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FRIB Theory Alliance

Annual Progress Report

(June 2021 - May 2022)

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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 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 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 second 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 delivered 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:

- Drischler was recognized with the 2021 FRIB Early Achievement Award (theory) for his work on the nuclear equation of state.
- A reaction theory study showed that the adiabatic approximation often used in one-neutron removal reactions does not hold for differential observables and that the dynamics of the neutron-target interaction should be included [1].
- Our fellows Drischler and Zhang have made important contributions to developing emulators for nuclear reactions [2–5].
- The recent work by Pastore's postdoctoral fellow's Andreoli on benchmarking the short-time-approximation for describing electron and neutrino scattering from nuclei was a PRC editor's suggestion [6].
- Two of our bridge faculty received a CAREER award, Koenig from the National Science Foundation, to expand the finite-volume research program, and Piarulli from the Department of Energy, to go from atomic nuclei to infinite nucleonic matter within chiral dynamics.

In addition, we have two new fellows to begin their appointment this summer (one to be hosted by Florida State University and one at University of Washington). There is a bridge faculty search ongoing at Ohio University. Due to the pandemic, we ran a summer school (see Section 5) virtually and the two approved topical programs are planned to run in person this Spring. As usual we ran the annual meeting during the low energy community meeting (Section 6.1), also 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 concerns (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 272 members, 186 of which are from the U.S. The breakdown according to rank is: 118 faculty members, 36 staff members, 6 fellows, 52 postdoc members and 60 students.

The newly revamped FRIB TA website (fribtheoryalliance.org) continues to serve as an effective means to communicate with our membership (Section 8.4). The newly formed committee on Diversity, Inclusion and Equity is working to expand the DEI efforts across programs (Section 7). There has been significant progress towards establishing a conflict of interest document (see Section 8.1), and we continue to seek ways to enhance theory-experiment collaboration in preparation for the start of FRIB operations (Section 6.2). Toward the end of this report, a summary of the 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.

All in all, the FRIB-TA is continuing the implementation of its original plan, and while there have been some delays due to the pandemic, we have made significant progress on many fronts. Our fellows and bridges have been extraordinary in continuing to persevere in difficult circumstances. The FRIB-TA leadership would welcome a mid-term panel review next year. Such a review will help in creating a vision for the next cycle.

3 FRIB Theory Fellow Program

The FRIB Theory Fellowship is a five-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. 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 and Kevin Fossez have each successfully transitioned into permanent positions.

Currently we have three fellows: Chloë Hebborn hosted at Livermore National Laboratory and Christian Drischler and Xilin Zhang at MSU. Reports on their research activities are given below. Two more fellows will join us in the summer as a result of the FRIB theory fellow search run in 2021. This is described in Sec. 3.4.

3.1 Science highlights from Christian Drischler

Christian's work on the equation of state and on emulator methods is important to connect measurements at FRIB with the larger astrophysical picture in order to understand where the elements came from.

Nuclear scattering and reaction experiments yield invaluable data for testing and improving theoretical models such as chiral effective field theory (EFT) and optical models. But, taking full advantage of the available data using rigorous statistical methods, such as Bayesian parameter estimation [7] and model comparison [8], requires fast & accurate predictions across a wide range of model parameters. While, in principle, the scattering equations can be solved accurately in few-body systems, doing so is prohibitively slow for the statistical analyses of three- and higher-body scattering, and even for two-body scattering more efficient alternatives are appealing. Emulators—computationally inexpensive algorithms capable of approximating exact model calculations with high accuracy—are very promising new tools to overcome this computational limitation. They have already been shown to be game changers for statistical analyses of bound-state observables.

Christian and his collaborators [3] have constructed an efficient emulator for two-body scattering observables using the general (complex) Kohn variational principle and trial wave functions derived from eigenvector continuation (EC) [9]. The emulator simultaneously evaluates an array of Kohn variational principles associated with different boundary conditions. This novel approach allows for the detection and removal of spurious singularities known as Kohn (or Schwartz) anomalies [10, 11], which can render (variational) scattering emulators ineffective. When applied to the K-matrix only, the new emulator resembles the one recently constructed by Furnstahl *et al.* [2], although with reduced numerical noise. After a few applications to real potentials, including a chiral potential, demonstrating the efficacy of the new approach, they emulated differential cross sections for $^{40}\mathrm{Ca}(n, n)$ scattering based on a realistic optical potential and quantified the model uncertainties using Bayesian methods. These calculations serve as a proof of principle for future comprehensive studies to improve optical models in the FRIB era. Christian's collaborators on this project included colleagues at FRIB/MSU, as well as members of the BAND framework project [12].

In another publication [4], Christian and his BUQEYE [13] collaborators studied an alternative emulator for two-body scattering with potential future extensions to higher-body systems. They introduced a fast & accurate emulator of the Lippmann–Schwinger integral equation (rather than the Schrödinger differential equation) using Newton's variational method [14, 15] combined with ideas from EC [9, 16]. Newton's variational method has the advantage that scattering observables can be predicted using trial scattering matrices (*e.g.*, the K matrix) rather than trial wave functions. They provide several applications to short-range potentials with and without the Coulomb interaction and partial-wave coupling, and showed that the new emulator can accurately extrapolate far from the support of the training data. When used to emulate the neutron-proton cross section with a modern chiral interaction as a function of 26 free parameters, the emulator reproduced the exact calculation with negligible error and provided a remarkable 300x improvement in CPU time. These are exciting prospects for rigorous Bayesian uncertainty quantification in nuclear physics and reaction theory. Furthermore, the fast convergence observed with EC-inspired trial matrices (instead of wave functions) motivated the exploration of the EC concept applied to stationary functionals in a more general context, including optimizing energy density functionals.

