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Semimicroscopic description of the odd-A Te isotopes

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The structure of low-lying levels in odd-mass Te isotopes ($115 \leq A \leq 131$) is discussed in the framework of the quasiparticle-phonon model. In addition, the properties of ^{131}Te are also investigated by means of the three-particle cluster-phonon coupling, where the pairing force is taken as the residual particle-particle interaction. Excitation energies and spectroscopic factors are calculated and compared with the experimental data.

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I. INTRODUCTION

Theoretical investigations of some odd-A Te isotopes have been performed in the framework of the quasiparticle-phonon model [1,2]. The nuclides ^{123,125,127}Te were studied by Sen [1] in a version which incorporates both pairing effects and anharmonicity in the core vibrations. The available experimental data on energy levels and electromagnetic properties $\mu, Q, B(M1), B(E2)$, mixing and branching ratios were reasonably well reproduced. Afterwards, Fernandes and Rao [2] by means of neutron pickup reactions (^{3}He,α) studied transferred angular momenta and spectroscopic factors for low-lying levels in ^{121,123,125}Te nuclei. The spectroscopic information obtained was compared with calculations based on a quasiparticle-phonon coupling scheme.

After the papers of Sen [1] and Fernandes and Rao [2], much experimental spectroscopic information on low-lying levels in the odd-A Te isotopes became available [3–13]. The experimental data for the nuclides ^{115,117,119,121,123,125,127,129,131,133}Te were summarized in Refs. [3–12], respectively.

In addition, using the same experimental method and DWBA analysis employed in Ref. [2], the equivalent spectroscopic data for ^{127,129}Te isotopes were extracted by Dias [13]. Subsequently, Shahabuddin *et al.* [14] by means of neutron stripping reactions obtained spectroscopic information in ^{125,127,129,131}Te nuclei, Gales *et al.* [15] using pickup reactions deduced spectroscopic data for ^{121,123,129}Te isotopes; Rodland *et al.* [16–18] with reactions (d,t) and (^{3}He,α) extracted transferred angular momentum, and spectroscopic factors for the observed levels in ^{125}Te, ^{127}Te, and ^{119}Te, respectively; and de Souza and Saxena [19] with γ-γ directional correlation measurements suggest and confirm spin assignments to low-lying levels in ^{129}Te.

The main goal of the present work is to analyze the more recent experimental information on the energy spectra and spectroscopic factors of the odd-nuclides $^{115-131}$Te, within the quasiparticle-phonon coupling. In the case of ^{131}Te, the influence of seniority-three states is examined by also employing a cluster-phonon coupling calculation.

II. THE MODEL AND PARAMETERS

A detailed description of the quasiparticle-phonon coupling model is given in Ref. [20]. Here we only sketch the main formulas in order to establish the notation. In this model the system is described by the Hamiltonian

$$H = H_c + H_{sqp} + H_{\text{int}} , \tag{1}$$

where (i) H_c describes the harmonic quadrupole field of the even Te core; (ii) H_{sqp} is associated with the quasiparticle in the effective spherical potential; and (iii) H_{int} represents the interaction between the quasiparticle and the vibrational field and is given by

$$H_{\text{int}} = -\frac{\beta_2}{\sqrt{5}} k(r) \sum_{\mu=-2}^{2} (b_\mu^\dagger + (-1)^\mu b_{-\mu}) Y_\mu(\theta,\phi) , \tag{2}$$

where $b_\mu^\dagger(b_\mu)$ is the creation (annihilation) operator of the quadrupole vibration field, $Y_\mu(\theta,\phi)$ is the angular part of the quadrupole operator for the particle, β_2 is the quadrupole deformation parameter of the core nucleus, and $k(r)$ is the coupling strength.

In addition, the properties of ^{131}Te have also been calculated on the basis of the three-particle cluster-phonon coupling model (CPM) [21]. The model Hamiltonian is

$$H = H_{\text{coll}} + H_{sp} + H_{\text{res}} + H_{\text{int}} . \tag{3}$$

Here, (i) H_{sp} is associated with the motion of the three-valence shell neutrons in an effective spherical potential; (ii) the residual interaction energy between the neutrons in the valence-shell cluster, H_{res}, only includes the pairing force explicitly; and (iii) H_{int} represents the interaction energy between the three-particle cluster and the quadrupole vibrational field [similar expression given in equation (2)].

