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FRIB Theory Alliance

Annual Progress Report

(June 2022 - May 2023)

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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 U.S. nuclear science community. The FRIB theory bridge program creates permanent positions nationwide. The FRIB theory visitors program and topical programs foster interdisciplinary collaborations and international initiatives. The FRIB Theory Alliance educational initiatives introduce exciting interdisciplinary areas to the next generation of nuclear theorists.

2 Executive Summary

The long-term goals of the 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 retain 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 third year of the renewed five-year cycle for the FRIB Theory Alliance. The FRIB-TA fellow program (see Section 3) and the bridge program (as described in Section 4) are now well established. Our current fellows and bridge faculty have delivered excellent work of great relevance to FRIB. Below we provide a few highlight of this years activities:

- The ab initio no core shell model prediction for the radiative capture of ^{4}He(d,γ)^{6}Li, important for the Big Bang nucleosynthesis predictions, by one of the FRIB theory fellows was published in Phys. Rev. Letts.
- The ab initio Greens Function Monte Carlo predictions for the β-decay spectrum of ^{6}He done by two of our bridge faculty was highlighted as editors choice in Phys. Rev. C.
- Two of our fellows secured permanent positions, Drischler at Ohio University and Hebborn at Michigan State University.
- The first faculty member supported on the FRIB theory bridge program obtained tenure.
- FRIB theory fellows and bridges where involved in the preparation of a wide range of white papers for the long range plan [1–10]
- Several theory fellows were part of proposals submitted to FRIB PAC2.

There are two new fellows to begin their appointment this summer (Linda Hlophe to be hosted by Los Alamos National Laboratory and Grigor Sargsyan at Michigan State University).

We continue to run impactful topical programs relevant to FRIB and summer schools that bridge FRIB science into other areas. Due to the backlog from COVID, we ran three topical programs during 2022: the topical program Optical Potentials in Nuclear Physics which resulted in a white paper to appear in JPG; the topical program on Nuclear Isomers in the FRIB era; and the topical program on Few-body clusters in exotic nuclei which resulted in perspective pieces to be published in Few-body systems. Our summer school on Quantum Computing attracted a very large audience. We also made progress on updating our MoU with ECT* in connection with the Europe U.S. Theory in Physics of Exotic Nuclei (EUSTIPEN) program (see 6.3).

Our membership captures the vast majority of the national theoretical efforts in low energy nuclear physics. Currently, we have 291 members, 198 of which are from the U.S. The breakdown according to rank is: 130 faculty members, 38 staff members, 4 fellows, 63 postdoc members and 56 students. The FRIB TA website (fribtheoryalliance.org) continues to serve as an effective means to communicate with our membership (Section 8.4). The committee on Diversity, Inclusion and Equity worked with the Website committee to add demographic information to our membership database and to the event registrations (Section 7). A conflict of interest document is now established to increase transparency in how the FRIB-TA does business (see Section 8). We continue to seek ways to enhance theory-experiment collaboration through work done in connection with the FRIB users organization and PAC2 (Section 6.2). Toward the end of this report, a summary of the managing director and research administrator activities in Section 8.3 is presented, as well as a list of publications and presentations (Sections 9.1 and 9.2), followed by an update on our milestones in Section 9.3.

In summary, the FRIB-TA is making significant progress on many fronts. As stated last year, the FRIB-TA leadership would welcome a mid-term panel review as soon as possible and well ahead of the preparations of the renewal proposal. Such a review is important in creating a vision for the next cycle.

3 FRIB Theory Fellow Program

The FRIB Theory Fellowship is a five-year research position with a competitive initial annual salary capable of attracting advanced postdocs 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. Fellows are 100% MSU employees with a title of visiting assistant professors, including full benefits and a travel budget. They are in residence at a partner institution that covers 48% of their salary. 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, Diego Lonardoni, Kevin Fossez and Christian Drischler have each successfully transitioned into permanent positions.

Currently we have four fellows: Chloë Hebborn hosted at Livermore National Laboratory, Anna McCoy hosted at Washington University St. Louis, Chien Yeah Seng hosted by University of Washington and Xilin Zhang at MSU. Reports on their research activities are given below. Chloë will be moving into a permanent position in August and two more fellows will join us in the summer as a result of the FRIB theory fellow search run in 2022. This is described in Sec. 3.5.

3.1 Science highlights from Chloë Hebborn

Hebborn's research focuses on improving the theoretical description of reactions involving exotic nuclei, needed to interpret experimental data in order to arrive at a more fundamental understanding of nuclear structure and reactions, and to plan new experiments.

The rate at which helium (^{4}He) and deuterium (d) fuse together to produce lithium-6 (^{6}Li) and a γ ray is a critical puzzle piece in resolving the discrepancy between big bang predictions and astronomical observations for the primordial abundance of ^{6}Li. At low energy, direct measurements are hindered by low counting rates, they are therefore scarce and have large uncertainties. Accurate theoretical predictions are needed to guide the extrapolation of the existing direct measurements to the whole big bang nucleosynthesis (BBN) range of energies. To this end, in collaboration with Kravvaris and Quaglioni (LLNL), Navratil and Gysbers (TRIUMF) and Hupin (IJClab), Hebborn carried out *ab initio* no-core shell model with continuum [11] calculations of the ^{4}He$(d, \gamma)^6$Li reaction, which describes ^{4}He-d scattering dynamics and the bound ^{6}Li final state on an equal footing, allowing to consistently determine the contributions of the main electromagnetic transitions driving the radiative capture process. By comparing predictions obtained with different microscopic Hamiltonians derived within chiral EFT, Hebborn *et al.* quantified the uncertainties associated with the choice of the chiral 3N force and the truncation of the model space. Their results reveal an enhancement of the capture probability below 100 keV owing to previously neglected magnetic dipole (M1) transitions and reduce by an average factor of 7 the uncertainty of the thermonuclear capture rate between 0.002 and 2 GK. Their analysis suggests that the discrepancy between the predicted BBN abundance of ^{6}Li and the one inferred from astrophysical observation is larger than previously reported. This work has been published in Phys. Rev. Lett. [12]. Hebborn also contributed to the *ab initio* informed evaluation of the solar fusion reaction ^{7}Be$(p, \gamma)\,^8$B [13], important for modeling the solar neutrino flux [14, 15], led by Kravvaris.

For reactions involving heavier nuclei, the complex many-body reaction problem is simplified into a few-body one, composed of tightly bound clusters assumed structureless. Such methods are particularly well suited to treat clustering in nuclei. The quality of these few-body predictions depends on the effective cluster-cluster interactions (the so-called optical potentials) and the accuracy of the few-body method. Hebborn took the lead in organizing a FRIB-TA program focusing on optical potentials, which aimed at reviewing the current status and making recommendations for future developments. With Fossez, König and Hebborn also co-organized another FRIB-TA program focusing on few-body clusters in exotic nuclei and their role in FRIB experiments. These two programs led to the production of a whitepaper on optical potentials [1], the creation of a website gathering useful ressources for reaction calculations and a collection of perspective pieces [16] addressing the effective progress needed to bridge the gap between theoretical efforts and FRIB experimental program.

Hebborn has also worked in collaboration with Potel (LLNL) on improving few-body reaction models used to describe both one-nucleon addition or removal reactions, which are a key probe of the single-particle structure of nuclei. They derived the Green's Function Knockout (GFK) formalism, which has the advantages of treating on the same footing bound and scattering states with dispersive optical potentials and to account for dissipative effects in the nucleon extraction process. They argue that the inclusion of such effects might play a role in the long standing puzzle of the quenching of spectroscopic factors in nuclei with extreme neutrons-to-protons ratios. This formalism was published in Phys Rev. C earlier this year [17]. In the future, they plan to compare knockout and transfer observables obtained within a standard reaction model, with the GFK calculation along an isotopic chain.

