Collective states and shape coexistence in the Z = 50 region

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Abstract.
Shape coexistence was established in the Sn and Cd nuclei, and in the odd mass In and Sb nuclei, some time ago but firm evidence has been lacking for its presence at low spin in the Te nuclei. However, strong circumstantial evidence exists, and recent highly-sensitive γ-ray spectroscopic studies have observed transitions for candidate rotational 2^+ band members in ^{122}Te and ^{124}Te.

1 Introduction

Shape coexistence in the $Z = 50$ region was first proposed nearly 50 years ago, in part of explain the appearance of "extra" states in the low-excitation part of the level spectrum of the mid-shell Cd isotopes [1, 2]. Since that time, there has been tremendous progress in characterising the shape-coexisting states in Sn and Cd isotopes, as well as the odd-mass In and Sb. Shown in Fig. 1 are the energy systematics of the low-lying states in the Pb and Hg isotopes, with $Z = 82$ and 80, respectively, and the states in the Sn and Cd isotopes, with $Z = 50$ and 48. The similarity of the pattern of the shape-coexisting states as a function of the neutron number is striking and points to a common underlying cause. As has been discussed for many years, this cause is the promotion of a pair of protons across the closed-shell gap into unoccupied orbitals increasing the correlation energy which maximizes at the neutron mid-shell, giving rise to the characteristic "V"-shaped pattern of the shape-coexisting states [3, 4]. For a review of the presence of shape coexistence in the $Z = 50$ region, and the data associated with its assignment, see Refs. [5, 6]. While the evidence in support of shape coexisting states, based on $2p - 2h$ proton "intruder" excitations, is quite firm for the Cd and Sn isotopes (and $1p - 1h$ in the odd-mass In and Sb), it is much less so for other nuclei in the region [6]. In the Te isotopes, for example, while it can be expected that they should possess shape-coexisting states based on $4p - 2h$ proton configurations, analogous to the $2p - 4h$ states for the Cd isotopes, there has been considerable debate regarding their appearance in the low-excitation energy region; the energy systematics, shown in Fig. 2 could be nearly equally well explained by the evolution of structure from a predominately $U(5)$, or spherical vibrator, towards an $O(6)$, or γ-soft, behaviour (see, for example, Refs. [7, 8]), and even the possibility of $E(5)$ [9] behaviour in some cases [10–12].

The occurrence of shape coexistence in the low-excitation energy region of nuclei can greatly complicate the elucidation of their underlying structure. This is particularly the case when the shape-coexisting states strongly mix; signatures of structure can then be somewhat smeared. For a long time, this was suggested to be the case for the Cd isotopes [13–17],

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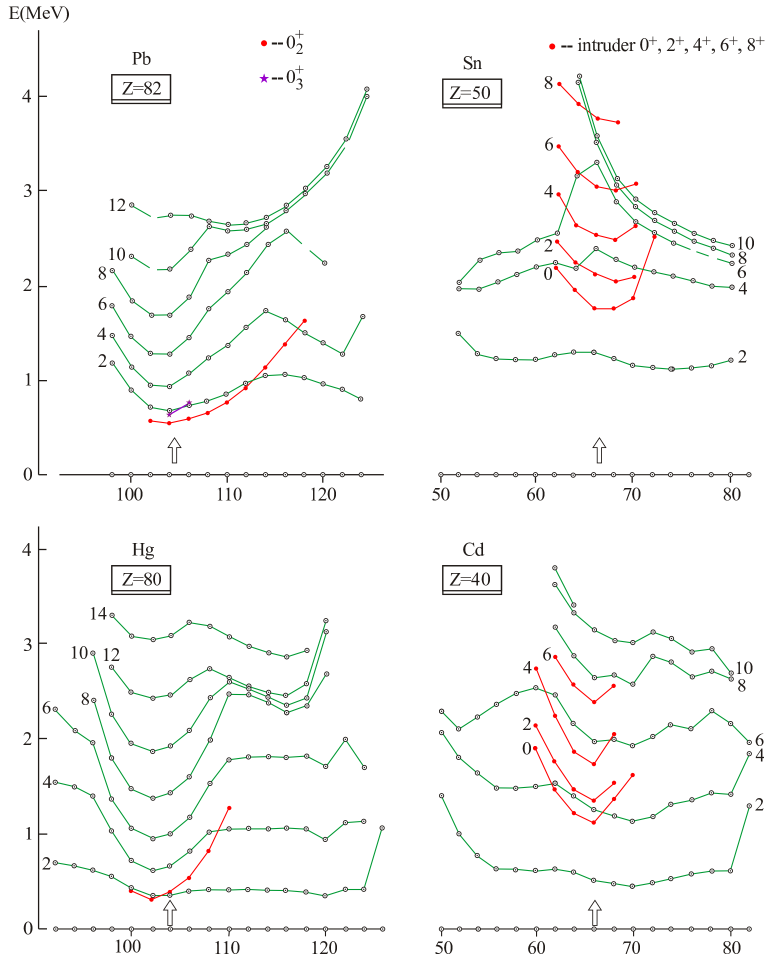

