# Highly anomalous yrast $B(E2)$ values and vibrational collectivity

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It is shown that the existing yrast $B(E2)$ values [especially the $B(E2;4_1^+ \to 2_1^+)/B(E2;2_1^+ \to 0_1^+)$ ratio] in $^{98}$Ru are highly anomalous and cannot be plausibly interpreted with existing models. A survey of all even-even nuclei from $40 \leqslant Z \leqslant 80$ shows that this phenomenon is rare in collective nuclei. It occurs to a much lesser extent in $^{114}$Te, $^{114}$Xe, and possibly a few other nuclides. The combination of vibrational-like energies and nonvibrational $B(E2)$ values perhaps points to a different kind of vibrational behavior.

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In standard collective models, even those that take account of the finite number of valence nucleons, a universal feature is that $B(E2;4_1^+ \to 2_1^+) > B(E2;2_1^+ \to 0_1^+)$. In the harmonic vibrator model the ratio $B_{4/2} \equiv B(E2;4_1^+ \to 2_1^+)/B(E2;2_1^+ \to 0_1^+)$ is 2. In the rotor it is 1.43. In finite particle models such as the IBA, these ratios are slightly smaller but still exceed unity by a large margin for reasonable boson numbers. In numerical calculations with collective models $B_{4/2}$ values $<1$ are also difficult to obtain.

The only benchmark situation in which $B_{4/2} < 1$ occurs where seniority is a good quantum number. In this case, in a $|j^n J\rangle$ configuration, $B(E2;2_1^+ \to 0_1^+)$ increases with $n$ to midshell while $B(E2;4_1^+ \to 2_1^+)$ decreases and it can occur that $B_{4/2} < 1$. This happens, for example, in a number of magic and near magic nuclei in the Pb, Sn, and other regions, and has recently been discussed [1]. In particular, near-magic trans-Pb nuclei such as Rn and Ra with $N \sim 120-126$ display this effect. However, elsewhere, $B_{4/2}$ values less than unity are not expected and, as we shall see, rarely observed.

The inspiration for the present short paper was a study [2] of $^{98}$Ru with the $(\alpha, 2n)$ reaction, in which, as a by-product, it was noted that the latest literature compilation [3], and the latest measurements [4] of $B(E2;4_1^+ \to 2_1^+)$ and $B(E2;2_1^+ \to 0_1^+)$ values, give an extraordinarily low value of $B_{4/2}$ of 0.38(11). We note that the analogously defined ratio $B_{6/2} = 0.40(8)$ [3] which is also surprising. At the same time, recent accurate measurements [5] of yrast level lifetimes with small errors have given the first $B(E2)$ values for $^{114}$Te, resulting in $B_{4/2}(^{114}\text{Te}) = 0.85(12)$ [5]. It is important to stress that, while this value is quite a bit higher than that claimed for $^{98}$Ru, a reasonable lower limit of expected values is not, in fact, unity, but rather a value of about 1.3. The $B_{4/2}$ value for $^{114}$Te, with its small uncertainty, therefore falls well below such a scale. It is interesting, albeit possibly accidental, that the level schemes of $^{98}$Ru and $^{114}$Te present almost identical-looking patterns for the low lying states, as shown in Fig. 1, and their $B(E2;2_1^+ \to 0_1^+)$ values of 32 and 34 W.u. are also essentially the same. The $B_{6/2}$ ratio in $^{114}$Te, however, is 1.26(26), a ratio closer to expectations of collective models than is the case for $^{98}$Ru.

Noting these unexpected results, we have carried out a survey of medium and heavy nuclei to determine where this phenomenon exists, and if there might be any informative systematics that could shed light on its origins. The upshot is that the $B_{4/2}$ value in $^{98}$Ru is one of the lowest ratios known in heavy nuclei and, by far, the lowest for nonmagic nuclei. The nucleus $^{114}$Te also has a credible $B_{4/2}$ value slightly less than unity. A few other nuclei may have such values but, in some cases, the data are less firm.

