The MONSTRE Project

(IS: Iniziativa Specifica)

Danilo Gambacurta (INFN-LNS)

TNPI2023 - XIX Conference on Theoretical Nuclear Physics, Cortona-Italy 11 Oct - 13 Oct, 2023

The MONSTRE Project: **MO**deling **N**uclear **ST**ructure and **Re**actions

Established in 2020

Project 2020-2023:
National Coordinator: Francesco Pederiva @TIFPA-Trento => Enrico Vigezzi @INFN-Milano

Project 2024-2026:
National Coordinator: Danilo Gambacurta @INFN-LNS

Project 2024-2026: Brief Summary

- ✔ Research Units
- ✔ Staff Members
- ✔ The Scientific Project
- ✔ Work Packages
- ✔ Some recent highlights
- ✔ The MONSTRE Website

The MONSTRE Project:

Research Units

- ✔ INFN-Bologna (Local Coordinator: Paolo Finelli)
- ✔ INFN-Catania (Local Coordinator: Isaac Vidana)
- ✔ INFN-LNS (Local Coordinator: Maria Colonna)
- ✔ INFN-Milano (Local Coordinator: Javier Roca Maza)
- ✔ INFN-Padova (Local Coordinator: Lorenzo Fortunato)
- ✔ INFN-TIFPA-Trento (Local Coordinator: Alessandro Roggero)

The MONSTRE Project: staff members (FTE=20.7, 33 members)

INFN-Bologna (FTE=1)
- ✔ Paolo Finelli

INFN-Catania (FTE=3.1)
- ✔ Edoardo Lanza
- ✔ Massimo Papa
- ✔ Michelangelo Sambataro
- ✔ Isaac Vidana
- ✔ **Rui Wang (Post-doc)**

INFN-LNS (FTE=3.9)
- ✔ Angela Bonaccorso (INFN-Pisa)
- ✔ Aldo Bonasera
- ✔ Stefano Burrello
- ✔ Maria Colonna
- ✔ Danilo Gambacurta
- ✔ Enzo Greco
- ✔ Angela Gargano (INFN-Napoli)
- ✔ **Jessica Bellone (Post-doc)**

INFN-Padova (FTE=1.7)
- ✔ Lorenzo Fortunato
- ✔ Silvia Monica Lenzi
- ✔ Paolo Lotti

INFN-Milano (FTE=5.8)
- ✔ Carlo Barbieri
- ✔ Gianluca Colò
- ✔ Javier Roca Maza
- ✔ Enrico Vigezzi
- ✔ **Pietro Klausner (Ph.D. student)**
- ✔ **Francesco Marino (Ph.D. student)**
- ✔ **Imane Moumene (Post-doc)**
- ✔ **Stefano Brolli (Ph.D. student)**

INFN-TIFPA-Trento (FTE=5.2)
- ✔ Maurizio Dapor
- ✔ Alessandro Lovato
- ✔ Francesco Pederiva
- ✔ Alessandro Roggero
- ✔ Simone Taioli
- ✔ **Valentina Amitrano (Ph.D.)**
- ✔ **Luca Vespucci (Ph.D.)**
- ✔ **Iyadh Chaker (Ph.D.)**

The MONSTRE Project:

Abstract of the proposal:

Our project aims to establish a comprehensive and integrated framework for the study of atomic nuclei, nuclear reactions, and strongly interacting matter. The synergistic efforts of the various units, based on their complementary expertise in advanced many-body and computational methods, will be devoted to the study of complex nuclear phenomena occurring at different scales of energy and size. Modern *ab initio* techniques will be refined and applied making use of microscopic interactions, derived from nuclear effective field theories. Density functionals will be developed using *ab initio* and/or phenomenogical constraints and applied to the calculation of bulk, spectroscopic, and decay properties of finite nuclei throughout the whole nuclear chart, Collective modes will be studied making use of many body techniques including beyond mean-field correlations. The consistent merging of structure and reaction theories will offer the opportunity to directly compare theoretical calculations with empirical data for nuclear systems under extreme conditions, also deriving microscopic optical potentials. These investigations will also be performed by developing mathematical methods, quantum computing-based algorithms and machine learning techniques specifically tailored for the study of the nuclear many-body problem. Special attention will be devoted to the current experimental projects related to the production of rare isotopes, dark-matter detection, and the physics of electroweak interactions, including neutrino physics and double-beta decay. Combined astrophysical and terrestrial constraints, together with predictions based on state-of-the-art models, will be employed to achieve an improved, multi-faceted understanding of the nuclear equation of state.