In an invited contribution to the special issue "Celebrating 30 years of Steven Weinberg's papers on Nuclear Forces from Chiral Lagrangians" published in Few-body Systems [17], Christian and Scott Bogner reviewed the important role chiral EFT has played in leading nuclear physics into a precision era and discussed selected advances recently made in *ab initio* calculations of nuclear structure and nuclear matter observables with quantified uncertainties.

The telescope Neutron star Interior Composition ExploreR (NICER) recently measured x-ray emissions from the heaviest precisely known neutron star, PSR J0740+6620, suggesting that it may also have a large radius at the 68% credibility level, $R \approx (11.4 - 16.1)$ km. In collaboration with Sophia Han and Sanjay Reddy, Christian studied [18] the implications of such a large radius for the sound speed in the neutron star's inner core using his EOS calculations with EFT truncation errors fully quantified. In particular, they derived a lower bound on the maximum speed of sound in the inner core, which can provide insights up to which density chiral EFT is an efficient expansion for nuclear forces. Future studies in this direction will also benefit from Christian's explicit high-order calculations of neutron star matter currently running on Summit thanks to the GPU acceleration and an awarded OLCF Director's Discretion Project.

Christian's cutting-edge work on the nuclear EOS with modern theoretical and statistical approaches was recognized with an invited contribution to Annu. Rev. Nucl. Part. Sci [19], the 2021 FRIB Early Achievement Award (theory), and a plenary talk at the conference Chiral Dynamics.

3.2 Science highlights from Chloë Hebborn

Chloöe's research focuses on improving the theoretical description of reactions involving exotic nuclei, essential for the study of nuclear structure far from stability, and predictions of reaction rates of astrophysical interest. It is core to the reaction program at FRIB.

The Big-Bang nucleosynthesis $^4\mathrm{He}(d,\gamma)\,^6\mathrm{Li}$ plays a key role in determining the primordial abundances of Lithium isotopes [20]. At the energies relevant for astrophysics, the cross section is suppressed and consequently there are only scarce and uncertain experimental data. Starting from nucleons with chiral-EFT interactions, *ab initio* predictions guide the extrapolation of existing measurements at higher energies towards the astrophysically relevant low energies. Chloöe employed the *ab initio* no-core shell model with continuum (NCSMC) [21] to describe ^{4}He-d scattering dynamics and the bound ^{6}Li product on an equal footing, and extended the NCSMC formalism to account for electromagnetic transitions between the deuterium states. This work [22] accurately and consistently determines the contributions of the main electromagnetic transitions driving the $^4\mathrm{He}(d,\gamma)\,^6\mathrm{Li}$ reaction, revealing an enhancement of the capture probability below 100 keV owing to the usually neglected magnetic dipole transitions. Dr. Hebborn also contributed to the *ab initio* informed evaluation of the solar fusion reaction $^7\mathrm{Be}(p,\gamma)\,^8\mathrm{B}$ [23], important for modeling the solar neutrino flux [24, 25], working in collaboration with K. Kravvaris (LLNL), P. Navrátil (TRIUMF), S. Quaglioni (LLNL) and G. Hupin (IJCLab). Both efforts significantly reduce the theoretical uncertainty on these rates at the astrophysically relevant energies.

Breakup and one-neutron removal reactions at intermediate energy (50 MeV/nucleon) are often used to probe exotic nuclei [26–28]. The description of reactions at these energies is out of reach of *ab initio* calculations, as the number of reaction channels increases significantly. The many-body problem is therefore often simplified into a few-body one, where the projectile is seen as composed of clusters of nucleons impinging on a structureless target. To reach accurate reaction predictions and to reliably interpret experimental data, one needs robust few-body methods, using interactions that account for the neglected many-body structure of the projectile's clusters and the target.

Because halo nuclei exhibit a clear separation of scale between the size of the halo and the rest of the nucleus, they are well suited for a effective field theory (EFT) treatment [29]. With P. Capel (JGU Mainz), Chloë showed that the EFT descriptions of one-neutron halo projectiles ^{11}Be and ^{15}C can be efficiently used to predict one-neutron removal observables and that constraining the EFT parameters with *ab initio* NCSMC predictions leads to an excellent agreement with experimental data [30]. For removal reactions of a more deeply-bound neutron, Chloë identified the relevant nuclear-structure information via a systematic analysis [31]. This work shows that these observables do not depend linearly on spectroscopic factors, as often assumed [28], but on the mean square radius of the single-neutron wave function. Both analyses have important consequences for future FRIB experiments, since they set up a clear connection between microscopic nuclear-structure predictions and reaction observables.

Other important ingredients of few-body models are optical potentials, typically obtained with local parametrizations constrained with elastic-scattering data on the same system. To reach a predictive theory, together with scientists at LLNL, Chloë is working on deriving a nucleon-nucleus optical potential from *ab initio* NCSMC predictions. Chloë has also taken the lead in the organization of a FRIB-TA topical program on optical potentials that will be held in-person in March 2022.

Microscopic optical potentials are intrinsically non-local, owing to the antisymmetrization and coupling to excited modes. With F. Nunes (MSU), Chloë has assessed whether non-locality in the optical potentials is expected to impact reactions at intermediate energies. Their work [32] shows that non-locality significantly affects transfer observables in this energy regime, and therefore likely to have a large effect on one-nucleon removal observables. The eikonal model being the tool of choice for such reactions, different avenues for extending these methods to include non-local interactions were studied. Their analysis indicates that the eikonal model cannot be easily generalized and suggests that other few-body methods would be better suited to deal with this non-locality.

Finally, the dynamics of the few-body system influences breakup and one-neutron removal observables. While one can fully include these dynamical effects within the description of the breakup channel, it is not straightforward for one-neutron removal reactions. This difficulty can be overcome by treating the neutron-target interaction adiabatically, while still including the dynamics of the core-target system [33]. While being efficient for integrated cross section, Chloë showed that this approximation does not hold for differential observables and the dynamics of the neutron-target interaction should be included [1].

