

Thirty Years of Education and Research on Nuclear Many-Body Physics at the ECT*; from traditional methods to quantum computing and machine learning

Morten Hjorth-Jensen¹

Department of Physics and Astronomy and FRIB, Michigan State University,
USA, and Department of Physics and Center for Computing in Science Education,
University of Oslo, Norway¹

30th anniversary ECT*, October 4, 2023

What is this talk about?

The main emphasis is to give you a short and pedestrian introduction to the whys and hows we can use (with several examples) machine learning methods in nuclear physics. And why this could (or should) be of interest. And how this can be linked with standard many-body theories. And perhaps some quantum computing.

I will also try to highlight educational initiatives and strategies where the ECT* has played and will play an important role in educating the next generation of nuclear scientists

Additional info

Parts of this talk are based on [Artificial Intelligence and Machine Learning in Nuclear Physics](#), Amber Boehnlein et al., Reviews Modern of Physics 94, 031003 (2022)

Thanks to many

Jane Kim (MSU), Julie Butler (MSU), Patrick Cook (MSU), Danny Jammooa (MSU), Daniel Bazin (MSU), Dean Lee (MSU), Witek Nazarewicz (MSU), Michelle Kuchera (Davidson College), Even Nordhagen (UiO), Robert Solli (UiO, Expert Analytics), Bryce Fore (ANL), Alessandro Lovato (ANL), Stefano Gandolfi (LANL), Francesco Pederiva (UniTN), and Giuseppe Carleo (EPFL). Niyaz Beysengulov and Johannes Pollanen (experiment, MSU); Zachary Stewart, Jared Weidman, and Angela Wilson (quantum chemistry, MSU) Jonas Flaten, Oskar, Leinonen, Øyvind Sigmundson Schøyen, Stian Dysthe Bilek, and Håkon Emil Kristiansen (UiO). Marianne Bathen and Lasse Vines (experiments (UiO). Excuses to those I have omitted.

The first postdocs and long-term visitors, 1994-1996

- ▶ Two Brazilians professors on sabbatical leave, Marta Barroso and Carlos Aguiar; Ed Tomosiak from Canada
- ▶ Alexandar Belic; Dennis Bonatsos
- ▶ Fabio Vittorio De Blasio; Dima Fedorov
- ▶ Hilmar Forkel; Antje Hoering
- ▶ Gianluca Lazzari; Mathias Lutz
- ▶ Jochen Rau":<https://www.q-info.org/about-me/>"; MHJ

Villa Tambosi, summer 1995, Tempus Fugit (sadly)



One of the first many-body workshops, June-July 1997



Educational mission and strategic initiatives

- ▶ First doctoral training program summer 2002 under the Marie Curie program, Hot and dense QCD
- ▶ First Nuclear Talent course summer 2012, focus on computational many-body methods, nuclear shell-model and Monte Carlo methods

The Nuclear TALENT initiative

Training in Advanced Low Energy Nuclear Theory, aims at providing an advanced and comprehensive training to graduate students and young researchers in low-energy nuclear theory. The initiative is a multinational network between several Asian, European and Northern American institutions and aims at developing a broad curriculum that will provide the platform for a cutting-edge theory for understanding nuclei and nuclear reactions. These objectives are met by offering series of lectures, commissioned from experienced teachers in nuclear theory. The educational material generated under this program will be collected in the form of WEB-based courses, textbooks, and a variety of modern educational resources. No such all-encompassing material is available at present; its development will allow dispersed university groups to profit from the best expertise available. The ECT* and the INT have played central roles here.

The first ever Nuclear Talent course, ECT*, summer 2012

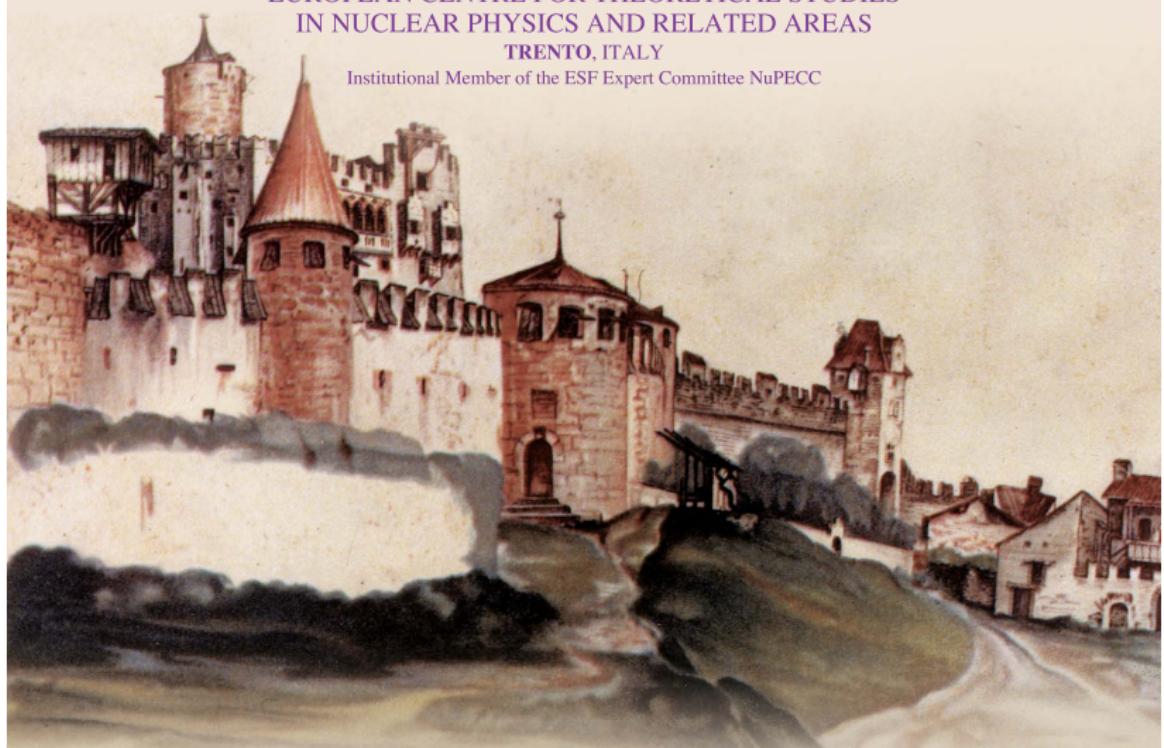


ECT*



EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

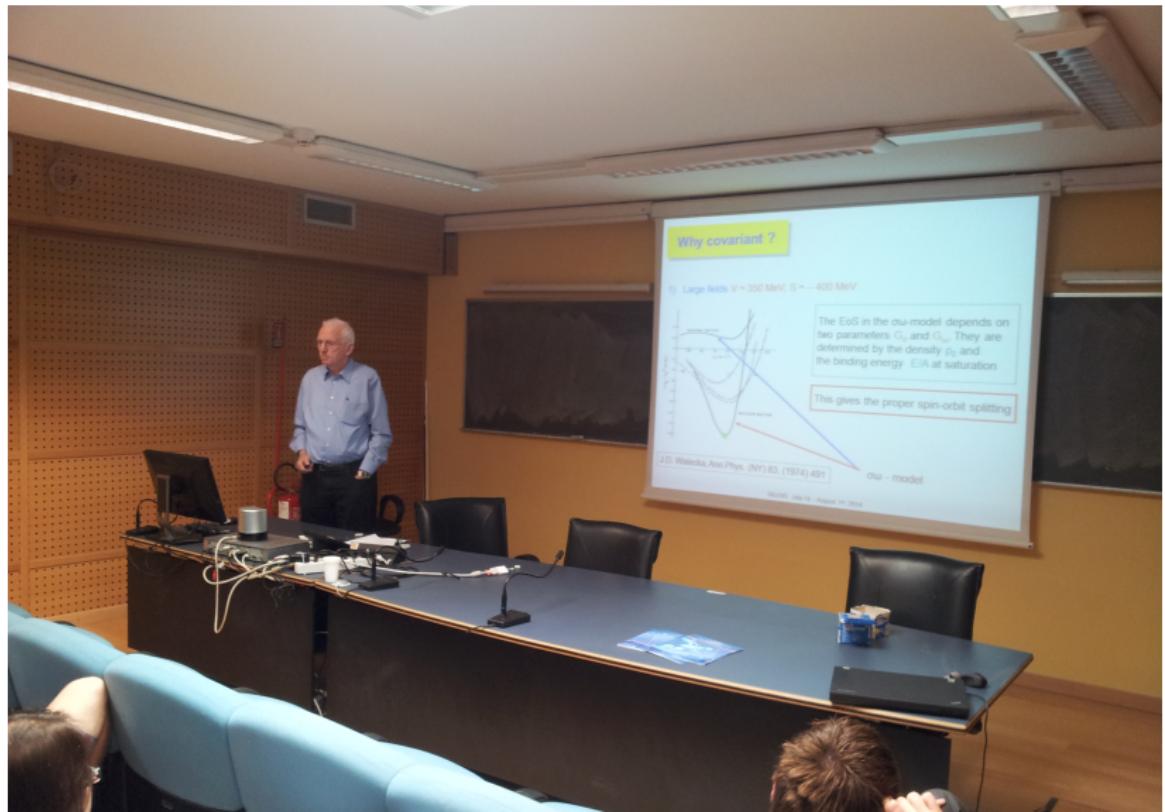
Institutional Member of the ESF Expert Committee NuPECC



The second Nuclear Talent course at the ECT*, summer 2014



The second Nuclear Talent course at the ECT*, summer 2014



Nuclear Talent course summer 2017



Nuclear Talent course summer 2018 in China

TALENT Course 2018

"Many-body methods for nuclear physics, from structure to reactions"

Lecturers:

Kevin Fossez (Michigan State U)

