Effective Charges and Octupole Collectivity in the ^{132}Sn region

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A measurement of $B(E3)$ in the two-proton nuclide ^{134}Te was made, giving the first empirical value of the effective proton octupole charge in the neutron rich doubly closed shell region at ^{132}Sn. It is demonstrated that the effective $E2$ and $E3$ charges can be used to derive the core phonon strengths in ^{132}Sn and ^{208}Pb. The octupole charge and the corresponding phonon strength were found to be substantially lower at ^{132}Sn than at ^{208}Pb, thus confirming long standing theoretical predictions of a weak octupole collectivity in the heavy Sn region.

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The properties of the low-lying excitations in the few-nucleon systems near doubly closed shells (DCS) are of fundamental interest as they are simple to interpret and are described within basic theoretical models. The most notable recent progress in the studies of such systems is the investigations of the nuclei near ^{100}Sn [1] and ^{132}Sn [2], which represent exotic far-off stability DCS regions that nevertheless are amenable to direct investigation. Furthermore, they fill a critical gap in the systematical properties for the DCS systems that exists between the other well-studied cases of $A \leq 56$ and the ^{208}Pb region. On the neutron rich side, detailed studies [2,3] of the ^{132}Sn region were made possible at the OSIRIS fission-product mass separator [4] at Studsvik.

The shell gaps at ^{132}Sn are large, giving this DCS nucleus an exceptional "stiffness" with respect to excitations. Consequently, the collective properties of the low-lying states are of particular interest. In the study of ^{132}Sn populated from the decay of ^{132}In, the 3_1^- state at 4351.9 keV was firmly identified [2] as collective, thus confirming the long standing theoretical predictions [5] that one of the lowest-lying states in this nucleus would be due to a surface octupole vibration. The unresolved issue, however, is the *degree* of collectivity, which is predicted [6–8] to be substantially lower than in ^{208}Pb. The much higher excitation energy of the 3_1^- level in ^{132}Sn (4352 keV) than in ^{208}Pb (2615 keV) may support these predictions. This issue can be resolved by studies of excitations in the nuclei neighboring ^{132}Sn. The octupole collectivity at a DCS is a regional property that enters with some fractional strength in several types (in terms of the quasiparticle structure) of $E3$ transitions in the few-particle systems of the region. Bergström *et al.* have nicely illustrated this point in their extensive systematics of $B(E3)$ rates near ^{208}Pb [9]. An experimental $B(E3)$ rate in a close-lying nucleus, whose structure is simple, could thus provide a direct measure of the $E3$ collective strength at ^{132}Sn. Yet, prior to this work, no such rate was measured in close vicinity to ^{132}Sn, nor would a particular fractional collective strength observed at ^{208}Pb be appropriate to use in the ^{132}Sn region, because the octupole (or quadrupole for that matter) strength of a particular transition is linked to the *regional* structure in terms of single particle and phonon energies. The strength may be parametrized by the use of effective charges, $e_{\text{eff}}(E\lambda)$, which incorporate these structure effects and give a direct measure of the $E\lambda$ strength in a particular region. The derivation process makes the effective charges model dependent to some degree. A consistent application of the same model is thus needed for comparisons between different regions of the nuclear chart. This model must include a proper description of the polarization of the DCS core nucleus, in terms of virtual $E\lambda$ transitions between the major shells. For the quadrupole case, the rather high energies of these virtual transitions, which for parity reasons mainly have to cross over an intermediate shell, result in a weak coupling to the experimentally observed transitions. In this case, the effective charge derived at a particular transition energy will indeed practically correspond to the static (i.e., reduced to zero transition energy) value of $e_{\text{eff}}(E2)$. The situation is very different in the octupole case, where the polarizing virtual $E3$ transitions mainly connect adjacent shells, and thus have much lower energies. An adiabatic treatment is then no longer possible. A derivation of the static $E3$ effective charges

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therefore relies critically on a correct description of their energy dependence.

