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Electromagnetic Moments of Radioactive ^{136}Te and the Emergence of Collectivity 2p $\oplus$ 2n outside of Double-Magic ^{132}Sn *

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Radioactive ^{136}Te has two valence protons and two valence neutrons outside of the ^{132}Sn double shell closure, providing a simple laboratory for exploring the emergence of collectivity and nucleon-nucleon interactions. Coulomb excitation of ^{136}Te on a titanium target was utilized to determine an extensive set of electromagnetic moments for the three lowest-lying states, including $B(E2;0_1^+\rightarrow 2_1^+)$, $Q(2_1^+)$, and $g(2_1^+)$. The results indicate that the first-excited state, 2_1^+, composed of the simple 2p $\oplus$ 2n system, is prolate deformed, and its wavefunction is dominated by excited valence neutron configurations, but not to the extent previously suggested. It is demonstrated that extreme sensitivity of $g(2_1^+)$ to the proton and neutron contributions to the wavefunction provides unique insight into the nature of emerging collectivity, and $g(2_1^+)$ was used to differentiate among several state-of-the-art theoretical calculations. Our results are best described by the most recent shell model calculations.

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Atomic nuclei with two valence protons and two valence neutrons outside of double shell closures provide a simple and unique laboratory for exploring the emergence of collectivity and nucleon-nucleon interactions. Radioactive ^{136}Te, which possesses a robust ^{132}Sn core [1, 2], is such an example. Previous measurements on neutron-rich Te isotopes around the $N = 82$ shell closure [3–7] have revealed both regular and irregular features in the electromagnetic moments with respect to empirical expectations and the nuclear shell model. In particular, an initial study of ^{136}Te [3] observed unexpectedly low electric quadrupole collectivity, i.e, $B(E2;0_1^+\rightarrow 2_1^+)$, with respect to ^{132,134}Te and shell-model calculations. The small $B(E2)$ value was attributed, in part, to a reduction in the pairing force. Furthermore, g-factor predictions [7–9], which are extremely sensitive to the wavefunction, yield discrepant values, indicating uncertainty on the underlying structure of this simple 2p $\oplus$ 2n system. In this Letter, the collectivity of ^{136}Te is explored through the measurement of a complete set of electromagnetic moments, $B(E2;0_1^+\rightarrow 2_1^+)$, $Q(2_1^+)$, and $g(2_1^+)$.

A radioactive ion beam of ^{136}Te at an energy of 410 MeV was Coulomb excited on a 1.5-mg/cm^2 titanium target. The measurement was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) of Oak Ridge National Laboratory (ORNL). The experimental setup included a HPGe Clover array, CLARION [10], a 2π CsI array, BareBall [11], and a Bragg-Curve gas detector. Electromagnetic moments were determined by measuring cross sections and particle-γ angular corre-

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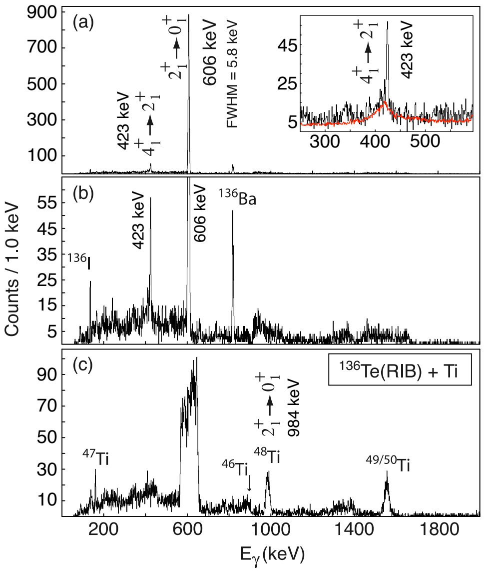

FIG. 1: The γ-ray spectra of (a) ^{136}Te, (b) ^{136}Te with a reduced vertical scale, and (c) $^{46-50}$Ti, using a different Doppler correction. The inset in panel (a) shows the $4_1^+ \to 2_1^+$ γ-ray transition and the Compton background. The Compton edge component (red) was modeled from data on ^{126}Te.

lations of excited states following Coulomb excitation, cf. Refs. [7, 12–16].

