Date: 10th March 2021

Research Statement

Tomohiro Oishi (toishi@phy.hr)

Keywords: nuclear theory; nuclear structure; energy-density functional (EDF) theory; covariant EDF (CEDF); Hartree-Fock-Bogoliubov (HFB) calculation; quasi-particle random-phase approximation (QRPA); time-dependent and open-quantum systems; radioactivity.

1 Summary of past research

I (TOMOHIRO OISHI) have been working on the theoretical and computational nuclear physics since 2010. I obtained Ph.D. in March 2014 in the Tohoku University (Sendai, Japan), under a supervision by Prof. Kouichi Hagino and Prof. Hiroyuki Sagawa: they are coauthors in papers [Oishi 2010, Oishi 2011, Maruyama 2012, Oishi 2014]. After obtaining my Ph.D., I had the post-doctoral experiences in Jyvaskyla (Finland), Padova (Italy), and Zagreb (Croatia). In my experiences, I have obtained the appropriate skills for scientific research, including the mathematical, physical, and computational ones, as well as the presentation abilities. Also, I have continuously published to appear my research achievements. I the following, I summarize the past activities and links with my research plan proposed.

Past research 1: CEDF approach to nuclear magnetic-dipole excitation

- Publication - Papers [Oishi 2020, Kruzic 2020] in the Bibliography after "(5) Research plan" section. Paper [Oishi 2019] based on the three-body model is also related with this topic.
- Background - I have worked for the development of the covariant (relativistic) energy-density functional theory under a supervision by Prof. Nils Paar in the University of Zagreb from September 2018. Covariant energy-density functional (CEDF) theory is one candidate to realize the universal theory for atomic nuclei whole in the chart of nuclides. For the achievement of this universal theory, there are several tasks and problems remain in the present CEDF framework. My researches have been devoted mainly to the relativistic description of the magnetic-dipole (M1) excitation of atomic nuclei and the corresponding improvement of the CEDF theory.
- Method - Self-consistent mean-field calculation based on the CEDF theory has been employed. The relativistic quasi-particle random-phase approximation (QRPA) has been implemented for the description of M1 excitation.
- Result and impact - With my colleagues, Prof. Nils Paar and Mr. Goran Kruzic, I have investigated the magnetic-dipole (M1) excitation, and its link with the model parameters in the CEDF theory [Oishi 2020, Kruzic 2020]. Our result shows that the M1 excitation is closely related with the nuclear spin-orbit splitting and so-called residual interaction, which originates from the one-pion exchange. The M1-experimental data can be a good reference to improve this CEDF-residual interaction. A strong sensitivity of the M1 mode to the nuclear-pairing correlation is concluded also. Our result can promote the further improvement of the CEDF theory within a collaboration of new experiments.
- Note - This work has been performed in my post-doctoral position in Zagreb (2018-present), which has been based on the fellowship with the financial resources of [1] "Structure and Dynamics of Exotic Femtosystems" (project ID: IP-2014-09-9159) by Croatian Science Foundation, and [2] "QuantiXLie Centre of Excellence" (project ID: KK. 01.1.1.01) by Croatian Government and European Union.
- Future plan - Based on the experience and products obtained in this project, I am aiming to extend the CEDF framework to the various interests. See the research plan for details.

Past research 2: Collective excitation based on the Skyrme meanfield calculation

- Publications - Papers [Oishi 2016, Oishi 2011].
- Background - Energy-density functional (EDF) theory has been one standard platform for the nuclear many-body problems. Based on the idea of EDF, the self-consistent mean-field calculation has been developed on the non-relativistic or relativistic EDF [Bender 2003, Dean 2003, Reinhard 1989, Vretenar 2005, Nakatsukasa 2016, Roca-Maza and Paar 2018, ?]. For an optimization of EDF parameters, the collective excitation can give the useful reference. The quasiparticle random-phase approximation (QRPA), within a framework of the EDF theory, has been a standard tool to access the nuclear collective excitation. However, the full description of various collective modes has not been completed. The traditional matrix QRPA has been numerically demanding especially for heavy and neutron-rich nuclei.
- Method - In paper [Oishi 2016], finite amplitude method (FAM) for the efficient QRPA calculation has been implemented into the self-consistent Hartree-Fock-Bogoliubov (HFB) code. The calculation was based on the non-relativistic nuclear EDF of the Skyrme type. For a large-scale and parallel computation, we utilized super computers in Finland and Japan.
- Result and impact - In paper [Oishi 2016], our FAM-QRPA scheme demonstrates a remarkable efficiency, which enables us to perform the systematic analysis of the giant-dipole resonance for heavy rare-earth nuclei. The experimental energy and width can be well reproduced with our FAM-QRPA. A role of the isovector effective mass, which is an important pseudo-observable quantity of the infinite nuclear matter, is discussed.