The MONSTRE Project:

- ✔ **Modern *ab initio* techniques** will be refined and applied making use of **microscopic interactions**, derived from nuclear **effective field theories**
- ✔ **Density functionals** will be developed using ***ab initio* and/or phenomenogical** constraints to describe the of finite nuclei throughout the whole nuclear chart
- ✔ EDF methods including **beyond mean-field correlations** (2p-2h, phonon coupling, ...)
- ✔ **Merging of structure and reaction theories** (also deriving **microscopic optical potentials**)
- ✔ Multi-faceted understanding of t**he nuclear equation of state**
- ✔ **Mathematical methods, quantum computing-based algorithms and machine learning techniques** specifically tailored for the study of the **nuclear many-body problem**
- ✔ Special attention to the **current experimental projects** (production of rare isotopes, dark-matter detection, the physics of electroweak interactions, neutrino physics and double-beta decay, ...)

The MONSTRE Project: Work Packages (WPs)

- ✔ WP1) ***Ab initio* many body methods for nuclei and nuclear matter**: increasing the accuracy and predictive power
- ✔ WP2) **Advanced theoretical studies of nuclear phenomena**: addressing the experimental challenges
- ✔ WP3) **Nuclear matter under extreme conditions**: from nuclear dynamics to compact objects
- ✔ WP4) **Emerging computational technologies**: quantum computing and machine learning techniques

WP1: *Ab initio* many body methods for nuclei and nuclear matter

- ✔ Self-consistent Green's functions (SCGF), Quantum Monte Carlo, (QMC), Configuration Interaction Monte Carlo (CIMC) and Shell Model (SM), with effective interactions from the chiral EFT including 3-N terms
- ✔ Quantum computing and neural-network quantum states, to extend the domain of their applicability (WP4)
- ✔ Accurate optical nucleon- and nucleus-nucleus potentials within the SCGF approach at low energy (spectator expansion and the impulse approximation)
- ✔ Study of nuclear and hyperonic matter, exotic and deformed nuclei

WP2: Advanced theoretical studies of nuclear phenomena

- ✔ Extending EDF models (*ab initio* constraints, atomic parity-violating data, inclusion of SRCs, beyond mean-field approaches, symmetry restoration,...)
- ✔ Exotic Nuclei: shell structure evolution, low-lying states (PDR), collective excitations (deformed nuclei), ...
- ✔ Phenomenological nucleus-nucleus optical potentials to extract spectroscopic information via breakup and transfer reactions.
- ✔ Direct reactions populating weakly bound systems, unbound resonances.
- ✔ Neutrino physics: single and double-beta decay, charge-exchange reactions

WP3: Nuclear matter under extreme conditions

- ✔ Heavy ion collisions (HICS) at Fermi/intermediate energies
- ✔ DWBA, Coupled-Channel (CC) calculations, semi-classical and transport models to study the collision mechanism
- ✔ Combined astrophysical and terrestrial constraints to improve the EoS
- ✔ The formation of clustering structures at sub-saturation densities in modelization of the EoS (extended EDF incorporating SRCs)

WP4: Emerging computational technologies

✔ Developing scalable quantum algorithms for *ab initio* calculations and implementation on current quantum technologies (INFN, CERN and IBM).

✔ Different possible encodings of pion-less effective theory for light-nuclei (benchmark calculations)

✔ Entanglement properties of light nuclei and infinite nuclear matter to characterize many-nucleon correlations

✔ Variational MC methods based on neural-network (N-N) quantum states

The MONSTRE Project: Work Packages (WPs)

- ✔ WP1) **Ab initio many body methods for nuclei and nuclear matter**: increasing the accuracy and predictive power
  Research Units: [Milano, Trento, LNS]

- ✔ WP2) **Advanced theoretical studies of nuclear phenomena**: addressing the experimental challenges
  Research Units: [Catania, Milano, Padova, Trento, LNS]

- ✔ WP3) **Nuclear matter under extreme conditions**: from nuclear dynamics to compact objects
  Research Units: [Catania, Milano, LNS]

- ✔ WP4) **Emerging computational technologies**: quantum information and machine learning techniques
  Research Units: [Catania, Milano, Trento]

The MONSTRE Project: Experimental colllaborations

- ✔ Asfin collaboration, LNS Italia
- ✔ Chimera Collaboration, LNS Italia
- ✔ CHIRONE - NUCLEX collaboration INFN-Catania and LNS-Catania
- ✔ GAMMA Experiment, INFN, Italy
- ✔ INDRA-FAZIA international collaboration
- ✔ LAND-Chimera collaboration, GSI Darmstadt, Germania
- ✔ MAGNEX and NUMEN collaboration, LNS Italia
- ✔ SπRIT international collaboration
- ✔ Australian National University-Canberra, Australia:
- ✔ CSIC, Madrid, Spain:
- ✔ i-Themba, Capetown, South Africa:
- ✔ Oak RIdge NL, USA:
- ✔ Research Center for Nuclear Physics ,Osaka, Japan
- ✔ RIKEN, Japan
- ✔ Technische Universität Darmstadt, Germany
- ✔ Thomas Jefferson National Accelerator Facility, Newport News, USA

