Nuclear shell structure and response toward the limits of mass, temperature and isospin

E. Litvinova*, B.A. Brown†, D.-L. Fang*,**, T. Marketin‡, P. Ring§, V.I. Tselyaev¶ and R.G.T. Zegers†,**

*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA
†Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA
**Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824-1321, USA
‡Physics Department, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia
§Physik-Department der Technischen Universität München, D-85748 Garching, Germany
¶Nuclear Physics Department, St. Petersburg State University, 198504 St. Petersburg, Russia

Abstract. We present a short overview of our recent theoretical developments aiming at the description of exotic nuclear phenomena to be reached and studied at the next-generation radioactive beam facilities. Applications to nuclear shell structure and response of nuclei at the limits of their existence, with a special focus on the physics cases of astrophysical importance, are discussed.

Keywords: nuclear shell structure, nuclear spin-isospin response, extended covariant density functional theory, particle-vibration coupling, coupling to single-particle continuum

PACS: 21.10.Pc, 21.60.Jz, 25.40.Lw, 27.60.+j, 21.30.Fe, 21.60.Cs, 24.30.Cz, 25.40.Kv, 24.10Jv

Last decades, low-energy nuclear physics has expanded considerably its domain due to the opportunities opened by rare isotope beam facilities of the new generation. In particular, the techniques of the isotope separation online and in-flight production have been implemented at the major low-energy nuclear physics facilities with great success: numerous experiments on synthesis of exotic nuclei and on studies of their dynamical properties have been performed. This has produced a strong catalyzing effect on theoretical developments toward finding a high-precision and highly universal solution of the nuclear many-body problem. In this contribution, we give a brief overview of our recent developments and applications to nuclear systems toward the limits of mass, isospin and temperature.

QUASIPARTICLE-VIBRATION COUPLING IN RELATIVISTIC FRAMEWORK: SHELL STRUCTURE OF SUPERHEAVY Z=120 ISOTOPES

We show how the shell structure of open-shell nuclei can be described in a fully self-consistent extension of the covariant energy density functional theory. The approach implies quasiparticle-vibration coupling (QVC) in the relativistic framework being an extension of the Ref. [1] for superfluid systems [2]. Medium-mass and heavy nuclei
represent Fermi-systems where single-particle and vibrational degrees of freedom are strongly coupled. Collective vibrations lead to shape oscillations of the mean nuclear potential and, therefore, modify the single-particle motion. As a result, single mean-field states split into levels occupied with fractional probabilities which correspond to spectroscopic factors of these fragments. The Dyson equation is formulated in the doubled quasiparticle space of Dirac spinors and solved numerically for nucleonic propagators in tin isotopes which represent the reference case: the obtained energies of the single-quasiparticle levels and their spectroscopic amplitudes are in excellent agreement with data, see Fig. 1(a). Because of high universality of the approach it can be applied to nuclei at the limits of their existence with respect to their proton and neutron numbers, for instance, to superheavy nuclei. Selected results on the single-quasiparticle strength distributions in the neutron and the proton subsystems of the Z = 120 isotopic chain are displayed in Fig. 1(b). One can see the evolution of these distributions with an increase of the neutron number from N = 172 to N = 184. The shell gap in the proton subsystems of the considered nuclei diminishes only little when the neutron number increases, so that the proton number Z = 120 remains a rather stable shell closure while the detailed structure of the proton levels shows some rearrangements induced by the neutron addition. In the neutron subsystems both pairing and QVC mechanisms are active and show a very delicate interplay: pairing correlations tend to increase the shell gap while the QVC alone tends to decrease it and at the same time causes the fragmentation of the states in the middle of the shell. As a result, in the presence of both mechanisms the gap in the neutron subsystem remains almost steady while the newly occupied levels jump down across the gap when the neutrons are added. Thus, in contrast to the pure mean field studies [3], no sharp neutron numbers appear as the candidates for the spherical shell closures in this region: the shell closures are delocalized.

**FIGURE 1.** (a) Single-quasiparticle spectrum of \(^{120}\text{Sn}\): Relativistic mean field (RMF, left column), QVC (center) and experimental data (right). In the 'QVC' and 'EXP' cases only the dominant levels are shown. (b) Single-quasiparticle strength distribution for the orbits around the Fermi surfaces in the neutron (left panels) and proton (right panels) subsystems of the Z=120 isotopes calculated in the relativistic quasiparticle-vibration coupling model. The dashed lines indicate the neutron chemical potentials.
SPIN-ISOSPIN RESPONSE OF NEUTRON-RICH NUCLEI

Although last decade the three major concepts in low-energy nuclear theory (i) ab-initio approaches, (ii) configuration interaction models (known also as shell-models) and (iii) density functional theory (DFT) have advanced considerably, they still have to be further developed to meet the requirements demanded by contemporary nuclear experiment and astrophysics. Furthermore, each of these concepts has principal limitations of their applicability in the nuclear physics domain. Fig. 2(a) shows an image of the nuclear chart taken from Ref. [4]. The areas of the nuclear landscape which can be described by each of the three theoretical concepts are outlined (here we focus on the spin-isospin nuclear properties, e.g., Gamow-Teller response).

The sectors of the nuclear landscape where the applicability areas of the different models overlap are of particular interest because within these sectors the models can constrain each other. Ab-initio models can replace the phenomenological input which is traditionally used in the shell-model with the microscopic effective interaction computed from the first principles. In turn, the shell model with its very advanced configuration interaction concept can guide the DFT-based developments beyond its standard random phase approximation. Thus, in contrast to considering different models as independently developing alternatives, we rather admit their complementarity which can be used for their further advancements.