We have surveyed the existing data in NDS and some recent work [6–9] up through approximately the end of 2003 for nuclei with $40 \leqslant Z \leqslant 80$. Figures 2–5 present these results in several easily visualizable ways to highlight different perspectives. Figure 2 presents $B(E2;4_1^+ \to 2_1^+)$ values against

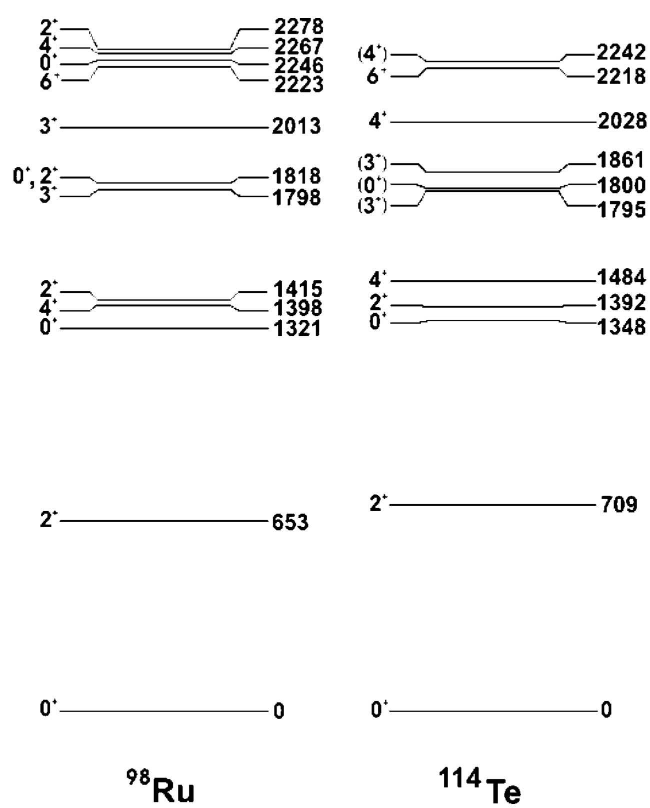


FIG. 1. Comparison of $^{98}$Ru and $^{114}$Te level schemes. From Refs. [2,7].

 

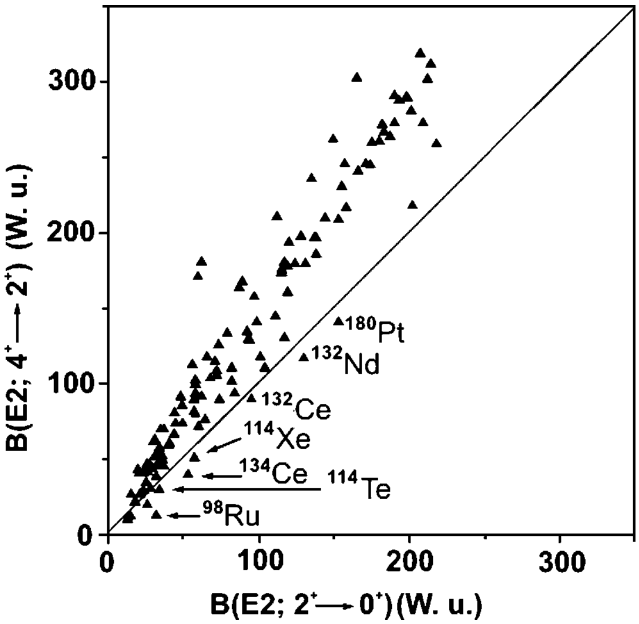


FIG. 2. Experimental yrast $B(E2)$ values for nonmagic nuclei with $40 \leqslant Z \leqslant 80$. The diagonal line shows $B_{4/2}=1$. Data points below the line have $B(E2;4_1^+ \rightarrow 2_1^+) < B(E2;2_1^+ \rightarrow 0_1^+)$, and are labeled. (Three of these nuclei, $^{134}$Xe, $^{144}$Nd, and $^{152}$Dy near the origin, are not labeled simply to keep the figure uncluttered. For the same reason, error bars are not shown. They are, however, shown for nuclei with $B_{4/2} < 1.0$ in Figs. 3 and 4.)

$B(E2;2_1^+ \rightarrow 0_1^+)$ values for nonmagic nuclei such that the diagonal line represents $B_{4/2}=1$. With this figure it is easy to discern cases with $B_{4/2} < 1$ values and to correlate these with the collectivity of the $B(E2;2_1^+ \rightarrow 0_1^+)$ values.

The figure clearly shows the very anomalous nature of $^{98}$Ru. Moreover, it shows that this is not due to some remnant of near-magic structure but occurs in a nucleus with well developed equilibrium collectivity: the $B(E2;2_1^+ \rightarrow 0_1^+)$ value is 32 W.u., the same as in the Cd isotopes from $A = 108-118$ where yrast states with up to three-phonon vibrational structure have been found with collective $B(E2)$ values [10–15]. Indeed, the contrast with $^{114}$Cd [12] is striking. Both have $B(E2;2_1^+ \rightarrow 0_1^+)$ values of $\sim 31$ (2) W.u., as just noted. However, $B(E2;4_1^+ \rightarrow 2_1^+)$ in $^{114}$Cd is 62 (4) W.u., while the result of Ref. [4] for $^{98}$Ru is 12 W.u. Moreover, $B(E2;6_1^+ \rightarrow 4_1^+)$ in $^{114}$Cd is 119 (15) W.u., compared to 13 W.u. in $^{98}$Ru.