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The eigenvalue problem is solved in the basis

$$|j, NR; I\rangle \tag{4a}$$

for the Hamiltonian (1) and in the basis

$$|(j_1 j_2)J_{12}, j_3, J, NR; I\rangle \tag{4b}$$

for the Hamiltonian (3). Here $j = (nlj)$ stands for the quantum numbers of the particle states, J is the total angular momentum of the particles, N and R represent the phonon number and the angular momentum, respectively, and I is the total angular momentum.

Within the quasiparticle-phonon coupling model the corresponding eigenfunctions read

$$|I_n\rangle = \sum_{jNR} C^{I_n}_{jNR} |j, NR; I\rangle \tag{5}$$

where the index n distinguishes between states of the same angular momentum.

The spectroscopic factor for forming the state $|I_n\rangle$ by pickup and transferring a neutron from the orbit j of the target nucleus is given, respectively, by

$$S_j(I_n) = (2j+1)v_j^2 |C^{I_n}_{j00}|^2 \tag{6}$$

and

$$S_j(I_n) = u_j^2 |C^{I_n}_{j00}|^2 , \tag{7}$$

where u_j and v_j represent the quasiparticle and quasihole amplitudes in state j, respectively.

We describe the states of Te isotopes with the $2d_{5/2}, 1g_{7/2}, 3s_{1/2}, 2d_{3/2}$, and $1h_{11/2}$ neutron orbitals and the quadrupolar phonon states up to $N = 2$. The phonon energies $\hbar\omega$ and the deformation parameters β_2 were fixed from the experimental data [22–27]. The 2_1^+ states in the even mass nuclei are taken as quadrupolar vibrations. For the radial part of the particle-phonon interaction we have adopted the fixed values $\langle K\rangle = 35$ MeV which corresponds to the estimate from Ref. [28]. In the quasiparticle calculations, the gap parameters Δ were obtained from odd-even mass differences [29]. The resulting pairing strengths G were in agreement with the estimate of Kisslinger and Sorensen [20]. The values of the quadrupolar deformation parameters employed in the ^{129,127,125}Te calculations were adopted for the nuclides ^{115,117,119}Te, respectively; the parameter G was taken from the estimate for the nucleus ^{121}Te. All these parameters are listed in Table I.

The single particle energies were determined by the following criteria: (i) For ^{121}Te in the neighborhood of the lower extreme of the chain of nuclei studied, the set of values was extracted from the work of Cohen [30]. (ii) At the upper extreme, ^{133}Te was considered as a neutron hole in the $N = 82$ shell coupled to a quadrupole-harmonic core. Our starting point was based on previous work [31]. The final values were determined by requiring a fit to the energies of the low-lying states shown in Fig. 1. (iii) For the ^{115,117,119}Te nuclei, a linear extrapolation was considered, and for the remaining odd-mass Te isotopes, a linear interpolation between ^{121}Te and ^{133}Te energy values was adopted. These single particle energy values are shown in Table II.

TABLE I. Parameters used in the present calculations.

Core	$\hbar\omega = E(2_1^+)$ (MeV)	β_2	Δ_n (MeV)	G (MeV)
^{114}Te	0.709	0.135	1.365	0.201
^{116}Te	0.679	0.158	1.410	0.201
^{118}Te	0.605	0.166	1.338	0.201
^{120}Te	0.560	0.184	1.265	0.201
^{122}Te	0.564	0.187	1.246	0.203
^{124}Te	0.603	0.166	1.262	0.205
^{126}Te	0.666	0.158	1.238	0.209
^{128}Te	0.743	0.135	1.163	0.211
^{130}Te	0.840	0.108	1.078	0.226
^{132}Te	0.973	0.090	0.980	0.272
^{134}Te	1.280	0.075		0.180

III. RESULTS AND DISCUSSION

A. Energy spectra

In order to examine the influence of seniority-three degrees of freedom, the calculated spectra with the quasiparticle-phonon model (QPM) and cluster-phonon model (CPM), and the experimental energy levels of ^{131}Te are compared in Fig. 2. In Table III, the wave functions of low-lying states obtained with QPM and CPM are plotted. Only the $3/2_1^+$, $11/2_1^-$, and $1/2_1^+$ have a dominant seniority-one component. The other low-lying positive-parity states have mixed seniority-one and -three character and, in some cases, they are partially described by QPM. The other low-lying negative-parity levels, $7/2_1^-$, $9/2_1^-$, $13/2_1^-$, and $15/2_1^-$, are seniority-three states and cannot be reproduced by QPM calculations.

