PHYSICAL REVIEW C VOLUME 57, NUMBER 3 MARCH 1998

Octupole correlations at low spin in $^{108}_{52}Te_{56}$

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(Received 4 September 1997)

Excited states in ^{108}Te have been identified up to spins of $\sim 20\hbar$ using the extremely weak $2p2n$ evaporation channel ($\sim$0.2% of σ_{fus}) from the bombardment of a backed ^{54}Fe target with 243 MeV ^{58}Ni ions. Channel selection and enhancement was made possible using the power of the GAMMASPHERE array to measure high-fold γ-ray coincidences and the resultant application of multiple γ-ray gating techniques. The observation in ^{108}Te of two interleaved sequences of levels with assumed opposite parity connected by enhanced $E1$ transitions is interpreted in terms of octupole correlations. The current results for ^{108}Te make it the closest nucleus to the predicted region of octupole deformation centered at $N=Z=56$ yet studied to high spin. [S0556-2813(98)50403-7]

PACS number(s): 21.10.Re, 23.20.Lv, 25.70.Gh, 27.60.+j

Deformed shell model calculations predict that the nucleon numbers 34, 56, 88, and 134 are strongly octupole driving due to the proximity to the Fermi surface of single-particle levels (with $\Delta l = \Delta j = 3$) which are connected by large octupole-interaction matrix elements [1,2]. Of the predicted regions of stable octupole deformation, the best studied and most well-developed regions are centered around $^{224}_{90}Th_{134}$ and $^{144}_{56}Ba_{88}$ [1,2]. An interesting proposition is that nuclei with $N \approx Z$ both near one of the above octupole magic numbers might exhibit especially strong octupole effects; firstly, because both the neutrons and protons can contribute, and secondly, because of the added possibility for a proton-neutron interaction. Indeed, experimental and theoretical evidence has been presented for octupole effects in the $N=Z=32$ nucleus ^{64}Ge [3], although it is well known that it is the heavier nuclei which exhibit the strongest octupole correlations. Possibly the heaviest $N=Z$ region which could be accessed experimentally lies near $^{112}_{56}Ba_{56}$, a region for which there are theoretical predictions of ground state octupole deformation [4–6]. This has led to recent experimental investigations which have revealed enhanced $E1$ transitions connecting interleaved positive and negative-parity bands in the lightest even-mass xenon and tellurium isotopes studied to high spin, i.e., ^{114}Xe [7] and ^{110,112}Te [8,9]. The next lighter even-mass tellurium isotope, ^{108}Te, is predicted to show the most pronounced octupole effects of the tellurium isotopes ($N=56$ being an octupole magic number) but is extremely difficult to access experimentally due to its neutron deficiency. Excited states are only known in ^{108}Te up to $8\hbar$ from two previous studies [10,11] and no evidence for octupole correlations was observed. The current work has applied the power of GAMMASPHERE to extract a high-spin level scheme for ^{108}Te in the presence of an intense background of γ rays from more strongly populated channels. This makes ^{108}Te the closest nucleus to the predicted region of octupole deformation at $N=Z=56$ which has been studied to high spin. This Rapid Communication reports the observation of interleaved positive and (assumed) negative-parity bands at low spin in ^{108}Te connected by enhanced $E1$ transitions. The deduced $B(E1)$ transition strengths suggest a weaker dependence on T_Z than was implied by the results for ^{114}Xe [7], in agreement with the results for ^{110}Te [8]. A pronounced spin dependence of the $E1$ transition moment is also observed. The results provide a strong motivation for future studies of the light xenon and barium nuclei approaching ^{112}Ba.