Figure 1. Systematics of the energies of the yrast, and near-yrast, states in the closed shell isotopes of Pb and Sn (top panels), and the 2-proton-hole nuclei Hg and Cd (bottom) as a function of neutron number. The arrows indicate the neutron mid-shell. Red indicates non-yrast states. Figure courtesy of J.L. Wood.

although there were issues associated with such a strong-mixing interpretation [18, 19]. It was pointed out in ^{114}Cd that the available $B(E2)$ data could be interpreted with either a strong or weak mixing scenario [20]. More recently, evidence in favour of weak mixing between the configurations was presented for ^{110}Cd [21], and the analysis of $E0$ transitions in ^{114}Cd also strongly support weak mixing [6, 22]. While the mixing may be weak, it can still have important consequences and lead to enhanced $B(E2)$ values, especially for the $0_2^+ \rightarrow 2_1^+$ transitions that arise from the contribution of the large intruder in-band $B(E2; 2^+ \rightarrow 0^+)$ value and the $2I + 1$ spin factor involved [23].

2 Evidence for intruder states in Te

While the energy systematics presented in Fig. 2 for the Te isotopes has a characteristic "V"-shaped pattern for the 0_2^+ states (and even the 0_3^+ states), this does not prove that they are of intruder origin. Shown in Fig. 3 is a detailed comparison of the available data for assigned intruder band heads in the Cd isotopes (top) and the suggested analogous states in the Te isotopes (bottom). Concentrating first on the Cd isotopes, it is seen that, especially in ^{110,112}Cd, the 0_2^+ states have a very strong population in the Pd($^3He, n$) reactions [24], of 42% and 55% relative to the ground state population, respectively. The Pd target nuclei have 4 proton holes

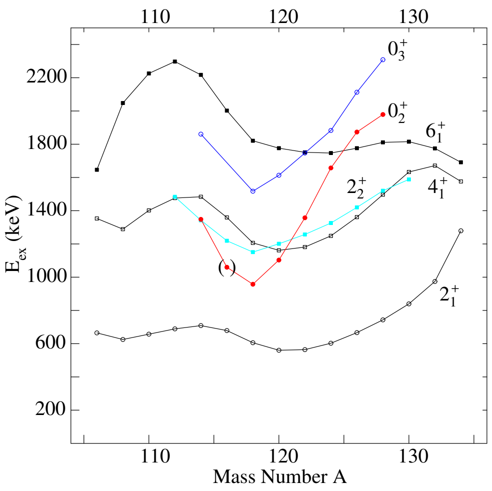

Figure 2. Systematics of the low-lying states in the even Te isotopes. The energy pattern of the 0_2^+ and 0_3^+ states suggests that there may be a crossing in the vicinity of ^{126}Te. Figure from Ref. [23].

with respect to the $Z = 50$ closed shell, and thus the two-proton-stripping reaction would be expected to populate either the ground state ($2h$) or the $2p-4h$ configurations. These data

