On the origin of low-lying $M1$ strength in even-even nuclei

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Abstract. The 2_2^+ state in ^{132}Te is identified as the one-phonon MSS in a projectile Coulomb excitation experiment presenting a firm example of a MSS in unstable, neutron rich nuclei. The results of shell-model calculations based on the low-momentum interaction V_{low-k} are in good agreement with experiment demonstrating, the ability of the effective shell-model interaction to produce states of mixed symmetry character.

1. Introduction

Neutron-rich nuclei in the vicinity of double-magic shell closures away from the line of stability are currently of great interest. This interest is motivated by new experimental data which have become available in the recent years due to the progress made in the production of radioactive ion beams (RIBs). On the journey towards the neutron drip line one needs a reliable theoretical model which incorporates the known features of the nuclear many-body system and has enough predictive power for wide range of nuclei. The nuclear shell model provides the basic framework for understanding the structure of complex nuclei as arising from the individual motion of nucleons and the effective nuclear interaction between them [1]. In this model, the nuclei around doubly closed shells play a special role. They provide direct information on the single-particle energies and the best testing ground for different components of the effective interaction.

In this context, a good examples is given by ^{136}Te where a reduction of both the $E_x(2_1^+)$ and the $B(E2; 2_1^+ \rightarrow 0_1^+)$ with respect to the lighter isotopes is observed [2]. This simultaneous decrease clearly violates the empirical rules for properties of quadrupole collective states [3, 4]. In addition, the fact that the $B(E2; 2_1^+ \rightarrow 0_1^+)$ in ^{136}Te is significantly lower than the one

in ^{132}Te implies a considerable difference between the structures of the 2^+_1 states in these nuclei. Indeed, it is suggested [5, 6, 7] that neutron dominance in the wave function of the 2^+_1 state in ^{136}Te is the main reason for the observed peculiar properties. This proton-neutron asymmetry is a combined effect of the asymmetry in the excitation energies of the basic 2^+ proton ($E_x(2^+_1; {}^{134}$Te)= 1279 keV) and neutron ($E_x(2^+_1; {}^{134}$Sn)= 762 keV) configurations (which originates from the reduction of the neutron pairing above $N = 82$) and the weak pn-interaction which cannot compensate for the above energy difference [6]. The situation in ^{132}Te is quite different; the excitation energy of the basic neutron 2^+ configuration in ^{132}Te ($E_x(2^+_1; {}^{130}$Sn)= 1221 keV) is comparable to the excitation energy of the basic proton 2^+ configuration. This suggests that the 2^+_1 state in ^{132}Te has a more balanced proton-neutron character than that in ^{136}Te, which leads to a $B(E2; 2^+_1 \rightarrow 0^+_1)$ value in agreement with the expected trends as has been observed experimentally [2]. A direct proof for the above scenario may come from a comparison of the magnetic moments of the 2^+_1 states in ^{132}Te [8, 10] and ^{136}Te. Another way to investigate the proton-neutron balance of the wave function is based on the decay properties of the isovector analogue of the 2^+_1 state [11], the so called one-phonon state with mixed proton-neutron symmetry (MSS) – $2^+_{1,\mathrm{ms}}$ [12]. The one-phonon 2^+ vibrational states in even-even nuclei are the simplest collective excitations. Due to the two-fluid nature of nuclear matter they appear as a symmetric [the one-phonon 2^+_1 fully symmetric state (FSS)] or an antisymmetric combination of the involved proton and neutron configurations. Because of its isovector nature the $2^+_{1,\mathrm{ms}}$ state decays with a strong $M1$ transition to the one-phonon FSS and with a weak $E2$ transition to ground state. This unique decay serves as an experimental fingerprint for the $2^+_{1,\mathrm{ms}}$ state. In the framework of IBM-2 [12] the one-phonon FS and MSS are orthogonal states, built on the same microscopic configurations. Moreover, it has been shown that the absolute $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1)$ strength is highly sensitive to the proton-neutron balance of the wave functions through a mechanism dubbed configuration isospin polarization (CIP) [13]. The case of significant CIP which can be expected in ^{136}Te is manifested by small absolute $M1$ rates. The opposite case of vanishing CIP can be expected in ^{132}Te which leads to a very strong $M1$ transition between the one-phonon MS and FSSs.

