Structure of $2^{+}_{1,2}$ states in ^{132,134,136}Te

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Proposal to the ISOLDE and Neutron Time-of-Flight Committee

(Following HIE-ISOLDE Letter of Intent I-111)

2^+ Anomaly and Configurational Isospin Polarization of ^{136}Te

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Outline

- Introduction
- The method
- The first and second 2^+ excitations in $^{132,134,136}Te$
- Summary

particle-hole channel

particle-particle channel

Skyrme interaction

$$V_0\left(1-\eta\frac{\rho(r_1)}{\rho_0}\right)\delta\left(\vec{r}_1-\vec{r}_2\right)$$

$\Downarrow$

HF-BCS calculations

$\Downarrow$

QRPA calculations $\quad Q_\nu^+|0>$

$$Q_\nu^+=\frac{1}{2}\sum_{jj'}X_{jj'}^\nu A^+(jj';JM)-(-1)^{J-M}Y_{jj'}^\nu A(jj';J-M)$$

$$A^+(jj';JM)=\sum_{mm'}<jmj'm'|JM>\alpha_{jm}^+\ \alpha_{j'm'}^+$$

Using the equation-of-motion approach one can get

$$\begin{pmatrix}\mathcal{A} & \mathcal{B}\\ -\mathcal{B} & -\mathcal{A}\end{pmatrix}\begin{pmatrix}X\\ Y\end{pmatrix}=\omega\begin{pmatrix}X\\ Y\end{pmatrix}$$

Making use of the finite rank separable approximation for the residual interaction enables one to perform the calculations in very large configuration spaces

Nguyen Van Giai, Ch. Stoyanov, and V. V. Voronov, Phys. Rev. C57,1204 (1998).
A.P.S., V. V. Voronov, and Nguyen Van Giai, Phys. Rev. C77, 024322 (2008).

The coupling between one- and two-phonon terms in the wave functions of excited states are taken into account

$$|\Psi_{JM\nu}\rangle = \left\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_2 i_2} Q^+_{\lambda_1 i_1} \right]_{JM} \right\} |0\rangle$$

with the normalization condition

$$\sum_i [R_i(\lambda\nu)]^2 + 2 \sum_{\lambda_1 i_1 \lambda_2 i_2} \left[P^{\lambda_1 i_1}_{\lambda_2 i_2}(\lambda\nu) \right]^2 \left(1 + K^\lambda(\lambda_1 i_1, \lambda_2 i_2)\right) = 1$$

$$K^\lambda = (2\lambda_1 + 1)(2\lambda_2 + 1) \frac{1}{1+\delta_{\lambda_1 i_1, \lambda_2 i_2}}$$

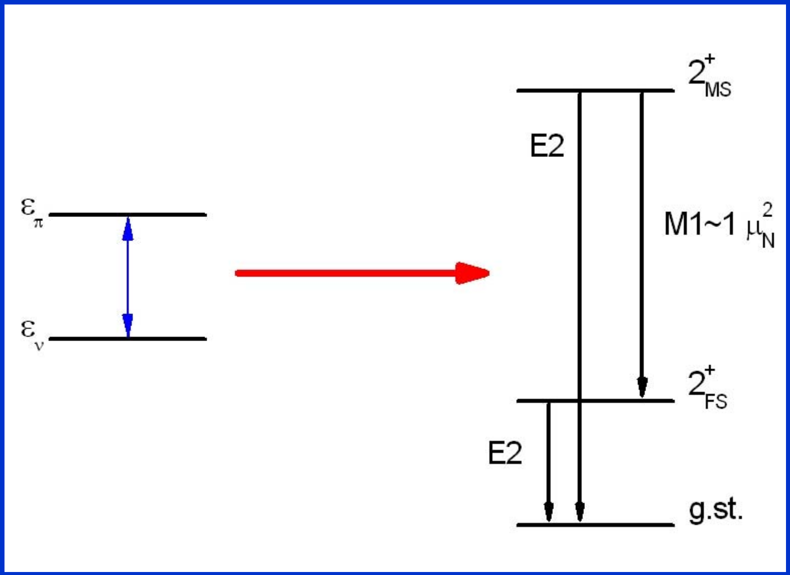
$$\times \sum_{j_1 j_2 j_3 j_4} (-1)^{j_2 + j_4 + \lambda} \begin{Bmatrix} j_1 & j_2 & \lambda_2 \\ j_4 & j_3 & \lambda_1 \\ \lambda_1 & \lambda_2 & \lambda \end{Bmatrix} \left(X^{\lambda_1 i_1}_{j_1 j_4} X^{\lambda_1 i_1}_{j_3 j_4} X^{\lambda_2 i_2}_{j_3 j_2} X^{\lambda_2 i_2}_{j_1 j_2} - Y^{\lambda_1 i_1}_{j_1 j_4} Y^{\lambda_1 i_1}_{j_3 j_4} Y^{\lambda_2 i_2}_{j_3 j_2} Y^{\lambda_2 i_2}_{j_1 j_2} \right)$$