As a good understanding of theoretical uncertainties is essential to infer accurate nuclear-structure information from experimental data, Hebborn has made progress in the quantification of uncertainties in reaction models. In collaboration with Whitehead (MSU), Lovell (LANL) and Nunes (MSU), Hebborn used Bayesian analysis to estimate the optical potential uncertainties in predictions for knockout reactions. This work is currently under review [18]. Hebborn and collaborators plan to study the impact of these uncertainties onto the asymmetry dependence of the spectroscopic strengths extracted from knockout data [19]. This future work might also shed some light on the long standing puzzle of the quenching of spectroscopic factors.

In addition, Hebborn has made contributions to the NSAC Long Range Plan Town Hall Meeting held at ANL, she was involved in several experimental proposals submitted to the FRIB PAC2 and she co-organized with Wei Jia Ong (LLNL) an online seminar series for the nuclear and data theory group (NDT) and the nuclear physics and accelerator technology (NPAT) at LLNL.

3.2 Science highlights from Anna McCoy

As FRIB experiments explore nuclei far from stability, accurate theoretical predictions for observables which are not readily measurable play an important role. One of the primary goals of McCoy's research is the development of accurate *ab initio* methods for predicting properties of nuclear structure and reactions. In particular McCoy works on developing variants of the no-core shell model (NCSM) including symmetry adaptive methods such as the symplectic no-core configuration interaction (SpNCCI) framework and its extension to include continuum effects. The development of these frameworks is an ongoing effort in collaboration with Pieter Maris (Iowa State) and Mark Caprio (Notre Dame) with graduate students Patrick Fasano and Jakub Herko.

In developing accurate predictive theories, it is necessary to identify and quantify uncertainties in theoretical calculations. A first step towards disentangling theoretical error associated with modeling nuclear dynamics (Hamiltonians and currents) from errors arising from solving the Schrodinger equation, is comparison of calculated results obtained using the same *ab initio* interactions but with different methods. An ongoing effort, in collaboration with Pastore and Piarulli, is to benchmark results for energies and electroweak observables obtained in NCSM and Quantum Monte Carlo (QMC) frameworks obtained using the Norfolk interaction. McCoy has also been working with experimentalist Lee Sobotka and Robert Charity (WUSTL) to identify $M1$ and $E2$ transitions which could be measured at, e.g., FRIB or ATLAS, and would be of interest for comparison with *ab initio* predictions.

While, *ab initio* methods have significant potential in terms of predictive power, they typically lack the physically intuitive understanding provided by simple models. However, *ab initio* methods like the NCSM do provide direct access to the underlying wave functions, which can be used to probe the symmetries and correlations that give rise to simple patterns, e.g., rotational bands, as well as test the validity of the simple models used to interpret experimental data.

McCoy's recent efforts have been focused on understanding the relation between emergent phenomena and approximate symmetries of the nucleus, e.g. Elliott's U(3) and its multi-shell extension Sp(3,R). In particular, McCoy has found that in the neutron-rich beryllium isotopes, namely ^{10,11,12}Be, phenomena such as parity inversion, the breakdown of the $N = 8$ shell closure, shape coexistence, and the emergence of rotational bands can all be understood in the context of the simple framework provided by these symmetries. Moreover, these symmetries emerge in *ab initio* calculations throughout the p shell. Going forward, McCoy plans to extend the exploration of symmetries to the Wigner SU(4) symmetry which is expected to play an important role in weak processes.

3.3 Science highlights from Chien Yeah Seng

Seng's current research is focused on hadronic and nuclear physics that directly impact the forefront of searches of physics Beyond the Standard Model (BSM), in particular through precision tests of fundamental symmetries. In particular, he and his collaborators perform high-precision calculations of the Standard Model (SM) theory inputs in hadron and nuclear beta decays that could further sharpen the signal of the observed anomalies via the determination of the quantities V_{ud} and V_{us}, which is currently one of the most promising avenues to search for BSM physics.

Seng assumed the position on October 2022. Right before the starting date, he presented a new theory proposal in the Low Energy Community Meeting (LECM) 2022, which suggested to constrain the so-called isospin-symmetry-breaking correction $\delta_{\rm C}$ in superallowed nuclear beta decays, one of the most important theory inputs for the precise determination of V_{ud}, model-independently through experimental measurements of electroweak nuclear radii [20]. Shortly after that he proposed, along the same line of thought, that the information of nuclear charge radii pairs can also be used to determine the nuclear charge weak form factor in beta decay processes which, in existing literature, were only computed using rather crude approximations without a proper estimation of theory uncertainties [21]. These new ideas provide extra theory motivations for some of the planned measurements of charge radii in FRIB PAC2, for example ^{14}O, ^{26}Si, ^{42}Ti and ^{50}Fe. He is also working with collaborators on a comprehensive re-analysis of the superallowed beta decay ft-values based on existing data of nuclear charge distributions, which will have a profound impact on the value of V_{ud}.

Another ongoing research effort of Seng concerns the high-precision determination of the nuclear-structure-dependent radiative correction $\delta_{\rm NS}$ in superallowed beta decays, another central theory input for the V_{ud} determination. Together with Mikhail Gorchtein in Germany, he outlined a complete dispersive formalism that relates $\delta_{\rm NS}$ to the parity-odd nuclear structure function F_3 [22], based on the same method they pioneered earlier in the single-nucleon sector [23, 24] which has enjoyed great success. The dispersive formalism sets the foundation for *ab-initio* nuclear theory calculations of $\delta_{\rm NS}$ which have never been attempted before. Seng is currently collaborating with the group of Saori Pastore (WUSTL) and Petr Navratil (TRIUMF) on the calculation of $\delta_{\rm NS}$ in $^{10}\text{C}\rightarrow^{10}\text{B}$ using two distinct ab-initio approaches.

Seng has contributed to the writing of two white papers submitted for the NSAC Long Range Plan, one on fundamental neutron physics [2] and the other on nuclear beta decay [25]. He will also be directly involved in the research program conducted by a new DOE-funded Topical Collaboration "Nuclear Theory for New Physics" (NTNP). Finally, he is also preparing for two invited review papers this year, one on radiative corrections in neutron beta decay which will be submitted to *Universe*, and the other on nuclear structure effects in superallowed beta decays which will be submitted to *Annual Review of Nuclear and Particle Science.*

3.4 Science highlights from Xilin Zhang

Zhang's main research studies nuclear scattering and reactions (continuum physics) at microscopic (many-body) and macroscopic (few-body) levels. In the past few years, he has been focusing on adapting and developing the so-called projection-based emulators to solve important problems in this area. Generally speaking, for a parameterized model, an emulator provides an efficient way to interpolate and extrapolate the model outputs in the model input-parameter space, after the emulator gets "trained" against those outputs. In several studies [26–30], projection-based emulators have been shown to have remarkably robust extrapolation capabilities.

In the last year, Zhang has been exploring ways to capitalize on this capability to enable new bound and continuum state calculations. The basic strategy is to extrapolate calculations performed in the region of the parameter space where the calculations are feasible to the difficult region where the realistic problems sit. Two new ideas emerged in his explorations of this strategy within simplified toy systems. They led to ongoing collaborations with few and many-body (*ab initio*) calculation experts on testing these ideas for solving nuclear physics problems. These collaborations, in turn, started extending Zhang's interests into nuclear structure.

To emulate the continuum states of a given Hamiltonian, the new approach treats the complex plane of the energy variable (E) as part of the input parameter space. By contrast, the existing continuum state emulators (e.g., [27, 31–33]) are designed for fixed real energies, i.e., the training and emulation calculations share the same real E. The new emulators are trained against the full calculations performed with Es far away from the real axis in the complex plane and then applied to extrapolate the continuum observables to the real axis and further onto the nonphysical Riemann sheet (where resonances can be located). Since the solutions of those training calculations are localized spatially, they, in principle, can be computed via current nuclear structure methods. As a result, this complex-E emulation could create a new type of *ab initio* continuum state calculations based on existing bound-state solvers. Zhang's preliminary results [34] on two and three-body scattering and reactions demonstrate the feasibility of this approach. Currently, he is collaborating with Bijaya Acharya and Alex Gench (experts in different *ab initio* methods) to study this approach for many-body continuum physics.