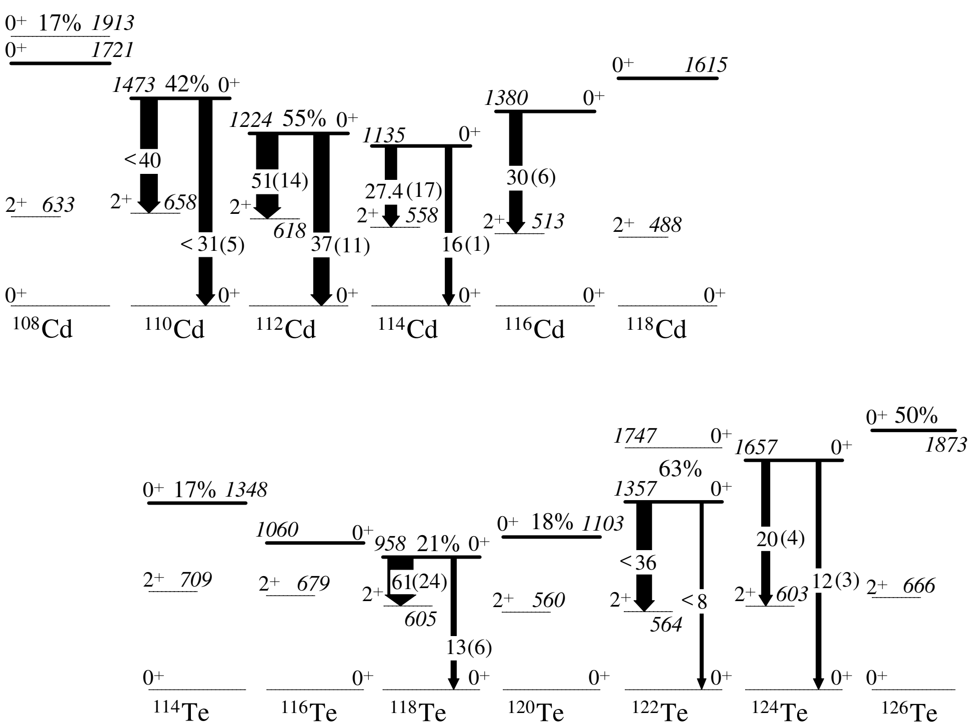

Figure 3. A comparison of the key data for the assigned deformed intruder band heads in the $^{108-118}$Cd isotopes (top) and those for the suggested 0^+ intruder states in $^{114-126}$Te (bottom). The levels with bold horizontal lines are the assigned or suggested intruder band heads. The numbers in percentages are the ($^3He, n$) cross sections relative to the ground state cross sections. The arrows represent the $B(E2)$ values for the $0^+ \rightarrow 2_1^+$ transitions, with their values in W.u., or $\rho^2(E0) \cdot 10^3$ values for $0^+ \rightarrow 0^+$ transitions. The nuclei are aligned vertically to a common neutron number. Figure adapted from Ref. [6].

