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ELECTRIC MONOPOLE TRANSITIONS: WHAT THEY CAN TELL US ABOUT NUCLEAR STRUCTURE

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Abstract

A brief survey of E0 strength in a number of nuclei in different regions of the nuclear chart is presented. The connection between E0 strength and shape coexistence is reviewed. Nuclear structure information obtained from measurements of electric monopole transitions in ^{184}Pt and ^{187}Au is discussed. Plans for future experiments utilizing radioactive ion beams and E0 internal-pair-formation is presented.

Introduction

There are many interesting and important aspects of nuclear structure associated with the electric monopole transition (E0). The mixing of configurations with different mean-square radii gives rise to E0 transitions that can serve as signatures for the occurrence of shape coexistence.[1] It has also been suggested[2] that the draining of superdeformed bands, which mix (even slightly) with other configurations, proceeds via enhanced E0 transitions. There is recent indirect evidence for this.[3] The E0 transition can also provide information on the nature of excitations in terms of their particle-hole structure. Among other things, E0 transitions are associated with isotope and isomer shifts, compressibility of nuclear matter, monopole degrees of freedom, and radial density oscillations.

The E0 Transition Strength

The E0 strength parameter for a transition from state $|i\rangle$ to state $|f\rangle$, ρ_{if}, is defined by

$$\rho_{if} = \langle f | \sum_j e_j r_j^2 | i\rangle / eR^2 \equiv \langle f | m(E0) | i\rangle / eR^2 \equiv M_{if}(E0)/eR^2$$

where e_j is the effective monopole charge of the j^{th} nucleon located at r_j, e is the unit of electric charge, and $R = 1.2A^{1/3}\,fm$ is the nuclear radius. If states $|1\rangle$ and $|2\rangle$ with different $\langle r^2\rangle$ mix, then $|i\rangle = \alpha|1\rangle + \beta|2\rangle$, $|f\rangle = -\beta|1\rangle + \alpha|2\rangle$ and

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

Thus, $M_{if}(E0)$ is proportional to the mixing of the configurations and the difference in their mean-square radii. This is a general result, not dependent on a specific nuclear model. $M_{if}(E0)$ will be large whenever the initial and final states involve mixed configurations with very different $\langle r^2\rangle$, as occurs when shape coexistence is present. $M_{if}(E0)$ is more sensitive to $\Delta\langle r^2\rangle$ than to the amount of mixing. For example: for maximum mixing $\alpha\beta=0.5$, for 10% mixing $\alpha\beta=0.3$, and for 1% mixing $\alpha\beta=0.1$. Mixing is essential to the generation of E0 strength however, and the decay of the superdeformed band at 2558 keV in ^{238}U provides an excellent example.[4] The E0 transition between the 225 ns 0^+ fission isomer at 2558 keV and the 0^+ ground state in ^{238}U is the slowest E0 transition known ($\rho^2=1\times10^{-9}$).

Electric monopole transition rates are given by

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

where $\tau(E0)$ is the lifetime for E0 decay and $\Omega_k(Z,E)$ is the electronic factor which depends upon the nuclear charge, Z, and the transition energy, E. The index k spans the various processes by which the E0 transition can proceed (K, L_1, L_2 ... shell internal conversion or internal-pair formation). The E0 strength parameter is conventionally quoted in units of $\rho^2 x 10^3$.

E0 Strength and Shape Coexistence

One of the earliest clear-cut examples of shape coexistence was provided by the neutron deficient even-even Hg isotopes[5], several of which are depicted in fig. 1. The ground-state band of these isotopes is based on a proton 2h configuration, while the deformed excited band is based on a proton 2p-4h configuration which arises from the excitation of a proton-pair into the intruder $h_{9/2}$ orbital. In addition to the electric monopole transitions between the 0^+ states in these nuclei, the E0 strength is enhanced for the $\Delta I=0$, $I\neq 0$ transitions between the shape coexisting configurations. This is a common feature identified with shape coexistence. The lifetimes of the 0_2^+ states in these isotopes are difficult to measure because they fall in the picosecond range and have no γ-ray branching to the 2_1^+ state. However, recent measurements[6] have yielded half-lives of 204^{+147}_{-45} ps and ≤ 72 ps which correspond to $\rho^2(E0) \times 10^3$ values of $7.7^{+2.2}_{-3.2}$ and ≥ 32 for ^{188}Hg and ^{186}Hg, respectively. Additionally, the mixing of the bands in ^{188}Hg (1%), when computed using the experimental[6] ρ^2(E0) and a deformation of $\beta=0.25$ for the 0_2^+ band, is consistent with the mixing obtained using the experimental[6] ρ^2(E0) and an experimental value[7] for $\Delta\langle r^2\rangle$.