Morten Hjorth-Jensen (Michigan State U)

Thomas Papenbrock (U Tennessee)

Ragnar Stroberg (Reed College/U Washington)

Yu-Min Zhao (Shanghai Jiaotong U)

Organizers:

Morten Hjorth-Jensen (Michigan State U)

Chun-Wang Ma (Henan Norm. U)

Fu-Rong Xu (Peking U)

Shan-Gui Zhou (ITP, CAS)

July 15-August 5, 2018
Xinxiang, China

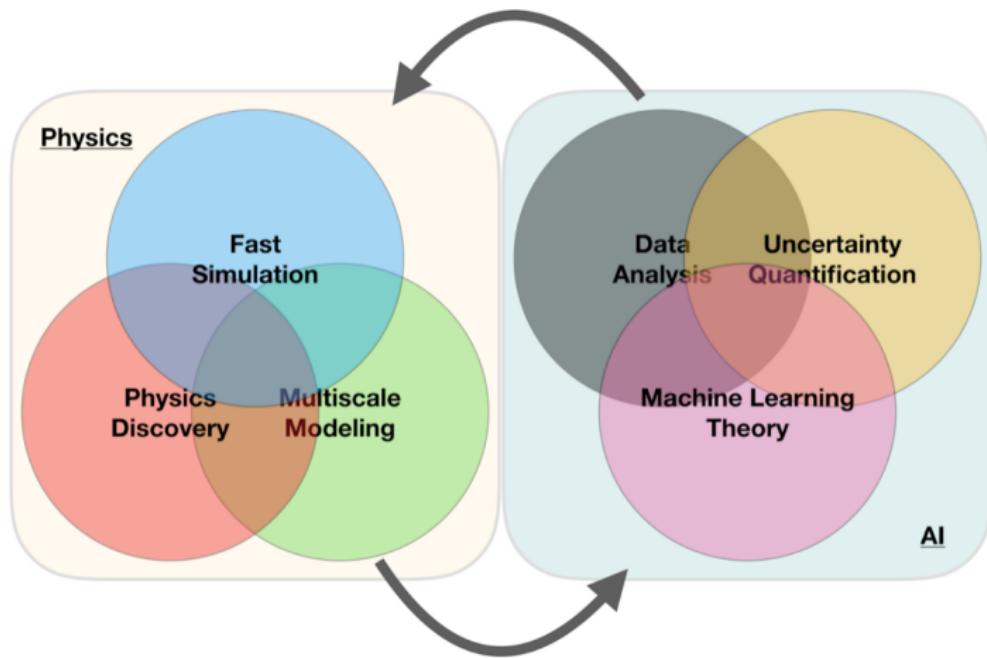
TALENT 2018

Educational strategies

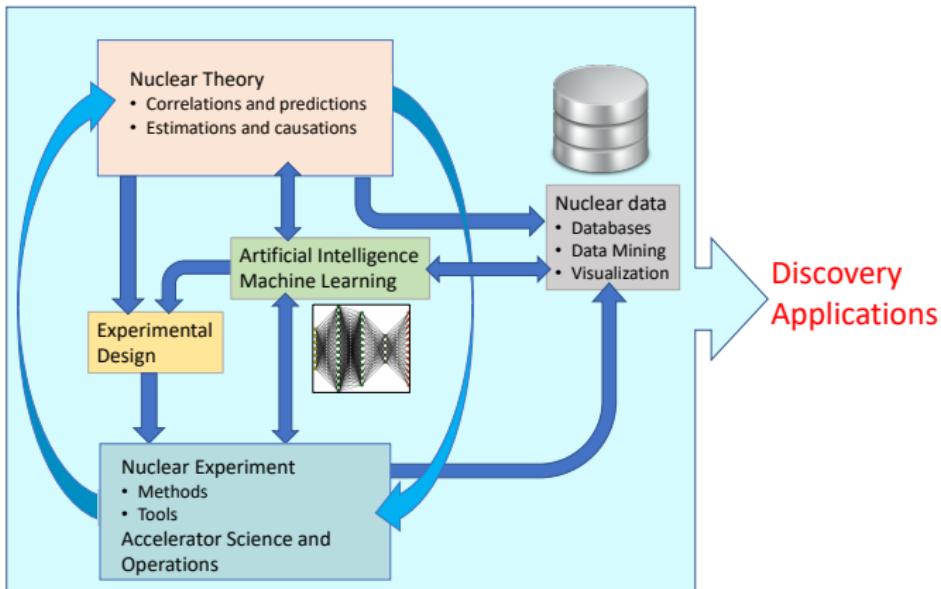
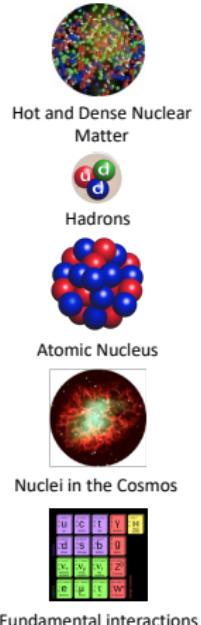
The ECT* should continue to play a key role in educating the next generation of nuclear scientists.

1. Through the organization of DTPs and possibly nuclear Talent courses
2. Be at the forefront in introducing new theoretical developments to nuclear physics (now quantum computing and AI/Machine learning)
3. Foster and care for PDs and their careers, develop career plans with European universities and national laboratories, for example larger training networks with selected laboratories and universities.
4. Similarly, in collaboration with European universities (note the European perspective), develop training networks in nuclear theory at the PhD level and possibly also master level. This has to be done in collaboration with universities.
5. Develop regional, national, European and international initiatives that encompass the above

Machine learning. A simple perspective on the interface between ML and Physics



ML in Nuclear Physics



AI/ML and some statements you may have heard (and what do they mean?)

1. Fei-Fei Li on ImageNet: **map out the entire world of objects** ([The data that transformed AI research](#))
2. Russell and Norvig in their popular textbook: **relevant to any intellectual task; it is truly a universal field** ([Artificial Intelligence, A modern approach](#))
3. Woody Bledsoe puts it more bluntly: **in the long run, AI is the only science** (quoted in Pamilla McCorduck, [Machines who think](#))

If you wish to have a critical read on AI/ML from a societal point of view, see [Kate Crawford's recent text Atlas of AI](#)

Here: with AI/ML we intend a collection of machine learning methods with an emphasis on statistical learning and data analysis

Scientific Machine Learning

An important and emerging field is what has been dubbed as scientific ML, see the article by Deiana et al [Applications and Techniques for Fast Machine Learning in Science](#), arXiv:2110.13041

The authors discuss applications and techniques for fast machine learning (ML) in science – the concept of integrating power ML methods into the real-time experimental data processing loop to accelerate scientific discovery. The report covers three main areas

1. applications for fast ML across a number of scientific domains;
2. techniques for training and implementing performant and resource-efficient ML algorithms;
3. and computing architectures, platforms, and technologies for deploying these algorithms.

Machine Learning and Physics

Machine learning is an extremely rich field, in spite of its young age. The increases we have seen during the last three decades in computational capabilities have been followed by developments of methods and techniques for analyzing and handling large date sets, relying heavily on statistics, computer science and mathematics. The field is rather new and developing rapidly.

Popular software packages written in Python for ML are

- ▶ Scikit-learn,
- ▶ Tensorflow,
- ▶ PyTorch
- ▶ Keras,

and more. These are all freely available at their respective GitHub sites. They encompass communities of developers in the thousands or more. And the number of code developers and contributors keeps increasing.

Lots of room for creativity

Not all the algorithms and methods can be given a rigorous mathematical justification, opening up thereby for experimenting and trial and error and thereby exciting new developments.

A solid command of linear algebra, multivariate theory, probability theory, statistical data analysis, optimization algorithms, understanding errors and Monte Carlo methods is important in order to understand many of the various algorithms and methods.

Job market, a personal statement: A familiarity with ML is almost becoming a prerequisite for many of the most exciting employment opportunities. And add quantum computing and there you are!

Types of machine learning

The approaches to machine learning are many, but are often split into two main categories. In *supervised learning* we know the answer to a problem, and let the computer deduce the logic behind it. On the other hand, *unsupervised learning* is a method for finding patterns and relationship in data sets without any prior knowledge of the system. Some authours also operate with a third category, namely *reinforcement learning*. This is a paradigm of learning inspired by behavioural psychology, where learning is achieved by trial-and-error, solely from rewards and punishment.

Main categories

Another way to categorize machine learning tasks is to consider the desired output of a system. Some of the most common tasks are:

- ▶ Classification: Outputs are divided into two or more classes. The goal is to produce a model that assigns inputs into one of these classes. An example is to identify digits based on pictures of hand-written ones. Classification is typically supervised learning.
- ▶ Regression: Finding a functional relationship between an input data set and a reference data set. The goal is to construct a function that maps input data to continuous output values.
- ▶ Clustering: Data are divided into groups with certain common traits, without knowing the different groups beforehand. It is thus a form of unsupervised learning.

Machine learning and nuclear theory (my bias): Why?

