Phases Transitions: Summary of Discussion Session II of Camerino 2005

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Abstract

A brief report of the topics which received attention during the discussion session II of the International Workshop on Symmetries and Low-Energy Phase Transitions in Nuclear-Structure Physics, held in Camerino on 9-11 October 2005, is given. These include special solutions of the Bohr Hamiltonian for various potentials, the study of triaxial shapes and of degrees of freedom other than the quadrupole one (octupole, scissors), as well as the search for experimental manifestations of the critical point symmetries E(5) and X(5), and of the recently proposed critical point supersymmetry E(5/4).

1. Solutions of the Bohr Hamiltonian with different potentials

In the original E(5) and X(5) papers, an infinite square well potential in $\beta$ is used in accordance to the expectation that the potential at the critical point has to be flat and scale invariant.

1.1 Solutions related to E(5)

Different potentials used in the E(5) framework include a well of finite depth [3], the sextic oscillator [4], Coulomb-like and Kratzer-like potentials [5], a linear potential [6], Davidson potentials [7, 8, 9] of the form $\beta^2 + \beta_0^2/\beta^2$, where $\beta_0$ is the position of the minimum of the potential [10, 11], the $\beta^4$ potential [12, 13], as well as the $\beta^6$ and $\beta^8$ potentials [14] (the $\beta^2$ potential [15, 16, 17] corresponding to the well known U(5) case [18]). A hybrid model employing a harmonic oscillator for $L \leq 2$ and an infinite square well potential for $L \geq 4$ has also been developed [19]. A recent review of this topic has been given in [6].

L. Fortunato reported on a detailed study of the potential [20]

$$u(\beta) = \frac{(1-\eta)}{2} \beta^2 + \frac{\eta}{4}(1 - \beta^2)^2,$$

which is known [20] to correspond to the U(5)-O(6) transition region of IBM, U(5) being obtained for $\eta = 0$ and O(6) being obtained for $\eta = \infty$, the critical point occurring at $\eta_C = 0.5$ and corresponding to a $\beta^4$ potential, in agreement with the findings of [12, 13]. This potential has also been considered in [11, 14], but only within the region $0 \leq \eta \leq 1$. Fortunato allowed $\eta$ to obtain higher values, observing that best agreement between E(5) and the potential of Eq. (1) is obtained for $\eta \simeq 5$, in which case the potential develops a bump at the center. It was remarked that B(E2)s should be calculated before final conclusions can be drawn. It is however remarkable that a bump results in the X(5) framework when using an effective $\beta$ deformation, determined by variation after angular momentum projection and two-level mixing [21], as well as in Nilsson-Strutinsky-BCS calculations [22] for $^{152}$Sm and $^{154}$Gd, which are good examples of X(5), as will be seen in subsec. 3.2.

1.2 Solutions related to X(5)

Different potentials used in the X(5) framework include a potential with linear sloped walls [23], the confined $\beta$-soft (CBS) rotor model [24, 25] (which utilizes an infinite square well potential displaced from zero), Coulomb-like and Kratzer-like potentials [26], Davidson potentials [10, 11], as well as the $\beta^2$, $\beta^4$, $\beta^6$, and $\beta^8$ potentials [27]. A recent review of this topic has been given in [6].

The special case in which $\gamma$ is frozen to $\gamma = 0$, while an infinite square well potential is used in $\beta$, leads to an exactly separable three-dimensional model, which has been called X(3) [28].

The approximate separation of variables used in X(5) has been tested recently through exact numerical diagonalization of the Bohr Hamiltonian [29], using a recently introduced [30, 31, 32] computationally tractable version of the Bohr–Mottelson collective model.

1.3 Triaxial solutions

In the E(5) case [1] the potential is supposed to be $\gamma$-independent, while in the X(5) case [2] the potential is supposed to be of the form $u(\beta) + u(\gamma)$, with $\gamma$ obtaining values close to $\gamma = 0$. Another family of solutions of the Bohr Hamiltonian can be obtained by allowing the potential to be of the form $u(\beta) + u(\gamma)$ and confining $\gamma$ around $\gamma = 30^\circ$. An infinite square well potential in this case leads to the Z(5) solution [33] if $\gamma$ is allowed to vary around the $\gamma = 30^\circ$ value (the $\gamma$-soft case), and to the Z(4) solution [34] if $\gamma$ is fixed to this value, being a parameter and not a variable any more (the $\gamma$-rigid case). In the $\gamma$-soft case Coulomb-like and Kratzer-like potentials have been used [35], while a solution similar to Z(5), but with a different $\gamma$-potential, has been given in [36]. A recent review of the various solutions of the Bohr Hamiltonian has been given in [6].