Excited states in ^{108}Te were populated by bombarding an ^{54}Fe target with 243 MeV ^{58}Ni ions from the 88-inch cyclotron at Lawrence Berkeley National Laboratory. Gamma rays were observed using the GAMMASPHERE array, which at the time of the experiment consisted of 95 large-volume (75–80 % efficient) Compton-suppressed HPGe detectors. A 600 μg/cm^2 foil of enriched ^{54}Fe backed with 15.2 mg/cm^2 of gold was the principal target, although a smaller amount of data with a thin 500 μg/cm^2 foil of ^{54}Fe was also collected. Both previous studies of ^{108}Te utilized this same beam/target combination, but under different reaction conditions [10,11]. Although this is the most favorable reaction to make ^{108}Te, the $2p2n$ evaporation channel is only very weakly populated ($\sim$0.2% of the total fusion cross section). The strong ^{109}Sb [12] ($3p$), ^{108}Sn [13] ($4p$), and ^{106}Sn [14] ($\alpha 2p$) channels, which comprise approximately 27%, 42%, and 17% of the total fusion cross section, respectively, provide an intense background obscuring the ^{108}Te γ rays. The use of a backed target resulted in excellent energy resolution to resolve the multitude of γ rays created in the reaction. This resolution combined with the resolving power of GAMMASPHERE allowed the construction of a level scheme for ^{108}Te up to spins of $\sim 20\hbar$, despite the small cross section.

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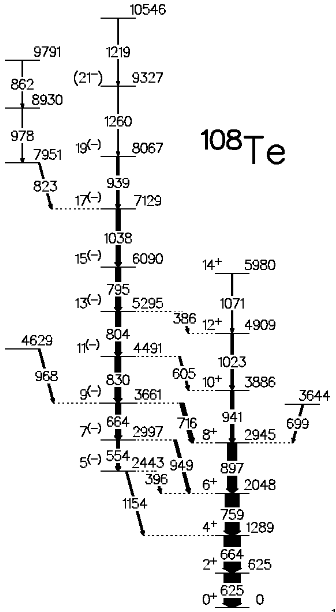

FIG. 1. Proposed level scheme for ^{108}Te.

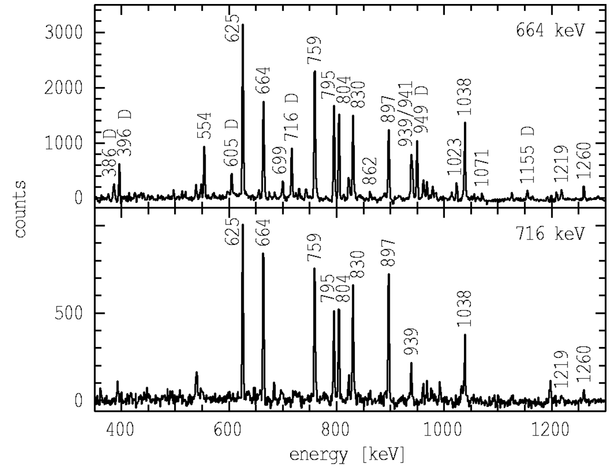

FIG. 2. Coincidence spectra obtained from the double-gated matrix. Peaks labeled with the letter D correspond to interband $E1$ transitions. Note that not all identified peaks are labeled and some weak contaminant peaks are present.

Approximately 2.5×10^9 events in which four or more γ rays were detected in prompt coincidence were written to magnetic tape. During replay, the data were unfolded into 20×10^9 triple-coincidence events which were incremented into a RADWARE cube [15]. The LEVIT8R code [15] was then used to project double-gated, background-subtracted coincidence spectra from the cube and the deduced γ-ray coincidence relationships and intensities were used to begin constructing the level scheme shown in Fig. 1.

Since the proportion of ^{108}Te in the data set was extremely small, special procedures were required. To analyze angular correlations and identify some of the weakest transitions it proved beneficial to sort coincidence matrices which were gated by the main transitions in ^{108}Te, thus reducing the competing background from the more strongly populated channels. These gated matrices were analyzed with the RADWARE suite of software [15].