In this Letter we describe an experimental and theoretical study of the two-proton excitations of ^{134}Te, addressing the issue of quadrupole and octupole phonon strength in the ^{132}Sn region. The main part of the theoretical work, a description of the model, the calculated level spectrum of ^{134}Te, and the electromagnetic properties of the positive parity states, was published before [10]. Here the theoretical work was extended to include the octupole transitions.

Measurements were performed at the OSIRIS mass separator. The levels of ^{134}Te were populated in the β decay of 7^- ^{134}Sb. Experiments included γ-ray singles, $\gamma\gamma$ coincidences, and $\gamma\gamma(\theta)$ angular correlation measurements, as well as half-life measurements using the fast-timing $\beta\gamma\gamma(t)$ method [11]. The latter method was crucial for obtaining the transition rates discussed here. The method utilizes coincident γ transitions observed in a Ge detector to select a particular decay path through the level scheme. The time between the occurrence of a β particle and a γ ray in this decay path is then measured with two small scintillator detectors (one plastic and one BaF_2). This method allows even weak decay branches to be studied due to the "filtering" effect of the high resolution Ge-detector gate. The fast-timing results are presented in Table I, while the delayed coincidence time spectrum due to the half-life of the 9^- level at 4013.3 keV is shown in Fig. 1.

Previously, only a few of the excited states in ^{134}Te were identified in the decays of the high-spin $J^\pi = 7^-$ and low-spin $J^\pi = 0^-$ isomers of ^{134}Sb [12–14]. The present work established 52 levels interconnected by about 85 transitions. Some spin assignments and multipole mixing ratios were determined from the $\gamma\gamma(\theta)$ angular correlations for the strongest transitions; see Ref. [15].

Blomqvist [7] has pointed out that each single particle state $(n, l, j,)$ at ^{132}Sn has a corresponding state $(n, l + 1, j + 1)$ at ^{208}Pb, with generally the same ordering and similar spacings. This results in a close similarity of some properties in the two DCS regions. The single-proton states of interest here are well separated in these regions. Consequently, the lower-lying levels of both of the two-proton valence nuclides ^{210}Po and ^{134}Te (see Fig. 2) are split into three separate groups, each characterized by a specific two-proton excitation. The structures of the two nuclides are remarkably similar, allowing for the higher angular momenta in ^{210}Po.

The lowest two groups in ^{134}Te are members of the $1g_{7/2}^2$ and $1g_{7/2}2d_{5/2}$ proton states, respectively. All members of these two multiplets have positive parity and were identified in this work or in Ref. [14] except for the 3^+ state of the $1g_{7/2}2d_{5/2}$ configuration. Our remeasured lifetimes for the 6^+ and 4^+ levels are given in Table I together with data from previous works [16,17]. Note the discrepancy with one of the previous results.

In the next group of levels (see Fig. 2) there are negative parity states from the $1g_{7/2}1h_{11/2}$ configuration, which are expected above the $1g_{7/2}2d_{5/2}$ multiplet and well separated from it. The levels of the $1g_{7/2}1h_{11/2}$ multiplet have some unique fingerprints which allow their identification. Most importantly, the 6^-, 7^-, and 8^- members are the *only* states in the 4–5 MeV region that can be strongly populated in the beta decay of 7^- ^{134}Te. The highest spin state, 9^-, is predicted to be the lowest-lying one and thus becomes an yrast isomer. (A general property of the residual interaction for like nucleons is that the $J_{\max}$ level becomes the lowest one in a $j_1 + j_2 =$ odd multiplet having an odd parity. Since the orbitals involved have the highest angular momenta in the shell, the $J_{\max}$ level becomes strongly yrast.) We observe a group of levels showing these features. Accepting these as members of the multiplet, the observed lifetimes, the patterns of feeding and decay, and the branching of intramultiplet transitions give unique assignments of 6^-, 7^-, 8^-, and 9^- for the levels at 4557.5, 4298.8, 4562.6, and 4013.3 keV, respectively. The 9^- state deexcites to the 6_1^+ and 6_2^+ states via $E3$ transitions for which the $B(E3)$ rates were measured in this work. Thus, we have well-defined $E2$ and $E3$ transitions in ^{134}Te between states expected to be rather pure. These may serve for a derivation of the quadrupole and octupole effective charges. Furthermore, their counterparts in ^{210}Po give the means to compare directly these two DCS regions.