The characteristic differences among the various models were discussed in detail. It was pointed out that E(5) and Z(4) possess very similar ground state bands and $\beta_1$ bands, as well as similar intraband and
interband B(E2)s obeying the same selection rules. The main difference between the two models occurs in the \( \gamma_1 \) band, which exhibits opposite odd-even staggering in the two models, since in E(5) its levels are exactly grouped as \( 2^+, (3^+, 4^+), (5^+, 6^+), \ldots \), which is a feature of the underlying O(5) subalgebra, while in Z(4) the approximate grouping is \( (2^+, 3^+), (4^+, 5^+), \ldots \), which is a feature of rigid triaxial models \( \gamma_R \). It is known that \( \gamma \)-soft and \( \gamma \)-rigid models provide very similar results if \( \gamma_{rms} \) of the former equals \( \gamma_{rigid} \) of the latter. Since no clear examples of triaxial nuclei have been identified, it is expected that Z(4) and Z(5)] would provide results in reasonable agreement with experiment only when this condition is approximately fulfilled.

The proton-neutron triaxiality occurring in the SU(3) limit of IBM-2 was also discussed, in connection to relevant shape phase transitions occurring in the study of the phase structure of IBM-2. It was pointed out that the main features of proton-neutron triaxiality are a low-lying K=2 band and B(E2)s resembling very closely the predictions of the Davydov model \( \gamma_R \) with \( \gamma \approx 30^\circ \). These findings are in agreement with the assumption of \( \gamma \approx 30^\circ \) made in Z(5) and Z(4), as well as with the prediction of low-lying \( \gamma_1 \)-bands in these models.

For experimental manifestations of the transition towards triaxiality, \(^{168,170}\)Er were suggested as possible candidates.

It was also pointed out that Z(4), as well as X(3), are solutions in which the separation of variables is exact. Therefore it might be easier to clarify their algebraic structure, while this task seems more difficult in the cases of X(5) and Z(5), where separation of variables is approximate.

2. Additional degrees of freedom

2.1 Octupole deformation

It is generally accepted that octupole deformation (\( \beta_3 \)) has to be taken into account simultaneously with the quadrupole deformation (\( \beta_2 \)), which plays a dominant role. In the approaches developed so far for the description of the transition from octupole vibrations to octupole deformation in the light actinides, either only axially symmetric shapes are taken into account \( \sim 3 \), or slight triaxiality is allowed \( \sim 4 \). In the Analytic Quadrupole Octupole Axially symmetric (AQOA) model \( \sim 5 \) the angles are left out from the very beginning and a single axis is used for both the quadrupole and the octupole deformations, with no relative angle in between. Both methods lead to a satisfactory description of \(^{226}\)Th and \(^{226}\)Ra involving an infinite square well potential \( \sim 7 \). In these cases the \( \beta_1 \) bandhead is higher than the X(5) bandhead by a factor of almost two, in agreement with experiment. The question of a transition from octupole deformation to octupole vibrations in the rare earth region has also been raised, along with suggestions to examine if the N=90 isotones \(^{150}\)Nd and \(^{152}\)Sm, which are known to be the best examples of X(5) (see subsec. 3.2), are also critical with respect to the transition from octupole deformation to octupole vibrations, a question which remains open.

It was pointed out that one has to be very careful in separating out the intrinsic variables, as in the old work by Rohoziński \( \sim 10 \). When building the spdf-IBM \( \sim 11 \), \( \sim 12 \) it became clear that separation of the intrinsic and angular variables was very difficult when taking into account only the s, d, and f bosons, while it became easy when the p boson was also included. The p boson was also helpful for taking into account the center of mass motion. The detailed study of the phase space of spdf-IBM, in analogy to the similar study carried out recently for IBM-2 \( \sim 13 \), \( \sim 14 \) would be very helpful in clarifying shape phase transitions involving the octupole degree of freedom, but it is technically quite demanding \( \sim 15 \).