1. ML tools can help us to speed up the scientific process cycle and hence facilitate discoveries
2. Enabling fast emulation for big simulations
3. Revealing the information content of measured observables w.r.t. theory
4. Identifying crucial experimental data for better constraining theory
5. Providing meaningful input to applications and planned measurements
6. ML tools can help us to reveal the structure of our models
7. Parameter estimation with heterogeneous/multi-scale datasets
8. Model reduction
9. ML tools can help us to provide predictive capability
10. Theoretical results often involve ultraviolet and infrared extrapolations due to Hilbert-space truncations
11. Uncertainty quantification essential
12. Theoretical models are often applied to entirely new nuclear systems and conditions that are not accessible to experiment

The plethora of machine learning algorithms/methods

1. Deep learning: Neural Networks (NN), Convolutional NN, Recurrent NN, Boltzmann machines, autoencoders and variational autoencoders and generative adversarial networks
2. Bayesian statistics and Bayesian Machine Learning, Bayesian experimental design, Bayesian Regression models, Bayesian neural networks, Gaussian processes and much more
3. Dimensionality reduction (Principal component analysis), Clustering Methods and more
4. Ensemble Methods, Random forests, bagging and voting methods, gradient boosting approaches
5. Linear and logistic regression, Kernel methods, support vector machines and more
6. Reinforcement Learning
7. Generative models and more

Examples of Machine Learning methods and applications in nuclear physics

- ▶ **Machine learning for data mining:** Oftentimes, it is necessary to be able to accurately calculate observables that have not been measured, to supplement the existing databases.
- ▶ **Nuclear density functional theory:** Energy density functional calibration involving Bayesian optimization and ML.
- ▶ **Nuclear properties with ML:** Improving predictive power of nuclear models by emulating model residuals.
- ▶ **Effective field theory and A-body systems:** Truncation errors and low-energy coupling constant calibration, nucleon-nucleon scattering calculations, variational calculations with ANN for light nuclei, NN extrapolation of nuclear structure observables
- ▶ **Nuclear shell model UQ:** ML methods have been used to provide UQ of configuration interaction calculations.

Examples of Machine Learning methods and applications in nuclear physics, continues

- ▶ **Low-energy nuclear reactions UQ:** Bayesian optimization studies of the nucleon-nucleus optical potential, R-matrix analyses, and statistical spatial networks to study patterns in nuclear reaction networks.
- ▶ **Neutron star properties and nuclear matter equation of state:** constraining the equation of state by properties on neutron stars and selected properties of finite nuclei
- ▶ **Experimental design:** Bayesian ML provides a framework to maximize the success of an experiment based on the best information available on existing data, experimental conditions, and theoretical models.

More examples

The large amount of degrees of freedom pertain to both theory and experiment in nuclear physics. With increasingly complicated experiments that produce large amounts data, automated classification of events becomes increasingly important. Here, deep learning methods offer a plethora of interesting research avenues.

- ▶ Reconstruction of particle trajectories or classification of events are typical examples where ML methods are being used. However, since these data can often be extremely noisy, the precision necessary for discovery in physics requires algorithmic improvements. Research along such directions, interfacing nuclear physics with AI/ML is expected to play a significant role in physics discoveries related to new facilities. The treatment of corrupted data in imaging and image processing is also a relevant topic.
- ▶ Design of detectors represents an important area of applications for ML/AI methods in nuclear physics.

And more

- ▶ An important application of AI/ML methods is to improve the estimation of bias or uncertainty due to the introduction of or lack of physical constraints in various theoretical models.
- ▶ In theory, we expect to use AI/ML algorithms and methods to improve our knowledge about correlations of physical model parameters in data for quantum many-body systems. Deep learning methods show great promise in circumventing the exploding dimensionalities encountered in quantum mechanical many-body studies.
- ▶ Merging a frequentist approach (the standard path in ML theory) with a Bayesian approach, has the potential to infer better probability distributions and error estimates. As an example, methods for fast Monte-Carlo- based Bayesian computation of nuclear density functionals show great promise in providing a better understanding
- ▶ Machine Learning and Quantum Computing is a very interesting avenue to explore.

Selected references

- ▶ Mehta et al. and Physics Reports (2019).
- ▶ Machine Learning and the Physical Sciences by Carleo et al
- ▶ Artificial Intelligence and Machine Learning in Nuclear Physics, Amber Boehnlein et al., Reviews Modern of Physics 94, 031003 (2022)
- ▶ Dilute neutron star matter from neural-network quantum states by Fore et al, Physical Review Research 5, 033062 (2023)
- ▶ Neural-network quantum states for ultra-cold Fermi gases, Jane Kim et al, Nature Physics Communcication, submitted
- ▶ Message-Passing Neural Quantum States for the Homogeneous Electron Gas, Gabriel Pescia, Jane Kim et al. arXiv.2305.07240,
- ▶ Efficient solutions of fermionic systems using artificial neural networks, Nordhagen et al, Frontiers in Physics 11, 2023
- ▶ Report from the A.I. For Nuclear Physics Workshop by Bedaque et al., Eur J. Phys. A 57, (2021)

What are the basic ingredients?

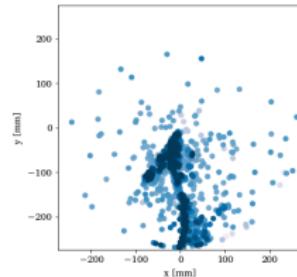
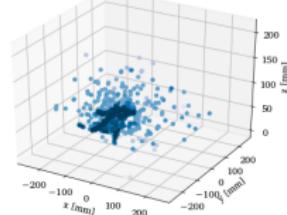
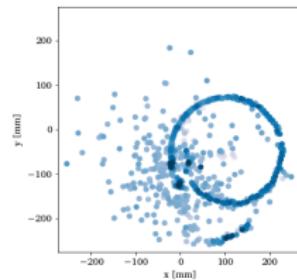
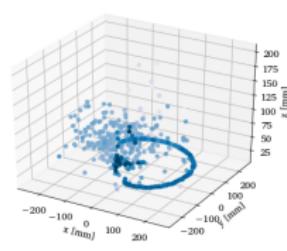
Almost every problem in ML and data science starts with the same ingredients:

- ▶ The dataset x (could be some observable quantity of the system we are studying)
- ▶ A model which is a function of a set of parameters α that relates to the dataset, say a likelihood function $p(x|\alpha)$ or just a simple model $f(\alpha)$
- ▶ A so-called **loss/cost/risk** function $\mathcal{C}(x, f(\alpha))$ which allows us to decide how well our model represents the dataset.

We seek to minimize the function $\mathcal{C}(x, f(\alpha))$ by finding the parameter values which minimize \mathcal{C} . This leads to various minimization algorithms. It may surprise many, but at the heart of all machine learning algorithms there is an optimization problem.

Argon-46 by Solli et al., NIMA 1010, 165461 (2021)

Representations of two events from the Argon-46 experiment. Each row is one event in two projections, where the color intensity of each point indicates higher charge values recorded by the detector. The bottom row illustrates a carbon event with a large fraction of noise, while the top row shows a proton event almost free of noise.



Quantum Monte Carlo and deep learning

Given a hamiltonian H and a trial wave function Ψ_T , the variational principle states that the expectation value of $\langle H \rangle$, defined through

$$\langle E \rangle = \frac{\int d\mathbf{R} \Psi_T^*(\mathbf{R}) H(\mathbf{R}) \Psi_T(\mathbf{R})}{\int d\mathbf{R} \Psi_T^*(\mathbf{R}) \Psi_T(\mathbf{R})},$$

is an upper bound to the ground state energy E_0 of the hamiltonian H , that is

$$E_0 \leq \langle E \rangle.$$

In general, the integrals involved in the calculation of various expectation values are multi-dimensional ones. Traditional integration methods such as the Gauss-Legendre will not be adequate for say the computation of the energy of a many-body system. **Basic philosophy: Let a neural network find the optimal wave function**

Monte Carlo methods and Neural Networks

Machine Learning and the Deuteron by Kebble and Rios and
Variational Monte Carlo calculations of $A \leq 4$ nuclei with an
artificial neural-network correlator ansatz by Adams et al.

Adams et al:

$$H_{LO} = - \sum_i \frac{\vec{\nabla}_i^2}{2m_N} + \sum_{i < j} (C_1 + C_2 \vec{\sigma}_i \cdot \vec{\sigma}_j) e^{-r_{ij}^2 \Lambda^2 / 4} + D_0 \sum_{i < j < k} \sum_{\text{cyc}} e^{-(r_{ik}^2 + r_{ij}^2) \Lambda^2 / 4}, \quad (1)$$

where m_N is the mass of the nucleon, $\vec{\sigma}_i$ is the Pauli matrix acting on nucleon i , and \sum_{cyc} stands for the cyclic permutation of i , j , and k . The low-energy constants C_1 and C_2 are fit to the deuteron binding energy and to the neutron-neutron scattering length

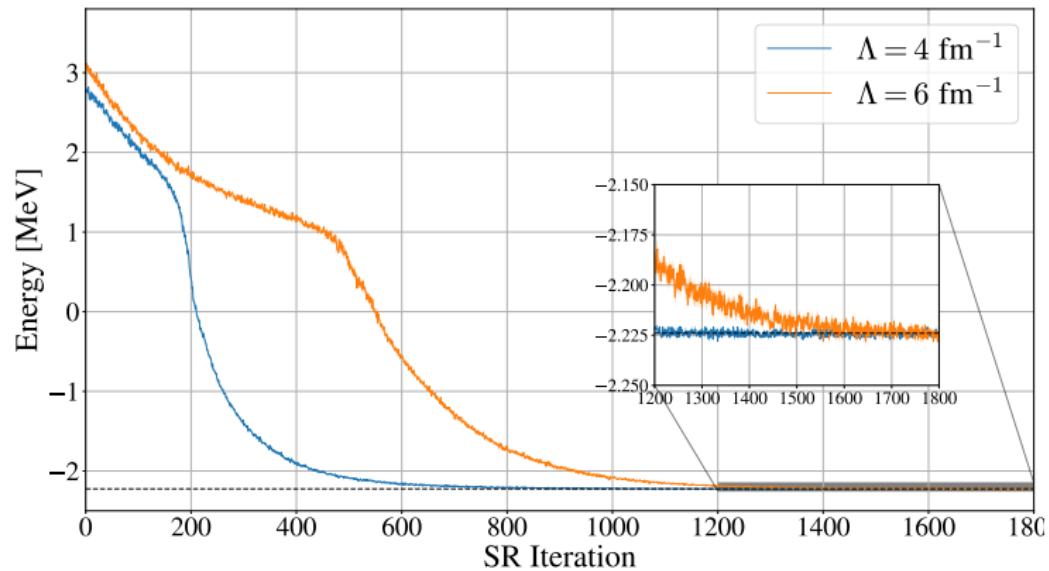
Deep learning neural networks, Variational Monte Carlo calculations of $A \leq 4$ nuclei with an artificial neural-network correlator ansatz by Adams et al.

