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# Problems in contemporary nuclear physics

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ABSTRACT

Last decade research topics of the Nuclear Theory Group of the M..C.S. University in Lublin are presented in this article. The achivements of the group and its further plans are confronted with current problems of modern nuclear physics.

## 1. INTRODUCTION

A hundred years ago, in the same year, when the great Polish scientist Maria Curie Skłodowska was awarded the Nobel Price in Chemistry[1], Ernst Rutherford, also a Nobel Prize winner[2] discovered atomic nucleus. His discovery, made in 1911, opened a new branch of science: nuclear physics, which is nowadays also called subatomic physics. Until that time the origin of radioactivity was unclear for the majority of scientists. Several groundbreaking hypotheses were present. Even Maria Curie had not know the structure of atom. She, as majority of scientists, believed in the Thomp-

[1] In recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element for the investigation of radioactive elements.

[2] For his investigations into the disintegration of the elements, and the chemistry of radioactive substances.

son's model of atom composed from proton matter in which electrons were planted like *rasins in a cake.* The energy emitted by her new elements was a mysterious "perpetuum mobile" for people.

Three years after the discovery of Rutherford, Niels Bohr formulated his planetary model of atom, which had fundamental significance for understanding atomic spectra and many other phenomena of atomic and molecular physics. The Bohr model has given foundations of the quantum mechanics, new branch of physics which developed rapidly in the 20-s of the previous century.

The understanding of the mechanisms leading to radioactivity as well as the structure of nucleus were, for almost two decades, unclear for physicists. Each progress in experiments was followed by new theoretical ideas and vice versa. It was barely the success of Lisa Meitner, expatriated from Berlin to Sweden by Nazis in 1939, and Otto Robert Frisch, then Niels Bohr to explain the energetic power of nuclear reactions by shell and liquid drop structure.

After 100 years since the discovery of atomic nucleus it is worth to watch the great progress made in understanding of the world structure, from elementary particles to macrocosmos. Nuclear theory has developed models, based on various interactions, which explain processes in nuclear matter. The spectrum of questions, which are still to be answered is so large that we limit our retrospection mostly to the problems investigated by the members of the Nuclear Physics Group (NPG) of Maria Curie Skłodowska University.

The staff of NPG consists of 14 scientists, among which are five full professors, which means that the nuclear theory group of the MCS University are among the largest teams in Europe working in this field. A complete list of publications written within the last decade by the members of NPG is given in References. The subjects of these more than 200 papers published in the scientific journals of the world range prove that the tradition of Maria Curie Skłodowska is alive in the University which carries her name [1-204]. The tradition of the French-Polish collaboration is present in our group. Several nuclear scientists from Lublin conduct joint researches with the French physicists from laboratories in Bordeaux, Bruyères-le-Châtel, Cean, Orsay and Strasbourg. for 18 years we have organised the joint Polish-French Workshop on Nuclear Physics in Kazimierz Dolny which has already become a well known world wide conference devoted to current problems of nuclear theory.

## 2. EXOTIC NUCLEAR STATES AND NEW SYMMETRIES

There are a lot of new interesting problems in nuclear structure. One of them is related to the “exotic” deformations of nuclei. The term “exotic” denotes here a different meaning, from the standard definition due to the context in which it is used. Roughly speaking, an ensemble of the nuclear shapes which differ from ”standard” quadrupole shapes is considered exotic.

There are also expected new isomers with exotic symmetries corresponding to the point groups related to the exotic deformations, well known and physically important symmetries in molecular physics. The most well-known cases of exotic deformations are superdeformed and hyper-deformed nuclei. In this case the term ”exotic” refers to nuclear elongation corresponding to the axis-ratios around 1:2 and 1:3, respectively.

### 2.1. ISOSPECTRAL SUPERDEFORMED BANDS

One of the interesting problems is the isospectral bands (also called “identical” bands). One can investigate them using the average nuclear field approach together with its realistic non-selfconsistent (deformed Woods-Saxon Hamiltonian) and selfconsistent (Hartree-Fock with the Skyrme interaction) versions. The first pilot project suggests that the polarization of the moments of inertia by an odd, non-intruder nucleon, is markedly lower in the case of the selfconsistent approach as compared to the non-selfconsistent calculations.

Further investigations should elucidate the role of pseudo-symmetries in the super- and hyper-deformed state structure. In this case one needs to extend the calculations to several mass ranges (A~80, A~132, A~150, A~190, A~230) in particular by using the improved Hamiltonians. The combination of the superdeformation-oriented calculations with the results on the pseudo-spin transformation project is expected to be fruitful.

