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FRIB Theory Alliance

Annual Progress Report

(June 2020 - May 2021)

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Contents

1 Abstract

Advances in theory provide the essential underpinning to understanding nuclei and their role in the cosmos. The FRIB Theory Alliance, working together with the theory community, has the goal to enhance theoretical efforts related to the Facility of Rare Isotope Beams (FRIB), across the country. It has been recognized as a key ingredient to the success of the science associated with FRIB. Its national FRIB Theory Fellow program attracts new young talent to the field. The FRIB theory bridge program creates permanent positions nationwide. The FRIB theory visitors program and topical programs fosters interdisciplinary collaborations and international initiatives. The FRIB Theory Alliance educational initiatives introduces exciting interdisciplinary areas to the next generation of nuclear theorists.

2 Executive Summary

The long-term goals of the proposed FRIB-TA are: i) to deliver excellent research in theory relevant to the big science questions associated with FRIB; ii) to serve as a focal point for stimulating continuous interactions between theory and experiment, drawing theory activity toward those problems relevant for the science at FRIB; iii) to rejuvenate the field by creating permanent positions in FRIB theory across the country; iv) to attract young talent through the national FRIB Theory Fellow program; v) to strengthen theory in areas of most need; vi) to foster interdisciplinary collaborations and build scientific bridges to wider theory communities; vii) to contribute toward a sustainable educational program in advanced low-energy nuclear theory; and viii) to coordinate international initiatives in the theory of rare isotopes.

This is the first year of the renewed five-year cycle for the FRIB Theory Alliance. As planned, we continued to expand the FRIB-TA fellow program (see Section 3) and the bridge program (as described in Section 4). Our current fellows and bridge faculty have produced excellent work of great relevance to FRIB. We highlight four examples that have been completed over the last year, although many more can be found in Sections 3 and 4:

- Recent ab-initio calculations of the equation of state of dense matter, the nuclear symmetry energy, and its slope, with quantified uncertainties, fall within currently available experimental constraints [1].
- An extensive review of the sequence of nuclear effective field theories provide a unified picture of the status of nuclear theory [2].
- Quantum Monte Carlo calculations based on the Norfolk two- and three-body forces predict weak transitions in light nuclei and validate the correlations included in the framework [3, 4].
- Insight on the relations between the binding energy of finite nuclei and the equation of state of infinite nuclear matter calls into question previous assumptions [5].

In addition, we have two new fellows to begin their appointment in July this year (one at MSU and one at Ohio University). There is a bridge faculty search ongoing at Florida State University and we have identified the partner institution that will host the next bridge position. Restricted due to the pandemic, we still ran a summer school (see Section 5), had our annual meeting during the low energy community meeting (Section 6.1) and organized a series of dialogues in nuclear physics (Section 6.3), all in a virtual setting. Unfortunately, activities around the Europe U.S. Theory in

Physics of Exotic Nuclei (EUSTIPEN) program were suspending due to the COVID related travel restrictions (see 6.4).

Our membership continues to grow and is now capturing the vast majority of the national theoretical effort in low energy nuclear physics. Currently, we have 261 members, 183 of which are from the U.S. The breakdown with the U.S. is: 75 faculty members, 29 staff members, 35 postdocs members and 40 students.

The FRIB TA website (fribtheoryalliance.org) continues to serve as an effective means to communicate with our membership (Section 8.3) and is now being revamped. The newly formed committee on Diversity, Inclusion and Equity has begun operations with the development of a Code of Conduct (Section 7). There have been some changes in the charter of the theory alliance, which are summarized in Section 8.1, and we have introduced an important initiative to enhance theory-experiment collaboration in preparation for the FRIB first PAC (Section 6.2). Toward the end of this report, a summary of the director and research administrator activities in Section 8.2 is presented, as well as a list of publication and presentations (Sections 9.1 and 9.2), followed by an update on our milestones in Section 9.3.

All in all, this has been a good first year of the renewal FRIB-TA, and in this report we demonstrate progress on many fronts, despite the setbacks due to the pandemic. We are excited with the scientific contributions of our fellows and bridges, that have managed to continue their work even in the difficult circumstances of working from home. We are continuing to expand the programs as planned and engaging with experimental community in preparation for the the first experiments at FRIB.

3 FRIB Theory Fellow Program

The FRIB Theory Fellowship is a 5-year research position with an initial annual salary well above a postdoctoral salary and an independent annual budget for travel and visitors. The fellow is expected to develop high-caliber work on important theoretical problems relevant to research with FRIB. The initial 2-year appointment is renewed on an annual basis for an additional 3 years depending on performance and the availability of funds. The maximum tenure for the FRIB Theory Fellow is five years. The program has proven to be highly competitive and has increased the visibility of low-energy nuclear theory worldwide. The FRIB theory fellow is expected to advance into an open faculty or permanent staff position in the field within 5 years of the initial appointment. Previous fellows, Elena Litvinova, Heiko Hergert, Gregory Potel, have each successfully transitioned into permanent positions.

In our previous grant cycle, the fellow program consisted of three fellows hosted by MSU, LANL, and ANL. These were Gregory Potel at MSU, Diego Lonardoni hosted by Los Alamos National Laboratory and Kevin Fossez at Argonne National Laboratory. We have since added two more fellows Chloë Hebborn hosted at Livermore National Laboratory [1] and Christian Drischler at MSU. Reports on their research activities are given below. In 2020, an FRIB theory fellow search was conducted and is described in Sec. 3.5.

[1]Note that Hebborn has initiated her appointment with LLNL remotely from Belgium due to COVID restrictions.

3.1 Science highlights from Christian Drischler

In October 2020 Christian joined MSU and has since then been very active exploring collaborations that can enhance his research goals. He has been collaborating with Scott Bogner's and Morten Hjorth-Jensen's groups to continue his research program on deriving microscopic constraints on the nuclear equation of state (EOS) and the structure of neutron stars using chiral effective field theory (EFT), many-body perturbation theory (MBPT), and Bayesian methods for quantifying theoretical uncertainties. Scott and Morten are leading experts in the application of the non-perturbative frameworks In-Medium Similarity Renormalization Group (IM-SRG) and Coupled Cluster (CC) theory, respectively. Together with the efficient Monte Carlo approach to evaluating MBPT diagrams up to unprecedented high orders that Christian developed when he was a Humboldt fellow at University of California, Berkeley, this setting enables exciting new possibilities for deriving state-of-the-art microscopic constraints on the nuclear EOS up to high densities and quantified EFT truncation errors in the near future.

From October 2020 through February 2021 Christian and his international collaborators finished two projects that had started earlier in 2020. The journal *Annual Review of Nuclear and Particle Science* invited him to contribute to this year's issue with the 25-page review article *Chiral EFT and the high-density nuclear EOS*, which has already been peer-reviewed and accepted for publication [6]. In light of the recent insights from neutron star observations, the article reviews the advances made in chiral EFT and their impact on studying strongly interacting matter across the wide range of densities relevant for modeling neutron stars. Also laboratory experiments, such as those conducted soon at FRIB, will provide valuable information for constraining the EOS further.

For decades the dilute Fermi gas has been a central problem for many-body calculations; especially in more recent years due to the striking progress in experiments with ultracold atomic gases. In a preprint [7] submitted to Phys. Rev. C, Christian and his collaborators have calculated the Fermi-momentum (or $k_{\mathrm{F}}a_s$) expansion for the ground-state energy of the dilute Fermi gas up to fourth order in two regularization and renormalization schemes. Using their high-order calculations and Bayesian methods, they have shown that in the case of spin one-half fermions the expansion is well-converged for $|k_{\mathrm{F}}a_s| \lesssim 0.5$ and that relatively simple resummations techniques can considerably improve the convergence for $|k_{\mathrm{F}}a_s| \lesssim 1$. The results provide important constraints for nonperturbative (i.e., Quantum Monte Carlo) calculations of ultracold atoms and dilute neutron matter, and may be useful for improving models of the neutron star crust.

