Nuclear moments and nuclear structure near $^{132}\text{Sn}$

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Abstract. Several $g$-factor measurements have been performed recently on nuclei near the neutron-rich, double-magic nucleus $^{132}\text{Sn}$. The focus here is on $^{134}\text{Te}$, the $N = 82$ isotone which has two protons added to $^{132}\text{Sn}$. Comparisons are made with other nuclei that have two protons outside a double-magic core. The extent to which $^{132}\text{Sn}$ is an inert core is discussed based on these comparisons.

1. Introduction

The recoil in vacuum (RIV) method has proved to be a powerful method to measure the $g$ factors (gyromagnetic ratios) of the first $2^+$ states in neutron-rich isotopes near double magic $^{132}\text{Sn}$. Following on from the pioneering work on $^{132}\text{Te}$ [1, 2], RIV $g$-factor measurements have also been published recently for the isotopes $^{124}\text{Sn}$, $^{126}\text{Sn}$ and $^{128}\text{Sn}$ [3]. The measurements were performed at the Holifield Radioactive Ion Beam Facility (HRIBF). The quality of the radioactive beams, which were produced by the ISOL method and accelerated through the 25UR tandem, together with the segmentation and angular coverage of the CLARION [4] and bare HYBALL [5] detector arrays contributed to the success of these measurements.

In execution, an RIV $g$-factor measurement on a radioactive beam is identical to a measurement of $B(E2; 0^+ \rightarrow 2^+)$ by safe Coulomb excitation. In simplified terms, the $B(E2)$ is determined by the total intensity of the $\gamma$ radiation emitted, whereas the $g$ factor is determined by examining the spatial pattern of the $\gamma$ radiation. As a consequence, a statistically precise $B(E2)$ is measured along with the $g$ factor. The measurements are complementary as the $g$ factor probes single-particle aspects of the wavefunction whereas the $B(E2)$ probes collectivity.

This paper will focus on $^{134}\text{Te}$ [6], which has two valence protons added to $^{132}\text{Sn}$. Comparisons will be made with other nuclides that have two valence protons added to a double magic core.

2. Magnetic moments and the structure of $^{134}\text{Te}$

Figure 1 shows the experimental [1, 2, 6–8] and theoretical [9–12] $g(2^+)$ systematics for the Te isotopes near $N = 82$. There is quite good agreement between theory and experiment for $^{130}\text{Te}$ and $^{132}\text{Te}$, however the theories do not agree for $^{134}\text{Te}$ where the experimental $g$ factor [6] falls between the predictions of the QRPA calculation [11] and the two shell model calculations [9, 10]. Elsewhere we have shown that these three calculations in fact predict similar wavefunctions, dominated by the $\pi(g_{7/2})^2$ configuration [6]. Once the differences in the $M1$ operator are considered, the QRPA can be brought into agreement with the shell model. The Monte Carlo Shell Model (MCSM) calculation [12], however, used the same $M1$ operator as the QRPA.
Theoretical g factors in the even Te isotopes near $N = 82$ compared with experimental data [1, 2, 6–8]. Jacob et al. [9] and Brown et al. [10] performed shell model (SM) calculations. Terasaki et al. [11] used the Quasiparticle Random Phase Approximation (QRPA), and Shimizu et al. [12] used a Monte Carlo Shell Model (MCSM) approach.

Calculations. Thus the difference in the predicted g factors for these two models implies that there is a significant difference between their wavefunctions, which requires further investigation, particularly as the MCSM is two standard deviations from the experimental $g(2^+_1)$ value.

