PERSPECTIVES IN HIGH SPIN PHYSICS (THEORETICAL REMARKS)*

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Current trends in physics of fast rotating nuclei are reviewed from the theoretical perspective.

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1. Introduction

It is my great pleasure to give this talk on perspectives in high spin nuclear physics during the *High Angular Momentum Phenomena* workshop organized in honor of Zdzisław Szymański, my scientific father, collaborator, and friend. Zdzisław has had a tremendous impact on the development of low-energy nuclear physics, particularly in Warsaw, and on the careers of many physicists working in nuclear structure physics, including myself. He has pioneered, using simple and elegant theoretical tools, many areas of nuclear gamma ray spectroscopy. *Wszystkiego najlepszego, Szefie!*

Let me begin by discussing nuclear rotations in the context of the variety of rotational motions in the universe. Figure 1 displays, in a log-log scale, the characteristic period of rotation, T (in sec), as a function of the characteristic size of the rotating body, L (in cm) [1]. A few general comments regarding details of Fig. 1 are in order. The smallest objects shown in Fig. 1 are one-dimensional superstrings, with $L{=}(\hbar G/c^3)^{1/2}{\sim}1.6{\times}10^{-33}$ cm (Planck length) and $T{\sim}10^{-43}$ sec. Some excited states of hadrons, viewed as

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quark-gluon systems, can be interpreted as rotational bands. The moment of inertia of the nucleon and Δ is $\mathcal{J}\approx$20-25 MeV/$\hbar^2$ [2]; the corresponding rotational frequencies are of the order of $\hbar\omega$=0.5 GeV ($T\sim10^{-24}$ sec). Molecules, $T=10^{-16}$-10^{-13} sec, offer many beautiful examples of a very rigid quantum-mechanical rotation. Discrete molecular states with angular momenta of the order of $I = 80\,\hbar$ are measured routinely today (see, *e.g.*, Ref. [3] for ^{120}Sn^{16}O bands), and the rotational energy of a band is extremely well fitted by a two-parameter formula $E = AI(I+1)+B[I(I+1)]^2$ with $B/A\sim10^{-6}$. One of the dizziest mechanical manmade objects is an ultra-centrifuge used for isotope separation. The Oak Ridge gas centrifuge could make $\sim10^4$ rotations/sec [4], but there exist even faster ones. The pulsars, with their dimensions of several km and T ranging from 10 min to 10^{-1} sec are, considering their huge masses, amazingly fast [5]; they are wonderful laboratories of high-spin nuclear superfluidity [6]. For the gravitational body, the Jacobi instability takes place at angular momentum $I = 0.304\,\tilde{I}$, where $\tilde{I}=(GM^3L)^{1/2}$. The fission into two symmetric fragments takes place at a slightly higher spin, I=0.39$\tilde{I}$. The largest bodies shown in Fig. 1 are galaxy clusters, with a typical period of rotation of 10^{17} sec. In this company, atomic nuclei with their typical dimensions of several fm and rotational frequencies ranging from 10^{20} to 10^{21} Hz, are among the giddiest ones. What is *really* amazing, the data in Fig. 1, spanning around sixty orders of magnitude in L and T, and different interaction ranges (from strongest in the unification scale to gravitational), cluster around the "universal" line given by $T\approx10^{-7}L^{1.09}$.

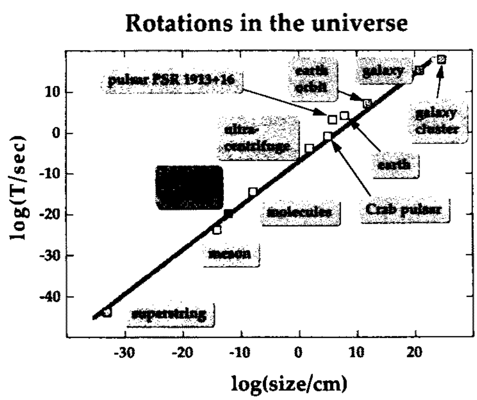

Fig. 1. Typical period of rotation versus characteristic dimension of a rotating object [1].