The self-supported titanium target was enriched and the isotopic composition was subsequently measured by inductively coupled plasma mass spectrometry (ICP-MS), resulting in 1.64(3)% ^{46}Ti, 1.35(3)% ^{47}Ti, 12.09(12)% ^{48}Ti, 3.52(4)% ^{49}Ti, and 81.40(81)% ^{50}Ti. The beam composition and energy loss through the target were directly measured with a zero-degree Bragg detector. The average beam composition was 3.9(6)% ^{136}Ba, 1.2(2)% ^{136}Cs, 9.3(14)% ^{136}I, and 85.6(15)% ^{136}Te. The energy loss of the beam through the target was determined to be 86(2) MeV from the Bragg detector and 83(2) MeV from the Doppler shifted $2_1^+ \to 0_1^+$ transition of ^{136}Te, averaging to an adopted value of 84.5(14) MeV.

The Ti-gated γ-ray spectra are shown in Fig. 1(a)-(c). The $2_1^+ \to 0_1^+$ (606 keV) and $4_1^+ \to 2_1^+$ (423 keV) transitions of ^{136}Te are clearly observed in Fig. 1(a). Unfortunately, the background under the $4_1^+ \to 2_1^+$ transition at 423 keV is obscured by the Compton edge of the $2_1^+ \to 0_1^+$ transition. The Compton background was modeled, cf. the inset in Fig. 1(a), from Coulomb-excitation data on ^{126}Te, which has a similar 2_1^+ energy but a different 4_1^+ energy. The $A = 136$ beam contaminants can be observed in Fig. 1(b). By changing the Doppler correction to the recoiling target nuclei, γ-ray transitions from the titanium isotopes can be observed, as shown in Fig. 1(c).

Coulomb-excitation cross sections and particle-γ angular correlations were measured at four different recoiling target angles using rings 1 through 4 of BareBall, covering $\theta_{\mathrm{lab}} = 7° - 60°$ or $\theta_{\mathrm{c.m.}} = 166° - 60°$. A leading concern with using Coulomb excitation to extract accurate electromagnetic moments is the role of Coulomb-nuclear interference on the measured cross sections, which is destructive near the barrier [15, 17, 18]. Table I provides the effective $B(E2; 0_1^+ \to 2_1^+)$ values of ^{136}Te per BareBall ring for normalizations to Rutherford scattering and the $B(E2)$ of ^{48}Ti [19], assuming all other matrix elements are zero; the $4_1^+ \to 2_1^+$ yield of ^{136}Te has little to no impact on the $2_1^+ \to 0_1^+$ yield or effective $B(E2)$ value. Excellent consistency is found between the two normalizations for rings 2 and 3. The ^{48}Ti normalization for ring 1 is absent due to a lack of statistics. The Rutherford normalization for ring 4 is absent because the particle identification was not cleanly separated from the detector threshold, due to the low energy of the recoiling target nuclei at the larger lab angles.

TABLE I: Effective $B(E2; 0_1^+ \to 2_1^+)$ e^{2}b^2 values of ^{136}Te per BareBall ring for normalizations to Rutherford scattering and the $B(E2)$ of ^{48}Ti, assuming all other matrix elements are zero. Only the statistical uncertainties are given.

Normalization	Ring 1 θ_{lab} =7-14° $\theta_{\mathrm{c.m.}}$ =166-152°	Ring 2 14-28° 152-124°	Ring 3 28-44° 124-92°	Ring 4 44-60° 92-60°
		Nominal		
Rutherford	0.137(10)	0.154(5)	0.158(4)	
^{48}Ti^a		0.149(18)	0.155(12)	0.173(11)
		$V = 100$ MeV, $W = 0$ MeV		
Rutherford	0.139(10)	0.155(5)	0.159(4)	
^{48}Ti^a		0.149(18)	0.155(12)	0.173(11)
		$V = 100$ MeV, $W = 40$ MeV		
Rutherford	0.142(10)	0.157(5)	0.159(4)	
^{48}Ti^a		0.153(18)	0.156(12)	0.173(11)

$^a B(E2; 0_1^+ \to 2_1^+) = 0.0662(29)$ e^{2}b^2 [19].

