Evidence for hexadecapole collectivity in closed-shell nuclei

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Evidence for hexadecapole collectivity in closed-shell nuclei is presented by examining the observed characteristics of the lowest 4^+ excited state in each case. These 4^+ states, presently identified in the $N = 82$ isotones ^{132}Sn and ^{140}Ce, and the $Z = 82$ isotopes, ^{202}Pb and ^{204}Pb, have nanosecond half-lives, and are found to decay by enhanced $E4$ transitions to the respective 0^+ ground state, whereas $\Delta I = 2$ $E2$ transitions from, and to, these states have $B(E2)$ values which are only a fraction of a Weisskopf unit. These features, suggestive of a significant one-phonon hexadecapole component in the structure of these 4^+ states, are interpreted in terms of their shell model configurations. Similar characteristics are predicted for some other closed-shell nuclei.

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Low-energy spectroscopic studies of even-even nuclei across the periodic table have generally focused on an interpretation of the $I^\pi = 2^+$ and 3^- states as single phonon (vibrational) states of $\lambda = 2$ (quadrupole) and $\lambda = 3$ (octupole) type, respectively. The lowest 4^+ states in spherical nuclei are either viewed as two-phonon (members of two $\lambda = 2$ phonon triplets having $I^\pi = 0^+$, 2^+ and 4^+ states) or $(j^2)_{4+}$ configurations. In either of these interpretations the 4_1^+ states decay primarily to the 2_1^+ state, with hardly any strength going into the direct $4_1^+ \to 0_g^+$ $E4$ transition. If this $E4$ transition has relatively significant strength, it can imply a one-phonon λ=4 character for the 4_1^+ states. This strength would then provide an experimental evidence for hexadecapole collectivity through enhanced $B(E4)$ values relative to their single particle estimates (Weisskopf units, henceforth abbreviated as W.u.). Although evidence of $E4$ collectivity had been suggested long ago [1,2] through inelastic scattering experiments, no systematic study of the 4_1^+ to 0_g^+ gamma transitions has been reported so far to examine the hexadecapole collectivity in spherical nuclei. Currently an interesting debate is underway [3] on the hexadecapole-phonon versus double-γ-phonon interpretation for K^π=4^+ bands in deformed even-even nuclei. Also careful microscopic calculations [2,4,5] have been undertaken to study the complex composition of these low-lying states with a view to understanding their interrelationships. Against this background we report here the results of our survey of the observed properties of the 4_1^+ states in even-even closed-shell nuclei. The present report focuses on an attempt to deduce experimental evidence for hexadecapole collectivity in such nuclei based on the following criteria: an experimentally observed gamma transition between 4_1^+ and 0_g^+ with $B(E4)$ value of several W.u.'s and $B(E2; 4_1^+ \to 2_1^+)$ value of a fraction of a single particle estimate in the same spectrum. Experimental information related to 4_1^+ levels in the four nuclei satisfying these criteria is presented in Fig. 1 and summarized in Table I. We have also included, wherever available, experimental information on the 6_1^+ to 4_1^+ $E2$ transition in each spectrum. As seen in Fig. 1 and Table I, presently only nuclei with nucleon number (N or Z) = 82 satisfy these criteria. Later we mention a few other cases wherein a similar situation is

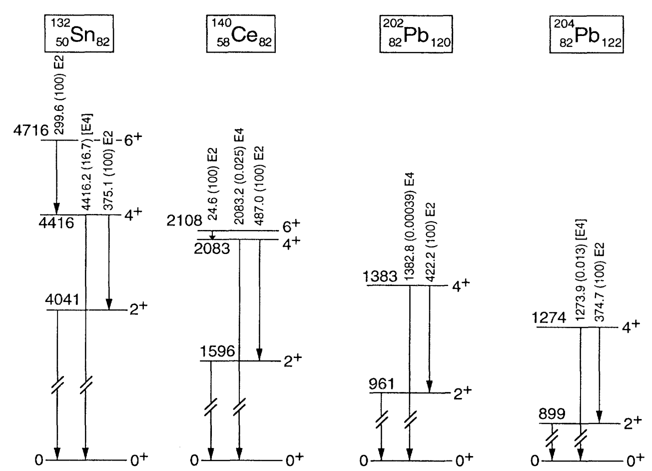

FIG. 1. Partial level schemes for the four nuclei wherein the first excited 4^+ states decay by a direct gamma transition to the respective 0^+ ground state. The entries on each level are I^π (right) and excitation energies in keV (left). The entries above each transition (shown by vertical arrows) successively denote the gamma-ray energy (in keV), the relative photon branching and the multipolarity. All the deexciting transitions are shown from the levels given in this figure with the exception of a 64.4-keV transition (to a 3^- level) in $^{132}_{50}$Sn$_{82}$ with a relative gamma intensity of 1.3 units.

