

Quadrupole-collective isovector excitations of stable and radioactive nuclei

I. Nuclear structure research in Bulgaria and Europe

This project is in the field of experimental nuclear physics – nuclear structure research. The primary objective of this scientific field is to understand the atomic nucleus as a quantum many-body system which constituents' neutron and protons are Fermi particles. The properties of this system are governed by the interplay between the electromagnetic, weak and strong interactions. In this respect the atomic nucleus is a unique quantum laboratory where many quantum effects can be identified and studied. The experimental determinations of the properties of the atomic nucleus and their theoretical modeling have great implications for understanding of other quantum systems. The longstanding questions which are central for the nuclear structure research are: What are the limits of existence of nuclei? How does the nuclear force depend on varying proton-to-neutron ratios? How to explain collective phenomena from individual particle motion? How are complex nuclei built from their basic constituents?

All the attempts to answer comprehensively to these questions have lead to surprises and new challenges. This is especially true for the experimental part of the nuclear structure research which strongly depends on the technological developments in accelerator physics and detector technology. In recent years progress made in production of radioactive ion beams (RIBs) spurred revival of interest in low spin nuclear structure studies, opening up many new opportunities to investigate nuclei unreachable before. To meet this situation and to preserve the European leadership in the field of nuclear structure research several large scale European facilities were proposed to be built and will become operational very soon. Such facilities are the international “Facility for Antiproton and Ion Research (FAIR)” at the GSI, Darmstadt (Germany), SPIRAL II, GANIL (France), the upgrade of REX-ISOLDE (High Intensity and Energy ISOLDE “HIE-ISOLDE”) at CERN and the project AGATA, a 4π array of highly segmented Ge detectors for γ -ray detection and tracking and in no so distant future EURISOL, a high-power, high-intensity linear accelerator facility for the production of radioactive beams.

The nuclear structure research in Bulgaria has a longstanding tradition which can be traced back to the pioneering studies of Prof. Karamihailova in 20's of last century. In the modern times, Prof. W. Andrejtscheff and Prof. I.Zh. Petkov established world-wide recognized schools in experimental and theoretical nuclear physics, respectively. Nowadays, world class nuclear structure research is conducted at the Faculty of Physics of the Sofia University St. Kliment Ohridski and at the Institute of Nuclear Research and Nuclear Energy at the Bulgarian academy of science. Our group at the University of Sofia is relatively young but at the same time is known in the international nuclear structure community. Our previous studies were conducted in collaborations with other groups from Europe and USA. These studies have been concentrated on the nuclear symmetries, the nuclear collectivity and the properties of high-spin states. Recently, we have also become involved in studies with RIBs.

In the present project we propose to investigate the properties of the quadrupole-collective isovector excitations of stable and radioactive nuclei. These exotic nuclear excitations reflect the coexistence and the interplay between the main aspects of nuclear structure – the nuclear collectivity, the shell structure, and the isospin degrees of freedom. Detailed investigations of these states in stable nuclei in different mass regions became possible in last few years. ***No such states have ever been identified in radioactive nuclei.*** To close this gap in knowledge new experimental techniques and methods have to be developed and employed. Herewith, we seek funding which will enable us to carry out this fundamental research and to become a reliable and vital group in the European nuclear structure research community.

II. Research environment

The current project will enable the Nuclear Structure Group at Sofia University to participate actively in contemporary nuclear physics studies, performed at large European and American laboratories. The group members will participate in all of the proposed experiments, assuming responsibilities for preparing the experiments, carrying out the actual experimental work, analyzing the data, working with students and publishing the results. The financial independence of the group will allow us to act as an equal partner to the other European research groups. The importance of the physics questions addressed in the project together with the experimental challenges will lead to an international recognition of our group.

Sofia University “St. Kliment Ohridski” is the first Bulgarian university. It has always been and still is the largest state university – *a national center for higher education, scientific research and culture.*

The university offers majors at all three levels of education and manages the most advanced research in the fields of the social and humanitarian sciences (liberal arts) and the so-called hard sciences such as physics and mathematics. There are sixteen faculties, three teaching centers and numerous research centers and laboratories. For the academic 2007/2008 year the distribution of the students flow is as follows: overall number of students in the three levels – 25 060; students in Bachelor’s programs – 18 235; students in Master’s programs – 4 656; students in Doctoral programs – 829; foreign students – 1 340.

Sofia University employs the best specialists, lecturers and researchers in both the hard sciences and the humanities. At present it employs 1 651 full-time lecturers. Two of the employees are academicians; four are corresponding members of the Bulgarian Academy of Sciences; two hundred and fifteen are full professors, six hundred and twenty-three - associate professors, four hundred and seventy-nine - senior assistant professors; one hundred and ninety-three – assistant professors and one hundred and forty-one - junior assistant professors. Eighty hundred and twenty-nine of the teaching staff holds Doctoral degrees and one hundred and fifty three are Dr. Habil.

Sofia University “St. Kliment Ohridski” is the leading university in South- Eastern Europe. It is comparable in quality and achievements to all major European universities – with its research developments, both theoretical and applied, scientific achievements, national influence, international relations, number of students and faculty, library and information services, all material conditions for teaching and studying, the professional realization of its alumni and in all other academic respects.

In the conditions of its growing independence and its autonomy and uniqueness as a national higher education institution for the education and “production” of highly qualified human resources, the University will keep exerting great efforts to maintain and further enhance the quality and value of its scientific and educational activities. Sofia University “St. Kliment Ohridski” has taken on its shoulders the binding responsibility to conduct high quality scientific research, to launch successful and fruitful fundamental theoretical research projects and applied projects, which will provide the necessary mutually beneficial interaction among education, science, technological development and innovational policies. On a par with the Bulgarian Academy of Sciences, Sofia University “St. Kliment Ohridski”, has established itself as a national center, a generator of science contributing beyond comparison to the Bulgarian participation in the world advancement of science and education.

The Faculty of Physics and Mathematics was founded in 1904. The Faculty of Physics separated as an independent structure in 1963. Among its founders was Prof. Karamihailova, a former

Rutherford's associate, who also was the founder of experimental nuclear physics research in Bulgaria in 1923. The Faculty of Physics is the main national centre for education in the field of physics in all three degrees (bachelor, master and PhD). It consists of 13 departments. The department of Atomic physics educates students and conducts research in the fields of Nuclear physics, High energy and particle physics, Radiation protection, Atomic physics, and Medical physics. The department maintains the following certified laboratories - Nuclear Physics laboratory, Dosimetry and Radiation protection laboratory, Nuclear structure laboratory, Nuclear electronics laboratory.

The Nuclear structure laboratory has been renewed in the last few years partially through the support from the Bulgarian National Science Fund under contract VUF 06/05. At present the laboratory has all the necessary computing infrastructure which allows for planning of experiments and analyzing large data sets. The Nuclear structure group consists out three permanent members (one Associate Professor, one Head Assistant Professor and one Senior Assistant Professor), two master students as one of them is expected to become a PhD student in the autumn of 2008 and three undergraduate students. The permanent members of the group have rich international experience. We have participated in many experiments at large European and American laboratories – REX-ISOLDE (CERN), GSI (Germany), LN Legnaro (Italy), IReS (France), Yale University (USA), Argonne National Laboratory (USA) and Oak Ridge National Laboratory (USA). The principal investigator Dr. Georgi Rainovski have been a spokesperson on two large experiments one with EUROBALL IV at IReS, France, and one with Gammaphysics at Argonne National Laboratory, USA. Dr. Miroslav Danchev has led two experiments on magnetic moments measurements at Oak Ridge national laboratory, USA. He is one of the world experts in using Recoil in vacuum technique for magnetic moment measurements. Dr. Kalin Gladnishki has participated in many experiments at REX-ISOLDE (CERN) and GSI (Germany). His expertise is in the lifetime measurements using plunger techniques.