For the theoretical description of ^{134}Te we used the particle-particle random phase approximation (RPA) method [19,20], which does not take into account the particle-hole (phonon) vibrations of the core in the neutral channel and the corresponding admixtures to the single particle states. The method thus requires effective matrix elements which depend on the energy of the emitted γ

TABLE I. Experimental level half-lives for ^{134}Te.

Level energy (keV)	I^π	$T_{1/2}$ previous (ns)	$T_{1/2}$[a] present work (ns)
1279.2	2_1^+	<0.17[b]	
1576.2	4_1^+	1.50 ± 0.13[b]	1.28 ± 0.10
1691.4	6_1^+	165 ± 3,[c] 196 ± 7[d]	164 ± 1
4013.3	9_1^-		0.703 ± 0.026

[a]Adopted in further analysis, except for the 1576.2 keV level for which the average value of $T_{1/2} = 1.36 \pm 0.08$ ns was used.
[b]From Ref. [16].
[c]An averaged value from a few results from the ^{134}Te IT decay, from Ref. [22].
[d]From ^{134}Sb β^- decay [17]. Discrepant result; see Ref. [18].

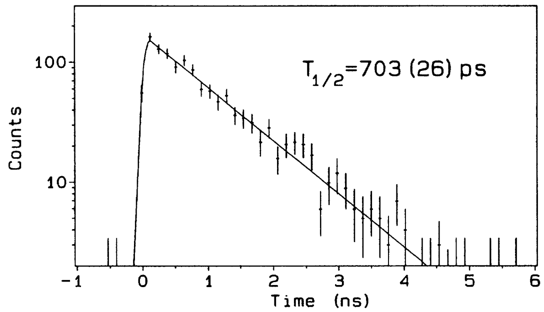

FIG. 1. The time distribution of delayed coincidences between radiation feeding and deexciting the 4013.3 keV 9^- level of ^{134}Te. The level half-life was determined by fitting a single decay component, as shown.

quanta. Consequently, the $E\lambda$ transitions of moderate energy ω_γ [$\omega_\gamma \ll \omega_\lambda$(core)] should be parametrized by introduction of an effective charge that characterizes the nuclear polarizability with respect to vibrations of the corresponding multipolarity. (ω_λ denotes the vibrations of the core.) By comparing the experimental values of $B(E\lambda)$ for low energy transitions between states with the same number of quasiparticles (in the present case, two-quasiparticle states) to those calculated in the framework of our method, we define the values of electric quadrupole and octupole charges.