To expand the reach of the *ab initio* bound-state calculations to heavier nuclei, Zhang has been applying projection-based emulators to connect easy calculations to the calculations for the full-rank realistic problem. Projection-based emulators have the potential to treat larger systems since they compute eigensystems of Hamiltonians with low-rank matrices. He has been working with Kenneth Sun (a MSU undergraduate student) to develop this idea in a single-particle system. They recently achieved encouraging results. Currently, they are working with Alex Gnech to test this approach in the nuclear many-body problem. Lately, Zhang initialized a project to study this approach for continuum state calculations and emulations.

In addition, by collaborating with Drischler (previous FRIB Theory Alliance Fellow and now a faculty member at Ohio University) and Furnsthal's group (at The Ohio State University), Zhang has been actively introducing the projection-based emulators from the field of model order reduction to the nuclear physics community. Zhang and collaborators have published a semi-review on emulators (known as "guide" of the Journal of Physics G) [35] and an invited contribution [36] to the "Uncertainty quantification in nuclear physics" Topic in Frontiers in Physics, which are also mentioned in Sec. 4.1. Moreover, Zhang is working with Satoshi Nakamura (an expert in hadronic physics) to develop continuum-state emulators for hadronic coupled-channel models and to introduce these emulators to the field of hadronic physics, where the potential of these emulators in drastically improving model calibrations has not been fully appreciated.

3.5 FRIB Theory Fellow search

In 2022, a search for two FRIB Theory Fellows was conducted, following the document providing guidance for fellow searches[1]. The members of the search committee were: Scott Bogner (FRIB & MSU; MSU representative), Alexandra Gade (FRIB & MSU), Calvin Johnson (SDSU; co-chair and affirmative action representative), Gaute Hagen (ORNL), Saori Pastore (WashU; chair), Gre-

[1] See https://fribtheoryalliance.org/ under Resources and Procedures for Inititatives.

gory Potel (LLNL; former FRIB Theory Fellow), and Nicole Vassh (TRIUMF). Only one partner institution was identified, *i.e.*, Los Alamos National Laboratory. Ingo Tews (LANL) served on the committee as a voting representative from the partner institution. In years past, in order to limit potential conflicts of interest, representatives of the partner institutions could provide comments but not vote. However, given there was only one partner institution in 2022, the search committee, under the guidance of Filomena Nunes, agreed to grant voting rights to the partner institution's representative.

Given the two positions advertised and the strong pool of candidates, five FRIB Theory Fellow candidates were interviewed. The interviews were held in-person at FRIB on the MSU campus from December 5–9, 2022. The final search committee deliberations took place on December 12, 2022, and produced a ranked list based on the following criteria: excellence of research, including intellectual leadership; relevance to the FRIB mission and the ability to be an effective FRIB Theory Alliance ambassador; and promise of future leadership, not only in research but also in mentoring and in Diversity, Equity and Inclusion. The list was reported to the FRIB TA Board, who approved the list of candidates ranked by the search committee. This selection was corroborated by DOE-NP and the FRIB laboratory director. The two top ranked candidates, Linda Hlophe and Grigor Sargsyan, accepted the offer: Hlophe to be hosted by Los Alamos National Laboratory and Sargsyan by MSU, both starting in the summer of 2022.

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 four faculty under its bridge program and next we include their research progress, with faculty member Saori Pastore having moved out of the program since obtaining tenure at WashU. Other considerations for the FRIB theory bridge program are discussed in Section 4.6.

4.1 Science highlights from Christian Drischler

In mid-August 2022, Christian joined the Department of Physics & Astronomy at Ohio University as FRIB Theory Alliance Bridge Faculty. He is excited to continue his research on the nuclear equation of state (EOS) and projection-based emulators for nuclear physics and reactions within the FRIB community. His research puts measurements at FRIB in the broader context of nuclear astrophysics, enabling studies of their implications for the structure and evolution of neutron stars using chiral effective field theory (EFT) and many-body theory.

At Ohio University, Christian has become the faculty advisor of the Physics & Astronomy Graduate Students (PandA GradS). Founded in 2020, PandA Grads is an Ohio University Student Organization to foster camaraderie between graduate students of all fields and years and engages them in activities pertaining to their academic progress. An essential aspect of Christian's role as the organization's faculty advisor has been advancing and promoting DEIB (Diversity Equity Inclusion and Belonging) in close collaboration with the organization's executive committee. Several DEIB-oriented events, including student discussion sessions, have been planned for the academic year 2023. Furthermore, Christian currently serves on the search committee for hiring an Assistant Professor (Tenure-Track) in Experimental Low-Energy Nuclear Physics at Ohio University.

Christian completed several projects exploring model order reduction (MOR) to construct fast & accurate emulators for nuclear physics and reactions. The projects were conducted in collaboration with the Ohio-based BUQEYE collaboration, including FRIB Theory Fellow Xilin Zhang. Emulators are low-dimensional surrogate models capable of rapidly and reliably approximating high-fidelity model calculations. Although mature in applied mathematics, the field of MOR has only recently become of growing importance in nuclear physics due to its ability to extract key insights from complex simulations while discarding computationally demanding and superfluous information. In general, uncertainty quantification (UQ) is a fertile area for these new emulators [37–45]. Applications that these emulators will facilitate include Bayesian parameter estimation for EFT and optical models, UQ for nuclear structure pushing toward larger masses and for reactions across the chart of nuclides and experimental design [46–48] for the next generation of precision experiments probing the nuclear dripline (e.g., those at FRIB).

Christian and collaborators wrote two review articles [35, 36] aimed at fostering a wider adoption of emulators in nuclear physics and reactions through the evangelization of their potential and the creation of pedagogical guides for readers new to MOR. The first article [35] provided a comprehensive overview of the established MOR literature in applied mathematics. This work identified "eigenvector continuation"—a game changer recently rediscovered in nuclear physics [26]—as a special case of a much more general and well-studied MOR formalism for parameterized systems.

The second article [36] was an invited contribution to the Research Topic "Uncertainty quantification in nuclear physics" in Frontiers in Physics (edited by Maria Piarulli, Evgeny Epelbaum, and Christian Forssén). It presented a pedagogical introduction to projection-based emulators, including variational and Galerkin projection methods, efficient offline-online decompositions for Hamiltonians with affine parameter dependencies, and hyperreduction methods. The article explored how these general tools, which are not well-known in the nuclear physics community, lead to emulators for bound and scattering systems that enable fast & accurate calculations using many model parameter sets. Among the scattering emulators were three new types: unconstrained Kohn emulators, Schwinger emulators, and origin emulators. The latter type promises a high compatibility with existing MOR software libraries. A companion website [49] provides interactive, open-source Python code in the form of annotated Jupyter notebooks so that practitioners can readily adapt projection-based emulators for their own work.

Building on their previous work [31, 50], Christian and collaborators extended their emulator for two-body scattering based on the Kohn variational principle (KVP) to momentum space and coupled-channel scattering. Spurious singularities known as Kohn anomalies are mitigated using the general KVP, which allows for the simultaneous emulation of scattering solutions with different boundary conditions. This efficient method of mitigating Kohn anomalies had been developed by Christian in collaboration with Filomena Nunes' group at FRIB [31]. The new KVP-based emulator was successfully tested on a modern chiral nucleon-nucleon interaction, and its efficacy in emulating a variety of scattering observables benchmarked against the promising Lippmann-Schwinger-based emulator developed in Ref. [50]. The conclusion of this work has enabled two-body scattering emulators to be readily implemented in workflows to construct improved chiral potentials—and soon optical potential as well. Novel chiral nucleon-nucleon and three-nucleon interactions will be crucial for improved predictions of the nuclear EOS and derived observables for astrophysical applications—a research avenue that Christian is pursuing with his collaborators at Ohio University, MSU/FRIB, and UC Berkeley. Several contributions to Town Halls and White Papers in preparation for the upcoming NSAC Long Range Plan along these lines of research were made [3, 4].

