Quantum Computing (QC) for many-body systems at the nucleonic scale or below: some current international status and recent examples

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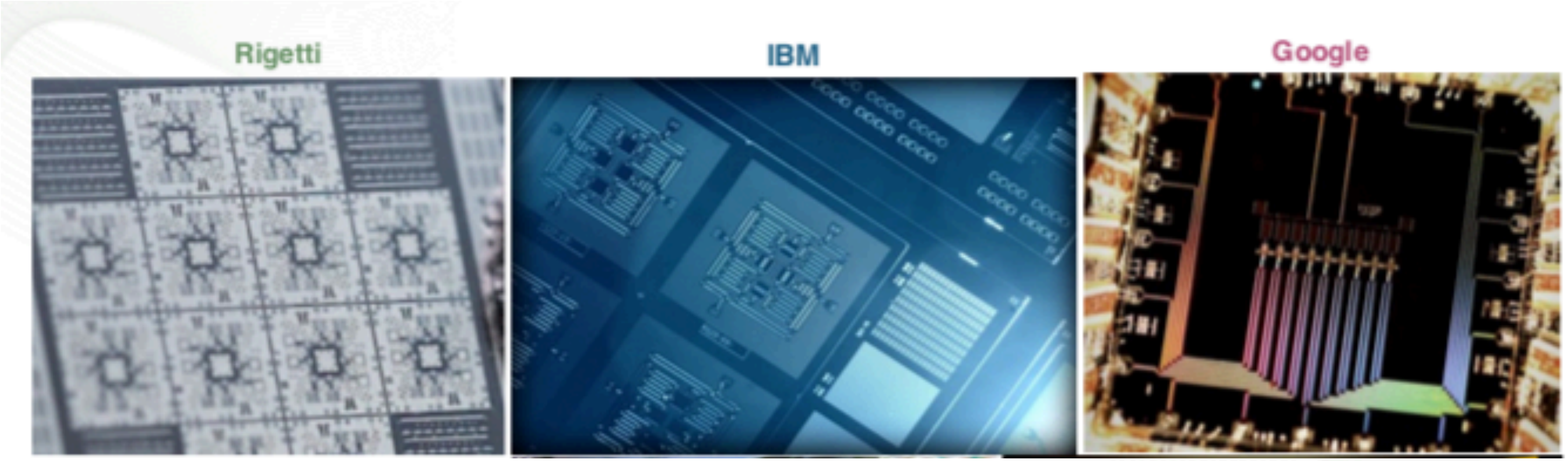
Summary

- Generalities
- Few examples of recent QC applications to nuclear/particle physics
- Example of international initiative: the US QC/QIS collaboration
- Discussion

A viewpoint from an external actor

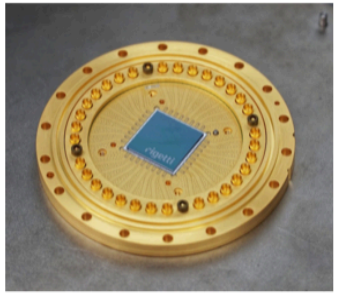


Limitations:
~ 50 qubits
~ 50 gates

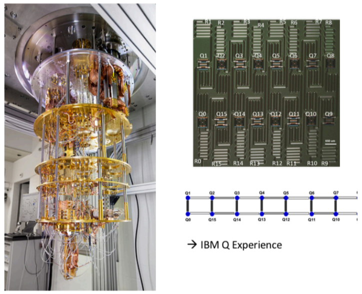
Future:
~ 500 qubits
~ 500 gates

Example

RIGETTI superconducting 19 Qubit



IBM QX5 (16 qubits)