Past research 3: Time-dependent method for nucleon-emitting radioactive process

- Publication - Papers [Oishi 2010, Maruyama 2012, Oishi 2014, Oishi 2017, Oishi 2018-PRC, Oishi 2018-JPG]. Several awards and invited presentations were given as described in my list of publications.
- Background - Quantum time-dependent system or meta-stability is a basic concept to understand several dynamical processes of atomic nuclei. Two-proton (2p) emission is one of those processes with quantum tunneling with multi degrees of freedom. The connection between the 2p radioactivity and the nuclear-pairing interaction has attracted lots of interests.
- Method - We have developed a time-dependent (TD) three-body model for 2p-emitting nuclei. This method can provide an intuitive way to discuss the broad-resonance system, for which the multi-particle dynamics should be carefully taken into account.
- Result and impact - By applying the TD three-body model to 2p emission, we have found that 2p emission is controlled by the proton-proton pairing interaction, which is indispensable to explain the experimental data of energy and width. Also, the diproton correlation, where two protons are localized and coupled to the spin-singlet ($S_{12} = 0$) form, plays an essential role in the 2p emission: two protons are promoted to be emitted to the same direction at the same time. In my paper [Oishi 2018-PRC], the TD calculation was utilized to study the proton emission from the hypernucleus.
- Future plan - TD picture is essential to understand the nuclear dynamical processes. I am now planning to develop the TD-CEDF framework for some research targets [Nakatsukasa 2016, Bulgac 2012, Sekizawa 2016, Schuet 2016].

Other activities

I have presented several out-reaching articles as in the list of publications. As a peer reviewer, I have cooperated for several academic journals. As described in my CV, I have some teaching experiences. In my future research, if possible, I expect to employ the Ph.D. student and/or post-doctoral fellow. My research plan includes some objectives and tasks being suitable for their dissertaion and publications.

2 Research plan

2.1 Mission of research

- Development and implementation of the covariant (relativistic) energy-density functional framework enabling dynamical calculations for atomic nuclei;
- Its application to nucleon-emitting radioactivity and nuclear collective excitation;
- Inter-disciplinary collaborations with other fields, including astrophysics, high-energy physics, nuclear engineering, etc.

Dream of nuclear physics: universal theory of nuclear structure

Universal theory of nuclear structure has been one dream of nuclear physics since the first observation of atomic nuclei by Ernest Rutherford (UK) in 1911. This theory, when it will be completely established, is able to reproduce all the physical properties for arbitrary nuclei: those include the binding energy, excitation features, active mode(s) of radioactivity, lifetime, etc. However, even though lots of efforts have been devoted, the complete version of the universal theory is not established.

What is the main problem or difficulty against the realization of the universal theory? That indeed originates in the quantum-mechanical multi-body problem. Atomic nucleus is a quantum-mechanical, finite many-body system comprised of nucleons (protons and neutrons) [Ring and Schuck 1980]. Namely, the two parameters, (Z, N), are necessary to indicate one nuclide, where Z and N are the number of protons and neutrons, respectively. Their typical order is 10-100. By considering the possible combinations of (Z, N), approximately 2000-3000 nuclides have been experimentally measured until today. In addition, from the theoretical prediction, 6000-10000 nuclides are expected to exist. There are several unique features measured in atomic nuclei as listed below.

- For the composition of atomic nuclei, the strong, weak and electromagnetic fundamental interactions play an important role at the most profound level. The study of the atomic nucleus has been therefore crucial for elucidating the origin of matter (or nucleosynthesis processes), the tests of fundamental symmetries, and even for practical applications.
- How to understand the structure of nuclei is essentially an inter-disciplinary subject, since it applies to various fields of quantum physics such as condensed matter, atomic and molecular systems, quantum chromodynamics (QCD), hadron and particle phenomenology, etc.
- The radioactivity is one fundamental feature of atomic nuclei, and represents the indispensable, basement knowledge for the radioactive-material science, chemistry, nuclear engineering, nuclear-power generation, astronomy, etc. In terms of physics, the radioactivity is interpreted as a time-dependent, dynamical phenomenon controlled by the multi-nucleon interactions [Oishi 2014, Oishi 2017, Oishi 2018-PRC, Oishi 2018-JPG].

For such multi-body systems, the analytic solutions are not available in general. For computational solutions as alternative, however, this multi-body problem often requires impossible amount of resources. Therefore, the theoretical model of atomic nuclei with elegance and efficiency has been seriously demanded.

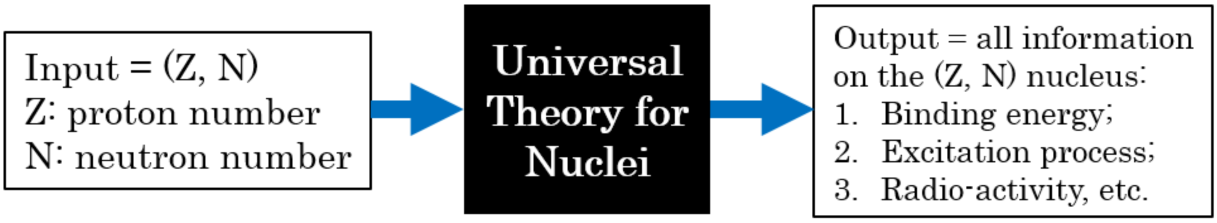


Figure 1: The universal theory for atomic nuclei.

Covariant energy-density functional (CEDF) theory

Toward the goal of the universal theory of nuclear structure, the CEDF theory is one of the best promising candidates. My proposal is based on the CEDF framework, and aims to improve that. This contribution may benefit the realization of the universal theory, even though it should be far in the future.