III. Project description

i. Introduction – proton-neutron mixed symmetry states as a unique quantum system

Atomic nuclei are examples of mesoscopic two-fluid quantum systems. The physics of these systems is determined by three main properties: the many-body aspect, the quantum nature, and the two-fluid character. Nuclear phenomena that reflect these three properties are collectivity, shell structure, and the isospin degrees of freedom.

Despite the long decades of investigation of nuclear collectivity there are still several astonishing aspects which are not well understood. Among them is the microscopic nature of Quadrupole-collective isovector valence-shell excitations, so-called **mixed-symmetry states (MSSs)** [1,2], which reveal the mutual balance and the interplay between collective, single-particle and isospin degrees of freedom. *The main aim of the present proposal is to investigate in details the properties of the MSSs in stable nuclei and to expand search for MSSs to radioactive nuclei. This will extend the current knowledge to new, still unexplored regions of nuclear chart and possibly will provide for deeper understanding of the mesoscopic two-fluid quantum systems.*

Of particular importance for understanding the dynamics of the nuclear system are those nuclear phenomena which reflect the mutual balance and interplay between the nuclear collectivity, the shell structures, and the isospin degree of freedom. The proton-neutron MSSs [1,2] are the best studied examples of this class of phenomena. A special type of MSS, the 1^+ scissors mode, was first discovered in nuclei [3] and subsequently found or suggested to exist in Bose-Einstein condensates [4] and metallic clusters [5]. In this respect, the impact of a deeper understanding of the structure of these states is beyond the field of nuclear physics.

States with proton-neutron mixed symmetry have first been defined in the framework of IBM-2 [1]. There the concept of proton-neutron mixed symmetry is formalized by the F -spin quantum number [6], which is the isospin analogue for bosons. Within this concept the fully symmetric states have $F=F_{max}=(N_\pi+N_\nu)/2$ ($N_{\pi,\nu}$ denote the proton/neutron boson numbers), while MSSs are those states with $F=F_{max}-1$ [6]. In other words, the F -spin quantum number counts the number of protons and neutrons pairs which are in phase. As we noted already, the IBM-2 states with maximum F -spin quantum number are called Full Symmetry States (FSSs). All other basic states with good F -spin quantum numbers $F < F_{max}$ are called MSSs. The F -spin is an approximate quantum number for low-lying collective states of heavy nuclei. The lowest states in a given nucleus are those formed by the fully symmetric states with the quantum number $F = F_{max}$. The (approximate) validity of the F -spin limit is supported by the sheer fact that the IBM-1 successfully describes many properties of the lowest-lying states of heavy open-shell nuclei and that MI transitions between such states are observed to be small on an absolute, single-particle scale. With little modifications due to symmetry restrictions, the MSSs in the IBM-2 repeat the multiplet structure observed for the FSSs albeit at higher energy and with different decay properties. The energy difference between the FS and MS states with the same phonon number is determined by the size of the Majorana interaction in the IBM-2 [1].

The most distinct feature of MSSs (those with $F = F_{max} - 1$) is the existence of allowed F -vector ($\Delta F = 1$) MI transitions to symmetric states. This is of importance because the MI transitions are forbidden between FSSs and can, thus, very well serve as a unique signature for MSSs. Since the relevant difference of boson g -factors, $g_\pi - g_\nu$, can be expected to be of the order of the orbital value for protons, $1 \mu_N$, one can expect the allowed MI matrix elements to be roughly of that size too. Analogously, it can be shown that the $E2$ transitions between FSSs are proportional to $(e_\pi N_\pi + e_\nu N_\nu)^2$, and $E2$ transitions between MSSs and FSSs are proportional to the expression $(e_\pi - e_\nu)^2 N_\pi N_\nu$

[7]. The proportionality factors depend on the structures of the wave functions that are involved in a given transition and typically can be analytically calculated only in the dynamical symmetry limits [7].

The fundamental MSS in weakly collective vibrational nuclei, is the one-quadrupole phonon $2^+_{1,ms}$ state [1] which is the first isovector quadrupole excitation in the valence shell. Its close relation to the 2^+_1 state is evident in the Q -phonon scheme for MSSs [8], where the wave functions of the one-quadrupole phonon excitations are well approximated by the expressions:

$$\begin{aligned} |2^+_1 \rangle &\propto [Q_\pi + Q_\nu] |0^+_1 \rangle \equiv Q_s |0^+_1 \rangle & F &= F_{max} \\ |2^+_{1,ms} \rangle &\propto [(Q_\pi/N_\pi) - (Q_\nu/N_\nu)] |0^+_1 \rangle \equiv Q_m |0^+_1 \rangle & F &= F_{max-1} \end{aligned}$$

where $Q_{\pi,\nu}$ denote the proton and neutron quadrupole operators and $|0^+_1 \rangle$ is the ground state of a collective even-even nucleus. Analogously the two-phonon FS and MSSs are given by:

$$\begin{aligned} |2^+_2 \rangle &\propto Q_s Q_s |0^+_1 \rangle & F &= F_{max} \\ |1^+_{ms} \rangle &= |1^+_{sc} \rangle \propto [Q_s Q_m]^{(1)} |0^+_1 \rangle & F &= F_{max-1} \\ |3^+_{ms} \rangle &\propto [Q_s Q_m]^{(3)} |0^+_1 \rangle & F &= F_{max-1} \\ |2^+_{2,ms} \rangle &\propto [Q_s Q_m]^{(2)} |0^+_1 \rangle & F &= F_{max-1} \end{aligned}$$

Within the framework of this model the following signature for one- and two-phonon MSSs in vibrational nuclei can be expected:

- The one-phonon $2^+_{1,ms}$ state should be the lowest-lying MSS.
- This $2^+_{1,ms}$ state should decay to the 2^+_1 by a strong MI transition with an absolute matrix element of about $1 \mu_N$.
- Since the $2^+_{1,ms}$ state is a one-phonon excitation it should have collective $E2$ matrix elements to the ground state for both, protons and neutrons, however, with opposite signs, which might lead to partial cancellation in the total $\langle 0^+ || E2 || 2^+_{1,ms} \rangle$ matrix element. We, thus, expect a small-to-weakly-collective $E2$ transition strength (\leq a few W.u.) from the $2^+_{1,ms}$ state to the ground state.
- Two-phonon MSSs should decay by a collective $E2$ transition to the one-phonon $2^+_{1,ms}$ state with an $E2$ strength comparable to that of the $2^+_1 \rightarrow 0^+_1$ transition.
- Two-phonon MSSs should decay by a strong MI transition to the symmetric two-phonon states with MI strengths comparable to that of the $2^+_{1,ms} \rightarrow 2^+_1$ transition, i.e., with a matrix element of about $1 \mu_N$.
- Two-phonon MSSs should decay to the symmetric 2^+_1 state by a weakly collective $E2$ transition comparable in strength to the $2^+_{1,ms} \rightarrow 0^+_1$ transition.
- All MSSs must be expected to be very short lived, typically a few hundred femtoseconds or less, because of the strong MI matrix elements and typical transition energies ≈ 1 MeV in vibrational nuclei.