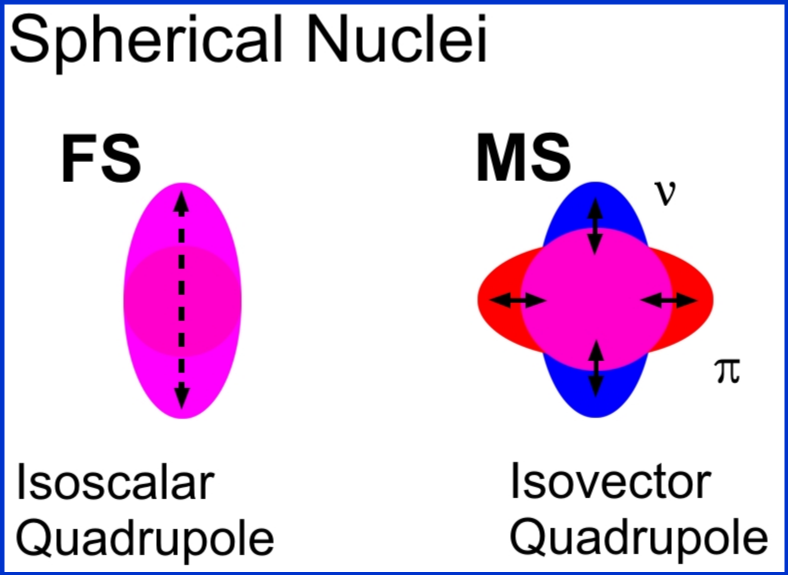
The two-phonon components of the wave functions may violate the Pauli principle. To solve this problem, we take into account exact commutation relations between the phonon operators.

A.P.S., V.V. Voronov, and Nguyen Van Giai, Eur. Phys. J. A22, 397 (2004).

V. V. Voronov, D. Karadjov, F. Catara, and A.P.S., Phys. Part. Nucl. 31, 452 (2000).

What is a "Mixed-Symmetry" State?





Low-lying isovector excitations of the valence shell of heavy nuclei represent a unique laboratory for studying the balance between collectivity, shell structure, and the isospin degree of freedom. These excitations, so-called mixed-symmetry (MS) states, have been predicted in the proton-neutron version of the interacting boson model (IBM-2), where the proton-neutron symmetry of the wave functions is quantified by the bosonic analog of isospin, termed F spin. There are the fully symmetric (FS) states with maximum F-spin ($F=F_{max}$) and the MS states with $F<F_{max}$.

M1 transitions between the excited states within the QRPA

$$\hat{M}(M;\lambda\mu) = \mu_N \sum_{i=1}^{A} \left(g_i^{(s)} \vec{s}_i + \frac{2}{1+\lambda} g_i^{(l)} \vec{l}_i \right) \nabla (r_i^{\lambda} Y_{\lambda\mu}(\theta_i, \varphi_i))$$

$$g^{(s)} = \begin{cases} 5.5856 & for \quad protons \\ -3.8263 & for \quad neutrons \end{cases} \qquad g^{(l)} = \begin{cases} 1 & for \quad protons \\ 0 & for \quad neutrons \end{cases}$$

$$B\left(M\lambda; \lambda_2^{\pi_2} i_2 \to \lambda_1^{\pi_1} i_1\right) = (2\lambda_1 + 1)$$

$$\times \left| \sum_{\tau=n,p} \sum_{j_1 j_2 j_3} \langle j_1 \| M\lambda \| j_2 \rangle v_{j_1 j_2}^{(+)} \begin{Bmatrix} \lambda_2 & \lambda_1 & \lambda \\ j_1 & j_2 & j_3 \end{Bmatrix} \left(X_{j_2 j_3}^{\lambda_2 i_2} X_{j_3 j_1}^{\lambda_1 i_1} - Y_{j_2 j_3}^{\lambda_2 i_2} Y_{j_3 j_1}^{\lambda_1 i_1} \right) \right|^2$$