It was also pointed out that one has to be very careful with the terminology, since octupole deformation (the merging of the ground state band and the nearby negative parity band into a single band with levels of alternating parity) occurs in nuclei which are near-vibrational or transitional from the quadrupole point of view, while octupole vibrations (negative parity bands built on bandheads corresponding to one or more quanta of octupole vibration, their levels thus lying systematically higher than the levels of the ground state band with similar angular momenta) are observed in nuclei which are well deformed from the quadrupole point of view.

Furthermore, it was pointed out that there is no \textit{a priori} reason for criticality in the transition from octupole deformation to octupole vibrations to occur in the same nuclei, in which criticality in the transition from quadrupole vibrations to axial quadrupole deformation occurs. Such a conclusion has to be based on experimental evidence, since the relevant models contain many drastic approximations, made in order to make them analytically soluble.

2.2 Scissors mode

It is known \( \sim 16 \), \( \sim 17 \), \( \sim 18 \) that there is a strong correlation between the low lying dipole excitations, referred to as the \textit{scissors mode} \( \sim 19 \) and quadrupole deformation. On the basis of systematics of experimental data in the Xe, Ba, Nd, Sm, and Gd isotopic chains it has been argued \( \sim 20 \) recently that the M1 scissors mode strength distribution exhibits a transitional behaviour in the same nuclei in which the transition from spherical to quadrupole deformed shapes is seen. In other words, it is expected that the low-lying dipole mode would exhibit critical behaviour in the same nuclei which are critical with respect to the quadrupole mode, since the former is driven by the latter, while no similar coincidence is expected \textit{a priori} for the octupole mode, as already remarked. Recent experimental data on \(^{124−136}\)Xe \( \sim 21 \) reinforce this argument.
3. Experimental manifestations of critical point symmetries and supersymmetries

3.1 Experimental manifestations of E(5)

The first nucleus to be identified as exhibiting E(5) behaviour was $^{134}$Ba [27], while $^{102}$Pd [58] also seems to provide a very good candidate. Further studies on $^{134}$Ba [59] reinforced this conclusion. $^{104}$Ru [60], $^{108}$Pd [61], $^{114}$Cd [62], and $^{130}$Xe [63] have also been suggested as possible candidates. A systematic search [64] on available data on energy levels and B(E2) transition rates suggested $^{102}$Pd, $^{106,108}$Cd, $^{124}$Te, $^{128}$Xe, and $^{134}$Ba as possible candidates, singling out $^{128}$Xe as the best one, in addition to $^{134}$Ba.

S. F. Ashley reported on recent measurements, performed at Yale of B(E2)s in $^{106}$Cd, and planned measurements of low-lying B(E2)s in $^{102-108}$Cd at Cologne, since earlier B(E2) measurements, by Coulomb excitation, in $^{106,108}$Cd seem unreliable. Detailed information on B(E2)s will clarify the presence of E(5) examples in this region, suggested in [63].

S. Harissopulos reported on recent measurements carried out at Legnaro on B(E2)s of $^{102}$Pd [66], singling out this nucleus as the best example of E(5) so far, in agreement with earlier work [58], among other reasons because no backbending occurs in its ground state band, which remains in excellent agreement with the parameter-free E(5) predictions up to high angular momenta.

S. Harissopulos also reported on measurements to be carried out in Jyväskylä on $^{128}$Xe, which has been suggested [64] as a very good candidate of E(5), but also is not far from a Z(4) behaviour [34]. This is in agreement with a recent report [63] on measurements of E1 and M1 strengths of $^{124-136}$Xe carried out at Stuttgart, which provides evidence for a shape phase transition around $A \approx 130$.

S. Harissopulos also mentioned, as possible E(5) candidates, $^{140}$Xe, which lies far from stability, and $^{48}$Ti, for which Coulomb excitation can be performed for the B(E2)s.