From the above fingerprints it is obvious that the MSSs can be identified experimentally by their unique decay to the low-lying fully symmetric states [1,9]. This however, comprises a major experimental challenge because it requires full spectroscopic information, i.e. the spin-parities of these highly excited non-yrast states, their lifetimes and the branching and multipole mixing ratios of their γ -decay have to be determined. For more detailed insight in the structure of these states information on their magnetic moments is also necessary. Until recently obtaining all this information was possible for several stable nuclei only. ***No MSSs have ever been identified in unstable nuclei.***

ii. State-of-the-art and objectives

The main physics questions in the context of the research of the collective isovector valence-shell excitations (MSSs) can be summarized as follow:

- What is the influence of the underlying microscopic structure on the properties of these collective excitations?
- How do MSSs evolve with increase of nuclear deformation?
- How does the balance between the number of valence protons and neutrons influence the properties of the MSSs?
- What is the spin dependence of the excitation energies of the MSSs?

All these questions have been only partially studied, mostly because they require detailed experimental information on entire isotopic or isotonic chains. Until recently performing such study in a reasonable experimental time has been beyond the capabilities of the available experimental techniques.

Available information on MSSs of vibrational nuclei has recently been summarized in a review article [9]. The best examples of MSSs in stable nuclei are found in the mass $A \approx 90$ region [9–18]. Among them the clearest case of multi-phonon MS structure has been found in ^{94}Mo [15–18]. There are only few MSSs identified in the mass $A \approx 130$ region [19–21]. The main reason for this comes from the fact that the stable opened-shell nuclei in this region have relatively low abundance. Apparently, in order to investigate MSSs, new experimental methods, in particular, those that could potentially be applied to radioactive isotopes are needed. Recently, the principal investigator (PI) of the current project in collaboration with Prof. N. Pietralla (TU Darmstadt, Germany) has shown that the Coulomb excitation reactions can serve as a powerful tool to study MSSs [22].

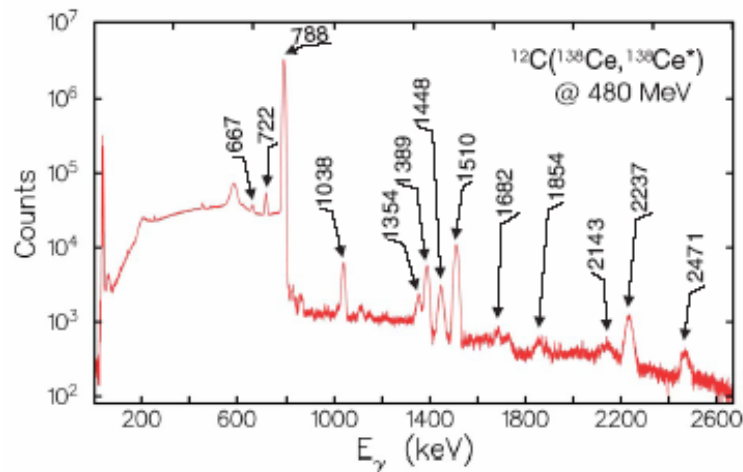


Fig. 1: Background-subtracted, Doppler corrected γ -ray spectrum of ^{138}Ce beam observed by our group with Gammasphere array after Coulomb excitation on a carbon target. (see Rainovski et al. [22]).

Using the Gammasphere Ge-detector array at Argonne National Laboratory near Chicago, U.S.A. we have studied the nucleus ^{138}Ce [22] in a Coulomb excitation reaction of ^{138}Ce beam on carbon target. This experimental technique can be straightforwardly applied to the Radioactive Ion Beams (RIBs). A sample spectrum from this experiment is shown in Fig. 1.

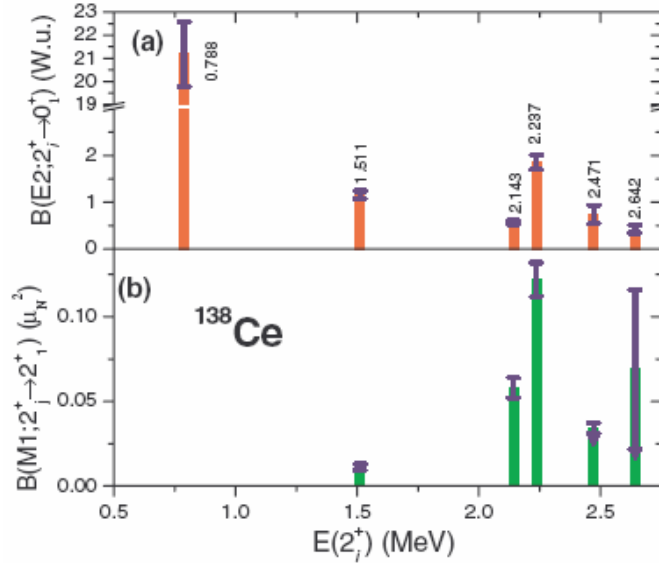


Fig. 2 (a) $E2$ and (b) $M1$ transition strength distributions for all observed 2^+ states below 2.7 MeV in ^{138}Ce . The arrows indicate upper limits (Rainovski et al. [22]).

The data yields the $E2$ and $M1$ strength distributions between low spin states (see Fig. 2) which reveals the $2^+_{1,\text{ms}}$ state in ^{138}Ce . In contrast to the neighboring even-even isotone ^{136}Ba , the $2^+_{1,\text{ms}}$ state in ^{138}Ce is strongly mixed with a nearby 2^+ fully symmetric state with a mixing matrix element of $V_{\text{mix}} = 44(3)$ keV first measured directly for a MSS.

The results for the ^{138}Ce [22] demonstrate not only a new experimental approach for investigation of the MSSs but also show that the microscopic structure can have a dramatic influence on the properties of these states. In fact, for low-collective vibrational nuclei the single-particle structure of the wave function can be the most important factor for preserving or fragmenting the MSSs. The observed mixing in ^{138}Ce is attributed to the lack of *shell stabilization* at the proton $g_{7/2}$ subshell closure. The evolution of the MSSs from ^{136}Ba to ^{138}Ce shows for *the first time* that the strength concentration of collective-isovector excitations in the valence shell reflects the underlying single-particle structure. This hypothesis has been recently confirmed in an extended microscopic calculations of the structures of the MSSs of the $N = 80$ isotones [23].

To elaborate further this conclusion and to quantify the mechanism of shell stabilization evolution of the MSSs along $N = 80$ isotones must be studied. There are only three stable nuclei in this isotonic chain ^{138}Ce , ^{136}Ba and ^{134}Xe , which only cover the transition from proton $g_{7/2}$ subshell closure to the proton $d_{5/2}$ subshell closure. Obviously, if we want to investigate the shell stabilization of MSSs we have to expand our investigation to unstable nuclei – ^{140}Nd , ^{142}Sm , ^{144}Gd , ^{146}Dy , ^{148}Er and ^{150}Yb . The identification of one-phonon $2^+_{1,\text{ms}}$ states in these nuclei should make transparent the shell stabilization of the MSSs (or the lack of it) in the proton $d_{5/2}$ (^{140}Nd , ^{142}Sm , ^{144}Gd , ^{146}Dy) and the proton $d_{3/2}$ (^{148}Er , ^{150}Yb) subshell closures. The different sizes of the subshells will allow for quantitative description of the shell stabilization.

