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One-phonon isovector $2^+_{1,\mathrm{MS}}$ state in the neutron rich nucleus ^{132}Te

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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 the endeavour to understand the nuclear many-body system at extreme neutron excess and fuelled 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). Nuclei with a few nucleons outside 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 used in nuclear shell model.

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 the ground state. This unique decay serves as an experimental fingerprint for the $2^+_{1,\mathrm{ms}}$ state. In the framework of IBM-2 [1] the one-phonon FSS and mixed-symmetry state (MSS) are orthogonal states, built on the same microscopic configurations. Moreover, it has been shown that the absolute $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1)$ strength is highly sensitive to the proton-neutron balance of the wave functions through a mechanism dubbed configurational isospin polarization (CIP) [2]. The CIP mechanism and its manifestations have been experimentally confirmed in ^{92}Zr [3]. The case of significant CIP, which can be expected in ^{136}Te, should be manifested by comparatively

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small absolute $M1$ rates. The opposite case of vanishing CIP can be expected in ^{132}Te which leads to a strong $M1$ transition between the one-phonon MS and FSSs. Apparently, 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 and comparing their absolute $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1)$ values. The new experimental data on MSSs in the stable $N = 80$ isotones have revealed their evolution with increasing proton number which allows a prediction for the energy of the one-phonon MSS in the ^{132}Te to be made [4]. The fit procedure [5] used in Ref. [4] suggests the 2^+_2 level in ^{132}Te at 1665 keV as a candidate for the one-phonon MSS. Shell-model calculations [6] have corroborated this prediction.

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 $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1)$ value is in agreement with the expectations for vanishing CIP which is also confirmed by the performed shell model calculations.

2. Experimental details and discussion

^{132}Te is one of the first radioactive neutron-rich nuclei in hich the $B(E2; 2^+_1 \to 0^+_1)$ value was measured in projectile Coulomb excitation reactions of a RIB [7]. The excited states of ^{132}Te have been identified in a $\gamma - \gamma$ measurement following the β^- decay of ^{132}Sb [8]. The second excited state at 1665.3 keV discovered in the latter study decays predominantly to the 2^+_1 state by a 690.9 keV transition and to the ground state by a very weak 1665.3 keV transition $[I_\gamma(691\mathrm{keV})/I_\gamma(1665\mathrm{keV}) = 100(52)]$. The observed intensity dominance of the decay to the 2^+_1 state relative to the high-energy decay to the 0^+_1 ground state is typical for the decay of a $2^+_{1,\mathrm{ms}}$ state due to its large $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1)$ value. The magnetic moment of the 2^+_1 state in ^{132}Te has been determined experimentally by using the technique of recoil in vacuum (RIV) after a projectile Coulomb excitation reaction on a carbon target [9]. 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 combination with the known $B(E2; 0^+_1 \to 2^+_1)$ value [7] can give the decay strength. This information 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 described in [9].

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 on a thick self-supporting ^{12}C target. The data were acquired for 64 hours with a beam intensity of about 3×10^7 pps. γ rays resulting from Coulomb excitation and decay of ^{132}Te nuclei were detected with the CLARION array [10]. ^{12}C ions scattered out of the target were detected in the HyBall array [10]. The used rings in HyBall covered carbon scattering angles between 7° and 44° [9]. γ-rays observed in coincidence with the ^{12}C ions detected in HyBall were corrected for Doppler shift. In order to reduce the background from uncorrelated CLARION-HyBall coincidences, the time difference between CLARION and HyBall was projected and the γ spectrum from the gate set on uncorrelated events was subtracted from the γ spectrum from the gate set on correlated events. This procedure yields the γ-ray spectrum shown in figure 1. In this spectrum all γ-rays from the radioactive decays of the beam are completely subtracted. Besides the 974-keV transition, which dominates the spectrum 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 figure 1). This peak is sharp and well pronounced, which indicates that it is emitted in flight with a speed and direction equal to those of the excited ^{132}Te ions. From this observation, together with the coincidence conditions and the background subtraction procedure, it is clear that the 691-keV γ-line represents the decay of a low-lying Coulomb-excited state of ^{132}Te. Indeed, a γ-ray with this energy is known [8] in the decay scheme of ^{132}Te. It represents the $(2^+_2) \to 2^+_1$ transition. As seen in figure 1 the 691 keV line is certainly not the known 697 keV $4^+ \rightarrow 2^+$ transition [8]. The 1665-keV level was tentatively assigned spin-parity 2^+ in Ref. [8] on the basis of observed decay to the 2_1^+ and 0_1^+ states. Given the observation of the 1665-keV level under the present experimental conditions, the only possible spin-parity assignment for it is 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 figure 1 and the reported branching ratio for the decay of the 2_2^+ state [8] 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. [7, 9]. The correct thickness of the target in both references was 1.13(6) mg/cm^2. As a consequence, the values for the $B(E2; 0_1^+ \rightarrow 2_1^+)$ in ^{132,134,136}Te given in Table II of Ref. [7] 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 $B(E2; 0_1^+ \rightarrow 2_1^+)$ 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 [9, 11]. From the re-evaluated lifetime of the 2_1^+ state ($\tau = 2.2(5)$ps) and using the RIV calibration from [11] 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. [7].