While still at FRIB/MSU, Christian supervised a college student within the 2022 Summer Research Opportunities Program (SROP) at Michigan State University (MSU). SROP aims to increase the number of underrepresented students who pursue graduate study and research careers and helps prepare undergraduates for graduate study through intensive research experiences with faculty mentors and enrichment activities. The research project analyzed empirical constraints of the nuclear saturation point from various density functional theory calculations using Bayesian statistical methods, resulting in statistically rigorous benchmarks for chiral interactions.

4.2 Science highlights from Kevin Fossez

Kevin Fossez joined Florida State University (FSU) as an FRIB Bridge in August 2021 where he is pursuing 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), or traditional facilities such as the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL) and the local John D. Fox Laboratory at FSU. Exotic nuclei play an important role in astrophysical processes leading to the formation of elements in the Universe, and their properties reveal important information about nuclear forces [51] and how atomic nuclei self-organize [52]. To achieve the theoretical exploration of the drip lines, Kevin uses and develops various many-body techniques such as the Gamow shell model (GSM) [53], the density matrix renormalization group (DMRG) method for open quantum systems [54], and the in-medium similarity renormalization group (IM-SRG) method [55], 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 [56]. However, a first attempt at simplifying a shell model interaction using effective scale arguments gave surprisingly precise and accurate predictions for some of the most exotic nuclei ever created [57], 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.

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 [58, 59] 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 $N = 20$. These efforts led to successful collaborations with the experimental group MoNA at FRIB in the past, and recently motivated an experiment on the isotope ^{30}F which was accepted as one of the first experiments at FRIB. In 2022, a detailed DMRG study of the unbound spectra of $^{25-33}$F isotopes was published to guide future experiments [60]. Moreover, efforts are underway to use the newly introduced eigenvector continuation method [26] in the *ab initio* context to access resonant states of light nuclei otherwise nearly impossible to converge using conventional techniques. A first collaboration with Sebastian König's group gave successful results at the two-body level (to be submitted) and opened promising avenues for larger systems.

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.

Kevin was also co-organizer of the FRIB-TA Topical Program "Few-body cluster structures in exotic nuclei and their role in FRIB experiments" (2022) together with Sebastian König (initiator) and Chlöe Hebborn, to foster theory-experiment collaborations on this topic. This program led to a white paper [5] (submitted) provided as input for the NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics held at ANL in November 2022. Beyond this contribution, Kevin also participated actively in the writing of the low-energy nuclear theory report for the Long-Range Plan.

4.3 Science highlights from Sebastian König

Sebastian Koenig has worked as FRIB-TA bridge faculty in the Physics Department at NC State University since January 2020. His research covers a range of topics in theoretical low-energy nuclear physics, centered around effective field theories (EFTs) applied to few-nucleon systems, finite-volume techniques, and other aspects of *ab initio* calculations. His research program has an impact on the nuclear structure and nuclear reaction program at FRIB, particularly concerning the most loosely bound systems such as halo nuclei.

Finite-volume calculations are a powerful and versatile method to treat both bound and unbound systems, giving access in particular to otherwise difficult to obtain asymptotic properties of wavefunctions. Together with his research group at NC State, Koenig combines formal theory developments with efficient numerical simulations of quantum systems, covering the few-nucleon sector as well as heavier systems with effective few-body character. At the center of this work are studies of unstable states (resonances) with different methods, and the development of new frameworks to describe nuclear halo and cluster states.

In August 2021, Koenig received a CAREER award from the National Science Foundation to expand the finite-volume research program. Two graduate students, Nuwan Yapa and Hang Yu, are now funded in part by this grant, titled "Few-Body Phsyics in Finite Volume."

Early last year, Yapa and Koenig completed work, published in Physical Review C [61] that extends the powerful framework that has become well known in nuclear physics "eigenvector continuation (EC)" to perform highly efficient extrapolations of finite-volume calculations across large ranges of volumes. This technique greatly leverages the reach of finite-volume searches for few-body resonance states, for which experimental indications exists in few-neutron systems, and which are also likely to be found in halo states near the driplines. In a collaboration that spans across FRIB-TA Bridge faculty positions, Yapa and Koenig are working with Kévin Fossez at FSU on another extension of EC that applies the method directly to resonance states. A first preprint on this topic will appear shortly.

Yu has been working on deriving the finite-volume correction for bound states of charged particles, which plays a crucial role in extending finite-volume studies to a larger range of nuclei and reactions. In particular, knowing the functional form of the volume dependence enables precise extractions of otherwise difficult to determine asymptotic normalization coefficients that govern low-energy nuclear capture reactions. A preprint [62] with results has been posted in December 2022 and is being reviewed by Physical Review Letters at the time this report is being written.

Koenig organized an FRIB-TA Topical Program entitled "Few-body cluster structures in exotic nuclei and their role in FRIB experiments" together with Kévin Fossez and Chloë Hebborn. This program was held in person at FRIB in August 2022 and brought together theorists and experimentalists working on this topic. Together the organizers and participants authored a white paper [5] submitted to the 2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics held at Argonne National Lab in November 2022.

4.4 Science highlights from Saori Pastore

Saori Pastore's research lies at the intersection of nuclear physics, fundamental symmetries and neutrino physics. It is of direct relevance to the fundamental symmetries program of FRIB and to the recently formed DOE Topical Collaboration: Nuclear Theory for New Physics, of which Pastore and Piarulli are members.

To date, Pastore has focused on the development and implementation of many-body electroweak current operators [63–65] in studies of electroweak transitions and scattering in atomic nuclei [66–70]. Pastore uses chiral effective field theory along with more phenomenological approaches to construct many-nucleon 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 for a full accounting of 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 are essential to accurately explain the data. For example, correlations and currents are required to explain the observed nuclear magnetic moments in light nuclei [66], and Gamow-Teller and electromagnetic decay rates [68, 71].

Pastore and collaborators developed the Short-Time-Approximation (STA) to study electron and neutrino scattering from nuclei [70, 72]. The scope of this new QMC algorithm is to access nuclei of experimental relevance in the $A \sim 40$ region without losing the resolution attained in light systems, that is, without losing the important contributions arising from nuclear many-nucleon effects. Additionally, 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 [70, 72]. A recent development has been reported in Ref. [73] where different computational methods, including the STA, are benchmarked and compared to the available experimental data for inclusive cross sections of electron scattering from ^{3}He and ^{3}H. This benchmark allowed for a precise quantification of the uncertainties inherent to factorization schemes used to develop the STA. This work resulted in a PRC Editors' Suggestion publication with first author Lorenzo Andreoli, a post-doctoral fellow working at Washington University in St. Louis. Ground state properties of the target nuclei have been recently reported in Ref. [74] with lead author Maria Piarulli. This work resulted in a PRC Editors' Suggestion publication reporting on a comprehensive study of single- and double-nucleon densities and momentum distributions based on the chiral Norfolk many-nucleon interactions.