The success of the ^{138}Ce experiment has initiated a new program at Argonne National Laboratory led by Prof. Norbert Pietralla (TU Darmstadt, Germany). Our group took an active part in this program. Within this program our search for MSSs was extended over the whole chain of stable even-even Xe isotopes together with data on ^{136}Ce . Within this study we have unambiguously identified the $2^+_{1,\text{ms}}$ state of ^{134}Xe [24] and we have shown that no MSS exists below 2.3 MeV in ^{124}Xe [25]. The rest of the experimental data on the isotopes from the Xe-chain are currently under analysis. The preliminary results show that the absolute $B(M1)$ strength of the one-phonon $2^+_{1,\text{ms}}$ mixed-symmetry state decreases with increasing of collectivity as the number of neutron decreases,

i.e. further from the closed shell $N=82$. At the same time the excitation energy of the one-phonon MSS increases. In fact, this behavior presents the evolution of the fundamental isovector collective excitations on the path from $U(5)$ to $O(6)$ limits of the IBM [7], *i.e.* with the transition from vibrational to gamma-soft quadrupole-collective structures. It is natural to expect that the same evolution also has to be observed in the barium isotopic chain. However, the available experimental data on MSSs in the barium isotopes are scarce. A pure MSS is identified in ^{136}Ba [21] which has two neutron holes in the $\nu h_{11/2}$ sub-shell and two proton holes in the $\pi g_{7/2}$ sub-shell. In ^{134}Ba [19], however the $2^+_{1,\text{ms}}$ is already slightly fragmented between two states at 2.029 MeV and 2.088 MeV. It seems that the behavior of the $B(M1)$ strength is similar to the Xe isotopes but this requires to be experimentally confirmed. On the other hand side, the variation in energy of the one-phonon $2^+_{1,\text{ms}}$ in ^{136}Ba and ^{134}Ba seems to be inversed in comparison to the Xe isotopic chain although the difference in energy between the $2^+_{1,\text{ms}}$ in ^{136}Ba and ^{134}Ba is smaller than 100 keV. Whether this behavior represents a real physical effect or it is just a fluctuation is unclear due to the lack of experimental information, especially for the MSSs of ^{132}Ba and ^{130}Ba . In this respect, experimental information on the evolution of the MSSs is urgently needed. Once available, it will allow the evolution in energy and the MI collectivity of the MSSs to be revealed within the Ba isotopic chain and compared with the Xe isotopic chain. Moreover, one could also see the influence of the proton degree of freedom on the MSSs in these two chains. The combination of these aspects in two different isotopic chains has never been experimentally investigated so far. This comparison has to provide the final answer to the question how do the MSSs evolve with the transition from vibrational to gamma-soft quadrupole-collective structures.

Another part of the question how the MSSs evolve with deformation is related to their evolution from vibrational to axially-symmetric quadrupole-collective structures. The chain of the stable Sm nuclei exhibits the best documented example of such shape changes from the $N = 82$ neutron shell closure toward mid-shell. The one-phonon $2^+_{1,\text{ms}}$ state of the $N = 86$ isotope ^{148}Sm has been identified in a photon-scattering experiment [26]. The nucleus ^{148}Sm is the heaviest nucleus for which an unambiguous identification of a $2^+_{1,\text{ms}}$ state from absolute MI transition rates have been made so far. From physics point of view Coulomb excitation reactions are equivalent to photon-scattering reactions with a difference that not real but virtual photons are exchanged between the target and the projectile. As we have already shown, the Coulomb excitation reactions allow for quick and reliable identification of the MSSs in an entire isotopic chain [24,25]. It is very promising to study the evolution of MSSs in Sm nuclei as a function of the quadrupole shape phase transition by using predominantly one-step Coulomb excitation for all open-shell stable Sm isotopes. The $2^+_{1,\text{ms}}$ states in these nuclei are expected to evolve from one-phonon state at about 2.1 MeV in vibrational nuclei to a member of the $K = 1$ rotational band build on scissors mode excitation in deformed nuclei as is sketched in Fig. 1 from Ref. [26]. More information on the details of that evolution would help to quantify the parameters of the Majorana operator of the IBM-2 [1].

As a result from the series of experiments on MSSs using Coulomb excitation reactions in inverse kinematics [22,24,25] performed in the last few years, huge amount of experimental data were collected. It has to be noted however that the data are not completely explored. We have shown that in many cases angular distribution of the emitted γ -rays can be determined [22,24]. We found that the experimentally determined distributions differ from the ones expected from the theoretical calculations using standard Coulomb excitation theory. This difference is attributed to hyperfine interaction between the nuclear magnetic moment and the atomic electrons when the projectiles emerge from target into vacuum. This hyperfine interaction leads to gradual decrease of initial alignment of nuclear spin and hence to the attenuation of γ -ray angular distribution [27]. This is the so-called Recoil-in-Vacuum effect. Recently, some of us (Dr. Miroslav Danchev) have shown that this effect can be used to determine nuclear magnetic moments in experiments with use of RIBs [28]. The same technique after some modifications can be applied to the already existing data from the experiments at Argonne National Laboratory. This potentially will allow for determination of

magnetic moments of MSSs. The magnetic moments are sensitive to the proton-neutron balance in the structure of the MSSs which finally leads to the phenomenon configuration isospin polarization (CIP) [29].

Besides the one-phonon $2^+_{1,ms}$ state, the lowest-energy 1^+_{ms} and 3^+_{ms} states are of utmost theoretical importance. Together, these three states completely specify the three parameters of the IBM-2 Majorana operator. Only two out of these three key states with mixed-symmetry character have been systematically investigated up to now. The 1^+_{ms} state is known as *MI* scissors mode in deformed nuclei. In vibrational nuclei the scissors mode appears as a vibrational two-phonon 1^+_{ms} state of mixed-symmetry character. A mixed-symmetry 3^+ state has firmly been identified on the basis of large absolute *MI* transition rates in one nucleus, only: the $N = 52$ nuclide ^{94}Mo . Its 3^+_{ms} state at 2965 keV was discovered [16] in a time consuming series of γ -ray spectroscopy experiments that involved angular correlation measurements following beta-decay, DSAM lifetime measurements in (α, n) reactions and neutron scattering reaction [9]. As we have mentioned already such time consuming approach is impractical for systematic investigations. A promising candidate for another 3^+_{ms} state has been proposed [30] at 2896 keV excitation energy in the $N = 52$ isotone ^{96}Ru on the basis of its decay pattern. Other credible candidates for a 3^+_{ms} state are unknown until now. The reason for this lack of knowledge on the important 3^+_{ms} state comes from the fact that unlike the 1^+_{ms} and $2^+_{1,ms}$ states a direct population path is missing. The 1^+_{ms} states can best be studied in predominantly dipole excitations-inducing photon scattering reactions. The $2^+_{1,ms}$ one-phonon states can best be studied in predominantly one-step quadrupole-excitations inducing reactions, such as Coulomb excitation with a light collision partner. Structure-sensitive population of the two-phonon 3^+_{ms} state requires a two-step excitation path. Establishing an appropriate method is highly desirable. Even more so, if this method could potentially be applied to beams of radioactive ions. Based on our successful method for identifying and investigating one-phonon $2^+_{1,ms}$ states in Coulomb excitation reactions in inverse kinematics on light targets, we plan to go a step further and use inverse kinematics Coulomb excitation reactions on medium-heavy targets for the population of two-phonon MSSs by two-step excitation paths predominantly through the one-phonon $2^+_{1,ms}$ state. As a first step, the influence of multi-step Coulomb excitation processes on the Coulomb excitation cross-section for reactions on a light targets has to be estimated. Most appropriately for such program is to begin by performing Coulomb excitation experiments of ^{94}Mo and ^{96}Ru beams on a carbon target. Results from these experiments will allow for determination of diagonal matrix elements of states involved in two-step Coulomb excitation population of the two-phonon mixed symmetry states. With this information available, the transition strengths of the decay of 3^+_{ms} states of ^{94}Mo and ^{96}Ru can be determined in Coulomb excitation reactions on medium-heavy targets, *i.e.* from multi-step Coulomb excitation reactions.

iii. Research plan and experimental methods

The present project is planned for a period of three years. Within that time a series of experiments will be planned, proposed and carried out at large European and American laboratories (IKP Cologne, GSI, Germany; LNL Italy; ANL, USA; REX-ISOLDE, CERN). The data analysis and dissemination of results will be carried out at the Nuclear Structure laboratory at Faculty of Physics, St. Kliment Ohridski, University of Sofia.