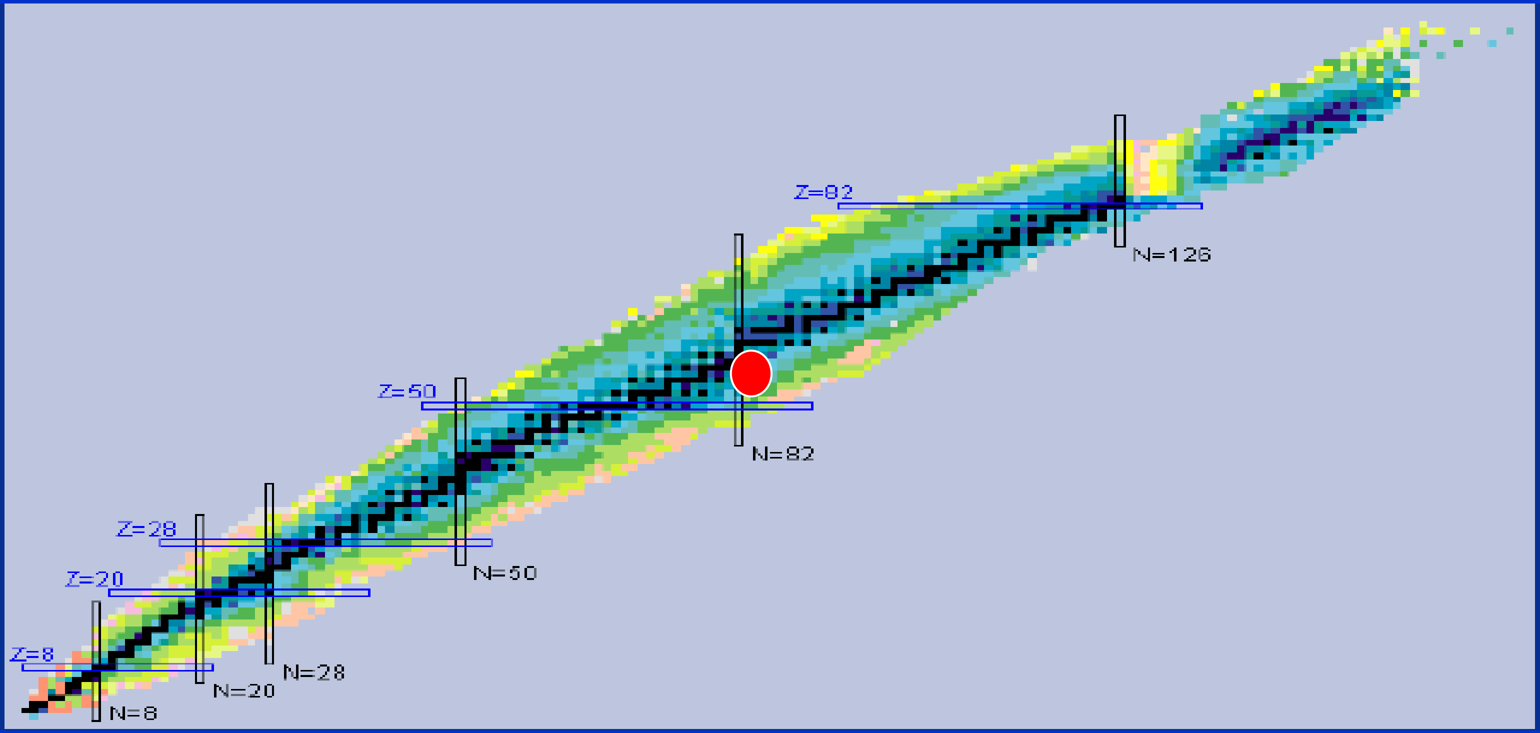
where

$$v_{12}^{(+)} = u_1 u_2 + v_1 v_2$$

$$\langle j \| M1 \| j \rangle = \mu_N \sqrt{\frac{3}{32\pi}} \sqrt{\frac{2j+1}{j(j+1)}}$$

$$\times \left(\left(g^{(s)} - g^{(l)} \right) \left(1 + (-1)^{l+1/2-j} (2j+1) \right) + g^{(l)} j(j+1) 2\sqrt{2} \right)$$

The first and second 2^+ excitations in $^{132,134,136}Te$



The low-energy quadrupole excitations of $^{132,134,136}Te$ show interesting properties. The good experimental knowledge of the remarkable reduction for excitation energy and B(E2)-value of the first 2^+ state of ^{136}Te with respect to ^{132}Te makes the properties of the first 2^+ states an attractive topic for theoretical studies. This anomaly has been attributed to a neutron dominance of the first 2^+ state of ^{136}Te. It would be helpful to study the effect of the variational configuration space on the behaviour of the $B(M1;\ 2_2^+ \rightarrow 2_1^+)$ value of the Te isotopes.

The B(E2)-anomaly and the isovector character of the second 2^+ state of ^{132}Te

	$\lambda_i^\pi = 2_i^+$	Energy (MeV)		Structure	$B(E2; 0_{gs}^+ \to 2_i^+)$ (e^2fm^4)		$B(E2; 2_i^+ \to 2_1^+)$ (e^2fm^4)		$B(M1; 2_i^+ \to 2_1^+)$ (μ_N^2)	
		Expt.	Theory		Expt.	Theory	Expt.	Theory	Expt.	Theory
^{132}Te	2_1^+	0.974	0.83	$87\%[2_1^+]_{QRPA}$	1996±200	2460				
	2_2^+	1.665	2.33	$79\%[2_2^+]_{QRPA}+$ $13\%[2_3^+]_{QRPA}$	100±20	30	0-799	20	> 0.23	0.30
	2_3^+	1.788	2.46	$85\%[2_4^+]_{QRPA}$		50		40		0.18
^{134}Te	2_1^+	1.279	2.09	$99\%[2_1^+]_{QRPA}$	960±120	1380				
	2_2^+	2.464	2.55	$97\%[2_2^+]_{QRPA}$		10		0		0.27
	2_3^+	2.934	2.62	$98\%[2_3^+]_{QRPA}$		0		0		0.10
^{136}Te	2_1^+	0.606	0.92	$97\%[2_1^+]_{QRPA}$	1030±150	1120				
	2_2^+	1.568	2.01	$94\%[2_2^+]_{QRPA}$		740		20		0.51
	2_3^+		2.37	$65\%[2_3^+]_{QRPA}+$ $25\%[2_4^+]_{QRPA}$		30		10		0.04

A.P.S., N.N. Arsenyev, N. Pietralla and V. Werner, Phys. Rev. C 90, 011306(R) (2014).