The g factors of the longer-lived $4^+_1$ and $6^+_1$ states in $^{134}$Te have been measured [13, 14], as have the moments of the ground states of $^{133}$Sb and $^{135}$I [15]. To the extent that these states can be associated with pure $\pi(g_{7/2})^n$ configurations, their g factors should be the same. Shell model calculations, using OXBASH [16], have been performed for $^{134}$Te and its neighbors. The interactions and model space were those of Brown et al. [10] (the two protons can occupy $g_{7/2}$, $d_{5/2}$, $s_{1/2}$, $h_{11/2}$, $d_{3/2}$), but the empirical $M1$ operator of Jakob et al. [9] was used. The calculated g factors are compared to the experimental data in Table 1. It is evident that the shell model predicts only small differences between the g factors of the states considered. Experimentally, the g factor of the $6^+_1$ state in $^{134}$Te is the same, within uncertainties, as that of the ground-state of $^{133}$Sb, which represents the single-proton case. The $g(2^+_1)$ value is also consistent with the g factor of the single-proton $g_{7/2}$ state. Overall, the g-factor data point to rather pure $\pi(g_{7/2})^2$ configurations for the yrast $2^+_1$, $4^+_1$ and $6^+_1$ states in $^{134}$Te.

### Table 1. Shell model and experimental $g$ factors of few-proton states near $^{132}$Sn.

| Nuclide | $J^\pi$ | Main configuration | Brown [10] | Present | Experiment |
|---------|---------|---------------------|------------|---------|------------|
| $^{133}$Sb | $7/2^+_1$ | $\pi g_{7/2}$ | 0.807 | 0.857(3) |
| $^{134}$Te | $2^+_1$ | $\pi (g_{7/2})^2$ | 0.833 | 0.824 | 0.76(9) |
|          | $4^+_1$ | $\pi (g_{7/2})^2$ | 0.830 | 0.819 | 0.70$^{+0.55}_{-0.38}$ |
|          | $6^+_1$ | $\pi (g_{7/2})^2$ | 0.838 | 0.829 | 0.847(25) |
| $^{135}$I | $7/2^+_1$ | $\pi (g_{7/2})^3$ | 0.808 | 0.840(1) |
3. Comparison of nuclei with two protons added to a double-magic core

We have seen that the $g$ factors of the $2^+_1$, $4^+_1$ and $6^+_1$ states in $^{134}$Te are consistent with these states being predominantly due to the $\pi(g_{7/2})^2$ configuration. Cases where two protons are added to a closed-shell, and both the $2^+_1$-state and the maximum-spin state with $J_{\text{max}} = 2j - 1$ (usually an isomer) have known $g$ factors are rare. Aside from $^{134}$Te these are: $^{50}$Ti, $^{54}$Fe, $^{92}$Mo, and $^{134}$Te. Along with the discussion of the $g$ factors, it is useful also to consider the $E2$ transition rates. For transitions between the states of the pure $j^2$ configuration, the $B(E2)$ values are related to the single-particle matrix element $\langle j|\gamma(T(E2))|j\rangle$, by

$$B(E2; J_i \rightarrow J_i - 2) = 4(2J_i - 3) \left\{ \begin{array}{c} j \\ J_i \\ \end{array} J_i - 2 \begin{array}{c} j \\ 2 \end{array} \right\}^2 |\langle j|\gamma(T(E2))|j\rangle|^2.$$

The $B(E2)$ data for $^{50}$Ti, $^{54}$Fe, $^{92}$Mo, and $^{134}$Te are compared with Eq. (1) in Figure 2.

In order to judge the degree to which the $E2$ properties of these nuclei are consistent with the predictions for a pure $j^2$ model, we define the double ratio

$$R_{E2} = \frac{B(E2; 2 \rightarrow 0)^{\text{exp}}}{B(E2; J_{\text{max}} \rightarrow J_{\text{max}} - 2)^{\text{exp}}} \times \frac{B(E2; J_{\text{max}} \rightarrow J_{\text{max}} - 2)^{j^2}}{B(E2; 2 \rightarrow 0)^{j^2}}.$$

Thus $R_{E2}$ is unity if the experimental ratio of $B(E2)$ values is consistent with the pure $πj^2$ model, and it exceeds unity if there is additional quadrupole collectivity in the $2^+_1$ state.