The project can be divided in four sub-tasks. Each sub-task addresses a specific physic question as described in the previous section. Each sub-task includes a series of experiments as outlined below:

- 1) Search for MSSs in unstable $N=80$ isotones – the main objective is to investigate the effect of shell stabilization of MSSs. The MSSs in unstable $N=80$ isotones ^{140}Nd , ^{142}Sm , ^{144}Gd , ^{146}Dy , ^{148}Er and ^{150}Yb will be identified using Coulomb excitation reaction in inverse kinematics. The program will start with a search for MSSs in ^{140}Nd and ^{142}Sm . If development in the experimental techniques allow latter on we will continue with the other nuclei. For each nucleus the search consists of three consecutive steps:
 - 1.1) Determination of the lifetimes of the first excited 2^+ states – in order to identify MSSs by using inverse kinematics Coulomb excitation reaction the strength of the $2^+_1 \rightarrow 0^+_1$ transition has be known with sufficiently high precision. However, for all nuclei of interest this information is missing. Therefore, before performing Coulomb excitation reactions with radioactive beams this important parameters have to be determined. These quantities for the nuclei of interest can be determined by lifetime measurements using plunger technique. Series of experiments for determination of the lifetime of the first 2^+ states will be planed, proposed and carried out at The Institut für Kernphysik (IKP) at the University of Cologne, Germany or National Laboratory Legnaro Italy.
 - 1.2) Identification of the one-phonon $2^+_{1,\text{ms}}$ states – the $2^+_{1,\text{ms}}$ states will be identified in inverse kinematics Coulomb excitation reactions at REX-ISOLDE (CERN). The Nuclei ^{140}Nd and ^{142}Sm already can be produced and are available as Radioactive ion beams (RIBs) with sufficiently high intensities at REX-ISOLDE (CERN). The experiments using inverse kinematics Coulomb excitation reactions do not require any special equipment and can be carried out using the MINIBALL array and the CD detector.
 - 1.3) Identification of multi-phonon MSSs – this experimental program will be possible when the upgrade of REX-ISOLDE, the HIE-ISOLDE becomes operational (expected 2008-2009). Then the energy of the delivered RIBs will be high enough (up to 5.4 MeV/n) to perform multi-step inverse kinematics Coulomb excitation reactions which could populate the multi-phonon states in the nuclei of interest. This stage presents a challenge which goes beyond the current experimental state-of-the-art and will require developing of new expertise and experience.
- 2) Search for multi-phonon MSS in the stable nuclei – the main objective is to investigate the possibility of using inverse kinematics Coulomb excitation reaction on medium-heavy targets for the population of two-phonon MSSs by two-step excitation paths, predominantly through the one-phonon $2^+_{1,\text{ms}}$ state. Developing a reliable method for population and study of the two-phonon MSSs is of utmost importance, especially for the 3^+_{ms} . Inverse kinematics Coulomb excitation reactions on medium-heavy targets seems to be promising candidate for such a method. However, it has not ever been used before for studying the MSSs and there

are several experimental obstacles which need to be addressed beforehand. This program will consist of three steps:

- 2.1) Estimation of effects of unknown quadrupole moments of $2^+_{1,ms}$ mixed-symmetry states on the Coulomb excitation yields – this can be quantified by measuring Coulomb excitation yields of the $2^+_{1,ms}$ mixed-symmetry states for which the lifetimes are known beforehand. The best candidates for such investigation are ^{94}Mo and ^{96}Ru . The one-phonon $2^+_{1,ms}$ mixed-symmetry state of ^{94}Mo is its 2^+_3 state at 2067 keV. The lifetime of this state and the branching ratio of its γ -decay are known with sufficiently high precision [18]. It decays by a strong $M1$ transition of $0.549(56) \mu^2_N$ to the 2^+_1 and by a weakly collective $E2$ transition of $2.20(32) \text{ Wu}$ to the ground state [18]. Furthermore, three two-phonon MSSs of ^{94}Mo are known, too: the 1^+_{ms} , the $2^+_{2,ms}$, and the 3^+_{ms} states at 3129 keV, 2870 keV, and 2965 keV, respectively. A partial level scheme of ^{94}Mo , showing the known mixed symmetry states and the fully symmetric states whose $E2$ matrix elements could be thought of having an impact on the Coulomb excitation population of the $2^+_{1,ms}$ state, is presented in Fig. 3. The figure also shows the corresponding structure of the neighboring even-even isotope ^{96}Ru .

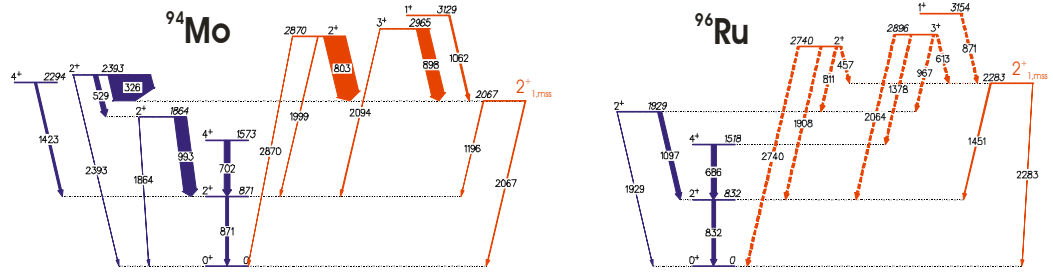


Fig. 3: Partial low-spin level schemes of ^{94}Mo and ^{96}Ru showing the known mixed symmetry states (red) and the fully symmetric states (blue) whose $E2$ matrix elements may influence the Coulomb excitation population of the $2^+_{1,ms}$ states. Only the strong $E2$ transitions which determine the Coulomb excitation populations are drawn. The width of the arrows is proportional to their $B(E2)$ strength in W.u. [18,30]. The dashed arrows represent transitions for which the transition strength is not known.

It is obvious from Fig. 3 that in a predominantly one-step Coulomb excitation reaction on a light target the $2^+_{1,ms}$ state will be the second most populated state because this is the only excited low-spin state above the 2^+_1 state which is connected to the ground state via a matrix element which corresponds to a transition strength higher than 1 W.u.. The calculated Coulomb excitation cross-sections [31] for low-spin states in ^{94}Mo for the $^{12}\text{C}(^{94}\text{Mo}, ^{94}\text{Mo}^*)$ reaction at 258 MeV beam energy show that due to their weak population and small matrix elements to the MS structure, the other low-spin excited states in ^{94}Mo have no influence on the Coulomb excitation population of the $2^+_{1,ms}$ state. In this way, the only unknown parameter which determines the Coulomb excitation population of the $2^+_{1,ms}$ state in ^{94}Mo is its relative quadrupole moment with respect to the quadrupole moment of the 2^+_1 state. The estimated [31] effect from the quadrupole moments of the 2^+_1 and the $2^+_{1,ms}$ states on cross-sections for the Coulomb excitation reaction $^{12}\text{C}(^{94}\text{Mo}, ^{94}\text{Mo}^*)$ at 258 MeV is in the range of 3% to 5%. If the relative yield of $2^+_{1,ms}$ state in ^{94}Mo is measured with precision better than 1% then the size and the sign of its quadrupole moment can be determined. In our previous experiments [22] we have already shown that the necessary precision can be achieved by using large detector arrays such as Gammasphere at Argonne National Laboratory, USA.

