NUCLEAR STRUCTURE FAR FROM STABILITY

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Several aspects of the structure of exotic nuclei are discussed. Some problems interesting for the experimental investigations are considered.

Introduction

The structure of nuclei removed from stability is not the first question which arises in the investigations of the properties of the exotic nuclei. First of all they must be produced and information on their masses, life-times and decay modes should be obtained. When we discuss a structure of a nucleus we have in mind, in fact, its excited states. Among them the more interesting are the softest modes which are manifested in the properties of the low-lying states.

In the previous years an evolution of the structure of nuclei with the excitation energy and the angular momentum have been investigated and the interesting results including multiphonon states, shape coexistence, band crossing, superdeformation phenomenon and others have been obtained. With radioactive beams a new “coordinate”, namely, Z/N ratio is introduced into consideration.

Below are considered the following effects which are related to the structure of nuclei removed from stability and discussed in publications:

-Medium effects;

- Prolate-oblate phase transition;
- Pseudospin symmetry and the structure of the very heavy nuclei;
- F-spin symmetry.

Medium effect

Starting from the two-body nucleon-nucleon interaction as determined from the scattering data all kinds of correlations caused by the presence of more nucleons around, i.e., the so called medium effect, will show up and make a picture quickly complicated. Effective mass of a nucleon is one of the manifestations of the medium effect. A decrease of the effective mass compare to the bare nucleon mass can lead to the central depression of the nuclear density which can influence on the spin-orbit interaction and therefore the magic numbers. It can be explained classically since a nucleon with a given kinetic energy (potential energy inside a nucleus can be considered approximately as a constant) is more likely to be found in a region with a larger effective mass than in a region with a smaller effective mass because of the lower velocity. These effect strengths a polarization related to the occupation of the high-j orbits which are located in a nuclear surface.

An appearance of a deep at the center of a nucleus decreases a binding of the single-particle states with small orbital momenta and influences on the spin-orbit interaction which is proportional to the radial derivative of the average nuclear potential. The radial dependence of the nuclear average potential mainly follows to the radial dependence of the nuclear density. This effect has been investigated in [1]. It was shown that the radial dependence of the nucleon effective mass influences significantly on the single-particle level scheme of both protons and neutrons. For instance a gap between the proton single-particle states $1i_{11/2}$ and $2f_{5/2}$ increases. As a result Z=120 becomes a magic number. The source of the significant radial dependence of the nucleon effective mass can be a presence in the Dirac equation for a nucleon not only of the scalar but also of the vector potential.

Prolate-oblate phase transition

It is well known that the stable well deformed nuclei have a prolate shape. However, a question arises: is it a property inherent to nuclei or the reason is a relation between the numbers of protons and neutrons in the stable deformed nuclei? Will we find both prolate and oblate nuclei would we have more possibilities in variation of the Z to N ratio. The calculations performed in [2] have shown that increasing the number of neutrons in the isotopes of Yb, Hf, W and Os we can obtain a transition from prolate to oblate nuclear shapes. According to the results of calculations this transition takes place when the number of neutrons is equal to 116. At this number of neutrons the calculated energies of the second excited 2^+ state have a minimum.

Pseudospin symmetry in the structure of the very heavy nuclei

The spherical shell model single-particle orbits having quantum numbers (n,l,j=l+1/2) and (n-1,l+2,j=l+3/2) have been observed in the relatively stable heavy nuclei to be quasidegenerate. This doublet structure was expressed in terms of the pseudospin and pseudoorbital momentum. Then it was shown that pseudospin symmetry exists in deformed nuclei as well and this fact has been used to explain some features of the well deformed and superdeformed nuclei.

It was shown by the calculations that the pseudospin symmetry improves as the binding energies of the single-particle states decrease. This condition is realized in exotic nuclei removed from the valley of stability. Thus, the low-lying states in nuclei with Z>100 are interesting objects for studing a manifestation of the pseudospin symmetry.