Figure 3 presents the same data as in Fig. 2 in the form of $B_{4/2}$ against neutron number and shows the large number of $B_{4/2}$ values at $\sim 1.4 \pm 0.2$, again highlighting the few anomalous cases. Note a couple of numbers well above the pure vibrator value of 2.0. These are $^{184}$Hg where a low lying intruder configuration affects the spectrum and $^{146}$Ba for which no obvious explanation occurs.

The $^{98}$Ru anomaly is shown in a context that explicitly focuses on structural evolution in Fig. 4. It is well known [16] that the $P$ factor ($P = N_p N_n / [N_p + N_n]$) excellently correlates collectivity with valence proton and neutron number. For example, collectivity sets in for $P \gtrsim 2$ and deformation does so between $P=4$ and 5. Figure 4 shows that, from this

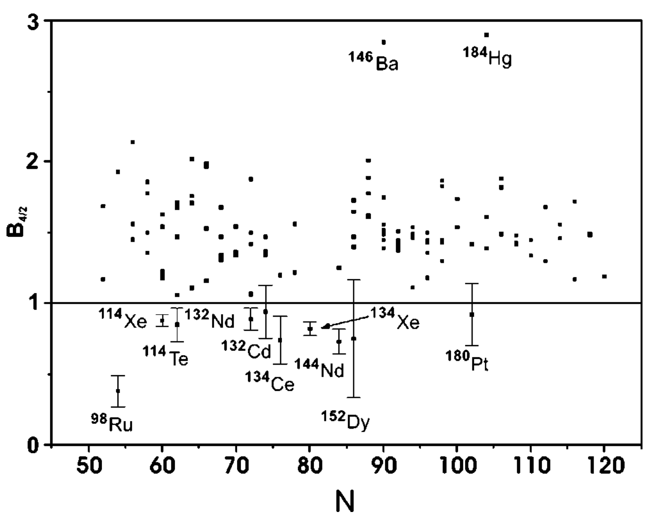


FIG. 3. $B_{4/2}$ values vs neutron number for the same nuclei as in Fig. 2.

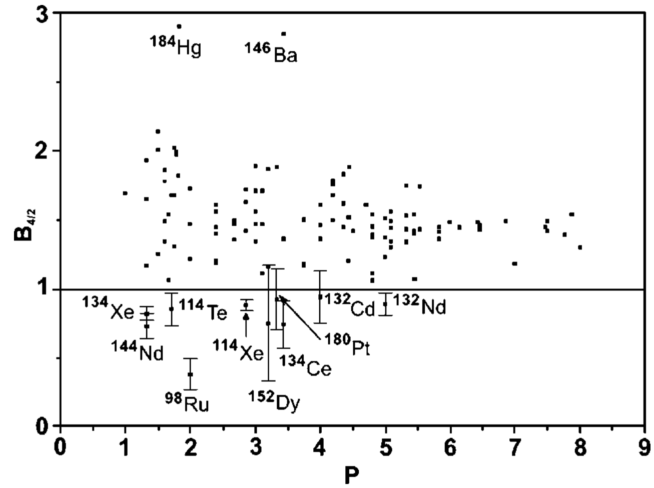


FIG. 4. Similar to Fig. 3, except $B_{4/2}$ values against the $P$ factor.

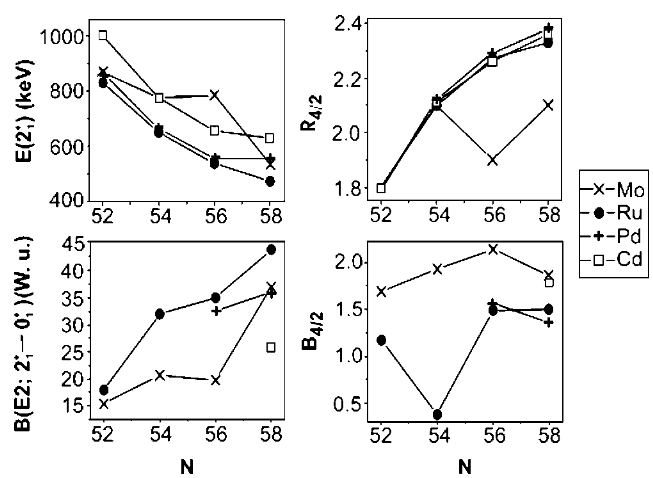


FIG. 5. Systematics of key collective observables for $Z = 42-48$ nuclei.