The energy-density functional (EDF) theory was originally invented by W. Kohn et. al. in order to compute the multi-electron systems [Kohn 1999]. This theory indeed enables us to compute the multi-electron energy and the corresponding state with a noticeable reduction of numerical costs. In the last decades, the EDF theory has been also applied to atomic nuclei as the multi-fermion systems. Its implementation has been done in the framework of the self-consistent mean-field calculations [Bender 2003, Dean 2003, Reinhard 1989, Vretenar 2005, Meng 2006].

In terms of the EDF theory, both the non-relativistic and relativistic EDFs have been utilized in the nuclear physics. Comparing these two versions, there have been some drawbacks in the relativistic one. First, in general, the relativistic formalism is more complicated. One spinor as nucleon must have 4 components, whereas it can reduce to 2 components in the non-relativistic formalism. In correspondence, the numerical implementation and cost become demanding for CEDF. Also, the relativistic EDF has not been optimized sufficiently, in contrast to, e.g. the frequently-used Skyrme-type EDF for non-relativistic mean-field calculations [Ring and Schuck 1980, Bender 2003, Dean 2003, Reinhard 1989, Vretenar 2005, Meng 2006]. For the collective-excitation phenomena, including the magnetic modes [Oishi 2020, Kruzic 2020], weak-decaying modes [Niksic 2005, Niu 2012], etc., the ambiguity in the CEDF parameters has prevented us from the accurate evaluation. Thanks to the recent progress in the theoretical and computational CEDF framework [Reinhard 1989, Vretenar 2005, Meng 2006, Niksic 2011], these problems are expected to be resolved.

Considering the future developments, which also relate to the high-energy, hadron, and/or astrophysics, it is appropriate to adopt the CEDF approach. The proposed research expects to utilize the following advantages in the relativistic framework:

- The original motivation of J. D. Walecka to introduce the relativistic nuclear theory was to evaluate the energy-momentum tensor, which is necessary as input to solve the Einstein equation of neutron stars [Walecka 1974]. This purpose needs the relativistic formalism. As a successful result by Walecka there, the repulsive core of the nuclear force in the high-density region can be naturally concluded [Walecka 1974, Boguta 1977];

- Spin-orbit level splitting, as one fundamental feature of atomic nuclei, can be naturally concluded from the CEDF. This ability is essential to investigate, e.g. the magnetic-dipole excitation [Oishi 2019, Oishi 2020];

- Meson-exchange picture of the nuclear interaction holds. When all the mesons and their coupling constants are determined, the CEDF theory becomes "close". Also, the time-even and time-odd parts of EDF can be treated in the unified framework [Vretenar 2005, Meng 2006]. These points can provide a substantial help to systematically optimize the model parameters of CEDF;

- Chiral symmetry originally from the quantum chromodynamics (QCD) can be smoothly plugged-in and discussed. Indeed, "how to bridge the QCD with various phenomena of nuclear systems" has been a serious problem in modern nuclear physics. The CEDF may provide one answer to this question;

- For the application to high-energy phenomena, the relativistic effect as well as the causality can be taken into account.

2.2 Research questions and/or hypotheses

The main interest in this research is the possibility of CEDF theory to explain the (i) nuclear collective excitation and (ii) radioactive processes. After researches in the past decades [Reinhard 1989, Vretenar 2005, Meng 2006], CEDF theory become one of the most successful frameworks to explain the static features of nuclei throughout the nuclear chart: those include the binding energy, charge radii, deformation, etc. On the other side, however, its applicability to the dynamical phenomena has not been sufficiently investigated. Especially, the collective excitation and the radioactivity still remain as “frontier” for the CEDF theory.

Nucleon-emitting radioactive processes

Several radioactive nuclides decay by emitting the nucleon or its composite systems, e.g. alpha particle. The decay modes in this category include the alpha decay, neutron-emitting decay, proton-emitting decay, as well as the spontaneous fission. The characteristic lifetime of each mode is substantially dependent on the nuclide, where no universal rule for various nuclides has been established. In terms of quantum mechanics, these processes are described as time-dependent, non-static phenomena of multi-nucleon systems. Therefore, a dynamical framework is necessary for the theoretical and computational treatment. This kind of framework, however, has not been sufficiently developed: the relativistic or non-relativistic EDF framework for atomic nuclei was originally designed to reproduce only the static features, e.g. binding energy.

For the implementation of a computational, dynamical framework based on the CEDF theory, one needs (i) a flexible and accurate basement, which can reproduce the well-known, static properties of atomic nuclei, and also (ii) the expansion of that basement method to the time-dependent picture: the second task is the main subject now. In the non-relativistic EDF case, recently there have been noticeable developments toward this direction. That time-dependent EDF method has been utilized to investigate the nuclear reaction, collective excitation, and some radioactive processes with fruitful results [Bulgac 2012, Sekizawa 2016, Nakatsukasa 2016, Schuet 2016]. In the relativistic case, on the other hand, expansion to the time-dependent picture has been less achieved, mainly because of the computational cost and some problems especially in the relativistic formalism, e.g. fermion doubling. These problems as an obstacle, however, are expected to be resolved thanks to the recent progress in the theoretical and computational CEDF framework [Reinhard 1989, Vretenar 2005, Meng 2006]. Considering this situation, it can be appropriate to propose the implementation of time-dependent CEDF as well as its application to the nucleon-emitting radioactivity.

I have been working on the time-dependent quantum-mechanical models, which has been utilized mainly for the two-proton-emitting radioactivity [Oishi 2014, Oishi 2017, Oishi 2018-PRC, Oishi 2018-JPG]. This experience can be a great help also in the CEDF version of the time-dependent framework.