The results of QRPA calculations

	State	Energy (MeV)	$B(M1;2_i^+\to 2_1^+)$ (μ_N^2)	$B(E2;0_{gs}^+\to 2_i^+)$ $(e^2\,\mathrm{fm}^4)$	$\{n_1l_1j_1,n_2l_2j_2\}_\tau$	X	Y	%
^{132}Te	2_1^+	1.42		2640	$\{1h_{11/2},1h_{11/2}\}_\nu$	1.02	0.26	49
					$\{1g_{7/2},1g_{7/2}\}_\pi$	0.65	0.17	20
					$\{2d_{5/2},2d_{5/2}\}_\pi$	0.56	0.14	14
	2_2^+	2.57	0.48	10	$\{1h_{11/2},1h_{11/2}\}_\nu$	0.45	-0.02	10
					$\{2d_{5/2},2d_{5/2}\}_\pi$	-1.29	0.01	83
	2_3^+	2.63	0.01	0	$\{1g_{7/2},2d_{5/2}\}_\pi$	-0.92	0.00	84
					$\{1g_{7/2},1g_{7/2}\}_\pi$	0.56	-0.01	16
	2_4^+	2.67	0.23	40	$\{1h_{11/2},1h_{11/2}\}_\nu$	-0.82	0.04	34
					$\{1g_{7/2},1g_{7/2}\}_\pi$	1.07	-0.03	57
^{134}Te	2_1^+	2.15		1380	$\{1g_{7/2},1g_{7/2}\}_\pi$	1.05	0.06	55
					$\{2d_{5/2},2d_{5/2}\}_\pi$	0.74	0.06	27
	2_2^+	2.63	0.23	10	$\{1g_{7/2},1g_{7/2}\}_\pi$	-0.89	0.01	40
					$\{2d_{5/2},2d_{5/2}\}_\pi$	0.85	0.01	36
					$\{1g_{7/2},2d_{5/2}\}_\pi$	0.49	0.00	24
^{136}Te	2_1^+	1.05		1010	$\{2f_{7/2},2f_{7/2}\}_\nu$	1.32	0.14	86
					$\{2d_{5/2},2d_{5/2}\}_\pi$	0.32	0.13	4
					$\{1g_{7/2},1g_{7/2}\}_\pi$	0.30	0.12	4
	2_2^+	2.20	0.44	920	$\{2f_{7/2},2f_{7/2}\}_\nu$	-0.52	0.13	13
					$\{1g_{7/2},1g_{7/2}\}_\pi$	0.83	0.04	34
					$\{2d_{5/2},2d_{5/2}\}_\pi$	0.82	0.04	34

A.P.S., N.N. Arsenyev, N. Pietralla and V. Werner, Phys. Rev. C 90, 011306(R) (2014).

The results of calculations in the space of one- and two-phonon configurations.

	$\lambda_i^\pi = 2_i^+$	Energy (MeV)		Structure	$B(E2; 0_{gs}^+ \to 2_i^+)$ ($\mathrm{e^2fm^4}$)		$B(E2; 2_i^+ \to 2_1^+)$ ($\mathrm{e^2fm^4}$)		$B(M1; 2_i^+ \to 2_1^+)$ (μ_N^2)	
		Expt.	Theory		Expt.	Theory	Expt.	Theory	Expt.	Theory
^{132}Te	2_1^+	0.974	0.83	$87\%[2_1^+]_{QRPA}$	1996±200	2460				
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	2_3^+	2.934	2.62	$98\%[2_3^+]_{QRPA}$		0		0		0.10
^{136}Te	2_1^+	0.606	0.92	$97\%[2_1^+]_{QRPA}$	1030±150	1120				
	2_2^+	1.568	2.01	$94\%[2_2^+]_{QRPA}$		740		20		0.51
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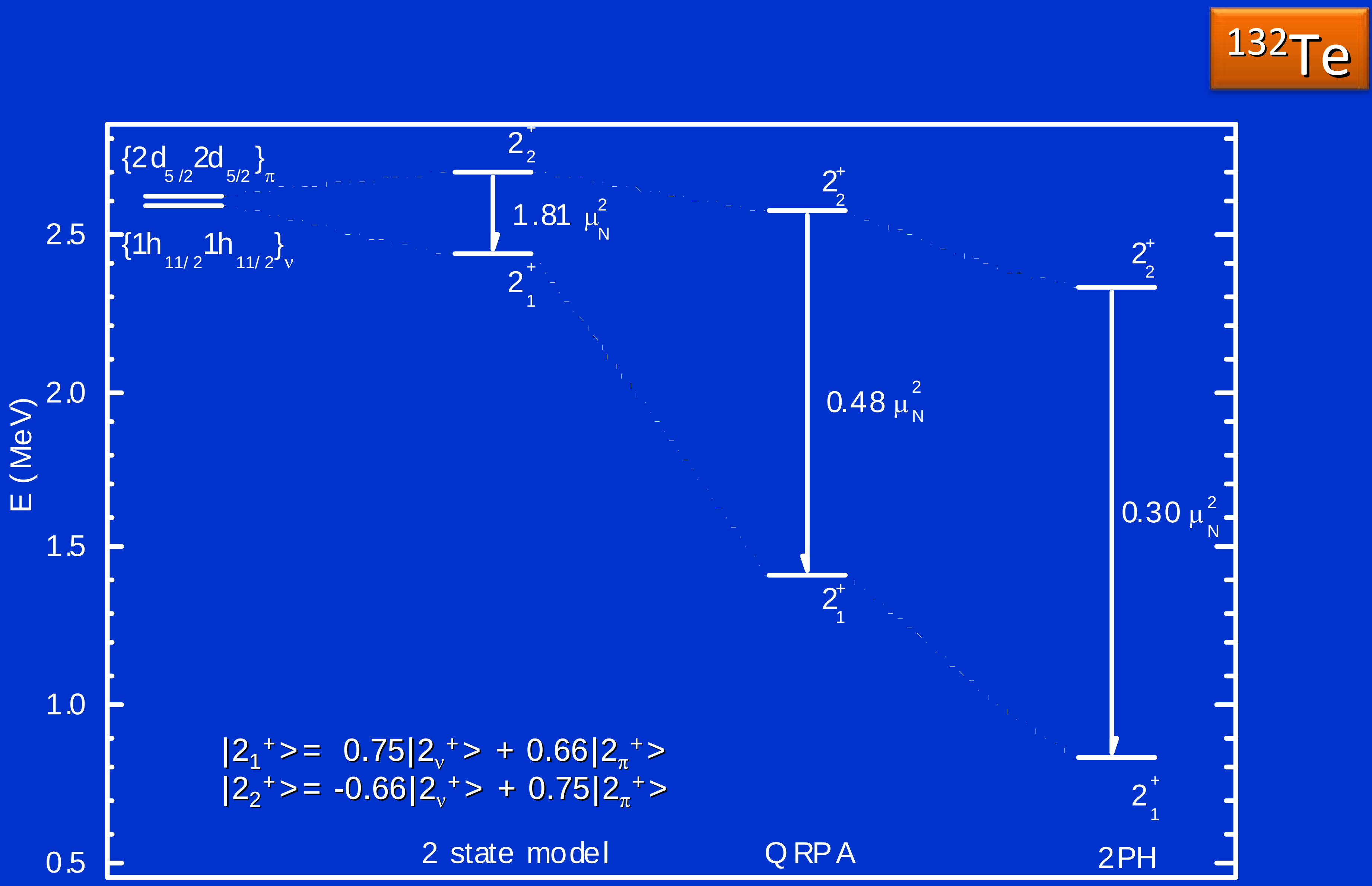