For all isotopes considered, the influence of three-quasiparticle components in low energy spectra can be

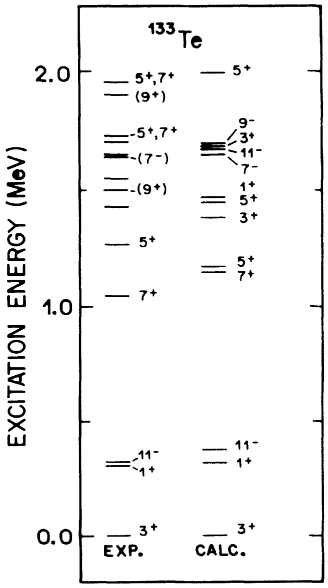

FIG. 1. Experimental [12] and calculated spectrum of ^{133}Te. The spins are in $2J$ form.

TABLE II. Single-particle energies for tellurium isotopes with the mass number A.

Energy/A	115	117	119	121	123	125	127	129	131	133
$\epsilon g_{7/2}$ (MeV)	1.30	1.01	0.70	0.40	0.10	−0.20	−0.50	−0.80	−1.10	−1.40
$\epsilon d_{5/2}$ (MeV)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\epsilon s_{1/2}$ (MeV)	2.24	2.14	2.02	1.90	1.80	1.70	1.55	1.44	1.32	1.20
$\epsilon d_{3/2}$ (MeV)	2.98	2.86	2.73	2.60	2.45	2.28	2.12	2.08	1.95	1.82
$\epsilon h_{11/2}$ (MeV)	2.44	2.33	2.22	2.10	2.00	1.88	1.74	1.64	1.52	1.40

roughly understood by means of the variation of quasiparticle single particle energies as a function of mass (Fig. 3). It is clear that for the odd isotones with mass in the range 115–121 the first $1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$, and $11/2^-$ states are all one-quasiparticle states. With increasing mass the influence of seniority-three components in low-lying states grows, especially for the first $5/2^+$, $7/2^+$ states. And, for the heavy isotopes only, the first $1/2^+$, $3/2^+$, and $11/2^-$ states may be predominantly seniority-one states, in agreement with the calculated wave functions for ^{131}Te.

In the following, the quasiparticle-phonon coupling

TABLE III. Wave function of a few low-lying states in ^{131}Te. Only those amplitudes which are larger than 4% are listed. See text.

	QPM			CPM						
I_i^π	j	NR	Amplitude	j_1	j_2	J_{12}	j_3	J	NR	Amplitude
$\frac{3}{2_1}^+$	$\frac{3}{2}$	00	0.922	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	00	0.778
	$\frac{1}{2}$	12	−0.230	$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	00	0.438
	$\frac{3}{2}$	12	−0.217	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	00	−0.211
				$\frac{3}{2}$	$\frac{3}{2}$	2	$\frac{1}{2}$	$\frac{5}{2}$	12	0.215
$\frac{11}{2_1}^-$	$\frac{11}{2}$	00	0.924	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{11}{2}$	$\frac{11}{2}$	00	0.776
	$\frac{11}{2}$	12	−0.371	$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{11}{2}$	$\frac{11}{2}$	00	0.268
				$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{11}{2}$	$\frac{11}{2}$	12	0.276
$\frac{1}{2_1}^+$	$\frac{1}{2}$	00	0.811	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	00	0.786
	$\frac{3}{2}$	12	0.484	$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	00	−0.383
	$\frac{5}{2}$	12	0.274	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.221
				$\frac{3}{2}$	$\frac{3}{2}$	2	$\frac{1}{2}$	$\frac{5}{2}$	12	0.213
$\frac{5}{2_1}^+$	$\frac{5}{2}$	00	0.400	$\frac{3}{2}$	$\frac{3}{2}$	2	$\frac{1}{2}$	$\frac{5}{2}$	00	0.774
	$\frac{3}{2}$	12	−0.631	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	−0.451
	$\frac{1}{2}$	12	0.531	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.214
	$\frac{3}{2}$	24	0.287							
$\frac{7}{2_1}^+$	$\frac{3}{2}$	12	0.919	$\frac{11}{2}$	$\frac{11}{2}$	2	$\frac{3}{2}$	$\frac{7}{2}$	00	0.648
	$\frac{1}{2}$	24	−0.221	$\frac{11}{2}$	$\frac{11}{2}$	4	$\frac{3}{2}$	$\frac{7}{2}$	00	0.363
				$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.369
				$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.249
				$\frac{11}{2}$	$\frac{11}{2}$	4	$\frac{3}{2}$	$\frac{11}{2}$	12	0.249
				$\frac{11}{2}$	$\frac{11}{2}$	2	$\frac{3}{2}$	$\frac{5}{2}$	12	−0.244
$\frac{3}{2_2}^+$	$\frac{3}{2}$	00	0.218	$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	00	0.651
	$\frac{3}{2}$	12	0.925	$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	00	−0.392
	$\frac{1}{2}$	12	−0.212	$\frac{3}{2}$	$\frac{3}{2}$	2	$\frac{1}{2}$	$\frac{3}{2}$	00	−0.232
				$\frac{3}{2}$	$\frac{3}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.266
				$\frac{11}{2}$	$\frac{11}{2}$	0	$\frac{3}{2}$	$\frac{3}{2}$	12	0.263