Nuclear collective excitation

For an accurate evaluation of stellar nucleosynthesis, nuclear aspects of supernova collapse and explosion, or neutrino-induced reactions, one needs as input the properties of thousands of nuclei far from the beta-stability line. Many of these nuclei are not accessible in experiments. Therefore, certain theoretical framework, which can predict the variety of collective excitation and reactions throughout the nuclear chart, has been on a serious demand. Those include the electro-magnetic excitation as well as the weak-interaction processes, e.g. Gamow-Teller mode of the beta decay [Niksic 2005, Niu 2012]. For this purpose, the self-consistent mean-field calculation based on the nuclear CEDF theory can be a suitable option, taking care of the relativistic effect, causality, and QCD knowledge.

For the evaluation of the collective excitation in terms of the EDF theory, the quasi-particle random-phase approximation (QRPA) has been a standard tool [Ring and Schuck 1980, Nakatsukasa 2016, Roca-Maza and Paar 2018]. I have the experience of EDF-QRPA [Oishi 2020, Oishi 2016], and the theoretical and computational skills can be also utilized in the proposed research.

2.3 Expected research results and their anticipated scientific impact, potential for scientific breakthroughs and for promoting scientific renewal

- The universal theory of atomic nuclei, which must provide full information on arbitrary nuclear systems, has not been complete. The proposed plan can provide one milestone toward this goal, and profit not only in the nuclear physics, but also the relevant researches generally for the quantum-mechanical multi-body systems, e.g., atomic, molecular, and solid-state physics. This statement is based on the general applicability of non-relativistic or relativistic EDF theory to the multi-body systems [Kohn 1999].

- Certain framework to predict the physical properties, especially of nuclides far away from the experimental accessibility, has been required for some astrophysical interests, e.g. for supernova and nucleosynthesis processes. The similar requirement has been found in the nuclear engineering. The proposed research may answer to this requirement.

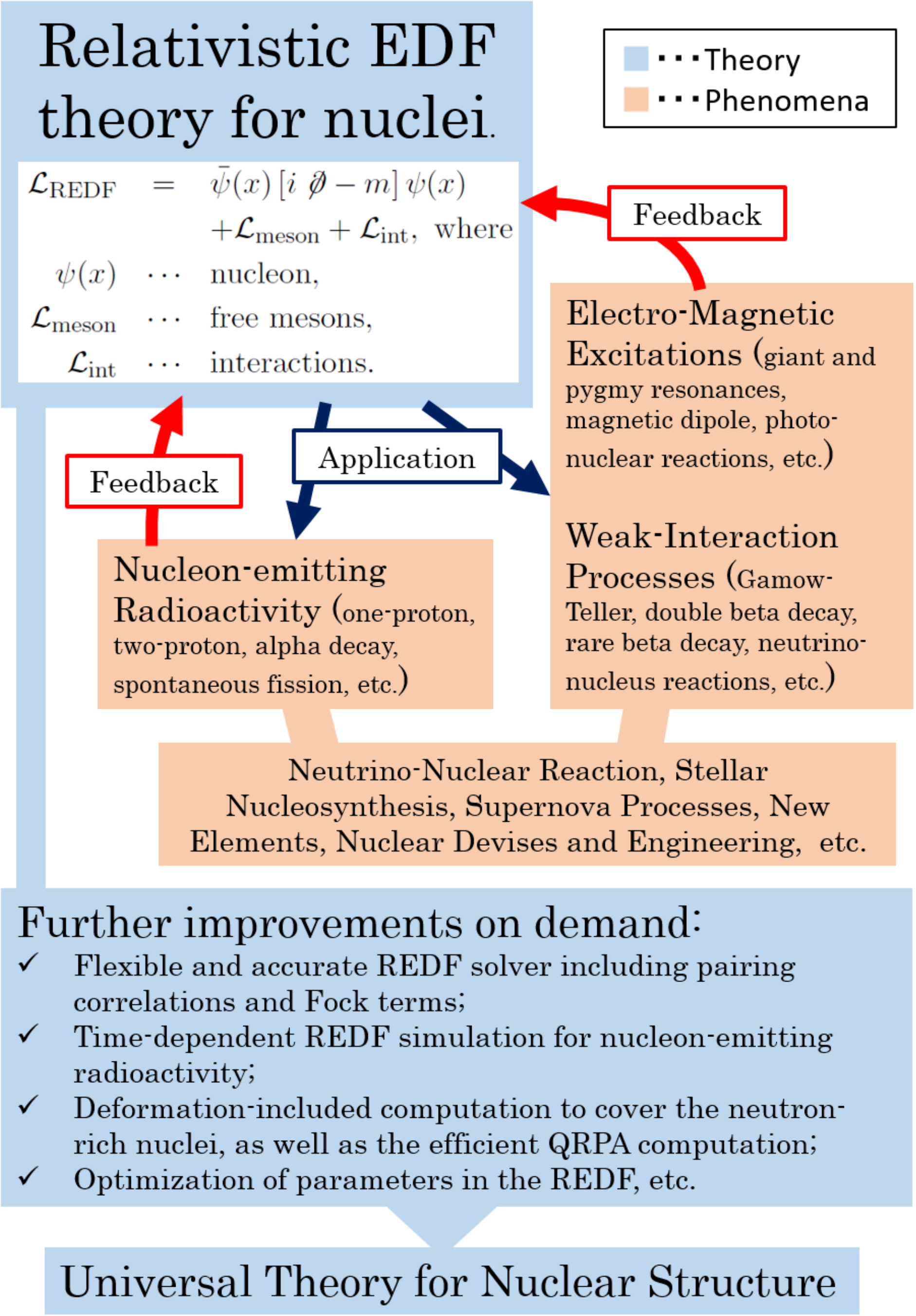


Figure 2: The map of contents in this research.