To identify and place the very weakest transitions in ^{108}Te, a double-gated coincidence matrix was created using a gate-list consisting of transitions with energies of 625, 664, 759, 897, 941, 830, 804, and 795 keV. Approximately 120×10^6 dual coincidences were sorted into this matrix and a 16-fold enhancement of the proportion of ^{108}Te (from $\sim$0.2% up to $\sim$3.2%) was obtained. Coincidence spectra projected from this matrix are presented in Fig. 2. The top panel illustrates that the 664 keV γ ray is in self-coincidence, while also showing all of the γ rays assigned to ^{108}Te in the present work (since all of the assigned transitions are in coincidence with either one or the other member of the 664 keV doublet). The lower panel is a coincidence spectrum gated upon the most intense interband transition with energy 716 keV. The absence of all other linking transitions in this lower spectrum, taken together with the selection of the upper and lower parts of the two band sequences, supports the integrity of the proposed level scheme in Fig. 1.

To obtain accurate γ-ray intensities for the transitions it is again helpful to use a data set in which ^{108}Te has been enhanced. However, the double-gated matrix was not appropriate for this, since the intraband transitions used in the gate-list (see above and Fig. 1) are reduced in intensity. Instead, a coincidence matrix singly gated by the 625 keV, $2^+\rightarrow0^+$ transition was created and used solely for the purpose of fitting the intensities of the transitions. A total of 149×10^6 gated coincidences were sorted into this matrix with a resultant enhancement of the proportion of ^{108}Te from $\sim$0.2% to $\sim$3.0%.

To ascertain the multipolarities of the transitions, matrices were sorted in which γ rays detected at selected angles were sorted onto one axis, with coincident γ rays detected at all angles on the other axis. By gating on the ''all-angle'' axis, the spectrum of coincident γ rays detected at a particular angle could be projected, reducing the background considerably. To clean up these spectra further, the matrices were also single-gated using the same gate list as that for the double-gated matrix described above. The 17 rings of detectors were split into six angular groupings (17.3°), (31.7°, 37.4°), (50.1°), (58.3°), (69.8°), and (79.2°, 80.7°, 90.0°), chosen to be roughly equally spaced across the range from $\cos^2\theta=0.012$ to 0.912 and with the rings at θ and $(180°-\theta)$ treated as the same angle. The intensities of the γ rays in the spectra associated with the various angles were measured and then fitted to the expression $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, where the intensity normalization factor has been omitted. Because there was close to uniform solid angle coverage with 95 detectors present out of a total of 110 in the complete array, the deduced values of A_2 and A_4 were close to those usually expected. This was checked using intense transitions of known multipolarity in ^{108}Sn [13] and ^{106}Sn [14]. For stretched $E2$ and $E1$ transitions, the resulting A_2 and A_4 coefficients were grouped around values of $A_2=0.30(2)$, $A_4=-0.12(2)$ and $A_2=-0.28(3)$, $A_4=-0.01(2)$, respectively. Examples of the experimental results for both ^{108}Sn calibration transitions and newly observed ^{108}Te transitions are presented in Fig. 3.

The level scheme for ^{108}Te was known previously up to a spin of $8\hbar$ [10,11] and was extended by the current work up to $\sim20\hbar$ as shown in Fig. 1. The measured and deduced properties of the transitions assigned to ^{108}Te are summarized in Table I. Two sequences of stretched quadrupole transitions are observed, all of which up to the $19^{(-)}$ level were

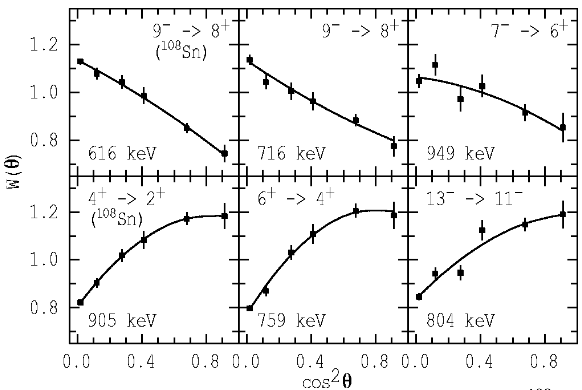

FIG. 3. Angular distributions for selected γ rays from ^{108}Sn and ^{108}Te (see text).

also observed in the thin-target data set, ruling out the possibility of $M2$ assignments and confirming their $E2$ character. The results of the angular distribution analysis for the transitions linking between the two $E2$ sequences suggest that the 605, 716, and 949 keV γ rays are stretched dipole transitions. The other linking transitions can then be inferred to be stretched dipoles despite being either too weak and/or contaminated to be measured themselves. The excited band at low E_x decaying into the ground state band via stretched dipole transitions is suggestive of a negative-parity octupole structure. This is in agreement with theoretical expectations to be outlined below and with systematics [1,2]; thus, the following discussion assumes the excited band has negative parity and the dipole transitions have $E1$ character.