### 2.2. $\Delta I$=2 STAGGERING AND ITS RELATION TO NUCLEAR SYMMETRIES

Another group of subjects strongly related in particular to the SD bands, concerns the often discussed, but not satisfactorily documented, problem of the so-called ($\Delta I$=2)-staggering. This effect, claimed to exist in some SD bands, corresponds to an up-ward (down-ward) shift of states with spins

$I = I_0$, $I = I_0+4$, $I = I_0+8$ etc. with respect to the rotor-type average [$E \sim I(I+1)$], and a down-ward (up-ward) shift of the states with spins $I = I_0 +2$, $I = I_0+6$, $I = I_0+10$ etc., with respect to the same average. This problem is related *more generally* to the question of possible systematic deviations in rotational bands from the rotor-type behaviour - deviations that may signify new, specific point-group symmetries as proposed e.g. by I. Hamamoto and B. Mottelson[3].

There is an interesting puzzle of the ($\Delta I$=2)-staggering and other possible forms of deviations from the usual, regular rotational pattern in super- and hyper-deformed nuclei. It was shown that the nuclear average field theory both non-selfconsistent and the self-consistent Hartree-Fock (the latter one) do *not* support the idea of the $C_4$-symmetry as a possible origin of the ($\Delta I$=2)-staggering, at least in the A ~ 150 superdeformed nuclei. It would be important to study also the other mechanisms that may produce either regular (cyclic) or irregular deviations from the “rigid-rotor” behaviour. An open problem is a possible correlation of intrinsic symmetries with the precise forms of those deviations. Both studies can be done by using the model Hamiltonians expressed as expansions in terms of the nuclear angular momentum operators ($\hat{I}_x$, $\hat{I}_y$, $\hat{I}_z$). This type of “generalized rotor” has been successfully used in molecular physics for a similar problem.

To be more realistic one needs to optimize the commonly used “universal” parametrisation of the deformed Woods-Saxon Hamiltonian, in particular, in order to better simulate the effect of the average neutron-proton interactions which are rather poorly represented so far. We would then also further develop the density-dependent version (partly self-consistent version) of the spin-orbit interactions in the Woods-Saxon Hamiltonian. With the improved Hamiltonian one expects to obtain a more reliable predictions related to the nuclear hyperdeformation and the corresponding realistic, hyperdeformed shell-closures.

Another way to extend and to improve the high-spin calculations of the properties of the hyper-deformed nuclear states is introducing the Dirac mean field Hamiltonian consisting of the scalar and vector potentials. The form of the Dirac Hamiltonian is established on basis of the relativistic mean field theory and its parameters will be fixed by a direct fit to the experimental data.

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[3] I. Hamamoto and B.R. Mottelson, Phys. Lett, **B333** (1994) 294.

2.3. NEW ISOMERS WITH EXOTIC SYMMETRIES: TETRAHEDRAL NUCLEI

The realistic nuclear mean-field method calculations suggest the existence of atomic nuclei whose shapes are tetrahedral-symmetric. The underlying symmetry of the corresponding mean-field Hamiltonian is then the double-point group $T_d^D$ while that of the nuclear shapes is given by the 'single' group $T_d$. The calculations show that, to a first approximation, the nuclei whose shapes are characterised by the exact tetrahedral symmetry have vanishing multipole moments except for the Q32 one. Therefore, unlike the rotational bands of quadrupole-deformed nuclei whose E2-transitions dominate, the E2-transitions in the rotational bands of tetrahedral-symmetric nuclei are predicted to vanish or to be very weak since the implied quadrupole moments are zero or small[4]. This result, however, is only true for the model with static deformations [16,72]. The other possibilities are open while the nuclear vibrations are taking into account.

Recent experiments[5] on the $^{156}$Gd and $^{156}$Dy nuclei gave new and more precise information, in particular on the spectroscopic properties of the negative-parity bands, possible tetrahedral-symmetry candidates. According to Jentschel and co-workers[6], the quadrupole moment of the tetrahedral-symmetry candidate-band in $^{156}$Gd is comparable to the one in the ground-state band.

The tetrahedral symmetry concept to collective-vibration Hamiltonian provides collective nuclear wavefunctions which depend on various deformation parameters through the potential energy surfaces (obtained using the Macroscopic-Microscopic method with the so-called Universal Woods-Saxon Hamiltonian). This description goes far beyond the extreme static viewpoint involving only the equilibrium. It allows to explain tetrahedral puzzle of large quadrupole transitions in the tetrahedral bands as originating from the vibrational motion.

The investigations concerning the tetrahedral nuclei open a new field of searching for a classification of nuclear energy bands. The proposed classification could be based on their symmetries. The point groups seem to be natural candidates for such symmetries, however the problem should be considered in its full generality.

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[4] J. Dudek *et al.*, Phys. Rev. Lett. **97** (2006) 072501.
[5] Q.T. Doan *et al.*, Acta Phys. Polon. **B40** (2009) 725; L. Riedinger *et al.*, *private communication*; O. Burglin *et al.* Phys Rev **C51** (1995) 547.
[6] M. Jentschel *et al.*, Phys. Rev. Lett. **104** (2010) 222502.