In the past, nuclear β decays have been instrumental in establishing the Standard Model as the theory of electroweak interactions. Nowadays, β decays still provide very sensitive and unique probes of physics beyond the Standard Model. For example, β decay spectra provide sensitive probes of charged-currents with different chiral structure from the Standard Model. With experimental sensitivity approaching the permille level, it is crucial to provide comparably accurate theoretical predictions of the β spectrum in the Standard Model. This is a necessary prerequisite to properly disentangle nuclear physics effects from new physics signals. In Ref. [75], Garrett King, a graduate student at Washington University in St. Louis, performed *ab initio* calculations of the β decay spectrum of ^{6}He and analyzed their sensitivity to variations in the cutoff used to regularize the Norfolk nucleon-nucleon interaction, and in the data set used to fit the low-energy constants entering the Norfolk nucleon-nucleon potential. The ensuing theoretical uncertainty on the β spectrum is found to be well below the permille level. This work resulted in a PRC's Editors' Suggestion. Additionally, Garrett King performed *ab initio* calculations of *i*) partial muon capture rates for ^{3}He and ^{6}Li nuclei, which were recently published in Ref. [76]; and *ii*) B(GT) values for the ^{11}C$\rightarrow^{11}$N and ^{11}B$\rightarrow^{11}$Be transitions, while the extraction of the experimental data was carried out by Jaclyn Schmitt, a graduate student at MSU/FRIB. In 2021-2022, Pastore participated in the writing of white papers and topical group reports [6–10] relevant to the Snowmass community exercise. In 2022, Pastore participated in the writing of an invited review on '50 Years of Quantum Chromodynamics' appeared on the European Physical Journal C.

The computational time for these calculations was provided by the 2021/2022; 2022/2023 ALCC and INCITE allocations for proposals of which Pastore and Piarulli are co-PIs.

4.5 Science highlights from Maria Piarulli

Piarulli's research focuses on the development of theoretical and computational approaches for accurately explaining nuclear properties observed in light nuclei and massive systems such as neutron stars. A particular strength of Piarulli's work relevant to the FRIB program in general is the formulation and optimization of realistic nuclear interactions (and electroweak currents) that are the main input of sophisticated computational methods, including Quantum Monte Carlo (QMC) methods.

Over the last two decades, chiral effective field theory (χEFT) [77–79] has gained popularity in the field of low-energy nuclear physics due to its deeper connection to the fundamental theory of quantum chromodynamics (QCD), as opposed to the more traditional phenomenological approaches previously used [80]. Specifically, Piarulli and collaborators have constructed a family of high-precision two- and three-body chiral nuclear interactions suited for QMC calculations, referred to in the literature as the Norfolk potentials (NV2+3s) [81–83]. These models have been implemented in Variation Monte Carlo (VMC) and Green's Function Monte Carlo (GFMC) codes and used to perform calculations of the energy levels [84, 85], charge radii, as well as longitudinal elastic form factors [86], and single beta-decay transitions [71, 87] of $A = 4 - 12$ nuclei, which were found to be in very satisfactory agreement with the experimental data. Two of the NV2+3s have been also used to perform VMC calculations of the Fermi, Gamow-Teller, and tensor densities for ^{6}He $\to$ ^{6}Be and ^{12}Be $\longrightarrow$ ^{12}C transitions [88], relevant for studies of $0\nu\beta\beta$.

Taking advantage of the computational resources provided by the DOE ALCC-2020/2021/2022 and INCITE programs, the Norfolk interactions were used to computed inclusive muon captures for light nuclei with mass numbers $A = 3$ and $A = 6$ [76], carried out by the graduate student Garrett King at WashU. The study of these processes, for which experimental data are available, will allow us to test the predictive power of our theoretical models in an energy-momentum regime relevant for low-energy neutrino-nucleus scattering and neutrinoless double beta decay, where data are scarce or absent. Garrett King also conducted calculations of the beta-decay spectrum of ^{6}He using Quantum Monte Carlo methods and the Norfolk chiral interactions. These studies are sensitive probes of physics beyond the Standard Model which are highly complementary to searches at the energy frontier. This work was published in Ref. [75] as an Editor's suggestion article. Moreover, as mentioned in Section 4.4, the B(GT) values for the ^{11}C$\to$^{11}N and ^{11}B$\to$^{11}Be transitions were computed through Quantum Monte Carlo calculations by Garrett King, alongside the extraction of experimental data which was conducted by Jaclyn Schmitt, a graduate student at MSU/FRIB.

A comprehensive set of new results of one- and two-body densities and momentum distributions has been compiled for a variety of nuclei in the range $A = 2 - 12$ using the NV2+3s forces. Our findings have been reported in Ref. [74] and published as an Editor's suggestion article. The results are available online for the benefit of the nuclear physics community at large. These calculations are particularly relevant for understanding features of the short-range structure of nuclei and providing useful insights into various reaction processes. It should be noted that a few of these calculations have already contributed to a novel study of many-body factorization and the position-momentum equivalence of nuclear short-range correlations, using a Generalized Contact Formalism (GCF), which was reported in Nature Physics [89].

The auxiliary diffusion Monte Carlo (AFDMC) is a more efficient algorithm for dealing with larger nuclear systems compared to the GFMC. In 2020, we published in Ref. [90] AFDMC calculations of the equation of state (EoS) of neutron matter by using the set of Norfolk two-body model set, NV2s. Benchmarking the AFDMC results with the Fermi hypernetted chain + single-operator chain (FHNC/SOC) and Brueckner-Hartree-Fock (BHF) many-body methods, it was realized that previous AFDMC calculations overestimate the energy per particle of infinite neutron matter when spin-orbit terms are present in the nuclear interaction. To remedy this shortcoming, ultimately due to the constrained-path approximation employed to deal with the fermion-sign problem, unconstrained propagations for 14 and 38 nucleons in a periodic box were performed. These new AFDMC results are in much better agreement with FHNC and BHF predictions, thereby allowing for a robust estimate of infinite neutron-matter properties. As a follow-up to this work, similar benchmark calculations that included the three-body forces, consistently derived with the two-body NV2s, were completed. The findings of this study have been published in Ref. [91].

Piarulli, along with Jason Bub, a graduate student at WashU, and Ingo Tews from LANL, were invited to contribute a Chapter to the "Handbook of Nuclear Physics" published by Springer in 2022. The Chapter provides an overview of "Local Two- and Three-nucleon Interactions Within Chiral Effective Field Theory". Moreover, Piarulli had the opportunity of collaborating with Professor Lee Sobotka, a nuclear experimentalist at WashU, to author a "News and Views" article in the journal Nature. The article was a commentary on the groundbreaking research paper "Observation of a correlated free four-neutron system" by M. Duer et al., and was published in the June 2022 edition of Nature [92].

In July 2021, Piarulli received the 2021 U.S. Department of Energy Office of Science (DOE-SC) Early Career Research Program award. One graduate student, Jason Bub, is now funded by this grant titled "From Atomic Nuclei to Infinite Nucleonic Matter within Chiral Dynamics". PhD student Jason Bub is working on improving the precision and accuracy of chiral nuclear models by using Bayesian statistics for parameter estimation and uncertainty quantification. In 2022, Piarulli was invited to be a co-organizer of the Working Group session on Theory of Nuclear Structure, Decays and Reactions for the *2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics*.

Pastore and Piarulli were co-PIs of the newly formed DOE Topical Collaboration, "Nuclear Theory for New Physics", and the Nuclear Computational Low Energy Initiative (NUCLEI), both awarded in 2022.

4.6 Update on FRIB-TA Bridge Committee

The search for a faculty member at Ohio University, conducted in collaboration with the FRIB-TA Bridge program, concluded successfully in March 2022, with Christian Drischler accepting an offer to join the Department of Physics and Astronomy at Ohio University.

Pastore has received tenure at Washington University, and further promotions to Associate Professor from amongst the ranks of the FRIB-TA bridge faculty are anticipated soon. The FRIB-TA Bridge Committee has therefore solicited applications for partners for another FRIB-TA bridge position. Applications close at the end of February and the institution selected will be announced in late March or early April, so that they can conduct a search in Fall 2023.