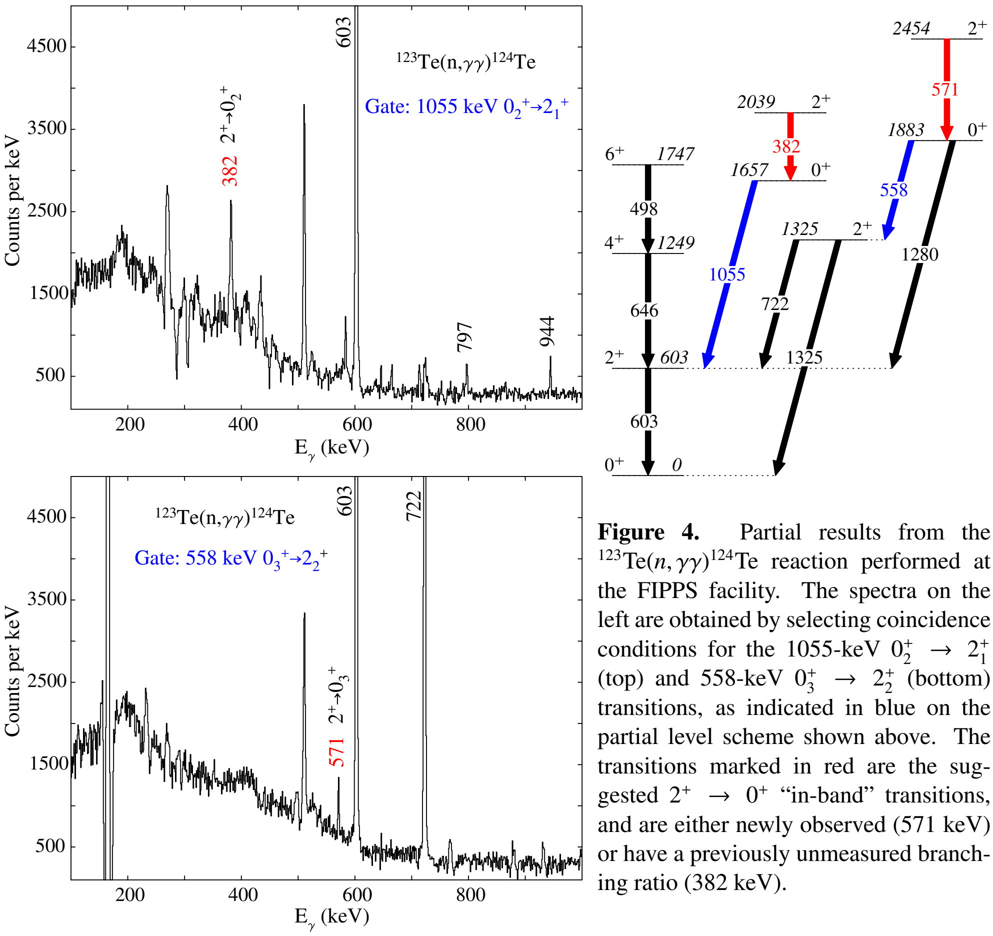

Figure 4. Partial results from the ^{123}Te$(n,\gamma\gamma)^{124}$Te reaction performed at the FIPPS facility. The spectra on the left are obtained by selecting coincidence conditions for the 1055-keV $0_2^+ \to 2_1^+$ (top) and 558-keV $0_3^+ \to 2_2^+$ (bottom) transitions, as indicated in blue on the partial level scheme shown above. The transitions marked in red are the suggested $2^+ \to 0^+$ "in-band" transitions, and are either newly observed (571 keV) or have a previously unmeasured branching ratio (382 keV).

were, in fact, key in establishing the nature of the intruder configurations. The intruder band heads also, generally, possess enhanced $B(E2)$ values for decay to the 2_1^+ state, with values of 51 ± 14 W.u., 27.4 ± 1.7 W.u., and 30 ± 6 W.u. for ^{112,114,116}Cd, respectively. Furthermore, moderately enhanced $E0$ transitions for decay to the ground state are also observed.

Turning to the Te isotopes, a very similar pattern is observed. Where the data are available, it is seen that the Sn($^3He, n$) reactions strongly populates the 0_2^+ states in ^{114,118,120}Te, and apparently both the 0_2^+ and 0_3^+ levels in ^{122}Te. In ^{118,120,122,124}Te the 0_2^+ states have enhanced $B(E2)$ values for decay to the 2_1^+ levels, and also moderately enhanced $E0$ transitions to the ground state. This striking similarity to the Cd isotopes is strongly suggestive that the states identified in Fig. 3 for the Te isotopes are the analogous intruder $4p-2h$ excitations.

Until very recently, one of main issues in preventing a firm identification of the intruder excitations at low spin in the Te isotopes was the non-observation of enhanced in-band $E2$ transitions. In ^{122}Te, Hicks *et al.* [25] observed a 395-keV γ ray with $B(E2; 2_I^+ \to 0_I^+) = 194^{+26}_{-24}$ W.u. The 4^+ band member was not identified. In order to remedy this situation for other Te isotopes, a program of detailed spectroscopy using the newly constructed fission product prompt γ-ray spectrometer (FIPPS) [26] at the Institute Laue Langevin has been initiated. For the first experiment of our program, the ^{123}Te(n,γ) reaction, FIPPS consisted of 10 clover HPGe detectors. The flux of neutrons available is $\approx 1\times10^8$ n/cm^2 s^{-1}. An $\approx$ 4 mg sample of enriched ^{123}Te was irradiated in the neutron beam. Figure 4 displays partial results from the ^{123}Te(n,γ) reaction. The top-left panel shows the γ-ray spectrum obtained using a coincidence gate on the 1055-keV $0^+_2 \rightarrow 2^+_1$ γ ray (top); a 382-keV γ ray, placed as the $2^+_3 \rightarrow 0^+_2$ transition, is clearly seen. The bottom-left panel displays the γ-ray spectrum with a gate on the 558-keV $0^+_3 \rightarrow 2^+_2$ γ ray, showing clearly the presence of a new 571-keV γ ray. This is assigned as the $2^+_7 \rightarrow 0^+_3$ transition as shown in the partial level scheme on the right. The analysis is ongoing, but with the extraction of the branching ratio the $B(E2)$ values will be determined since the level lifetimes are known [12].