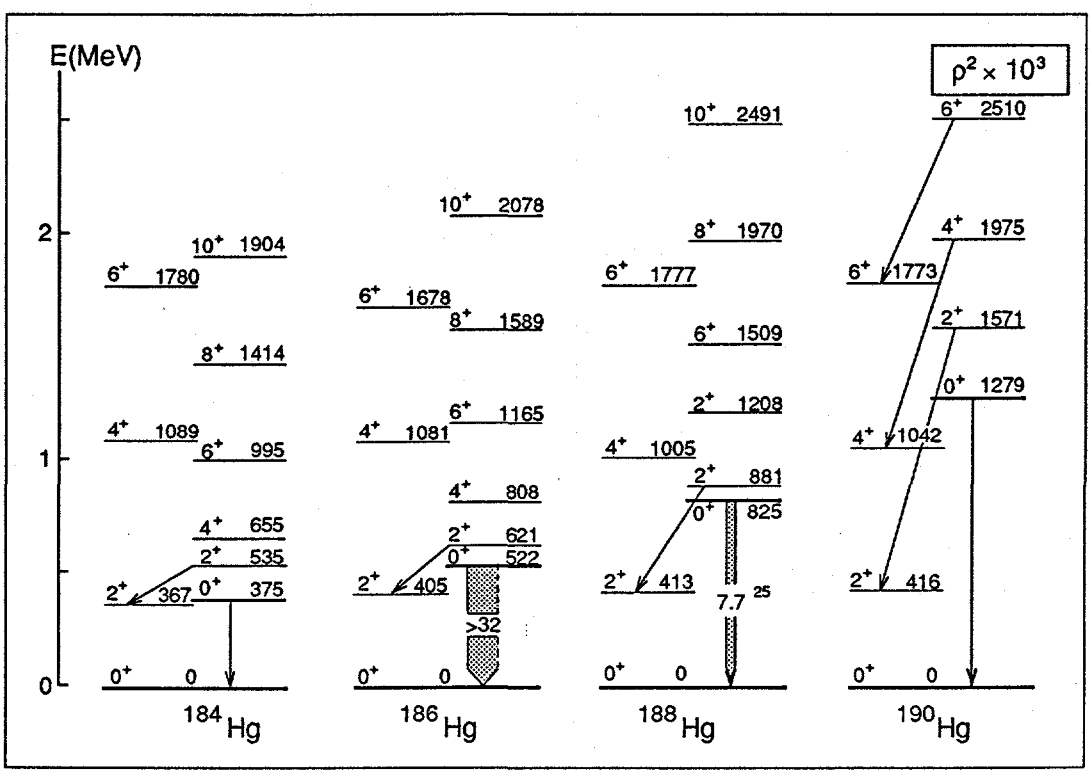

Fig. 1. Weakly deformed (0_1^+) and strongly deformed (0_2^+) bands in several even-even Hg isotopes (see ref. 5 for complete details). The ρ^2 values (units $\rho^2 \times 10^3$) are taken from ref. 6.

The tin and cadmium isotopes also provide a dramatic illustration of shape coexistence. In the Sn isotopes, bands of states connected by low-energy transitions with relative B(E2)s that support excited deformed bands are shown in Fig. 2. Exceptionally strong E0 strength from the excited deformed structures is observed. The B(E2) values for transitions between low-lying states in ^{114}Cd indicate vibrational and triaxial-deformed structures. The pattern of E0 transitions shown in Fig. 3, weak on the left and strong on the right, clearly indicate which transitions involve the greatest $\Delta\langle r^2\rangle$.

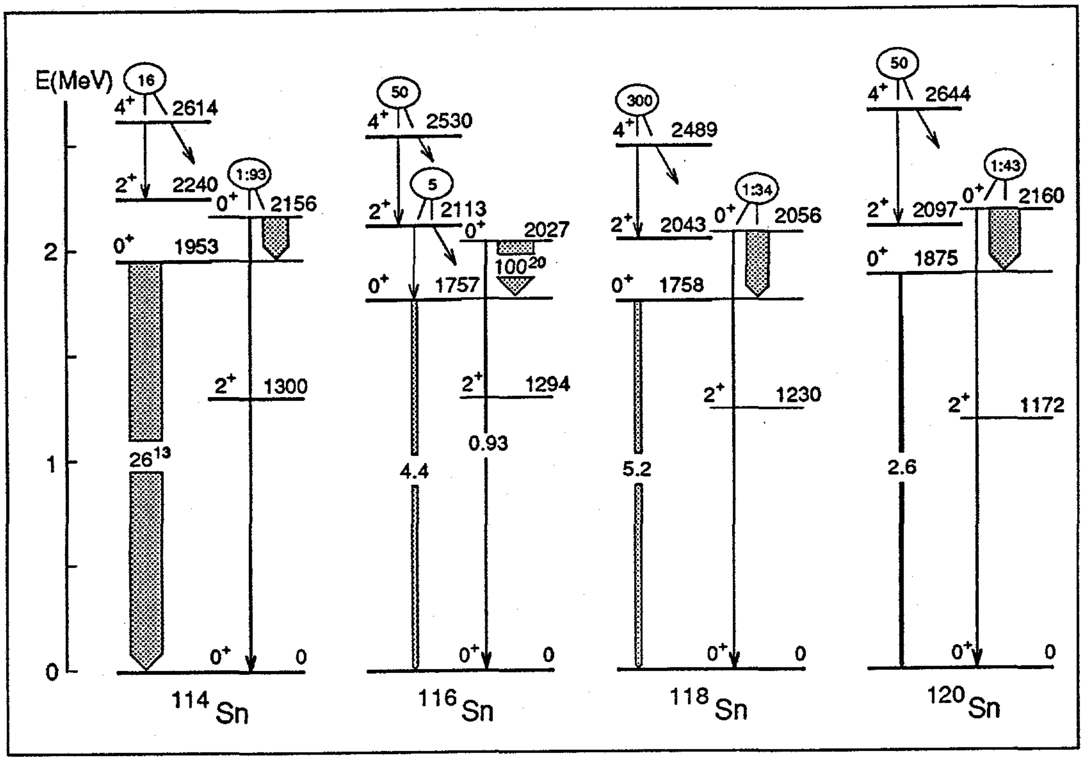

Fig. 2. Electromagnetic decay data for $^{114-120}$Sn. E0 strengths are in units of $\rho^2 \times 10^3$. The numbers in circles are in-band/out-of-band B(E2) ratios. The ratios in circles are the relative E0 branches. The data are taken from ref. 5 and Nuclear Data Sheets.