In parallel, we have been discussing modifications to the bridge program that would make it more appealing to a broader range of institutions than those that have applied thus far.

5 Education

5.1 Summer school

The FRIB-TA Summer School on *Quantum Computing and Nuclear Few- and Many-Body Problems*, organized by Alexei Bazazov, Scott Bogner, Heiko Hergert, Matthew Hirn, Morten Hjorth-Jensen, Deen Lee, Huey-Wen Lin, and Andrea Shindler, all from MSU, was held June 20 – 22, 2022 at FRIB. The school combined a series of lectures and hands-on exercises to cover the ways in which quantum-computing algorithms can be used to study few- and many-body problems in low-energy nuclear physics. After first introducing basic ideas in the field of quantum computing, the lectures focused on particularly promising algorithms and on error mitigation. The instructors were Alexei Bazavov, Joey Bonitati, Benjamin Hall, Morten Hjorth-Jensen, Ryan Larose, and Zhenrong Qian. The school attracted 56 participants (chosen from 71 applicants). More information is at the school's website: https://indico.frib.msu.edu/event/54/.

The education and topical program committee has selected another summer school for this coming year and an announcement will be made soon. We expect to hold this school in-person in the summer of 2023.

5.2 FRIB Achievement Award for Early Career Researchers.

The FRIB Achievement Award for Early Career Researchers, bestowed for the first time in 2021, 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. The 2022 awards for theory and experiment were presented at the Low-Energy Community Meeting. Amy Lovell (LANL) won the FRIB Achievement Award for Earlier Career Researchers in the Theory category. Lovell's works focuses on (among other things) Bayesian optimization and uncertainty quantification for optical model potentials, propagation of uncertainties to reaction observables, and machine-learning approaches to fission-fragment mass yields, which are relevant to astrophysics and applied nuclear science. Lovell currently serves on the FRIB-TA board. The award in the Experimental category went to Jaspreet Singh Randhawa (Notre Dame).

A new call for nominations has been issued and the TA will work again with the FRIB UO to identify and continue to honor early-career scientists and their achievements.

6 Meetings and connections beyond theory

6.1 Annual meeting and topical programs

The Theory Alliance held its annual meeting and reported to the broader community on TA activities at the Low-Energy Community Meeting, in hybrid mode on August 8-10, 2022. The FRIB theory Fellows (Chloë Hebborn, Xilin Zhang, Anna McCoy) and FRIB theory bridge faculty (Christian Drischler, Kevin Fossez, Sebastian König, Maria Piarulli) presented a summary of their activities and Saori Pastore as director-elect gave an overview of recent TA activities to the whole community.

This year we are in the midst of a community long range plan exercise. The FRIB-TA had a large presence at the Nuclear Structure and Reactions Town Hall Meeting that took place in ANL, 14-16 November 2022. FRIB theory fellows and bridge faculty were actively engaged in the preparation of the white papers which serve as input to the Long Range Plan writing group. In addition, support for the FRIB-TA and all its initiatives is featured prominently in the first recommendation from this Town Hall.

In 2022, we ran three topical programs in person. Normally we run one topical program per year, but due to the backlog created by the pandemic, the FRIB-TA board agreed to run several programs to catch up. The first was on "Optical potentials in nuclear physics", organized by Chloë Hebborn, Wim Dickhoff, Jeremy Holt, Filomena Nunes, and Gregory Potel, and took place March 21 – April 1. There were 33 attendees and the outcome of the meeting was a white paper accepted for publication in J. Phys. G. [1]. The second was the program "Nuclear isomers in the era of FRIB", organized by Filip Kondev, Wendell Misch, and Matt Mumpower, which took place in May 9-20. This program has 30 attendees. And the third was "Few-body cluster structures in exotic nuclei and their role in FRIB experiments", organized by Sebastian König, Kevin Fossez, and Chloë Hebborn and took place 15-26 August. It has 26 attendees and the resulting perspective pieces have been submitted for publication in Few Body Systems [16].

6.2 Enhancing theory-experiment collaborations

The Theory Alliance has been collecting data on the effectiveness of its efforts to build collaborations with experimental colleagues. In October 2022 a survey was sent to all FRIB-TA members to ascertain the extent of FRIB-TA participation in the PAC-1 process.

About 25% of those surveyed participated in the proposal process for PAC-1. The survey data indicated that FRIB-TA members were listed as co-authors on at least 37 proposals to the FRIB PAC and, of these, at least 25 were awarded beam time. Thanks to help from FRIB management these data will be checked against information from successful PAC-1 proposals. For future PAC calls we hope to collaborate with FRIB management to collect these statistics directly from PAC proposals—thereby avoiding the potential inaccuracies of under-reporting on surveys.

The FRIB-TA has also continued its efforts to foster these collaborations. In December 2022 then FRIB-TA Director Phillips participated in a Webinar for those interested in submitting a proposal to the FRIB PAC-2. He explained the ways that FRIB-TA members can help before, during, and after the formulation of an experimental proposal. Phillips highlighted that, as noted in last year's report, the FRIB-TA has put together a list of theorists who are interested in collaborating on the formulation and interpretation of experiments.

As discussed in the previous subsection, the Theory Alliance ran Topical Programs of high relevance to the FRIB experimental program in 2022. Furthermore, the next FRIB-TA Topical Program "Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments" will take place in May 2023 and is explicitly designed to foster dialogue and collaboration between FRIB-TA members and experimental colleagues.

6.3 International links

The Europe-U.S. Theory Institute for Physics with Exotic Nuclei (EUSTIPEN) program was re-instituted in September 2022 with an agreement signed by FRIB director Thomas Glasmacher and Gert Aarts, director of the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*). A similar agreement already existed in the past, but had expired in May 2020 and was not revived rightaway due to the COVID-19 pandemic, which forced scientists to stop traveling. The goal of the program is to facilitate 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 with exotic nuclei. The EUSTIPEN program is intended to fund travel grants to 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. The program funds travel both to collaboration meetings at ECT* with Europe-based colleagues and, for junior scientists and postdocs, to attend workshops and training programs at ECT*. In the fall of 2022, the FRIB-TA webpage was updated with the relevant information on this newly re-instituted program. In December 2022, after the ECT* scientific program was made public, the current FRIB-TA committee for international links — Sonia Bacca (chair), Jon Engel, and Elena Litvinova — helped the ECT* director to select the workshops eligible for the EUSTIPEN program. The committee is now looking forward to receiving and evaluating applications.

In parallel, the committee is discussing possibilities for other agreements that will connect the FRIB-TA at the international level and provide further visibility and collaboration opportunities. In particular, the possibility of re-instituting the pre-existing collaboration program between the

U.S. and France (FUSTIPEN) is presently being investigated and a possible collaboration with the SAIFR-ICTP institute in Brazil is being discussed.

7 Diversity, Equity and Inclusion

The Diversity, Equity and Inclusion (DEI) committee focused on collecting demographic information about its membership (voluntarily given). Working with the Webpage committee (details in Sec. 8.4), the FRIB-TA's membership sign up was updated to not only include information about a member's professional status and contact information, but also their Gender Identity, Ethnicity, Race, and whether they have a disability. Collecting voluntary demographic information from members allows us to compare the make up of summer schools, topical programs, and other FRIB-TA activities with the representation in the nuclear theory community as a whole. We intend to track how the representation in these programs compares to the overall membership and identify trends. In the long term, these statistics will allow us to determine the success of our outreach to broad, diverse communities.

Additionally, the DEI committee has been discussing ways to interact more closely with other FRIB-TA committees. This type of interaction has already lead to some DEI changes, such as the inclusion of a diversity plan in the topical program submissions. However, to more consistently integrate DEI into the broader FRIB-TA community the DEI committee is brainstorming other ways to formally ensure that diversity, equity, and inclusion efforts are weighted with other considerations when FRIB-TA decisions are made.