Bayesian methods combined with efficient and accurate emulators (prominently, using eigenvector continuation [8]) have the potential to set the standard for uncertainty quantification in nuclear physics—even for the most computationally demanding applications. Christian has joined forces with Filomena Nunes's group and other members of the *Bayesian Analysis of Nuclear Dynamics* (BAND) Framework project to develop a fast eigenvector continuation emulator for nuclear scattering and transfer reactions [9]. Such an emulator may enable systematic Bayesian uncertainty quantification and model comparison for these processes; in particular aimed at improving the underlying optical potentials, which is a crucial task in the upcoming FRIB era.

3.2 Science highlights from Kevin Fossez

In March 2019, Kevin Fossez joined Argonne National Laboratory where he started a research program focused on the development of novel theoretical approaches to study the structure of exotic nuclei at the limits of nuclear stability, also called drip lines, and on guiding low-energy nuclear physics experiments in facilities such as the Facility for Rare Isotope Beams (FRIB) at

Michigan State University (MSU) and the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL). Exotic nuclei play an important role in astrophysical processes leading to the formation of new elements in the Universe, and their properties reveal important information about nuclear forces [10] and how atomic nuclei self-organize [11]. To achieve the theoretical exploration of the drip lines, Kevin uses and develops various many-body techniques such as the Gamow shell model (GSM) [12], the density matrix renormalization group (DMRG) method for open quantum systems [13], and the in-medium similarity renormalization group (IM-SRG) method [14], in both the *ab initio* and shell model pictures, and using both phenomenological and effective field theory (EFT) potentials as input. Even though these approaches are designed to handle the large model spaces required to describe exotic nuclei, the coming online of FRIB will require unprecedented theoretical and computational developments.

Past studies have shown that the current precision of both *ab initio* and phenomenological approaches appears to be insufficient to describe the properties of medium-mass exotic nuclei of high experimental interest [15]. However, a first attempt at simplifying a shell model interaction using effective scale arguments gave surprisingly precise and accurate predictions in some of the most exotic nuclei ever created [16], motivating a proposal for the construction of a tritium target at FRIB. For that reason, Kevin is developing new shell model forces inspired by the EFT framework to improve significantly the reliability of such calculations in neutron-rich nuclei, which will be critical for the success of the FRIB program. He is currently testing the new model and the first applications will be submitted for publication this year.

A second critical area for progress is the extension of computational capabilities for *ab initio* and phenomenological configuration interaction calculations. The current version of the C++ DMRG code is only parallelized using MPI, but it can deal with matrices of dimensions orders of magnitude larger than the most powerful shell model codes on the market, and its ongoing optimization coupled with the use of natural orbitals [17, 18] has already unlocked new possibilities, in particular for the study of the neutron-rich fluorine isotopes holding the key for understanding the dramatic evolution of nuclear structure in the so-called "island of inversion" around $N = 20$. Moreover, efforts are underway to use the newly introduced eigenvector continuation method [8] in the *ab initio* context to access resonant states of light nuclei otherwise nearly impossible to converge using conventional techniques.

Finally, the generalization of the *ab initio* IM-SRG method in the Berggren basis will offer one of the few *ab initio* techniques that can reach nuclei with $A = 100$ nucleons while including couplings to continuum states. The aim of this project is to build the capability to test fundamental nuclear forces against exotic phenomena and provide predictive power where shell model approaches fail. Additionally, the combination of the IM-SRG and DMRG methods, which will be tested and applied this year, will offer a new way to capture both static and dynamic many-body correlations, by pre-processing the *ab initio* Hamiltonian using the IM-SRG method before further renormalization by the DMRG method for both ground and excited states.

3.3 Science highlights from Chloë Hebborn

Chloë joined Lawrence Livermore National Laboratory (LLNL) in October 2020, where she started collaborating with Konstantinos Kravvaris, Sofia Quaglioni and Gregory Potel on the development of nucleon-nucleus optical potentials within the framework of the *ab initio* no-core-shell model with continuum (NCSMC) [19]. *Ab initio* optical potentials provide a bridge between microscopic-structure theory and few-body models for nuclear reactions and could in principle be developed for any nucleus accessible by the chosen *ab initio* theory. Since the NCSMC has successfully described light unstable nuclei [20], such optical potentials promise to be predictive away from stability, in one of the region of interest for FRIB science. This would constitute the main advantage compared to the usual phenomenological potentials fit from elastic-scattering data, the applicability of which is restricted to stable nuclei. During these first four months, Chloë derived the formalism to build optical potentials from NCSMC wavefunctions.

Parallel to the derivation of *ab initio* optical potential, Chloë got up to speed with the NCSMC formalism and codes. She started work to arrive at the *ab initio* prediction of the low-energy $^2\mathrm{H}(\alpha,\gamma)\,^6\mathrm{Li}$ radiative capture. This reaction is of great astrophysical interest since it is responsible for the Big-bang nucleosynthesis of ^{6}Li [21]. With LLNL collaborators and Guillaume Hupin at IJCLab, she completed the numerical implementation of the NCSMC formalism for the radiative capture of deuterons by including the electromagnetic transitions between the deuteron states. The next step will be to include isospin-forbidden E1 transitions in the calculations. All these developments will enable an accurate *ab initio* estimate of the S-factor for the $^2\mathrm{H}(\alpha,\gamma)\,^6\mathrm{Li}$ radiative capture.

During her PhD, Dr. Hebborn has studied improvements to the eikonal approximation to model breakup and knockout reactions. These two reactions, corresponding to the dissociation of a nucleon from the nucleus, have been widely used to probe nuclear-structure away from stability. Surprisingly, Gade *et al.* observed that the theoretical predictions obtained from eikonal analyses underestimate the experimental knockout data, and this discrepancy increases with the binding energy of the nucleus [22]. Since knockout reactions are inclusive, i.e., the nucleon is not detected in coincidence with the remaining nucleus, a possible explanation for this discrepancy is the decay of the remaining nucleus before it reaches the detector [23]. Together with Gregory Potel and Cole Pruitt at LLNL, Chloë has started to study the computation within an eikonal model of the cross sections associated with this decay. This work will help understanding the systematic trend observed by Gade *et al.*

Finally, it is well known that optical potentials are complex, energy-dependent and non-local [24]. To be able to use *ab initio* optical potentials in analyses of reactions that will be measured at FRIB, reaction models able to deal with such interactions are needed. The eikonal approximation can treat complex and energy-dependent potentials but has not been generalized yet to non-local interactions. In collaboration Filomena Nunes at MSU, Chloë is studying how to treat this non-locality within the eikonal model.

3.4 Science highlights from Diego Lonardoni

Diego Lonardoni and collaborators have used state of the art ab-initio quantum Monte Carlo (QMC) methods combined with realistic nuclear Hamiltonians derived from chiral effective field theory (EFT) [25, 26], to consistently calculate the EOS of dense matter, the nuclear symmetry energy, and its slope [1]. Results have been compared with constraints coming from terrestrial experiments and from astrophysical observations, including the gravitational wave signal of the neutron star merger event GW170817 [27]. Within the quoted uncertainties, coming from both the many-body method and the theory, all the computed results are compatible with currently available constraints (see Fig. 1). Thanks to the success of this study, they derived other neutron-star related quantities, such as the spin susceptibility in neutron-rich matter [28]. This plays an important role in general relativity simulations of violent phenomena, such as supernova explosions or neutron star mergers [29–31], where the fluctuation of the magnetic field magnitude can reach very high peaks [32].