The numerous developments focusing on the eikonal description of reactions involving exotic nuclei, carried out by Chloë during her PhD [34], were recognized by the PhD Solvay Award 2020.

3.3 Science highlights from Xilin Zhang

Xilin Zhang's current research is focused on nuclear scattering and reactions in two main categories: low-energy processes happening in various astrophysical environments and the so-called direct nuclear reactions used as nuclear experimental tools at FRIB (e.g., deuteron-nucleus reactions) to study rare isotopes.

Xilin Zhang started his fellow position in July 2021. Since then, he and his collaborators have posted a paper [5] on developing fast and accurate emulators for three-body scattering. The work, with proper generalizations to reactions, will solve a long-standing bottleneck problem in three-body scattering and reaction research in various fields (including nuclear, particle, and atomic physics): the expensive computational cost of the full solutions restricts or even precludes many calculations of interest, including employing the full solutions in data analysis.

Within nuclear physics, the emulators will allow implementation of the full theoretical formalism in calibrating chiral EFT interactions (in particular three-nucleon interactions) against a large amount of nucleon-deuteron scattering and reaction data and potentially against Lattice QCD calculations of three nucleon systems. This chiral EFT interaction is the basic input for the modern nuclear *ab initio* calculations. As pertinent to FRIB physics, the work also demonstrates the emulator's capability in emulating deuteron-nucleus-like scatterings and thus its application in analyzing related experimental data. The future generalizations to reactions and to the systems with strong Coulomb effects could help us control theoretical uncertainty in modeling the deuteron-nucleus reactions that will be measured in FRIB experiments.

The current work [5] generalizes the previous studies of Xilin Zhang and his collaborators on two-body scattering emulators [2, 4]. All these emulators have two major ingredients: a variational method for estimating scattering (and reaction) observables and a very efficient way of constructing the trial ansatz based on so-called eigenvector-continuation concept [9]. Importantly, the current work [5] introduced the 3rd ingredient that could be broadly useful; it applied a machine learning method (Gaussian Process) to further extend these emulators' capability into the situations where the ranges of the interactions between particles need to be varied and explored.

3.4 FRIB Theory Fellow search

In 2021, 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: Alexandra Gade (NSCL & MSU), Chuck Horowitz (Indiana), Calvin Johnson (SDSU), Daniel Phillips (Ohio U., Chair), and Gregory Potel (LLNL, former FRIB Theory Fellow). Four partner institutions were identified: Florida State University (FSU), Los Alamos National Laboratory (LANL), the University of Washington (UW), and Washington University in St. Louis (WUSTL). A representative from each partner institution was added to the search committee: Aurel Bulgac (UW), Amy Lovell (LANL), Saori Pastore (WUSTL), and Alexander Volya (FSU). These four scientists 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, five FRIB Theory Fellow candidates were interviewed. The interviews were held predominantly in-person at FRIB from December 6–10, 2021. (Two candidates could not travel to MSU because they were coming from overseas and were unable to obtain visas in time for their trip. Their interview schedule was essentially the same as for the three candidates who came to East Lansing. Six out of the nine committee members came to MSU for the interviews, the other three attended the talks and discussions with candidates via Zoom.) The final search committee deliberations took place on December 12, 2021, and produced a ranked list based on the following criteria: excellence of research; proposed research plan demonstrating relevance to the FRIB mission, as well as overlap with hosting institutions; appropriateness for the rank of FRIB Theory Fellow (independent scientific maturity); diversity of the applicants and representation of disciplines. The list was reported to the FRIB TA Board, who approved the candidates ranked first and second by the search committee. This selection was corroborated by DOE-NP and the FRIB laboratory director. These two top ranked candidates, Anna McCoy and Chien-Yeah Seng, accepted the offer: McCoy to be hosted by Florida State University and Seng by the University of Washington, both starting in the summer of 2022. We note that these will be the first FRIB Theory Fellows hosted at a university other than MSU.

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

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 are. 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. A new faculty search at OU is nearing completion and an update is provided in Section 4.5.

4.1 Science highlights from Kevin Fossez

In August 2021, Kevin Fossez joined Florida State University (FSU) on an FRIB Bridge position, and 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 new elements in the Universe, and their properties reveal important information about nuclear forces [35] and how atomic nuclei self-organize [36]. To achieve the theoretical exploration of the drip lines, Kevin uses and develops various many-body techniques such as the Gamow shell model (GSM) [37], the density matrix renormalization group (DMRG) method for open quantum systems [38], and the in-medium similarity renormalization group (IM-SRG) method [39], 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 [40]. 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 [41], 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 [42, 43] 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. Moreover, efforts are underway to use the newly introduced eigenvector continuation method [9] 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.

4.2 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 impact on the nuclear structure and nuclear reaction program at FRIB, particularly concerning the most loosely bound systems such as halos.

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.

Recently, Koenig and collaborators in Germany completed a study of the three-neutron system using pionless EFT [44], the most general theory capturing the universal implications of the large neutron-neutron scattering length. This work combines the search for resonance using Faddeev equations in momentum space with complementary finite-volume methods, developing in particular the formalism and numerical implementation to handle separable potential in finite volume. This paper is currently under review for Physical Review C.

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."

Currently, Yapa is working on a framework to apply eigenvector continuation to resonance states, while Yu is deriving the finite-volume correction for bound states of charged particles, which plays a crucial role in extending FV studies to a larger range of nuclei and reactions. Both projects are progressing well, and preliminary results have been presented by Yapa and Yu at the virtual APS DNP Fall Meeting 2021. Yapa moreover presented his work at the 88th Annual Meeting of the APS Southeastern Section, held in person Florida State University in November 2021. Koenig and a third gradate student Andrew Andis also attended this conference for invited and contributed talks, respectively. This transition back to in-person meetings certainly marks a highlight of the year.