The CIP of one-phonon MS and FSSs in ^{132}Te and ^{136}Te allows the proton-neutron balance in their wave functions to be studied by measuring the $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1)$ values. The experimental identification of one-phonon MSSs also allows tests of the ability of the effective interaction to produce states of such character. However, the information on MSSs is relatively scarce [14]. This is particularly true for the mass $A \approx 130$ region where until recently only few MSSs were known [15, 16, 17]. In the last several years the number of identified MSSs in this mass region has grown substantially; by using projectile Coulomb excitation reactions and the Gammasphere array at Argonne National Laboratory, the one-phonon MSSs were identified in several low-abundant stable nuclei, namely ^{134}Xe [18], ^{138}Ce [19], ^{136}Ce [20], and ^{130,132}Xe [21]. This experimental technique is considered to be applicable for identification of MSSs of RIBs but this has not been demonstrated in practice, yet. There have already been a few unsuccessful experimental attempts to identify one-phonon MSSs in neutron rich nuclei using various experimental technique [22, 23]. This leaves open the question: what is the appropriate technique to identify and study the properties of MSSs in radioactive nuclei? *No MSSs have ever been solidly identified in unstable nuclei on the basis of large absolute $M1$ transition rates.*

The new experimental data on MSSs in the stable $N = 80$ isotones allow predictions to be made of the energy of one phonon MSS in the unstable, neutron rich nucleus ^{132}Te [18]. The fit procedure [24] used in Ref. [18] suggests the 2^+_2 level in ^{132}Te at 1.665 MeV as a candidate for the one-phonon MSS. In this study we report on the first firm experimental identification of a one-phonon MSS in the neutron rich unstable nucleus ^{132}Te demonstrating that the projectile Coulomb excitation of RIBs is the proper experimental technique to study the MSSs in exotic nuclei. The observed strong $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1)$ transition is in agreement with the expectations

for vanishing CIP which is also confirmed by the performed shell model calculations.

2. Experimental details

^{132}Te is one of the first radioactive neutron-rich nuclei in which the $B(E2; 2_1^+ \to 0_1^+)$ have been measured in a projectile Coulomb excitation reaction of RIB [2]. The excited states of ^{132}Te have been identified in a $\gamma - \gamma$ measurement following the β^- decay of ^{132}Sb [27]. The second excited state at 1665 keV decays predominantly to the 2_1^+ state by a 690.9-keV transition ($I_\gamma(690.9\text{keV}) = 20(3)$) and to the ground state by a very weak 1665.3-keV transition ($I_\gamma(1665.3\text{keV}) = 0.2(1)$) which leads to a tentative spin-parity assignment of (2^+) [27]. The observed branching ratio is typical for the decay of a $2_{1,\text{ms}}^+$ state. The magnetic moment of the 2_1^+ state in ^{132}Te has also been determined experimentally by using the technique of recoil in vacuum after a projectile Coulomb excitation reaction on a carbon target [8]. Providing that states above the 2_1^+ are also populated in this experiment, their relative γ-ray yields with respect to the 2_1^+ state measure the relative Coulomb excitation cross-sections. This experimental information in a combination with the known $B(E2; 2_1^+ \to 0_1^+)$ value [2] may allow some conclusions on the decay strength to be drawn in the same manner as was demonstrated in the case of stable nuclei [19, 18, 20, 21]. This eventually could reveal the character of the 2_2^+ state in ^{132}Te. With this idea in mind we have re-evaluated the data from the experiment on the projectile Coulomb excitation reaction of ^{132}Te on a carbon target [8].