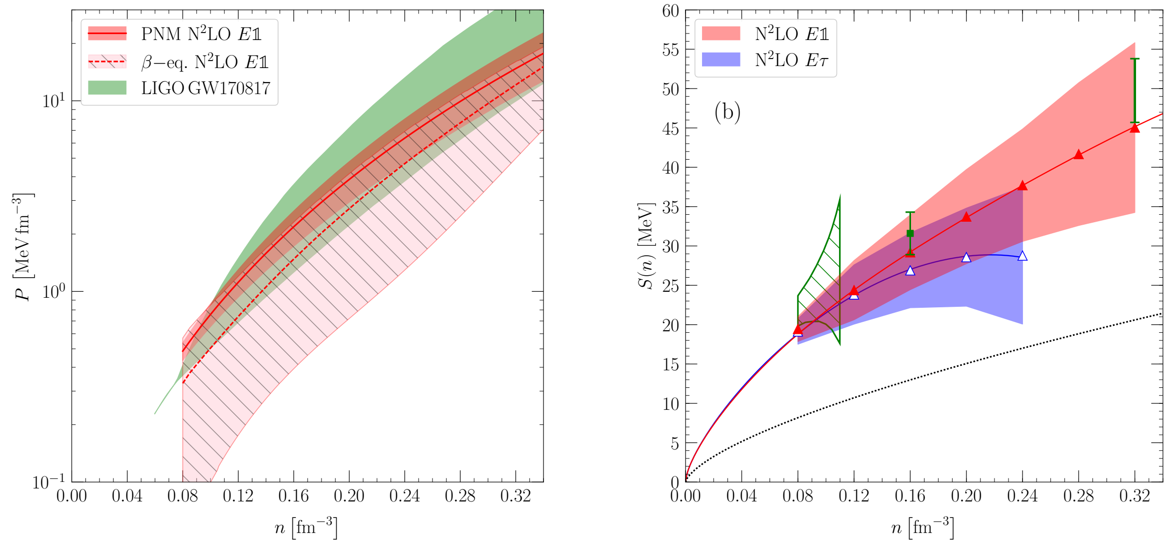

Figure 1: Left: EOS of dense matter from QMC calculations employing chiral EFT interactions (red curves and bands). The green area is the pressure extracted from the GW signal GW170817 [27]. Right: Nuclear symmetry energy. Red and blue symbols are the QMC results. Green symbols indicate empirical [33] and experimental constraints [34–36]. In both panels, red and blue bands represent the full uncertainty of the calculations, coming from both the many-body method and the theory. Figures taken from Ref. [1].

Short-range correlations (SRCs) emerge from pairs of nucleons having large relative momentum compared to their center-of-mass momentum and to the typical nuclear Fermi momentum k_F. At momenta just above k_F, they are primarily due to proton-neutron pairs and are thought to dominate the nuclear wave function [37, 38]. SRCs play a fundamental role in lepton scattering from nuclei, and have substantial implications for the internal structure of nucleons bound in nuclei [37, 39, 40], neutrinoless double beta decay [41], nuclear charge radii [42], the nuclear symmetry energy, and neutron-star properties [43]. Therefore, understanding their formation mechanisms and specific characteristics is required for obtaining a complete description of atomic nuclei.

QMC techniques are best suited for SRC studies since the short-range / high-momentum components of the nuclear many-body wave function can be easily accessed. Dr. Lonardoni and collaborators have used complementary QMC techniques employing different nuclear Hamiltonians to study SRC scaling factors in light and medium-mass nuclei ($A \leq 40$) [44], finding good agreement with available experimental values. QMC two-nucleon distributions for a variety of nuclei and nuclear interactions have been analyzed using the effective pair-based Generalized Contact Formalism [45, 46]. They have observed a universal factorization of the many-body nuclear wave function at short-distance into a strongly-interacting pair and a weakly-interacting residual system. Spin- and isospin-dependent "nuclear contacts" have been extracted in both coordinate and momentum space for different realistic nuclear potentials, proving the position-momentum equivalence of SRCs, and showing the independence of contact ratio upon the specific nuclear interaction model. These findings, published in Nature Physics [47], allow extending the application of mean-field approximations to short-range correlated pair formation by showing that the relative abundance of short-range pairs in the nucleus is a long-range (*i.e.*, mean-field) quantity that is insensitive to the short-distance nature of the nuclear force. This and future SRC studies will shed some light on our understanding of the nuclear force, the SRC formation mechanism, and the consequent emergence of nuclear properties and structures, of particular relevance for systems characterized by large neutron-to-proton imbalance.

Dr. Lonardoni completed his term with the FRIB-TA, and has now moved into a new position, as a visiting assistant professor at Michigan State University. This position began in October 2020.

3.5 FRIB Theory Fellow search

In 2020, a search for two FRIB Theory Fellows was conducted, following the updated document providing guidance for fellow searches [2]. The members of the search committee were: Edward Brown (MSU representative), Alexandra Gade (NSCL & MSU), Kristina Launey (Louisiana State University, chair), Erich Ormand (LLNL), and Gregory Potel (LLNL, former FRIB Theory Fellow). Two partner institutions were identified: Washington University in St. Louis (WUSL) and Ohio University (OU). A representative from each partner institution was added to the search committee, Saori Pastore (WUSL) and Daniel Phillips (OU), who participated in the selection of the short list and interviews, but were recused from the final deliberations in order to limit potential conflicts of interest. Given the two positions advertised and the strong pool of candidates, seven FRIB Theory Fellow candidates were interviewed. The interviews were held virtually during Dec. 7^{th}-15^{th}, 2020. The search committee met virtually on Dec. 17^{th}, 2020, and selected a ranked list based on the following criteria: excellence of research, relevance of research to the FRIB mission, independent scientific maturity, as well as diversity of the applicants and representation of disciplines. The list was reported to and approved by the FRIB TA Board, and corroborated by the DOE program manager and the FRIB laboratory director. Two of the top ranked candidates, Nicole Vassh and Xilin Zhang, accepted the offer: Vassh to be hosted by Ohio University and Zhang to be hosted by Michigan State University, both starting July 2021.

4 FRIB Theory Bridge program

The goal of the FRIB Theory Bridge program is to enhance the opportunities of theory faculty hires at Universities or theory staff hires at National Laboratories. These positions are modeled after those created by the RIKEN/BNL program at RHIC, with 50% of the cost being covered by DOE through the FRIB-TA and 50% by the home institution, until the faculty/staff member is granted tenure over a maximum period of 6 years. Bridge faculty/staff are outstanding young theorists who develop exceptional theoretical research relevant to rare isotope science. Bridge faculty/staff are 100% employees of their home institution, with all the associated benefits. For bridge positions located at universities, the bridge faculty are expected to build a research group, attract federal funding and have teaching duties, just as all other faculty at their home institution. Equally for bridge positions located at national laboratories, the bridge staff is expected to perform at the level of new staff members at national laboratories. In addition, bridge faculty/staff are expected to contribute significantly to the scientific program at FRIB and be spokespersons for FRIB theory, nationally and internationally. They are expected to spend a significant amount of time at FRIB and, for this reason, teaching relief could be negotiated on a case-by-case basis. Currently the FRIB-TA has three faculty under its bridge program and next we include their research progress. A new faculty search at FSU nearing completion and an update is provided in Section 4.4. A new

[2]See https://fribtheoryalliance.org/content/Resources/Procedures/.

call for bridge applications went out in the Fall 2020 and the selection update is provided in Section 4.5.

4.1 Science highlights from Sebastian König

Sebastian König joined the Physics Department at NC State University in January 2020. König's research covers the development and application of nuclear effective field theories (EFTs), with particular emphasis on perturbative expansions of nuclear systems, as well as using finite-volume (FV) calculations as a tool to study nuclear bound states and resonances.

Recently, König and collaborators published an extensive review [2] of the sequence of nuclear EFTs that are formulated in terms of nucleons (and clusters thereof) as degrees of freedom: Pionless EFT, Chiral EFT, and Halo/Cluster EFT. This article, published in Reviews of Modern Physics, summarizes the state of the field and discusses the similarities and differences between the three theories in a unified picture.

In Ref. [48] König and collaborators introduced the "unitarity expansion," which, based on Pionless EFT, expands few-nucleon systems around the so-called "unitarity limit" in which the two-nucleon scattering lengths are infinite. Recently, König extended this approach to study $3N$ and $4N$ radii and charge form factors in addition to binding energies [49]. Finding good convergence of the unitarity expansion for these observables strengthens the conjecture of Ref. [48] that the approach captures a significant part of low-energy nuclear structure. An important development of Ref. [49], extending the ideas of Refs. [50, 51], is the derivation and implementation of perturbative corrections based on Faddeev and Faddeev-Yakubowsky equations in a highly efficient manner.