An appealing feature of the neural network ansatz is that it is more general than the more conventional product of two- and three-body spin-independent Jastrow functions

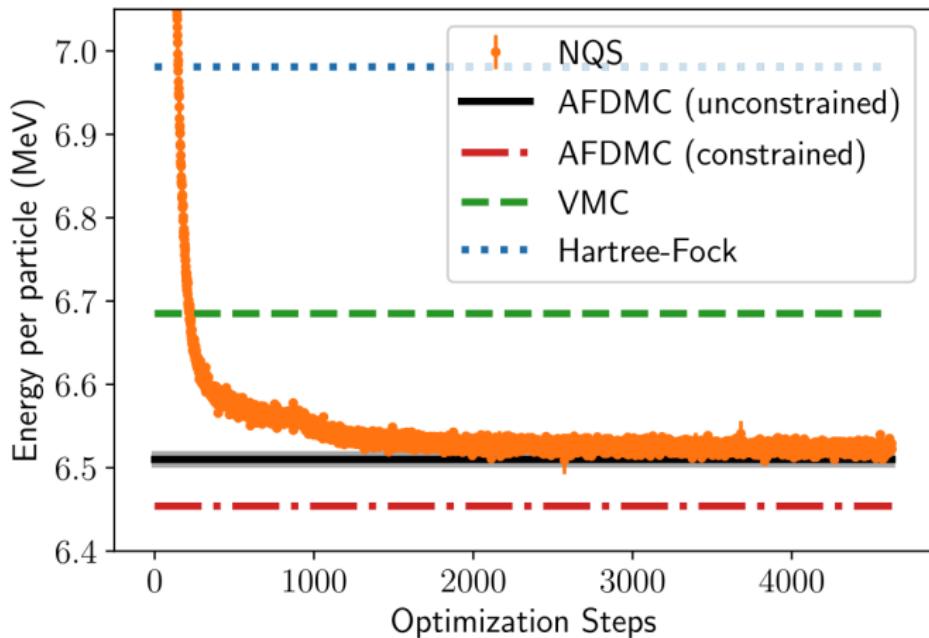
$$|\Psi_V^J\rangle = \prod_{i < j < k} \left(1 - \sum_{\text{cyc}} u(r_{ij})u(r_{jk})\right) \prod_{i < j} f(r_{ij}) |\Phi\rangle, \quad (2)$$

which is commonly used for nuclear Hamiltonians that do not contain tensor and spin-orbit terms. The above function is replaced by a four-layer Neural Network.

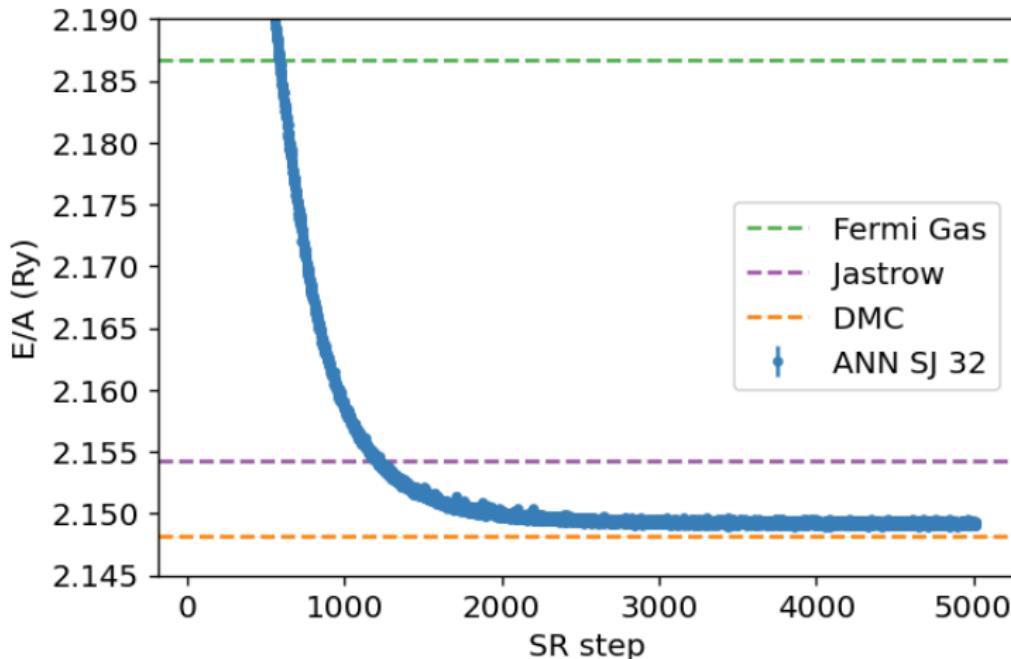
Explicit results



Dilute neutron star matter from neural-network quantum states by Fore et al, Physical Review Research 5, 033062 (2023) at density $\rho = 0.04 \text{ fm}^{-3}$



The electron gas in three dimensions with $N = 14$ electrons
(Wigner-Seitz radius $r_s = 2$ a.u.), Gabriel Pescia, Jane Kim
et al. arXiv.2305.07240,



Efficient solutions of fermionic systems using artificial neural networks, Nordhagen et al, Frontiers in Physics 11, 2023

The Hamiltonian of the quantum dot is given by

$$\hat{H} = \hat{H}_0 + \hat{V},$$

where \hat{H}_0 is the many-body HO Hamiltonian, and \hat{V} is the inter-electron Coulomb interactions. In dimensionless units,

$$\hat{V} = \sum_{i < j}^N \frac{1}{r_{ij}},$$

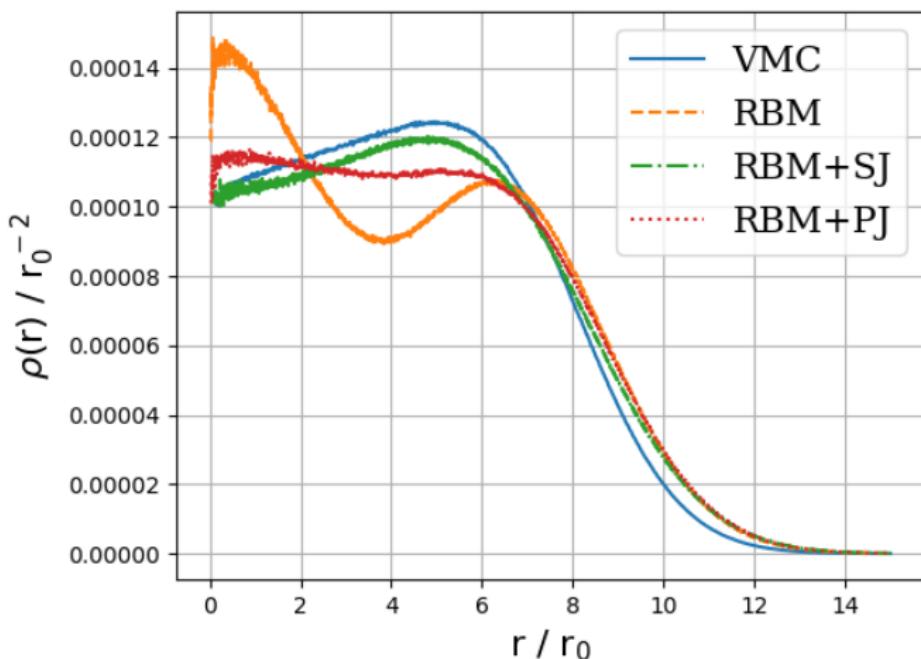
with $r_{ij} = \sqrt{r_i^2 - r_j^2}$.

This leads to the separable Hamiltonian, with the relative motion part given by ($r_{ij} = r$)

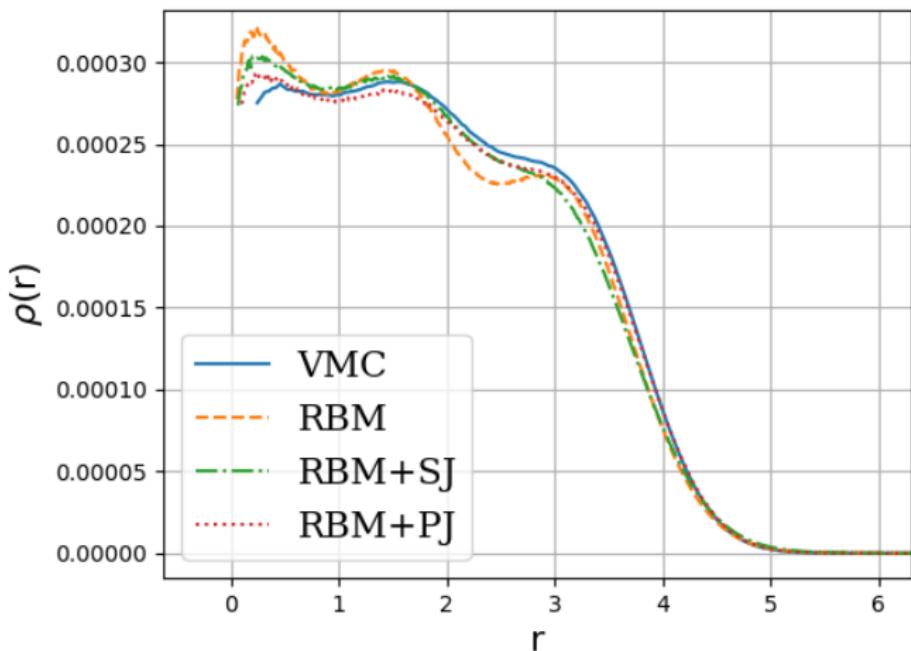
$$\hat{H}_r = -\nabla_r^2 + \frac{1}{4}\omega^2 r^2 + \frac{1}{r},$$

plus a standard Harmonic Oscillator problem for the center-of-mass motion. This system has analytical solutions in two and three dimensions (M. Taut 1993 and 1994).