The MONSTRE WebSite (https://www0.mi.infn.it/monstre/)

INFN Istituto Nazionale di Fisica Nucleare

MoNStRe

Modeling **N**uclear **St**ructure and **Re**actions

A RESEARCH PROJECT OF INFN NATIONAL SCIENTIFIC COMMITTEE 4

HOME TEAM MEETINGS RESEARCH TOOLS TRAINING THEORY AND EXPERIMENT DOCUMENTATION NEWS

MONSTRE is a research project sponsored and financed by the National Scientific Committee for Theoretical Physics (CSN4) of the Istituto Nazionale di Fisica Nucleare (INFN).
The main goal of our collaboration is to implement an integrated framework for the physics of atomic nuclei, nuclear reactions, and strongly interacting matter. We aim to match the development of nuclear structure and reaction theory with the experimental progress currently underway in areas like the production of rare isotopes, dark-matter detection, and the physics of electroweak interactions, including neutrino-oscillation and double-beta decay. The recent progress in gravitational-wave detection also calls for a better understanding of the nuclear interactions aiming to reconcile terrestrial nuclear physics observations with the new constraints of astrophysical origin. We will not disregard important applicative aspects like those related to nuclear medicine. Different complementary aspects in the field will be tackled by networking the combined expertise of the various units, who are active in developing a set of advanced and complementary many-body analytic and computational methods. We plan to use our experience in a concerted way in the effort of bridging the gap between the different scales involved in a modern nuclear physics research program.

The MONSTRE WebSite (https://www0.mi.infn.it/monstre/)

Workpackage WP1

2021

C. Adams, G. Carleo, A. Lovato and N. Rocco, Variational *Monte Carlo calculations of A ≤ 4 nuclei with an artificial neural-network correlator ansatz*, Phys. Rev. Lett. 127, 022502 (2021)

C. A. Bertulani, A. Idini and C. Barbieri, *Examination of the sensitivity of quasifree reactions to details of the bound-state overlap functions*, Phys. Rev. C104, L061602 (2021)

G. Cò, M. Anguiano and A.M. Lallena, *Tensor force and deformation in even even nuclei* , Phys Rev. C 104 (2021) 014313

L. Coraggio, S. Pastore and C. Barbieri, *Editorial: The future of nuclear structure: challenges and opportunities in the microscopic description of nuclei*, Front. Phys. 8, 626976 (2021)

L. Coraggio, G. De Gregorio, A. Gargano, N. Itaco, T. Fukui, Y. Z. Ma and F. R. Xu, *Shell-model study of titanium isotopic chain with chiral two- and three-body forces*, Phys. Rev. C 104, 054304 (2021)

G. De Gregorio, F. Knapp, N. Lo Iudice and P. Vesely,*Removal of the center of mass in nuclei and its effects on 4He* , Phys. Lett. B 821, 136636 (2021)

T. Fukui, L. Coraggio, G. De Gregorio, A. Gargano, N. Itaco, Y. Z. Ma and F. R. Xu, *Realistic shell model with chiral interaction and its application to drip-line predictions*, Few-Body Syst. 62, 64 (2021)

J. Isaacson, W.I. Jay, A. Lovato, P. Machado and N. Rocco, *New approach to intranuclear cascades with quantum Monte Carlo configurations*, Phys. Rev. C 103, 015502 (2021)

F. Marino, C. Barbieri, A. Carbone, G. Colò, A. Lovato, F. Pederiva, X. Roca-Maza and E. Vigezzi, *Nuclear energy density functionals grounded in ab initio calculations*, Phys. Rev. C 104, 024315 (2021)

R. Romano, X. Roca-Maza,G. Colò and S. Shen, *Extended Lipkin-Meshkov-Glick Hamiltonian*, J. Phys. G: Nucl. Part. Phys. 48 05LT01 (2021)

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-mass nuclei*, Phys. Rev. C 103, 054003 (2021)

G. Selva, X. Roca-Maza and G. Colò, *Isospin Symmetry Breaking Effects on the Mass-Radius Relation of a Neutron Star*, Symmetry 13, 144 (2021)

V. Somà, C. Barbieri, T. Duguet and P. Navrátil, *Moving away from singly-magic nuclei with Gorkov Green's function theory*, Eur. Phys. J A57, 135 (2021)

T. Aumann, C. Barbieri, et al., *Quenching of single-particle strength from direct reactions with stable and rare-isotopes beams*, Prog. Part. Nucl. Phys. 118 103847 (2021)

A. Fernandez, S.M. Lenzi et al., *Mirror energy differences above the 0f7/2 shell: First γ-ray spectroscopy of the Tz = -2 nucleus 56Zn*, Phys. Lett. B 823, 136784 (2021)

A. Gade, S.M. Lenzi et al., *In-beam γ spectroscopy of 62,64C*, Phys.Rev. C 103, 014314(2021)

S.M. Lenzi, A. Poves and A. O. Macchiavelli, *Shell model analysis of the B(E2,2+→0+) values in the A=70, T=1 triplet 70Kr, 70Br, and 70Se*, Phys.Rev. C 104, L031306 (2021).