Eigenvector continuation (EC), first introduced in Ref. [8], is a powerful (yet strikingly simple in practice) method to address physics problems which are otherwise not feasible to solve. Based on analytic function theory, it exploits small amounts of information contained in eigenvectors far away (in some parameter space) from the physical point of interest, enabling a robust extrapolation to this point. With EC, the essence of the system is "learned" through the construction of a highly effective (non-orthogonal) basis, leading to a variational calculation of the states of interest with rapid convergence [52]. König and collaborators recently studied two distinct applications of EC in nuclear physics. Ref. [53] uses EC to set up an "emulator," i.e., an inexpensive way to vary parameters of a calculations based on a set of training points obtained from (expensive) full solutions of the Schrödinger equation. These EC emulators are found to be extremely efficient even in high-dimensional parameter spaces, and vastly more accurate compared to, for example, Gaussian processes and is crucial for statistically rigorous uncertainty quantification of nuclear-theory prediction with Bayesian methods. Due to its grounding in analytic function theory, EC can interpolate and extrapolate across large distances from a small number of data points. In particular, the extrapolation capability can be applied to systems where perturbation theory converges slowly or not at all. Ref. [54] (highlighted as PRC Editors' Suggestion) demonstrated how EC can be used as a resummation tool for many-body perturbation theory that is superior to often used phenomenological techniques.

At NC State, König and associated graduate students are investigating the use of finite-volume (FV) techniques to implement novel calculations based on EFT interactions. This approach is based on the insight that the physical S-matrix governs the volume dependence of energy levels [55–57] and is widely used for example in Lattice QCD. Recently, König reviewed how the technique can be applied to calculate properties of bound and unbound few-body states [58].

Finally, König is a co-author of a joint theory and experimental publication that studies the role of chiral two-body currents in ^{6}Li in light of a new precision measurement [59]. This paper was recently accepted to appear in Physical Review Letters.

4.2 Science highlights from Saori Pastore

Saori Pastore's research to date has emphasized the development and implementation of many-body electromagnetic and weak current operators in studies of electroweak transitions and scattering in atomic nuclei [60, 61]. Pastore uses chiral effective field theory, supplemented by more phenomenological approaches, to construct many-body operators, and Quantum Monte Carlo (QMC) computational methods (both Variational MC and Green's function MC) to solve the many-body nuclear problem. QMC methods allow to fully account for many-nucleon correlations and currents. This microscopic approach yields a picture of the nucleus and its interactions with external electroweak probes where many-body effects in both nuclear interactions and currents are essential to accurately explain the data. For example, correlations and currents are required to explain the observed nuclear magnetic moments in light nuclei [62], and the Gamow-Teller decay rates [63].

Recently, Pastore and collaborators presented VMC and GFMC calculations of weak transitions in $A \leq 10$ nuclei–including beta decays of ^{6}He, ^{8}Li, ^{8}B, ^{8}He and ^{10}C and electron-capture in ^{7}Be. The calculations were based on the Norfolk two– and three– body potentials derived by Piarulli and collaborators (see Sec. 4.3) and associated axial many-body currents. Pastore and collaborators investigated the sensitivity of the matrix elements to choices of different cutoffs, ranges of laboratory energy of the nucleon-nucleon scattering data used to constraint the two-body potential, and different strategies used to constrain the three-body potential. This work resulted in a PRC *Editor's Suggestion* publication [3] with first author Garret King, a graduate student at Washington University in St. Louis, and an invited publication on Frontiers in Physics [4]. These studies provide a validation of nuclear many-body correlations and currents entering *ab initio* calculations, and impact studies of more exotic observables, such as neutrinoless double beta decay, and searches for beyond standard model physics using beta decays. Studies alsong these lines were performed by Pastore and collaborators in Ref. [64] calculated neutrinoless double beta decay ($0\nu\beta\beta$) matrix elements and transition densities in $A \leq 12$ nuclei. These studies are determinant to assess the relative importance of the different lepton-number-violation many-nucleon potentials contributing to the $0\nu\beta\beta$ matrix elements. The computational time for these calculations was provided by the 2019/2020 ALCC allocation for proposals of which Pastore and Piarulli are PIs. A mini-review on the status of many-body calculations of $0\nu\beta\beta$ matrix elements has been reported in Ref. [65].

Pastore and collaborators developed the Short-Time-Approximation (STA) to study electron and neutrino scattering from nuclei. The scope of this new QMC algorithm is to access nuclei of experimental relevance in the $A \sim 40$ region. Moreover, the STA allows for the implementation of final states and has the potential to describe inelastic processes. This method has been extensively tested on the alpha particle and resulted in two recent publications [66, 67].

4.3 Science highlights from Maria Piarulli

A major thrust of Piarulli's research is based on the theoretical formulation and optimization of models for nuclear interactions using chiral effective field theory (χEFT) [68–70]. During the last two decades, such an approach has become popular amongst the low-energy nuclear physics community because of its deeper connection with the fundamental theory of quantum chromodynamics (QCD) in contrast to the old and more traditional phenomenological approaches adopted in the past [71]. Piarulli and collaborators have developed a high-precision family of chiral nuclear interactions suitable for Quantum Monte Carlo methods, referred in the literature as the Norfolk potentials (NV2+3s) [72–74]. These models have been implemented in both the Variation Monte Carlo (VMC) and Green's Function Monte Carlo (GFMC) codes and used to perform calculations of the energy levels [75, 76], charge radii, and longitudinal elastic form factors [77] of light nuclei that are found to be in very satisfactory agreement with the experimental data.

Recently, two of the NV2+3s have been also used to compute transitions corresponding to the cases in which the initial and final nucleus have the same isospin, $\Delta I = 0$, or the nuclear isospin changes by two units, $\Delta I = 2$. The latter is the case for all the experimentally relevant $0\nu\beta\beta$ emitters. In particular, we have performed VMC calculations of the Fermi, Gamow-Teller, and tensor densities $\rho(r)$ for ^{6}He $\rightarrow$ ^{6}Be and ^{12}Be $\longrightarrow$ ^{12}C transitions as reported in Ref. [64].

Taking advantage of the ALCC-2019 Theta allocation, VMC and GFMC calculations of beta decays, electron-capture rates, and two-body weak transition densities in $A = 3 - 10$ systems using the Norfolk potentials and associated one- and two-body currents [78–82] have been performed [3, 4] as discussed in Sec. 4.2.

Furthermore, the NV2 models have been used in benchmark calculations of the energy per particle of pure neutron matter (PNM) as a function of the baryon density using three independent many-body methods: Brueckner-Bethe-Goldstone (BBG), Fermi hypernetted chain/single-operator chain (FHNC/SOC), and Auxiliary Field Diffusion Monte Carlo (AFDMC) [83]. These types of calculation are particularly relevant for the quantitative assessment of the systematic error of the different many-body approaches and how they depend upon the nuclear interaction of choice. Next step for this project will involve a realistic description of the equation of state (EoS) of PNM, which would require the inclusion of many-nucleon forces. This project has led to an Editors' suggestion paper published in Physical Review C [83]. It has also been highlighted in the DOE Office of Science website: https://www.energy.gov/science/np/articles/probing-equation-state-neutron-matter-stuff-neutron-stars-are-made. The results of this research are relevant to a wide range of present and future nuclear physics experiments at low-, medium-, and high-energy facilities. For instance, calculations of the nuclear spectra are tested via $M1$ and $E2$ electromagnetic transitions which are measured at ATLAS, NSCL and other facilities around the world. These types of experiments will continue at FRIB, which will be the cornerstone of nuclear structure and nuclear astrophysics research in the coming decades. FRIB will place an emphasis on the study of neutron-rich nuclei far from the valley of stability, so investigating the behavior of three-nucleon forces in PNM will provide an important calibration for applications in larger nuclei.