TABLE I. Experimental information about the first excited 4^+ levels in closed shell nuclei for which the $\Delta I = 4$ transition to the 0^+ ground state has $B(E4) > 1$ W.u., whereas the $\Delta I = 2$ transitions from, and to, this 4^+ level have $B(E2) < 1$ W.u. The numbers following the entries for $t_{1/2}$, and $B(E4)$ and $B(E2)$ are uncertainties in the last digit(s). The uncertainties in $B(E4)$ and $B(E2)$ values have been calculated by compounding the experimental uncertainties in level $t_{1/2}$ and in gamma-ray branchings.

${}^{A}_{Z}X_N$	$E(2^+)$ (keV)	$E(4^+)$ (keV)	$t_{1/2}(4^+)$ (ns)	$B(E4: 4_1^+ \to 0_g^+)$ W.u.	ΔI=2 $I_i \to I_f$	E_γ (keV)	$B(E2: I_i \to I_f)$ W.u.	Ref.
${}^{132}_{50}Sn_{82}$	4041.1	4416.2	3.95 13	7.9 5	$4^+ \to 2^+$	375.1	0.40 2	[11]
					$6^+ \to 4^+$	299.6	0.282 8	
${}^{140}_{58}Ce_{82}$	1596.2	2083.2	3.45 3	12.1 8	$4^+ \to 2^+$	487.0	0.137 1	[6]
					$6^+ \to 4^+$	24.6	0.29 9	
${}^{202}_{82}Pb_{120}$	960.7	1382.9	1.97 2	4.7 8	$4^+ \to 2^+$	422.2	0.291 3	[7]
${}^{204}_{82}Pb_{122}$	899.2	1274.0	265 10	2.5 5	$4^+ \to 2^+$	374.7	0.00382 14	[12]

expected but not presently identified. In the following we briefly discuss each of these four cases. It may be remarked that the $E4$ character of the transitions in ^{140}Ce and ^{202}Pb has been experimentally determined based on conversion electron spectroscopy [6,7], whereas it is deduced for ^{132}Sn [8–11] and ^{204}Pb [12] from gamma-ray spectroscopic studies.

The experimental, as well as the theoretical, characteristics of the 2083 keV 4_1^+ state in ^{140}Ce have been investigated extensively [2,6]. The multipolarity of the 4_1^+ to the 0^+ ground-state gamma transition has been unambiguously established as $E4$ from conversion electron spectroscopy. Meanwhile, detailed microscopic structure calculations for the low-lying collective states have been reported recently [2] in connection with the inelastic electron scattering experiments. In particular, calculations using Soloviev's quasiparticle-phonon model (QPM) approach [13] conclude [2] that the 4_1^+ state in ^{140}Ce is "essentially a pure first one-phonon 4^+ configuration." As seen in our Table I, the 4_1^+ to 2_1^+ transition rate $B(E2) = 0.137$ W.u., whereas $B(E4; 4_1^+ \to 0_g^+)$=12.1 W.u. Also the 4_1^+ has a long half-life ($t_{1/2}$=3.45 ns). These experimental features can be understood by looking at the microscopic structures [2] of the involved states. Whereas the first quadrupole-phonon 2_1^+ state has $\pi(d_{5/2})^2$ as its main (91%) component, this two-quasiparticle configuration contributes only 13.1% to the 4_1^+ state; this one-hexadecapole-phonon 4_1^+ state has, in addition, $\pi(g_{7/2})^2$ as its dominant (53.8%) constituent with a 29.4% contribution from the $\pi(g_{7/2})\pi(d_{5/2})$ configuration. In contrast, it is interesting to note that the addition of two more protons to the ^{140}Ce core brings about a change in the character of the 2098 keV 4_1^+ state in ^{142}Nd which is assigned [5] almost a pure $\pi(d_{5/2})^2$ configuration.

The exotic doubly magic nucleus ^{132}Sn has been the subject of several investigations [8–11] with precise experimental results on its level scheme reported very recently [11] in the context of "first observation of octupole collectivity." However, the unusually large (13.9%) 4416.2 keV 4_1^+ to 0_g^+ gamma branch observed in this nucleus has not received much attention. The lowest positive parity states (2^+, 4^+, 6^+, and 8^+) have been interpreted [8,9] as constituting a $\nu(f_{7/2})\nu(h_{11/2})^{-1}$ multiplet. Shell model calculations [8,9] assuming this characterization are in good agreement for the observed $B(E2)$ transition rates for the higher spin states while "the 4^+ to 2^+ transition rate is observed to be enhanced by a factor of 2." It was concluded [9] that the 4_1^+ state may have admixtures of the $\nu(p_{3/2})\nu(h_{11/2})^{-1}$ configuration, and both the 4_1^+ and 2_1^+ states may also have configuration admixtures of collective nature, in particular proton excitations involving the $\pi(g_{9/2})^{-1}$ orbital. QPM calculations yielding microscopic composition of these collective states, similar to those discussed above for ^{140}Ce, are desired for a detailed comparison. However, the very similar observed experimental characteristics for ^{132}Sn and ^{140}Ce, as listed in Table I, point to a similar one-hexadecapole-phonon interpretation for the 4416.2 keV 4_1^+ state in ^{132}Sn.