TABLE IV. Comparison of experimental and calculated S_j pickup spectroscopic factors [see Eq. (6)] for the first low-lying states of odd-mass Te isotopes.

	^{115}Te	^{117}Te		^{119}Te			^{121}Te			^{123}Te	
I^π	Calc.	Calc.	(^{3}He,α)^a	$(d,t)^a$	Calc.	(^{3}He,α)^b	Calc.	(^{3}He,α)^b	(^{3}He,α)^c	$(d,t)^b$	Calc.
$\frac{1}{2}^+$	0.35	0.43	0.6	0.9	0.55	0.67	0.67	1.22		1.10	0.85
$\frac{3}{2}^+$	0.20	0.28		1.4	0.37	1.24	0.50	1.70		1.70	1.96
$\frac{11}{2}^-$	1.65	2.07	3.8		2.79	2.68	4.06	4.17	3.30	5.75	5.73
$\frac{5}{2}^+$	3.03	2.34	2.9	2.7	1.59		1.45	1.08		1.20	1.45
$\frac{7}{2}^+$	4.25	4.56	5.3	6.6	4.18	2.40	3.51	3.22	2.92		2.60

			^{125}Te					^{127}Te				^{129}Te			^{131}Te
I^π	(^{3}He,α)^b	(^{3}He,α)^d	$(d,t)^e$	$(d,t)^d$	Calc.	(^{3}He,α)^f	$(t,\alpha)^g$	$(d,t)^e$	$(d,t)^g$	Calc.	(^{3}He,α)^f	(^{3}He,α)^h	$(d,t)^e$	Calc.	Calc.
$\frac{1}{2}^+$	1.0	1.3	0.82	1.4	1.02			1.22	1.5	1.02	1.40		1.30	1.04	1.11
$\frac{3}{2}^+$	1.87	2.4	2.40	2.5	1.39	1.12	2.3	2.56	2.8	1.66	3.60	2.1	2.92	1.97	2.32
$\frac{11}{2}^-$	5.07	5.1	5.76	6.2	6.65	2.25	4.5		6.4	6.94	6.20	7.2	6.84	7.51	8.34
$\frac{5}{2}^+$				0.08	1.36				0.008	1.27				1.07	1.00
$\frac{7}{2}^+$				1.9	1.40		0.11		0.56	0.88				0.48	0.34

[a] Reference [18].
[b] Reference [2].
[c] Reference [15].
[d] Reference [16].
[e] Reference [32].
[f] Reference [13].
[g] Reference [17].
[h] Reference [15].

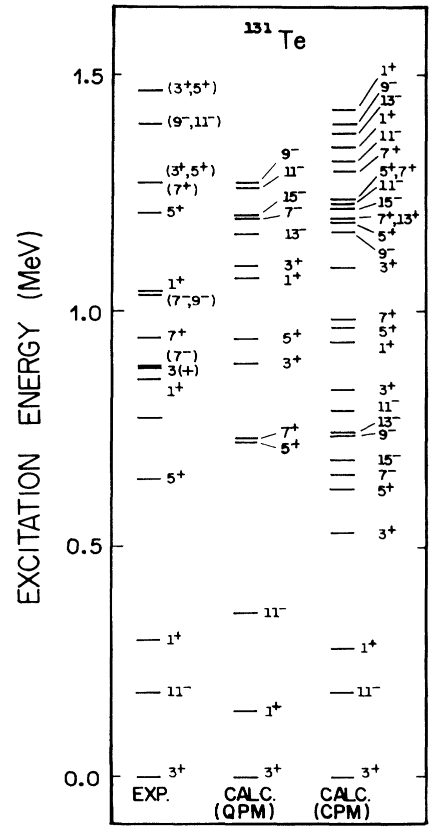

FIG. 2. Experimental [11,14] and calculated spectrum of ^{131}Te. The spins are in $2J$ form. See text.