The phenomenon of nuclear rotation has a long history. As early as 1924 it was suggested by Pauli [7] that the hyperfine structure of atomic and molecular energy levels resulted from the electromagnetic interaction with *nonspherical* atomic nuclei. The fact that nuclei need not be spherical was then emphasized by N. Bohr in his classic paper on the nuclear liquid-drop model [8] in which he introduced the concept of nuclear *shape vibrations*. If a quantum-mechanical system is deformed, its spatial density is anisotropic. For a deformed system, it is possible to define its orientation as a whole and this naturally leads to the presence of collective rotational modes. This possibility was realized as early as 1937 by N. Bohr and Kalckar [9] who had estimated for the first time the energies of lowest rotational excitations and introduced the notion of the *nuclear moment of inertia*.

Fifty-eight years later, nuclear high-spin physics is a mature field, with many accomplishments. We have learned a lot about the basic mechanisms governing the behavior of fast nuclear rotation [10], especially the interplay between collective and non-collective degrees of freedom, competition between rotation, deformation, and pairing, and many global and detailed aspects of high-spin gamma-ray spectroscopy. This does not mean that the field of high spins is a closed chapter. Just the opposite: the longer we investigate the motion of a many-body nuclear system *at extreme spins*, the more surprises and questions are encountered. The new-generation experimental tools, such as multidetector arrays (EUROGAM, GAMMASPHERE, GA.SP) combined with the new-generation particle detectors, enable us to study discrete nuclear states up to the fission limit as well as a high-spin quasi-continuum, and explore new limits of excitation energy, angular momentum, and energy resolution. New high-quality data tell us more about the structure of wave functions of intrinsic states [11]. Here, beautiful examples are the intrinsic quadrupole moments recently measured with a very good relative accuracy in several superdeformed (SD) bands of ^{148,149}Gd and ^{152}Dy [12] and intrinsic g_K factors in superdeformed bands in ^{193}Hg [13] and ^{193}Tl [14].

A similar transition from qualitative to quantitative description is taking place in nuclear theory of high spins. There is growing evidence that many extremely successful phenomenological models involving a limited number of parameters (such as shape and pair deformations or rotational frequency) have already approached their limits of applicability. They are now being replaced by more microscopic self-consistent models, exploring both static and dynamic aspects of nuclear motion.

The richness of the field is reflected by the workshop program. On the theoretical side are represented a variety of models, approaches, and techniques: rotating Thomas–Fermi, cranked Nilsson–Strutinsky, self-consistent Hartree–Fock (HF), shell model, projection methods, RPA. New data are extremely helpful in pinning down the details of the effective nucleon-nucleon interaction, both in the particle-hole and pairing channels.

It had been recognized early that various nuclear collective modes and deformations could be attributed to specific symmetries of the single-particle Hamiltonian and residual interaction. That is, the rotational band structures involve families of states labeled by the different quantum numbers of the internally broken symmetries [15]. The program of this workshop contains many excellent examples of nuclear modes of rotation associated with nuclear shapes: super- and hyperdeformations, reflection-asymmetric and hexadecapole modes, multi-cluster structures, shape coexistence, and band terminations. Last but not least, are discussed exciting new avenues in high-spin physics of hot nuclei: quasicontinuum and rotational damping, and giant resonances.

In this talk, I would like to concentrate on several aspects of state-of-the-art nuclear spectroscopy accessible to the modern detector systems. Namely, in Section 2 are discussed recent advances in the theoretical modeling of high-spin states. Sections 3 and 4 contain, respectively, comments on the high-spin spectroscopy on a very small energy scale and on the quest for the fingerprints of the regular motion at high excitation energies and high spins. Finally, conclusions are contained in Section 5.

2. Theoretical developments

Unexpected experimental data from large arrays have generated a great deal of theoretical interest and activity. As a result, many new insights have been gained regarding the behavior of atomic nuclei at high spins. The traditional models, such as the Nilsson-Strutinsky approach, are still extremely successful in making global and detailed predictions, and explaining vast amounts of experimental data. A great success of the unpaired cranked single-particle picture of superdeformation is the treatment of SD bands in the Gd/Dy region [16]. The calculations based on the standard Nilsson-Strutinsky cranking model reproduce the effective alignments in SD bands extracted from the data and explore regions of even more exotic shapes, such as hyperdeformations [17].