At the 2022 April meeting, Pastore gave a talk during the Mini-Symposium on "Broadening Participation in Nuclear Science" regarding the efforts of the FRIB-TA. She had good interactions with members of the community following her talk and brought questions back to the DEI committee.

8 Organization and Logistics

The FRIB-TA is ruled by its charter (https://fribtheoryalliance.org/content/charter.php). The director-line of the FRIB-TA are members of the board, selected by the board, responsible for the overall governance of the board and called upon to represent the FRIB-TA to the outside world. Currently, Saori Pastore (WashU) is serving as director, Daniel Phillips (OU) is past-director and Jon Engel (UNC) is director-elect.

8.1 Organizational Committee

The organization committee is composed of the director-line and Kate Jones who chairs the committee. The Conflicts of Interest document, "Policies relating to Conflicts of Interest in Theory Fellow, Faculty Bridge and Early Achievement Award Selection processes" was approved by the Executive Board. These policies provide more transparency on how decisions are made about awards that come with significant financial and/or career benefits to individuals and institutions. The policy is available on the Theory Alliance web page under “Procedures for Initiatives", here.

8.2 Mentoring

The full FRIB-TA executive board, including past members, are available to serve as mentors to our theory fellows and bridge faculty. This mentoring program enables junior talent to extend their mentoring network to include senior researchers that would otherwise not be immediately accessible. The mentor meets regularly with the mentee, offering a wide range of advice, including but not limited to research considerations, funding strategies and career development. We have found that fellow mentees keep in touch with their mentors even after moving on to permanent positions.

Concerning our fellows, Hebborn is mentored by Daniel Phillips (OU), McCoy is mentored by Amy Lovell (LANL), Seng is mentored by Jon Engel (UNC) and Zhang is mentored by Alex Gade (MSU). Concerning our bridge faculty, Drischler is mentored by Jorge Piekarewicz (FSU), Kevin Fossez is mentored by Dick Furnstahl (OSU), König is mentored by Jutta Escher (LLNL), Piarrulli is mentored by Filomena Nunes (MSU).

8.3 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 sub-awards and being responsible for reporting to DOE. Currently Filomena Nunes is serving as managing director, but at the start of the next funding period Scott Bogner is expected to take over this role. The managing director ensures the implementation of the overall plan for the FRIB-TA, and oversees the activities on the sub-awards to universities supporting bridge positions, as well as the several sub-awards from laboratories and universities supporting theory fellows. None of these functions draw funds from the FRIB-TA grant and are fully supported by MSU funds.

The logisitcs associated with FRIB-TA activities is supported by one research administrator. Gillian Olson started to work for the FRIB-TA 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 room 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.

8.4 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 members Kevin Fossez, Kristina Launey and Calvin Johnson. The website content is supplied by all board members. The new design of the FRIB-TA website implemented in 2021 features a responsive web design suitable for any device (desktops, tablets, and phones), as well as a calendar of upcoming events. A link to the FRIB-TA code of conduct has been added to the homepage. The webpage content includes information about the FRIB-TA science and governance, such as links to "What is the FRIB-TA?", "Mission and Initiatives", a science overview, the FRIB-TA charter, and members of the Executive Board and committees. "Quick links" on the homepage and menu items lead to progress reports and solicitations for FRIB initiatives such as the FRIB-TA Fellows and Bridge faculty positions, supported scientists, 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 2023 is 291, including 198 from the United States and 93 from 22 countries around the world. The list of FRIB-TA members is directly accessible on the website where the database can be filtered by name, 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.

Beginning of 2023, per request of the Diversity, Equity and Inclusion (DEI) committee, the format of the FRIB-TA membership sign up form was updated to provide members with the possibility to add their gender identity, ethnicity, race, and whether they have a disability. This information is added to the database along with other personal information, but is not available to the public, and its safety is ensured by the MSU-IT and FRIB-IT. Committee members who want to access the source code of the website and the database must use a virtual private network (VPN).

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. To support the experimental program at FRIB, the homepage provides a link to 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 (2022)

1. A. Sorensen, K. Agarwal, K. Brown, Z. Chajecki, P. Danielewicz, C. Drischler *et al.*, *Dense Nuclear Matter Equation of State from Heavy-Ion Collisions*, arXiv:2301.13253.

2. A.J. Garcia, C. Drischler, R.J. Furnstahl, J.A. Melendez, Xilin Zhang, *Wave function-based emulation for nucleon-nucleon scattering in momentum space*, arXiv:2301.05093.

3. C. Drischler, J.A. Melendez, R.J. Furnstahl, A.J. Garcia, Xilin Zhang, *BUQEYE Guide to Projection-Based Emulators in Nuclear Physics*, arXiv:2212.04912 (invited review article; Front. in Phys. 10, 92931). The article has a comprehensive companion website [49] with interactive, open-source Python code so that practitioners can readily adapt projection-based emulators for their own work.

4. A. Lovato *et al.* [84 authors including C. Drischler], *Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars*, arXiv:2211.02224.

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9.2 Presentations

Fortunately, this year there was a much larger number of conferences and workshops and it was possible to hold some of them in person. The following lists contain both in-person and virtual presentations.

Christian Drischler (2022, in person unless stated otherwise)

1. Nuclear matter in the FRIB era, October 24, invited Nuclear Physics Seminar, University of Notre Dame, South Bend, IN, USA

2. How well do we know the nuclear saturation point?, October 1, contributing talk, The 33rd Midwest Theory Get-Together 2022 (organizers: Fossez, Cloët, Lovato, Stroberg, Zhao), Argonne National Laboratory, Lemont, IL, USA

3. Equation of State of Neutron-Rich Matter and Relevance for Neutron Stars, September 1, invited plenary talk, 14th Conference on the Intersections of Particle and Nuclear Physics (organizers: Casey, Balantekin), Orlando, FL, USA

4. Theoretical advances and uncertainty quantification of neutron star properties, July 21, invited overview talk, INT–22–2a: Neutron Rich Matter on Heaven and Earth (organizers: Chatziioannou, Piekarewicz, Watts), Institute for Nuclear Theory, Seattle, WA, USA

5. Chiral effective field theory and the nuclear equation of state, April 18, invited (virtual) seminar talk, Modular Unified Solver of the Equation of State (MUSES) collaboration, University of Illinois Urbana-Champaign, Champaign, IL, USA

6. Nuclear matter from chiral effective field theory with quantified uncertainties, April 14, invited (virtual) seminar talk, University of Maryland, College Park, MD, USA

7. Nuclear Matter from Chiral Effective Field Theory in the Era of Multi-Messenger Astronomy, April 17, faculty interview colloquium, Ohio University, Athens, OH, USA

8. Nuclear Matter from Chiral Effective Field Theory in the Era of Multi-Messenger Astronomy, April 9, faculty interview colloquium, University of Notre Dame, South Bend, IN, USA

Kevin Fossez (2022)

1. Colloquium, Sep. 30, 2022, Argonne National Laboratory (ANL), Lemont, IL, USA.
2. Invited talk at the *CIPANP* conference, Sep. 3, 2022, Orlando, FL, USA.
3. Two invited talk at the *Low Energy Community Meeting* (LECM 2022), Aug. 9, 2022, Argonne National Laboratory (ANL), Lemont, IL, USA.
4. Invited talk at the conference *Halo Week*, Jul. 12, 2022, Bergen, Norway.
5. Invited talk at the program *Living Near Unitarity* of the conference *Opportunities and Challenges in Few-Body Physics: Unitarity and Beyond*, May 26, 2022, Kavli Institute for Theoretical Physics (KITP), UC Santa Barbara, CA, USA.
6. Seminar, Mar. 30, 2022, TRIUMF, Vancouver, Canada.

