Supersymmetry of identical bands in $^{171,172}$Yb supported by lifetime data

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Abstract

Precision lifetimes of six states in the ground-state bands of $^{171}$Yb have been measured using the recoil distance method following Coulomb excitation with a detector of the EUROBALL CLUSTER type at the FN-Tandem accelerator in Cologne. From these and previous data on branching and mixing ratios from Canberra, we found, that the transition quadrupole moments for corresponding E2 transitions in $^{171,172}$Yb are almost equal. This gives strong support for a weakly broken supersymmetry in $^{171,172}$Yb. On the other hand, the neighbor pair of nuclei $^{171}$Tm and $^{172}$Yb shows no supersymmetry demonstrating the importance of an even pseudoorbital angular momentum as condition for supersymmetry.

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The concept of supersymmetry has intensively been investigated in nuclear physics [1–14]. It is related to the widely known concept of supersymmetry in particle physics, but shows some differences. A comparison will be given below. Attempts to develop a supersymmetric classification in which several nuclei, e.g. even, odd and odd–odd ones, are described by the same Hamiltonian have been quite successful [1–11]. In the dynamic symmetry approach one describes all the collective spectra of nuclei linked by supersymmetry. Here we investigate another manifestation of supersymmetry paying special attention to those groups of states, which are characterized by identical or at least similar $\gamma$-transition energies in odd–even and even–even neighboring nuclei. They are examples of an approximate partial supersymmetry of a different kind [15]. Because supersymmetry is of general interest, it is very useful to show, that it is realized in experimental nuclear spectra. It is the purpose of the present paper to present high precision data on transitional quadrupole moments within two supersymmetric bands and to give one unique example for realization of partial supersymmetry in nuclei.

Identical bands, in which the energies differ by less than 1%, have been observed in superdeformed nuclei [16–19]. Subsequently, many of such bands have also been discovered in normally deformed nuclei (for a review, see [20]). In this case, the energies differ by 10–20% or more. Thus one should properly call these
bands “similar bands”, but in the literature the term “identical bands” is used for these bands, too. So we keep this term. To explain the phenomenon of identical bands several theoretical approaches have been developed. The first explanation of the twin superdeformed bands in $^{151}$Tb and $^{152}$Dy [17] was based on the particle-rotor model [21] and the concept of decoupled pseudospin. In another approach, suggested in [22], the identical superdeformed bands have been interpreted in terms of superalgebras giving rise to a dynamic supersymmetry. There are, however, strong limitations on energies and single particle structures of the states involved in this latter approach. Therefore, another approach without such restrictions has been formulated. It has been shown in [23], that the particle-rotor model description of the rotational band in the odd–A nucleus built upon the $K = 1/2$ pseudoorbital singlet Nilsson state, with an odd principal oscillator quantum number $N$, can be reformulated as a realization of partial supersymmetry. Here supersymmetry is, however, only realized for special values of the parameters of the particle-rotor model. In this approach, the $K = 1/2$ rotational band in an odd–A nucleus together with the ground-state band of the even–even neighbor nucleus are considered to be members of a super multiplet. An unbroken supersymmetry implies identical $\gamma$-transition energies in the even–even and the odd–A superpartner rotational bands. Of course, a small breaking of the supersymmetry will lead to deviating energies.