3 Summary

Using the properties of the well-established intruder structures in the Cd nuclei as a guide, the 0^+_2 states in the mid-shell Te nuclei are suggested to be of intruder origin based on $4p-2h$ proton excitations. To firmly establish their nature, evidence for the associated rotational-like band must be obtained. An experiment using the (n,γ) reaction has permitted the observation of a γ-ray transition linking the 2^+_3 state to the 0^+_2 state in ^{124}Te, and it is suggested that the 2^+_3 state is the 2^+ band member of an intruder band based on the 0^+_2 level.

References

[1] L.K. Peker and M.E. Voichansky, Izv. Akad. Nauk SSSR Ser Fiz. **32**, 892 (1968).
[2] G. Gneuss and W. Greiner, Nucl. Phys. **A171**, 449 (1971).
[3] P. Federman and S. Pittel, Phys. Lett. **B69**, 385 (1977).
[4] K. Heyde, P. Van Isacker, R.F. Casten, and J.L. Wood, Phys. Lett. **B155**, 303 (1985).
[5] K. Heyde and J.L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[6] P.E. Garrett, J. Phys. G: Nucl. Part. Phys. **43**, 084002 (2016).
[7] N. Warr *et al.*, Nucl. Phys. **A636**, 379 (1998).
[8] J.R. Vanhoy *et al.*, Phys. Rev. C **69**, 064323 (2004).
[9] F. Iachello, Phys. Rev. Lett. **85**, 3580 (2000).
[10] R.M. Clark *et al.*, Phys. Rev. C **69**, 064322 (2004).
[11] D.G. Ghiţă *et al.*, Int. J. Mod. Phys. E: Nucl. Phys. **17**, 1453 (2008).
[12] S.F. Hicks *et al.*, Phys. Rev. C **95**, 034322 (2017).
[13] K. Heyde *et al.*, Phys. Rev. C **25**, 3160 (1982).
[14] J. Kern *et al.*, Nucl. Phys. **A512**, 1 (1990).
[15] M. Délèze *et al.*, Nucl. Phys. **A551**, 269 (1993).
[16] F. Corminboeuf *et al.*, Phys. Rev. Lett. **84**, 4060 (2000).
[17] F. Corminboeuf *et al.*, Phys. Rev. C **63**, 014305 (2000).
[18] R. Julin *et al.*, Z. Phys. **A296**, 315 (1980)
[19] C. Fahlander *et al.*, Nucl. Phys. **A485**, 318 (1988).
[20] R.F. Casten *et al.*, Phys. Lett. **297B**, 19 (1992).
[21] P.E. Garrett *et al.*, Phys. Rev. C **86**, 044304 (2012).
[22] P.E. Garrett *et al.*, E. Phys. J. Web of Conf. **123**, 02005 (2016).
[23] P.E. Garrett, J.L. Wood, and S.W. Yates, Phys. Scr. *in press* (2018).
[24] H.W. Fielding *et al.*, Nucl. Phys. **A281**, 389 (1977).
[25] S.F. Hicks *et al.*, Phys. Rev. C **71**, 034307 (2005).
[26] C. Michelagnoli *et al.*, *Proc. 6th Workshop on Nuclear Fission and Spectroscopy of Neutron-Rich Nuclei*, Chamrousse, Mar. 2017, E. Phys. J. Web of Conf. *in press* (2018).