It would be interesting to derive the quantum manifestations of the symmetry problem introduced above. Each of those symmetries manifests itself via a set of conserved quantum numbers which differ from symmetry to symmetry (for instance, in the case of the $C_3$-symmetry of cranking field one may expect six families of rotational states in their spectra while the "traditional" triaxial ellipsoid potential would generate only 4 (determined essentially by combinations of both parities and both signatures).

### 2.4. UNITARY SYMMETRY, *P*-SYMMETRY AND RELATED

While the exotic symmetries discussed above refer to the point-group symmetry effects in nuclear structure, another type of symmetries reaching more profoundly into the effective nucleon-nucleon interactions has been discussed recently. There hass been discovered the so-called *P*-symmetry of the effective nuclear Hamiltonians, which exists more generally in the quantum-mechanical systems whose average field possesses at least one dichotomic symmetry, while the two-body interactions take the form of pairing or generalized pairing interactions. This new symmetry results in predictions of a new conserved quantum number (*P* quantum number) and it thus implies the existence of another classification of nuclear spectra[7]. It allows to systematically reinterpret the best high-spin experimental information with the explicit use of the *P*-symmetry concept. This should be a relatively obvious verification given the fact that according to this theory bands of the same parity and signature may additionally differ in their *P* quantum numbers: those with common *P* quantum numbers must strictly follow the Landau-Zener rule while those with different *P* quantum numbers may cross without repulsions.

## 3. SELECTED MATHEMATICAL METHODS IN NUCLEAR PHYSICS

In this group of subjects we would like to develop (or significantly improve) the methods of solving nuclear problems, especially those corresponding to nuclear phenomena studied in state-of-the-art experiments. The motivation of this research consists in observing that the theoretical description of several effects is not sufficiently powerful in view of the new precision and

[7] O. Burglin *et al.* Phys. Rev. **C51** (1995) 547.

of the actual abundance of the experimental information. We envisage therefore either new important extensions in the existing methods or preparation of new approaches.

### 3.1. SUPERSYMMETRY – RELATION WITH OTHER FORMALISMS

It is an interesting and important aspect of some of the group-theory-based formalisms that they allow for a simultaneous, correct from the many-body formulation point of view, description of fermions and bosons. In the simplest interpretation, the former are just unpaired nucleons while the latter correspond to the coupled pairs of nucleons. A starting point of the formalism consists in employing a unitary supersymmetry $\mathrm{U}(n/m)$ .

With the use of such a formalism it has been shown that the nuclei corresponding to the second half of the s-d shell are well described while those from the first half are not, important differences being predicted also from the shell model calculations. We would like to extend this type of studies and better approach the coupling mechanisms, in particular between odd proton and odd neutron. We would like to emphasize that the proton-neutron coupling, also in heavier rotating nuclei is an important current problem in high-spin physics. In this study one would bring an interesting possibility of confronting the results of various formalisms and conclude about a possible changing in the proton-neutron coupling schemes in the function of nuclear mass, isospin and spin.

The supersymmetry concepts are also directly applicable in another physical context: that of the pseudo-spin symmetry and pseudo-spin transformation, both introduced originally many years ago and revisited recently in the context of nuclear superdeformation. We would like to examine a pseudo-spin transformation on the level of the Dirac equation together with the relations between the group of Lorentz/Poincaré and the group $\mathrm{O}_{sp}(1/2)$. This research would allow to understand a deeper physical role of the pseudo-spin symmetry in both relativistic and non-relativistic formulations of the nuclear interaction problem.

### 3.2. QUANTUM GROUPS AND ALGEBRAS IN NUCLEAR PHYSICS CONTEXT

Quantum groups and algebras have recently received an increasing interest among both mathematicians and physicists. Some "mechanical" applications of the quantum groups to nuclear superdeformation (consisting in a successful fit of the $SU_q(2)$ based formula to the experiment) are present in the literature but do not allow for a deeper insight into the nuclear structure.

We would like to construct and study these quantum Lie algebras whose traditional partner-algebras have interesting interpretations in the nuclear physics context. In particular, the quantum-deformed SO(5)-algebra (SO(5) corresponding to the proton-neutron pairing problem) and a quantum-deformed correspondent of the rigid-rotor seem as an interesting starting point. In this case one can try to construct the irreducible representations and Casimir operators related to the above algebras and apply the implied classifications of the solutions to the dynamical problems of motion (spectra and their properties).

### 3.3. ALGEBRAIC GENERATOR COORDINATE METHOD AND ITS APPLICATIONS

The principal frame of the formalism is based on an algebraic construction introduced first by Gelfand, Neimark and Segal. Several publications strongly encourage a further extension of the formalism aiming at a uniform and elegant description of the nuclear collective motion together with the possible underlying symmetries [17].

One can apply the formalism to a systematic analysis of the rotational spectra and couplings of the rotational motion to other, first of all quadrupole and octupole vibrations. By analysing various possible model-symmetries introduced to the formalism we hope to learn about e.g. the isospectral bands.