3.2 Experimental manifestations of X(5)

The first nucleus to be identified as exhibiting X(5) behaviour was $^{152}$Sm [67], followed by $^{150}$Nd [68]. Further work on $^{152}$Sm [69] and $^{156}$Nd [70] reinforced this conclusion. The neighbouring N=90 isotones $^{154}$Gd [71] and $^{156}$Dy [72] were also seen to provide good X(5) examples, the latter being of inferior quality. In the heavier region, $^{162}$Yb [73] and $^{166}$Hf [74] have been considered as possible candidates. A systematic study [75] of available experimental data on energy levels and B(E2) transition rates suggested $^{126}$Ba and $^{130}$Ce as possible good candidates, in addition to the N=90 isotones of Nd, Sm, Gd, and Dy. A similar study in lighter nuclei [80] suggested $^{76}$Sr, $^{78}$Sr and $^{80}$Zr as possible candidates.

D. Balabanski reported on recent measurements carried out at Yale on $^{128}$Ce, the first results of which on the B(E2)s within the ground state band are promising, while the analysis is going on. R. F. Casten remarked that this is a nucleus with a $P$-factor [35] of 4.8, which is close to 5, thus it is expected to be a very good candidate for X(5). F. Iachello remarked that $^{128}$Ce, having 8 valence protons and 12 valence neutron holes, matches $^{152}$Sm, possessing 12 valence protons and 8 valence neutrons, thus it is expected to be a very good example of X(5), as $^{152}$Sm is.

P. G. Bizzeti referred to the current situation in the lighter region. $^{122}$Ba [81] has been identified as a possible X(5) candidate, based on experimental information for the energy levels. However, preliminary B(E2) measurements performed in Legnaro indicate that the B(E2)s within the ground state band appear to be closer to the rotational values and not to the X(5) ones. A similar situation seems to occur in $^{124}$Ba, according to a recent analysis, communicated by A. Dewald, of an earlier measurement performed at Cologne. The energy levels of $^{104}$Mo also suggested a X(5) interpretation [82], but B(E2) values turned out to favour the rotor interpretation [83].

S. Harissopulos reported on recent GASP measurements on $^{178}$Os [84], for which B(E2)s indicate that it is the first good example of X(5) in the $A \approx 180$ region, and on $^{176}$Os [31], for which the analysis is still going on.

3.3 Experimental manifestations of E(5/4)

E(5/4) [57] corresponds to a particle with $j = 3/2$ coupled to an E(5) core. Therefore possible candidates should be searched for among odd nuclei with the odd nucleon lying in a $j = 3/2$ level. The first suspects were the neighbours of $^{134}$Ba, a good example of E(5). $^{136}$Ba and $^{138}$Ba have been measured at Yale. It is already clear that $^{138}$Ba is not an example of E(5/4) [58], probably because of the presence of a $j = 1/2$ level close to the $j = 3/2$ one, while the analysis of $^{133}$Ba is ongoing. As pointed out by F. Iachello, mixing between the multiplets based on the 1/2 and 3/2 levels leads to raising of one of the multiplets and lowering of the other.

S. Harissopulos pointed out that a multiplet in $^{129}$Xe, based on a 3/2 level lying slightly above the 1/2 ground state, exhibits strong similarities to E(5/4). J. Jolie suggested that a U(6/20) [84] supersymmetry
[corresponding to single-particle orbits with \( j = 1/2, 3/2, 5/2, 7/2 \) coupled to an O(6) core] might be more appropriate for an overall description of this nucleus, since it corresponds to a 1/2 ground state and has been found appropriate for describing nuclei in the \( A \approx 130 \) region [87].

F. Iachello suggested that the Ir-Au region near closed shells is maybe appropriate for looking for experimental manifestations of \( E(5/4) \), since the \( U(6/4) \) supersymmetry was found there [88, 89]. \( ^{63}\)Cu, although of small size, could also be a candidate, as discussed in [85].

J. Jolie pointed out a recent study [90] bringing together the concepts of supersymmetry and shape phase transitions through the use of an IBFM [88, 89] Hamiltonian including a vibrational term and a quadrupole-quadrupole interaction, using single-particle orbits with \( j = 1/2, 3/2, 5/2, \) as in the framework of the \( U(6/12) \) supersymmetry [88, 89]. This approach has given good results in the Os-Hg region [90].

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