The basic model, its derivation and predictions had been discussed in [23]. We remind here only its most important features. It is worth to point out, that this kind of supersymmetry differs also from the ones proposed in Refs. [1–10] according to the interpretation of the bosons. In our case, the excitations of the even–even core nucleus are not considered to be coupled fermion pairs, but rather collective excitations. In this sense, one deals with a supersymmetry of the collective (liquid drop) model. If the particle–core interaction, in the Hamiltonian, does not depend on the direction of the pseudospin (decoupled pseudospin), the rotational band in the odd nucleus consists of degenerate doublets, excluding the $J = 1/2$ band head which is a singlet. Then, the supersymmetry generators of the superalgebra considered are given by the two operators $P_{\omega} (\sigma = \pm 1/2)$ and their Hermitian conjugates [23]. We stress, that this is not a case of weak coupling, although it superficially might seem so. The pseudoorbital momentum $i$ of the odd particle is strongly coupled to the core. The operator $P_{1/2, \sigma}$ is a pseudoorbital scalar and therefore does not change the total pseudoorbital momentum when acting on the eigenstates of the even nucleus. For a $K = 1/2$, $\Lambda = 0$ band ($\Lambda$ is the projection of the pseudoorbital momentum on the symmetry axis) the total pseudoorbital momentum $\tilde{L}$ and the particle pseudoorbital momentum $\tilde{i}$ are connected by the relation $(-1)^{\tilde{L} + \tilde{i}} = +1$. Since the core angular momentum of the even–even nucleus is even and the operator $P_{1/2, \sigma}$ does not change the value of the core angular momentum, we obtain, that the pseudoangular momentum of the particle is even for an odd nucleus. This means, that supersymmetry can be realized only if the odd particle belongs to an oscillator shell with even principal pseudospin quantum number $\tilde{N}$, i.e., with an odd total principal quantum number $N = \tilde{N} + 1$.

Identical $\gamma$-transition energies in supersymmetric partners imply the identity of the moments of inertia of the even–even nucleus and its odd–A superpartner. A different but equally important characteristic of electromagnetic intraband transitions is, that the E2 transitions in the even–even and odd–A superpartner have the same quadrupole-transition moments $Q_\gamma$. Furthermore, it is important for the realization of the supersymmetry, that the pseudospin–orbit interaction in the Hamiltonian can be neglected. Thus, there are four requirements which must be fulfilled in order to consider an even–even $K = 0$ and an odd–A $K = 1/2$, $\Lambda = 0$ rotational band in neighbor nuclei as superpartners of unbroken supersymmetry:

1. identity of the moments of inertia;
2. decoupling of the pseudospin (i.e., close doublets in the odd nucleus);
3. even pseudoangular momentum $\tilde{N}$ of the particle (i.e., an odd total principal quantum number $N$);
4. identity of the quadrupole-transition moments $Q_\gamma$.

There are many examples of pairs of even–even and odd nuclei in the rare earth and W–Os–Pt regions which show energy spectra, that approximately satisfy the first three conditions and which demonstrate this particular partial supersymmetry with some breaking. Examples are the following pairs: $^{165,166}$ Dy, $^{167,168}$ Er, $^{169,170}$ Er, $^{171,172}$ Er, $^{167,168}$ Yb, $^{169,170}$ Yb, $^{171,172}$ Yb, $^{173,174}$ Yb, $^{173,174}$ Hf, $^{175,176}$ Hf, $^{177,178}$ W, $^{179,180}$ W,
In these pairs of nuclei, the ground or excited rotational bands in the odd-A superpartner nucleus are based on the 1/2− state consisting of weakly split doublets: (3/2−, 5/2−), (7/2−, 9/2−), ... The moments of inertia of rotational bands in the odd-A nuclei are close to those in the even–even partner. However, the spectrum of the odd-A nucleus is often compressed relative to the even–even one. In the 15 examples listed above, the ratio of the moments of inertia take values from 0.60 to 0.99. There are 12 of these pairs with a ratio of the moments of inertia which is larger than 0.8. Moreover one finds, that this ratio is closer to 1 in well deformed nuclei than in transitional ones. Thus, the well and superdeformed nuclei correspond better to the requirements of an unbroken partial supersymmetry.

By inspection of these pairs of nuclei one finds, that the first three conditions are at least approximately fulfilled. But there is almost no experimental information about E2 transitions inside the rotational bands to check the remaining requirement. Of course, we generally know (e.g., from models) that the quadrupole deformations of a pair of strongly deformed neighboring nuclei are similar. But for an unambiguous claim of supersymmetry, one needs to establish this conformity with high precision. For reasons of experimental accessibility, we made a precision lifetime experiment with high precision. For reasons of experimentability, we made a precision lifetime experiment with high precision.

Fig. 1. Observed states of the ground-state bands of 171Tm, 171Yb and 172Yb which form supermultiplets. Energies are given in keV. The data are taken from [35].