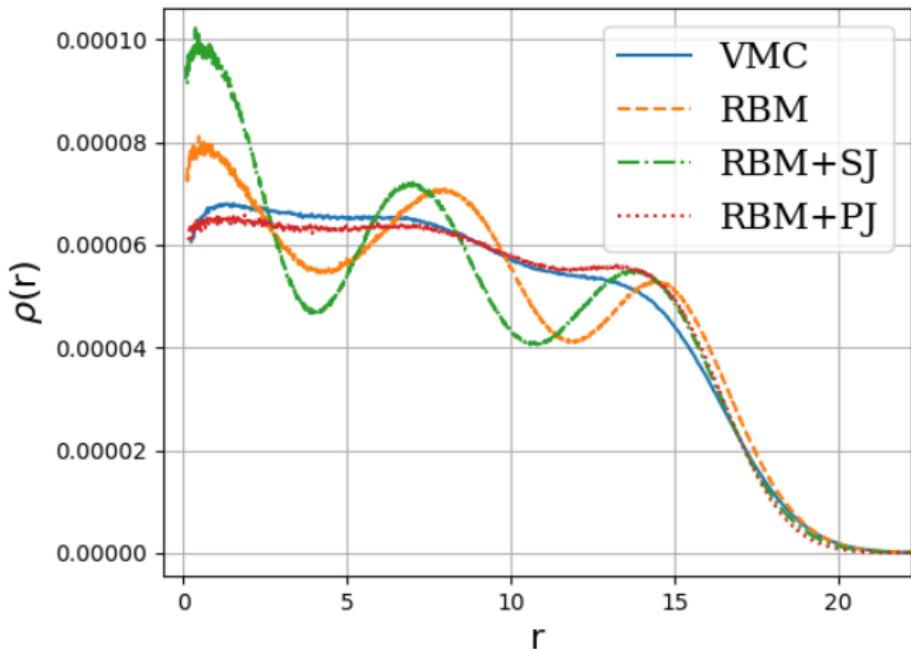
Quantum dots and Boltzmann machines, onebody densities
 $N = 6$, $\hbar\omega = 0.1$ a.u.



Onebody densities $N = 30$, $\hbar\omega = 1.0$ a.u.



Onebody densities $N = 30$, $\hbar\omega = 0.1$ a.u.



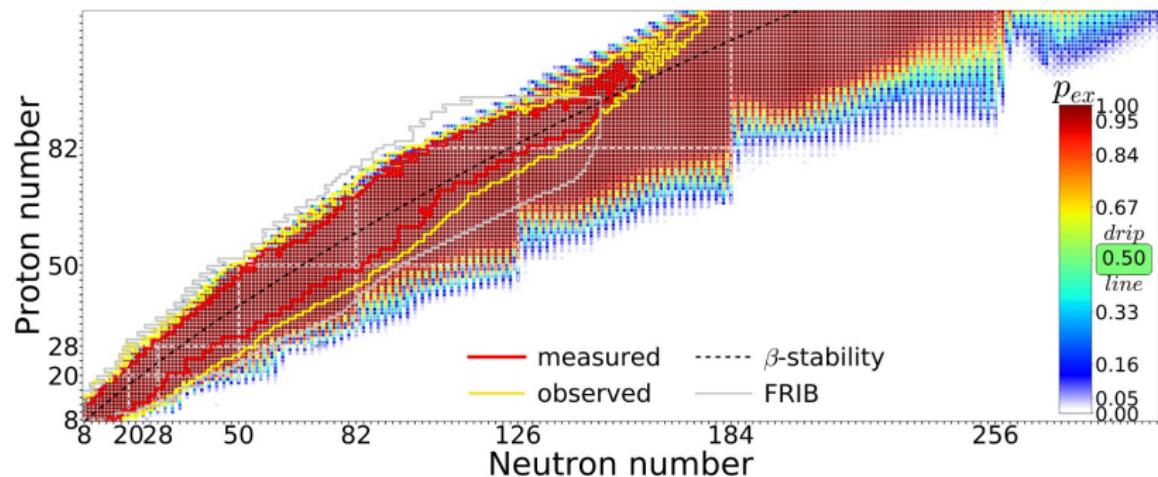
Folding and unfolding and response functions

A good read on folding/unfolding is [An Unfolding Method for High Energy Physics Experiments by Volker Blobel](#)

See notebook details and examples of simple data reconstructed with Gaussian processes.

Quantified limits of the nuclear landscape

Neufcourt et al., Phys. Rev. C 101, 044307 (2020) Predictions
made with eleven global mass model and Bayesian model averaging



Observations and perspectives

- ▶ Need for AI/Machine Learning in nuclear physics, lots of ongoing activities
- ▶ To solve many complex problems in the field and facilitate discoveries, multidisciplinary efforts efforts are required involving scientists in nuclear physics, statistics, computational science, and applied math.
- ▶ There is a need for focused AI/ML learning efforts that will benefit accelerator science and experimental and theoretical programs

How can we use ML in Nuclear Science?

- ▶ How do we develop insights, competences, knowledge in statistical learning that can advance our field?
 - ▶ For example: Can we use ML to find out which correlations are relevant and thereby diminish the dimensionality problem in standard many-body theories?
 - ▶ Can we use AI/ML in detector analysis, accelerator design, analysis of experimental data and more?
 - ▶ Can we use AL/ML to carry out reliable extrapolations by using current experimental knowledge and current theoretical models?
 - ▶ Future research may have a strong focus on generative models
- ▶ The community needs to invest in relevant educational efforts and training of nuclear physicists with knowledge in AI/ML
- ▶ Most likely tons of things we have forgotten

Possible start to raise awareness about ML in our field

- ▶ Make an ML challenge in nuclear physics a la Learning to discover: the Higgs boson machine learning challenge.
Alternatively go to kaggle.com at
<https://www.kaggle.com/c/higgs-boson>
- ▶ HEP@CERN and HEP in general have made significant impacts in the field of machine learning and AI. Something to learn from

Quantum computing, Overview and Motivation

How to use many-body theory to design quantum circuits (Quantum engineering)

1. Many-body methods like F(ull)C(onfiguration)I(nteraction) theory with
 - ▶ Adaptive basis sets (see for example Sigmundson et al arXiv:2111.09638)
 - ▶ Time dependence
 - ▶ Optimization of experimental parameter
 - ▶ Feedback from experiment
2. Finding optimal parameters for tuning of entanglement
3. Numerical experiments to mimick real systems, using many-body methods to develop **quantum twins** (inspiration from work by Herschel Rabitz et al on Control of quantum phenomena, see New Journal of Physics 12 (2010) 075008)!

What is this about?

Here we describe a method for generating motional entanglement between two electrons trapped above the surface of superfluid helium. In this proposed scheme these electronic charge qubits are laterally confined via electrostatic gates to create an anharmonic trapping potential. When the system is cooled to sufficiently low temperature these in-plane charge qubit states are quantized and circuit quantum electrodynamic methods can be used to control and readout single qubit operations. Perspectives for quantum simulations with quantum dots systems will be discussed.

Literature and more reading

1. Justyna P. Zwolak and Jacob M. Taylor, Rev. Mod. Phys. 95, 011006, Advances in automation of quantum dot devices control
2. Pollanen and many other, Accelerating Progress Towards Practical Quantum Advantage: The Quantum Technology Demonstration Project Roadmap
3. Osada et al, introduction to quantum technologies, Springer, 2022
4. Original inspiration a series of articles of Loss and DiVincenzo from the nineties, Quantum Computation with Quantum Dots

Quantum Engineering

Quantum computing requirements

1. be scalable
2. have qubits that can be entangled
3. have reliable initializations protocols to a standard state
4. have a set of universal quantum gates to control the quantum evolution
5. have a coherence time much longer than the gate operation time
6. have a reliable read-out mechanism for measuring the qubit states
7. ...more

Candidate systems

1. Superconducting Josephon junctions
2. Single photons
3. Trapped ions and atoms
4. Nuclear Magnetic Resonance
5. **Quantum dots, experiments at MSU**
6. Point Defects in semiconductors
7. ...more

Electrons (quantum dots) on superfluid helium

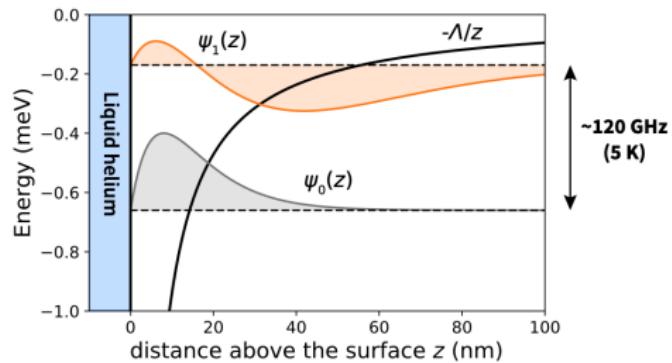
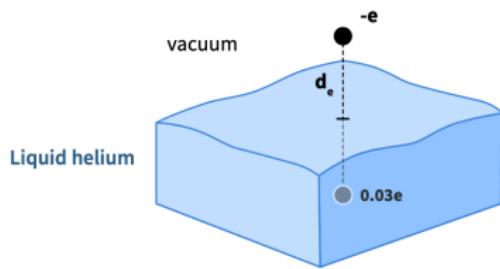
Electrons on **superfluid helium represent** (see
https://www.youtube.com/watch?v=EuDuM-fe-1A&ab_channel=JoshuaHeath) a promising platform for investigating strongly-coupled qubits.
A systematic investigation of the controlled generation of entanglement between two trapped electrons under the influence of coherent microwave driving pulses, taking into account the effects of the Coulomb interaction between electrons, may be of great interest for quantum information processing using trapped electrons.