A timely period

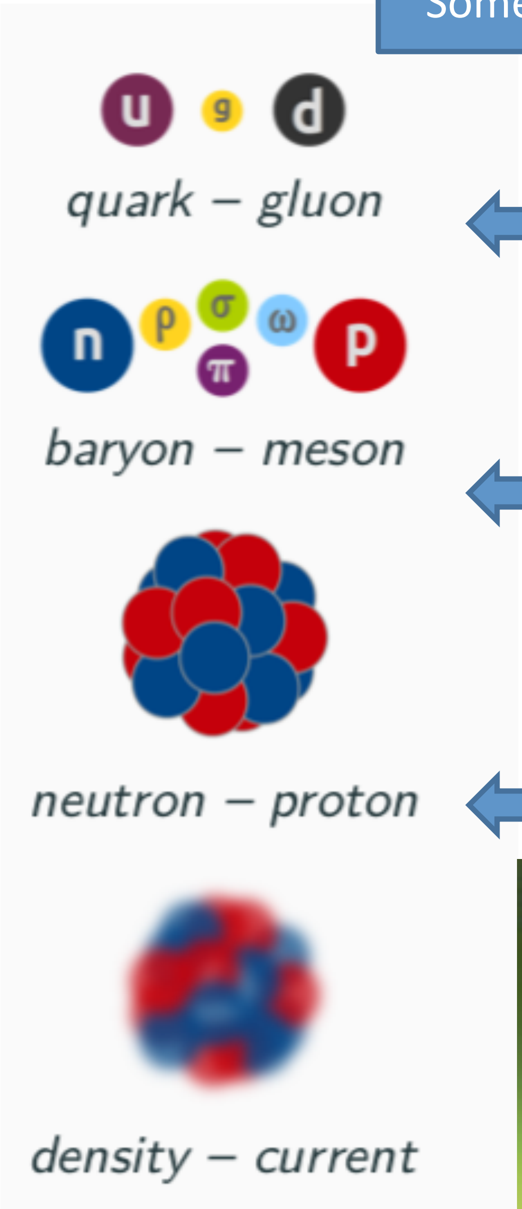
(from G. Hagen)

There is a lot of excitement in this field due to substantial progress

1. Quantum processing units now have ten(s) of qubits
2. Businesses are driving this: Google, IBM, Microsoft, Rigetti, D-Wave, ...
3. Software is publicly available (PyQuil, XACC, OpenQASM, OpenFermion)
4. First real-world problems solved: H_2 molecule on two qubits [O'Malley et al., Phys. Rev. X 6, 031007 (2016)]; BeH_2 on six qubits [Kalandar et al., Nature 549, 242 (2017)]; ...

Quantum Computing at the nucleon scale and below

Some current numerically costly challenges

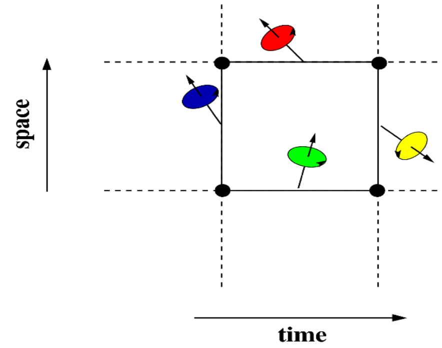


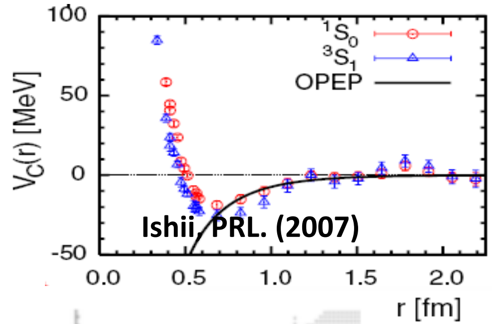
Understanding quarks, hadrons and mesons from first principle

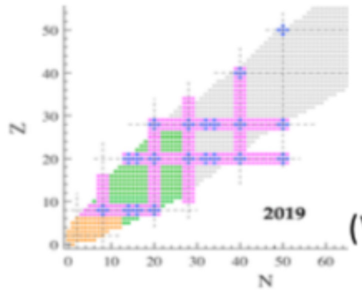
Understanding the strong Interaction from quarks