Table 1 Comparison of $Q_t$ values in the ground-state bands of 171Tm ($Q_t^{171}$) and 172Yb ($Q_t^{172}$).

| $L$ | $\Delta I = 2$ | $\Delta I = 1$ |
|-----|---------------|---------------|
| $Q_t^{171} (L+1/2)$ | $Q_t^{171} (L-1/2)$ | $Q_t^{171} (L+1/2)$ | $Q_t^{171} (L-1/2)$ |
| $Q_t^{172} (L+1/2)$ | $Q_t^{172} (L-1/2)$ | $Q_t^{172} (L+1/2)$ | $Q_t^{172} (L-1/2)$ |
| 3  | 0.96(3)       | 1.10(10)      | -               | 1.09(7)        |

The data is taken from Refs. [30,31].

error bars as shown in Table 1. Thus, one might expect the pair 171Tm, 172Yb to be a supermultiplet, too. However, this is not the case. This can be seen by comparing the spectra of the ground-state bands of 171Tm and 172Yb (Fig. 1). In 171Tm the proton hole occupies the [411]1/2+ single particle state, which is characterized by the total principal oscillator quantum number $N = 4$. Because of this the total orbital momentum $L$ takes the values: 1, 3, 5, ..., and we obtain the spectrum of the ground band in 171Tm, consisting of the doublets: (1/2+, 3/2+), (5/2+, 7/2+), ... Since the ground bands of 171Tm and 172Yb have different values of $L$, the γ-transition energies of the ground-state band of 171Tm deviate from those of 172Yb. However, the levels in 171Tm follow the $L(L + 1)$ rule ($L = 1, 3, 5, ...$) with approximately the same moment of inertia as in 172Yb. Although the ground band of the two neighbor nuclei 171Tm and 172Yb fulfill three of
the four conditions for supersymmetry, they are no example for supersymmetry, because the third one—an even pseudoangular momentum of the particle—is violated in $^{171}$Tm. On the other hand, the ground-state band of $^{171}$Yb is based on the $[521]1/2^-$ Nilsson state with $N=5$. In this case, the total orbital momentum $L$ is even: $L=0, 2, 4, \ldots$. As a consequence, the ground-state band of $^{171}$Yb is formed by the singlet $1/2^-$ and doublets: $(3/2^-, 5/2^-)$, $(7/2^-, 9/2^-)$, \ldots, and one indeed expects supersymmetry for the nuclei $^{171,172}$Yb.

The measurement was carried out using the COLOGNE PLUNGER device \cite{24}. At the Cologne FN Tandem accelerator a beam of $^{32}$S with an energy of 105 MeV was used to Coulomb excite states in $^{171}$Yb. The target consisted of highly enriched $^{171}$Yb isotope material evaporated to a thickness of 0.5 mg/cm$^2$ onto a 1.3 mg/cm$^2$ silver foil. The recoiling ytterbium nuclei had a mean velocity of 2.20(2)% of the velocity of light and were stopped in an 8.0 mg/cm$^2$ niobium foil. Acquisition runs were performed at 22 target-to-stopper distances ranging from 0 to 4000 µm. The $\gamma$-rays were detected with a detector of the EUROBALL CLUSTER type placed at 0° with respect to the beam axis and three additional germanium detectors of approximately 55% efficiency at backward angles. In order to fix the reaction kinematics, the COLOGNE PLUNGER device was equipped with six photodiode cells, manufactured by SILICON SENSORS, which were mounted approximately 1 cm upstream the target to cover an angular range of about 155°–175°. This corresponds to target nuclei, which are scattered