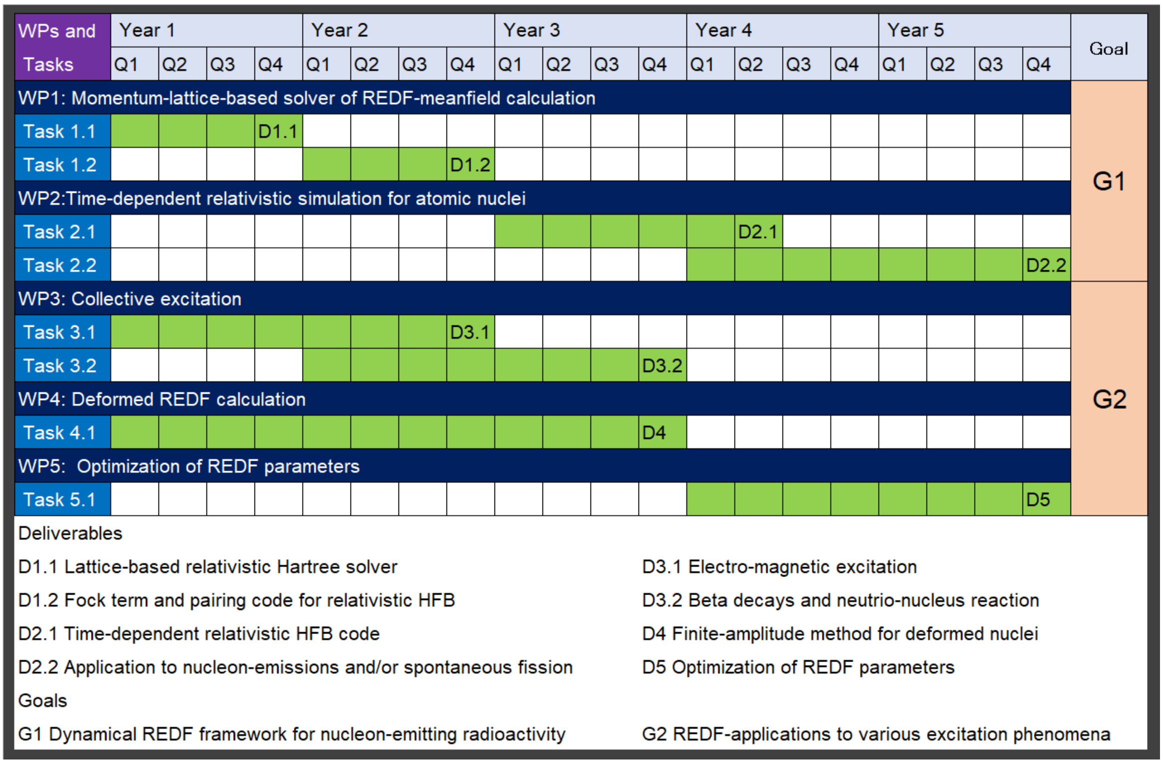
3 Implementation and work plan (5 years)

The proposed research consists of two divisions, i.e., main and sub ones. The main division includes two work packages, WP1 and WP2, whereas the sub division includes three packages, WP3-WP5.

- The main projects WP1 and WP2 aim to achieve the dynamical CEDF framework as introduced in the previous sections. The main target to finally approach is the nucleon-emitting radioactivity here. These projects involve the development of state-of-art methods, including the novel computing program and its expansion to the time-dependent version. Considerable amount of effort will be necessary for this purpose.

- The sub projects WP3-WP5 are designed for detailed topics, which continuously relate with the on-going studies I am engaging on [Oishi 2020, Kruzic 2020, Oishi 2019]. Methods utilized in those projects are solid and well-established: those include the basis-expansion solver of self-consistent CEDF calculation and the QRPA procedure for collective excitation [Liang 2013, Niksic 2013, Niksic 2014]. Because the performance of research methods has been already proven in the past researches, it can be expected to output the products, e.g. publications, in a short period. Also, these methods can work as the contingency plan for main projects, where the state-of-art solver will turn to be inadequate for the purpose.

Note that the main and sub projects can be in parallel proceeded, but even in that case, the main one always keeps the priority. The ratio of works devoted will be 7:3 or 8:2 for the main:sub ones. In the following, I present the details of each project, as well as their temporal schedule.