B. D. Linh, C. Barbieri et al., *Investigation of the ground state spin inversion in the neutron-rich Cl-47,Cl-49 isotopes*, Phys. Rev. C104, 044331 (2021)

R.Yajzey, S.M. Lenzi et al., *Spectroscopy of the Tz = 2 mirror nuclei 48Fe/48Ti using mirrored knockout reactions*, Phys. Lett. B 823, 136757 (2021)

D. Tonev, G. De Gregorio et al., *Transition probabilities in P-31 and S-31: A test for isospin symmetry*, Phys. Lett. B 821 136603 (2021)

2022

P. Arthuis, C. Barbieri, F. Pederiva and A. Roggero, *Quantum Monte Carlo in configuration space with three-nucleon forces*, arXiv:2203.16167 [nucl-th]

G. De Gregorio, F. Knapp, N. Lo Iudice and P. Vesely,*Spectroscopic properties of He-4 within a multiphonon approach*, Phys. Rev. C 105, 024326 (2022)

A. Liardi, F. Marino, G. Colò, X. Roca-Maza and E. Vigezzi, *Complete solution to the inverse Kohn-Sham problem: From the density to the energy*, Phys. Rev. C 105, 034309 (2022)

T. Naito, G. Colò, H. Liang, X.Roca-Maza, and H. Sagawa, *Towards ab initio charge symmetry breaking in nuclear energy density functionals*, Phys. Rev. C 105, L021304 (2022)

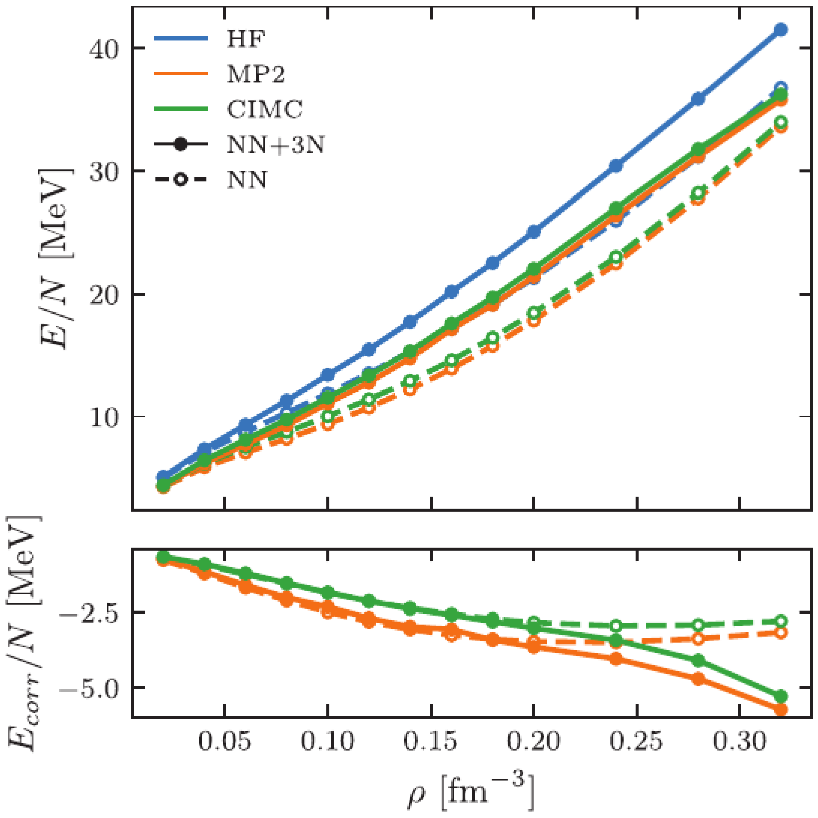
G. Co', M. Anguiano and A.M. Lallena, *Charge radii of Ca isotopes and correlations*, Phys. Rev. C 105, 034320 (2022)

PHYSICAL REVIEW C **107**, 044303 (2023)

WP1

Quantum Monte Carlo calculations in configuration space with three-nucleon forces

Pierre Arthuis,[1,2,*] Carlo Barbieri,[3,4,†] Francesco Pederiva,[5,6] and Alessandro Roggero[5,6,7]