The effective $B(E2)$ values provided in Table I reveal a systematic decrease in magnitude with decreasing ring number or increasing center of mass angle. This destructive effect could be due to Coulomb-nuclear interference or reorientation from a prolate quadrupole deformation. The possibility of Coulomb-nuclear interference was investigated by performing calculations with the quantum code PTOLEMY [20] using two different optical potentials (V is the real potential and W is the imaginary/absorption potential). The results indicate that the Coulomb-nuclear interference effect is $< 3.6\%$ for ring 1; the effect is smaller for ring 2 and negligible for rings 3 and 4. Thus the reorientation effect can be used to determine $Q(2_1^+)$.

Virtual excitations to higher-lying states were included in the analysis using the semi-classical Coulomb-excitation code GOSIA [21]. Details of the analysis procedures, including necessary corrections, can be found in Refs. [7, 12–16]. The sensitivity or correlation between $\langle 0_1^+ || M(E2) || 2_1^+ \rangle = \sqrt{B(E2; 0_1^+ \to 2_1^+)}$ and

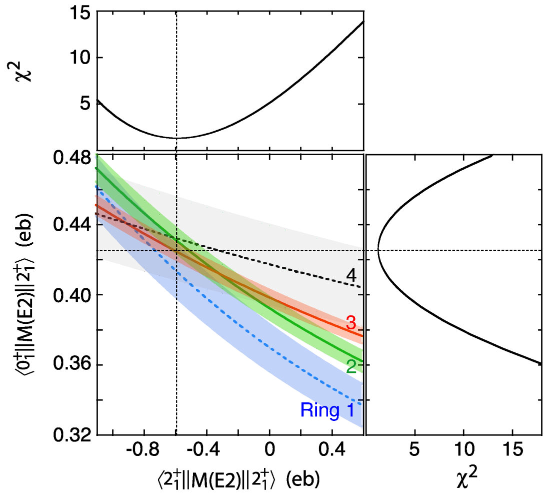

FIG. 2: Sensitivity of $\langle 0_1^+||M(E2)||2_1^+\rangle$ to $\langle 2_1^+||M(E2)||2_1^+\rangle$ per BareBall ring and the total χ^2.

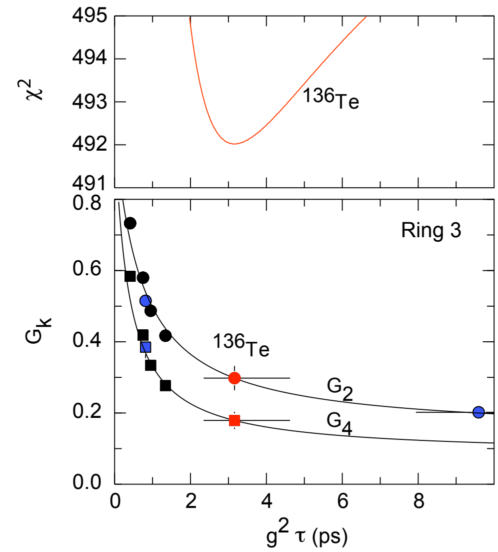

FIG. 3: (a) Total χ^2 versus $g^2\tau$ and (b) G_k versus $g^2\tau$ calibration curves for BareBall ring 3. The best fit $g^2\tau$ value for ^{136}Te, and its uncertainty, is projected onto the curves (red filled). Also shown are calibration data from stable Te isotopes [6, 13] that define the G_k curves [22]. Results for ^{125}Te are blue filled. Note that there is no G_4 term for $I = 3/2$ states and that the differences in G_k values for $I = 3/2, 2, 5/2$ are small compared to the experimental uncertainty.

$\langle 2_1^+||M(E2)||2_1^+\rangle = 1.319 \times Q(2_1^+)$ per BareBall ring is shown in Fig. 2, revealing the presence of reorientation from a prolate quadrupole moment with a value of $Q(2_1^+) = -0.45(23)$ eb. The new $B(E2; 0_1^+ \rightarrow 2_1^+)$ value of 0.181(15) e^{2}b^2 is larger than the previous measurement of 0.122(18) e^{2}b^2 [3, 4].