Fig. 4 shows that in the Pd and Ru isotopes, the E0 strength is small between vibrational excitations, but increases to larger values in the $^{98-100}$Mo isotopes and to a very large value in ^{102}Mo where a shape coexisting configuration (0_2^+) is known. In this same region, extending down from ^{100}Mo through the N=58 isotones to ^{96}Sr, shown in Fig. 5, one observes the strongest E0 strength ($\rho^2 \times 10^3 = 185 \pm 50$) known above ^{56}Ni.

The conventional view of E0 strength in deformed nuclei is that it is associated with β vibrations and is quite strong. The information on ρ^2 values in deformed nuclei is shown in Figs. 6 and 7. Figure 6 shows the information for strongly-deformed nuclei. The nuclei shown in Fig. 7 all have N=90 and are usually termed *transitional.* Evidently, the incidence of E0 strength in strongly-deformed nuclei

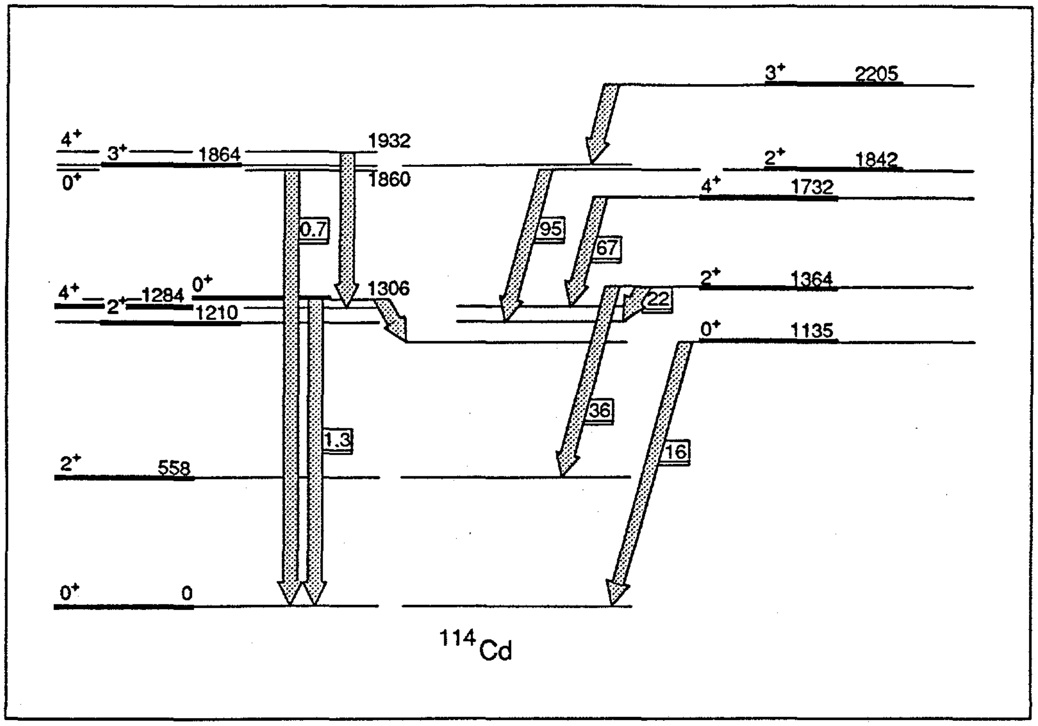

Fig. 3. Electric monopole transitions in ^{114}Cd. Values of $\rho^2 \times 10^3$ are shown boxed. The data are taken from ref. 5 and Nuclear Data Sheets.