The question of pairing, pairing blocking, and its importance for the rotational motion at normal and superdeformations has been discussed in several recent works. In the SD $A{\sim}150$ region, due to very large rotational frequencies and relatively low single-particle level density, pairing correlations are weak. However, in the SD bands in the $A{\sim}190$ region, pairing is important to describe the angular momentum alignment process due to rather low rotational frequencies involved. In particular, recent calculations indicate the importance of higher-order pairing interactions such as the rotation-induced $K^{\pi}{=}1^{+}$ pairing forces [18, 19], and the density-dependent pairing forces [20, 21]. The realistic (density-dependent) pairing interaction seems to reproduce well the behavior of the moments of inertia around

^{192}Hg, in particular the "delayed" crossing frequency [22]. Clearly, the newest high-spin data tell us a lot about effective nucleon-nucleon interactions, and about pairing force in particular. Interestingly, the question of the density dependence of pairing interaction is also of great interest for physics of nuclear radii, deep hole states, and properties of drip-line nuclei [23, 24]. That is, this important issue has also surfaced in a different corner of nuclear structure.

In the HF method, the average nucleonic field is obtained self-consistently from the nucleonic density. The interesting aspect of the cranked HF (CHF) method is that the time-odd cranking term, $-\omega I_x$, generates time-odd components in the HF potential [25, 26, 27]. These terms, not present in the deformed shell model, are expected to play a significant role at very high spins and they can shed some light on the yet-unexplored properties of effective forces.

Progress has been achieved in the self-consistent description of nuclear rotation using finite-range forces. Hartree-Fock-Bogolyubov calculations based on the Gogny interaction [28, 29] are quite successful in addressing physics of rotational motion at normal and superdeformations.

Another new avenue is a cranked relativistic mean field (RMF) theory [30, 31]. As a consequence of broken time-reversal invariance, the spatial contributions of the vector meson fields have a strong influence on the moments of inertia. Here, of particular interest is the effect of the nuclear magnetism (*i.e.*, the contributions from the spatial components of the vector meson fields). It still remains to be investigated what the relationship is between nuclear magnetism and time-odd components in the Skyrme functional.

3. Spectroscopy at a keV scale

The increased precision of experimental tools of gamma-ray spectroscopy has made it possible to probe very weak effects which are, energetically, at an eV or a keV scale. Those signals, small perturbations atop a smooth rotational behavior, are particularly clearly seen in superdeformed nuclei because of the exceptional length and regularity of the rotational sequences involved.

The first example is the phenomenon of identical bands (IB's). Identical bands, in which the γ-ray energies are virtually identical over a wide range of γ-ray energies, were originally found in pairs of bands in adjacent odd and even mass SD nuclei. Now, bands with identical moments of inertia have been observed in several mass regions at both low and high spins, and span a wide variety of shapes [32]. The second example of high-spin physics at the 50-100 eV scale is the so-called ΔI=4 effect seen, *e.g.*, in the SD band of ^{149}Gd [33].

Although the phenomenon of IB's has triggered many microscopic attempts to describe nuclear high-spin states, a satisfactory explanation of this phenomenon is still lacking. It is rather clear that the puzzle of IB's is ultimately related to the questions normally addressed in the context of large amplitude collective motion, such as: What are the "strong" quantum numbers that stabilize collective rotation? There is also very little doubt that a proper description of pair correlations and nuclear dynamics at high spins are key factors.

Some answers to the above questions can be provided by the data. Here, especially instructive are band-pair distributions that assess the degree of similarity between the moments of inertia in different bands. Recently, the distributions of fractional changes in the dynamical moments of inertia of pairs of bands in SD nuclei were studied by de France *et al.* [34] who investigated the fractional change in $\mathcal{J}^{(2)}$, FC, defined as [35]

$$FC \equiv \frac{\Delta\mathcal{J}^{(2)}}{\mathcal{J}^{(2)}}. \tag{1}$$

The quantity FC has the advantage of being independent of the *absolute* spin, I. Instead, it depends only on the relative spin alignment, i, of the two bands. In situations where i is a linear function of I, the average value of FC can be extracted via a linear least-squares fit: $i = \overline{FC}\, I + i_0$.