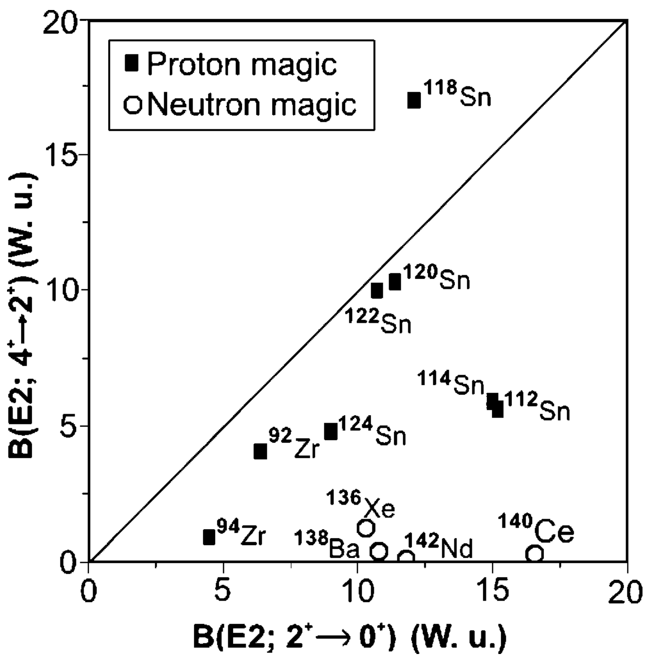


FIG. 6. Similar to Fig. 2 except for magic nuclei. The $^{116}$Sn, $^{152}$Gd points are omitted since the $B(E2)$ values are anomalously large and would distort the scale.

perspective as well, $^{98}$Ru (the low $P=2$ data point) is highly anomalous. Indeed, it is clear from Figs. 3 and 4 that the $^{98}$Ru point is easily the lowest value in this entire mass region from $A\sim 90$ to 200.

It is worth stressing that, in other respects, this nucleus behaves quite reasonably. Figure 5 shows the regional data on $E(2_1^+)$, $R_{4/2}\equiv E(4_1^+)/E(2_1^+)$, $B(E2;2_1^+\rightarrow 0_1^+)$, and $B_{4/2}$. The nucleus $^{98}$Ru follows all the regional patterns quite well except for $B_{4/2}$. This, in turn, suggests that it is *not* the $B(E2;2_1^+\rightarrow 0_1^+)$ value that is anomalous but $B(E2;4_1^+\rightarrow 2_1^+)$ [and $B(E2;6_1^+\rightarrow 4_1^+)$] values. We note in passing the hint of a $\nu d_{5/2}$ subshell closure that is nicely visible in Fig. 5 for Mo at $N=56$.

Figures 2–4 show that, while $^{98}$Ru is the most extreme case of $B_{4/2}$ values $<1$, it is not the only one. The best established other cases are, in fact, $^{114}$Te and $^{114}$Xe mentioned earlier. The nucleus $^{114}$Te was recently measured [5] using the advanced differential plunger method and has $B_{4/2}=0.85$ (12). The third well-established case, $^{114}$Xe was measured with the same method and has $B_{4/2}=0.71(8)$ [8]. The few other data points with $B_{4/2}<1$ in Figs. 2–4 are less convincing. In most cases the relevant lifetimes were measured in singles experiments in which it is now well known [9] that effects of level lifetimes involved in side-feeding transitions can give erroneous results. Of course, it could certainly be worthwhile remeasuring nuclei such as $^{134}$Ce and $^{132}$Nd with modern plunger or Coulomb excitation methods.

To complete this survey Fig. 6 presents results analogous to Fig. 2 except in this case for magic nuclei. Here a number of $B_{4/2}<1$ values occur, as expected [1], but all for $B(E2;2_1^+\rightarrow 0_1^+)$ values that are essentially noncollective [$B(E2;2_1^+\rightarrow 0_1^+)\lesssim 15$ W.u.]. $^{98}$Ru, $^{114}$Te, and $^{114}$Xe clearly do not fall into this class. The sequence of very small $B_{4/2}$ values for magic $N=82$ nuclei from Xe to Nd nicely reflect the hindrance of seniority conserving yrast transitions discussed in Ref. [1] in which the $B(E2;4_1^+\rightarrow 2_1^+)$ values decrease as a $j$ shell is filled. In this case, the protons are occupying a pair of close lying orbits $2d_{5/2}$ and $1g_{7/2}$, which can contain up to 14 protons, giving small $B(E2;4_1^+\rightarrow 2_1^+)$ values near $Z=54-60$.