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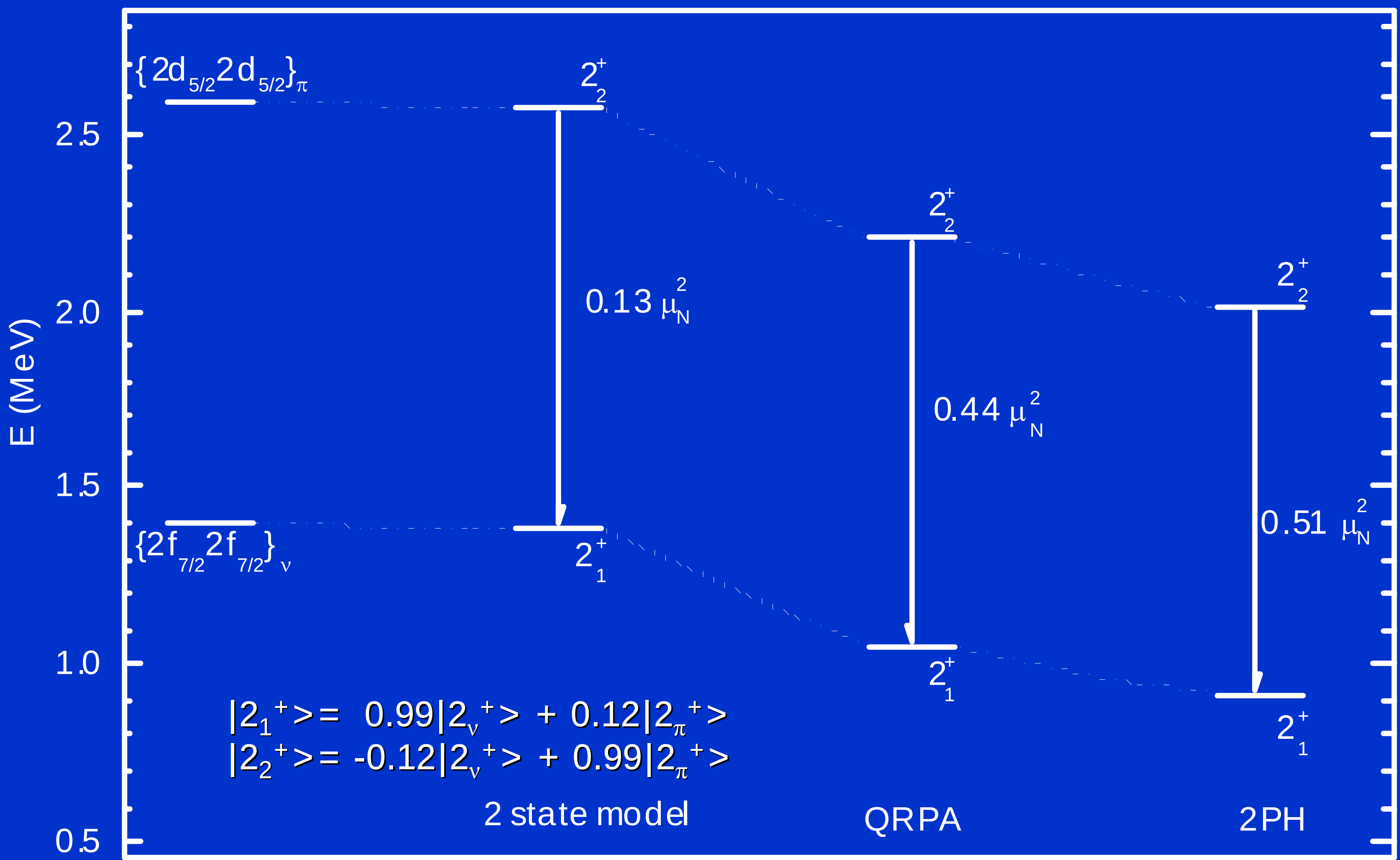
^{136}Te



A.P.S., N.N. Arsenyev, N. Pietralla and V. Werner, Phys. Rev. C 90, 011306(R) (2014).

The behaviour anomaly of B(E2)-values of its first 2^+ states and the isovector character of the second 2^+ state of ^{132}Te are the indispensable ingredients in the microscopic analysis. Our calculations with the f_- Skyrme interaction in the p-h channel and the volume pairing interaction describe it since the first two-quasiparticle state is the $\{1h_{11/2}, 1h_{11/2}\}_{\square}$ state while the second state is the $\{2d_{5/2}, 2d_{5/2}\}_{\pi}$ one. The proton single-particle structure around the Fermi level plays the key role to explain the effects of the variational-space extension. It is worth pointing out that the near-degeneracy of the proton subshells $2d_{5/2}$ and $1g_{7/2}$ remains valid for the SLy5 parameter set which is a starting point for the fitting protocol of the f_- set. However the two-quasiparticle state order is not reproduced in the case of the SLy5 set. This is mainly due to less isospin splitting of the effective mass.