The experiment was carried out at the HRIBF Facility at Oak Ridge National Laboratory. The ^{132}Te RIB was accelerated to 3 MeV/u and Coulomb excited in 1.13(6) mg/cm^2 thick self-supporting ^{12}C target. The data were acquired for 64 hours with a beam intensity of 3×10^7 pps. All γ rays resulting from Coulomb excitation and decay of ^{132}Te RIB were detected with the CLARION array [28] which consists of 11 clover detectors arranged in three rings. Five clover detectors are located at 90°, four at 132°, and two at 155° with respect to the beam axis. ^{12}C ions scattered out of the target were detected in the HyBall array [28] which consists of 9 annular rings of CsI charged–particle detectors, each ring subtending a relatively small range of angles θ_p. Only the three most forward rings were used in our experiments. There are 6 detectors in the first ring ($7° < \theta_p < 14°$), 10 detectors in the second ring ($14° < \theta_p < 28°$) and 12 detectors in the third ring ($28° < \theta_p < 44°$). The event trigger was set for either coincidence between CLARION and HyBall or every one of ten single HyBall hits. γ-rays observed in the experiment were corrected for Doppler shift using both the angle of emitted γ-ray and angle of detected ^{12}C recoil from the target. In order to reduce the background from uncorrelated CLARION-HyBall coincidences, the time difference between CLARION and HyBall was projected and the gate set on uncorrelated events was subtracted from the gate set on correlated events. This procedure yields the γ-ray spectrum shown in Fig. 1. Besides the 974-keV transition which dominates the spectrum in Fig. 1 and represents the decay of the 2_1^+ state, we also have observed a γ-ray with energy of 691 keV (see the inset in Fig. 1). This peak is sharp and well pronounced which indicates that it is emitted in flight at speed and direction equal to those of the excited ^{132}Te ions. From this observation, the coincidence conditions and the background subtraction procedure it is clear that the 691-keV γ-line represents the decay of a low-lying state in ^{132}Te. Indeed, a γ-ray with this energy is known in the decay scheme of ^{132}Te. It represents the $(2_2^+) \to 2_1^+$ transition [27]. Apparently the level at 1665 keV in ^{132}Te is populated in the present projectile Coulomb excitation experiment which confirms its tentatively suggested spin-parity assignment of 2_2^+. From the peak areas of the 974-keV [$N = 30400(500)$] and the 691-keV [$N = 354(102)$] transitions obtained from the spectrum in Fig. 1 and the reported branching ratio for the decay of the 2_2^+ state [27] the relative population of the 2_2^+ state with respect to the population of the 2_1^+ state is $1.01(28) \times 10^{-2}$. It measures the relative Coulomb excitation (CE) cross sections. Erroneous target thickness were reported in Ref. [8, 2]. The correct thickness of the target in both references was 1.13(6) mg/cm^2. As a consequence, the values for the $B(E2; 0_1^+ \to 2_1^+)$ in
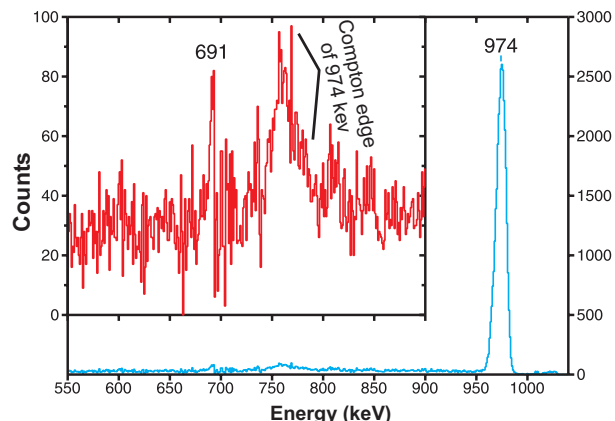
Figure 1. (Color on-line)Doppler corrected, background subtracted spectrum of all γ rays observed in coincidence with ^{12}C recoils detected in HyBall. For details see the text. The inset shows the existence of 691-keV transition.