Various theoretical calculations [4–6] make specific predictions regarding the presence of ground-state octupole deformation in the region near $^{112}_{56}\mathrm{Ba}_{56}$. In particular, the Strutinsky calculations of Skalski [4] exhibit octupole-deformed minima for the ground states of both ^{108}Te and ^{110}Te, although the energy gains of the octupole minima compared to the reflection-symmetric minima are only 60 and 10 keV, respectively. Thus, Skalski suggests that at best an octupole softness should be observed in the tellurium isotopes from $N=54$ to $N=60$. The tellurium isotopes would then be expected to show the characteristics of octupole vibration rather than rigid rotation of a reflection-asymmetric shape, with the largest effects apparent at $N=56$, i.e., ^{108}Te.

Various methods of characterizing the observed spectrum of excited states have been suggested for octupole nuclei [1,2]. Figure 4 presents results for the ratio of the rotational frequencies of the positive and negative-parity bands,

$$R(I)=\frac{\omega(-)}{\omega(+)}=2\,\frac{E[(I+1)^{-}]-E[(I-1)^{-}]}{E[(I+2)^{+}]-E[(I-2)^{+}]} \qquad (1)$$

TABLE I. Properties of transitions assigned to ^{108}Te.

E_γ [a]	I_γ [b]	A_2 [c]	A_4 [c]	$M\lambda$	$J_i^\pi \to J_f^\pi$
385.8	4.9(5)	<0		$(E1)$	$13^{(-)}\to 12^{+}$
395.5	8.4(12)			$(E1)$	$5^{(-)}\to 4^{+}$
553.6	17.1(15)	0.26(4)	−0.14(6)	$E2$	$7^{(-)}\to 5^{(-)}$
604.9	9.0(7)	−0.51(4)	−0.06(5)	$(E1)$	$11^{(-)}\to 10^{+}$
625.2	≡100	0.32(3)	−0.16(4)	$E2$	$2^{+}\to 0^{+}$
663.8	≡100	0.31(3) [d]	−0.15(4) [d]	$E2$	$4^{+}\to 2^{+}$
664.1	34.2(17)	0.31(3) [d]	−0.15(4) [d]	$E2$	$9^{(-)}\to 7^{(-)}$
699.4	8.1(10)				$\to 8^{+}$
716.0	24.3(12)	−0.25(3)	0.02(4)	$(E1)$	$9^{(-)}\to 8^{+}$
758.8	91(4)	0.34(3)	−0.15(4)	$E2$	$6^{+}\to 4^{+}$
795.3	35.1(15)	0.31(3)	−0.08(4)	$E2$	$15^{(-)}\to 13^{(-)}$
803.9	33.6(14)	0.27(3)	−0.08(4)	$E2$	$13^{(-)}\to 11^{(-)}$
822.7	7.0(7)				$\to 17^{(-)}$
830.2	36.2(17)	0.27(3)	−0.03(4)	$E2$	$11^{(-)}\to 9^{(-)}$
861.9	4.4(6)				
897.0	56.9(25)	0.32(3)	−0.12(4)	$E2$	$8^{+}\to 6^{+}$
938.7	14.8(11)	0.28(4) [d]	−0.18(6) [d]	$E2$	$19^{(-)}\to 17^{(-)}$
941.1	24.4(17)	0.28(4) [d]	−0.18(6) [d]	$E2$	$10^{+}\to 8^{+}$
949.2	15.6(13)	−0.16(4)	−0.04(5)	$(E1)$	$7^{(-)}\to 6^{+}$
968.1	8.8(10)				$\to 9^{(-)}$
978.2	6.6(7)				
1022.8	14.0(11)	0.24(4)	0.02(6)	$E2$	$12^{+}\to 10^{+}$
1038.3	25.7(12)	0.27(3)	−0.02(4)	$E2$	$17^{(-)}\to 15^{(-)}$
1071.2	6.1(8)	0.26(7)	−0.17(10)	$E2$	$14^{+}\to 12^{+}$
1154.5	8.9(18)			$(E1)$	$5^{(-)}\to 4^{+}$
1218.6	2.8(5)				
1259.9	3.5(5)	>0		$(E2)$	$(21^{-})\to 19^{(-)}$