WPs and Tasks	Year 1				Year 2				Year 3				Year 4				Year 5				Goal
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
WP1: Momentum-lattice-based solver of REDF-meanfield calculation																					G1
Task 1.1	🟩	🟩	🟩	D1.1																	
Task 1.2					🟩	🟩	🟩	D1.2													
WP2:Time-dependent relativistic simulation for atomic nuclei																					
Task 2.1									🟩	🟩	🟩	🟩	🟩	D2.1							
Task 2.2													🟩	🟩	🟩	🟩	🟩	🟩	🟩	D2.2	
WP3: Collective excitation																					G2
Task 3.1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	D3.1													
Task 3.2					🟩	🟩	🟩	🟩	🟩	🟩	🟩	D3.2									
WP4: Deformed REDF calculation																					
Task 4.1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	D4									
WP5: Optimization of REDF parameters																					
Task 5.1													🟩	🟩	🟩	🟩	🟩	🟩	🟩	D5	

Deliverables

D1.1 Lattice-based relativistic Hartree solver

D1.2 Fock term and pairing code for relativistic HFB

D2.1 Time-dependent relativistic HFB code

D2.2 Application to nucleon-emissions and/or spontaneous fission

D3.1 Electro-magnetic excitation

D3.2 Beta decays and neutrio-nucleus reaction

D4 Finite-amplitude method for deformed nuclei

D5 Optimization of REDF parameters

Goals

G1 Dynamical REDF framework for nucleon-emitting radioactivity

G2 REDF-applications to various excitation phenomena

Figure 3: Schedule for plan (5 years). Each Q1-Q4 unit includes 3 months.

3.1 Schedule

See the Figure 3. Each WP has 1 or 2 tasks and expects the corresponding deliverables. One deliverable expects 1-3 publications, including the Ph.D. student's dissertation.

WP1: Momentum-lattice-based solver of CEDF-meanfield calculation

The lattice-based calculation in the momentum space can be the most flexible and bias-free version of the CEDF calculations. In the CEDF framework, its implementation has been recently realized [Ren 2017]. There are some advantages to employ the momentum-lattice: the calculation can take into account all the possible shapes of atomic nuclei, and the fermion-doubling problem can be easily dealt with. On the other hand, because no open-source program exists at present, the computational code needs to be composed individually. This task needs a major part of efforts especially in the first 2-3 years.

Fock terms and pairing correlations: these parts have been omitted in old studies of CEDF, mainly due to the computing cost. However, from recent works [Vretenar 2005, Meng 2006, Niksic 2011, Liang 2012], some nuclear aspects are found to be sensitive to these terms. The implementation of Fock terms and/or pairing correlations requires further computational efforts. However, these ingredients need to be computed also, because it can provide the unnegligible effect on, e.g. the new magic numbers, collective excitation, and nucleon emissions.

WP2: Time-dependent relativistic simulation for atomic nuclei

Time-dependent (TD) simulation is a useful tool to understand, e.g. the nucleon-emitting process, simultaneous fission, etc. For this interest, the TD calculation based on the CEDF-meanfield procedure can be a suitable option. For the expansion to TD solver, the solid basement is necessary with accuracy and flexibility. The momentum-lattice solver introduced in the last project M1 can be suitable for this purpose. For technical and practical aspects of computing, I utilize the skills and products obtained in the previous researches with TD simulations [Oishi 2014, Oishi 2017, Oishi 2018-PRC, Oishi 2018-JPG]. The major part of works is devoted for the coding and testing the program [Poschl 1997]. For the computational works, the high-performance computers can be necessary. I am also planning to apply to the usage of super computers in Japan, Finland, and/or other sites.

In the TD-EDF framework, one long-standing problem exists: the quantum-tunneling effect cannot be reproduced above the threshold energy. As one solution for this problem, recently in Ref. [Hasegawa 2020], the generator-coordinate method (GCM) is utilized. I am planning to employ the similar GCM approach implemented in the CEDF.

By utilizing the time-dependent CEDF framework combined with GCM, I aim to investigate the one-nucleon and two-nucleon-emitting processes within a unified framework. If this application will be successful, that may give an essential contribution to predict these processes in the unstable nuclei, where the experimental access has not been possible. This information plays an important role in the nucleosynthesis, production of unknown heavy elements, etc. This project represents the main work in the latter half of the research period (5 years).

If possible, I am also planning to extend this TD-CEDF application to the alpha radioactivity and/or the spontaneous fission. The theoretical evaluation of these processes has been demanded especially for the production of new-heavy elements [Morita 2012]. The TD-CEDF calculation may support these experiments by predicting the alpha-fission branching ratio as well as their lifetimes in the unstable region.

WP3: Collective excitation

There are various modes of the nuclear collective excitation in nature. Those include the electric, magnetic, beta-decay radioactivity, etc. As one example, the magnetic-dipole mode takes an important place in the study of CEDF. In our recent studies [Oishi 2020, Kruzic 2020], it is shown that the magnetic-dipole excitation can be a good testing phenomenon for CEDF. Especially, so-called CEDF-residual interactions, which cannot contribute to the even-even ground-state properties, still have large ambiguities. For the adjustment of these residual interactions, we need to change our focus to the measurable process, namely magnetic-dipole, where those interactions can be active. In parallel, the experimental data have been on a serious demand for reference observables. A close collaboration of theory and experiment is also expected within this project.

This plan also expects the collaboration with studies of e.g. the neutrino-nucleus interactions, Gamow-Teller transitions, rare-beta decays, and/or double-beta decay [Niksic 2005, Niu 2012, Hyvarinen 2016, Kostensalo 2018, Kumar 2020]. The CEDF framework can be utilized and developed in order to implement the relativistic version of the solutions for these problems.