To read more

1. See Single electrons on solid neon as a solid-state qubit platform, David Schuster et al, Nature **605**, 46–50 (2022)
2. See Mark Dykman et al, Spin dynamics in quantum dots on liquid helium, PRB **107**. 035437 (2023) at <https://link.aps.org/doi/10.1103/PhysRevB.107.035437>.

Experimental setup |

Electrons on helium



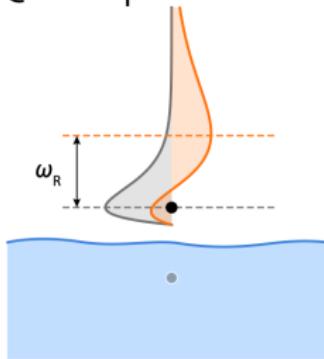
- Very high mobilities: $\mu > 10^7 \text{ cm}^2/(\text{V s})$
- Low densities: $n_s \approx 10^6 - 10^9 \text{ cm}^{-2}$
- Almost no screening: long range Coulomb interactions

“1D Hydrogen atom”
with Rydberg series of states

$$E_n = -\frac{m_e \Lambda^2}{2\hbar^2 n^2} \quad (n = 1, 2, 3\dots)$$
$$E_0 = -0.66 \text{ meV} \quad (\sim 160 \text{ GHz}, 7.6 \text{ K})$$
$$E_1 = -0.17 \text{ meV} \quad (\sim 40 \text{ GHz}, 1.9 \text{ K})$$

More on experimental setup II

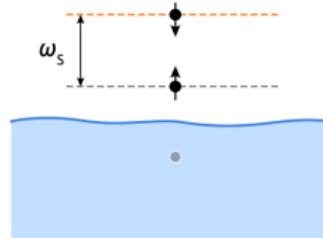
Qubit platforms with electrons on helium



Rydberg states

$$\omega_R/2\pi = 120 \text{ GHz}$$

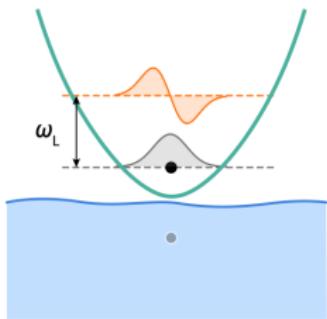
P.M. Platzman and M.I. Dykman
Science **284**(5422), pp.1967 (1999)



Spin states

$$\omega_s/2\pi = 5 \text{ GHz} \text{ at } B = 0.2 \text{ T}$$
$$(T_2 \approx 1.5 \text{ s})$$

S. A. Lyon, *Phys. Rev. A* **74**, 052338 (2006)



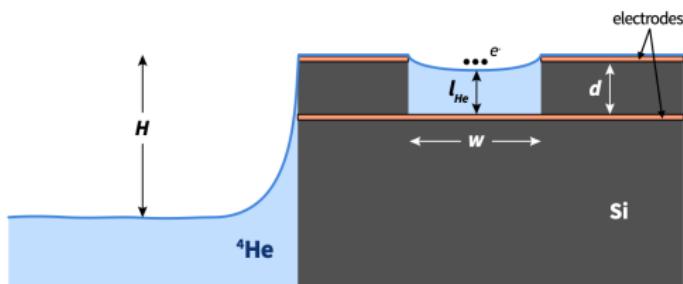
Lateral motional states

$$\omega_s/2\pi = 5 \text{ GHz}$$

D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (2010)

More on experimental setup III

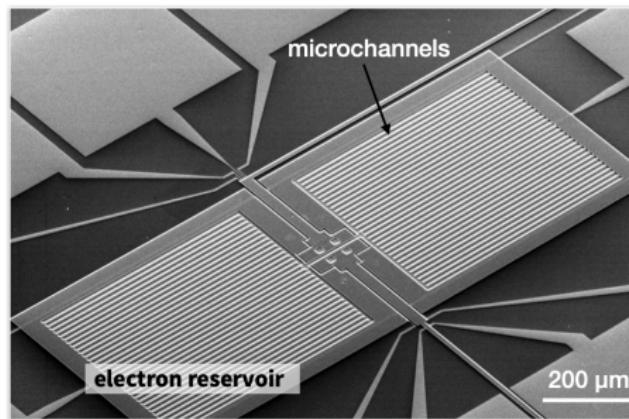
Electron storage/isolation



microstructures filled by capillary action of superfluid ${}^4\text{He}$

$$l_{\text{He}} = d - \frac{w^2}{8} \frac{\rho g H}{\alpha_t}$$

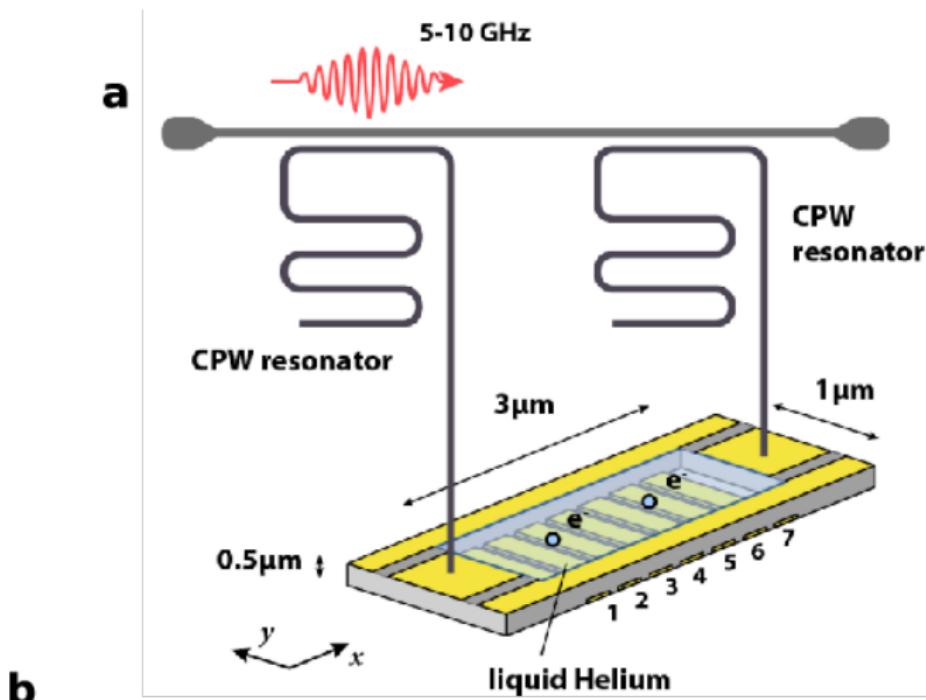
α_t - surface tension of liquid helium
 ρ - density liquid helium



Electron Reservoirs:

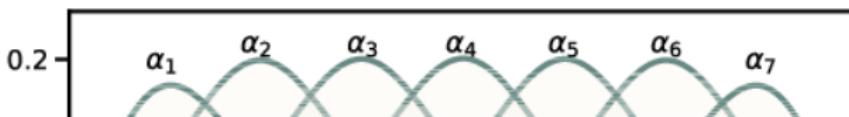
Set of long helium microchannels is used to store electrons

Experimental set up



b

constants, α_i



Entanglement

Entanglement is the fundamental characteristic that distinguishes quantum systems composed of two or more coupled objects from their classical counterparts. The study of entanglement in precisely engineered quantum systems with countably many degrees of freedom is at the forefront of modern physics and is a key resource in quantum information science (QIS). This is particularly true in the development of two-qubit logic for quantum computation.

The generation of two-qubit entanglement has been demonstrated in a wide variety of physical systems used in present-day quantum computing, including superconducting circuits, trapped ions, semiconductor quantum dots, color-center defects in diamond, and neutral atoms in optical lattices, just to name a few.

More on Entanglement

Generating an entanglement between two quantum systems rely on exploiting interactions in a controllable way. The details in the interaction Hamiltonian between two systems defines the protocol schemes for two-qubit logic.

In superconducting circuits the interaction between qubits may arise from direct capacitive coupling between circuit elements or by indirect coupling of two qubits to a common resonator (virtually populating resonator mode) which results in a non-local Hamiltonian in the form of exchange interaction. This allow to implement various schemes for entanglement, such as controlled-phase gate, resonator-induced phase gate, cross-resonance gates etc.

Entanglement gates in trapped ions and more

Entanglement gates in trapped ions are produced by means of the Coulomb interaction, where shared motional modes of two or more ions, entangled to their internal states, used for transferring excitations between ion qubits. This has been experimentally demonstrated.

In photonic quantum computing schemes two-qubit entangling operations are realized by nonlinear interactions between two photons scattering from quantum dots, plasmonic nanowires, diamond vacancy centers and others embedded into waveguides. Two-qubit gates in semiconductor quantum dots are based on spin-spin exchange interactions or generated by coupling to a superconducting resonator via artificial spin-orbit interaction.

Quantum dots and the Coulomb interaction

Coulomb interaction governed entanglement can be realized in the system of electrons on the surface of superfluid helium, where qubit states are formed by in-plane lateral motional or out-of plane Rydberg states. Trapped near the surface of liquid helium these states have different spatial charge configurations and the wavefunctions of different electrons do not overlap.