QMC calculations of the two-nucleon spatial/momentum distributions (for nuclei with $A \leq 6$) have been also obtained with the NV2+3s potentials for a recent study on many-body factorization and position-momentum equivalence of nuclear short-range correlations as discussed in Section 3.4 and were published in Nature Physics (2020) [47]. The work has gained public attention, as for example the piece in SciTechDaily [3].

Finally, Piarulli has contributed to a recent publication about the reexamination of the relation between the binding energy of finite nuclei and the equation of state of infinite nuclear matter. This study was performed in collaboration with Dr. Dickhoff and his former student Dr. Atkinson, and it led to an Editors' suggestion paper announced in Physical Review C [5].

[3] https://scitechdaily.com/party-pairs-no-matter-the-size-of-a-nuclear-party-some-protons-and-neutrons-will-always-pair-up-and-dance/

4.4 Update in FSU search

The FRIB-TA bridge faculty position in partnership with Florida State University is currently under way. The search committee is chaired by Jorge Piekarewicz (former FRIB-TA director) and includes five colleagues from various fields as well as Kristina Launey acting as the representative of the FRIB-TA Executive Board. From a total of 26 applicants, 8 of them have been interviewed via zoom, and the search committee is in the process of preparing a shortlist of 4-5 strong young researchers that will be invited for on-campus interviews. The talks by all the candidates will be recorded and posted on a password protected website to be viewed by the FRIB-TA Executive Board. We expect that the search will be completed by the second or third week in March.

4.5 Selection of the host for the next bridge position

The FRIB TA Bridge Faculty Committee received four applications in response to its 2020 call. The selection criteria include the institution's alignment with FRIB science, its intellectual environment, the diversity of the physics program in its department, the department's record with young faculty and quality of mentoring, the startup package it offers, its rank among universities, its ability to attract good students, the prospect of a new position rather than a replacement, as well as the DEI plans presented in the package. All four applications received were extremely strong. The FRIB TA Bridge Faculty Committee is in the process of deliberations. The institution to be selected would conduct a faculty search in the Fall of 2021 and the appointment of the new bridge hire would begin Fall 2022.

5 Education

5.1 Summer school

The FRIB-TA Summer School on Dense Matter in Astrophysics was held online (due to the COVID pandemic) from June 30 to July 2, 2020. The school focused on dense matter in the interior of neutron stars, dense matter created in supernova explosions and neutron star mergers, and comparisons with the nuclear matter created in terrestrial experiments. The lead organizer was Veronica Dexheimer and there were interactive activities and lectures from:

- Veronica Dexheimer (Kent State University): Introduction to modeling the core of neutron stars
- Luke Roberts (Michigan State University): The physics of supernova explosions and neutron star mergers
- Pawel Danielewicz (Michigan State University): Laboratory constraints for the equation of state of neutron stars
- Rodrigo Negreiros (Federal Fluminense University, Brazil): General relativity (including the formalism to describe stellar rotation and magnetic fields) and stellar cooling
- Thomas Klähn (California State University Long Beach): Deconfined quarks and phase transitions in the core of neutron stars

The school attracted a total of 94 participants and the summer school website can be found at https://indico.frib.msu.edu/event/22/. We hope to resume in-person summer schools in late summer of 2021.

5.2 FRIB Achievement Award for Early Career Researchers.

In collaboration with the FRIB Users Organization, the TA Executive Board developed a proposal for a new annual award. The FRIB Achievement Award for Early Career Researchers is designed to recognize outstanding original contributions to the field of nuclear physics through work at or relating to FRIB, performed by scientists early in their careers. The annual award consists of a plaque with the awardee's name and institution, participant support to attend the annual Low Energy Community Meeting, receive the award, and give an invited plenary presentation on the awarded work. Two awards will be given annually, one for primarily experimental research, and one for primarily theoretical research. The FRIB award is expected to be presented by the FRIB Laboratory based on selection by the FRIB Users Organization Executive Committee (UOEC) and the FRIB Theory Alliance Executive Board (TAEB). The proposal has been presented to the FRIB management and is currently under review.

6 Meetings and connections beyond theory

6.1 Annual meeting and topical programs

The FRIB-TA annual meetings are held concurrently with the Low Energy Community Meetings (LECM). This provides the opportunity to stay informed of important experimental developments and foster collaborations between theory and experiment. The 2020 FRIB-TA Annual Meeting took place on the 10th of August, 2020. Due to the COVID pandemic, the meeting was held online via Zoom. The morning session was a summary of science highlights. Presentations were given by Maria Piarulli, Diego Lonardoni, Saori Pastore, Kevin Fossez, Chloë Hebborn, and Christian Drischler. The afternoon session consisted of an overview of activities from the chairs of each FRIB-TA committee. This was followed by a panel discussion that engaged the executive board members and the FRIB TA members attending the meeting.

Due to the COVID pandemic, no FRIB-TA topical programs were run during 2020. We hope to resume the FRIB-TA topical programs in the fall semester of 2021.

6.2 Enhancing theory-experiment collaborations

In order to support the experimental program at FRIB right from the start, the FRIB TA Executive Board (TA-EB) compiled a list of theorists who are willing to provide their expertise to experimental groups. The list, with contact information and areas of expertise, is published in pdf format on the FRIB TA web site and allows experimentalists to identify potential theory partners for planning experiments, writing proposals, and collaboration beyond. The purpose of the list is to allow for establishing initial contacts which will hopefully lead to some successful collaborations. The initial list, comprising mostly TA-EB members, TA Fellows and Bridge Faculty, was made available in late December 2020, and additional interested theorists from the broader science community are being added regularly. The list is available at the TA website: https://fribtheoryalliance.org/

6.3 Broader Impacts

Nuclear physics, and FRIB-centered science in particular, is the common meeting ground of exciting developments in many areas of physics and astronomy. These areas include high energy physics and astrophysics, especially as regards to fundamental symmetries, dark matter, gravitational wave observatories and multi-messenger astronomy, and high performance computing. Our aim in the FRIB Theory Alliance is to build bridges to these subjects through joint conferences and workshops and outreach, stoking synergistic research and training activities.

In 2020, the broader impacts committee has championed a new online colloquium series titled "Nuclear Physics Dialogues", aimed at highlighting the connection of FRIB to other thrusts of nuclear physics and astrophysics. This series was prompted by the COVID lockdown, but intended to provide a more interactive format compared to the numerous online events that had emerged by summer 2020. To that end, each 'Dialogue' has included a 30-minute presentation followed by a 30-minute Q&A and discussion session, moderated by a host, with the speaker and two panelists. Emphasis has been placed on the dialogue aspect of these online events, given that the audience spans the broader FRIB physics community. We have held seven events (six between June and September and one in November), on topics including nuclear reactions, electroweak interactions and nuclei, neutron stars and gravitational waves, nuclear short range correlations. All events have raised awareness on the connection of FRIB physics to other forefront topics of nuclear physics and astrophysics. Emphasis has also been placed on the selection of a diverse group of speakers and panelists, ranging from junior to senior scientists. The series was by successful, with many of the events having an attendance of more than one hundred physicists, and rich and lively discussions between speaker, panelists and audience, often extending well beyond the assigned time. Moreover, the events attracted also a large number of experimental colleagues, which was part of the goal. While the start of fall-semester activities made it challenging to continue the Dialogues series, we plan to resume the Dialogues series over the summer 2021.

6.4 International links

Together with our European colleagues, the FRIB-TA established the Europe-U.S. Theory Institute for Physics with Exotic Nuclei (EUSTIPEN) with the goal of facilitating collaborations between U.S.-based and Europe-based scientists whose main research thrust is in the area of the physics of nuclei, including nuclear structure and reaction theory, nuclear astrophysics, and tests of the standard model using exotic nuclei.