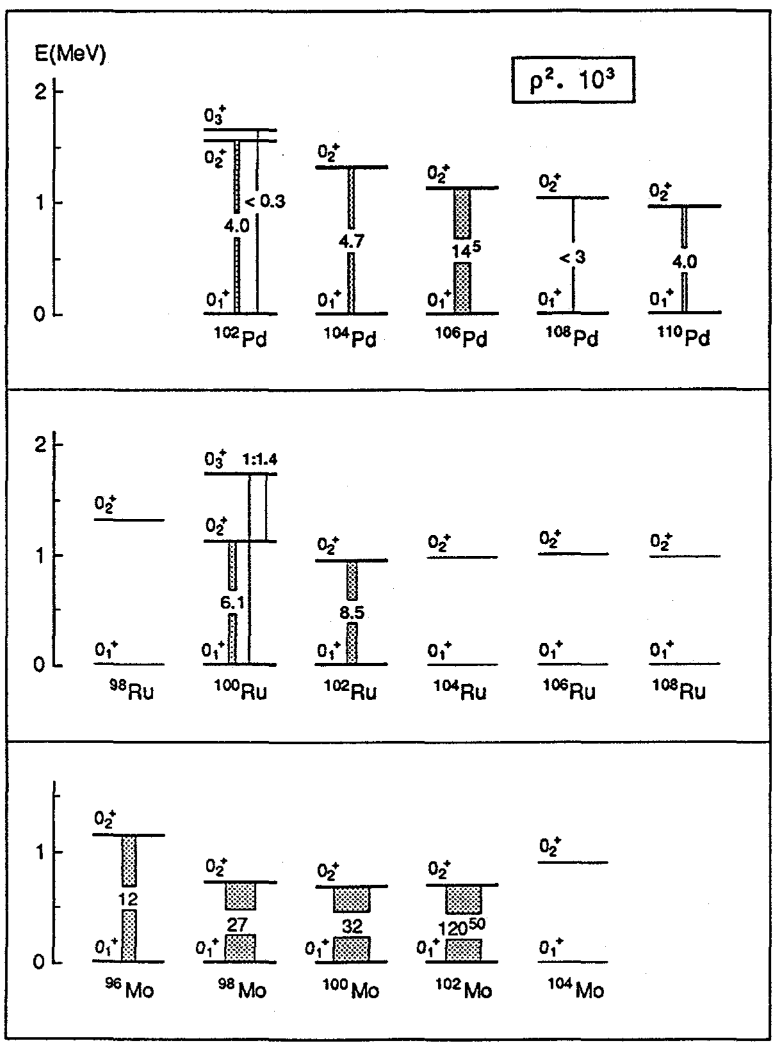

Fig. 4. E0 transition strength ($\rho^2 \times 10^3$) in even-even isotopes of Pd, Ru, and Mo. The data are taken from Nuclear Data Sheets.

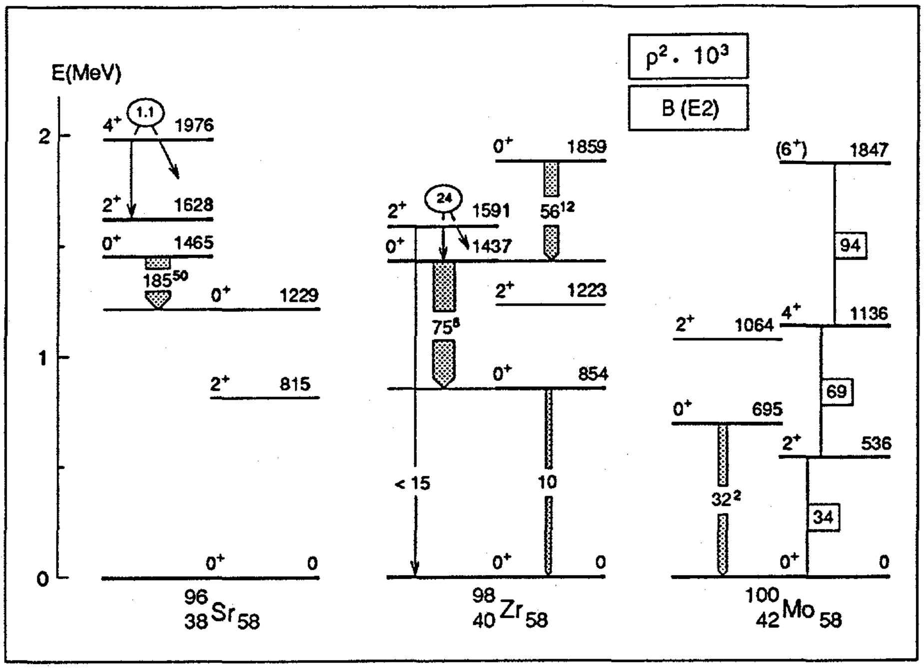

Fig. 5. E0 transition strength and B(E2) values in the N=58 isotones. The $\rho^2 \times 10^3$ values are given within the shaded arrows, B(E2) values in the boxes (in W.u.), and B(E2) ratios in the circles. The $0_3^+ \rightarrow 0_2^+$ E0 strength in ^{96}Sr is the strongest known above ^{56}Ni. The data are taken from Nuclear Data Sheets.