Another problem is to examine in detail the existence of all quantum numbers that may characterize collective modes; it would be useful to study this problem of symmetry by re-examining some of the most successful nuclear models (generalized Bohr model, algebraic model of Rowe and Rosentsteel, and the Interacting Boson Approximation).

## 4. EXOTIC NUCLEI, EXTREME ISOSPINS AND ASTROPHYSICS

The quantum behaviour and structural properties of exotic nuclei, i.e. nuclei far from the $\beta$-stability line, can be viewed as one of the most actual directions of research in contemporary nuclear physics. There exist numerous experimental projects under construction that will soon produce new output.

Several theoretical methods, although so far quite successful in various applications, must be re-examined. This concerns in particular the more adequate parametrisations of nuclear interactions as well as “practical” realisations of the implied approximations and methods (Hartree-Fock, macroscopic-microscopic method of Strutinsky, the shell model and probably others).

### 4.1. GROUND STATE AND LOW LYING EXCITED STATES IN EXOTIC NUCLEI

Several efforts were performed to adapt and re-develop well established formalisms, such as Hartree-Fock and Hartree-Fock-Bogolyubov Methods, Relativistic Mean Field Theory, Random Phase Approximation and Generator Coordinate Methods to make them directly applicable in the context of exotic nuclei.

A combination of the HF and HFB methods with the Random Phase Approximation, strength-function method and the Generator Coordinate Method has allowed to calculate the low-lying collective effects in exotic nuclei, in particular those close to the proton or neutron drip line and superheavy nuclei [71]. Further investigation-s are planned.

### 4.2. MICROSCOPIC DESCRIPTION OF PROTON EMISSION FROM EXOTIC NUCLEI

We have already performed some attempts to describe the proton emission from the nuclei close to the proton drip line. Continuing this research, we would like to develop a theoretical model of the structure of proton resonances which carry large angular momenta. This project seems of particular importance given numerous constructions of the secondary beam facilities in several countries.

Pairing correlations play a crucial role around the drip lines [29]. Pairing with isospin $T = 1$ is usually ignored in the microscopic analysis of heavy nuclei and thus quite misunderstood. The proton drip line and particularly the region of doubly magic nuclei like $^{100}$Sn will be essential to study this $T = 1$ channel [81].

### 4.3. ISOVECTOR DEFORMATIONS AT EXTREME ISOSPINS

The neutron and proton densities are expected to undergo an evolution when the proton and neutron numbers vary considerably. We have studied this problem using the modified Hartree-Fock approach (see above) together with a more phenomenological method based on two average potentials for each kind of particles and modified liquid drop model [15].

In a parallel way, a large excess of neutrons offers the possibility to have different deformations for proton and neutron densities in medium and heavy nuclei [84,85]. Microscopic theories have already been applied for this purpose and it was found that the absolute value of the difference between the proton and neutron deformations could even exceed 10% of the global deformation.

It is also interesting to investigate the change of the density distribution of both kinds of particles along the path to fission and for the shape isomers. We have already performed a preliminary study of this effect on the basis of the HFB calculation with the Gogny [41] and Skyrme forces.

We continue our searching of the bubble and toroidal structure in the region of neutron-deficient superheavy nuclei [142,157]. The HFB calculations with Gogny forces as well as some estimates using the ETF and the Skyrme forces have shown that such exotic structures of nuclei could exist.

## 5. NUCLEAR COLLISIONS – RELATION TO NUCLEAR STRUCTURE

The majority of current theoretical investigation in this field deals with the following subjects:

- heavy ion collisions at subbarrier and near barrier energies, − hot fusion,
- decay of the compound nucleus by light particles emission and fission.

The fusion and fission processes are described by an appropriate set of Langevin's equations. The model is based on the assumption that the collisions of heavy ions could be described within a statistical model which takes into account the effect of energy dissipation due to the presence of the friction forces and the diffusion phenomena. The corresponding transport equation of the Fokker-Planck type was originally proposed for nuclear fission by Kramers in 1940 and in 70-s it was adapted for heavy ion physics.

It has been shown that the Monte Carlo calculations combined with the local moment expansion method transform the Fokker-Plank equations into the set of the equations of motion with the random force which is equivalent to the Langevin ones. The Langevin equation has already been used by several authors to describe the heavy ions collisions and fission. This idea was very fruitful and allowed us to describe many phenomena occurring in heavy ions physics due to statistical fluctuation.

### 5.1. HEAVY ION COLLISIONS AT SUB-BARRIER AND NEAR BARRIER ENERGIES

The dissipative dynamics model in which one works with sharp trajectories (no fluctuations) was extended by adding random forces, so that the original equations of motion have been transformed into a set of coupled Langevin equations. It was found there, that without any change of the transport parameters and using the same set of collectives coordinates it was possible to describe the fusion probability for different near−barrier heavy− ion collisions. In the continuation of this study we demonstrated that the deformation of heavy ions in the entrance channel has a large effect on the spin distribution of the fused system. It was found that different orientations in space of the target nucleus and the projectile has led to large variations of the fusion barrier and consequently it had a large influence on the spin distribution of compound nuclei.