It is known that the structure of γ-phonons is mainly exhausted by a rather small number of the two-quasiparticle components. Due to this fact the energy of the γ-vibrational state can be strongly influenced by the presence of the low-energy two-quasiparticle state with $K^{\pi}=2^+$. This happens if near the Fermi level are located two nearly lying single-particle states having the same parity and $\Delta K=2$. Such closely lying single-particle states can be the members of the pseudospin doublet. The calculations performed in [3] have shown that for all considered isotopes of Cf, Fm, No and Rf the energy of the

$\gamma -$vibrational state takes its minimum in nuclei with the number of neutrons equal to 156. It was shown in addition that if the number of neutrons approaches the value N=156 a contribution of the neutron two-quasiparticle component 3/2[622]×1/2[620] to the wave function of the γ-vibrational one-phonon state becomes the largest one. It happens because at N=156 and $\beta_2=0.26$ the neutron Fermi level is located between the single-particle states $3/2^+$[622] and $1/2^+$[620]. However, these single-particle states are the members of the pseudospin doublet [521]. Small splitting of these states will mean that the pseudospin symmetry is approximately preserved. Thus, the experimental observation or not observation of the minimum of the energy of the γ-vibrational one-phonon state at N=156 is important for studying a manifestation of the pseudospin symmetry in very heavy exotic nuclei.

Possible other manifestations of the pseudospin symmetry [4] can be investigated also. Several calculations have shown that in odd Lr and Md isotopes the ground or one of the low-lying states is $1/2^-$[521]. This state is a pseudospin singlet. The rotational band based on this state has a very interesting structure: it consists of a singlet as the band head and a sequence of the weakly splitted doublets ($3/2^-$,$5/2^-$), ($7/2^-$,$9/2^-$), ($11/2^-$,$13/2^-$),…

It was shown also in some calculations that the pseudospin doublet $3/2^-$[512] and $1/2^-$[510] can appear at rather low excitation energies in the isotopes of the element with Z=111. In this case the excitation spectrum of the low-lying states will consists of the sequence of doublets and will be similar to that observed in ^{187}Os$_{111}$.

F-spin symmetry

A guideline to the structure of nuclei in the weakly excited states is given by the Interacting Boson Model (IBM). This model indicates on a strong influence on the properties of the low-lying nuclear states of the total number of the valence nucleons. This fact gives some grounds to expect an analogy in the properties of different nuclei with the same total number of the valence nucleons but with different numbers of protons and neutrons. This is related to the so called F-spin symmetry.

The concept of F-spin was introduced by A.Arima, F.Iachello, T.Otsuka and I.Talmi in the framework of the proton-neutron Interacting Boson Model (IBM-2). The F-spin is the analog of the isospin for bosons. A boson has F=1/2 and the projection +1/2 and -1/2 for proton or neutron boson respectively. If the value of the F-spin is a good quantum number then nuclei with the same value of the F-spin, i.e., with the same sum of the total numbers of the valence protons N_P and neutrons N_n but with different values of $(N_P - N_n)$ should have a similar spectra of the collective quadrupole excitations. Analysis of the properties of the low-lying states of the stable nuclei confirm this prediction. Thus, fixing the total number of the valence nucleons and varying Z to N ration we can check an applicability of the F-spin symmetry also to the exotic nuclei.

Later on it was shown by R.F.Casten and confirmed by the calculations in the IBM that the energy of the first 2^+ state is a decreasing function of the quantity $N_P \times N_n$. Consider from this point of view the experimental data on the energies of the first 2^+ states in nuclei with N~100. In a sequence of nuclei with the fixed number of neutrons and different numbers of protons we should have a minimum of the excitation energy of the first 2^+ state in the nucleus with the maximum number of the valence protons. From this we can determine or at least get an indication on the next proton magic number after Z=82.

For the isotones with N=150 the energy of the first 2^+ state has a minimum at Z=98. For the isotones with N=152 this minimum is also located at Z=98. In both cases for the larger values of Z the energy of the first 2^+ states increases. If the next proton magic number is Z=126 then the energy of the first 2^+ state should has a minimum at Z=104. If the next magic proton number is Z=120 – the minimum should be at Z=100, 102. If the magic number of protons is Z=114 the minimum of the energy of the first 2^+ state should be at Z=98. Thus the experimental data on the energies of the first 2^+ states indicate on Z=114 as the next proton magic number. Although, the differences in the considered energies are not large. The experimental data on the energies of the first 2^+ states in other nuclei with Z>100 are very desirable.

References

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