WP4: Deformed relativistic meanfield calculation

For the neutron-rich nuclei, the self-consistent mean-field calculation needs to take the deformation into account. This leads to the huge increase of the computational cost for excitation calculations. As one solution for the efficient calculation, I am planning to equip the finite-amplitude method (FAM), which was utilized in my past work [Oishi 2016], combined with the existing CEDF code [Liang 2013, Bjelcic 2020]. Note that, because there are already the open-source codes exist, this WP has a solid basement, and may be suitable for the Ph.D. student or Post-doctoral fellow.

WP5: Optimization of CEDF parameters

There have been many sets of parameters for the CEDF effective interactions: the interaction Lagrangian in Figure 2 contains these parameters. For sufficient optimization, applications of CEDF to various phenomena should be established: this is really the purpose in the above projects. Especially, the magnetic mode as well as the weak-interaction processes can be a suitable reference for some parameters in CEDF, where there is still a considerable ambiguities.

The optimization of CEDF parameters should be important but also complicated. I am now planning to employ the machine-learning technique for the efficient optimization. This task is advanced, but may represent a suitable collaboration for the Postdoctoral fellow to be employed, especially for who has expertise on the machine learning.

3.2 Research data and material, methods, and research environment

The proposed research is based on the theoretical and computational physics. Its activities include the mathematical discussions, physical discussions, design of computational solutions, coding for programs, numerical calculations, and analysis of results. To perform these works, high-performance computers will be necessary. There can be also a necessity to use the super computers, and for that case, several applications to obtain the computing resources in Finnish facilities or in abroad countries are planned.

The proposed research utilize the experimental data on atomic nuclei, where there can be several open-data bases, e.g. the National Nuclear Data Center in the United States [NNDC's data base]. Also, the collaboration with experimental researches may occur. However, this research itself does not include the experimental activities.

3.3 Risk assessment and alternative implementation strategies

(1) The proposed research is limited in the theoretical and computational physics, and thus, the expected risks of damaging, violence, or critical incident are substantially low. (2) There are no ethics-related data or materials involved in the proposed research. Therefore the possibility to suspend the research with ethical problems are substantially low. (3) Considering the constant output of results, the sub projects as plan-B introduced above can support the main ones, when there will be an unexpected obstacle.

4 Responsible science

4.1 Research ethics

Ethical principles of research in the human, social, and behavioral sciences are followed. I also confirm and guarantee that this proposal satisfies the following conditions on ethics: (1) the proposed research does not involve human cells, genetic materials, embryos, biological samples, neither any other biological or medical materials; (2) the proposed research does not involve children, patients, healthy volunteers, observation of people, neither collection of data on people; (3) the proposed research does not involve animals, live stocks, plants, neither other creatures; (4) the proposed research and its products are independent and isolated from any military services; (5) the proposed research and its products are independent and isolated from any crimes, terrorism, dangerous organizations, and other purposes of violence; (6) the research is performed with the accordance with the research integrity, without any possibilities of misconduct.

4.2 Equality and non-discrimination

The proposed research is designed as completely independent of any inequality or discrimination. All persons and organizations involved are accountable for fair and equitable laws. In the case of research-related employment, recruitment, or diplomacy, the princile of equality for the sex/gender types, races, nationalities, and all the other properties of human is first kept.

4.3 Open science

All the products, including the scientific results, data, computational codes, etc., are stored within a secure and accessible format. Those will become open for public in a certain point in future when the priority for those products will be validated. The general public keeps the right to check, probe, and criticize the quality, processes, products, and fairness of the proposed research.

4.4 Sustainable development objectives

One possible contribution of this research relevant to the sustainable development is that for nuclear engineering and power source. The physical properties of atomic nuclei, especially of radioactivity, represent indispensable information on the design and treatment of nuclear products. Even though it holds potentially a high risk, the nuclear technology provides one basement of the sustainable development in future. For the secure and efficient development of that technology, the universal theory of atomic nuclei, or as one candidate, CEDF theory can play an essential role. Considering the Goals by UN for sustainable development, the proposed research can benefit especially the “Goal 7: Affordable and Clean Energy” and “Goal 9: Industry, Innovation, and Infrastructure” from the point of the nuclear-power strategy in future.

5 Societal effects and impact

Quantum multi-body systems, including atomic nuclei, composing materials have represented a long-standing problem from the origin of quantum mechanics. Throughout the researches on this topic, there have been various products and technologies invented. Those include the electronic devices, computers, quantum-information devices, and nuclear industry. Similarly to these profits, after the achievement of the proposed research, innovative outputs, e.g., the sophistication of the nuclear device, production of new elements, etc. are expected.

The radioactivity and the other characters of atomic nuclei are widely known in the general public nowadays. Also, its benefits and risks are recognized, as well as the importance of controlling it. The correct knowledge is the first key to control the natural events. Therefore, so-called universal theory as introduced in this proposal can be an appropriate knowledge also for the general public.

6 Bibliography

[Bender 2003] M. Bender, P.-H. Heenen, and P.-G. Reinhard: Rev. Mod. Phys. **75** (2003) 121.

[Bjelcic 2020] A. Bjelčić and T. Nikšić, ComputerPhysics Communications **253**, 107184.

[Boguta 1977] J. Boguta and A.R. Bodmer: Nuclear Physics A **292** (1977) 413.

[Bulgac 2012] A. Bulgac, Y.-L. Luo, and K. J. Roche: Phys. Rev. Lett. **108** (2012) 150401.