[a]Energies are typically accurate to within ± 0.2 keV.
[b]Relative coincidence intensities obtained by fitting the gated $\gamma\gamma$ matrix (see text).
[c]Angular distribution coefficients (see text).
[d]Doublet, result obtained for composite peak.

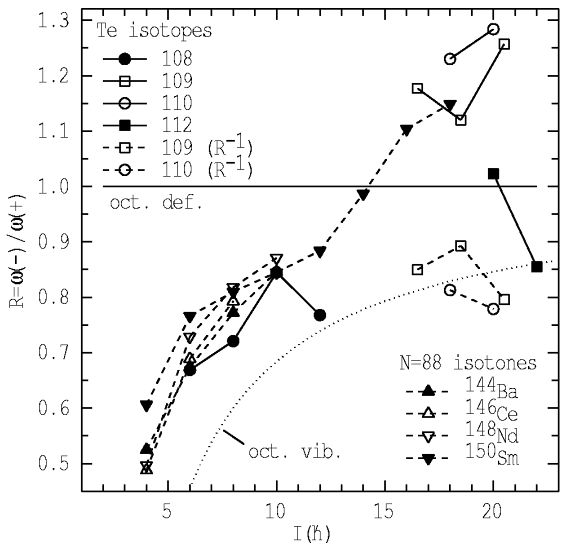

FIG. 4. Plot of $Rp=\omega(-)/\omega(+)$ for selected light tellurium nuclei [8,9,16] and $N=88$, $Z\approx 56$ nuclei [17–20].

for the light tellurium isotopes [8,9,16] and a number of $N=88$, $Z\approx 56$ nuclei [17–20]. The dotted line indicates the expected behavior when the negative-parity states result from the coupling of an aligned octupole phonon to the positive-parity states [1,2], while the solid line at $R=1$ would be the limit for pure rotation of a reflection-asymmetric shape. All of the previously studied $N=88$ nuclei lie closer to the vibrational limit; indeed, only in the thorium region are there nuclei which are known to approach the rotational limit smoothly (e.g., ^{222,224}Th [21,22]). The results for the even-mass tellurium isotopes in Fig. 4 generally show a less smooth behavior than the $N=88$ isotones. This may indicate a lack of collectivity which will be discussed further below. However, it does appear that the negative-parity states in ^{108}Te are best described in terms of an aligned octupole phonon coupled to the ground-state band. The alternative of a $\nu h_{11/2}\otimes(d_{5/2}/g_{7/2})$ two quasiparticle structure can be effectively ruled out by the fact that such a band is not observed at low E_x in the heavier tellurium isotopes. It is also interesting to compare the similarities and differences between the even-mass tellurium isotopes. For example, ^{108}Te and ^{112}Te are rather similar despite the negative-parity states being observed in different spin regimes. The results for ^{110}Te present a stark contrast however, since in that nucleus the negative-parity states are yrast at high spin and it is the positive-parity states which eventually decrease in energy to interleave with the negative-parity states. When the inverse ratio $R^{-1}=\omega(+)/\omega(-)$ is plotted for the states in ^{110}Te, the result looks very much like that for R for ^{108,112}Te (see Fig. 4). This unusual behavior (for an even-even isotope) is further evidence that octupole vibration is at work in the tellurium isotopes rather than the rotation of a stable octupole-deformed shape. The high-spin positive-parity states in ^{110}Te probably arise from the coupling of an aligned octupole phonon to the yrast negative-parity states. Further experimental and theoretical investigations would be of benefit to understand the differences between the tellurium isotopes.