The regional distributions of fractional changes in the moment of inertia indicate that *(i)* there is an excess of pairs of bands with very similar moments of inertia, and *(ii)* there exists a large excess of identical bands in SD nuclei compared to normally deformed nuclei at low spins. A striking example is presented in Fig. 2, where the SD band-pairs in neighboring nuclei from the $A{\sim}150$ and $A{\sim}190$ mass regions, believed to have the same high-$\mathcal{N}$ content, are clustered around $|\overline{FC}|{=}0$. At the same time, the distributions of $\overline{FC}$ for rare-earth nuclei at normal deformations and low spins are much broader. As discussed in Refs. [32, 34], the pattern shown in Fig. 2 can be attributed to residual correlations (such as pairing). At SD configurations pairing is expected to be quenched — thanks to high rotational frequency and/or many-quasiparticle nature of the band. Consequently, the underlying shell structure (*i.e.*, the high-$\mathcal{N}$ intruder content) is clearly reflected in their moments of inertia, especially in the SD $A{\sim}150$ region. Indeed, there exists a very nice correspondence between the theoretical single-particle shell structure, the occurrence of IB's, and the observed fine structures (peaks) in the distribution of fractional changes in moments of inertia [34]. On the other hand, the relation between intrinsic (intruder) occupation quantum numbers is lost at normal deformations where configuration mixing due to pairing correlations smears out the individuality of each band. Hence, the identical bands at normal deformations and low spins are less "identical" than the SD identical bands, as nicely illustrated in Fig. 2. Surprisingly, it is at very large deformations and high angular momenta where the very best examples of the extreme shell model (*i.e.*, an almost undisturbed single-particle motion) are found!

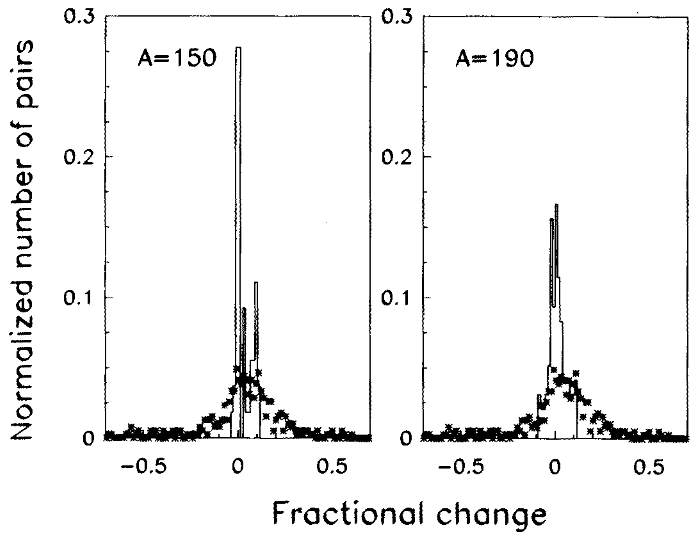

Fig. 2. Distributions (normalized to one) of average fractional changes in the moments of inertia of pairs of SD bands in the neighboring nuclei. The stars show the corresponding distribution for normally deformed bands in the rare-earth region. (From Ref. [34].)

Recently, there has been a considerable interest in the unusual variations seen in the spectra of some SD bands. The effect manifests itself by a systematic shift of the sequence of states with spins I, $I{+}4$, $I{+}8$, *etc.*, with respect to the sequence $I{+}2$, $I{+}6$, $I{+}10$, *etc.* The amplitude of the perturbation is very small, of the order of 100 eV. Since these oscillations separate a band into two families in which spins differ by *four* units of angular momentum, it seems natural to explain their origin by a coupling between the rotational motion and hexadecapole vibrations [33, 36, 37].