[Dean 2003] D. J. Dean and M. Hjorth-Jensen: Rev. Mod. Phys. **75** (2003) 607.

[Hasegawa 2020] N. Hasegawa, K. Hagino, and Y. Tanimura, Phys. Lett. B **808**, 135693 (2020).

[Hyvarinen 2016] J. Hyvärinen and J. Suhonen: Phys. Rev. C **93** (2016) 064306.

[Kohn 1999] W. Kohn: Rev. Mod. Phys. **71** (1999) 1253.

[Kostensalo 2018] J. Kostensalo, J. Suhonen, and K. Zuber: Phys. Rev. C **97**, 034309 (2018).

[Kruzic 2020] G. Kruzic, T. Oishi, D. Vale, and N. Paar, Phys. Rev. C **102**, 044315 (2020).

[Kumar 2020] A. Kumar, P. C. Srivastava, J. Kostensalo, and J. Suhonen: Phys. Rev. C **101** (2020) 064304.

[Liang 2012] H. Liang, P. Zhao, P. Ring, X. Roca-Maza, and J. Meng: Phys. Rev. C **86** (2012) 021302.

[Liang 2013] H. Liang, T. Nakatsukasa, Z. Niu, and J. Meng: Phys. Rev. C **87**, 054310 (2013).

[Maruyama 2012] T. Maruyama, T. Oishi, K. Hagino, and H. Sagawa: Phys. Rev. C **86**, 044301 (2012).

[Meng 2006] J. Meng, H. Toki, S. Zhou, S. Zhang, W. Long, and L. Geng: Progress in Particle and Nuclear Physics **57**, 470 (2006).

[Morita 2012] Kosuke Morita et. al., "New Result in the Production and Decay of an Isotope, $^{278}Z = 113$, of the 113th Element", Journal of the Physical Society of Japan **81**, 103201 (2012).

[Nakatsukasa 2016] T. Nakatsukasa, K. Matsuyanagi, M. Matsuo, and K. Yabana: Rev. Mod. Phys. **88** (2016) 045004.

[Niksic 2005] T. Nikšić, et al: Phys. Rev. C **71** (2005) 014308.

[Niksic 2011] T. Nikšić, D. Vretenar, and P. Ring: Progress in Particle and Nuclear Physics **66**(3), 519-548.

[Niksic 2013] T. Nikšić, N. Kralj, T. Tutiš, D. Vretenar, and P. Ring: Phys. Rev. C **88** (2013) 044327.

[Niksic 2014] T. Nikšić, N. Paar, D. Vretenar, and P. Ring: Computer Physics Communications **185** (2014) 1808 .

[Niu 2012] Y. F. Niu, G. Colò, M. Brenna, P. F. Bortignon, and J. Meng: Phys. Rev. C **85** (2012) 034314.

[NNDC's data base] "Chart of Nuclides", National Nuclear Data Center (NNDC) in US.

[Oishi 2020] T. Oishi, G. Kruzic, and N. Paar, Journal of Physics G: Nuclear and Particle Physics, Vol. **47**, 115106 (2020).

[Oishi 2019] T. Oishi and N. Paar: Phys. Rev. C **100** (2019) 024308.

[Oishi 2018-PRC] T. Oishi: Phys. Rev. C **97** (2018) 024314.

[Oishi 2018-JPG] T. Oishi, L. Fortunato, and A. Vitturi: Journal of Physics G: Nuclear and Particle Physics **45** (2018) 105101.

[Oishi 2017] T. Oishi, M. Kortelainen, and A. Pastore: Phys. Rev. C **96** (2017) 044327.

[Oishi 2016] T. Oishi, M. Kortelainen, and N. Hinohara: Phys. Rev. C **93** (2016) 034329.

[Oishi 2014] T. Oishi, K. Hagino, and H. Sagawa: Phys. Rev. C **90** (2014) 034303.

[Oishi 2011] T. Oishi, K. Hagino, and H. Sagawa: Phys. Rev. C **84** (2011) 057301.

[Oishi 2010] T. Oishi, K. Hagino, and H. Sagawa: Phys. Rev. C **82** (2010) 024315. With erratum.

[Poschl 1997] W. Pöschl, D. Vretenar, and P. Ring, Comp. Phys. Com. **103**, page 217-250 (1997).

[Reinhard 1989] P.-G. Reinhard: Reports on Progress in Physics **52** (1989) 439.

[Ren 2017] Z. X. Ren, S. Q. Zhang, and J. Meng: Phys. Rev. C **95** (2017) 024313.

[Ring and Schuck 1980] P. Ring and P. Schuck: *The Nuclear Many-Body Problems* (Springer-Verlag, Berlin and Heidelberg, Germany, 1980).

[Roca-Maza and Paar 2018] X. Roca-Maza and N. Paar: Progress in Particle and Nuclear Physics **101**, 96-176.

[Schuet 2016] B. Schuetrumpf, W. Nazarewicz, and P.-G. Reinhard: Phys. Rev. C **93** (2016) 054304.

[Sekizawa 2016] K. Sekizawa and K. Yabana: Phys. Rev. C **88** (2013) 014614.

[Vretenar 2005] D. Vretenar, A. V. Afanasjev, G. A. Lalazissis, and P. Ring: Physics Report **409** (2005) 101, and references therein.

[Walecka 1974] J. D. Walecka: Annals of Physics **83** (1974) 491.