	$\frac{m_n^* - m_p^*}{m}$
f_-	-0.284
SLy5	-0.182

Proton single-particle energies (in MeV)

	^{132}Te		^{134}Te		^{136}Te	
	f_-	SLy5	f_-	SLy5	f_-	SLy5
$2p_{1/2}$	-16.4	-16.3	-17.0	-16.9	-17.7	-17.5
$1g_{9/2}$	-14.5	-14.2	-15.2	-14.9	-15.8	-15.5
$1g_{7/2}$	-8.1	-7.9	-8.9	-8.6	-9.4	-9.2
$2d_{5/2}$	-8.1	-7.8	-8.7	-8.4	-9.4	-9.1
$2d_{3/2}$	-5.7	-5.5	-6.4	-6.2	-7.0	-6.8

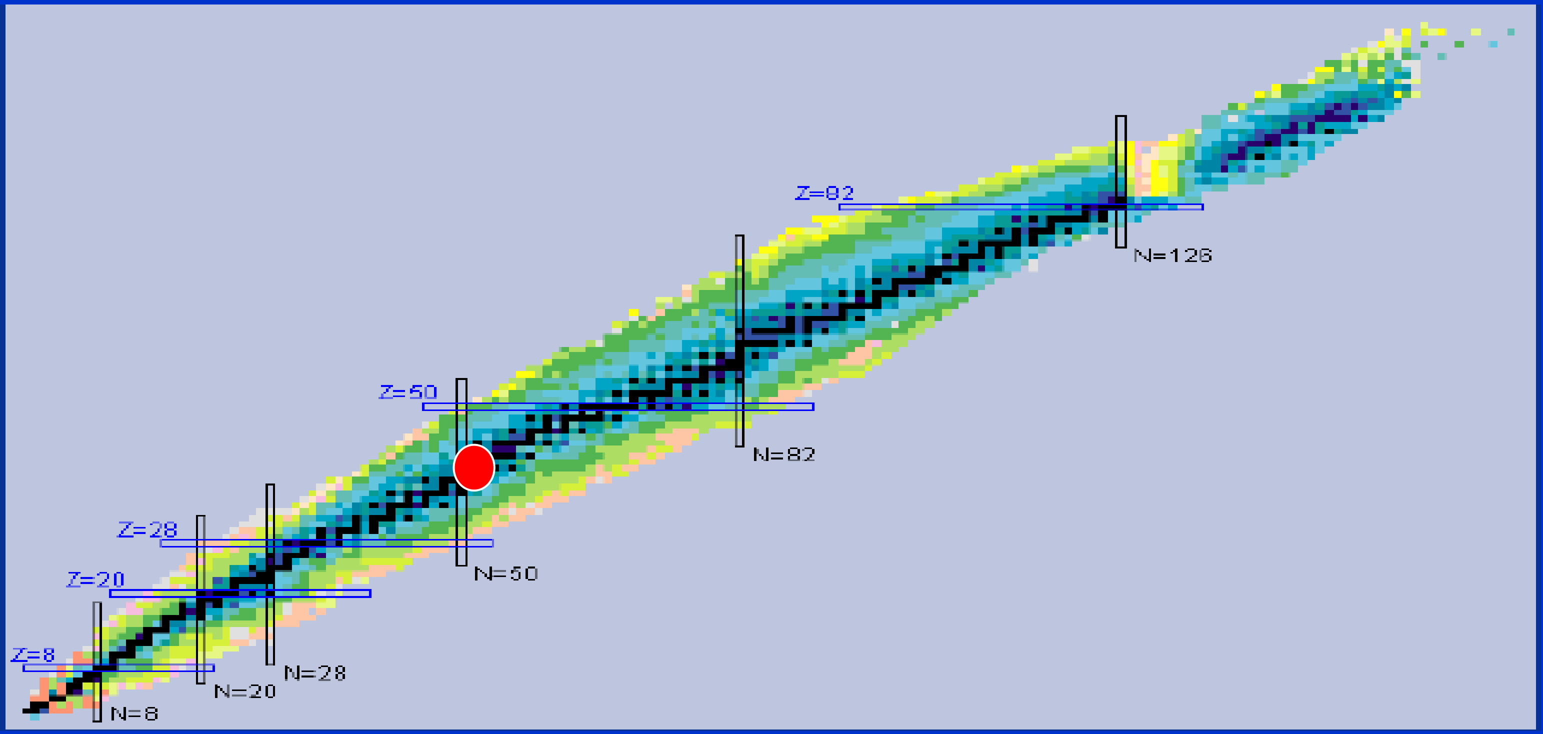
A.P.S., N.N. Arsenyev, N. Pietralla and V. Werner, Phys. Rev. C 90, 011306(R) (2014).

Summary

- Starting from the Skyrme mean-field calculations we have studied the properties of the low-energy spectrum of 2^+ excitations of ^{132,134,136}Te. Using the Skyrme interaction f_- in connection with the volume pairing interaction, a successful description of the anomalous behavior of excitation energies and the B(E2) values of the first 2^+ states is obtained. For ^{132}Te, we identify the second 2^+ state as a fully developed one-phonon MS state.
- For ^{136}Te, we observe a dominance of the neutron configurations in the wave function of the first 2^+ state. The second 2^+ state is a proton-dominated state, corresponding to a MS state with substantial configurational isospin polarization (CIP). Nevertheless, the B(M1; $2_2^+ \rightarrow 2_1^+$) value of ^{136}Te is larger than the value of ^{132}Te due to the mechanism based on the near-degeneracy of the proton single-particle states near the Fermi level. The f_- set seems to be appropriate for MS/CIP spectroscopy of neutron-rich isotopes.