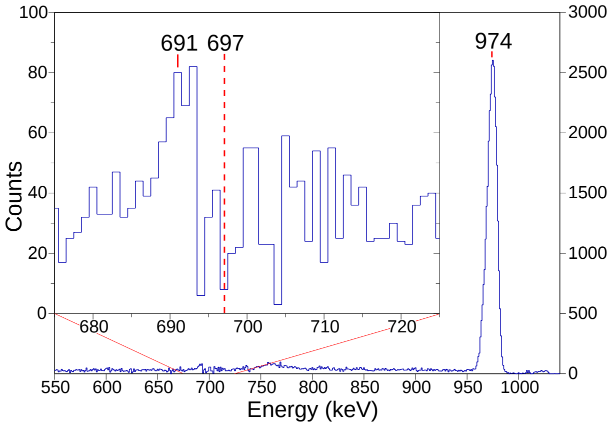

Figure 1. (Color online) Doppler corrected, background subtracted spectrum of all γ rays observed in coincidence with ^{12}C recoils detected in HyBall. For details see the text. The inset shows the existence of 691-keV transition.

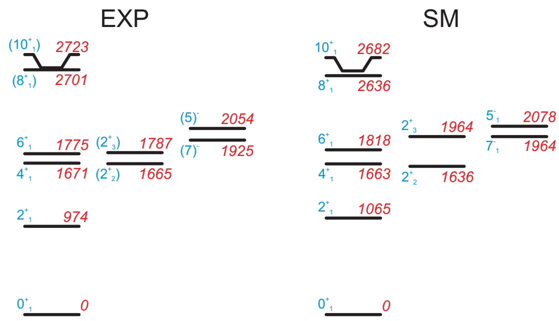

Figure 2. (Color on-line) The experimental [8] (EXP) and the calculated (SM) spectra of low-lying states of ^{132}Te.

The experimental relative population of the 2_2^+ state was fitted to the Winther-de Boer theory using a multiple CE code [12] 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 $B(E2; 0_1^+ \rightarrow 2_1^+)$=0.216(22) and the branching ratio for the decay of the 2_2^+ state [8].

The combination of the Coulomb excitation yields, the known decay branching ratio, and the fact that the $B(E2; 2_2^+ \rightarrow 2_1^+)$ value is extremely unlikely to exceed the vibrational estimate of twice the $B(E2; 2_1^+ \rightarrow 0_1^+)$ 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 $M1$ $2_2^+ \rightarrow 2_1^+$ transition and vanishing quadrupole moments, while the estimated uncertainties account for the variations of these quantities. The final results are

Observable	Unit	Experiment	Shell Model
$B(E2;2_1^+\rightarrow 0_1^+)$	[W.u.]	$10(1)^a$	7.8
$\mu(2_1^+)$	[μ_N]	$+0.92(10)^b$	0.68
$B(E2;2_2^+\rightarrow 0_1^+)$	[W.u.]	$0.5(1)^c$	0.21
$B(E2;2_2^+\rightarrow 2_1^+)$	[W.u.]	$0\div 20^c$	0.24
$B(M1;2_2^+\rightarrow 2_1^+)$	[μ_N^2]	$5.4(3.5)^c$ ($>0.23^d$)	0.20
$\mu(2_2^+)$			0.69

Table 1. Comparison of the available experimental data on the electromagnetic properties of the 2_1^+ and the 2_2^+ states in ^{132}Te with results of the shell model calculations.
[a] From Ref. [7] and the present work.
[b] From Ref. [11, 22] and the present work.
[c] From the Coulomb excitation analysis in this work and the branching ratio of the decay of 2_2^+ from Ref. [8].
[d] From the Coulomb excitation analysis and the detectability limit for 1665-keV transition in this work.

$B(E2;2_2^+\rightarrow 0_1^+) = 0.5(2)$W.u. and $B(M1;2_2^+\rightarrow 2_1^+) = 5.4(3.5)\mu_N^2$.

The extremely large $B(M1)$ value has a large uncertainty which is dominated by the uncertainty of the branching ratio [8]. 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 $B(E2;2_2^+\rightarrow 0_1^+)$ 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 (see e.g. [13]) 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. [8] with the calculated lower estimate we establish the lower limit of $B(M1;2_2^+\rightarrow 2_1^+) > 0.23\mu_N^2$. This value was obtained entirely on the basis of the current data. Even this lower limit for the $B(M1;2_2^+\rightarrow 2_1^+)$ 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. [14] 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 [15], respectively. The only exception is the proton $\epsilon_{s_{1/2}}$ which has been taken from Ref. [16] the $h_{11/2}$ neutron-hole level which has been taken from Ref. [17].

The two-body component of the effective Hamiltonian has been derived within the framework of perturbation theory [18] starting from the CD-Bonn NN potential [19] renormalized by way of the V_{low-k} approach [20] with a cutoff momentum of Λ= 2.2 fm^{-1}. The shell-model calculations were performed using the OXBASH computer code [21]. The calculated energy spectrum of low-lying states of ^{132}Te is compared with experimental data in figure 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 calculated and the experimental electromagnetic properties of 2_1^+ and 2_2^+ states are summarized in Table 1.

All the experimental values in Table 1 are well reproduced except the $B(M1;2_2^+\rightarrow 2_1^+)$ strength for which the calculations reproduce only the lower limit. The MS character of the calculated 2_2^+ state of ^{132}Te is evident from the structure of its wave function too. 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:

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

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

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

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. This is due to almost equal energies of the basic 2^+ proton [$E_x(2_1^+;\, ^{134}\mathrm{Te})$= 1279 keV] and neutron [$E_x(2_1^+;\, ^{130}\mathrm{Sn})$= 1221 keV] configurations which even in the case of very weak pn interaction leads to one-phonon 2^+ states with a balanced proton-neutron character. 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 Equation (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 $B(M1; 2_2^+ \rightarrow 2_1^+)$ 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.

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