^{132,134,136}Te given in Table II of Ref. [2] should read 0.216(22) e^{2}b^2, 0.114(13) e^{2}b^2, 0.122(18) e^{2}b^2, respectively. The new value for the $B(E2; 0_1^+ \to 2_1^+)$ in ^{132}Te influences the adopted value for the lifetime of the 2_1^+ state and consequently the value for its magnetic moment deduced in [8, 9]. From the re-evaluated lifetime of the 2_1^+ state ($\tau = 2.2(5)$ps) and using the RIV calibration from [9] we find $g(2_1^+) = (+)0.46(5)$. We stress that these new values do not affect the phenomenon of lowering the $B(E2)$ value in ^{136}Te and its consequences as discussed above and in Ref. [2]. The experimental relative population of the 2_2^+ state was fitted to the Winther-de Boer theory using a multiple CE code [29] and taking into account the energy loss of the beam in the target ($\sim$ 80 MeV). Absolute cross sections were derived using the new value $B(E2; 0_1^+ \to 2_1^+)=0.216(22)$ and the branching ratio for the decay of the 2_2^+ state [27].

The combination of the Coulomb excitation yields, the known decay branching ratio, and the fact that the $B(E2; 2_2^+ \to 2_1^+)$ value is extremely unlikely to exceed the vibrational estimate of twice the $B(E2; 2_1^+ \to 0_1^+)$ implies that the 691-keV transition is predominantly a $M1$ transition. Variation of unknown $E2$ strength between 0 and 20 W.u. introduces an uncertainty in the final matrix elements of less than 8%. Unknown quadrupole moments of the 2_1^+ and the 2_2^+ states were varied between the extreme rotational limits which introduces additional uncertainties for the matrix elements of about 1%. The sizes of the resulting matrix elements are insensitive to the choice of their signs within the statistical uncertainties. The mean values of the final results are derived assuming a pure $M1$ $2_2^+ \to 2_1^+$ transition and vanishing quadrupole moments, while the estimated uncertainties account for the variations of these quantities. The final results are:

$$B(E2; 2_2^+ \to 0_1^+) = 0.5(2)\text{W.u.}$$
$$B(M1; 2_2^+ \to 2_1^+) = 5.4(3.5)\mu_N^2.$$

The extremely large $B(M1)$ value has a large uncertainty which is dominated by the uncertainty of the branching ratio [27]. On the other hand, due to the use of a low-Z target the excitation processes are predominantly one step. Therefore, the result obtained for the $B(E2; 2_2^+ \to 0_1^+)$ value, which is also the primary fitting parameter in the Coulomb excitation code, is more reliable. We have not observed the 1665-keV transition in our data but from the detection limit at 1665 keV we obtained lower limit for $I_\gamma(691\text{keV})/I_\gamma(1665\text{keV}) > 4.2$. Replacing the branching ratio of 2_2^+ state from Ref. [27] with the calculated lower estimate we establish the lower limit of $B(M1; 2_2^+ \to 2_1^+) > 0.23\mu_N^2$. This value was obtained entirely on the basis of the current data. Even this lower limit for the $B(M1; 2_2^+ \to 2_1^+)$ value clearly shows that the 2_2^+ state of ^{132}Te at 1665 keV is the one-phonon MSS.

^{132}Te nucleus, with two proton and two neutron holes away from the double magic nucleus ^{132}Sn, is a natural candidate to be studied within the realistic shell-model framework, which has proved to be a valuable tool to investigate nuclei in this region (see Ref. [30] and references

therein). Calculations have been performed along these lines, focusing on the structure of the 2^+ states. We consider ^{132}Sn as a closed core and let the valence protons and neutron holes occupy the five levels $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ of the 50–82 shell. The single-particle and single-hole energies have been taken from the experimental spectra of ^{133}Sb and ^{131}Sn [33], respectively. The only exceptions are the proton $\epsilon_{s_{1/2}}$ which has been taken from Ref. [34] and the $h_{11/2}$ neutron-hole level which has been taken from Ref. [35].