The purpose of EUSTIPEN is to deliver an international venue for research on the physics of nuclei during an era of investigations on rare isotopes. The EUSTIPEN program is intended to fund travel grants to the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) in Trento (Italy) for nuclear theorists and students whose current primary institutional affiliation is with a U.S. university, national laboratory, or other research center. Currently, two kinds of EUSTIPEN grants are considered:

- Travel grants for collaboration meetings at ECT* with Europe-based colleagues. For such visits, EUSTIPEN will provide travel and local support in Trento. Funding for Europe-based collaborators to visit ECT* should be provided by European funding sources;
- Travel grants for junior scientists and postdocs to attend workshops and training programs at ECT*. Support for senior researchers to attend ECT* workshops will be provided in

exceptional cases, e.g., when no local support can be provided by ECT* (e.g., when a program is oversubscribed).

The current EUSTIPEN Steering Committee includes: Jochen Wambach (ECT* Director), Muhsin Harakeh (KVI Groningen, ENSAR2 Coordinator), and FRIB-TA Executive Board Members Vincenzo Cirigliano, Jonathan Engel, Kate Jones, and Jorge Piekarewicz (chair).

Although the program was enormously successful shortly after its inception – indeed, so successful that all funds earmarked for the initiative were disbursed – the EUSTIPEN program was suspended in March 2020, due to travel restrictions with COVID. We are optimistic that with the rollout of the vaccine we will be able to rekindle our partnership with our European colleagues in the near future.

7 Diversity Equity and Inclusion

This year, the FRIB-TA added the Diversity, Equity, and Inclusion (DEI) committee to address issues of diversity in the nuclear physics community, within the scope of the Theory Alliance and the broader nuclear theory community. To this end, there were several goals in the most recent proposal that have been accomplished this year.

First, a Code of Conduct (CoC) was written based on the DOE Office of Science CoC. The CoC outlines expected behavior from FRIB-TA members while participating in community events. If a report is filed of improper behavior, a process has been outlined by which the claim will be investigated by the FRIB DEI investigator. If the claim is verified, the FRIB-TA member could face consequences up to and including expulsion from the FRIB-TA. The CoC was approved by the executive board, has been shared with the members of the FRIB-TA, and is posted on the FRIB-TA website.

In addition, several application processes have been updated to include information on DEI, both for the fellow searches and bridge applications. For the fellow search, the search committee will be briefed by FRIB Human Resources on best practices to ensure that all applicants are treated equitably during the search process. The committee will make additional efforts to diversify the pool of applicants, and these efforts must be documented and reported to the FRIB TA managing director. For the bridge program, each of the potential partner institutions who apply for the bridge program must include a one-page statement from the potential chair of the search committee describing how the hiring department (or group) will address issues of diversity, equity and inclusion both during the bridge search process and the workplace experience of the to-be-hired junior faculty/staff. Along the same lines, we are currently in the process of updating the guidelines for applications to the FRIB-TA topical programs.

Finally, we have started to examine the available DEI data that has been collected for the various FRIB-TA programs and will continue discussions within the DEI committee about additional information that could be collected from program participants to better understand the current make-up of participants to FRIB-TA events. This information will then be used to determine strategies to address DEI issues in our community.

8 Organization and Logistics

8.1 Charter

The change from a 3-year DoE grant to a 5-year funding term marked a transition for the Theory Alliance to a more mature and stable organization. This fact, combined with feedback from TA members, experience during the prior grant periods, and anticipated needs associated with the impending start of FRIB operations, prompted a review of the TA Charter. The Organization Committee completed the review and proposed several changes:

- The term of the Managing Director was extended from 3 years to 5 years, to coincide with the grant period.
- To ensure smooth transitions from one director to the next, the position of Director was replaced by a Director line. Previously, a single person served as Director for three years. In the new scheme, a new Director-Elect serves alongside the Director and the Past Director, moves to the Director position in the following year, and to the Past Director position in the third year. Members of the Executive Board are eligible to be elected to the director line after about six months of board service. The new structure allows for continuity in this leadership position and more flexibility in dealing with emerging needs.
- To have a better representation of scientists from foreign institutions in the Theory Alliance, an additional modification to the charter was passed. In the past, foreign members could not vote or serve on the board. To better utilize input from these members, scientists at foreign institutions are now allowed to vote and one seat on the board will be set aside for a theorist from a foreign institution. As is required for all board positions, candidates for the position will be reviewed in consultation with the DOE Theory Program Manager prior to board elections.

The changes were unanimously endorsed by the Executive Board, agreed to by the FRIB Laboratory Director and the DOE Theory Program Manager, and approved by the majority of the voting membership (where applicable). The updated charter is accessible on the FRIB-TA web site (https://fribtheoryalliance.org/content/charter.php).

The director of the FRIB-TA is a member of the board, selected by the board members, responsible for the overall governance of the board and called upon to represent the FRIB-TA to the outside world. Currently, Jutta Escher is serving as director, Jorge Piekarewicz is past-director and Daniel Phillips is director-elect.

8.2 Other personnel

The managing director is appointed by the FRIB laboratory director and oversees all operational aspects of the FRIB-TA, including managing the FRIB-TA grant and associated subawards and being responsible for reporting to DOE. Currently Filomena Nunes is serving as managing director. None of these functions draw funds from the FRIB-TA grant.

Gillian Olson started to work as the FRIB-TA research administrator in January 2018 (this is now a 75% time appointment, fully covered by the FRIB-TA budget). Gillian coordinates and participates in the support and administration of FRIB Theory Alliance activities, overseeing a variety of complex activities including providing support to the fellow program and the bridge program, collecting, interpreting, analyzing and auditing documentation as well as other project support tasks. Gillian's responsibilities include: conference website development and maintenance; event budgets; travel documents and export controls screening for each participant; building access and building access badges for participants; meeting rooms reservations; purchasing supplies and food related to the event; organizing group coffee breaks, lunches and dinners; arranging lodging for participants and organizers; preparing and assembling all documents for the event, including, participant list, name tags, folders, agenda, logistical information and building signage. Gillian is also responsible for logistics associated with fellow searches. Additional responsibilities for Gillian include: preparing travel documents for FRIB-TA affiliates, maintaining the FRIB Theory Alliance website; communication with the FRIB-TA membership; attending the Board Meeting and taking minutes; distributing and collecting polling data for the FRIB TA votes.

While in a typical year, Gillian spends several hours a week supporting scientists traveling under the FRIB-TA, during the pandemic, that free time was used for professional development. Gillian has been taking courses on website development and grant administration.

8.3 Theory Alliance webpage

The FRIB Theory Alliance website continues to serve as a communication tool for the FRIB-TA community, to promote and disseminate FRIB-related theory, and for outreach. The FRIB-TA owns the domain (fribtheoryalliance.com) and has contracted with the MSU IT services to provide web hosting for the site, which includes dynamical page content through PHP and database interaction with MySQL. The website is primarily managed by Gillian Olson, with support by board member Kristina Launey and content supplied by all board members. A new and improved redesign of the FRIB-TA website by Kristina Launey is currently in progress. The present content on the webpage includes a range of information on FRIB-TA science and governance such as links to "What is the FRIB Theory Alliance?", "FRIB-TA Mission and Initiatives", a science overview, the FRIB-TA charter, and members of the Executive Board and committees. Menu items lead to progress reports and solicitations for FRIB initiatives such as the FRIB-TA Fellows, summer schools, and Topical Programs. There are also links to a wide range of relevant websites (e.g., theory collaborations and institutes).

The website database stores information on the FRIB-TA members. There is a form interface to the internal database associated with the website that makes it easy for users to join the FRIB-TA and to modify their information. Membership as of February 2021 is 198 from the United States with an additional 62 from 22 countries around the world. The list of FRIB-TA members is directly available from a menu item at fribtheoryalliance.com, where it can be filtered by institution, country, and status (i.e., faculty, laboratory staff, postdoc, or student). The FRIB-TA leadership can also create internal targeted mailing lists from the member database.