The pattern of the low-spin states in ^{96}Ru is quite similar to the one of ^{94}Mo although the experimental information is not as rich [10,30] (see Fig. 3). The one-phonon $2^+_{1,\text{ms}}$ state is identified at 2283 keV in a Coulomb excitation reaction [10]. It decays to the ground state by a weakly collective E2 transition of 1.6(3) W.u. [10] and to the 2^+_1 state by a strong M1 transition of 0.78(23) μ^2_{N} . Like in ^{94}Mo the Coulomb excitation population of $2^+_{1,\text{ms}}$ state of ^{96}Ru is determined by one-step excitation from the ground state and again the only unknown parameters are the quadrupole moments of the 2^+_1 and the $2^+_{1,\text{ms}}$ states. The estimated [31] effect from the quadrupole moments of the 2^+_1 and the $2^+_{1,\text{ms}}$ states on cross sections for the Coulomb excitation reaction $^{12}\text{C}(^{96}\text{Ru}, ^{96}\text{Ru}^*)$ at 258 MeV is again in the range of 3% to 5%.

Based on the above consideration experiments for determination of the quadrupole moments of the 2^+_1 and the $2^+_{1,\text{ms}}$ states in ^{94}Mo and ^{96}Ru will be planned, proposed and carried out at Argonne National laboratory, USA.

- 2.2) Inverse-kinematics two-step Coulomb excitation of two-phonon mixed-symmetry states of ^{94}Mo and ^{96}Ru – once the effects of the unknown quadrupole moments on the Coulomb excitation yields are estimated we plan to continue with experiments on medium-heavy targets for the population of two-phonon MSSs by two-step excitation Coulomb excitation reactions. The population of the two-phonon MS states can be estimated from the properties of the known two phonon MS states in ^{94}Mo (see Fig. 3). The cross sections for populating the $2^+_{2,\text{ms}}$ and the 3^+_{ms} in the $^{90}\text{Zr}(^{94}\text{Mo}, ^{94}\text{Mo}^*)$ reaction at 354 MeV are calculated [31] by using the known E2 strengths of their decays [10,18]. The results are $\sigma(2^+_{2,\text{ms}}) = 1.97$ mb and $\sigma(3^+_{\text{ms}}) = 0.19$ mb. This leads to relative populations of the $2^+_{2,\text{ms}}$ and the 3^+_{ms} states with respect to the population of the 2^+_1 state of 1.28×10^{-3} and 1.29×10^{-4} , respectively. Levels populated to such an extent can be observed within a beam time of as short as 1 day and their population can be measured precisely as we have demonstrated in our recent experiments [22]. Note, that the duration of the ^{138}Ce experiment was 14 hours and the cross section for the 2^+_1 state was about a factor of 15 lower compared to the proposed reactions on a ^{90}Zr target.

There are no data for absolute transition strengths for the decays of the two-phonon mixed-symmetry states of ^{96}Ru . These states of ^{96}Ru are proposed on the basis of their branching ratios [30]. Following the analogy between ^{94}Mo and ^{96}Ru , it is reasonable to expect that the two-phonon $2^+_{2,\text{ms}}$ and the 3^+_{ms} states of ^{96}Ru will be populated in the $^{90}\text{Zr}(^{96}\text{Ru}, ^{96}\text{Ru}^*)$ reaction with cross sections similar to the ones for the analogous states in ^{94}Mo . If this is the case, then we will be able to determine absolute transition strengths of their decay. If successful, the multiple-step Coulomb excitation reactions might be established as a new tool to study two-phonon mixed-symmetry states which potentially can open up a new field for the future.

Based on the above consideration an experiments will be planed, proposed and carried out at Argonne National Laboratory, USA.

- 2.3) Inverse-kinematics two-step Coulomb excitation of two-phonon mixed-symmetry states in radioactive nuclei – if the experiments described above are successful the accumulated knowledge and experience will be used in our experiments at REX-ISOLDE (CERN) which are described in 1.3).

3) Study the evolution of MSSs with deformation – this part of the project aims to investigate the evolution along the path from spherical to axially-deformed nuclei ($U(5)$ -to- $SU(3)$ transition in the IBA[8]) and along the path from spherical to γ -soft nuclei ($U(5)$ -to- $O(6)$ transition in the IBA[8]). In this respect it consists of two independent tasks:

3.1) Evolution of the one-phonon mixed-symmetry $2^+_{1,ms}$ state in the spherically-to-axially-deformed shape transition in Sm isotopes – the stable Sm isotopes lie exactly on the transition path of interest including a nucleus at the phase transitional point X(5) [32] – ^{152}Sm . An experiments using inverse kinematics Coulomb excitation reaction on beams of stable $^{148,150,152,154}\text{Sm}$ ions impinging on a carbon target at energies of 85% of the respective Coulomb barriers will be planed, proposed and carried out at Argonne National Laboratory, USA. The one-phonon $2^+_{1,ms}$ states will be identified from the $2^+_i \rightarrow 2^+_1$ MI strength distributions and from $0^+_1 \rightarrow 2^+_i$ $E2$ strength distributions. This experiment is an exact analog of our successful ^{138}Ce experiment [22].

3.2) Evolution of one-phonon mixed-symmetry $2^+_{1,ms}$ states in Ba isotopes – an experiment to study MSSs of $^{130,132}\text{Ba}$ will be planed, proposed and carried out at Argonne National Laboratory, USA. The experiment is an exact analog of the experiment described above and of our successful ^{138}Ce experiment [22]. It will clarify whether the evolution of mixed-symmetry states observed in the Xe chain [24,25] is a generic one.

4) Developing methods for determination of magnetic moments of the MSSs – determination of nuclear g-factors with the recoil in vacuum method (RIV) is based on a measurement of the magnitude of the attenuation of the γ -ray angular distribution. The Coulomb excitation reaction creates an anisotropic distribution of nuclear spin of the populated state. When individual nucleus emerge from target into vacuum the nuclear magnetic moment start to precess around the vector resultant \vec{F} of the nuclear spin \vec{I} and total electron angular momentum \vec{J} . Since the \vec{J} vectors of different nuclei from nuclear ensemble are randomly oriented in space, this precession leads to a gradual decrease of the initial nuclear spin alignment and hence to the attenuation of the measured angular distribution of the γ rays. The angular distribution function at time t from the population of the nuclear state is given by:

$$W(\theta, t) = \sum_{k=0,2,4} A_k Q_k G_k(t) P_k(\cos \theta)$$

where A_k are angular distribution coefficients, Q_k is a factor accounting for the finite angle of Ge detectors, $G_k(t)$ are the time dependent attenuating factors resulting from hyperfine interaction. A_k coefficients depend only on multipolarity of the transition and the statistical tensor of nuclear state, and thus can be calculated with the Winther de Boer Coulomb excitation code. $G_k(t)$ coefficients depend on strength of the hyperfine interaction and the g-factor of the nuclear state. A detailed theoretical description of hyperfine interaction and the relation between $G_k(t)$ and the g-factor of the nuclear state is very difficult since it requires knowledge of occupied electronic states and their lifetime. In the simple case of electronic configuration of spin \vec{J} , which produces magnetic field B at the nucleus, time dependent coefficients are given by:

$$G_k(t) = \sum_{F,F'} C_{IJ}^{FF'}(k) \cos(\omega_{FF'} t)$$

where

$$C_{IJ}^{FF'}(k) = \frac{(2F+1)(2F'+1)}{2J+1} \begin{Bmatrix} F & F' & k \\ I & I & J \end{Bmatrix}^2 \quad \text{and} \quad \omega_{FF'} = g \frac{\mu_N}{\hbar} B \frac{F(F+1) - F'(F'+1)}{2J}$$