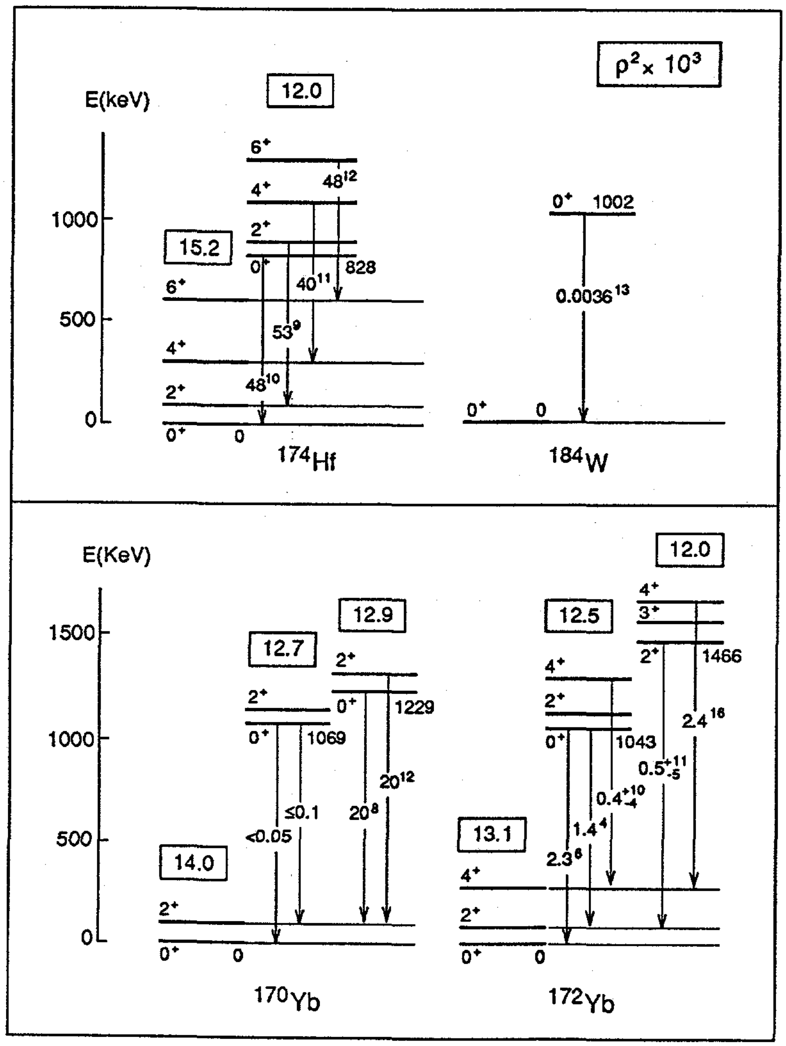

Fig. 6. E0 transition strength in several strongly deformed nuclei. The $\rho^2 \times 10^3$ values are given within the transition arrow. The rotational parameter for each band is given in the boxes. The data are taken from Nuclear Data Sheets.

(Fig. 6) does not reveal a definite pattern; and indicates that even the concept of β vibrations is poorly-defined in strongly-deformed nuclei. The lowest excited 0^+ bands in the N=90 nuclei (Fig. 7) conform to the standard view of β vibrations. However, the second excited 0^+ bands indicate that the structure of these nuclei is more complicated (see ref. 5, p. 183).

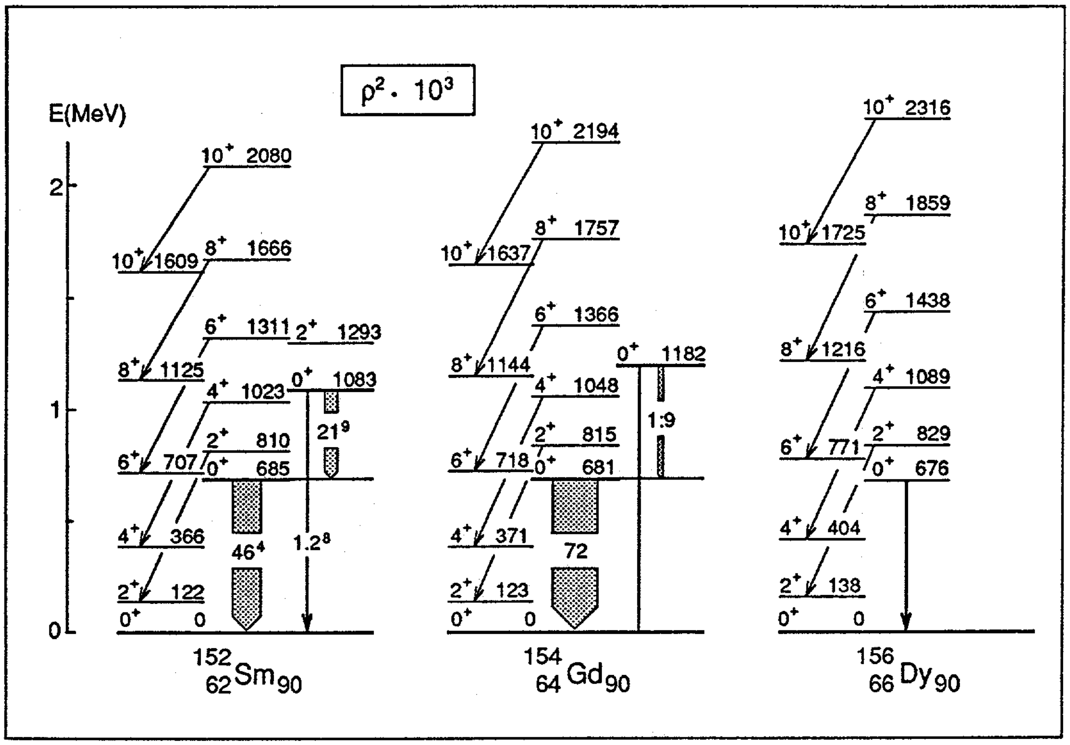

Fig. 7. E0 transitions between bands for several N=90 isotones. The $\rho^2 \times 10^3$ values are given within the arrows. The data are taken from ref. 8 and Nuclear Data Sheets.

