Conversion electron measurements of isomeric transitions in ^{130,132}Te and ^{134}Xe

J. Genevey, J. A. Pinston, and C. Foin
Institut des Sciences Nucléaires IN2P3-CNRS/Université Joseph Fourier, F-38026 Grenoble Cedex, France

M. Rejmund
DAPNIA/SPhN, CEA Saclay, F-91191 Gif-sur-Yvette, France

R. F. Casten
Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520

H. Faust and S. Oberstedt
Institut Laue-Langevin, F-38042 Grenoble Cedex, France

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In this work microsecond isomers in ^{130,132}Te and ^{134}Xe are investigated. These nuclei are produced by thermal neutron induced fission of ^{239}Pu and ^{241}Pu. The detection is based on time correlation between fission fragments selected by the LOHENGRIN spectrometer at ILL (Grenoble) and the γ rays or conversion electrons from isomers. The $10^+ \rightarrow 8^+$ isomeric transition of ^{132}Te and ^{134}Xe was measured for the first time and the half-life of the analogous transition in ^{130}Te was remeasured. The systematic behavior of the $B(E2)$ values of this isomeric transition is studied in Sn, Te, Xe, and Ba isotopes close to ^{132}Sn. A simple mechanism is proposed to explain the strong increase in the $B(E2)$ strengths from the Sn to the Te isotones.

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I. INTRODUCTION

The even Sn isotopes display a 10^+ yrast isomer in the mass range $A=116$–130 [1–4]. The $10^+ \rightarrow 8^+$ isomeric transition takes place between states of $\nu h^n_{11/2}$, seniority $v=2$, neutron main configuration. The behavior of the $B(E2)$ value of the isomeric transition in this series of isotopes reflects the filling of the $\nu h_{11/2}$ neutron subshell which shows a deep minimum for ^{123}Sn, corresponding to the midshell. This 10^+ level is also present in the even-even nuclei occupying the proton open subshells above $Z=50$. One may ask whether similar effects of $\nu h_{11/2}$ neutron subshell occupation are also present for these nuclei. Unfortunately, these 10^+ states are not always known and few $B(E2)$ values have been measured. To fill this gap we have performed new measurements on ^{130,132}Te and ^{134}Xe nuclei which have few valence proton and hole neutron pairs outside the doubly magic ^{132}Sn.

In the earlier experiments, two microsecond isomers were observed at about 2700 keV excitation energy in ^{132}Te [5] and ^{130}Te [6], respectively. Unfortunately, the isomeric transitions in the nuclei were not observed. However, the authors of these two papers suggested a spin and parity assignment 10^+ for these isomers which subsequently decay to an 8^+ state. Upper limits of 32 and 90 keV were fixed for the isomeric transition in ^{132}Te and ^{130}Te, respectively, and these isomeric transitions are expected to be strongly converted. To find these transitions, a very efficient setup for conversion electron measurements has been used in the present experiment. This detection system has already been described in detail in [7,8].

II. EXPERIMENTAL PROCEDURE

The nuclei of the $A=130$, 132, and 134 mass chains were produced by thermal neutron induced fission of ^{239}Pu and ^{241}Pu targets. The LOHENGRIN spectrometer at ILL has been used to separate the fission fragments (FF) recoiling from thin targets of about 400 μg/cm^2, according to their A/q ratios. The FF are detected by a ΔE gas detector of 13 cm length, and subsequently stopped in a Mylar window of 12 μm thickness. The γ rays deexciting the isomeric states are detected by two large volume Ge detectors and the conversion electrons are detected by two cooled adjacent Si(Li) detectors covering a total area of 2×6 cm^2 and located at 7 mm behind the Mylar window. The electron detection efficiency is about 30%. The gas pressure of the ionization chamber was tuned to stop the FF at about 2 μm from the outer surface of the Mylar window to minimize electron absorption and to have good energy resolution. With this setup it is possible to detect conversion electrons down to about 15 keV and the FWHM resolution for electrons above 40 keV is about 2.5 keV. Note that a very low electron detection threshold and a very high detection efficiency are absolutely necessary to observe the very low energy isomeric transitions expected in nuclei close to doubly magic systems.