The experiments provisioned in our scientific plan would determine the time integral attenuation factors only, which are:

$$G_k = \frac{1}{\tau} \int_0^{\infty} G_k(t) e^{-t/\tau} dt$$

where τ is the lifetime of the measured nuclear state. For an ensemble of many ions with a wide distribution of electron configuration the attenuation coefficients are given by

$$G_k = \sum_i w_i G_k^i$$

where G_k^i are deorientation coefficients for ion in the state i and w_i is the fraction of ions in that state. For many electron ions the hyperfine interaction is so complex that calculation of G_k from first principles is not possible. It was shown in [33] that with a very good approximation this sum can be written as:

$$G_k = \alpha_k + (1 - \alpha_k) \frac{1}{1 + |\Gamma_k| \tau}$$

where Γ_k is directly proportional to the g factor and Γ_k and α_k should be treated as independent parameters. The practical approach to this is to find an isotope of the nucleus of interest with known g-factors and to calibrate the interaction [28,33,34]. We already have data for low lying states of all stable Xe and $^{136,138}\text{Ce}$ isotopes taken with Gammasphere multi detector array. These data can be used to extract g- factors of the first and second 2^+ states. In order to calibrate hyperfine interaction we plan to use the chain of stable Ba isotopes which have known g- factors and lifetimes for the first 2^+ states. The experiments will be conducted at ANL, USA. If these measurements are successful we plan to measure also the g factors of first 2^+ state and the MSS of ^{140}Nd and ^{142}Sm RIBs. As a first step lifetimes of these states need to be measured. These nuclei lie far from Ba isotopes, so the Ba calibration of hyperfine field might not be adequate. In that case additional calibratory experiment with stable Nd isotopes will be performed. This experiment is provisioned to be carried out at UNILAC, GSI, Germany.

iv. Expected results

The main scientific results which may be expected to be obtained in the framework of the current project can be generalized in the following four points:

- 1) The effect of the shell stabilization of the MSSs will be experimentally investigated in the chain of $N = 80$ isotones by identifying the MSSs in unstable nuclei. This study can lead to the first identification of MSSs in unstable nuclei. If the behavior of MSSs in these nuclei is in accordance to what is expected from the effect of shell stabilization we will have experimental proof for existence of collective quantum states which are sensitive to the underlying subshell structure.
- 2) The evolution of the MSSs with deformation on both the transitions from vibrational to gamma-soft nuclei [$U(5)$ to $O(6)$] and from spherical vibrators to axially-symmetric rotors [$U(5)$ - $SO(3)$] will be revealed.
- 3) New experimental methods for identification of two-phonon MSSs will be developed and applied to stable and radioactive nuclei.
- 4) New experimental methods for determination of the magnetic moments of highly excited, none-yrast states will be developed and applied to stable and radioactive nuclei. If successful this development will allow the study of the phenomenon configuration isospin polarization (CIP) [29] of the MSSs in both $A = 90$ and $A = 140$ mass regions.

The results are expected to be published in international refereed journals and to be presented on international conferences and workshops. In average 2 to 3 peer-reviewed articles can be expected from each point, specified above. The results will also be used to plan future experiments, including experiments with radioactive beams and with the new European γ -ray array AGATA. It also can be expected that the proposed studies will result in 2 to 3 bachelor and master degree theses and one PhD thesis.

v. Undergraduate and Graduate Student Involvement

Beyond its scientific merits the project makes a broader impact. It advances future discoveries and understandings in nuclear physics by promoting the education and training of undergraduate and graduate students at the Sofia University. Students will be involved at all stages of the project. The goal is to attract students by offering them the opportunity to work on real scientific problems, to participate in experiments at large European laboratories and to work with advanced instruments and equipment. The opportunity to use world-class facilities and to contribute to the frontier research will help them to build the professional skills necessary either for their scientific career or work in industry. The students will use the results for their PhD, MSc and Bachelor theses. This project plays an important role in the process of accomplishing this task.

Ms. Asiya Dikova and Mr. Angel Givechev are master student at the Sofia University. Mr. Givechev is expected to graduate in the summer of 2008 and to continue his education as a PhD student. His research activities as a PhD student will be in the field of experimental nuclear physics as the results obtained within this project will comprise a major part of his PhD thesis. Ms. Asya Dikova is expected to graduate in summer of 2009. Her master thesis will be based entirely on results obtained in the framework of this project. She is also expected to continue her education as a PhD student.

Ms. Rositsa Topchiyska, Ms. Antoaneta Damyanova and Mr. Doycho Karagyozov are the youngest member of the research team. They are one of the most promising students in physics. Their participations and excellent achievements in number of national competitions prove their longstanding and steady interest in physics. If successful the current project will provide them with the option to work on the learning-by-doing basis in the highly competitive and mobile environment of the large European laboratories, which inevitably will facilitate their integration in the European academic society.

vi. International cooperation

The current project will be executed in a close collaboration with the Nuclear physics group from the TU Darmstadt, Germany led by Prof. Norbert Pietralla. The TU Darmstadt has outstanding infrastructure for nuclear structure research. The Institut für Kernphysik (IKP) operates the 130 MeV superconducting accelerator facility S-DALINAC. It represents the main instrument for the excellence program (Forschungsschwerpunkt) “radiation physics” of TU Darmstadt. Nuclear structure research at the IKP is funded by the DFG in the scope of the center of excellence (Sonderforschungsbereich) SFB 634 “*Nuclear structure, Nuclear Astrophysics and Fundamental Experiments at low Momentum transfer at the Superconducting Darmstadt Electron Accelerator (S-DALINAC)*”. The IKP has a scientific staff of about 25 scientists. The group led by Prof. Pietralla is well recognized all over the world as the leading group for research on proton-neutron mixed-symmetry structures.

The collaboration between our groups for the period 2006-2008 was partially supported by the Bulgarian National Science Fund under contract DAAD - 09. This close collaboration will continue in the future (see the letter from Prof. Pietralla) and it is an additional guarantee for successful execution and completion of the present project.