Together with researchers at Sichuan University, Koenig is working on perturbative power-counting schemes for Chiral Effective Field Theory. This work is important to address significant unresolved questions regarding the systematic construction of nuclear interactions based on QCD. Preliminary results of this effort were presented by Koenig at the INT program 21-1b "Nuclear Forces for Precision Nuclear Physics," held virtually in April/May 2021. Closely related work born out of this collaboration was recently completed [45] and is currently under review for publication in Physical Review C.

Koenig also organized a summer School entitled "A practical walk through formal scattering theory: Connecting bound states, resonances, and scattering states in exotic nuclei and beyond" together with Kévin Fossez and Heiko Hergert. This school was held virtually in August 2021 and offered an introduction to nonrelativistic quantum scattering theory, discussing its fundamental assumptions and techniques guided by concrete applications. Formal aspects, centered around the important concept of the S-matrix, were covered in detail, complemented at each step by numerical illustrations and hands-on programming exercises (see Section 5).

4.3 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 relevant to the fundamental symmetries program of FRIB.

To date, she has emphasized the development and implementation of many-body electroweak current operators [46–48] in studies of electroweak transitions and scattering in atomic nuclei [49–53]. Pastore uses chiral effective field theory along with 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 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 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[49], and Gamow-Teller and electromagnetic decay rates[51, 54].

Pastore and collaborators developed the Short-Time-Approximation (STA) to study electron and neutrino scattering from nuclei [53, 55]. 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-body 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. A recent development has been reported in Ref. [6] 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. For moderate to high momentum transfer, the STA is found to be in good agreement with the GFMC calculations and with experimental data. 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.

Searches for neutrinoless-double beta decay rates are crucial in addressing questions within fundamental symmetries and neutrino physics. The rates of these decays depend not only on unknown parameters associated with neutrinos, but also on nuclear properties. In order to reliably extract information about the neutrino, one needs an accurate treatment of the complex many-body dynamics of the nucleus. Neutrinoless-double beta decays take place at momentum transfers on the order of 100 MeV/c and require both nuclear electroweak vector and axial currents. Muon capture is a process in the same momentum transfer regime, moreover it has readily available experimental data to validate the model (and in particular, correlations and many-body currents) in this kinematic regime. In Ref. [56] Garrett King, a graduate student at Washington University in St. Louis, performed *ab initio* calculations of partial muon capture rates for ^{3}He and ^{6}Li nuclei using variational and Green's Function Monte Carlo computational methods and estimated the impact of three-nucleon interactions, cutoffs used to regularize two-nucleon interactions, and the energy range of scattering data used to fit these interactions. This work is currently under review. In 2021, Pastore participated in the work led by Thomas Richardson, at the time a graduate student at the University of South Carolina and now a post-doc at Duke University, on estimating the size of a new leading contact contribution in neutrinoless double beta decay [57] within the Large-N_c formalism [58].

The computational time for these calculations was provided by the 2020/2021; 2021/2022 ALCC allocation for proposals of which Pastore and Piarulli are co-PIs. In 2021, an invited mini-review on Electroweak Currents from Chiral Effective Field Theory was published in the Springer Topical Collection 'Celebrating 30 years of the Steven Weinberg's paper Nuclear Forces from Chiral Lagrangians'.

4.4 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) [59–61] 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 [62]. Specifically, Piarulli and collaborators have constructed a family of high-precision two- and three-body chiral nuclear interactions suited for QMC calculations, referred in the literature as the Norfolk potentials (NV2+3s) [63–65]. 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 [66, 67], charge radii, as well as longitudinal elastic form factors [68], and single beta-decay transitions [54, 69] 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 $^6\text{He} \rightarrow {}^6\text{Be}$ and $^{12}\text{Be} \longrightarrow {}^{12}\text{C}$ transitions [70], relevant for studies of $0\nu\beta\beta$.

Taking advantage of the computational resources provided by the DOE ALCC-2020/2021 program, the Norfolk interactions were used to computed inclusive muon captures for light nuclei with mass numbers $A = 3$ and $A = 6$ [56]. 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. Furthermore, 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. A paper on these findings will be submitted for publication shortly [71], and the results will be made 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 [72].

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. [73] 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 was 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 will be submitted for publication in the next few days [74].

In Ref. [75], a comprehensive analysis of the structure of light and medium-mass nuclei as it emerges from nuclear interactions derived within pion-less effective field theory was carried out. This study has highlighted the benefits and the shortcomings of utilizing nuclear forces in which the pions are integrated out, thereby shedding light on the features of the nuclear interactions that are more relevant for the stability of a variety of nuclei. To achieve this goal, a novel version of the AFDMC imaginary-time propagator was devised, which is amenable to nuclear interactions containing an isospin-dependent spin-orbit term.

In an invited contribution to the special issue "Celebrating 30 years of Steven Weinberg's papers on Nuclear Forces from Chiral Lagrangians", Maria and Rocco Schiavilla wrote a review on local chiral interactions and their applications using QMC methods. The paper is published in Few-body Systems [76].

Finally, in July 2021, Piarulli has 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.

4.5 Update on Ohio University search

The FRIB-TA bridge committee selected from various applications UC Berkeley as the institution for the next bridge position. However, as MSU and UCB started discussions on the MoU, it became clear that UCB's practice of running very broad searches is not compatible with the current process for the FRIB-TA bridge program. For this reason, the Department of Physics of UC Berkeley is proceeding with a faculty search without partnering with the FRIB TA.