The low energy excitation spectra of ^{202}Pb and ^{204}Pb show a remarkable similarity; the lowest six levels in each nucleus have identical I^π and very similar level energies. This may be simply understood by recalling that the two nuclei correspond to $\nu(f_{5/2})^2$ and $\nu(f_{5/2})^{-2}$ structures, respectively, with a filled $3p_{3/2}$ and an unfilled $3p_{1/2}$ neutron shell in each case. Thus the lowest 4^+ configuration in each case is expected to have $(\nu f_{5/2})^2_{4+}$ as its dominant component; this interpretation is supported by the observed $E5$ transition rates [14] to these 4^+ states from the respective 9^- $[(\nu i_{13/2})^{-1}(\nu f_{5/2})^{-1}]$ isomer. Detailed shell model calculations [4] aimed at revealing the multicomponent structure of these low-lying states in the lead isotopes concluded that, for this isotopic chain, $N = 114$ becomes a semimagic number and that the lowest 2^+ and 4^+ states in the A=198–204 isotopes are mainly built from the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ neutron orbitals. Further, these calculations [4] concluded that whereas the 2_1^+ strength in ^{202}Pb is widely distributed in all the available 5 combinations, the $(p_{1/2}, f_{5/2})$ configuration is the main component of the 2_1^+ state in ^{204}Pb; the 4_1^+ wave function in both these nuclei is predominantly $(f_{5/2})^2$ with ~15% contribution from the $(f_{5/2}, p_{3/2})$ configuration. Thus there is very little overlap between the wave functions of the 2_1^+ and 4_1^+ levels in these nuclei and consequently the $E2$ transition connecting these two levels is hindered. On the other hand, the observed enhanced $E4$ transition (see

Table I) connecting the 4_1^+ and 0^+ ground state is indicative of a significant one-phonon (hexadecapole) character for the 4_1^+ levels in these nuclei.

We have scanned the nuclear structure data bases at Brookhaven for all the known cases wherein 4_1^+ states have half-lives of the order of a nanosecond. All such cases are seen to belong to the semimagic ($N = 82$ or 126 or $Z = 82$) or doubly magic (^{48}Ca, ^{132}Sn) category. All the six $N = 82$ isotones with Z=50(2)60 fall in this category. Experimental observation of a direct 4_1^+ to 0_g^+ transition, expected in all such cases, is presently awaited. Such experiments are difficult in view of the crossover ($E4$) gamma energy being the same as the summed energy of the two $E2$ ($4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$) gamma energies, and the $E4$ branch being very small. However, with the advent of gamma detector arrays and advances in techniques for precise spectroscopic measurements, their identification should be possible. Based on the present known $B(E2{:}\,4^+ \rightarrow 2^+)$ transition rates, the particular cases of interest, as revealed from our present analysis, are the identification of the 4_1^+ to 0_g^+ transitions in the N=82 isotone ^{138}Ba and the N=126 isotone ^{214}Ra. The experimental half-lives and excitation energies for 4_1^+ states and $B(E2{:}\,4^+ \rightarrow 2^+)$ transition rates in these two nuclei are (^{138}Ba): 2.17 ns, 1898.6 keV, 0.286 W.u.; and (^{214}Ra): 32 ns, 1637.1 keV, 0.17 W.u. An assumed $B(E4) \sim 4$ W.u. predicts percentage of gamma branching ≈ 0.03 for the 4_1^+ to 0_g^+ $E4$ branch in ^{214}Ra. Experimental identification of these $E4$ transitions will be of interest from the point of view of the present discussion.

In summary, in this systematic survey, we have provided evidence for the occurrence of hexadecapole collectivity in closed shell nuclei by discussing the observed transition rates and deduced composition of the lowest 4^+ excited states in four closed shell nuclei, and have further pointed out specific cases wherein similar features may be expected to occur. Careful experimental investigations focused at identification of $E4$ gamma transitions, in parallel with theoretical studies aimed at revealing the collective one-phonon composition of 4_1^+ states, are desired to elucidate this challenging facet of nuclear structure.

Note added in proof. It has been brought to our notice, after acceptance of our manuscript, that Y. D. Devi and V. K. B. Kota had published, in Pramana J. Phys. **39**, 413 (1992), a review of hexadecapole degrees of freedom in nuclear structure within the framework of the *sdg* interacting boson model; however they did not include any discussion of the closed shell nuclei which are the subject matter of the present paper.

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