References

- [1] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).
- [2] N. LoIudice and F. Palumbo, Phys. Rev. Lett. **41**, 1532 (1978).
- [3] D. Bohle *et al.*, Phys. Lett. B **137**, 27 (1984).
- [4] O. M. Maragó *et al.*, Phys. Rev. Lett. **84**, 2056 (2000).
- [5] E. Lipparini and S. Stringari, Phys. Rev. Lett. **63**, 570 (1989).
V. O. Nesterenko *et al.*, Phys. Rev. Lett. **83**, 57 (1999).
- [6] T. Otsuka, A. Arima, F. Iachello, Nucl. Phys. **A309**, 1 (1978).
- [7] F. Iachello and P. Van Isacker, The Interacting Boson-Fermion Model, (Cambridge University Press, Cambridge, 1991).
- [8] K.H. Kim, T. Otsuka, P. von Brentano, A. Gelberg, P. Van Isacker, and R.F. Casten, in Capture Gamma-Ray Spectroscopy and Related Topics, edited by G. Molnár (Springer, Budapest, 1996), Vol. I, p. 195.
- [9] N. Pietralla, P. von Brentano, A.F. Lisetskiy, Prog. Part. Nucl. Phys. **60**, 225 (2008).
- [10] N. Pietralla *et al.*, Phys. Rev. C **64**, 031301 (2001).
- [11] V. Werner *et al.*, Phys. Lett. B **550**, 140 (2002).
- [12] S.W. Yates, J. Rad. Nucl. Chem. **265**, 291 (2005).
- [13] A. Giannatiempo *et al.*, Phys. Rev. C **44**, 1508 (1991).
- [14] D. Bandyopadhyay *et al.*, Phys. Rev. C **67**, 034319 (2003).
- [15] N. Pietralla *et al.*, Phys. Rev. Lett. **83**, 1303 (1999).
- [16] N. Pietralla *et al.*, Phys. Rev. Lett. **84**, 3775 (2000).
- [17] C. Fransen *et al.*, Phys. Lett. **B 508**, 219 (2001).
- [18] C. Fransen *et al.*, Phys. Rev. C **67**, 024307 (2003).
- [19] G. Molnár *et al.*, Phys. Rev. C **37**, 898 (1988).
B. Fazekas *et al.*, Nucl. Phys. **A548**, 249 (1992).
- [20] I. Wiedenhöver *et al.*, Phys. Rev. C **56**, R2354 (1997).
- [21] N. Pietralla *et al.*, Phys. Rev. C **58**, 796 (1998).
- [22] G. Rainovski *et al.*, Phys. Rev. Lett. **96**, 122501 (2006).
- [23] N. Lo Iudice, Ch. Stoyanov, D. Tarpanov, Phys. Rev. C **77**, 044310 (2008).
- [24] T. Ahn *et al.*, Phys. Rev. C 2008 (**submitted**).
- [25] G. Rainovski *et al.*, Phys. Rev. C 2008 (**submitted**).
- [26] T.C. Li, N. Pietralla *et al.*, Phys. Rev. C **71**, 044318 (2005).
- [27] G. Goldring, in *Heavy Ion Collisions*, edited by R. Bock (North-Holland, Amsterdam, 1982), Vol. 3, p. 484.
- [28] N.J. Stone, A.E. Stuchbery, M. Danchev *et al.*, Phys. Rev. Lett. **94**, 192501 (2005).
- [29] J.D. Holt, N. Pietralla, J.W. Holt, T.T.S. Kuo, G. Rainovski, Phys. Rev. C **76**, 034325 (2007).
- [30] H. Klein *et al.*, Phys. Rev. C **65**, 044315 (2001).
- [31] H. Ower, J. Gerl, H. Scheit, computer program CLX.
- [32] F. Iachello, Phys. Rev. Lett. **87**, 052502 (2001).
- [33] A.E. Stuchbery and N.J. Stone, Phys. Rev. C **76**, 034307 (2007).
- [34] M. Danchev *et al.*, Nucl. Instr. and Methods **B241**, 971 (2005).

IV. Sustainable development of the group after completion of the project

The proposed research plan includes experiments which are on verge of the possible for the contemporary nuclear structure facilities and experimental techniques. If successful the project will provide not only answers to important physics questions but also will develop expertise and experience at the Nuclear Structure group at Sofia University which can straightforwardly be applied at the next generation nuclear structure facilities which are expected to become operational approximately at the time when this project ends. Such facilities are the international “Facility for Antiproton and Ion Research (FAIR)” at the GSI, Darmstadt (Germany), SPIRAL II, Ganil (France), the up-grade of REX-ISOLDE (High Intensity and Energy ISOLDE “HIE-ISOLDE”) at CERN and the AGATA project, a 4π array of highly segmented Ge detectors for γ -ray detection and tracking and in a distant future EURISOL, a high-power, high-intensity linear accelerator facility for production of radioactive beams. In fact, the current project ensures a smooth transition in the development of the group’s expertise towards next generation nuclear structure facilities.

The physics questions addressed in the current project will also remain actual for the next decade. The question how the nuclear collectivity in general and the MSSs in particular, evolve for nuclei with high neutron excess is not clear. This question cannot be studied now, but with next generation nuclear structure facilities will be possible.

Another important part concerning the sustainable development of the group is related to the fact that the current project will engage young people in real scientific research. Due to economical situation in Bulgaria in the last decade most of the students have to work part-time in order to support their study. Quite often they are employed on low-qualified jobs or jobs which are not related to their study. One of the purposes of the present project is to show that the commonly used European and American practice of involving students in real scientific work in exchange for a stipend can also be applied in Bulgarian universities. In such a way students will have the possibility simultaneously to support their study and acquire higher qualification by participating in real research activities on learning-by-doing basis. The advantages for the students are obvious: 1) Efficiently distributing their time to receive the knowledge for which they come for to the university; 2) Acquiring good professional working habits highly useful either for research or industry; 3) opportunities to get in touch and to adapt to the highly competitive and mobile environment which is typical for the European research community; 4) Learning how to work in team, how to tackle the projects and to meet deadlines; 5) Being guided trough their studies. The applicability of this model is also of utmost importance for the Nuclear Structure group because it inevitably will raise the interest among students and will allow us to attract the most talented of them.

V. Dissemination of the results

The results from the project are expected to be published in international refereed journals. In average 2 to 3 peer-reviewed articles can be expected from each point, specified in subsection iv. The results will also be used to plan future experiments, including experiments with radioactive beams and with the new European γ -ray array AGATA which will require their presentation on International Program Advisory Committee meetings.

The results from the project will also be presented on international conferences. The students involved in the project will be strongly encouraged to present their own results obtained in the framework of the project on international conferences and schools.

In order to make the progress made on the project and the obtained results accessible for the general public we plan to launch a web of the project. The site will contain the description of the project, present status and the presentation from the monthly meetings of the group. All the presentation on conferences and workshops, abstracts and references to papers published in international journals will also be included. The site will also include information for the general public about the research in the field of nuclear structure physics, the large scale European nuclear structure facilities and the future research projects in which the group will be involved. In case of expressed interest the members of group will make popular presentations at high schools or other institutions.

VI. Project management

The current project consists of numerous tasks as described in section III. Each task will be assigned on a timely basis to a sub-group which will consist at least of one permanent member, one master or PhD student and one undergraduate student. The permanent member will supervise the execution of the task and will assume the full responsibilities for the quality of results. The principal investigator will coordinate the distribution of the tasks in a manner to ensure the progress in execution of project.

The progress of the project will be reviewed each month on a group meeting. The minutes of the meeting, the presentations concerning the progress on each sub-task will be published on the web site of the project. The group meetings will also be used for planning of travels for experiments, conferences etc. All the members of the group will participate in the planned experiments in order to provide the necessary man power.

The students involved in the project will be remunerated monthly on the basis of the actual working time spent on the project. This will be estimated openly on the group meetings. It is a responsibility of the principal investigator to ensure the engagement of the students with work on the project does not interfere with their lecture schedule. The permanent members of the group and the PhD students will be remunerated only after a successful completion of certain sub-task depending on the importance of this sub-task for the total progress on the project.