Fig. 2. Particle gated gamma spectra of all detectors at backward (left) and forward angles (right) at three different target-to-stopper distances. Flight peaks (f) and stop peaks (s) of three transitions in $^{171}$Yb and one in $^{172}$Yb are labeled. Some complications occur because of doublets: for the investigation of the stopped component of the $(11/2^- \rightarrow 7/2^-)$ transition, only forward spectra are useful, while for the investigation of the stopped component of the $(13/2^- \rightarrow 9/2^-)$ transition only backward spectra are of any use.
within a forward cone of about 0°–10°. The beam current was limited to 1 pA to avoid uncontrolled thermal expansion of the target. The mean coincidence rate was about 2 kHz. In Fig. 2 added γ-spectra of all detectors at forward and backward angles, respectively, taken at different target-to-stopper distances are shown. One notes the excellent statistics for the transitions in 171Yb. The Differential Decay Curve Method (DDCM) [25,26] in “singles mode” was used for the data analysis. Due to the excellent statistics, several different spectra of coincidences between single photodiodes and germanium detectors were analyzed separately as described in [28]. The given lifetimes $\bar{\tau}$ are weighted averages of these independent results. This method had previously been tested in [27,28].

Lifetimes were extracted for the 7/2$^-$, 9/2$^-$, 11/2$^-$, 13/2$^-$, 15/2$^-$, and 17/2$^-$ states in 171Yb. Because of a small admixture of 172Yb in the target, the lifetimes of the 4$^+_1$ and 6$^+_1$ levels in 172Yb were also obtained. The results of the lifetime measurements together with known data taken from literature are summarized in Tables 2 and 3. In all cases, the sums of flight and corresponding stop peaks were checked for constancy to observe possible deorientation effects. However, for all analyzed transitions in 171Yb no significant deviations were found within the experimental limits. Presumably, this is due to the high spin of the investigated levels. The 4$^+_1$ level in 172Yb is too long lived to be affected by deorientation. $B(E2)$ values and transitional quadrupole moments $Q_t$ were obtained using measured lifetimes and precision branching ratios taken from a beautiful experiment by Stuchberry et al. [29] and are shown in Tables 4 and 5. Together with the two existing values for 171Yb and 172Yb the present data allow a stringent test of the concept of supersymmetry in both nuclei. In Table 6, the $Q_t$ values for 171Yb and 172Yb are shown to be in excellent agreement. This striking agreement strongly supports the proposed su-

| Table 2 | Measured lifetimes $\bar{\tau}$ within the ground-state band of 171Yb from this experiment and for the 5/2$^-$ and the 3/2$^-$ states taken from [30] |
|---------|----------------------------------------------------------------------------------------|
| $I^+_J$ | $I^-_J$ | $E_y$ [keV] | $\bar{\tau}$ [ps] |
| 17/2$^-$ | 13/2$^-$ | 350 | 6.04(26) |
| 15/2$^-$ | 11/2$^-$ | 345 | 6.16(40) |
| 13/2$^-$ | 9/2$^-$ | 263 | 30.79(52) |
| 11/2$^-$ | 7/2$^-$ | 257 | 30.87(28) |
| 9/2$^-$ | 5/2$^-$ | 171 | 215(6) |
| 7/2$^-$ | 3/2$^-$ | 164 | 223(11) |
| 5/2$^-$ | 3/2$^-$ | 2366(231) |
| 3/2$^-$ | 1/2$^-$ | 1160(245) |

| Table 3 | Comparison of the measured lifetimes $\bar{\tau}$ from this experiment with previous ones for 172Yb [31] |
|---------|---------------------------------------------------------------------------------|
| $I^+_J$ | $I^-_J$ | $E_y$ [keV] | $\bar{\tau}$ [ps] | $r_{NDS}$ [ps] |
| 8$^+_1$ | 6$^+_1$ | 280 | 20.7(13) | 5.1(4) |
| 6$^+_1$ | 4$^+_1$ | 182 | 178.6(16) | 176.0(120) |
| 4$^+_1$ | 2$^+_1$ | 2380(30) |