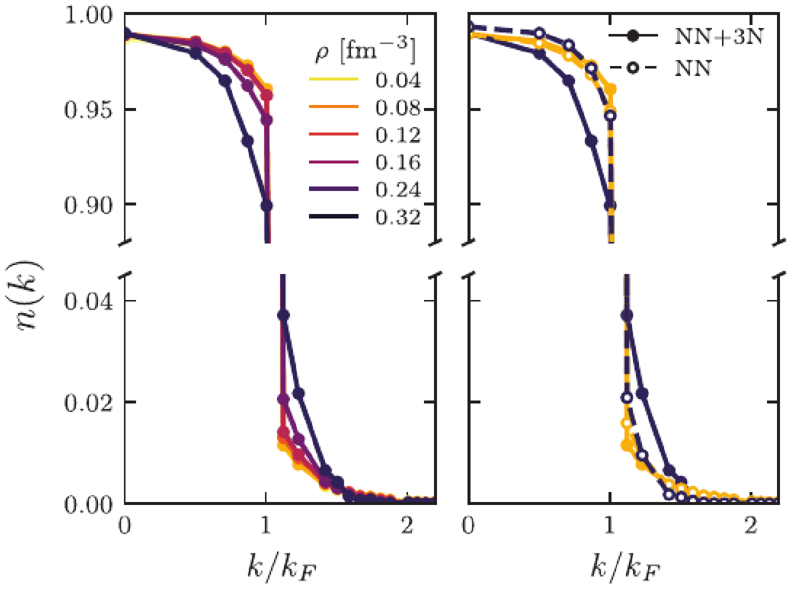


FIG. 3. Left: Momentum distribution of neutron matter for the $NNLO_{opt}$ Hamiltonian plus 3NFs, computed in a periodic box with 66 particles, for different densities. Right: Comparison of $n(k)$ computed with and without 3NFs for two cases, at half and twice saturation density. The momentum is expressed as a fraction of the Fermi momentum k_F.

Predictions for the momentum distribution and the static structure factor.

PHYSICAL REVIEW LETTERS **131**, 082501 (2023)

WP2

Toward a Unified Description of Isoscalar Giant Monopole Resonances in a Self-Consistent Quasiparticle-Vibration Coupling Approach