Events were stored on a disk each time a Si(Li) detector or a Ge detector was fired within a time range of 40 μs after a FF was detected. In this case, the parameters recorded are the ΔE signal of the ionization chamber and the signals of the Ge and Si(Li) detectors with their time delays; this allows one to record the possible γ-γ and γ-electron coincidences. The singles spectra of each detector are also recorded; this information is used to subtract the random events from the spectra measured in delayed coincidences with the FF.

III. EXPERIMENTAL RESULTS

In ^{132}Te [5] and ^{130}Te [6] the yrast line was already known up to the 8^+ level and the half-life of a not-yet-

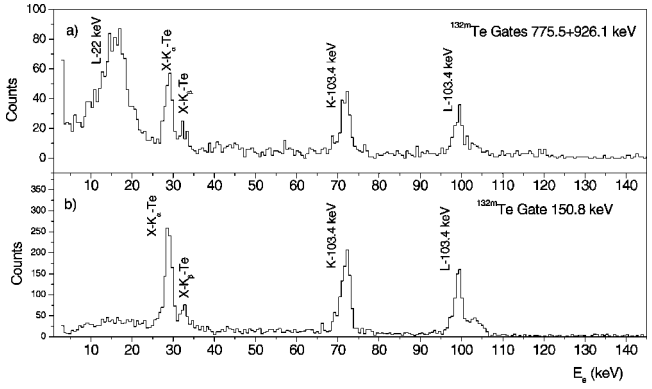

FIG. 1. Si(Li) coincidence spectra for ^{132m}Te gated by γ rays.

observed 10^+ isomer was also indicated for each of the two nuclei. In ^{134}Xe the even spin yrast line is well established up to the 4^+ state only [9,10].

A. ^{132}Te

The Si(Li) spectrum of Fig. 1(a), obtained by gating on two γ rays of 775.5 and 926.1 keV deexciting the 8^+ state of ^{132m}Te, shows a strong line at very low energy, interpreted as the L and M conversion electron groups of a new 22(1) keV transition. This electron line is not present in the spectrum of Fig. 1(b), obtained by gating on the γ ray of 150.8 keV deexciting the 7^- isomeric state (28 μs half-life) at 1925.2 keV. Consequently, one can conclude that this new 22 keV transition is above the 8^+ state at 2700 keV.

Figure 2 shows the γ decay spectrum of the ^{132m}Te isomer. In addition to the γ rays already observed in the previous measurement [5], a new line of 798 keV energy and 2(1)% relative intensity was observed. These new 22 and 798 keV transitions deexcite a new state at 2723 keV. This level is very likely the missing $\nu(h_{11/2}^{-2})_{10^+}$ isomeric state expected to decay by a strong $E2$ transition to the $\nu(h_{11/2}^{-2})_{8^+}$ state and by a weak $E3$ to the $\nu(h_{11/2}d_{3/2})_{7^-}$ state. From the measured half-life value, $T_{1/2}=3.70(9)$ μs, shown in Fig. 3, which is in good agreement with the previous value of

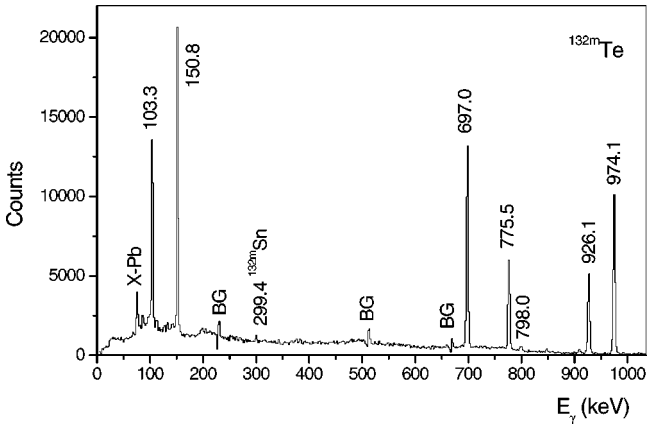

FIG. 2. γ ray decay of the ^{132m}Te isomer. A new line of 798 keV is observed. The ^{132m}Sn contaminant, previously studied [11], is very weakly produced in the present experiment.