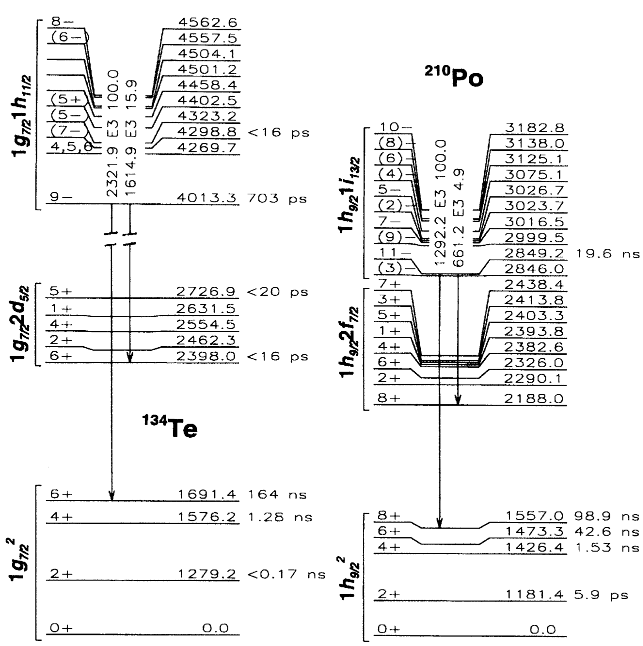

FIG. 2. Level structure of the two-proton nuclei ^{134}Te and ^{210}Po. The data are from the present work and Refs. [13,14,23]. All known ^{134}Te levels below 4.6 MeV are included. For ^{210}Po, only the levels belonging to the $1h_{9/2}^2$, $1h_{9/2}2f_{7/2}$, and $1h_{9/2}1i_{13/2}$ configurations are shown. See the text for details.

In the $E2$ case, the low energy $6_1^+ \rightarrow 4_1^+$ ($\omega_\gamma =$ 115.3 keV) and $4_1^+ \rightarrow 2_1^+$ ($\omega_\gamma = 297.0$ keV) transitions in ^{134}Te, which connect states of high purity in the $1g_{7/2}^2$ multiplet, are the most appropriate for defining the $e_{\rm eff}$. Using the $B(E2)$ values from Table II, we found that for both transitions $e_{\rm eff}(E2) \approx 1.9|e|$. This result is close to the value for nuclei adjacent to ^{208}Pb which is about $1.5 - 1.7|e|$ [21], in agreement with the conclusions of Blomqvist *et al.* [17].

The situation regarding the octupole transitions in ^{134}Te resembles that for nuclei close to ^{208}Pb, where Bergström *et al.* [9] have observed three main groups of $E3$ transitions. The fastest ones, with $\omega_\gamma \sim \omega_{3_1^-}$ (^{208}Pb), are due to the conversion of an octupole phonon into $E3$ radiation and are characterized by a reduction of the quasiparticle number by 2. The transitions in the second group correspond to a single particle transformation of the type $1i_{13/2} \rightarrow 2f_{7/2}$ and are relatively fast. Those from the third group correspond to a transformation of the type $1i_{13/2} \rightarrow 1h_{9/2}$ and are thus retarded due to spin flip. (Since the $E3$ operator does not contain spin variables, its matrix elements for spin-flip transitions are small.) The transitions in the second group are suitable for an evaluation of the octupole effective charge, using our particle-particle RPA method, for the dual reason that they are less influenced by uncertainties in the nuclear structure calculations, and because of their low energies. A low transition energy is essential for a reliable extrapolation to the static case. The model describing the energy dependence of the radiative matrix element need then include only one intermediate octupole phonon in the treatment of the interaction between a quasiparticle and the surface vibration. Using data for the ^{208}Pb region, Table II, we obtain an $e_{\rm eff}$ ($E3, \omega_\gamma \sim 0.7$ MeV) of about $3.3|e|$, which reduces to $e_{\rm eff}(E3, \omega_\gamma \sim 0) \approx 3.1|e|$ in the static case.

In ^{134}Te we have identified two $E3$ transitions, both from the 9^- level. The first one, feeding the 6_1^+ state, is weak, while the second one, going to the 6_2^+ level and having a small [compared to $\omega_{3_1^-}$(^{132}Sn) = 4.35 MeV] value of ω_γ, is fast. Neglecting for a moment the correlations, the first transition can be described as $\{1g_{7/2}, 1h_{11/2}\}_{9^-} \rightarrow \{1g_{7/2}, 1g_{7/2}\}_{6^+}$ with a spin-flip single particle transformation of the type $1h_{11/2} \rightarrow 1g_{7/2}$, giving retarded $E3$ radiation. The second transition involves the single particle transformation $1h_{11/2} \rightarrow 2d_{5/2}$ between the configurations $\{1g_{7/2}, 1h_{11/2}\}_{9^-} \rightarrow \{1g_{7/2}, 2d_{5/2}\}_{6^+}$, and is the most appropriate for defining the octupole effective charge, for the reasons mentioned above. By comparing the experimental and theoretical data we obtain $e_{\rm eff}(E3; \omega_\gamma \sim 1.6$ MeV$) = 2.0|e|$, which gives $e_{\rm eff}(E3; \omega_\gamma \sim 0) = 1.9|e|$ for the static case.