The FRIB-TA board approved Ohio University as the number two choice and this FRIB-TA bridge faculty position search is currently under way. The search committee is chaired by Daniel Phillips and includes Charlotte Elster (former FRIB-TA Board member), Zach Meisel (current Chair of the FRIB Users Organization Committee), Julie Roche (Director of Ohio U's Institute of Nuclear and Particle Physics), and Distinguished Professor David Drabold. In addition, Jorge Piekarewicz (Florida State) is acts *ex officio* on the committee as the representative of the FRIB-TA Executive Board. From a total of 22 applicants, the committee selected five for on-campus interviews. Those interviews took place between February 14 and March 1. The talks by all the candidates were streamed over Zoom and recorded to be made available upon request to the FRIB-TA Executive Board. The timeline of the search is such that we expect an offer will be made in the second or third week in March.

5 Education

5.1 Summer school

The FRIB-TA Summer School on *A practical walk through formal scattering theory: Connecting bound states, resonances, and scattering states in exotic nuclei and beyond* ran online (due to the COVID pandemic) August 4-6, 2021. It offered an introduction to nonrelativistic quantum scattering theory, discussing its fundamental assumptions and techniques guided by concrete applications. Formal aspects, centered around the important concept of the S-matrix, were covered in detail, complemented at each step by numerical illustrations and hands-on programming exercises. The organizer and lecturers were: Kevin Fossez (FSU), Sebastian Konig (NSCU), and Heiko Hergert (MSU). The school attracted a total of 23 participants (out of over 40 applicants). The summer school website can be found at https://indico.frib.msu.edu/event/43/. The feedback survey demonstrated the success of the program. A full report from the organizers is available if DOE has an interest.

The education and topical program committee has selected another summer school for this coming year and an announcement will be made soon. We hope to hold this school in-person in the summer of 2022.

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. The inaugural awards for theory and experiment were presented at the Low-Energy Community Meeting. Theory Fellow Christian Drischler received the inaugural FRIB Achievement Award for Earlier Career Researchers in the Theory category - *For his significant contributions to our understanding of dense matter and neutron-star properties using modern theoretical and statistical approaches.* Two awards were presented in the Experimental category - to Wei Jia Ong (LLNL) and Jack Bishop (Texas A&M University).

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, held virtually August 9-11, 2021. Three Theory Fellows (Chloë Hebborn, Xilin Zhang, and Kevin Fossez) and three Bridge Faculty members (Sebastian König, Maria Piarulli, and Saori Pastore) provided updates on their research during the annual meeting, Fellow Christian Drischler presented an award talk during the plenary session, and Jutta Escher gave an overview over recent TA activities.

The traditional summer schools and topical programs had to be curtailed due to the pandemic and the TA has been working on moving towards more in-person events. Two topical programs are in preparation to be held in-person in the spring of 2022: The program "Optical potentials in nuclear physics", organized by Chloë Hebborn, Wim Dickhoff, Jeremy Holt, Filomena Nunes, and Gregory Potel, will take place March 21 – April 1. The program "Nuclear isomers in the era of FRIB", organized by Filip Kondev, Wendell Misch, and Matt Mumpower, will take place May 9-20.

In addition, the TA plans to hold two Topical Programs in summer/fall of 2022, both of which will emphasize the connection to FRIB experiments in light of FRIB starting operations.

6.2 Enhancing theory-experiment collaborations

The Theory Alliance continued to explore new ways to connect to experimentalists and to the broader community: A list of theorists ready to collaborate with experimentalists was made available on the web site (https://fribtheoryalliance.org/) ahead of the FRIB PAC 1 proposal due date.

For 2022, the TA will return to a more interactive format to enhance theory-experiment collaborations, primarily through two Topical Programs.

6.3 Broader Impacts

FRIB-centered science is rich in interdisciplinarity opportunities. Areas of intersection include high-energy physics and astrophysics, dark matter, gravitational wave observatories and multi-messenger astronomy, quantum computing, machine learning and artificial intelligence. In order for the FRIB Theory Alliance to build bridges with these communities, the broader impacts committee introduced the online colloquium series titled “Nuclear Physics Dialogues”. The original series was successful, with many of the events having an attendance of more than one hundred physicists, and lively discussions. However, it became hard to do this without interfering with other long-standing seminar series that were meanwhile moved online. The broader impacts committee has paused this program and is looking into other ways to generate fruitful interactions between other communities.

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 with exotic nuclei.

The purpose of EUSTIPEN was to deliver an international venue for research on the physics of nuclei during an era of investigations into rare isotopes. The EUSTIPEN program was 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. The program funded 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*.

Although EUSTIPEN was successful, the COVID-19 pandemic forced its suspension in March 2020. ENSAR2, the program that funded the European side of the EUSTIPEN no longer exists and we will have to negotiate a new agreement, probably with ECT* itself. While pursuing that avenue, the current FRIB-TA committee for international links — Jon Engel (chair), Sonia Bacca, and Vincenzo Cirigliano — is also taking the opportunity to see whether independent arrangements with other institutions, for example MITP in Mainz, might also be possible.

7 Diversity, Equity and Inclusion

Continuing the Diversity, Equity and Inclusion (DEI) efforts from last year, which included updating the application process for the fellow and bridge searches, the topical program guidelines have been likewise updated to reflect the commitment of the FRIB-TA to DEI. In the call for topical programs, the proposal now has to contain a diversity plan which addresses the diversity of the participant list as well as speakers/lecturers, plans to foster an inclusive environment, and to encourage participation of scholars from under-represented groups in nuclear physics. The organizers must also designate a Diversity Coordinator. This year, there were two topical program submissions (one new and one resubmission). The new submission contained a very robust and well thought-out DEI plan; the resubmission needs to be updated based on the revised guidelines.

Additionally, the DEI committee coordinated with the current FRIB Theory Fellows to encourage them to submit a summer school proposal specifically focusing on DEI efforts in the community. The program would target a diverse group of undergraduates to bring to FRIB for a few days and introduce them to the topic of nuclear physics. This summer school would then introduce students to nuclear physics who might otherwise not have that opportunity, as well as give our Fellows mentoring and teaching experience.