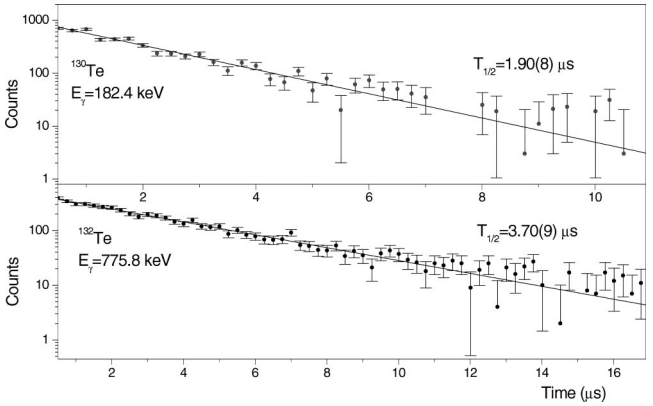

FIG. 3. Half-life spectra of the ^{130m}Te and ^{132m}Te isomers.

3.9(3) μs [5], it is possible to deduce a partial half-life $T_{1/2}=185(92)$ μs for the 798 keV and a hindrance factor $F_W=33(16)$ if one assumes an $E3$ multipolarity. In fact, since an $E3$ transition cannot take place between the $\nu(h_{11/2}^{-2})_{10^+}$ and the $\nu(h_{11/2}d_{3/2})_{7^-}$ configurations, the transition should proceed through an admixture of $\nu(h_{11/2}d_{5/2})_{7^-}$. However, this admixture is expected to be very weak, which explains the measured large hindrance factor. An $E3$ transition of the same nature is also present in ^{132}Xe [15]; its corresponding hindrance factor $F_W=96$ is slightly larger than for the analogous one in ^{132}Te.

Figure 4 shows the level scheme of the 3.7 μs isomer of ^{132m}Te including the new level at 2723 keV.

B. ^{130}Te

The γ-decay spectrum of the ^{130m}Te isomer agrees with the level scheme previously reported by Zhang *et al.* [6]. However, the half-life value of 1.90(8) μs found for the 182.4 keV transition, and shown in Fig. 3, is more than a

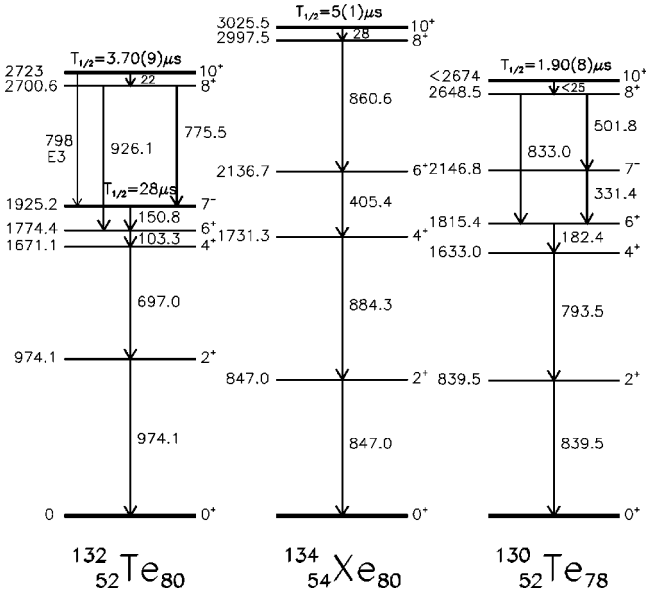

FIG. 4. Decay schemes of the 10^+ isomers in ^{132m,130m}Te and ^{134m}Xe.