Table 2 shows the $R_{E2}$ and $g(2^+_1)/g(J_{\text{max}}^\pi)$ ratios for the nuclei of interest. It is clear from Figure 2 and Table 2 that $^{54}$Fe and $^{92}$Mo show additional $E2$ collectivity in the $2^+_1$ state.

Table 2. $B(E2)$ and $g$ factor ratios for closed-shell nuclei plus two protons.

| nuclide | core  | $j^2$ | $J_{\text{max}}^\pi$ | $R(E2)$  | $g(2^+_1)/g(J_{\text{max}}^\pi)$ |
|---------|-------|------|-------------------|---------|-------------------------------|
| $^{50}$Ti | $^{48}$Ca | $f_{7/2}$ | $6^+$           | 0.77(4) | 0.93(11)                     |
| $^{54}$Fe | $^{56}$Ni | $f_{7/2}$ | $6^+$           | 1.48(6) | 0.77(5)                      |
| $^{134}$Te | $^{132}$Sn | $g_{9/2}$ | $6^+$           | 1.13(5) | 0.90(11)                     |
| $^{92}$Mo | $^{90}$Zr | $g_{9/2}$ | $8^+$           | 2.04(13)| 0.81(11)                     |
two cases also have \(g(2^n_+)/g(J_{\text{max}}^\pi)\) significantly less than unity (see Table 2). This behavior can be associated with added quadrupole collectivity in the \(2^n_+\) state, which has the effect of reducing \(g(2^n_+)\) toward \(Z/A \sim 0.4\). Both \(^{56}\text{Ni}\) and \(^{90}\text{Zr}\) are known to be soft cores. In the case of \(^{54}\text{Fe}\), for example, large-basis shell model calculations in the \(pf\) shell, which effectively include excitations of a \(^{46}\text{Ni}\) core, can account for the observed \(B(E2)\) and \(g\)-factor data [17].

The \(B(E2)\) and \(g\)-factor ratios in Table 2 enable an assessment of the extent to which the core nuclei are inert. Elsewhere [6] we have concluded that there is additional quadrupole collectivity in the \(2^n_+\) state of \(^{134}\text{Te}\) that is not accounted for by large-basis shell model calculations which assume an inert \(^{132}\text{Sn}\) core. We have also shown that coupling the valence \(\pi g_{7/2}\) configuration to a core vibration with the properties of the first-excited state in \(^{132}\text{Sn}\) can readily account for the observed \(2^n_+ \rightarrow 0^n_+\) transition strength in \(^{134}\text{Te}\) [6]. It was found that the wavefunctions of the \(2^n_+\), \(4^n_+\) and \(6^n_+\) states of \(^{134}\text{Te}\) nevertheless remain dominated by the \(\pi g_{7/2}\) configuration. Combining these insights with the discussion above, it can be concluded that \(^{132}\text{Sn}\) is a relatively inert shell-model core, roughly comparable to \(^{48}\text{Ca}\).

4. Concluding comments
The \(g\) factor and \(B(E2)\uparrow\) for the first-excited state of the neutron-rich \(N = 82\) isotope \(^{134}\text{Te}\) have been measured at HRIIBF [6]. The precision achieved for these radioactive beam measurements is remarkable: a comparison of the precision of the \(B(E2)\) and \(g\)-factor ratios in Table 2 shows that the radioactive beam case of \(^{134}\text{Te}\) matches the precision of the three stable-beam cases.

There is evidence of additional quadrupole collectivity in the \(2^n_+\) state of \(^{134}\text{Te}\) due to coupling between the valence protons and excitations of the \(^{132}\text{Sn}\) core. However, the electromagnetic properties of the low-excitation states of \(^{134}\text{Te}\) are generally well described by the shell model, even in the approximation that the two protons are restricted to the \(g_{7/2}\) orbit. The power of combined \(B(E2)\) and RIV \(g\)-factor measurements on radioactive beams has been demonstrated.

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