The irregular behavior for ^{108}Te which can be seen in Fig. 4 warrants further discussion. Since ^{108}Te is only eight nucleons outside the doubly closed shell at ^{100}Sn, it is obvious that a collective description may not be appropriate. Indeed, the maximum spin available within the lowest-energy positive-parity configuration $\pi(g_{7/2})^2_6\otimes\nu(g_{7/2}/d_{5/2})^6_{12}$ is only $18\hbar$, while for the lowest-energy negative-parity configuration $\pi(g_{7/2})^2_6\otimes[\nu h_{11/2}(g_{7/2}/d_{5/2})^5]_{17}$ it is only $23\hbar$. Since excited states are observed in ^{108}Te to within a few $\hbar$ of these maximum spins, termination effects may be important. Furthermore, the limited valence space for ^{108}Te makes this nucleus an excellent case for pursuing shell model calculations to help give a microscopic understanding of the onset of octupole correlations.

TABLE II. Measured $B(E1)/B(E2)$ ratios and deduced $E1$ transition strengths and dipole moments in light tellurium isotopes (assuming $Q_0=200\ e\ \mathrm{fm}^2$).

Nucleus	I^π	$B(E1)/B(E2)$ (10^{-6} fm^{-2})	$B(E1)$ ($10^{-3}\ e^2$ fm^2)	$\lvert D_0\rvert$ ($e$fm)
^{108}Te	7^-	0.043(5)	0.055(7)	0.0222(13)
	9^-	0.193(13)	0.256(18)	0.0476(17)
	11^-	0.34(3)	0.464(4)	0.064(3)
	13^-	0.66(7)	0.91(10)	0.089(5)
^{109}Te	$\frac{33}{2}^+$	0.73(8)	1.03(12)	0.094(5)
	$\frac{37}{2}^+$	0.80(8)	1.12(11)	0.098(5)
	$\frac{41}{2}^{+a}$	0.64(12)	0.90(17)	0.088(8)
	$\frac{45}{2}^{+a}$	2.1(4)	3.0(6)	0.160(17)
^{110}Te	18^+	0.63[b]	0.89[b]	0.087[b]
	20^+	0.94[b]	1.33[b]	0.107[b]
	22^+	1.37[b]	1.95[b]	0.130[b]
^{112}Te	21^-	0.95(7)[c]	1.35(10)	0.108(4)
	23^-	0.75(5)[c]	1.08(8)	0.096(3)
	25^-	2.65(19)[c]	3.8(3)	0.180(6)

[a] $\frac{41}{2}^+$: $E_\gamma(E1)=633$ keV, $E_\gamma(E2)=991$ keV and $\frac{45}{2}^+$: $E_\gamma(E1)=373$ keV, $E_\gamma(E2)=976$ keV.
[b] Results taken directly from Ref. [8] (errors $<10\%$ [8]).
[c] Results deduced from Ref. [9].

The deduced values of the $B(E1)/B(E2)$ branching ratios are presented in Table II for all tellurium isotopes in which enhanced $E1$ transitions have been observed [8,9,16]. The results given for ^{109}Te assume the dipole transitions observed at high spin are $E1$, contrary to the assignments of Ref. [16]. Furthermore, two additional points at high spin have been deduced for ^{109}Te from the present data, since ^{109}Te was populated via the $2pn$ channel. This extension of the level scheme agrees with the results of an unpublished report [23] which also interprets the dipole transitions in ^{109}Te as possibly being $E1$. Note however, that for all the tellurium isotopes, ^{108}Te, ^{109}Te [16], ^{110}Te [8], and ^{112}Te [9], as well as for ^{114}Xe [7], there is no definitive evidence that the octupole bands have negative (or for ^{109,110}Te, positive) parity. Thus it remains important to verify the electric nature of the linking transitions for at least one of these isotopes via experiment.