Now, using the fusion model based on the Langevin equations it is worth to study the following effects:

- the influence of the mass asymmetry in the entrance channel on fusion probability and the spin distribution of the fused system,
- the effect of differences in the proton and neutron densities distributions on heights of fusion barriers,
- fusion probability of very deformed heavy-ions,
- dependence of the fusion probability on energy of colliding ions and the magnitude of the extra−push energy.

By confrontation with the experimental data one can obtain an information about the magnitude of collective transport parameters like: fusion barriers, friction and diffusion parameters. These data were confronted later with predictions of theoretical microscopic models like e.g. the linear response theory. Our estimates of the fusion cross-section and its angular momentum dependence were also used by experimentalists working in the high−spin physics and those interested in the synthesis of exotic or superheavy nuclei. The question of the existence (substantial stability) of superheavy elements is one of the most challenging problems in nuclear physics. We plan to make a study of cross sections for reactions that may be used in the production of superheavy elements.

### 5.2. HOT FUSION

The hot fusion is a frequently used way to produce exotic nuclei. There are many experimental data concerning e.g. total and differential fusion cross−sections, spin distributions, multiplicities of particles emitted during fusion process or deep inelastic collision. One can compare these data with results of theoretical calculations.

The theoretical description of the heavy-ion collisions at energies of the order of a few hundred MeV would be of great interest for studying the validity of the transport equation. At these energies the fused system will reach the temperature of 4−5 MeV and such a high temperature will influence: the heights of the fusion and fission barriers, the magnitude of the friction forces, the value of the diffusion and the mass tensors.

The change of the fusion barrier with temperature could be estimated within of the extended Thomas−Fermi (ETF) method applied to the Skyrme interaction [27,28]. The ETF model predicts a significant decrease of the surface term with temperature in the liquid drop energy, while the Coulomb part is almost unchanged. The temperature dependence of the friction forces was extensively discussed within the linear response theory and other microscopic models. All theoretical models predict an increase of the friction forces with temperature and saturation at higher temperatures. Also the commonly used Einstein relation between the diffusion and the friction forces should be tested in the wide range of temperatures. The last theoretical works suggest that the Einstein relation should be modified.

### 5.3. DECAY OF THE COMPOUND NUCLEUS BY PARTICLES EMISSION AND FISSION

In the last few years, many experiments have been undertaken to determine the number of the pre- and post-fission neutrons by measuring evaporated neutrons in coincidence with fission fragments for different angles. From these data, the corresponding multiplicities were determined. In addition, the emitted protons, alpha-particles and $\gamma$-rays have been measured in various experiments. Due to the Coulomb barrier the charged particles are emitted more seldom than the neutrons [10].

It is important to study the influence of damping on decay of highly excited compound nuclei when the fission barrier is relatively small. In this case, fission and particle evaporation compete with one another and, consequently, particle emission depends on the dissipation. On the average, fission fragments have enough excitation energy to emit particles themselves. Since the directions of these particles are correlated with those of the emitting fragments, they can be separated, experimentally, from particles evaporated from the compound nucleus.

Our efforts were dedicated to a stepwise improvement of this general theory in order to reach a quantitatively reliable description of the decay of the compound nuclei. The principle of our approach was to describe the particle emission as a purely statistical process, i.e. by the Weißkopf theory and the nuclear fission as a transport process governed by the Langevin equation. We have performed some detailed calculations of the competing processes of particle evaporation and the fission of compound nuclei. A set of coupled differential equations formed by Fokker and Planck describing fission and master equations for calculating particle evaporation was used. From these equations, one is able to determine multiplicities of pre-fission neutrons, protons and alpha-particles and their energy spectra [24,25,37,38].

We would like to study more carefully how the evaporation probabilities depend on the deformation of the nucleus and on its collective rotation. In the standard form of the evaporation theory, the deformation of the decaying nucleus enters only through the level densities of the initial and final nucleus. We have also taken into account that the transmission coefficient depends on the deformation and, to a smaller degree, on the collective rotation of a nucleus.

Properties of excited nuclei in thermal equilibrium are of great physical interest. We consider excitation energies below some 500 MeV, where we may still describe the nucleus as a system of neutrons and protons which interact-s by effective forces. All the information on the physical state of hot nuclei is then to be obtained from a careful study of their decay by emission of neutrons, protons, and alpha−particles and their decay by fission.

## 6. NUCLEAR COLLECTIVE CORRELATIONS

The many-body correlations which were discussed in the previous sections significantly influence the collective phenomena in nuclei. Several problems related to collective correlations appear and they demand further studies. Here, especially interesting are the following topics:

- coupling of collective pairing and quadrupole vibrations,
- giant resonances of various types and multipolarities,
- modernized approach to the collective motion and its Hamiltonian.

In the following we present a more detailed discussion of the above problems.