The webpage regularly includes advertisements for important events, pointers to recognitions for FRIB-TA science, and job postings such as for FRIB-TA bridge and fellow positions. These and many other announcements are also distributed to the FRIB-TA membership via email from the automatically generated lists. Ongoing content development includes additional science overviews (such as Powerpoint slides promoting FRIB science) and resources for high performance computing (such as a page with links to codes), education, and outreach initiatives. One new feature added this past year is a list of potential nuclear theory collaborators. In order to support the experimental program at FRIB right from the start, we have compiled a list of theorists who are willing to provide their expertise to experimental groups. Theorists can contribute to successful proposals and experiments by providing background information, suggesting experts who can address specific questions, and by collaborating directly. In turn, experimentalists can support theorists by incorporating and acknowledging the input, as well as by including them in proposals and collaborative work beyond.

9 Deliverables

9.1 Publications

Christian Drischler (October 2020 through February 2021)

1. C. Drischler, J. W. Holt, and C. Wellenhofer, *Chiral Effective Field Theory and the High-Density Nuclear Equation of State*, arXiv:2101.01709 (invited review article; accepted for publication in Annu. Rev. Nucl. Part. Sci.)
2. C. Wellenhofer, C. Drischler, and A. Schwenk, *Effective field theory for dilute Fermi systems at fourth order*, arXiv:2102.05966 (submitted to Phys. Rev. C)

Kevin Fossez (2020)

1. Yu-Xuan Luo, Kévin Fossez, Quan Liu, and Jian-You Guo, *Role of quadrupole deformation and continuum effects in the "island of inversion" nucleus* ^{28}F, submitted.
2. C. W. Johnson *et al.*, *White paper: From bound states to the continuum*, J. Phys. G 47, 123001 (2020).
3. K. Fossez, J. Rotureau, W. Nazarewicz, N. Michel, and M. Płoszajczak, *Effective description of* $^{5-10}$*He and the search for a narrow 4n resonance*, Recent Progress in Few-Body Physics, 361 (2020). Proceedings of the 22nd International Conference on Few-Body Problems in Physics.

Sebastian König (2020)

1. H.-W. Hammer, S. König, and U. van Kolck, *Nuclear effective field theory: status and perspectives*, Rev. Mod. Phys. **92** 025004 (2020), doi: 10.1103/RevModPhys.92.025004.
2. S. König, A. Ekström, K. Hebeler, D. Lee, and A. Schwenk, *Eigenvector Continuation as an Efficient and Accurate Emulator for Uncertainty Quantification*, Phys. Lett. B **810** 135814 (2020), doi: 10.1016/j.physletb.2020.135814.
3. P. Demol, T. Duguet, A. Ekström, M. Frosini, K. Hebeler, S. König, D. Lee, A. Schwenk, V. Somà and A. Tichai, *Improved many-body expansions from eigenvector continuation*, Phys. Rev. C **101** 041302 (2020), doi:10.1103/PhysRevC.101.041302, PRC Editor's Suggestion.
4. S. König, *Energies and radii of light nuclei around unitarity*, Eur. Phys. J. A **56** 113 (2020), doi:10.1140/epja/s10050-020-00098-9.
5. S. König, *Few-body bound states and resonances in finite volume*, Few-Body Syst. **61** 20 (2020), doi:10.1007/s00601-020-01550-8.
6. C. W. Johnson *et al.*, *White paper: From bound states to the continuum*, J. Phys. G **47** 123001 (2020), doi:10.1088/1361-6471/abb129

7. U. Friman-Gayer *et al.*, *Role of chiral two-body currents in ^{6}Li magnetic properties in light of a new precision measurement with the relative self-absorption technique*, arXiv:2005.07837 [nucl-ex], to appear in Phys. Rev. Lett.

Diego Lonardoni (2020)

1. L. Riz, F. Pederiva, D. Lonardoni, and S. Gandolfi, *Spin Susceptibility in Neutron Matter from Quantum Monte Carlo Calculations*, Particles **2020**, 3(4), 706-718.

2. R. Cruz-Torres, D. Lonardoni, R. Weiss, M. Piarulli, N. Barnea, D. W. Higinbotham, E. Piasetzky, A. Schmidt, L. B. Weinstein, R. B. Wiringa, and O. Hen, *Many-body factorization and position-ĂŞmomentum equivalence of nuclear short-range correlations*, Nat. Phys. (2020).

3. D. Lonardoni, I. Tews, S. Gandolfi, and J. Carlson, *Nuclear and neutron-star matter from local chiral interactions*, Phys. Rev. Research **2**, 022033(R) (2020).

4. S. Gandolfi, D. Lonardoni, A. Lovato, and M. Piarulli, *Atomic nuclei from quantum Monte Carlo calculations with chiral EFT interactions*, Front. Phys. **8**, 117 (2020).

5. J. E. Lynn, D. Lonardoni, J. Carlson, J.-W. Chen, W. Detmold, S. Gandolfi, and A. Schwenk, *Ab initio short-range-correlation scaling factors from light to medium-mass nuclei*, J. Phys. G: Nucl. Part. Phys. **47**, 045109 (2020).

6. P. Massella, F. Barranco, D. Lonardoni, A. Lovato, F. Pederiva, and E. Vigezzi, *Exact restoration of Galilei invariance in density functional calculations with quantum Monte Carlo*, J. Phys. G: Nucl. Part. Phys. **47** 035105 (2020).

7. D. Lonardoni and I. Tews, *Local chiral EFT potentials in nuclei and neutron matter: results and issues*, PoS (CD2018) 100, (2020). Proceedings of the Ninth International Workshop on Chiral Dynamics, Sep 17-21, 2018, Durham, NC.

Saori Pastore (2020)

1. L. Coraggio, S. Pastore, and C. Barbieri, Editorial for the the Research Topic Booklet *The Future of Nuclear Structure: Challenges and Opportunities in the Microscopic Description of Nuclei*; Frontier of Physics, doi: 10.3389/fphy.2020.626976.

2. J. Barrow, S. Gardiner, S. Pastore, M. Betancourt, and J. Carlson, *Quasielastic Electromagnetic Scattering Cross Sections and World Data Comparisons in the GENIE Monte Carlo Event Generator*, to appear on Phys. Rev. D, arxiv:2010.04154.

3. L. Coraggio, N. Itaco, G. De Gregorio, A. Gargano, R. Mancino, S. Pastore, *Present Status of Nuclear Shell-Model Calculations of Neutrinoless Double Beta Decay Matrix Elements*, Universe 2020, 6, 233; https://doi.org/10.3390/universe6120233.

4. G.B. King, L. Andreoli, S. Pastore, and M. Piarulli, *Weak Transitions in Light Nuclei*, Frontier of Physics, doi: 10.3389/fphy.2020.00363.

5. G.B. King, L. Andreoli, S. Pastore, M. Piarulli, R. Schiavilla, R.B. Wiringa, J. Carlson, and S. Gandolfi, *Chiral Effective Field Theory Calculations of Weak Transitions in Light Nuclei*, Phys. Rev. C **102** (2020) 025501. PRC Editor's Suggestion.

6. S. Pastore, J. Carlson, S. Gandolfi, R. Schiavilla, and R.B. Wiringa, *Quasielastic lepton scattering and back-to-back nucleons in the short-time approximation*, Phys. Rev. C **101** (2020) 044612.