There would seem to be only two viable interpretations of the $^{98}$Ru result: either the existing $B(E2;4_1^+\rightarrow 2_1^+)$ and $B(E2;6_1^+\rightarrow 4_1^+)$ values in $^{98}$Ru are incorrect or some new form of heretofore unobserved collectivity is being manifest. Of course, a small $B(E2;4_1^+\rightarrow 2_1^+)$ value and hence a small $B_{4/2}$ ratio can also occur if the $4^+$ state has a structure different than the $0_1^+$ and $2_1^+$ states. This can happen in regions of shape coexistence but there is no evidence for such effects in $^{98}$Ru where the first $4^+$ state is quite isolated from other $4^+$ levels, and very near the other obvious candidates for two-phonon vibrator states. We suggest, primarily on the grounds of not being able to discover what new kind of collectivity might explain the low $B_{4/2}$ value, that the more likely explanation is that the experimental $B(E2)$ values might be in error. Moreover, as we have seen, the systematics of various collective observables in the Mo, Ru, Pd, and Cd nuclei for $52\leqslant N\leqslant 58$ are quite smooth, except for the low lying yrast $B(E2)$ values of $^{98}$Ru. Interestingly, a prior $B(E2;4_1^+\rightarrow 2_1^+)$ value for $^{98}$Ru [17], which was supplanted by that in Ref. [4], is 40 W.u., giving $B_{4/2}=1.25(21)$, a near normal value. For $^{114}$Te and $^{114}$Xe, the situation is different since the latest $B(E2)$ values are quite reliable (although they have only been measured with a single technique). Thus these nuclei are definitely anomalous. Regardless of the resolution of the $^{98}$Ru issue, these two nuclei, which have vibrational-like energies, and anomalous $B(E2)$ values, suggest that some new type of quadrupole vibrational collectivity is being manifest.

We have identified only one way to reproduce $B_{4/2}$ values $<1$ in a simple collective model approach, namely, using the IBA model but with parameter values that are generally considered nonphysical and which also produce incorrect (too low) energies for the $6_1^+$ state. Although we therefore do not advocate such an explanation, we offer it for completeness: $B_{4/2}$ values can be obtained with the IBA-1 Hamiltonian [18] in its multipole form $H=\epsilon n_d+\kappa\, Q.Q$, if positive $\kappa$ values are used.

To summarize, we have shown that some of the existing yrast $B(E2)$ values in several nuclei are highly anomalous. They exhibit $B_{4/2}$ values significantly less than those of $\gtrsim 1.3$ expected in collective nuclei. The case of $^{98}$Ru is particularly extreme, with $B_{4/2}=0.38$ (11) [and $B_{6/2}=0.40$ (8)]. This phenomena is very rare in medium and heavy nuclei as our survey from $Z=40$ to 80 shows. It exists in $^{114}$Te and $^{114}$Xe: most other possible candidates were measured with techniques of lifetime measurements that may not have incorporated corrections for side-feeding effects.

We have found no plausible interpretation of this anomaly and stress that it occurs in nuclei with definitely collective behavior [$B(E2;2_1^+\rightarrow 0_1^+)\sim 32$ W.u.]. The $^{114}$Te and $^{114}$Xe experimental results appear unassailable. It is, however, clearly of essential importance to remeasure the $B(E2;4_1^+$

$\rightarrow 2_1^+$) value for $^{98}$Ru and such experiments are indeed planned. If the present [3,4] value stands, it will be a severe challenge for collective models since it represents a gross violation of the vibrator picture in a nucleus whose yrast energy levels (up to the backbend at $J=10^+$) behave almost exactly according to the anharmonic vibrator model with minimal anharmonicity [2]. Even if the $^{98}$Ru result is altered by new experiments, the $B_{4/2}$ values for $^{114}$Te and $^{114}$Xe demand serious theoretical attention. These nuclei show a combination of vibrational-like energies and of yrast $B(E2)$ values not accommodated by existing models. This situation is reminiscent of that which occurred before 1956 when the vibrator and rotor model paradigms were known. Spectra with $R_{4/2} \sim 2.5$ (instead of $\sim 2.0$ or $\sim 3.33$) but collective $B(E2)$ values pointed the way to the recognition of the $\gamma$-soft rotor type of collective motion. It is not inconceivable that the $^{114}$Te, $^{114}$Xe, and $^{98}$Ru [if the anomalous $B(E2)$ values in this nucleus survive further experiments] could likewise reveal a different type of collective behavior.

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