Chloë Hebborn (2022)

1. Invited talk at *VIth Edition of the series of Topical Workshops on Modern Aspects of Nuclear Structure*, February 2023, Bormio, Italy.
2. Invited talk at *14th Conference on the Intersections of Particle and Nuclear Physics* (CIPANP 2022), August 2022, Lake Buena Vista, USA.
3. Invited talk at *Low Energy Community Meeting* (LECM 2022), August 2022, virtual meeting.
4. Contributed talk at *Direct Reaction for Exotic Beams* (DREB 2022), June 2022, Santiago de Compostela, Spain.
5. Invited talk at *Living near unitarity*, program at the Kavli Institute for Theoretical Physics (KITP), June 2022, USA.
6. Physics Colloquium at Michigan State University, April 2022, USA.
7. Physics Colloquium at University of Notre Dame, March 2022, USA.
8. Physics Colloquium at Louisiana State University, February 2022, USA.
9. Physics Theory seminar at Washington University, February 2022, USA.
10. Physics Colloquium at Ohio University, February 2022, USA.

Sebastian König (2022)

1. Contributed short talk *The role of universality and unitarity in nuclear physics* at the *NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics*, Argonne National Lab, November 2022.
2. Invited talk *Few-Body Perspectives in Finite Volume* at the *Low Energy Community Meeting (LECM) 2022*, August 2022, virtual talk.

3. Invited talk *Few-Neutron Systems in Pionless EFT* at the *9th International Conference on Quarks and Nuclear Physics*, September 2022, virtual talk.

4. *Few-nucleon systems expanded around unitarity* at the *KITP program "Living Near Unitarity"*, Santa Barbara, June 2022.

5. Invited talk *Few-Body Physics in Finite Volume* at the *13th International Spring Seminar on Nuclear Physics*, Sant'Angelo d'Ischia (Italy), May 2022.

6. Theory Seminar *Eigenvector continuation in nuclear physics* at Lawrence Livermore National Laboratory, March 2022; virtual talk.

7. Theory Seminar *Eigenvector continuation in nuclear physics* at Central China Normal University, January 2022; virtual talk.

Saori Pastore (2022)

1. Invited talk at the *2022 EMMI Workshop and International Workshop XLIX on Gross Properties of Nuclei and Nuclear Excitations*, Hirschegg, Austria, January 2023

2. Invited talk at the *2022 International Nuclear Physics Conference*, Cape Town, South Africa, September 2022

3. Invited talk at the *7th Symposium on Neutrinos and Dark Matter in Nuclear Physics*, Asheville, NC May 2022

4. Invited talk at the *13th International Spring Seminar on Nuclear Physics: Perspectives and Challenges in Nuclear Structure after 70 Years of Shell Model* Sant'Angelo d'Ischia, May 2022

5. Invited talk at the *NuSTEC Workshop on Electron Scattering*, held remotely, March 2022

6. FRIB Theory Alliance Status Report presented on behalf of the FRIB-TA Executive Board at the *2022 Low Energy Community Meeting*, Argonne National Lab, August 2022

7. Invited talk on behalf of the FRIB-TA DEI committee at the *APS DNP mini-symposium on DEI* New York, April 2022

8. *Theoretical Physics Colloquium at ASU*, AZ, November 2022

9. *UT Arlington Colloquium*, Arlington, TX, April 2022

10. *ODU Physics & REYES Colloquium*, Norfolk, VA, March 2022 - remote

11. *MSU Colloquium*, East Lansing, MI, February 2022 - remote

Maria Piarulli (2022)

1. Invited talk *Chiral EFT for Electro-Weak Processes* at the April APS Meeting, New York, NY, April 9-12 2022

2. Invited talk *Solving for Nuclear Structure in Light Nuclei* aNuclear Physics from Atomic Spectroscopy, ECT*, Trento, Italy April 11-15 2022

3. Invited talk *Analyzing the nuclear interactions: challenges and new opportunities* at the Low Energy Community Meeting, Argonne National Lab, Lemont, IL, August 9-10 2022

4. Invited talk *Analyzing the nuclear interactions: challenges and new opportunities* 14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022), Lake Buena Vista, Orlando, FL, August 29-September 4 2022

5. Contributed talk *Topic 1: Ab-initio many body framework, Topic 2: Nuclear Interactions and Effective Field Theory* at the 2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics. Working Group Session: Nuclear Structure and Reaction Theory, Argonne National Lab, Lemont, IL, Nov 14-16 2022

6. Theory seminar *Quantum Monte Carlo studies of nuclear systems* at University of Illinois Urbana-Champaign, Urbana-Champaign, April 18 2022

7. Theory seminar *Quantum Monte Carlo studies of nuclear systems with chiral effective field theory interactions* at TRIUMF, Vancouver, BC, Canada, April 20 2022

8. Theory seminar *The role of many-body nuclear effects in light nuclei* at Chalmers University of Technology, Gothenburg, Sweden, June 3 2022

Chien-Yeah Seng (2022)

1. *Precise determination of* V_{ud} *and the Cabibbo angle anomaly*, invited talk in the "KEK Flavor Factories 2023" workshop, Tsukuba, Japan, 10 February 2023.

2. *Nuclear structure effects in superallowed beta decays*, invited talk in the "Fundamental Symmetries at FRIB Workshop", FRIB, Michigan State University, 18 November 2022.

3. *Precision Measurement of* V_{ud} *from Beta Decays*, PRISMA+ Colloquium, Johannes Gutenberg Universität Mainz, Germany, 26 October 2022.

4. *Accessing isospin symmetry breaking effects in superallowed beta decays*, contributed talk in the "Low Energy Community Meeting 2022", Argonne National Laboratory, 9 August 2022.

Xilin Zhang (2022)

1. Invited talk at INT program: *Intersection of nuclear structure and high-energy nuclear collisions*, Feb. 2023, Institute for Nuclear Theory, Seattle, WA.

2. Two Contributed talks at the 2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics, Nov. 2022, Argonne National Lab, Lemont, IL.

3. Two invited talks at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2022*, August 2022; virtual meeting

4. Invited talk at FRIB-TA Topical Program: *Few-Body Clusters in Exotic Nuclei and Their Role in FRIB Experiments*, August 2022, FRIB, East Lansing, MI.

5. Colloquium, Feb 2022, Department of Physics, University of Notre Dame, Notre Dame, IN.

6. Colloquium, March 2022, FRIB, Michigan State University, East Lansing, MI.

9.3 Milestones

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

FY2022 (June 2022 - May 2023):

- Theory Fellows and Bridge Faculty continued to develop excellent research relevant for FRIB resulting in progress toward many topics identified in Table 1 of the renewal proposal.
- The two new fellows initiated activities with the FRIB-TA at WashU and UW.
- The 4th search for a bridge position was completed and the new faculty member fostering strong connections with the FRIB-TA.
- The FRIB-TA ran another summer school on a topic intersecting with FRIB science.
- ~~Two~~ Three FRIB-TA topical programs on topics of direct relevance to FRIB took place.
- The FRIB-TA ran its annual meeting concurrent with the Low-Energy Community Meeting.
- The EUSTIPEN program was reinstated to foster collaborations between U.S. scientists and European scientists.
- Elections for the replacement of another three members of the Board took place.
- A progress report describing the science achievements, Center's activities, and work-plan for Year-3 has been produced.

FY2023 (June 2023 - May 2024): We also present an update of our plans for year 3, assuming full funding.

- Theory Fellows and Bridge Faculty will continue to develop excellent research relevant for FRIB. Progress toward many topics in Table 1 will occur.
- As theory fellows move on to permanent positions, a call for partners for the fellow program will be sent out and a new fellow search will take place.
- 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.
- EUSTIPEN will continue to 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 site-visit and review of the FRIB-TA will take place
- A progress report describing the science achievements, Center's activities, and work-plan for Year-4 will be produced.

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