Provide a full ab-initio Picture of the whole nuclear chart

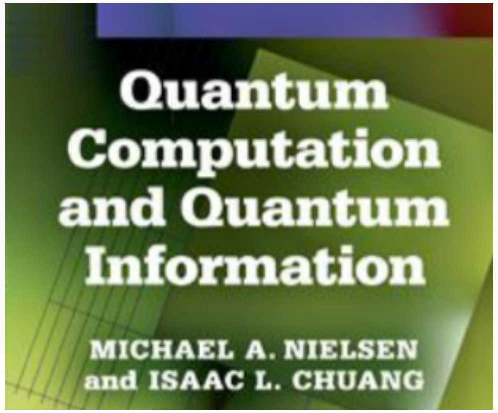
Overall Goal







(V. Soma)

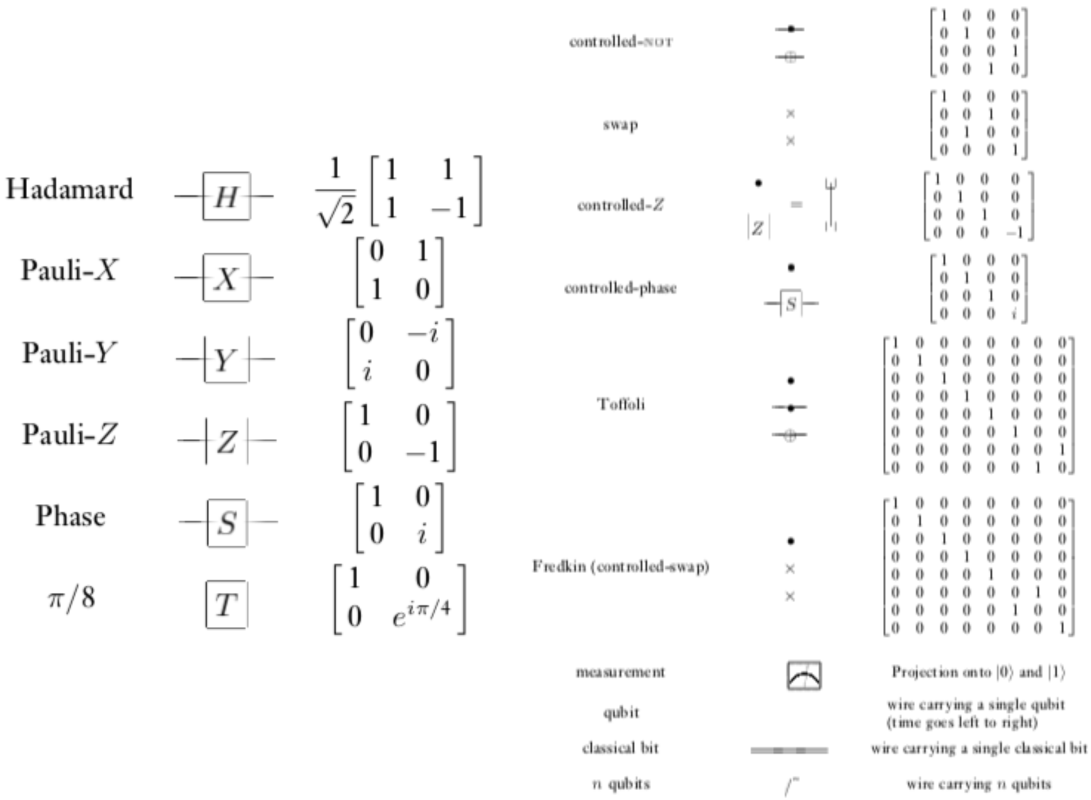


- QC is not a new subject
- Simple problems easily described in a CC can be very difficult on a QC
- QC can lead to major breakthrough In complex problems

Strategy

- Take a simple version of your favorite many-body problem
- ↓ Map/formulate it as a problem with Qubit
- ↓ Use standard QC algorithms or Propose new QC algorithms
- ↓ Test on a QC emulator / Test on a true QC