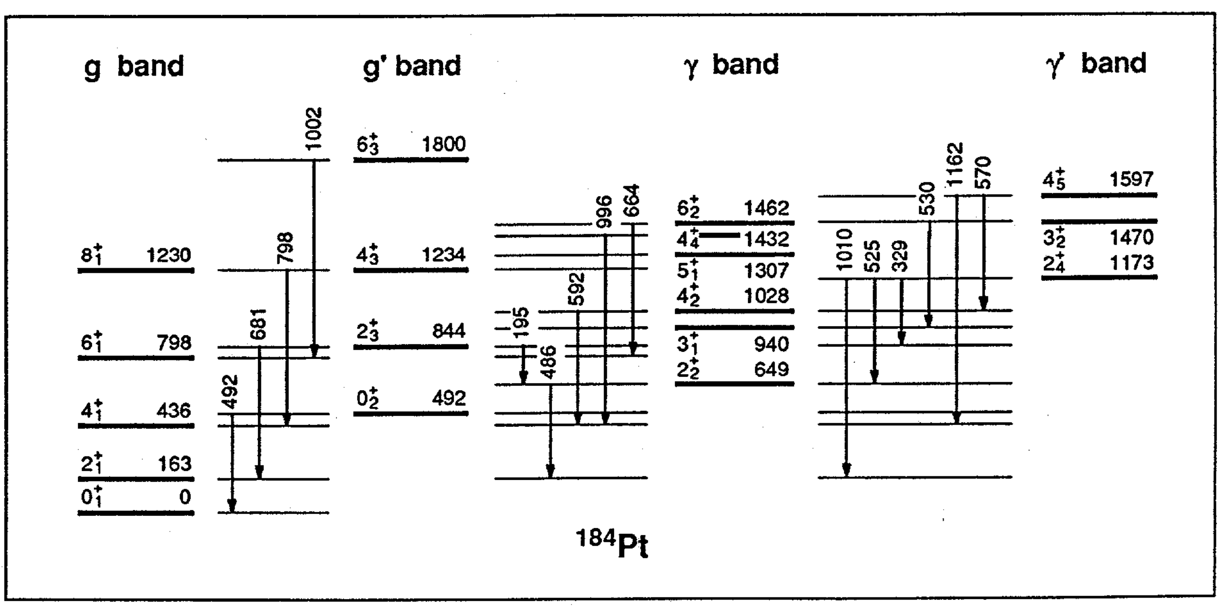

Fig. 8. The ΔI=0 transitions in ^{184}Pt. The $2_3 \rightarrow 2_1$ and $2_4 \rightarrow 2_2$ transitions are >20% E0, but the $3_2^+ \rightarrow 3_1^+$ transition between the γ' and γ bands is pure E0. This is unprecedented for $I^\pi \rightarrow I^\pi$, I≠0 transitions. The data are taken from ref. 9.

Recent results in the Z = 82 Region

Coexisting shapes based on a proton 2p-6h $(\pi h_{9/2})^2$ intruder configuration and a proton 4h configuration in $^{178\text{-}186}$Pt has been known[5] for some time. These configurations are shown in Fig. 8 for ^{184}Pt as *g* and *g'* respectively. Recent results[9] on ^{184}Pt, however, have added to that picture: Not only is E0 enhancement observed for $I^\pi \rightarrow I^\pi$ transitions between *g* and *g'*, but one also observes[9] two K=2 bands, labeled γ and γ' in Fig. 8. The pattern of E0 strength between all these bands is shown in Fig. 8. The $3_2^+ \rightarrow 3_1^+$ transition between γ' and γ is unprecedented in that it is a pure E0, $I^\pi \rightarrow I^\pi$ $(I \neq 0)$ transition. No γ-ray intensity is observed.[9] A similar structure is found[10] in ^{186}Pt as well.