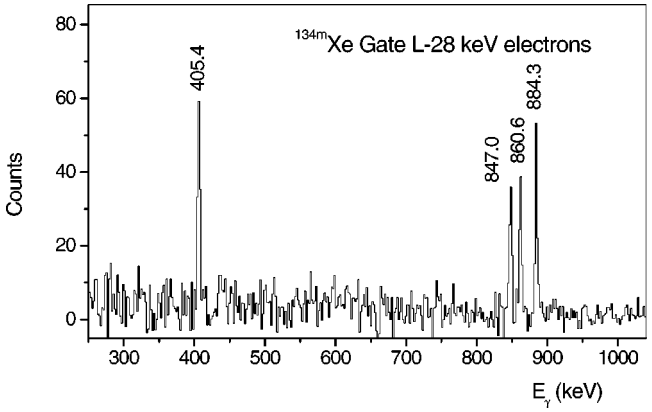

FIG. 5. γ spectrum of ^{134m}Xe gated by the 28 keV L-electron line detected by the Si(Li) detector.

factor of 2 smaller than the value of 4.2(9) μs, previously reported by these authors. Moreover, contrary to the ^{132}Te case, neither the $10^+ \rightarrow 8^+$ nor the $10^+ \rightarrow 7^-$ transitions were observed in this new measurement. The fact that the $10^+ \rightarrow 8^+$ isomeric transition was not observed requires a conservative upper limit of its energy of $E_\gamma = 25$ keV. Assuming a hindrance factor value for the $10^+ \rightarrow 7^-$, $E3$ transition analogous to the one measured for ^{132}Te, one obtains a partial half-life longer than 3.5 ms and a branching ratio smaller than 0.05%; this value is about 20 times lower than our detection limit. This explains why it was not observed in our measurement.

C. ^{134}Xe

A new isomer has been found in the $A = 134$ mass chain. It decays by a cascade of four γ rays of 847.0, 884.3, 405.4, and 860.6 keV energy as shown in Figs. 4 and 5. The first three lines have already been observed by Achterberg *et al.* [9,10] in the β decay of ^{134}Xe. The Si(Li) spectrum in coincidence with the 405.4 and 860.6 keV γ rays of Fig. 6 shows a unique 23(1) keV electron line which is interpreted as the

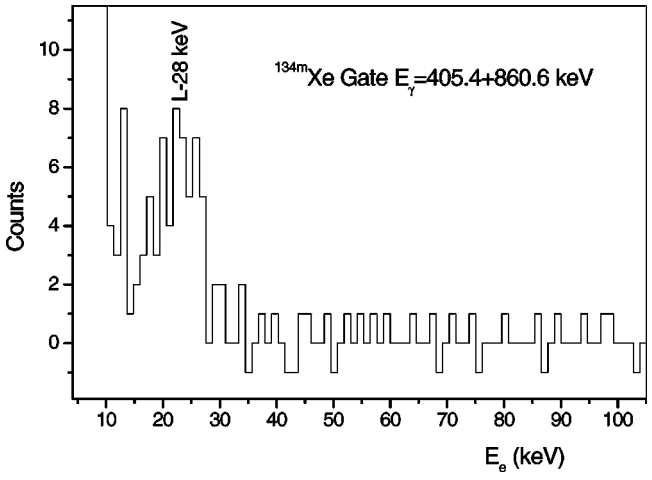

FIG. 6. Si(Li) spectrum of ^{134m}Xe gated by the sum of the 405.4 and 860.6 keV γ rays. The 23 keV electron line observed is interpreted as the L-electron group of the 28 keV isomeric transition.