A.P.S., N.N. Arsenyev, N. Pietralla and V. Werner, Phys. Rev. C 90, 011306(R) (2014).

The low-energy spectrum of 2^+ excitations of nuclei in the mass range A≈90



The low-energy spectrum of quadrupole excitations in ^{94}Mo is extensively studied in many experiments. The experimental efforts have stimulated theoretical analysis based on the interacting boson model (IBM-2), the QPM and the shell model.

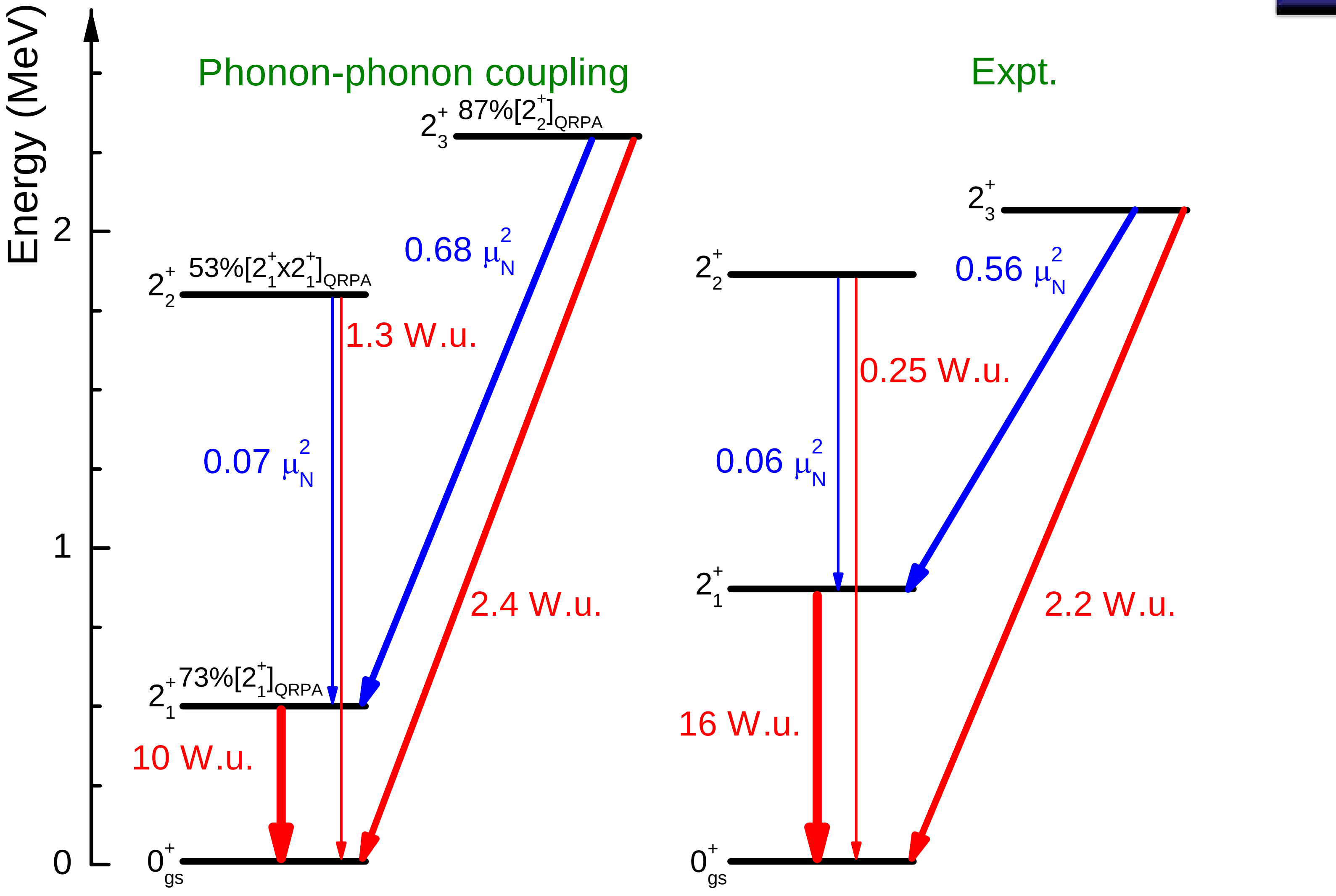
The results of QRPA calculations

	State	Energy (MeV)	$B(M1; 2_i^+ \rightarrow 2_1^+)$ (μ_N^2)	$B(E2; 0_{gs}^+ \rightarrow 2_i^+)$ (e^2fm^4)	$\{n_1 l_1 j_1, n_2 l_2 j_2\}_\tau$	X	Y	%
^{90}Zr	2_1^+	2.8		630	$\{2d_{5/2}, 1g_{9/2}\}_\nu$	-0.37	-0.11	13
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	1.03	0.06	53
					$\{2p_{1/2}, 2p_{3/2}\}_\pi$	-0.52	-0.03	26
	2_2^+	3.4	0.00	10	$\{2p_{1/2}, 2p_{3/2}\}_\pi$	0.79	0.00	63
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	0.85	0.00	36
^{92}Zr	2_1^+	1.7		410	$\{2d_{5/2}, 2d_{5/2}\}_\nu$	1.26	0.12	79
	2_2^+	2.9	0.53	310	$\{2d_{5/2}, 2d_{5/2}\}_\nu$	-0.63	0.09	20
					$\{3s_{1/2}, 2d_{5/2}\}_\nu$	-0.45	-0.04	20
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	0.85	0.04	36
					$\{2p_{1/2}, 2p_{3/2}\}_\pi$	-0.36	-0.02	13
^{92}Mo	2_1^+	1.9		1170	$\{2d_{5/2}, 1g_{9/2}\}_\nu$	-0.35	-0.16	10
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	1.32	0.19	86
	2_2^+	4.4	0.25	230	$\{2d_{5/2}, 1g_{9/2}\}_\nu$	-0.65	-0.07	42
					$\{2p_{1/2}, 2p_{3/2}\}_\pi$	-0.63	-0.02	40
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	-0.49	0.10	11
^{94}Mo	2_1^+	1.2		1730	$\{2d_{5/2}, 2d_{5/2}\}_\nu$	0.92	0.27	39
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	0.99	0.37	42
	2_2^+	2.4	1.23	160	$\{2d_{5/2}, 2d_{5/2}\}_\nu$	-1.08	0.07	58
					$\{1g_{9/2}, 1g_{9/2}\}_\pi$	0.89	0.02	40

A.P.S., N.N. Arsenyev, N. Pietralla, Phys. Rev. C 86, 024311 (2012).

SGII

^{94}Mo



A.P.S., N.N. Arsenyev, N. Pietralla, Phys. Rev. C 86, 024311 (2012).

Using the same set of parameters we have studied the properties of the 2^+ excitations of nuclei in the mass range A≈90

	$\lambda_i^\pi = 2_i^+$	Energy (MeV)		Structure	$B(E2;0_{gs}^+ \to 2_i^+)$ (e^2fm^4)		$B(E2;2_i^+ \to 2_1^+)$ (e^2fm^4)		$B(M1;2_i^+ \to 2_1^+)$ (μ_N^2)	
		Expt.	Theory		Expt.	Theory	Expt.	Theory	Expt.	Theory
^{90}Zr	2_1^+	2.186	2.6	$93\%[2_1^+]$	643±22	600				
	2_2^+	3.308	3.2	$95\%[2_2^+]$	53±14	1	65±17	1	0.088±0.025	0.00
^{92}Zr	2_1^+	0.934	1.6	$96\%[2_1^+]$	790±62	420				
	2_2^+	1.847	2.7	$87\%[2_2^+]$	419±49	230	10^{+12}_{-7}	4	0.37±0.04	0.41
	2_3^+	2.067	2.6	$45\%[2_4^+] + 37\%[2_1^+ \otimes 2_1^+]$	< 0.62	50	< 395	160	<0.024	0.17
^{92}Mo	2_1^+	1.509	1.9	$99\%[2_1^+]$	1036±62	1160				
	2_2^+	3.091	3.8	$91\%[2_1^+ \otimes 2_1^+]$	254±20	50	96±27	420	0.043±0.007	0.03