The g factor was determined by the recoil in vacuum method, following similar analysis procedures as for ^{124,126,128}Sn [13] and ^{132,134}Te [7, 22] but with modification to accommodate the longer lifetime of the 2_1^+ state; previous studies focused on states with $\tau \lesssim 3$ ps, whereas here the level of interest has $\tau \sim 30$ ps. Extensive RIV data were collected for ^{122,124,125,126,130}Te. These data will be reported in detail elsewhere [23]. The ^{125}Te data are particularly important here. The $3/2^+$, 444-keV state, with mean life $\tau = 27.6$ ps and g factor $g = +0.59(5)$ [24–26], allows calibration of the RIV interaction out to the necessary lifetime, while the $5/2^+$ 463-keV state in ^{125}Te with $\tau = 19.0$ ps and $g = +0.207(22)$ [24–26] has nearly the same $g\tau$ value as the 2_1^+ state in ^{122}Te ($\tau = 10.8$ ps, $g = +0.353(14)$ [25]), but the two levels have very different g factors and lifetimes. In our earlier work on shorter-lived states, calibration curves of the vacuum attenuation coefficients G_k versus $|g|\tau$ were employed. It is evident from the ^{122,125}Te comparison, however, that G_k versus $g^2\tau$ is appropriate here. This altered dependence can be anticipated because atomic transitions during the nuclear lifetime become important for longer-lived states [22, 27]. The G_k values were determined from fits to the angular correlations and calibration curves constructed, from which the g factor of ^{136}Te was then obtained. Fig. 3 shows the calibration curves for BareBall ring 3 and the result of the fit to determine $g^2\tau$ for ^{136}Te. A g factor of $(+)0.34(^{+8}_{-6})$ is then obtained using $\tau = 27.5(23)$ ps from the present $B(E2)$ measurement. The sign (+) is tentatively set by systematics and on the basis that no standard theory can predict a negative g factor of the observed magnitude.

The experimental electromagnetic moments for radioactive ^{136}Te are summarized in Table II and a comparison to several theoretical calculations is provided. Interestingly, with only 2p $\oplus$ 2n outside of double-magic ^{132}Sn, the experimental results and several of the theoretical calculations are consistent with rotational-like B_{42}/B_{20} ratios and $Q(2_1^+)$ values. Note that the $B_{20} \equiv B(E2; 2_1^+ \rightarrow 0_1^+) = B(E2; 0_1^+ \rightarrow 2_1^+)/5$ and $B_{42} \equiv B(E2; 4_1^+ \rightarrow 2_1^+)$ values in single-particle Weisskopf units are 8.71(74) and 14.4(22) W.u., respectively. Furthermore, the experimental magnitude of $g(2_1^+)$ is consistent with $0.8Z/A = 0.30$, which corresponds to the average empirical fraction of Z/A for heavy collective nuclei.

The present shell-model calculations (SM1 and SM2) included all proton single-particle orbits in the $Z = 50 - 82$ shell $(\pi 1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2}, 1h_{11/2})$ and all neutron orbits in $N = 82 - 126$ shell $(\nu 1h_{9/2}, 2f_{7/2}, 2f_{5/2}, 3p_{3/2}, 3p_{1/2}, 1i_{13/2})$. Single particle energies were set by reference to ^{133}Sb and ^{133}Sn for protons and neutrons, respectively. The two calculations differ somewhat in the choice of interaction, effective charges and effective $M1$ operator. Both, however, evaluated $E2$ matrix elements using standard harmonic oscillator radial wavefunctions, and both have been applied to ^{136}Te and neighboring nuclei in recent literature [32–35].

TABLE II: Summary of ^{136}Te electromagnetic moments, $B(E2)$ e^{2}b^2, Q eb, and g.