Finally, the FRIB-TA Code of Conduct (CoC) and DEI efforts have been featured prominently at many community meetings. Lovell gave a two-minute lightning talk on FRIB-TA DEI efforts at the Inclusive Excellence Workshop at the 2021 Low Energy Community Meeting and Nunes discussed the CoC at the 2021 fall meeting of the Division of Nuclear Physics (DNP). Pastore will be discussing this year's efforts at the 2022 APS April Meeting, during the Mini-Symposium on Broadening Participation in Nuclear Science. Lovell also had a discussion with several staff members at Brookhaven National Laboratory (BNL) who are part of the US Nuclear Data Program (USNDP) on the FRIB-TA's experiences implementing a CoC as they begin to introduce one to various nuclear data communities such as the USNDP and the Cross Section Evaluation Working Group (CSEWG).

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, Daniel Phillips is serving as director, Jutta Escher is past-director and Saori Pastore is director-elect.

8.1 Organizational Committee

The organization committee is composed of the director-line and Kate Jones that chairs the committee. This year, the Organizational Committee drafted a Conflicts of Interest document, "Policies relating to Conflicts of Interest in Theory Fellow, Faculty Bridge and Early Achievement Award Selection processes". These policies will provide more transparency on how decisions are made about awards that come with significant financial and/or career benefits to individuals and institutions. The draft has been circulated within the Executive Board, and discussed during a board meeting. The edited version will be presented to the Executive Board for approval at the next board meeting.

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 the junior talent to extend their mentoring network to include senior researcher 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 continue in touch with their mentors even after moving onto a permanent positions.

Concerning our fellows, Drischler is mentored by Jorge Piekarewicz (FSU), Hebborn is mentored by Daniel Phillips (OU), and Zhang is mentored by Alex Gade (MSU). Concerning our bridge faculty, Kevin Fossez is mentored by Dick Furnstahl (OSU), Koenig is mentored by Jutta Escher (LLNL), Piarrulli and Pastore are 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. None of these functions draw funds from the FRIB-TA grant and are fully supported by MSU funds.

The managing director ensures the implementation of the overall growth plan for the FRIB-TA, and oversees the activities on the three sub-award to universities supporting bridge positions, and one sub-award to LLNL supporting a fellow. Two more sub-awards are being developed to support the incoming fellows.

The logisitcs associated with FRIB-TA activities is supported by one research administrator. Gillian Olson started to work as 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. During the pandemic, Gillian completed several professional development modules to extend her knowledge in website development and grant administration.

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 Kristina Launey and Calvin Johnson. The website content is supplied by all board members. A new and improved design of the FRIB-TA website has been implemented last year. The website now 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 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 position, 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 2022 is 186 from the United States with an additional 86 from 25 countries around the world. The list of FRIB-TA members is directly accessible (`fribtheoryalliance.org/content/signup/show_members.php`), 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. 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 (2021)

1. C. Drischler, S. Han, and S. Reddy: *Large and massive neutron stars: Implications for the sound speed in dense QCD*. arXiv:2110.14896.
2. C. Drischler, M. Quinonez, P. G. Giuliani, A. E. Lovell, and F. M. Nunes: *Toward emulating nuclear reactions using eigenvector continuation*. Phys. Lett. B **823**, 136777.
3. C. Drischler and S. K. Bogner: *A brief account of Steven Weinberg's legacy in ab initio many-body theory*. Few Body Syst. **62**, 109. (Alejandro Kievsky invited me to contribute to the special issue *Celebrating 30 years of Steven Weinberg's papers on Nuclear Forces from Chiral Lagrangians*.)
4. J. A. Melendez, C. Drischler, A. J. Garcia, R. J. Furnstahl, and X. Zhang: *Fast & accurate emulation of two-body scattering observables without wave functions*. Phys. Lett. B **821**, 136608.
5. C. Wellenhofer, C. Drischler, and A. Schwenk: *Effective field theory for dilute Fermi systems at fourth order*. Phys. Rev. C **104**, 014003.
6. C. Drischler, J. W. Holt, and C. Wellenhofer: *Chiral Effective Field Theory and the High-Density Nuclear Equation of State*. Annu. Rev. Nucl. Part. Sci. **71**, 403 (Barry Holstein invited me).

Kevin Fossez (2021)

1. K. Fossez, and J. Rotureau, *Density matrix renormalization group description of the island of inversion isotopes* $^{28-33}F$, Submitted
2. Y.-X. Luo, K. Fossez, Q. Liu, and J.-Y. Guo, *Role of quadrupole deformation and continuum effects in the "island of inversion" nucleus* ^{28}F, Phys. Rev. C **104**, 014307 (2021), doi:10.1103/PhysRevC.104.014307

Chlöe Hebborn (2021)

1. C. Hebborn, G. Hupin, K. Kravvaris, S. Quaglioni, P. Navrátil and P. Gysbers, *Ab initio prediction of the* $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$ *big-bang radiative capture*, in preparation.
2. C. Hebborn and P. Capel, *Sensitivity of one-neutron knockout observables of loosely- to more deeply-bound nuclei*, in preparation.
3. K. Kravvaris, P. Navrátil, S. Quaglioni, C. Hebborn and G. Hupin, *Ab initio informed evaluation of the radiative capture of protons on* ^7Be, submitted.
4. C. Hebborn and F. M. Nunes, *Considering non-locality in the optical potentials within eikonal models*, Phys. Rev. C **104**, 034624 (2021).

5. C. Hebborn and P. Capel, *Halo effective field theory analysis of one-neutron knockout reactions of* ^{11}Be *and* ^{15}C, Phys. Rev. C **104**, 024616 (2021).