model was applied to the remaining odd-mass Te isotopes. The experimental and calculated spectra are compared in Fig. 4. Except for the restrictions on the influence of seniority-three degree of freedom mentioned above, the agreement between the measured and theoretical states up to about 1 MeV is reasonable. The calculations reproduce all the ground-state spins, except for ^{127}Te, and the characteristics of the low energy spectra composed of the $1/2_1^+$, $3/2_1^+$, $5/2_1^+$, $7/2_1^+$, and $11/2_1^-$ states.

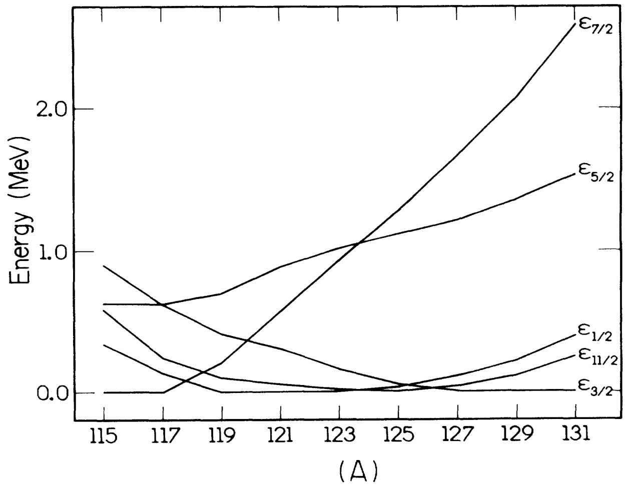

FIG. 3. The quasiparticle single-particle energies for the odd-mass Te isotopes.

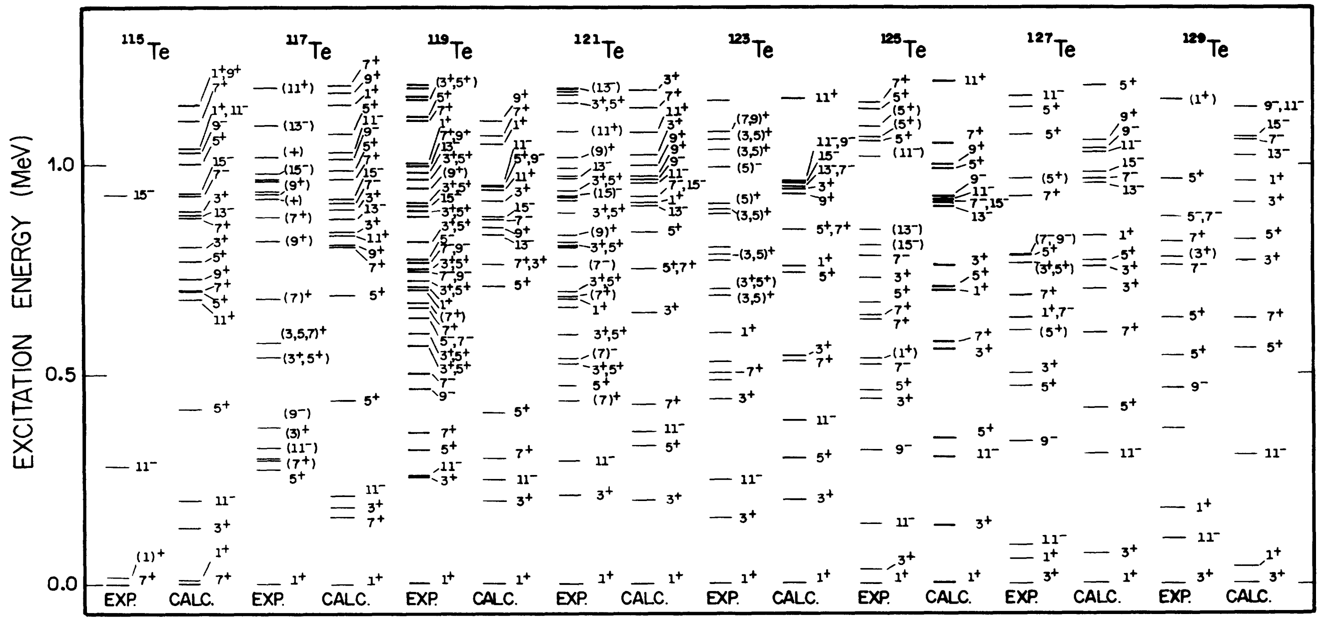

FIG. 4. Comparison of experimental levels of ^{115,117,119}Te [3–5], ^{121}Te [6], ^{123}Te [7,15], ^{125}Te [8,14,16], ^{127}Te [9,17], and ^{129}Te [10,15,19] with the calculated spectra. The spins are in $2J$ form.