	Present Exp.	Exp. [3, 4]	Present SM1	SM2	MCSM [8]	GCM-GOA [28]	QRPA [9]	QRPA2 [29]	α [30]	NSM [31]
$B(E2;0_1^+\to 2_1^+)^a$	0.181(15)	0.122(18)	0.170	0.206	0.150	0.23	0.09	0.11	0.15	0.24
$B(E2;2_1^+\to 0_1^+)$	0.0362(31)	0.0244(36)	0.034	0.041	0.030	0.046	0.018	0.022	0.029	0.048
$B(E2;4_1^+\to 2_1^+)$	0.060(9)		0.048	0.052	0.033				0.040	0.068
$B(E2;2_2^+\to 0_1^+)$	<0.004		0.0002	0.003	0.006			0.015		0.0002
$B(E2;2_2^+\to 2_1^+)$	<0.09		0.023	0.040	0.001			0.002		0.030
$Q(2_1^+)$	$-0.45(23)$		-0.30	-0.26	-0.21	-0.37	-0.43			
$g(2_1^+)$	$(+)0.34(^{+8}_{-6})$		$+0.34$	$+0.12$	-0.11		-0.17			
B_{42}/B_{20}	1.66(34)		1.41	1.27	1.1				1.38	1.42

$^a B(E2;0_1^+\to 2_1^+) = 5\times B(E2;2_1^+\to 0_1^+)$.

The SM1 calculation was performed with the NuShellX@MSU code [36]. As described in Refs. [32, 33], the interaction for the proton-proton space was based on the CD Bonn potential and the proton-neutron and neutron-neutron interactions, designated $jj56pnb$, were obtained from the N^3LO potential. The effective charges were $e_p = 1.5e$ and $e_n = 0.5e$. Adjusting e_p and e_n to observed $E2$ transitions in ^{134}Te and ^{134}Sn, respectively, results in $e_p = 1.56e$ and $e_n = 0.66e$. These "optimized" effective charges increase the $B(E2)$ values by roughly 28% and the $Q(2_1^+)$ magnitude by 14%. However, the standard effective charges were adopted. The effective $M1$ operator applied a correction $\delta g_l(p) = 0.13$ to the proton orbital g factor and quenched the spin g factors for both protons and neutrons to 70% of their bare values. (The tensor term was ignored.) The effective $M1$ operator is then similar to that of Jakob *et al.* [37] and in reasonable agreement with that of Brown *et al.* [32]. For SM2 the two-body effective interaction was derived from the CD-Bonn NNpotential, renormalized by means of the V_{low-k} approach [38], within the framework of the perturbative $\hat{Q}$-box folded-diagram expansion [39]. In this case $e_p = 1.7e$ and $e_n = 0.7e$, and the single-particle matrix elements of the effective $M1$ operator were calculated by perturbation theory, consistently with the derivation of the effective two-body interaction.

By comparing the various calculations in Table II and Fig. 4, the SM1 and SM2 shell-model calculations appear to best reproduce the experimental electromagnetic moments. All of the available $Q(2_1^+)$ predictions are consistent with the experimental value. However, while there is qualitative agreement amongst the predicted $E2$ transition strengths and $Q(2_1^+)$ values, there is a wide range of predictions for the $g(2_1^+)$ magnitude and sign; $g(2_1^+)$ is evidently very sensitive to the balance between proton and neutron contributions to the wavefunction. The larger g factor of SM1 relative to SM2 does not stem from the $M1$ operator, because the value with the bare $M1$ operator in SM1 ($g = +0.23$) is larger than that in SM2 ($g = +0.02$). For both calculations the decompositions of the wavefunctions indicate that the 2_1^+ wavefunction is dominated by excited valence neutron configurations. The leading component of the 2_1^+ wavefunction

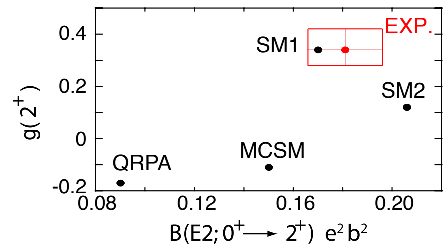

FIG. 4: The $g(2_1^+)$ versus $B(E2;0_1^+\to 2_1^+)$ experimental value (red) compared to the present SM1 and SM2 and previous MCSM [8] and QRPA [9] calculations.

in SM1(SM2) is 40%(60%) $J_n = 2$, $J_p = 0$. The next leading term is 20%(16%) $J_n = 0$, $J_p = 2$, with all remaining terms $< 10\%$. Although SM1 has an increased proton content, in better agreement with the experimental g factor, the wavefunction of the 2_1^+ state remains dominated by the neutron configuration. The leading components for the 4_1^+ and 2_2^+ states in SM1(SM2) are 32%(32%) $J_n = 4$, $J_p = 0$ and 42%(32%) $J_n = 2$, $J_p = 0$, respectively. With respect to the 2_2^+ state, the experimental limits on the $B(E2)$ values are inconsistent with recent predictions of a "mixed symmetry" state [8, 9]. This leaves the 2_3^+ state as the better "mixed symmetry" candidate, as predicted by Covello *et al.* [40]; more experimental data are needed to clarify this point.