6. C. Hebborn and P. Capel, *Detailed study of the Eikonal Reaction Theory for the breakup of one-neutron halo nuclei*, Phys. Rev. C **103**, 064614 (2021).

Sebastian König (2021)

1. S. Dietz, H. W. Hammer, S. König and A. Schwenk, *Three-body resonances in pionless effective field theory*, arXiv:2109.11356 [nucl-th].

2. R. Peng, S. Lyu, S. König and B. Long, *Constructing chiral effective field theory around unnatural leading-order interactions*, arXiv:2112.00947 [nucl-th].

3. H. Yu, S. König and D Lee, *Volume dependence of charged-particle bound states*, in preparation.

4. N. Yapa, K. Fossez and S. König, *Eigenvector continuation for resonance states*, in preparation.

5. R. Seutin, O. J. Hernandez, S. Bacca, K. Hebeler, S. König and A. Schwenk, *Magnetic dipole operator from chiral effective field theory for many-body expansion methods*, in preparation.

Saori Pastore (2021)

1. 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

2. Thomas R. Richardson, Matthias R. Schindler, Saori Pastore, and Roxanne P. Springer, *Large-Nc analysis of two-nucleon neutrinoless double-beta decay and charge-independence-breaking contact terms*, Phys. Rev. C 103, 055501 (2021), doi:10.1103/PhysRevC.103.055501

3. G.B. King, S. Pastore, M. Piarulli, R. Schiavilla, *Partial muon capture rates in* $A \leq 12$ *nuclei from chiral effective field theory*, e-Print: 2111.11360 [nucl-th]

Maria Piarulli (2021)

1. R. Schiavilla, L. Girlanda, A. Gnech, A. Kievsky, A. Lovato, L.E. Marcucci, M. Piarulli, and M. Viviani, *Two- and three-nucleon contact interactions and ground-state energies of light and medium-weight nuclei*, Phys. Rev. C **103**, 054003 (2021), doi:10.1103/PhysRevC.103.054003

2. M. Piarulli and R. Schiavilla, *Two- and three-nucleon local chiral interactions*, Few Body Syst. **62** 4, 108 (2021), doi:10.1007/s00601-021-01686-1

3. M.C. Atkinson, W.H Dickhoff, M. Piarulli, A. Rios, R.B. Wiringa, *Reply to "Comment on 'Reexamining the relation between the binding energy of finite nuclei and the equation of state of infinite nuclear matter' "*, Phys. Rev. C **104**, 5 (2021), doi:10.1103/PhysRevC.104.059802

4. G.B. King, S. Pastore, M. Piarulli, R. Schiavilla, *Partial muon capture rates in* $A \leq 12$ *nuclei from chiral effective field theory*, e-Print: 2111.11360 [nucl-th],

5. M. Piarulli, S. Pastore, R.B. Wiringa, *Densities and momentum distributions in* $A \leq 12$ *nuclei from chiral effective field theory interactions*, in preparation

6. A. Lovato, I. Bombaci, D. Logoteta, M. Piarulli, and R.B. Wiringa, *Benchmark calculations of pure neutron matter with realistic two- and three-nucleon-nucleon interactions*, in preparation

Xilin Zhang (2021)

1. C. W. Johnson *et al.*, *White paper: From bound states to the continuum*, J. Phys. G **47** 123001 (2020)

2. Ingo Tews *et al.*, *Nuclear Forces for Precision Nuclear Physics–a collection of perspectives*, arXiv:2202.01105

3. X. Zhang and R.J. Furnstahl, *Fast emulation of quantum three-body scattering*, arXiv:2110.04269

9.2 Presentations

As last year, and due to COVID, many conferences were either cancelled or moved online. Therefore many opportunities for our fellows and bridges to make their work visible to the community were lost. Most of the listed presentations below are from online presentations.

Christian Drischler (2021, all via Zoom)

1. Toward emulating nuclear reactions using eigenvector continuation, December 14, 2021, invited talk, Information and Statistics in Nuclear Experiment and Theory (ISNET) 8 conference (organizers: Danielewicz, Hjorth-Jensen, Lee et al.), Facility for Rare Isotope Beams at Michigan State University, MI, USA

2. Nuclear Equation of State with EFT Uncertainties Rigorously Quantified, November 19, 2021, invited plenary talk, The 10th International Workshop on Chiral Dynamics, Beijing, China

3. Fast & accurate emulation of two-body scattering observables, November 12, invited seminar, Nuclear Theory Seminar, Chalmers University of Technology, Gothenburg, Sweden

4. Equation of State of Dense Neutron-rich Matter at Zero Temperature, October 21, 2021, invited seminar, Biweekly Neutron Star Merger Meetings (organized by Sanjay Reddy), Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS)

5. Toward emulating nuclear reactions using eigenvector continuation, October 13, 2021, contributed talk, 2021 Fall Meeting of the APS Division of Nuclear Physics

6. Efficient emulators for two-body scattering observables using eigenvector continuation, October 6, 2021, Research Discussion at Facility for Rare Isotope Beams, MI, USA

7. Efficient emulators for two-body scattering using eigenvector continuation, September 30, 2021, invited seminar, Nuclear Physics Seminar, Washington University in St. Louis, MO, USA

8. Equation of state constraints from chiral effective field theory and astrophysics, September 23, 2021, invited review talk, International Symposium on Nuclear Symmetry Energy (NuSym 2021; organizers: Maria Colonna, Giuseppe Verde)

9. Dense matter EOS and the QCD phase diagram, August 24, 2021, invited panelist for the group discussion (with Essick, Han, Holt, Ratti, Dexheimer), Seventh Physics and Astrophysics at the eXtreme (PAX-VII) Workshop (chairs: Andrew Steiner, Jocelyn Read)