B. Spectroscopic factors

The measured and calculated pickup and stripping spectroscopic factors are compared in Tables IV and V, respectively, although experimental data are available only for the isotopes $^{119-131}$Te. The predictions for the three light isotopes $^{115-117}$Te are reported also. These tables show, in general, reasonable agreement between experiment and theory. In Table IV, measured and calculated values of pickup spectroscopic factor for $3/2_1^+$ in ^{121}Te and $11/2_1^-$ in ^{127}Te are discrepant. The calculated values for $3/2_1^+$ states, in all isotopes, are lowered by the mixing of an $s_{1/2}\otimes 2^+$ component. And, in the case of the value for the $11/2_1^-$ state in ^{127}Te, based on the experimental data for the neighboring isotopes, the available value from the analysis of (^{3}He,α) reaction [13] is very small. In Table V, the comparison indicates that the calculated stripping spectroscopic factors for $11/2_1^-$ states in light isotopes are overestimated.

IV. CONCLUSIONS

The properties of the odd-mass tellurium nuclei, in the mass region $115 \leq A \leq 131$, were predicted within the framework of the quasiparticle-phonon coupling model. The available data on the low energy spectra and pickup and stripping spectroscopic factors were examined. It was possible to give a reasonable description of these observables using a parametrization taken from experimental data and derived from earlier calculations. It should be emphasized that nine isotopes are described without any adjustable parameter. However, further experimental data are needed, especially on $^{115-117}$Te, before a more detailed comparison can be made.

In addition, the influence of seniority-three degrees of freedom in the low-energy spectrum of the ^{131}Te was examined. The properties of this nucleus were also investigated by means of the three-particle cluster-phonon coupling model. The three-particle correlations should

TABLE V. Comparison of experimental and calculated $(2J+1)S_j$ stripping spectroscopic factors [see Eq. (7)] for the first low-lying states of odd-mass Te isotopes.

	^{115}Te	^{117}Te	^{119}Te	^{121}Te		^{123}Te		^{125}Te			^{127}Te			^{129}Te			^{131}Te		
J^π	Calc.	Calc.	Calc.	$(d,p)^a$	Calc.	$(d,p)^b$	Calc.	$(d,p)^c$	$(t,d)^d$	Calc.	$(d,p)^e$	$(t,d)^d$	Calc.	$(d,p)^f$	$(t,d)^d$	Calc.	$(d,p)^g$	$(t,d)^d$	Calc.
$\frac{1}{2}^+$	1.18	2.13	0.93	0.58	0.76	0.78	0.65	0.84	0.52	0.54	0.50	0.51	0.36	0.44	0.39	0.22	0.31	0.32	0.18
$\frac{3}{2}^+$	1.67	1.75	1.72	1.3	1.68	2.02	0.87	1.85	1.27	2.02	1.53	1.41	1.54	1.30	1.27	1.24	1.	0.97	1.01
$\frac{11}{2}^-$	8.09	6.76	6.53	2.4	6.48	3.63	6.21	3.71	2.12	4.82	3.11	1.98	3.31	2.50	2.86	2.12	2.	1.93	1.75
$\frac{5}{2}^+$	0.39	0.28	0.17	0.50	0.14	0.30	0.12			0.10			0.09			0.48		0.01	0.04
$\frac{7}{2}^+$	3.17	1.84	0.93		0.48		0.23			0.09			0.04			0.01		0.05	0.01

[a] Reference [33].
[b] Reference [34].
[c] Reference [35].
[d] Reference [14].
[e] Reference [36].
[f] Reference [37].
[g] Reference [38].

be more pronounced in low-lying states of the heavy isotopes $^{121-131}$Te.

The results reported here indicate that this simple model can be considered as a good starting point for further theoretical calculations. And, for light isotopes, the predictions of spectroscopic factors can guide the analysis of new experiments.

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