### 6.1. COUPLING OF COLLECTIVE PAIRING AND QUADRUPOLE VIBRATIONS

The generalized microscopic Bohr Hamiltonian was used to describe the lowest collective levels of well deformed and transitional nuclei. The collective Hamiltonian contains new terms which describe the dynamical coupling of the pairing degrees of freedom with the quadrupole deformation. Our calculations have shown that such a model is very successful in the reproductions of the lowest ($I < 10$) collective states and electromagnetic transitions between them. Our investigations which have given very promising results for the rare-earth and light deformed nuclei were extended during the last years to the regions of actinide and superheavy nuclei. At present we study the coupling of the mean pairing field with the high spin rotation in the heaviest nuclei. Preliminary result shows that this effect significantly approaches theoretical estimates to the experimental data [9,13,23,43−45,53,76].

### 6.2. QUADRUPOLE EXCITATIONS OF NUCLEI IN THE RELATIVISTIC MEAN-FIELD THEORY

Using the self-consistent relativistic mean field theory we have evaluated the inertial functions and the collective potential for the quadrupole vibrations of even-even nuclei. Such investigation is very important when one wants to describe the excited states of nuclei far from stability, where the extrapolation of the usual macroscopic + microscopic + cranking models is rather uncertain. The first results obtained within this approach are very promising [176].

### 6.3. COLLECTIVE CORRELATIONS IN THE GROUND STATE OF NUCLEI

One can construct the collective Hamiltonian from the potential energy function with the zero−point vibration term and the mass parameters obtained within the cranking model as well as the generator coordinate method (GCM+GOA).

The calculations were performed for the well known nuclei in order to fix the parameters of the models. The obtained results for the atomic masses, the mean square radii and their isotopic shifts, as well as on the electric quadrupole moment $Q_2$ and the reduced transition probabilities B(E2) values and positions of the lowest excited states of nuclei were compared to the newest experimental data. We have applied the model to nuclei far from $\beta$-stability line (close to the proton and neutron drip lines) and from the superheavy region [13,23,70,71,97].

### 6.4. NEW PARAMETRIZATIONS OF NUCLEAR INTERACTIONS

Several proposals related to the new parametrizations have been formulated. They fall into the category of extensions and improvements of the existing and rather well established microscopic methods. This will allow, first of all, to make a progress in our understanding of the exotic nuclei and various exotic multi-fermion configurations that such nuclei are expected to produce.

In order to obtain a new and/or an improved parametrization of the effective nuclear interactions several standard calculations should be done. This task is very important but rather tedious and work-consuming. It demands several repetitive calculations of the nuclear properties in the ground- and low-lying excited states by using the following algorithms/techniques:

- potential energy surfaces evaluation and finding the equilibrium deformations,
- calculation of the mean-square charge radii (MSR) and $Q_{20}$ in the equilibria [6].

The calculation is performed on the basis of the microscopic, both non-selfconsistent and self-consistent methods. We feel that an interesting and important progress in the fine tuning of the nuclear Hamiltonians can be achieved by addressing in this context the experimental information about relatively less explored nuclear features:

- proton and neutron (proton vs. neutron) density distributions,
- neutron halo effect.

In particular variants of the microscopic-macroscopic method basing on the most realistic macroscopic models have already been advanced, see e.g. the Lublin Strasbourg Drop (LSD) model [36]. The single particle problem could be solved, depending on the particular context, with various average field Hamiltonians by employing either the newest version of the Yukawa-folded, Woods-Saxon or derived from the Dirac equation Hamiltonians. Of course it is not our intention to repeat the same work with the alternative models. We are rather going to concentrate the effort on optimizing one effective, realistic Hamiltonian that could serve at the same time to describe the single-nucleonic properties throughout the periodic table including the exotic nuclei.

It is particularly worthwhile at present to revisit the Skyrme-type parametrization of the effective nuclear forces within the self-consistent Hartree-Fock formalism [117]. The new possibilities are related to the exploration of the time-odd terms in the corresponding effective Hamiltonian and verification of the proposed improvements by using the large high-spin data bank available at present [146]. These interesting new data have been obtained during several years within various international collaboration projects and more recently from the top level projects such as EUROGAM or the US project GAMMASPHERE.

We intend to improve the average field parametrizations of the Woods-Saxon or Yukawa-folded type potentials. This can be done by taking into account all the available data on the single particle-binding energies, the relative order of the (quasi-) particle levels, the root-mean-square radii, the measured equilibrium deformations as well as the information available about fission isomers. This first step will allow us to accumulate and critically approach the existing experimental information.

The main ingredient of nearly all microscopic theories, the usual effective interactions, must be reviewed to be successful also near the neutron drip lines. Some progress have been recently made within the zero-range Skyrme interaction with the new set of parameters obtained by E. Chabanat and co-workers[8]. It is our intention to extend these efforts in order to obtain the highest standard effective force that can be acquired nowadays by using all empirical information available today (and totally unavailable when some of those concepts had been introduced several years ago).