To analyze small fluctuations in the moment of inertia, several criteria have been introduced in the literature. One possibility was suggested in Ref. [33], where the staggering was discussed in terms of the quantity $\Delta^3 E_\gamma(I)$ involving four consecutive gamma rays, while another staggering parameter, $\Delta^4 E_\gamma(I)$, involving five consecutive transition energies was proposed in Ref. [38]. The usefulness of quantities $\Delta^3 E_\gamma(I)$ and $\Delta^4 E_\gamma(I)$ for discussing irregularities in rotational bands has recently been discussed in Ref. [39], where it was concluded that, in some cases, these staggering parameters based on several transition energies can dramatically amplify perturbations in rotational levels (*e.g.*, due to accidental degeneracies) producing an oscillatory and regular pattern. In this context, it can be noted that one can construct a sequence of quantities, $\Delta^k E_\gamma$, related to various derivatives of E_γ with respect to I. Indeed, it is easy to see that [40]

$$\Delta^3 E_\gamma \approx 2\left(\frac{d^3 E_\gamma}{dI^3}\right) \quad \text{and} \quad \Delta^4 E \approx \left(\frac{d^4 E_\gamma}{dI^4}\right) . \tag{2}$$

That is, $\Delta^3 E_\gamma$ and $\Delta^4 E_\gamma$ are related, respectively, to the fourth and fifth derivative of the total energy, E, with respect to I. It is worth noting that for a "C_4" spectrum with the reference transition energy linear in I (perfect rotor) and constant perturbation, all fluctuation parameters, $\Delta^k E_\gamma$, are proportional to the value of perturbation.

The meaningful extraction of small perturbations requires experimental data of unprecedented accuracy. As discussed in Ref. [39], the smart application of derivatives $\Delta^k E_\gamma$ can be very useful when analyzing large numbers of rotational bands. Namely, from the behavior of $\Delta^k E_\gamma$, one can extract the magnitude of the perturbation and the angular momentum at the crossing point. On the other hand, the uncritical use of higher-order derivatives can be dangerous because of the error propagation.

Physics on a keV-scale demands better and more precise calculations. The phenomena of identical bands and staggering in $\mathcal{J}^{(2)}$ offer a wonderful opportunity to learn more about the effective interactions, especially those which depend on angular momentum. As discussed in Section 2, these challenges have already triggered many novel microscopic attempts to describe nuclear high-spin states — thus leading to significant progress in the theory of high spins and the nuclear many-body problem.

4. Complete spectroscopy and quasicontinuum: from chaos to order

In the near-yrast regime there exist intrinsic quantum numbers that can well *isolate* nuclear configurations. At high excitation energies, because of a very large level density, the concept of quantum numbers virtually breaks down because of the dramatic configuration mixing. It is not clear at the moment what the conditions are for the many-body system to give up its quantum characteristics. The usual argument involving high temperature (high excitation energy) should be used with some caution since it puts an almost exclusive emphasis on statistical aspects. As a matter of fact, even at high excitation energies there exist well-ordered states that can be beautifully described by stable mean fields. Examples of those are superdeformed states, high-K isomers, and giant resonances.

For the theories describing the nuclear large-amplitude collective motion of particular interest are the measurements of coexisting nuclear states