^{94}Mo	2_1^+	0.871	0.5	$73\%[2_1^+]$	2031±25	1280				
	2_2^+	1.864	1.8	$53\%[2_1^+ \otimes 2_1^+] + 21\%[2_3^+]$	32±7	170	720±260	190	0.06±0.02	0.07
	2_3^+	2.067	2.3	$87\%[2_2^+]$	279±25	310	124^{+76}_{-58}	10	0.56±0.05	0.68

A.P.S., N.N. Arsenyev, N. Pietralla, Phys. Rev. C 86, 024311 (2012).

STRUCTURE OF $2^+_{1,2}$ STATES IN ^{132,134,136}Te

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Low-lying quadrupole isovector excitations of the valence shell of heavy nuclei represent a unique laboratory for studying the balance between collectivity, shell structure, and the isospin degree of freedom. These excitations, so-called mixed-symmetry (MS) states, have been predicted in the proton-neutron (pn) version of the interacting boson model (IBM-2). An unbalanced pn-content of the wave functions can be interpreted as configurational isospin polarization (CIP) which denotes varying contributions to the 2^+ states by the active proton and neutron configurations due to subshell structure [1]. *M*1 transitions between low-energy quadrupole excitations of the valence shell are often used as signature for states of MS-character. Starting from a Skyrme interaction we study the properties of the low-energy spectrum of quadrupole excitations. The coupling between one- and two-phonon terms in the wave functions of excited states is taken into account [2]. We use the finite-rank separable approximation [3, 4] which enables one to perform the QRPA calculations in very large two-quasiparticle spaces. After the approach has been proven to be sufficiently good to reproduce characteristics of the well-known low-energy spectrum of quadrupole excitations of stable nuclei in the mass range $A \approx 90$ [5], we study the evolution of first and second quadrupole excitations of ^{132,134,136}Te. Using the Skyrme interaction f^- in conjunction with the volume pairing interaction, our calculations describe well the dramatic reduction of the experimental E2 excitation strength to the 2_1^+ state when going from ^{132}Te to ^{136}Te. For ^{132}Te, we identify the 2_2^+ state as a fully developed one-phonon MS state. We observe a dominance of the neutron configurations in the wave function of the 2_1^+ state of ^{136}Te. The 2_2^+ state of ^{136}Te is a proton-dominated state, corresponding to a MS state with substantial CIP. Nevertheless, the $B(M1;2_{\rm MS}^+\rightarrow 2_1^+)$ value of ^{136}Te is larger than that of ^{132}Te due to the subtle mechanism based on the near-degeneracy of the proton single-particle states near the Fermi level [6]. These results suggest the f^- parameter set for the description of MS states and CIP in neutron-rich isotopes.

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