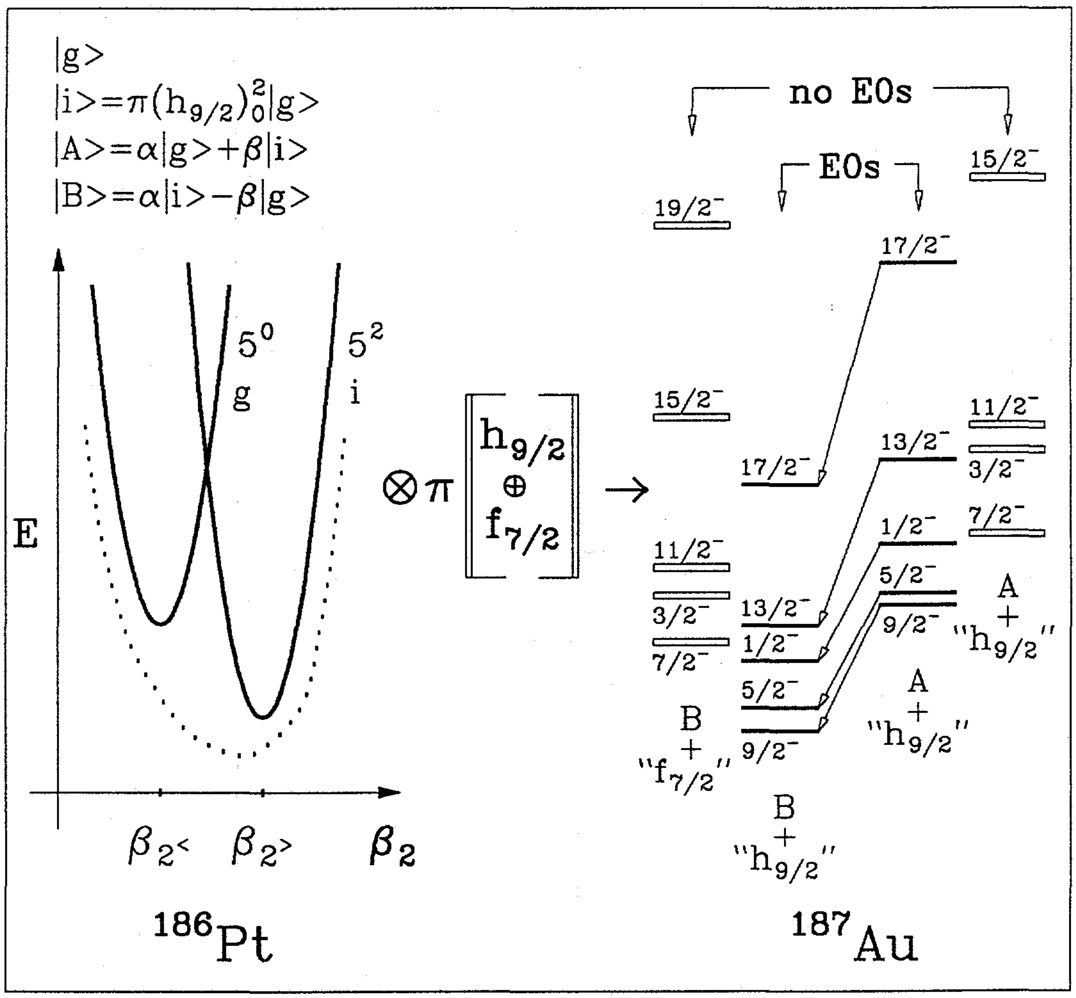

Fig. 9. A schematic illustration of the proposed coupling scheme between the unpaired proton in ^{187}Au and effective ^{186}Pt cores. The underlying core configurations contain 0 or 2 protons in the N=5 intruder orbitals, and the effective cores |A> and |B> are linear combinations of these. The dotted line indicates the adiabatic PES constructed from the quasiparticle vacuum state at each deformation, and the solid lines indicate diabatic configurations obtained by removing the interaction between the vacuum and two-quasiparticle states involving $h_{9/2}$ proton states. The figure is taken from ref. 11.

The ^{186}Pt nucleus serves as a core for proton-particle configurations in odd-proton ^{187}Au. Spectroscopy of ^{187}Au has revealed two bands based on $h_{9/2}$ proton particle excitations with identical spin sequence, nearly identical relative energies, and E0 transitions that connect only the favored members of the two bands[11] as shown in Fig. 9. Examples of γ-gated conversion electron and γ-ray spectra for the E0 transitions with highest statistics ($9/2^- \rightarrow 9/2^-$) and lowest statistics ($17/2^- \rightarrow 17/2^-$) cases are given in Fig. 10 . These bands in ^{187}Au, shown on the right side of fig. 9, represent a unique example of nuclear coexistence. In spite of rather similar deformation (both associated with near-prolate shapes) and similar rotational behavior, they can be characterized by different numbers of N=5 proton intruders. Calculations[11] indicate that the odd proton in ^{187}Au occupies the $h_{9/2}$ orbital in the favored band for both shapes. On the other hand, the odd proton mainly occupies the $f_{7/2}$ orbital for the lowest unfavored band and mainly the $h_{9/2}$ orbital for the excited unfavored band. The small overlap between the wave functions of the odd proton in the unfavored bands hinders the E0 transitions. This is illustrated in Fig. 9 where the $h_{9/2} \oplus f_{7/2}$ bands are obtained by coupling the unpaired intruder N=5 proton to effective ^{186}Pt cores $|A\rangle$ and $|B\rangle$.