This results in a strong exchange free Coulomb interaction which depends on the states of the electrons. The lack of disorder in the systems also leads to slow electron decoherence, which has attracted interest to the system as a candidate for quantum information processing.

Electrons on helium is another qubit platform

To our knowledge two qubit gates have never been discussed in a proper manner for these systems.

The static Coulomb interaction arises from a virtual photon exchange process between two charge particles according to quantum electrodynamics. This results in a correlated motion of two charges generating quantum entanglement.

Surface state electrons (SSE)

Surface state electrons (SSE) 'floating' above liquid helium originates from quantization of electron's perpendicular to the surface motion in a trapping potential formed by attractive force from image charge and a large ~ 1 eV barrier at the liquid-vacuum interface. At low temperatures the SSE are trapped in the lowest Rydberg state for vertical motion some 11 nm above the helium surface, which is perfectly clean and has a permittivity close to that of vacuum.

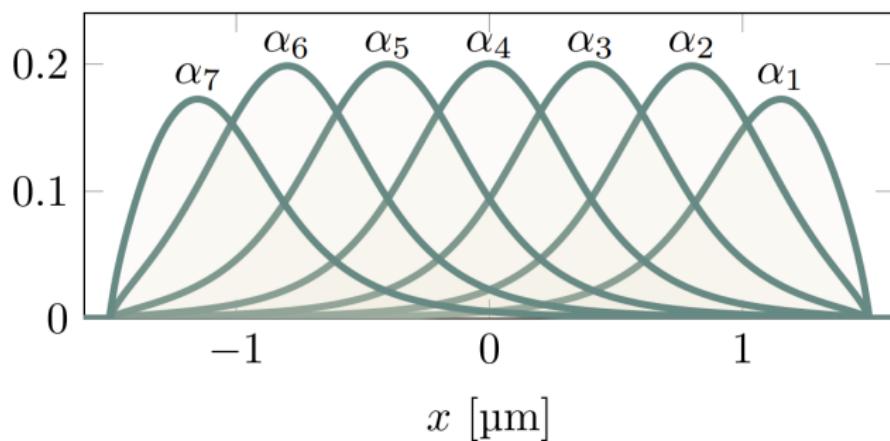
The weak interaction with the environment, which is mainly governed by interaction with quantized surface capillary waves (ripplons) and bulk phonons, ensures long coherence times - a vital ingredient for any qubit platform.

Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + \sum_{i=1}^7 V_i \alpha_i[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + \sum_{i=1}^7 V_i \alpha_i[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (3)$$

$$= h[\hat{p}_1, \hat{x}_1] + h[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (4)$$

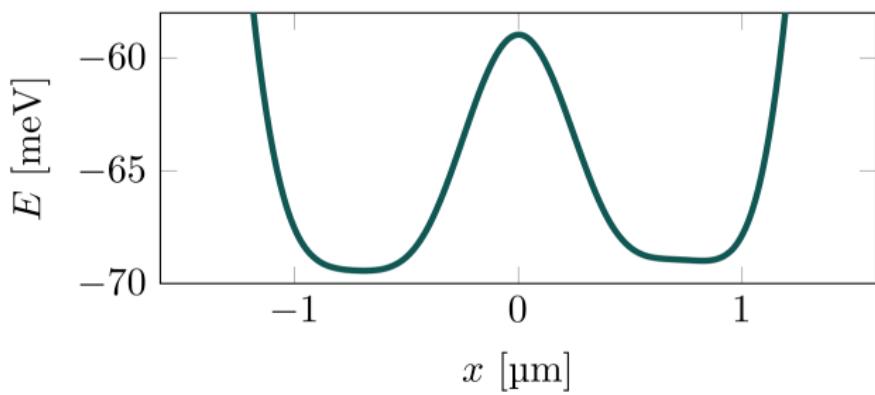


Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (5)$$

$$= h[\hat{p}_1, \hat{x}_1] + h[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (6)$$



Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (7)$$

$$\equiv h[\hat{p}_1, \hat{x}_1] + h[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (8)$$

Energy states:

$$|\Phi_k\rangle = \sum_{i < j} C_{ij,k} \frac{|\varphi_i \varphi_j\rangle - |\varphi_j \varphi_i\rangle}{\sqrt{2}}, \quad (9)$$

(Slater basis)

Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v^L[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v^R[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (10)$$

$$\equiv h^L[\hat{p}_1, \hat{x}_1] + h^R[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (11)$$

Energy states:

$$|\Phi_k\rangle = \sum_i \sum_j C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (12)$$

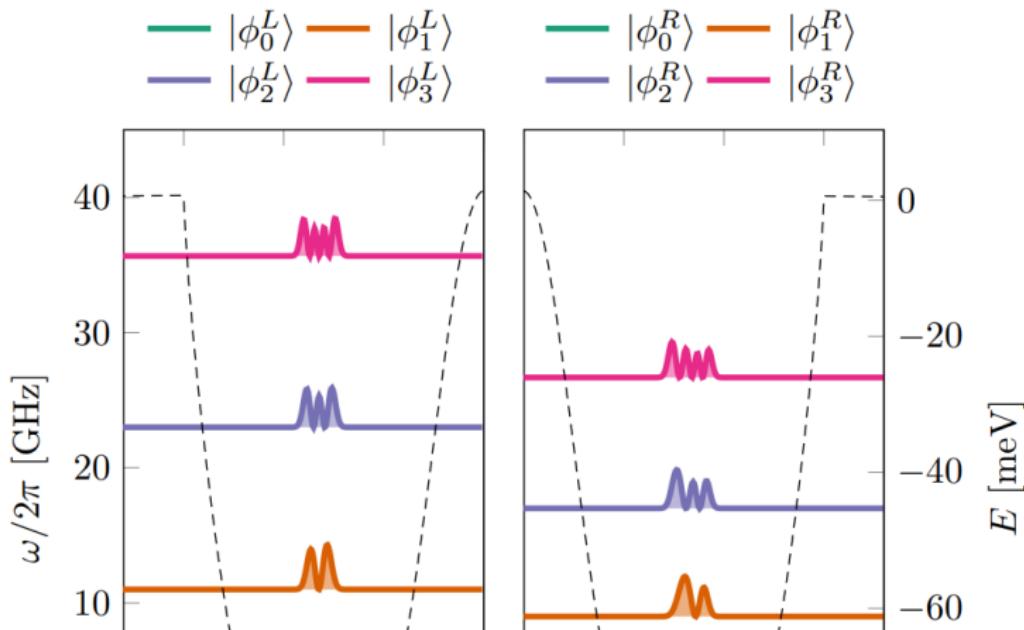
(product basis)

Calculational details

Energy states:

$$|\Phi_k\rangle = \sum_i \sum_j C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (13)$$

(product basis)



Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v^L[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v^R[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (14)$$

$$\equiv h^L[\hat{p}_1, \hat{x}_1] + h^R[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (15)$$

Energy states:

$$|\Phi_k\rangle = \sum_i \sum_j C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (16)$$

(Hartree basis)

Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v^L[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v^R[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (17)$$

$$\equiv h^L[\hat{p}_1, \hat{x}_1] + h^R[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (18)$$

Energy states:

$$|\Phi_k\rangle = \sum_{i=0}^{N^L} \sum_{j=0}^{N^R} C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (19)$$

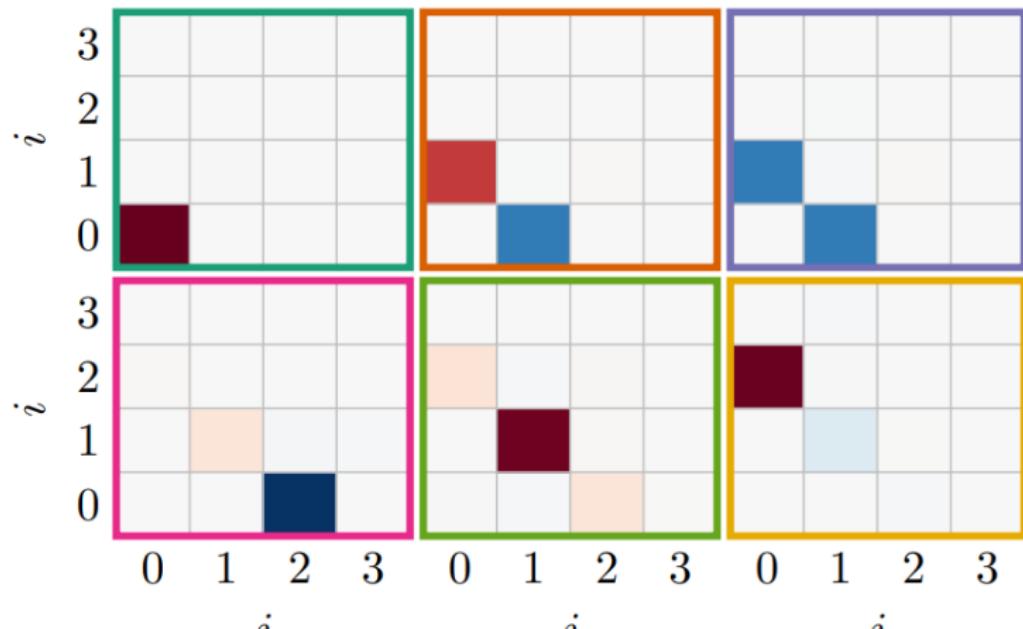
(Hartree basis)

Calculational details

Energy states:

$$|\Phi_k\rangle = \sum_{i=0}^{N^L} \sum_{j=0}^{N^R} C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (20)$$

(Hartree basis)



Calculational details

Hamiltonian:

$$\hat{H} = \frac{\hat{p}_1^2}{2} + v^L[\hat{x}_1] + \frac{\hat{p}_2^2}{2} + v^R[\hat{x}_2] + \frac{\kappa}{\sqrt{(\hat{x}_1 - \hat{x}_2)^2 + a^2}} \quad (21)$$

$$\equiv h^L[\hat{p}_1, \hat{x}_1] + h^R[\hat{p}_2, \hat{x}_2] + u[\hat{x}_1, \hat{x}_2] \quad (22)$$

Energy states:

$$|\Phi_k\rangle = \sum_{i=0}^{N^L} \sum_{j=0}^{N^R} C_{ij,k} |\varphi_i^L \varphi_j^R\rangle, \quad (23)$$

(Hartree basis)

Results and discussions

By adjusting the potential we can change the anharmonicities and detuning of the wells.