| Table 4 | $B(E2)$ and $Q_t$ values in 171Yb |
|---------|---------------------------------|
| $I^+_J$ | $I^-_J$ | $E_y$ [keV] | $B(E2) [e^2 b^2]$ | $Q_t [e b]$ |
| 17/2$^-$ | 13/2$^-$ | 350 | 2.3(1) | 8.38(14) |
| 15/2$^-$ | 11/2$^-$ | 323 | 0.06(3) | 9.8(7) |
| 13/2$^-$ | 9/2$^-$ | 263 | 1.84(3) | 7.6(7) |
| 11/2$^-$ | 9/2$^-$ | 241 | 0.07(1) | 7.8(2) |
| 11/2$^-$ | 7/2$^-$ | 257 | 1.78(2) | 7.68(4) |
| 9/2$^-$ | 5/2$^-$ | 171 | 1.56(4) | 7.41(7) |
| 7/2$^-$ | 5/2$^-$ | 155 | 0.16(1) | 7.5(1) |
| 7/2$^-$ | 3/2$^-$ | 164 | 1.36(7) | 7.29(13) |
| 5/2$^-$ | 3/2$^-$ | 9 | 0.3(21) | 7.6(12) |
| 5/2$^-$ | 1/2$^-$ | 76 | 0.88(10) | 6.65(25) |
| 3/2$^-$ | 1/2$^-$ | 67 | 1.2(3) | 7.8(6) |

| Table 5 | $B(E2)$ and $Q_t$ values in 172Yb |
|---------|---------------------------------|
| $I^+_J$ | $I^-_J$ | $E_y$ [keV] | $B(E2) [e^2 b^2]$ | $Q_t [e b]$ |
| 8$^+_1$ | 6$^+_1$ | 372 | 2.2(2) | 8.19(37) |
| 6$^+_1$ | 4$^+_1$ | 280 | 2.1(2) | 8.19(39) |
| 4$^+_1$ | 2$^+_1$ | 182 | 1.69(2) | 7.71(4) |
| 2$^+_1$ | 0$^+_1$ | 79 | 1.21(2) | 7.80(6) |
persymmetry for the bands in $^{171}$Yb and $^{172}$Yb. Indeed, all four requirements for supersymmetry discussed above are fulfilled for the $^{171,172}$Yb pair. We want to note, that for the $^{171}$Tm and $^{172}$Yb pair only three conditions are fulfilled, whereas condition (3)—an even pseudoangular momentum of the particle—is violated. And indeed, there are no identical bands and no supersymmetry in this case.

Finally, we compare the supermultiplets in nuclear and particle physics. The supermultiplets considered above are very similar to the supersymmetry for heavy leptons proposed in [32–34]. We note that supersymmetry is realized in several nuclei and is only slightly broken [1–14]. In particle physics, on the other hand, supersymmetry has not been observed so far and one expects it to be strongly broken. However, in particle physics supersymmetry refers to the fundamental Lagrangian, which describes all states [32], while in nuclear physics it is a property of a model Hamiltonian, which describes a subset of spectra in some nuclei. Both supersymmetries imply the existence of a relation between the numbers of the bosonic type states and of the fermionic ones. In our case, these are the ground state and a two-quasiparticle state created by applying the operator $P_{1/2}$ twice (with $\sigma = \pm1/2$) on the ground state of the core (bosonic) and the one-quasiparticle ground state (fermionic), respectively. Specifically, the number of bosonic magnetic substates (two) is equal to the number of fermionic magnetic substates (two) in the supermultiplet. This highlights both the interest in studying supersymmetry in the nuclear case and its differences to the supersymmetry, in the particle case.

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**Table 6** Comparison of $Q_t$ values in the ground-state bands of $^{171}$Yb ($Q_t^{171}$) and $^{172}$Yb ($Q_t^{172}$)

| $L$ | $\Delta I = 2$ | $\Delta I = 1$ |
|-----|----------------|----------------|
|     | $Q_t^{171}(L+1/2)$ | $Q_t^{171}(L-1/2)$ | $Q_t^{172}(L+1/2)$ | $Q_t^{172}(L-1/2)$ |
| 8   | 1.02(6)          | 1.03(6)         | –                | 1.20(10)         |
| 6   | 0.94(5)          | 0.94(5)         | –                | 0.95(6)          |
| 4   | 0.96(2)          | 0.95(3)         | –                | 0.97(2)          |
| 2   | –               | –               | 0.97(15)         | 1.00(8)          |
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