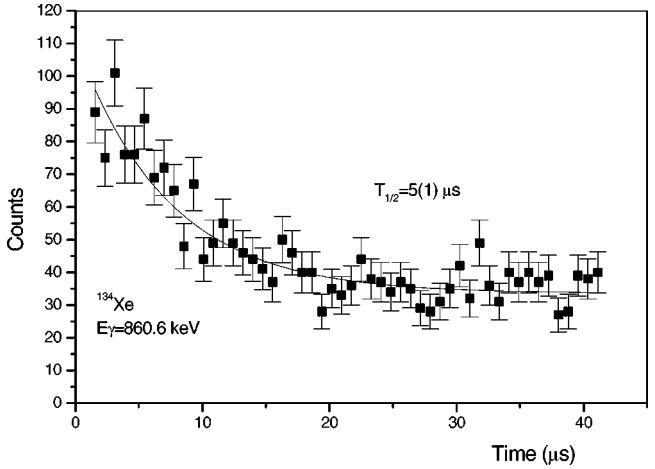

FIG. 7. Half-life spectrum of the ^{134m}Xe isomer.

L-conversion group of a 28(1) keV transition. This value is below the K electron binding energy of 34.6 keV and no x rays are expected in this case. A half-life $T_{1/2} = 5(1)$ μs is deduced for the isomer from the decay curve of Fig. 7. This lifetime is characteristic of an $E2$ transition as suggested by its transition probability $B(E2) = 26(5)e^2$ fm$^4 = 0.62(12)$ W.u.

Figure 4 shows the level scheme of the 5 μs isomer of ^{134m}Xe including the new levels at 2997.5 and 3025.5 keV. The excitation energy and the decay pattern of this isomer suggest a spin and parity assignment $I^\pi = 10^+$. The main difference with the previous level scheme obtained through the β decay of ^{134}I by Gualda *et al.* [9], concerns the 2136.7 keV level where the previous 5^+ assignment has been replaced by a 6^+ value from the present work. Note that this new assignment agrees with the fact that in the β-decay experiment this level is very weakly fed by the 4^+ state of ^{134}I and that an $E2$ multipolarity has been measured for the 405 keV transition by Achterberg *et al.* [10]. It is also possible that two levels coexist at about the same energy.

IV. TRANSITION PROBABILITIES

The $B(E2,\ 10^+ \rightarrow 8^+)$ values found in this work for ^{130,132}Te and ^{134}Xe are reported in Table I. In the previous section it was shown that the $10^+ \rightarrow 8^+$ isomeric transition energy for ^{130}Te should be lower than 25 keV. Consequently, the isomeric $E2$ transition probability in this case is almost independent of its energy, and corresponds to a value $B(E2) = 82(3)e^2$ fm$^4 = 2.01(0.07)$ W.u. In Table I the other values found in the literature for Sn, Te, Xe, and Ba isotopes having neutron numbers in the range $74 \leqslant N \leqslant 80$ [12–14] are also reported. In all cases we have chosen the $E2$ transition which takes place between 10^+ and 8^+ states present on the yrast line. Four values are still missing in this table; they correspond to ^{132,128}Xe and ^{136,130}Ba. In the case of ^{132}Xe, Kerek *et al.* [15] found a 10^+ level at 2752.3 keV which decays by a unique transition of $E3$ multipolarity to the 7^- level. The long half-life $T_{1/2} = 8.39$ ms found for the isomer suggests very strongly that in this case the 10^+ is below the 8^+ state. To our knowledge, it is the only case of

TABLE I. $B(E2)$ values of the $10^+ \rightarrow 8^+$ transitions in even-even Sn, Te, Xe, and Ba isotopes. The values of two different measurements are reported for ^{128}Te. The units are e^2 fm^4. The references on the existing data are given in square brackets.

Neutron number	Sn $B(E2)$	Te $B(E2)$	Xe $B(E2)$	Ba $B(E2)$
80	14.7(15) [1,3]	42(1)	26(5)	-
78	13.0(15) [1,3]	82(3)	-	4.2(1.5) [12]
76	5.6(3) [3,4]	53(4) [6] 79(13) [19]	65.0(1.5) [13]	19(2) [14]
74	0.9(1) [2]	126(6) [6]	-	-

a possible inversion of these two states in this mass region.

Several trends can be observed in the compilation of the $B(E2)$ values of Table I. The $B(E2,\ 10^+ \rightarrow 8^+)$ values in Te are larger than in the Sn isotones. Moreover, if one excepts the value of Zhang *et al.* [6] for the ^{128}Te isotope, these $B(E2)$ values increase smoothly when the neutron number decreases, while the trend is inverted for the Sn isotopes.