1. What values of these give interesting interactions?
2. Inspiration from superconducting qubits, see High-Contrast ZZ Interaction Using Superconducting Qubits with Opposite-Sign Anharmonicity, Zhao et al Phys. Rev. Lett. 125, 200503

We search for well configurations corresponding to three different types of interaction between the two electrons.

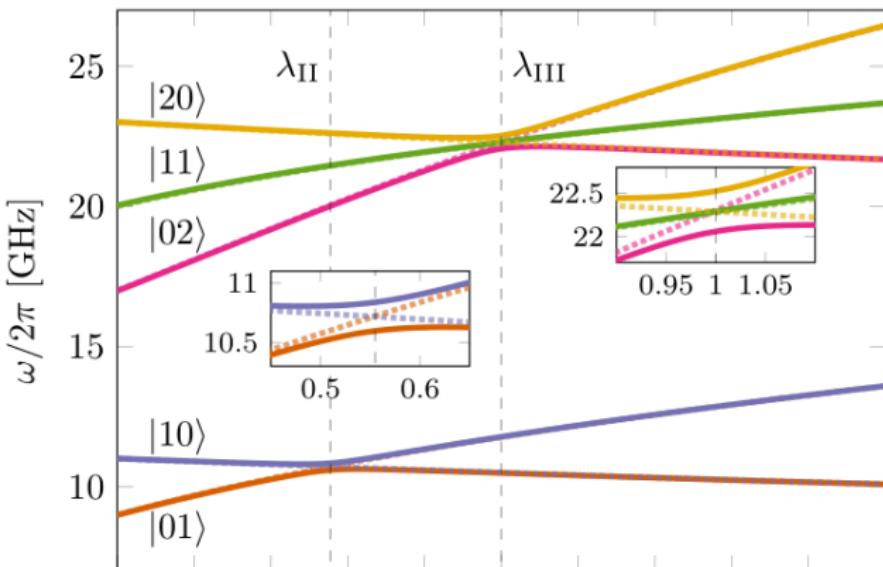
1. In configuration I we address both qubits independently and can thereby perform single-qubit state rotations and measurements.
2. Configurations II and III correspond to avoided level crossings between two (E_{01}, E_{10}) and three (E_{11}, E_{20}, E_{02}) energy levels respectively, where the electrons' motion becomes correlated, that is they are entangled.

Both anharmonicity and detuning changes with the shape of our well. We create a voltage parameterization

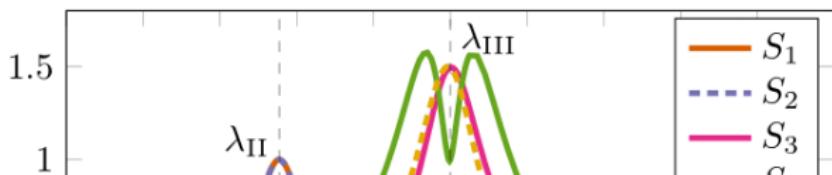
$$V(\lambda) = (1 - \lambda)V_I + \lambda V_{\text{III}} \quad (24)$$

Entanglement and more

(a)



(b)



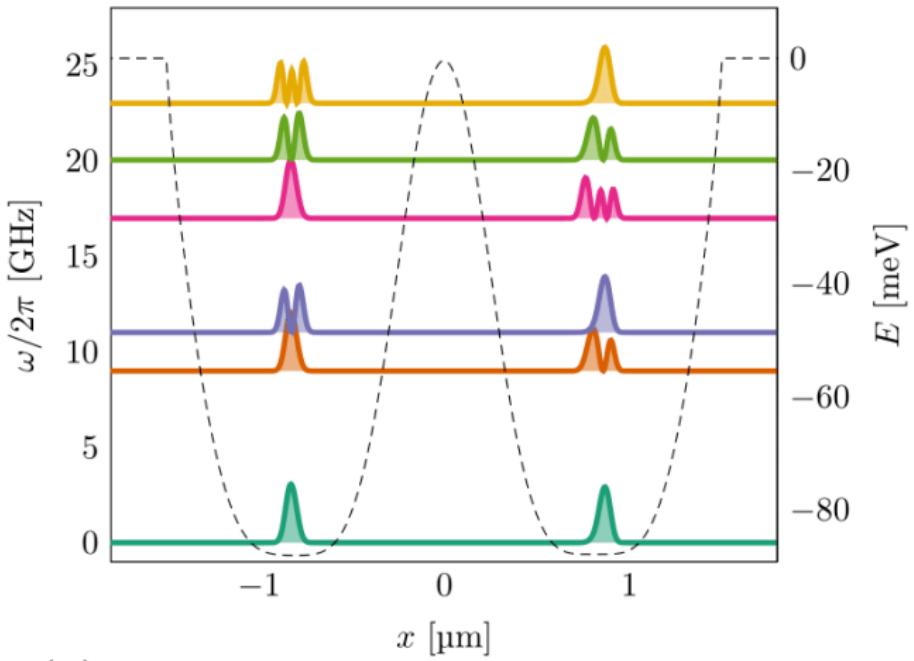
Legend to figure

1. (a) In this figure we have plotted the transition energy from the ground state to the labeled excited state as a function of the voltage parameter λ . The labeled states are the computational basis states when $\lambda = 0$.
2. (b) The von Neumann entropy of the five lowest excited states of the two-body Hamiltonian as a function of the configuration parameter λ . The ground state has zero entropy, or close to zero entropy. We have included the points for the double and triple degeneracy points. λ_{II} and λ_{III} in the figure. The von Neumann entropy is calculated using the binary logarithm.
3. (c) In this figure we have plotted the anharmonicites for the left well (α^L) and the right well (α^R) as a function of the well parameterization λ . We have also included the detuning $\Delta\omega = \omega^R - \omega^L$ between the two wells. We have marked configuration II at $\lambda_{II} \approx 0.554$ and configuration III at $\lambda_{III} = 1$.

Particle densities and coefficients

— $|\Phi_0\rangle$ — $|\Phi_1\rangle$ — $|\Phi_2\rangle$
— $|\Phi_3\rangle$ — $|\Phi_4\rangle$ — $|\Phi_5\rangle$

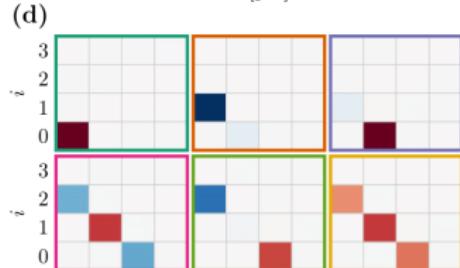
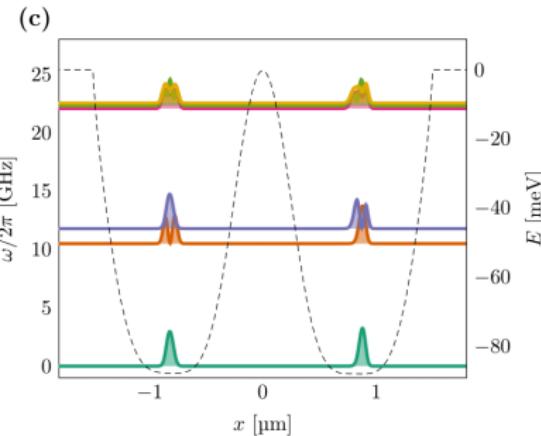
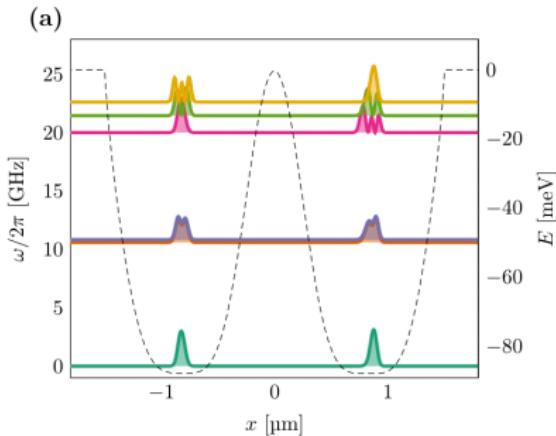
(a)



(b)

Potential wells, the one-body densities, and single-particle states

— $|\Phi_0\rangle$ — $|\Phi_1\rangle$ — $|\Phi_2\rangle$
— $|\Phi_3\rangle$ — $|\Phi_4\rangle$ — $|\Phi_5\rangle$



Where we are now

1. Adding time-dependent studies of two electrons in two wells in one and two dimensions
2. Studies of the time-evolution of entangled states (now two electrons only)
3. Use theory to find optimal experimental setup
4. Expect two-electron system realized experimentally in approx 1 year, great potential for studies of quantum simulations

Plans

1. Add two and three-dimensions in order to simulate in a more realistic way such many-body systems.
2. Develop time-dependent FCI code, useful up to approximately 10 particles with **effective** (and effective Hilbert space) Hamiltonians in two and three dimensions
3. Develop codes for studies of entanglement as function of time
4. Do tomography and extract density matrix and compare with experiment.
5. Study the feasibility of various setups for quantum simulations of specific Hamiltonians such as the Lipkin model
6. For larger many-body systems, study for example time-dependent CC theory