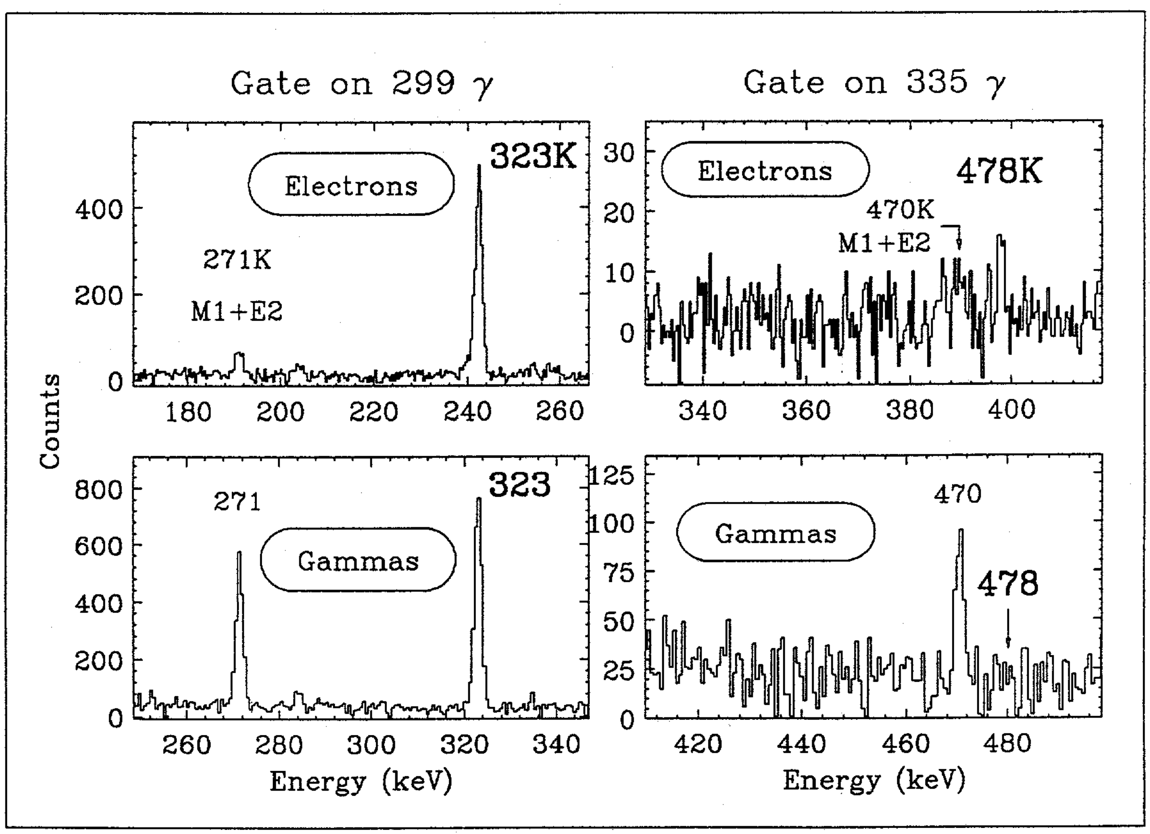

Fig. 10. The spectroscopic evidence for E0 enhancement for the strongest (323 keV, $I^\pi = 9/2^-$) and the weakest (478 keV, $I^\pi = 17/2^-$) $I^\pi \rightarrow I^\pi$ transitions between the favored levels of the $h_{9/2} \oplus f_{7/2}$ bands. The figure is taken from ref. 11.

A Future Application

With the availability of radioactive ion beams (RIBs), one can effectively use the electric monopole transition to locate and characterize multi-particle-multi-hole configurations in nuclei along the N=Z line beyond ^{40}Ca. This idea is illustrated for ^{40}Ca in Fig. 11 where the known 0^+ states, several particle-hole configurations, and several E0 strengths are noted. The E0 internal-pair process is the ideal experimental tool for these studies since the internal-pair coefficient is much greater than the internal-conversion coefficient for low Z and high transition energy. Plans are underway to identify and characterize these types of configurations up to ^{56}Ni along N=Z and in ^{74}Kr to ^{86}Mo along N=Z+2 using RIBs and the internal-conversion and internal-pair processes.

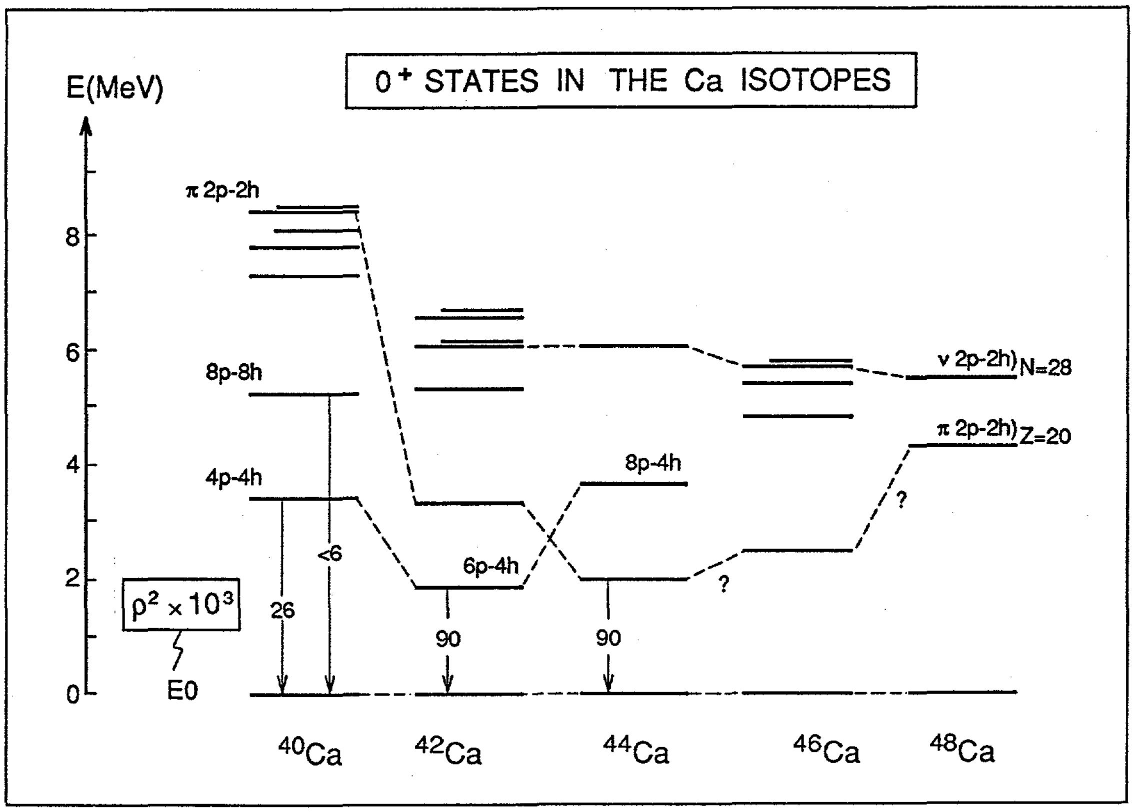

Fig. 11. E0 strength and 0^+ states in the even-even Ca isotopes. The labels 4p-4h and 8p-8h for 0_2^+ and 0_3^+ in ^{40}Ca are notation for π2p-2h $\oplus$ ν2p-2h and π4p-4h $\oplus$ ν4p-4h, respectively. The figure is taken from ref. 5.

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