In the Sn nuclei, the observed trend is a consequence of the $\nu h_{11/2}$ subshell filling. Hence, one may conjecture that in the Te isotopes this effect is completely masked by some admixtures from other configurations. In fact, the most efficient way to increase the $B(E2,\ 10^+ \rightarrow 8^+)$ strength in the Te isotopes is to suppose that the $\{\nu(h_{11/2}^{-2}) \times \pi(0^+)\}_{8^+,10^+}$ leading components are mixed with the $\{\nu(h_{11/2}^{-2}) \times \pi(2^+)\}_{8^+,10^+}$ ones, where the proton pair is excited to a 2^+ configuration. The underlying cause of the mixing is the residual p-n interaction. Then, the transition takes place between the initial state

$$|10^+\rangle = \{\nu(10^+) \times \pi(0^+)\}_{10^+} + \epsilon_1 \{\nu(8^+) \times \pi(2^+)\}_{10^+} \quad (1)$$

and the final state

$$|8^+\rangle = \{\nu(8^+) \times \pi(0^+)\}_{8^+} + \epsilon_2\ \{\nu(10^+) \times \pi(2^+)\}_{8^+} \quad (2)$$

with the coefficients $\epsilon_1, \epsilon_2 \ll 1$. Sistemich *et al.* [5] have already suggested this possible mechanism but they were unable to compare it with experimental data because the $B(E2)$ value of the $10^+ \rightarrow 8^+$ transition was not known with a sufficient precision in ^{132}Te and was totally unknown in the lighter Te isotopes. However, the new data now allow us to make this comparison.

In order to verify the validity of this hypothesis, one has to evaluate the amplitude of the mixing ratio and the strength of the residual p-n interaction which are necessary to reproduce the $B(E2)$ values measured in the Te isotopes. To perform this calculation, we have made the simple but realistic approximation that the 0^+ and 2^+ proton states can be identified with the ground and first excited state of the Te isotopes. Consequently, the separation energy between the $\{\nu(h_{11/2}^{-2}) \times \pi(0^+)\}_{8^+,10^+}$ and $\{\nu(h_{11/2}^{-2}) \times \pi(2^+)\}_{8^+,10^+}$ configurations is expected to be comparable to the experimental excitation energy of the first 2^+ in the Te isotopes.

The $\langle 8^+ \| E2(\mathrm{Te}) \| 10^+ \rangle$ matrix element between the Te wave functions defined in Eqs. (1),(2) contains four terms which can be evaluated as a function of the elementary $\langle \nu(8^+) \| E2 \| \nu(10^+) \rangle$ and $\langle \pi(0^+) \| E2 \| \pi(2^+) \rangle$ matrix elements using the recoupling coefficients defined in [16]. Note that the recoupling coefficients for the two cross terms in the matrix element connecting the states in Eqs. (1),(2) are comparable to each other and that the coefficient connecting the second terms is negligible. Moreover, it is easy to show that these four matrix elements add up coherently and one finds that the reduced $E2$ transition probability can be written as

$$B(E2(\mathrm{Te}), 10^+ \rightarrow 8+) \sim [\sqrt{B(E2, \nu(10^+ \rightarrow 8^+))} + \epsilon\, 1.9 \sqrt{B(E2, \pi(2^+ \rightarrow 0^+))}]^2 \quad (3)$$