The Gogny and Skyrme effective interactions will be used to extract the shell effects in proton and neutron density distributions in nuclei and to evaluate a new macroscopic formula for the nuclear energy [184].

## 7. NON-STANDARD PHYSICS OF EXOTIC PROCESSES AND NUCLEAR STRUCTURE

The Standard Model (SM) of electroweak and strong interactions cannot be considered as a complete and ultimate theory. Large number of free para-

[8] E. Chabanat, P. Bonche, P. Haensel, J. Meyer, R. Schaeffer, Nucl. Phys. **A635**, 231 (1998)

meters (> 15), three independent coupling constants and three independent gauge groups indicate a more general theory broken down to what we see by symmetry violations at low energy. Neutrinos are described as massless fermions, whereas there is stronger and stronger experimental evidence contradicting this assumption. At present there are five independent indications of finite neutrino masses:

− solar neutrino problem,

− atmospheric neutrino problem, supported by the Super−Kamiokande experiment,

− neutrinos as candidates for hot dark matter.

Also the anomalous data from the lepton−hadron colliders (HERA experiments H1 and ZEUS) can be analysed in the terms of new physics beyond the Standard Model.

To make progress in this field one has to look for observables that could give indication of physics beyond the SM. Here the nucleus constitutes a very useful laboratory where the fundamental conservation laws can be tested. The advantage of the nucleus is to have a wide spectrum of different initial and final states for transitions and reactions. These states can be chosen in such a way that the transitions are forbidden without violation of symmetries or that such a violation produces an appreciable different observables like the angular distribution of the electrons in the beta decay.

Specifically the double beta decay and *R*−parity violating supersymmetric (SUSY) processes are subjects of wide interest. From the non-observability of the neutrinoless mode of the double beta decay one can deduce limits of the non−standard model parameters, like the structure of the neutrino mass matrix or scale of left−right symmetry breaking what could confirm or rule out some Grand Unified Theory (GUT) scenarios. The currently running experiments, like the Heidelberg−Moscow collaboration can push the neutrino mass searches into the sub-eV range. But while an experimental limits on the half-life of the neutrinoless mode of the double beta decay is free from theoretical assumptions, the limit on the neutrino mass is not. It depends strongly on nuclear structure theory. Therefore, one of the more important aims of future researches is connected with the development of reliable nuclear models for such phenomena. Then one will be able to calculate the necessary nuclear matrix elements and to test the theory on other well measured processes, like two−neutrino double beta decay or double charge exchange (DCX) with low−energy pions. The last reaction is essentially a two−nucleon sequential process, proceeding via nonanalog routes showing thus strong dependence on nucleon−nucleon correlations. Recently the idea of a $d'$ dibaryon, a new exotic particle, has been proposed with connection to the reaction mechanism.

The disadvantage of testing fundamental symmetries in nuclei is that one has to solve the nuclear many-body problem reliably. So, in addition to calculating the observables, for example connected with the neutrinoless double beta decay, one has to calculate also other observables with the same wave functions. These observables have to be well measured and reproduced by the wave functions which one later needs for calculating the transition probabilities for neutrinoless double beta decay. Thus one has to develop methods for solving the nuclear problem and to test them for experimentally known observables to be sure that the quantities calculated for testing the SM are reliable.

### 7.1. NEUTRINOLESS DOUBLE BETA DECAY

The study of the nuclear double beta decay is a subject of the current intensive activity, both experimental and theoretical [2,12,32,33,59,60,90]. The neutrinoless mode of this process of the double beta decay with emission of two electrons only is related to physics beyond the Standard Model. It requires the existence of the lepton number violating massive Majorana neutrinos and/or right-handed current admixture to the standard $V - A$ weak interaction. The other possibility is to extend the SM to the Minimal Supersymmetric Standard Model (MSSM).

From the explicit dependence of the neutrinoless double beta decay transition probability one can deduce immediately that the transition depends on different nuclear matrix elements, which have to be calculated reliably if we expect reliable limits on the nonstandard physics parameters like the electron neutrino mass, the mixing angle between the vector bosons mediating left− and right−handed weak interactions and the mass ratio of these bosons.

### 7.2. DOUBLE CHARGE EXCHANGE REACTION WITH PIONS

It has been found that the observed low−energy DCX cross–section are in strong discrepancy with the predictions based on various nuclear models. Also the strong forward peaking of the cross−section at the pion kinetic energy remains in contrast with calculation results [50].

A new model of the above processes based on proton–neutron Quasiparticle Random Phase Approximation (pnQRPA) with realistic two–nucleon forces generated by one–boson exchange potential of Bonn type has been developed by Lublin–Tuebingen collaboration. This model has already been successfully used to describe two-neutrino double beta decay in heavier nuclei and at the same time the DCX reaction due to similar nuclear structure aspects of both processes.