The $E(2_1^+)$, $B(E2;0_1^+\to 2_1^+)$, and $g(2_1^+)$ systematics for the radioactive Te isotopes about the $N = 82$ shell closure are provided in Fig. 5 and compared to the present SM1 and SM2 and previous MCSM [8] and QRPA [9] calculations. The SM1 and SM2 calculations for ^{132}Te used nucleon-nucleon interactions that were consistently derived within the procedure described above but for neutrons in the five orbits of the 50-82 shell. The SM1 and SM2 calculations consistently perform the best, particularly with respect to the g factor.

In conclusion, a complete set of electromagnetic moments, $B(E2;0_1^+\to 2_1^+)$, $Q(2_1^+)$, and $g(2_1^+)$, have been measured from Coulomb excitation of radioactive ^{136}Te, which has two protons and two neutrons outside of double-magic ^{132}Sn. Additionally, the value of $B(E2;4_1^+\to 2_1^+)$, and upper limits for $B(E2;2_2^+\to 2_1^+)$

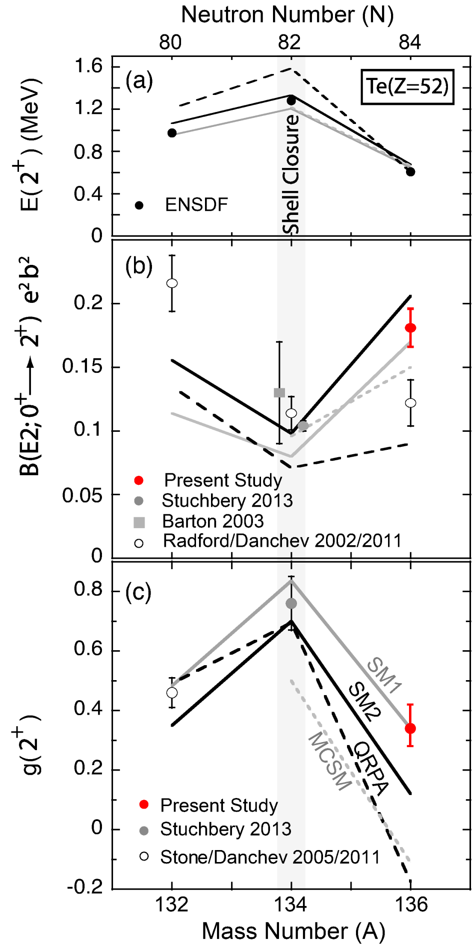

FIG. 5: The (a) $E(2_1^+)$, (b) $B(E2;0_1^+\to 2_1^+)$, and (c) $g(2_1^+)$ systematics for ^{132,134,136}Te from the present (red) and previous studies [3, 4, 6, 7] compared to the present SM1 (solid gray line) and SM2 (solid black line) and previous MCSM (dashed gray line) [8] and QRPA (dashed black line) [9] calculations.

and $B(E2;2_2^+\to 0_1^+)$ have also been determined. Present results for 2_1^+ indicate emergence of prolate-deformed quadrupole collectivity, and a greater proton content in its wavefunction than previously suggested. Further, these results are inconsistent with recent predictions of a 2_2^+ mixed-symmetry state, leaving the 2_3^+ state as the better candidate for this behavior. More importantly, it is demonstrated that extreme sensitivity of $g(2_1^+)$ to the proton and neutron contributions to the wavefunction provides unique insight into the nature of emerging collectivity, and may be utilized as a powerful tool to differentiate among various theoretical calculations. Our results are best described by the most recent state-of-the-art shell model calculations.

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