest are a number of regions where $\rho^2(0_3^+ \rightarrow 0_2^+) \gg \rho^2(0_3^+ \rightarrow 0_1^+)$ (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 ρ^2 values in deformed nuclei. A major effort is needed to systematize ρ^2 values in deformed nuclei.

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