Deducing the absolute $B(E1)$ values and electric dipole moments is problematic since the tellurium isotopes are not strongly collective and it is difficult to estimate a value for Q_0 [and hence $B(E2)$]. Since the isotopes from ^{112}Te to ^{108}Te have similar 2^+ energies, it is not unreasonable to assume the same value of Q_0 for all of the tellurium isotopes shown in Table II. Using $Q_0=200\ e\ \mathrm{fm}^2$ (as was previously assumed for ^{110}Te in Ref. [8]) and applying the methods given in Ref. [24], values for $B(E1)$ and $|D_0|$ have been deduced. Because of the assumed value of Q_0, these absolute values should only be considered accurate to within $\pm25\%$. (Only the error due to the measured branching ratios is given in Table II.) It can be seen that all four isotopes exhibit an increase in $|D_0|$ with spin. It is possible (although unlikely) that this is an apparent increase due to a decreasing value of Q_0 with spin. There have also been suggestions that octupole deformation is stabilized by rotation, which could explain the increase in $|D_0|$. However, Fig. 4 shows that the tellurium isotopes remain vibrationlike for all observed spin values, suggesting that the increase in $|D_0|$ is probably not due to the onset of stable octupole deformation. Lifetime measurements, while extremely difficult to perform, would help to resolve these issues.

Recently, Heenen *et al.* [5] have predicted that in the ^{112}Ba region the $E1$ transitions will be enhanced in odd-mass isotopes compared to the even-mass cores. No such enhancement is immediately apparent for ^{109}Te. Note also, that although ^{108}Te has even smaller T_z than ^{110}Te, the $B(E1)$ values for the two nuclei are consistent with one another. This could be taken as further evidence that the dependence of the $B(E1)$ on T_z is weaker than the authors of Ref. [7] have suggested. Since both these points depend on absolute transition strengths, lifetime measurements would again be necessary to make firm conclusions.

It is worth commenting on the nonobservation of a 3^- state in ^{108}Te. Applying the $B(E1)/B(E2)$ branching ratio measured for the $7^{(-)}$ state (see Table II) to the $5^{(-)}$ state, the relative intensity of a (estimated) 450 keV, $5^-\rightarrow3^-$ transition is calculated to be 1.6, below the experimental sensitivity. Since a lower energy transition would have an even weaker intensity, the nonobservation of the $5^-\rightarrow3^-$ transition can be easily understood. In doing this analysis, it becomes apparent that the transition strength for the 396 keV, $5^{(-)}\rightarrow6^+$ transition is 24 times larger than for the 1154 keV, $5^{(-)}\rightarrow4^+$ transition. This unusual behavior requires theoretical interpretation.

To conclude, a moderate-spin level scheme has been constructed for the neutron-deficient nucleus ^{108}Te, using the power of GAMMASPHERE to resolve weakly populated structures. A band with assumed negative parity which decays to the ground-state band via enhanced $E1$ transitions has been observed at low spin and excitation energy in ^{108}Te. The spectrum of negative-parity states is characteristic of an aligned octupole vibration, in agreement with prior theoretical calculations which predict a stable (but very shallow) octupole minimum for the ground state of ^{108}Te. Similar octupole-vibrational features are seen in a number of the light tellurium isotopes, with in each case a similar pronounced spin dependence for $|D_0|$. The unusual features of weak collectivity, the spin dependence of the dipole moment and the differences between the various tellurium isotopes, all require further theoretical investigation. Finally, these new observations of octupole correlations in the light tellurium isotopes provide a strong motivation for future studies of the light xenon and barium isotopes; such studies await the development of new and more sensitive experimental techniques, and, for the very lightest nuclei, radioactive beams.

The authors wish to thank A. Lipski for making the targets and the staff of the 88-inch cyclotron for providing the ^{58}Ni beam. This work was supported in part by the U.S. National Science Foundation, the U.S. Department of Energy, the U.K. EPSRC, AECL Research, and the Canadian NSERC. C.M.P. acknowledges support from the University of York.

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