Z. Z. Li (李征征),[1,2,3] Y. F. Niu (牛一斐),[1,2,*] and G. Colò[3,4,†]

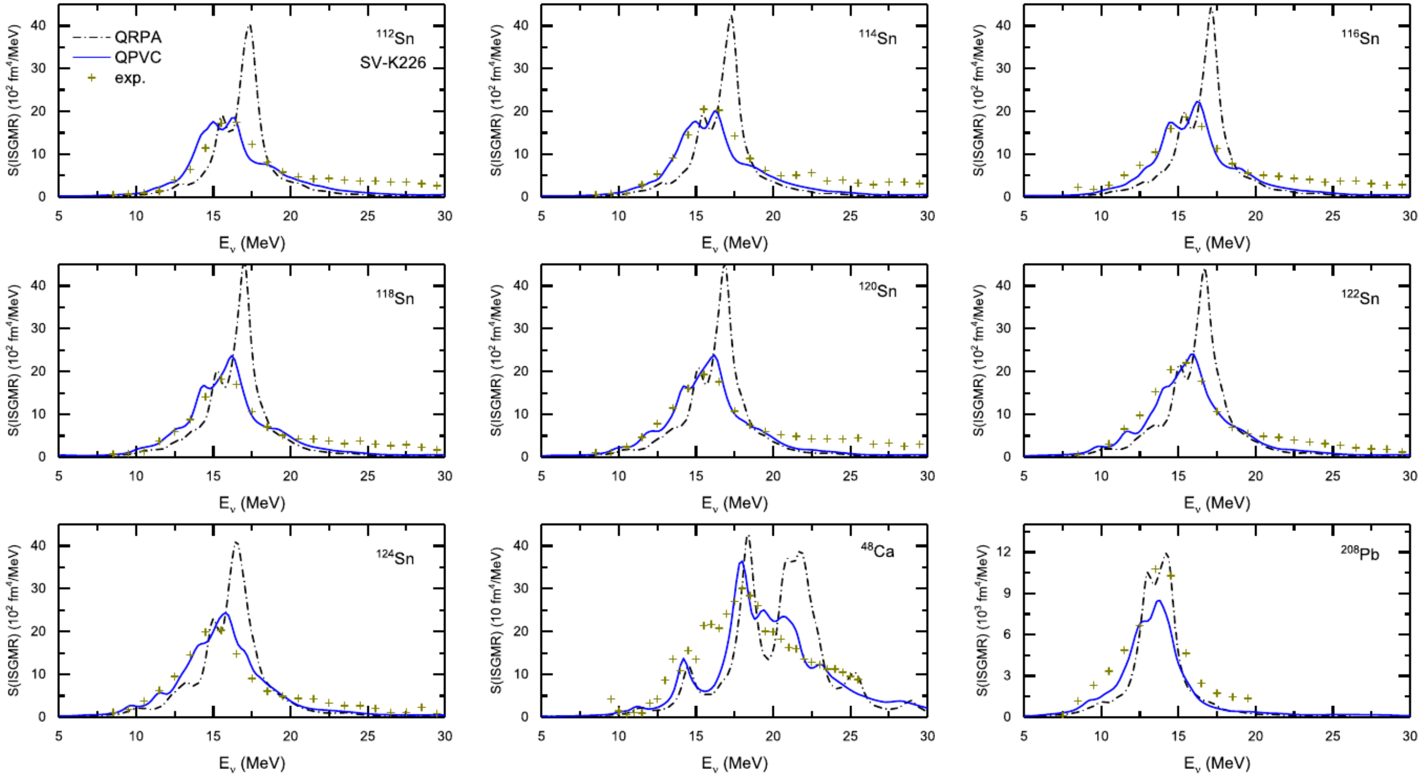
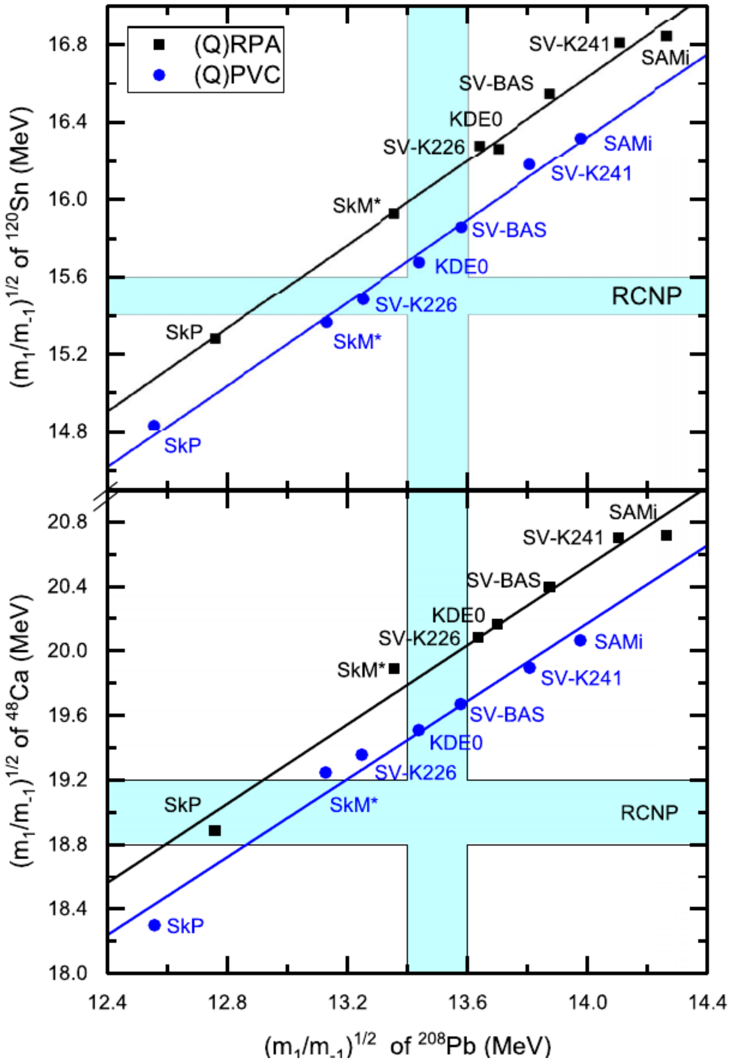


FIG. 1. ISGMR strength functions in even-even $^{112-124}$Sn, ^{48}Ca, and ^{208}Pb isotopes, calculated either by (Q)RPA using a smoothing with Lorentzian having a width of 1 MeV [dash-dotted (black) line], or (Q)RPA + (Q)PVC [solid (blue) line]. The SV-K226 Skyrme force is used. The experimental data are given by green crosses [8,15,45].