Constraint: -Work with a restricted number of operation



-Design new algorithms adapted to the many-body problem

-Control the inherent quantum noise

Illustration I

Strategy

Take a simple version of your favorite many-body problem

↓

Map/formulate it as a problem with Qubit

↓

Use standard QC algorithms
or
Propose new QC algorithms

↓ ↓

Test on a QC emulator | Test on a true QC

PHYSICAL REVIEW LETTERS 120, 210501 (2018)

Editors' Suggestion | Featured in Physics

Cloud Quantum Computing of an Atomic Nucleus

E. F. Dumitrescu,[1] A. J. McCaskey,[2] G. Hagen,[3,4] G. R. Jansen,[5,3] T. D. Morris,[4,3] T. Papenbrock,[4,3,*] R. C. Pooser,[1,4] D. J. Dean,[3] and P. Lougovski[1,†]

Schematic deuteron Hamiltonian in Harmonic basis

$$H_N = \sum_{n,n'=0}^{N-1} \langle n'|(T+V)|n\rangle a_{n'}^\dagger a_n.$$

$$n,\, n' = 0, 1, \ldots N-1$$

$a_n^\dagger (a_n)$ create (annih.) 1 deuteron in $|n\rangle$

Use Pauli matrices+Jordan-Wigner transformation

$$a_n^\dagger \to \frac{1}{2}\left[\prod_{j=0}^{n-1} -Z_j\right](X_n - iY_n)$$

0 (1) particles in $|n\rangle \longrightarrow |\uparrow\rangle (|\downarrow\rangle)$

→ This automatically map the Hamiltonian as a function of Pauli Matrix

→ Use the VQE quantum-classical algorithm with 10000 measurements on QX5 (19Q)

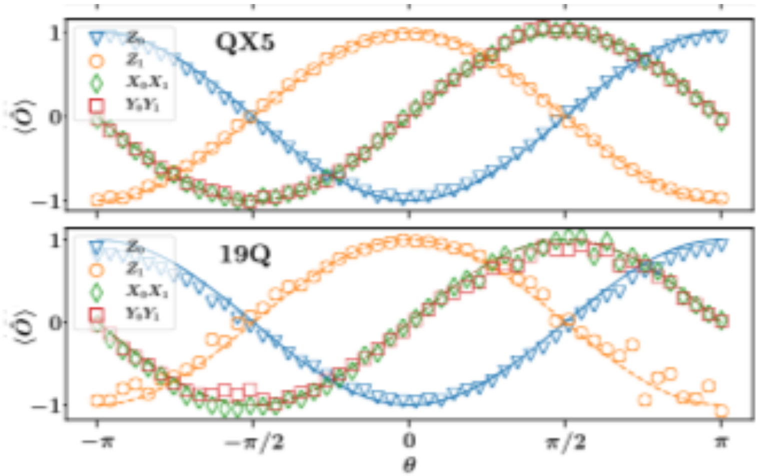


Illustration II

PHYSICAL REVIEW LETTERS 123, 090501 (2019)

σ Models on Quantum Computers

Andrei Alexandru,[1,2,*] Paulo F. Bedaque,[2,†] Henry Lamm,[2,‡] and Scott Lawrence[2,§]

(NuQS Collaboration)

Strategy

Take a simple version of your favorite many-body problem

↓

Map/formulate it as a problem with Qubit

↓

Use standard QC algorithms
or
Propose new QC algorithms

↓ ↓

Test on a QC emulator | Test on a true QC

Start with the discretized σ model

$$\mathcal{H} = \sum_r \left(\frac{g^2}{2} \boldsymbol{\pi}(r)^2 + \frac{1}{2g^2 \Delta x^2} [\mathbf{n}(r+1) - \mathbf{n}(r)]^2 \right)$$

Map it to a Spin algebra (fuzzy sphere)

$$-\frac{g^2}{2} \nabla^2 \psi \to H^0 \Psi = \kappa \frac{g^2}{2} \sum_{k=1}^{3} [\mathbb{J}_k, [\mathbb{J}_k, \Psi]],$$