### 7.3. CURRENT AND FUTURE RESEARCHES

One of the main subject of the future researches is to generalize existing procedures and develop new approximations used in description of many-body nuclear wave-functions which will than be applied in searches of the neutrinoless double beta decay, cold dark matter and the double charge exchange with pions. In other words, one expects to achieve reasonable description of finite many–body nuclear system via some extension of the Quasiparticle Random Phase Approximation in a way which will help to considerably enhance the understanding of such complex system [50].

The following topics are the potential subjects of interest:

− The application of the usual QRPA to charge–changing modes was used by several authors to investigate beta + decay in heavier nuclei, to double charge exchange reactions and double beta decay. Most of such calculations have shown that nuclear matrix elements of the above mentioned processes are sensitive to the particle–particle interaction. On the other hand, comparison between the pnQRPA and exact shell–model indicates that usual QRPA could not reproduce shell–model results without adjusting the parameters in the pnQRPA equation. Attempts to improve the QRPA results by developing projected QRPA or extend it by involving proton–neutron pairing could be of some importance in this context. Also inclusion of the so–called higher order corrections to the QRPA or new modes of excitations (*B*–modes) could offer a satisfactory solution to difficulties connected with the sensitivity of QRPA upon the particle–particle interaction strength. However, while applying all such corrections and approximation one should keep in mind that many particle excitations are obviously missing in the normal pnQRPA. Also the Pauli exclusion principle increasingly is violated by the growing ground state correlations. Thus the so–called renormalized version of the QRPA method should be applied. It has been shown recently that the method reduces the dependence of the calculated matrix elements or cross sections on the strength of the particle−particle interaction. On the other hand the self−consistency between the description of the ground state and the excited states is broken in this approach. One should develop a self−consistent version of the QRPA taking also the ground−state correlations into account. It is clear as well that the QRPA equation of motion corresponds exactly to the full many-body Schrodinger equation if and only if the ground state in the equation of motion is the true ground state and a phonon creation operator exhausts the whole Hilbert space, e.g. all excitations: lp(article)−lh(ole), 2p−2h, 3p−3h, and so on. Till now only one-particle−one-hole creation and destruction operators have been used.

− One is going to use such tested nuclear many-body wave functions to calculate nuclear matrix elements in the neutrinoless double beta decay and SUSY/CDM searches, and to deduce limits on nonstandard physics parameters: the mass of Majorana light electron neutrino, the mass of right-handed vector boson, the mixing angle between left- and right-handed vector bosons, the *R*−parity breaking constant and the strength of neutralino interaction with nuclear matter.

− These wave functions can be also used in description of the DCX reaction with pions. Improvements of the model of the reaction can involve:

The full and consistent treatment of the neutral pion propagation between reaction vertices in the *s*-wave sequential mechanism. The formalism, based on the *S*−matrix approach has been already developed.

Taking into account distortion and absorption effects of pions, both incoming/outgoing and intermediate. The wave functions of the charged pions should be taken as a solutions of the Klein−Gordon equation with the pion−nucleus optical potential with phenomenological parameters fitted to pionic single charge exchange and scattering data. The necessary modifications of the model have been outlined in, extended and applied in some cases. Medium modifications of neutral pion propagation between two nucleons has been studied — accommodation of these results is not straightforward and some approximations should be developed. As previously, these effects should result in reduction of the cross-section above $T_\pi$ = 50MeV giving more resonance-like shape of the cross-section vs. energy curve.

The answer to the still opened question of how far the DCX processes are influenced by the isobaric degrees of freedom of the nucleon. Delta isobars are supposed to pre−exist in the ground state of the nucleus or can be virtually excited by an incoming pion, giving rise to other mechanisms than the conventional two−nucleon route. Apart from the fact that they start to play the main role for the pion kinetic energies around 100 MeV, they can give some contribution in the low−energy region too.

− We plan the extension of the neutrinoless double beta decay description to the framework of MSSM with supersymmetry breaking mediated by gravitational interactions (SUGRA). When confronted with the last communications of Super−Kamiokande and LSND collaborations it makes this version of MSSM an extremely interesting framework for the studies of the neutrinoless double beta decay. Such an approach allows to obtain limits on the super-symmetry breaking parameters, using standard (motivated by supergravity theories) technique of unification of proper supersymmetric parameters at the GUT scale, followed by renormalization group evolution (RGE) to the weak scale.

The next task is connected with the recently developed idea of supersymme-try breaking mediated by gauge interactions. In these models, the technique of finding low−scale SUSY parameters is different: the mechanism of gauge mediation sets the values of scalar masses at the so called Messenger scale $M$, reducing huge, in the case of gravity−mediated MSSM, number of free parameters, and, after RGE evolution, effecting with interesting phenomenology of low−energy world. Moreover, it has been found that limits on $R$−parity breaking by trilinear (not bilinear LH) terms in gauge mediated model coming from non−observability of the neutrinoless double beta decay in $^{76}$Ge are much stronger than in the usual MSSM. We propose to extend the studies to the case of bilinear term, with bigger sample of nuclei and improved nuclear part of calculations.

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