FIGURE 2. (a) Chart of the nuclei [4] representing stable nuclei and nuclei found in nature (black), those produced and investigated in the laboratory (green) and theoretical limits of bound nuclei (yellow). The domain of ab-initio models is the lightest nuclei (blue outline), the configuration interaction approach is applicable in the pink areas and density functional theory covers the region outlined in green. (b) The Gamow-Teller strength distribution in neutron-rich $^{132}$Sn calculated within the various theories (see text for details): low-energy and total strength distributions (upper panels) and their cumulative sums (lower panels), respectively.

In Fig. 2(b) we present studies of the Gamow-Teller resonance (GTR) in $^{132}$Sn within the three theoretical concepts: (i) non-relativistic quasiparticle random phase approximation (QRPA) with realistic G-matrix interaction [5], (ii) covariant DFT-based relativistic random phase approximation (RRPA) and its extension to particle-hole⊗phonon configurations called relativistic time blocking approximation (RTBA) [6], and (iii) shell-model (SM) with the configuration interaction CI-jj7a truncated by the Tamm-Dancoff
proton-neutron phonon coupled to particle-hole core vibrations [7]. The gross and fine features of the GTR obtained within these models are compared, the advantages and drawbacks of the considered models are discussed. Based on such comparative studies, future directions are outlined for each of the above mentioned microscopic models [8]. Constraints on the many-body coupling schemes and underlying interactions from measurements at the future rare isotope facilities are anticipated.

FINITE-TEMPERATURE EFFECTS ON LOW-ENERGY NUCLEAR RESPONSE

Excitation energy is another characteristic of excited nuclei which imposes limitations of their existence and plays a very important role in astrophysical modeling. We consider the finite-temperature effect on the low-energy nuclear response known as upbend phenomenon, which was first reported in Ref. [9], later observed systematically in the $\gamma$-ray strength functions below neutron threshold of various light and medium-mass nuclei and probed by different experimental techniques [10]. Studies of Ref. [11] have revealed that this phenomenon, occurring in various astrophysical sites, can have a significant impact on their elemental abundances.

![Figure 3](image_url)

FIGURE 3. (a) The E1 $\gamma$-strength for the thermally excited state of $^{94}$Mo near the neutron separation energy (blue band), compared to the strength for the ground state (dash-dotted) and to Oslo data. (b) Schematic picture of the lowest-energy single-quasiparticle transitions from the thermally unblocked states with effective occupation probabilities $\tilde{n}(E)$ to the continuum.

We propose a microscopic approach for the radiative strength function which is based on the statistical description of an excited compound nucleus. The thermal mean field describes the nuclear excited states of the compound type very reasonably and, at the same time, it is simple enough to allow a straightforward generalization of very complicated microscopic approaches to nuclear response in terms of finite temperature corresponding to the nuclear excitation energy. To describe transitions from a thermally excited state, in the first approximation we employ the finite-temperature continuum QRPA developed in [12]. The two-quasiparticle propagator in nuclear medium is calculated in terms of the Matsubara temperature Green functions in the coordinate space. The continuum part of
this propagator is responsible for transitions from the thermally unblocked discrete spectrum states to the continuum. The radiative dipole strength function $f_{E1}$ is determined from the propagator in the standard way. Fig. 3(a) displays the $\gamma$-strength in $^{94}$Mo at the excitation energy around its neutron separation energy, that represents the case of radiative thermal neutron capture, compared to $\gamma$-strength in the ground state. The origin of the $\gamma$-strength upbend due to the transitions to the continuum is illustrated schematically in Fig. 3(b). The upbend appears as a typical feature of the $\gamma$-strength in medium mass nuclei while in heavy nuclei the strength is flat at $E_\gamma \to 0$ [13]. The obtained results have an important consequence for astrophysics, namely for the approaches to r-process nucleosynthesis: as shown in Ref. [11], the low-energy upbend in the $\gamma$-strength can give rise to a considerable enhancement of the neutron capture rates in neutron-rich nuclei and, consequently, influences the global abundance distribution.

Based on the obtained results, we expect further advancements of the theoretical approaches discussed in this contribution. The proposed developments on many-body coupling schemes and underlying interactions will need constraints from data on nuclei away from the valley of stability. Such data will be obtained in experiments performed at existing, and vastly enhanced capabilities presented by future rare isotope facilities.

REFERENCES

1. E. Litvinova and P. Ring, Phys. Rev. C 73, 044328 (2006).
2. E. Litvinova, Phys. Rev. C 85, 021303(R) (2012).
3. W. Zhang et al., Nucl. Phys. A 753, 106 (2005).
4. G.F. Bertsch, J. Phys.: Conf. Ser. 78, 012005 (2007).
5. J. Suhonen, T. Taigel and A. Faessler, Nucl. Phys. A 486, 91 (1988).
6. T. Marketin, E. Litvinova, D. Vretenar, and P. Ring, Phys. Lett. B 706, 477 (2012).
7. M. Horoi and B. A. Brown, Phys. Rev. Lett. 110, 222502 (2013).
8. D.-L. Fang, T. Marketin, B. A. Brown, E. Litvinova, and R. G. T. Zegers, in preparation.
9. A. Voinov et al., Phys. Rev. Lett. 93, 142504.
10. M. Wiedeking et al., Phys. Rev. Lett. 108, 162503.
11. A.C. Larsen and S. Gorieli, Phys. Rev. C 82, 014318 (2010).
12. E.V. Litvinova, S.P. Kamerdzhiev, and V.I. Tselyaev, Phys. Atomic Nuclei 66, 558 (2003).
13. E. Litvinova and N. Belov, arXiv:1302.4478.