$$K_\infty = 226 \text{ MeV and } 229 \text{ MeV},$$

WP3

ELSEVIER

Progress in Particle and Nuclear Physics

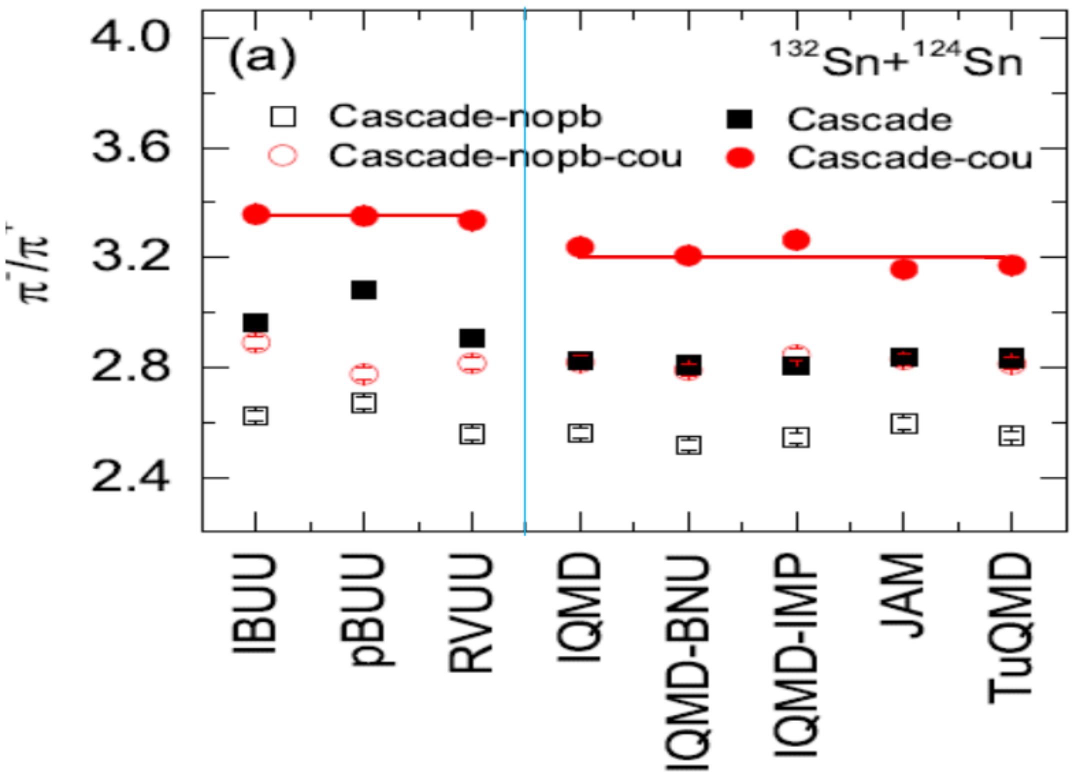
Volume 125, July 2022, 103962

Review

Transport model comparison studies of intermediate-energy heavy-ion collisions

Hermann Wolter[1], Maria Colonna[2], Dan Cozma[3], Pawel Danielewicz[4 5], Che Ming Ko[6], Rohit Kumar[4], Akira Ono[7], ManYee Betty Tsang[4 5], Jun Xu[8 9], Ying-Xun Zhang[10 11], Elena Bratkovskaya[12 13], Zhao-Qing Feng[14], Theodoros Gaitanos[15], Arnaud Le Fèvre[12], Natsumi Ikeno[16], Youngman Kim[17], Swagata Mallik[18], Paolo Napolitani[19], Dmytro Oliinychenko[20], Tatsuhiko Ogawa[21]…
Wen-Jie Xie[41]

^{132}Sn + ^{124}Sn, b=4 fm E/A = 270 MeV/A



Transport Model Evaluation (Comparison) Project -- **TMEP**

- **CASCADE**: difference **BUU**/**QMD** due to better treatment of Pauli-Blocking in **BUU**

WP4

Trapped-ion quantum simulation of collective neutrino oscillations

Valentina Amitrano,[1,2,*] Alessandro Roggero,[1,2] Piero Luchi,[1,2] Francesco Turro,[1,2] Luca Vespucci,[1,2,3] and Francesco Pederiva[1,2]

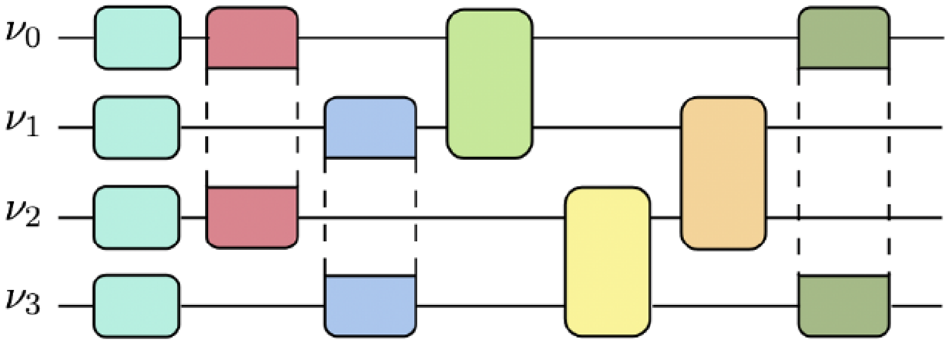


FIG. 8. Scheme for implementing a single Trotter step. We first apply the single-qubit gates corresponding to the one-body propagator $U_1(dt)$ and then the pair propagator using the optimal ordering implementing $U_2(dt)$.