The two-body component of the effective Hamiltonian has been derived within the framework of perturbation theory [36] starting from the CD-Bonn NN potential [32] renormalized by way of the V_{low-k} approach [31] with a cutoff momentum of $\Lambda = 2.2$ fm^{-1}. The shell-model calculations were performed using the OXBASH computer code [37]. The calculated energy spectrum of low-

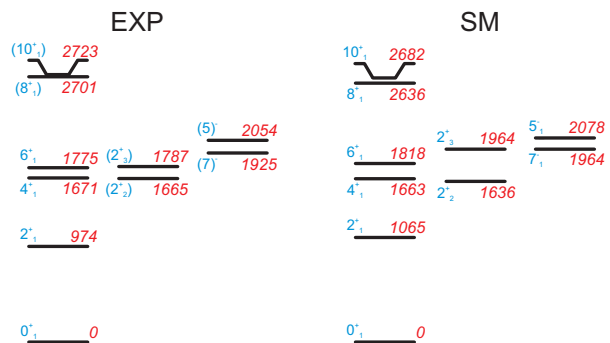**Figure 2.** (Color on-line)The experimental [27] (EXP) and the calculated (SM) spectra of low-lying states of ^{132}Te.

lying states of ^{132}Te is compared with experimental data in Fig. 2. The shell model calculations reproduce the ordering and the excitation energies of the states. The largest deviations between the calculated energies and the experimental data are 91 keV for the 2_1^+ state and 177 keV for the 2_3^+ state while for the other states the deviations are less than 50 keV.

The MS character of the calculated 2_2^+ state of ^{132}Te is evident from the structure of its wave function. In terms of the basic 2^+ proton and neutron excitations the shell-model wave functions of the ground and the two lowest lying 2^+ states can be presented as follows:

$$|0_1^+\rangle \;=\; 0.94|0_1^+\rangle_\nu|0_1^+\rangle_\pi + ... \qquad (1)$$

$$|2_1^+\rangle \;=\; 0.66|0_1^+\rangle_\nu|2_1^+\rangle_\pi + 0.62|2_1^+\rangle_\nu|0_1^+\rangle_\pi + ... \qquad (2)$$

$$|2_2^+\rangle \;=\; 0.58|0_1^+\rangle_\nu|2_1^+\rangle_\pi - 0.63|2_1^+\rangle_\nu|0_1^+\rangle_\pi + ... \qquad (3)$$

where $\pi(\nu)$ denote the respective excitations in ^{134}Te (^{130}Sn) and "..." means minor components. Equations (2,3) indicate almost equal proton and neutron contributions to the 2_1^+ and the 2_2^+ states of ^{132}Te, *i.e.* no CIP is present. The main difference between Eqs. (2) and (3) is the opposite sign of the neutron and proton components of the wave function of the 2_2^+ state [see Eq. (3)] which makes it antisymmetric with respect to interchanges of proton and neutron components in the wave function. Eq.(3) represents a shell-model wave function which describes a MSS. The isovector character of this wave function leads to the relatively large $B(M1; 2_2^+ \to 2_1^+)$ value. The shell-model calculations confirm the nature of the two lowest lying 2^+ states of ^{132}Te as FS and MS states, respectively with balanced neutron and proton components.

3. Summary

In summary, by using the data from a projectile Coulomb excitation experiment we have identified the 2_2^+ state of ^{132}Te as the one-phonon MSS. This is the first case of a MSS of an unstable, neutron rich nucleus identified on the basis of a large absolute $M1$ transition strength. The experimental results prove that projectile Coulomb excitation experiments on

light targets are an appropriate technique to study MSSs of exotic nuclei. The performed shell model calculations based on the V_{low-k} interaction successfully reproduce the experimental data and the isovector character of the 2_2^+ state of ^{132}Te. The shell-model wave functions of the one-phonon states have a balanced proton-neutron character as expected from the evolution of collectivity in the neutron rich tellurium isotopes around the $N = 82$ shell closure.

Acknowledgments

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