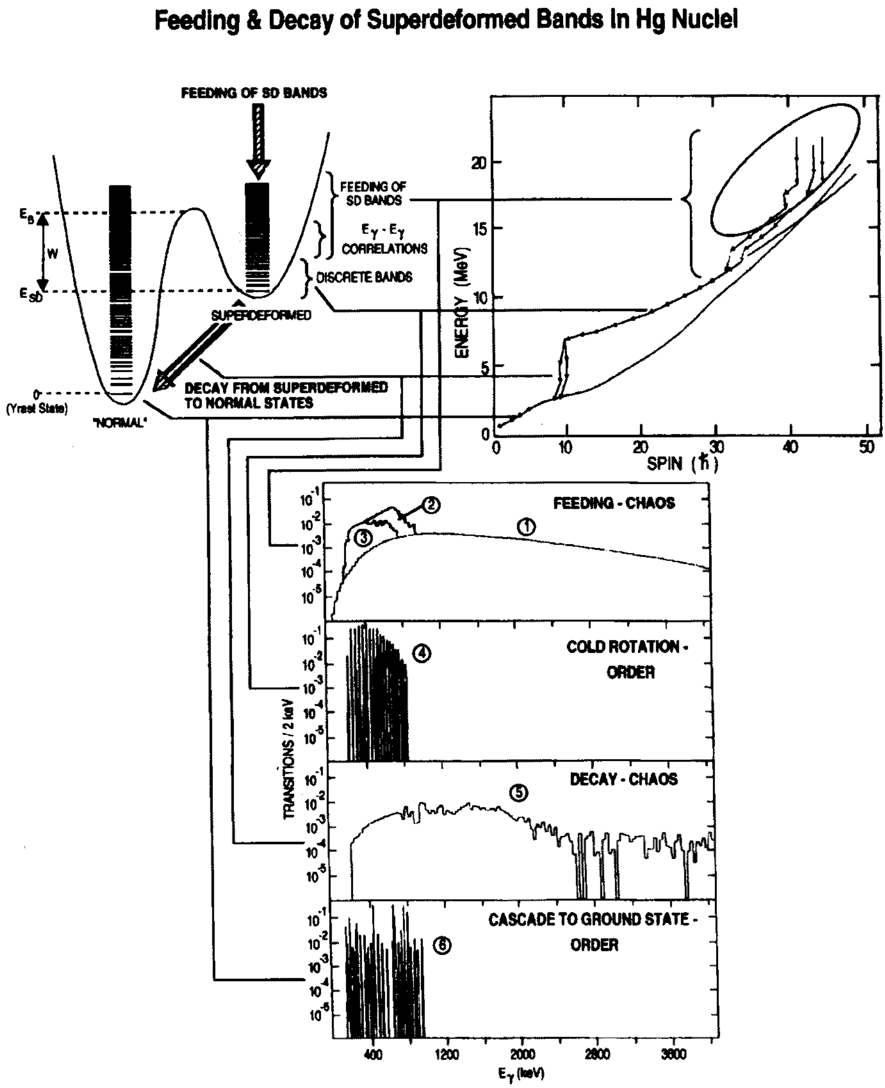

Fig. 3. The experimentally extracted gamma-ray emission spectra of the feeding and the decay of superdeformed bands. The lower four boxes display the measured spectra that correspond to the gamma-ray transitions shown schematically in the top figure, which the excited nucleus follows in shaking off excitation energy and spin. The data illustrate the double cycle between disorder and order, as a rapidly rotating nucleus is formed and gradually loses its angular momentum. (From Ref. [45].)

built upon configurations with very different intrinsic properties. A set of single-particle orbitals in the intrinsic system is, around the stationary HF minimum, well described by intrinsic (self-consistent) quantum numbers [41]. The origin of the coexistence phenomenon can be explained in terms of several local minima in the potential energy surface (or: several stable mean fields with different deformations) in the time-dependent HF manifold. Introducing more than two local minima requires the full analysis of the gauge structure of the many-body phase space [42–44].

The experimental illustration of the local potential minima (integrable stable mean fields) separated by the stochastic sea is illustrated in Fig. 3 [45], which shows the feeding and the decay of SD bands in the $A{\sim}190$ mass region. The decay is the consequence of the mixing of a cold SD state with a sea of hot normal states in which it is embedded. The spectra emitted at different stages of the cascade show in sequence: (1) an unresolved statistical spectrum associated with the feeding into the SD state, (4) discrete lines emitted from the cold SD band, (5) statistical spectrum associated with the decay of the SD band, and (6) discrete lines corresponding to the cold near-yrast cascade.

Clearly, there exist islands of order at high temperatures; the statistical arguments, based, *e.g.*, on the nearest-neighbor distribution, should be taken with a grain of salt. In this context, two recent examples illustrating the presence of good quantum numbers at high excitation energies can be quoted: experimental separation of quasicontinuum built upon SD minimum in ^{143}Eu [46] and the evidence for the conservation of the K quantum number in excited rotating nuclei [47, 48].

5. Summary

There is a lot to be done! In my talk, because of time constraints, I mentioned only a few challenges and puzzles facing our high-spin community. It is amazing that, after so many years, there are still so many deep and unanswered questions about very basic aspects of nuclear rotations. The new-generation detector systems will certainly open up many new avenues in nuclear physics. We should be prepared for many surprises and a lot of excitement.

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