with the additional simplification that $\epsilon_1 = \epsilon_2 = \epsilon$. One observes in Eq. (3) that the $B(E2)$ value in Te is now the sum of a neutron and a proton contribution. These values can be approximated by the experimental $B(E2(\mathrm{Sn}),\ 10^+ \rightarrow 8^+)$ value taken from the Sn isotopes having the same neutron numbers as the Te isotopes and the $B(E2(\mathrm{Te}),\ 2^+ \rightarrow 0^+)$ value taken from the same Te nucleus. The latter $B(E2)$ value is much larger than the former (which occurs in a magic nucleus). Therefore, even a rather small mixing amplitude can lead to a large enhancement of the total $B(E2)$ value for the $10^+ \rightarrow 8^+$ transitions in Te. The experimental $B(E2(\mathrm{Te}),\ 2^+ \rightarrow 0^+)$ values as well as the excitation energies of the first 2^+ states E_{2^+} in the Te isotopes were taken from [17]. The amplitude of the mixing ratio ϵ, extracted from Eq. (3) by fitting the $B(E2,\ 10^+ \rightarrow 8^+)$ data, are reported in Table II. From the ϵ values and the proton excitation energy E_{2^+}, it is possible to deduce the residual p-n interactions Δ, also reported in Table II.

From these calculations one can conclude that a very weak mixing amplitude of proton two-particle components in the 10^+ and 8^+ levels in Te, $\epsilon = 0.08 - 0.17$, is able to produce the very strong increase in the $B(E2)$ values as observed experimentally from the Sn to the Te isotones. In contrast, the calculated energy shifts of the 8^+ and 10^+ states in Te isotopes due to the p-n residual interaction are always smaller than 20 keV, which indicates that the energies of these levels are only very weakly affected by the mixing. The residual p-n interaction strengths $\Delta = 80-120$ keV deduced from these calculations are of the

TABLE II. Values of the ϵ mixing amplitude and of the Δ p-n residual interaction matrix element deduced from the experimental $B(E2)$ values and the E_{2^+} excitation energy of the first 2^+ state in Te. The $B(E2)$ values are in e^2 fm^4.

Nucleus	E_{2^+} keV	$B(E2,2^+\rightarrow 0^+)$ Te	$B(E2,10^+\rightarrow 8^+)$ Sn	$B(E2,10^+\rightarrow 8^+)$ Te	ϵ	Δ keV
^{132}Te	974	286[a]	14.7	42	0.08	80
^{130}Te	839	590	13.0	82	0.12	102
^{128}Te	743	766	5.6	53–79	0.09–0.12	70–90
^{126}Te	666	950	0.9	126	0.17	118

[a]Value deduced from the experimental $B(E2,\ 6^+\rightarrow 4^+)$ [5], assuming that the 0^+ to 6^+ levels all have the same pure $\pi(g^2_{7/2})$ configuration.

same order of magnitude as empirical ones, about 250 keV, extracted from the binding energies in the vicinity of ^{132}Sn [18].

In conclusion, the proposed mechanism is able to explain the large observed difference in the behavior of the $B(E2)$ strengths in the Sn and Te isotopes. We conjecture that this feature is more general and is very likely present in other closed shell regions of the nuclear chart, but it is much easier to observe in the Sn-Te region.

An analogous behavior is observed in Table I when the number of proton pairs increases in Xe and Ba isotopes: the $B(E2)$ values increase when the neutron number decreases, but they are systematically lower than in the Te isotones. Note that when several pairs of neutrons and protons are simultaneously active the possibilities of configuration mixing increase considerably. However, it is more difficult to take into account all these effects and to predict the trend of the $B(E2)$ from very simple arguments like in the Te case.

V. CONCLUSION

In this work we have measured the $B(E2)$ values of the $10^+\rightarrow 8^+$ transitions in three even-even nuclei very close to the doubly magic ^{132}Sn nucleus. Although the experimental data are still incomplete, it is already possible to observe a systematic trend in these $B(E2)$ values. We have shown that one can explain the strong increase in the $B(E2)$ strength from Sn to Te isotones: small configuration mixings involving proton 2^+ configurations in the 8^+ and 10^+ levels due to the p-n interaction can have very strong effects on the $B(E2)$ values, but they negligibly perturb the energies of these states. We expect that analogous effects should be present in other regions around closed shells. New experiments are necessary in the future to complete the data in the ^{132}Sn region but also in other regions of closed shell nuclei. Moreover, it was also observed in this work that the $B(E2)$ values decrease as a function of the number of valence proton pairs, from Te to Ba, but no definitive explanation was proposed to explain this trend.

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