10. Rigorous uncertainty quantification of the nuclear EOS in the FRIB era, August 11, 2021, inaugural FRIB Early Achievement Award Presentation, Low Energy Community Meeting 2021

11. Eigenvector Continuation for scattering with local chiral nucleon-nucleon and optical potentials, April 26, 2021, invited talk, workshop INT 21-1b: Nuclear Forces for Precision Nuclear Physics (organizers: Davoudi, Ekström, Holt, Tews), Institute for Nuclear Theory, Seattle, WA, USA

12. From chiral interactions to neutron stars and why EFT truncation errors matter, April 6, 2021, invited colloquium, Texas A&M University, TX, USA

13. Implications of chiral EFT truncation errors for neutron star properties, March 19, 2021, invited seminar, Nuclear Physics Seminar, Washington University in St. Louis, MO, USA

14. Nuclear EOS: uncertainty quantification and applications to neutron stars, March 8, 2021, invited seminar, UK Lockdown Nuclear Seminar, organized by the University of Liverpool and University of Manchester

Kevin Fossez (2021)

1. Invited talk at the SESAPS conference, Nov. 18, 2021, Florida State University, Tallahassee, FL, USA.

2. Seminar, Sep. 24, 2021, Florida State University, Tallahassee, FL, USA.

3. Invited talk at the LECM, Aug. 9, 2021, virtual meeting.

4. Invited talk at the FRIB workshop *The Neutron-Unbound Systems Around the Dripline*, July 13, 2021, virtual meeting.

5. Colloquium (interview), March 2, 2021, Florida State University, Tallahassee, FL, USA.

Chloë Hebborn (2021)

1. Seminar, November 9, 2021, Ohio University, virtual talk.

2. Seminar, November 5, 2021, Université libre de Bruxelles, Belgium.

3. Contributed talk at APS DNP meeting, October 13, 2021, virtual meeting.

4. Invited talk at *Low Energy Community Meeting*, August 9, 2021, virtual meeting.

5. Invited talk at ECT* workshop *Nuclear physics at the edge of stability*, June 30, 2021, virtual meeting.

6. Seminar in the Reaction Seminar Series 2021, May 6, 2021, virtual talk.

7. Contributed talk at APS April meeting, April 20, 2021, virtual meeting.

8. Research discussion "Introduction to Kostas Kravvaris seminar on First Principles Calculations Of Light Ion Reactions" at FRIB, March 30, 2021, virtual talk.

9. Seminar of Nuclear Data & Theory Group, March 17, 2021, Lawrence Livermore National Laboratory, virtual talk.

Sebastian König (2021)

1. Theory Seminar *Eigenvector continuation in nuclear physics*, Washington University in St. Louis, February 25, 2021; virtual talk.

2. Invited talk *Few-body perspective for partly perturbative pions* at the INT Program 21-1b "Nuclear Forces for Precision Nuclear Physics," April 26, 2021; virtual talk.

3. Invited talk *Few-Body Physics in Finite Volume* at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2021*, August 10, 2021; virtual meeting.

4. Invited talk *Few-Body Physics in Finite Volume* at the 88th Annual Meeting of the APS Southeastern Section, November 19, 2021; held in person at Florida State University.

5. TRIUMF Theory Group Seminar *Few-Body Physics in Finite Volume*, November 24, 2021; virtual talk.

6. Cyclotron Institute Colloquium *Nuclear physics in a box*, December 7, 2021; held in person at Texas A&M University.

Saori Pastore (2021)

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

Maria Piarulli (2021)

1. Invited talk *Chiral nuclear interactions for Quantum Monte Carlo methods* at 3rd Workshop on Quantitative Challenges in EMC and SRC Research, March 22-26, 2021; virtual

2. Theory seminar *Quantum Monte Carlo studies of nuclear systems* at Lawrence Berkeley National Laboratory, May 26, 2021; virtual

3. Invited talk *Quantum Monte Carlo studies of nuclear systems* at 2021 NUCLEI/SciDac Meeting, June 2-4, 2021; virtual

4. Invited talk *From atomic nuclei to infinite nucleonic matter: opportunities, challenges, and needs* at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2020*, August 9-10, 2021; virtual meeting

5. Theory seminar *Quantum Monte Carlo studies of nuclear systems* at Argonne National Laboratory, Oct 4, 2021, virtual

6. Colloquium *The microscopic model of nuclear theory: from atomic nuclei to infinite nucleonic matter* at San Diego State University, Oct 22, 2021; virtual

Xilin Zhang (2021)

1. Invited talk at ISENT-8 meeting *Information and Statistics in Nuclear Experiment and Theory*, Dec. 2021, FRIB, Michigan State University, East Lansing, MI

2. Invited talk at Workshop *Shedding light on X17*, Sep. 2021, Enrico Fermi Research Center, Rome, Italy; virtual meeting

3. Invited seminar, Sep. 2021, Tongji University, Shanghai, China; virtual meeting

4. Invited talk at the FRIB Theory Alliance Meeting during the *Low Energy Community Meeting 2021*, August 2021; virtual meeting

9.3 Milestones

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

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. - in progress
- 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 - two programs are taking place March and May 2022
- 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*. - operations did not resume yet.
- 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.

FY2023 (June 2022 - May 2023): 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 identified in Table 1 of the renewal proposal will occur.
- The two new fellows will initiate activities with the FRIB-TA at FSU and UW.
- The 4th search for a bridge position will be completed and the new faculty member will initiate activities with the FRIB-TA.
- The FRIB-TA will run another summer school on a topic intersecting FRIB science.
- Two FRIB-TA topical programs on topics of direct relevance to FRIB will take place.
- The FRIB-TA will run its annual meeting concurrent with the Low-Energy Community Meeting.

- The EUSTIPEN program will be reevaluated to better strengthen collaborations between U.S. scientists and European scientists.
- 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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