Maria Piarulli (2020)

1. M. Piarulli, *The Basic Model of Nuclear Theory: From Atomic Nuclei to Infinite Matter*, Springer Proc. Phys. **238**, 351-360 (2020).
2. M. Piarulli, I. Bombaci, D. Logoteta, A. Lovato, R.B. Wiringa, *Benchmark calculations of pure neutron matter with realistic nucleon-nucleon interactions*, Phys. Rev. C **101**, 045801 (2020), Editor's suggestion.
3. M. Piarulli and I. Tews, *Local nucleon-nucleon and three-nucleon interactions within chiral effective field theory*, Front. in Phys. **7**, 245 (2020).
4. S. Gandolfi, D. Lonardoni, A. Lovato, M. Piarulli, *Atomic nuclei from quantum Monte Carlo calculations with chiral EFT interactions*, Front. in Phys. **8**, 117 (2020).
5. M.C. Atkinson, W.H Dickhoff, M. Piarulli, A. Rios, R.B. Wiringa, *Reexamining the relation between the binding energy of finite nuclei and the equation of state of infinite nuclear matter*, Phys. Rev. C **102**, 044333 (2020), Editor's suggestion.
6. G.B. King, L. Andreoli, S. Pastore, M. Piarulli, *Weak Transitions in Light Nuclei*, Front. in Phys. **8** 363 (2020), original research article.
7. G.B. King, L. Andreoli, S. Pastore, M. Piarulli, R. Schiavilla, R.B. Wiringa, J. Carlson, S. Gandolfi, *Chiral effective field theory calculations of weak transitions in light nuclei* Phys. Rev. C **102**, 025501 (2020) , Editor's suggestion.
8. R. Cruz-Torres, D. Lonardoni, R. Weiss, M. Piarulli, N. Barnea, D.W. Higinbotham, E. Piasetzky, A. Schmidt, L.B. Weinstein, R.B. Wiringa, and O. Hen, *Many-Body Factorization and Position-Momentum Equivalence of Nuclear Short-Range Correlations*, Nature Physics (2020).

9.2 Presentations

This year is unusual. Due to COVID, many conferences were cancelled, and therefore lost were many opportunities for our fellows and bridges to make their work visible to the community. Regardless, some workshops took place online. Most of the examples below are from online presentations.

Christian Drischler (October 2020 through February 2021)

1. Contributed talk at the *2020 Fall Meeting of the APS Division of Nuclear Physics*, November 1, 2020; virtual meeting.
2. Invited talk at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2020*, August 10, 2020; virtual meeting.

Kevin Fossez (2020)

1. *Exotic nuclei from the ab initio and shell model perspectives*; Seminar, October 20, 2020, TRIUMF, Vancouver, Canada
2. *Alpha clustering and nuclear forces*; Colloquium, August 10, 2020, Low-Energy Community Meeting (LECM)
3. *Nuclear theory in the FRIB era*; Colloquium, July 27, 2020, Argonne National Laboratory, Lemont, IL, USA
4. *FRIB-TA: MoNA physics and related topics*; FRIB day-1 experiments, May 7, 2020, MSU, East Lansing, MI, USA

Chloë Hebborn (October 2020 through February 2021)

1. Invited talk at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2020*, August 10, 2020; virtual meeting.

Sebastian König (2020)

1. *Eigenvector continuation in nuclear physics*, contributed talk at the TRIUMF Nuclear Theory Workshop, March 2020, presented at TRIUMF, Vancouver, BC.
2. *Few nucleons and other stories* Argonne National Lab Physics Seminar, March 2020, presented at ANL.
3. *Status and perspectives of nuclear effective field theories*, invited talk at the APS Division of Nuclear Physics Fall Meeting, October 2020, virtual meeting.
4. *Nuclear structure and reactions from effective field theory* invited talk at the APS Division of Nuclear Physics Fall Meeting, October 2020, virtual meeting.

Diego Lonardoni (2020)

1. *Nuclear and neutron-star matter from local chiral interactions*, contributed talk at the APS-DNP Fall Meeting 2020, remote meeting, November 1, 2020.
2. *Exploring short-range correlation effects with quantum Monte Carlo*, contributed talk at the APS-DNP Fall Meeting 2020, remote meeting, October 30, 2020.
3. *Ab-initio nuclear matter equation of state*, invited talk at the FRIB Theory Alliance Meeting during the Low Energy Community Meeting 2020, remote meeting, August 10, 2020.
4. *Nuclear and neutron-star matter from local chiral interactions*, contributed talk at the 2020 NUCLEI SciDAC Collaboration Meeting, remote meeting, June 11, 2020.
5. *Monte Carlo calculations of hypernuclear properties*, invited talk at the JLab Workshop on ^{208}Pb (e, eK) and neutron stars, remote workshop, May 11, 2020.
6. *From nuclei to the nuclear matter EOS: theory opportunities, challenges, and needs*, invited talk at the FRIB First Experiments: Proposal Preparation Workshop, remote workshop, May 5, 2020.

Saori Pastore (2020)

1. Invited talk at the *APS Division of Nuclear Physics*; October 2020, virtual meeting.
2. Invited talk at the *Low Energy Community Meeting*; August 2020, virtual meeting.
3. Invited talk at the *INT Program 20-2b BSM Physics with Nucleons and Nuclei*; August 2020, virtual meeting.
4. Invited talk at the *FRIB Dialogues on Nuclear Physics*; August 2020, in-person meeting, talk given remotely.
5. Invited talk at the *Neutrinoless double beta decay - Topical collaboration Meeting*; July 2020, virtual meeting.
6. Invited talk at the *Workshop: New Physics on the Low-Energy Precision Frontier CERN*; January 2020, in-person meeting, talk given remotely.
7. HIT seminar at *Berkeley National Laboratory, CA*; December 2020, virtual meeting.
8. Nuclear seminar at *University of Maryland, MD*; October 2020, virtual meeting.
9. Theory seminar at *Jefferson Laboratory, VA*; March 2020, virtual meeting.

Maria Piarulli (2020)

1. Invited talk at *APS-April Meeting*, April 18-21 2020, virtual meeting.
2. Invited talk at *Joint exp-theory Short Range Correlations series*, June 26 2020, virtual meeting.
3. Invited talk at *Low Energy Community Meeting 2020*, August 10-11 2020, virtual meeting.
4. Theory seminar at *Ohio University*, October 6 2020, remotely.
5. Theory seminar at *University of Minnesota*, October 20 2020, remotely.
6. Invited talk at *Uncertainties in Calculations of Nuclear Reactions of Astrophysical Interest*, December 7-11 2020, virtual meeting.

9.3 Milestones

Below we present the list of milestones accomplished (blue) and to be accomplished (red), during this first year of the renewal grant.

FY2021 (June 2020 - May 2021):

- Theory Fellows and Bridge Faculty continued to develop excellent research relevant for FRIB.
- Two additional fellows started their positions affiliated with the FRIB-TA.
- A call for partners for the fellow program was sent out and a search for new fellows was conducted.
- The 3rd search for a bridge position is underway at FSU and the new faculty member is expected to initiate activities with the FRIB-TA in the Fall 2021.
- The FRIB-TA actively participated in the workshop *FRIB First Experiments Workshop: Proposal Planning*.
- The FRIB-TA ran another summer school on a topic intersecting FRIB science.
- An FRIB-TA topical program on a topic of direct relevance to FRIB will take place. This did not take place due to the pandemic.
- The FRIB-TA ran its annual meeting virtually, concurrent with the Low-Energy Community Meeting.
- EUSTIPEN operations were suspended due to the pandemic.
- A call for bridge faculty proposals was sent out and a forth optimal case for a FRIB-TA bridge position is being identified.
- Elections for the replacement of three members of the Board took place.
- A progress report describing the science achievements, the FRIB-TA's activities, and a workplan for Year-2 is produced.

We also present an update of our plans for year 2, assuming full funding.

FY2022 (June 2021 - May 2022):

- Theory Fellows and Bridge Faculty will continue to develop excellent research relevant for FRIB. Progress toward many of the topics identified in the renewal proposal will occur.
- The 4th search for a bridge position will be conducted and the new faculty member will initiate activities with the FRIB-TA.
- A call for partners for the fellow program will be sent out and a search for a new national fellow will be conducted.
- The FRIB-TA will run another summer school on a topic intersecting FRIB science.

- An FRIB-TA topical program on a topic of direct relevance to FRIB will take place.
- The FRIB-TA will run its annual meeting concurrent with the Low-Energy Community Meeting.
- If travel restrictions are released, EUSTIPEN will resume its operations and fund collaborations between U.S. scientists and European scientists at the ECT*.
- Elections for the replacement of another three members of the Board will take place.
- A progress report describing the science achievements, Center's activities, and work-plan for Year-3 will be produced.

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