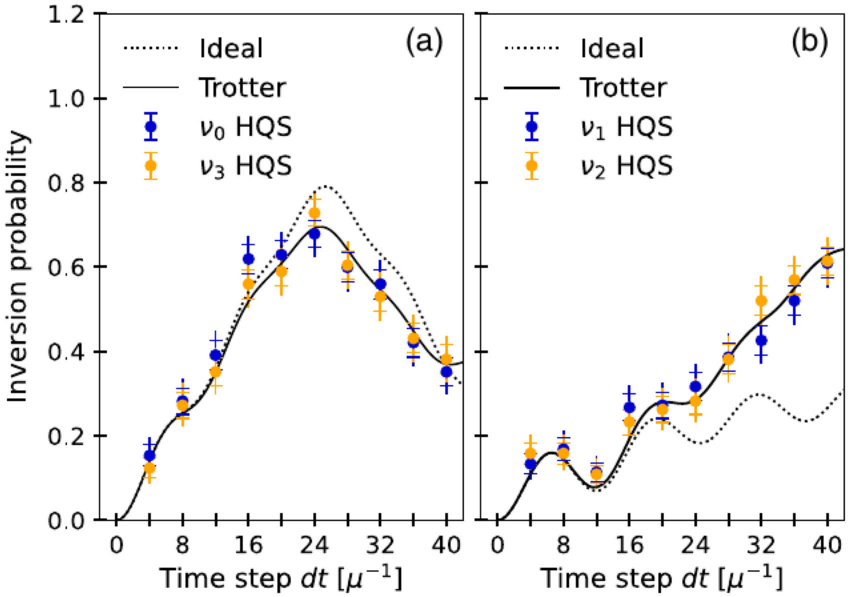


FIG. 9. Single Trotter step evolution for the inversion probability starting with the initial state $|\Psi_0^{(4)}\rangle = |0011\rangle$. Panel (a) is for neutrinos ν_0 and ν_3, and panel (b) is for ν_1 and ν_2. The dotted line represents the ideal results using the exact propagator, while the solid black line indicates the ideal result obtained using one Trotter step. The results obtained from experiments on QSM H1-2 are represented by data points and error bars with and without caps corresponding to 68% and 90% confidence intervals, respectively.

The MONSTRE Project: Talks

- ✔ *Quantum computing for nuclear physics [35']*
  Alessandro Roggero, Università di Trento

- ✔ *Digital quantum computing for collective neutrino oscillations[20']*
  Valentina Amitrano, Università di Trento, **(Ph.D. student)**

- ✔ *Microscopic theory of infinite nuclear matter and connections to the nuclear energy functional [20']*, Francesco Marino, Sezione di Milano, **(Ph.D. student)**

- ✔ *Systematics of reaction cross sections from double folding and single folding optical potentials [20']*, Imane Moumene, Sezione di Milano, **(Post-doc)**

- ✔ *Clustering and two-body correlations within extended density functional approach [35']*, *Stefano Burrello*, LNS-Catania

- ✔ *Kinetic approach of light-nuclei production in intermediate-energy heavy-ion collisions [20']*, Rui Wang, Sezione di Catania, **(Post-doc)**

MOdeling
Nuclear
STructure and
REactions

Thanks for your kind attention !!!

WP2: Advanced theoretical studies of nuclear phenomena

- ✔ Extending EDF models (*ab initio* constraints, atomic parity-violating data, inclusion of SRCs, beyond mean-field approaches, symmetry restoration,...)
- ✔ Exotic Nuclei: shell structure evolution, low-lying states (PDR), collective excitations (deformed nuclei), ...
- ✔ Phenomenological nucleus-nucleus optical potentials to extract spectroscopic information via breakup and transfer reactions.
- ✔ Direct reactions populating weakly bound systems, unbound resonances.
- ✔ Neutrino physics: single and double-beta decay, charge-exchange reactions
- ✔ Merging symmetry methods with molecular models of the nucleus
- ✔ Clustering and alpha-like correlations induced by the p-n pairing force

WP3: Nuclear matter under extreme conditions

- ✔ Heavy ion collisions (HICS) at Fermi/intermediate energies
- ✔ DWBA, Coupled-Channel (CC) calculations, semi-classical and transport models to study the collision mechanism
- ✔ Combined astrophysical and terrestrial constraints to improve the EoS
- ✔ Isospin dependence of in medium nucleon-nucleon interaction and EoS
- ✔ The formation of clustering structures at sub-saturation densities in modelization of the EoS (extended EDF (incorporating SRCs) and CoMD).

WP4: Emerging computational technologies

- ✔ Developing scalable quantum algorithms for ab initio calculations and implementation on current quantum technologies (INFN, CERN and IBM).
- ✔ Different possible encodings of pion-less effective theory for light-nuclei (benchmark calculations)
- ✔ Flavour evolution of neutrinos in dense astrophysical environments
- ✔ Entanglement properties of light nuclei and infinite nuclear matter to characterize many-nucleon correlations
- ✔ Variational MC methods based on neural-network (N-N) quantum states