The octupole effective charge is thus about 60% larger at ^{208}Pb compared to ^{132}Sn, which in itself indicates that the octupole strength differs by about a factor of 2 for these regions. A quantitative estimate of the $E2$ and

TABLE II. Effective charges and $B(E\lambda)$ transition rates in ^{134}Te and ^{210}Po.

Nuclei	γ transition (keV)	$I_i^\pi \to I_f^\pi$	Multipolarity	SP transformation	$B(E\lambda)^a$ (W.u.)	Effective charge^b
^{134}Te	297.0	$4_1^+ \to 2_1^+$	$E2$	$1g_{7/2} \to 1g_{7/2}$	4.3 ± 0.3	1.83 ± 0.05
	115.3	$6_1^+ \to 4_1^+$	$E2$	$1g_{7/2} \to 1g_{7/2}$	2.05 ± 0.03	1.90 ± 0.02
	1615.5	$9_1^- \to 6_2^+$	$E3$	$1h_{11/2} \to 2d_{5/2}$	8.0 ± 1.3	1.90 ± 0.17
	2321.9	$9_1^- \to 6_1^+$	$E3$	$1h_{11/2} \to 1g_{7/2}$	3.8 ± 0.2	3.25 ± 0.10
^{210}Po	245.3	$4_1^+ \to 2_1^+$	$E2$	$1h_{9/2} \to 1h_{9/2}$	4.53 ± 0.15	1.75 ± 0.03
	46.9	$6_1^+ \to 4_1^+$	$E2$	$1h_{9/2} \to 1h_{9/2}$	3.00 ± 0.12	1.72 ± 0.03
	83.5	$8_1^+ \to 6_1^+$	$E2$	$1h_{9/2} \to 1h_{9/2}$	1.10 ± 0.05	1.66 ± 0.04
	661.2	$11_1^- \to 8_2^+$	$E3$	$1i_{13/2} \to 2g_{7/2}$	19.7 ± 1.1	3.14 ± 0.10
	1292.2	$11_1^- \to 8_1^+$	$E3$	$1i_{13/2} \to 1h_{9/2}$	3.71 ± 0.10	4.54 ± 0.09

[a]The ^{210}Po data (except column 7) was taken from the compilation by Browne [23].
[b]The effective charges were reduced to "static" values, i.e., corresponding to $\omega_\gamma = 0$.

$E3$ transition rates from the one-phonon states of ^{132}Sn to the ground state is obtained by using the model for nuclear surface vibrations and our values of $e_{\rm eff}$. The resulting transition rates are 11 and 15 W.u. (Weisskopf units), respectively. For ^{208}Pb, a similar procedure gives estimated $E2$ and $E3$ phonon transition rates of 13 and 30 W.u., respectively, as compared to the experimental values of 8.2 and 34 W.u. The near agreement lends some credibility to the values presently derived for ^{132}Sn. One should note that the presently studied $E3$ transitions carry a substantially larger proportion of collective strength than the $E2$ case. Our empirical derivation of the phonon strengths should thus be more reliable for $E3$ than for $E2$ transitions. This is perhaps also reflected in the published [6,8] results of RPA calculations for ^{132}Sn, which both agree very well with our $B(E3)$ of 15 W.u., but give lower values in the range 2–7 W.u. for the $B(E2)$ from the first 2^+ state.

In summary, we have derived the static proton octupole charge at ^{132}Sn from new experimental data and found this quantity to be markedly lower than at ^{208}Pb. Using this empirical value we estimated the octupole phonon transition rate, and thus confirmed the predictions of a relatively weak octupole collectivity at ^{132}Sn.

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