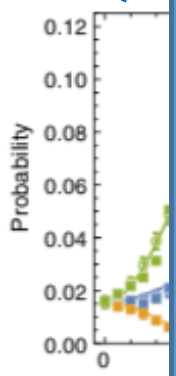
J_k are generators of the SU(2) algebra

"only" j=1/2 was considered

$$j_1 = \mathbb{1} \otimes \sigma_2 / \sqrt{3}, \quad j_2 = \sigma_2 \otimes \sigma_3 / \sqrt{3}, \quad j_3 = \sigma_2 \otimes \sigma_1 / \sqrt{3},$$

This gives the link with Pauli matrices

⇒ Use the Suzuk
+ specific QC



GAUGE THEORIES FOR QUANTUM COMPUTING

Very limited studies exist, e.g.:

- 1+1 D QED (Schwinger model) on a few-qubit trapped-ion quantum computer [E. A. Martinez et al., Nature 534 (2016) 516, arXiv: 1605.04570]
- Quantum-Classical calculation of Schwinger Model [N. Klco et al., Phys. Rev. A 98 (2018) 032331, arXiv:1803.03326]
- U(1) lattice gauge theory without matter in 2 & 3 spatial dimensions [D. Kaplan, J. Stryker, arXiv:1806.08797]
- Zeta-regularized vacuum expectation values [T. Hartung, K. Jansen, arXiv:1808.06784]
- O(3) nonlinear sigma model in 1+1 dimensions [F. Bruckmann, K. Jansen, S. Kuhn, arXiv:1812.00944]

Extending the studies to 2+1 dimensions is extremely hard and has not been established yet on quantum devices

(from M. constantinou, Santa Fe)

Quantum Information Science and Quantum Computing for Nuclear Theory

Illustration of the QC/QIS for nuclear theory project (USA)

Nov. 2017 Early INT-Seattle workshop on Quantum Computing for Nuclear Physics

Decision for a pre-pilot project granted by DOE

→ The QC/QIS scientific community

Mission

Quantum Information Science and Quantum Computing have the potential to enable breakthrough discoveries in nuclear physics and alter paradigms in theoretical research in disruptive ways. Our goal is to anticipate and prepare the community for these changes, and to identify opportunities to make rapid progress toward the Grand Challenges facing our field.

Jan. 2019

Sante Fe meeting of the QC/QIS for nuclear theory

→ Converge on the final project (5 years, size: 20 PostDoc, 30 PhD)

- Identify main areas-of-focus within NT, e.g.
  - Nuclear Structure and Reactions
  - Quantum Chromodynamics and Quantum Field Theories
  - Nuclear Astrophysics and the Early Universe
- close collaboration with qubit/quantum device/algorithm efforts at National Labs and Technology companies

CERN openlab **Quantum Computing for High Energy Physics workshop**

5-6 novembre 2018
CERN
Fuseau horaire Europe/Zurich
There is a live webcast for this event.

Rechercher...

- Accueil
- Ordre du jour
- Liste des contributions
- Inscription
- Salles de visioconférence
- Accommodation
- How to get to CERN

Motivations and Objectives

The ambitious upgrade programme for CERN's Large Hadron Collider (LHC) will result in significant challenges related to information and communications technologies (ICTs) over the next decade and beyond. It is therefore vital that we — members of the high-energy physics (HEP) research community and beyond — keep looking for innovative technologies, so as to ensure that we can continue to maximise the discovery potential of the world-leading research infrastructures at our disposal. Technologies related to quantum computing hold the promise of substantially speeding up computationally expensive tasks.

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Quantum computing

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June 12-14th
PROGRAM ProgramESNT_QC_NuclPhys_June19.pdf

Quantum computing and scientific research: state of the art and potential impact in nuclear physics

Some general concluding (personal) remarks

- Computation with QC is a very challenging/exciting challenge
- It is also intellectually satisfactory to think about our problem in a very different way
- It might ultimately lead to major breakthrough in different IN2P3 fields
- It also leads to natural synergies between public research and private companies
- There is nowadays emerging strong collaborations that start to work actively in the field
- (Rapid) actions if we want to be competitive? And major effort should be done to learn and be at the forefront of the field.
- Eventually this will not work...

Thank you ...