Quantum Computing and Quantum Information for Nuclear Physics

Presentation to NSAC
Washington DC, Nov 2, 2018

Martin J Savage
The Potential of Quantum Computing

~ 100 qubit devices can address problems in chemistry that are beyond classical computing
50 qubits : ~ 20 petabytes ~ Leadership-Class HPC facility
300 qubits : more states \[10^{90}\] than atoms in universe \[10^{86}\]
Finding the ground state of Ferredoxin

Ferredoxin

$\text{Fe}_2\text{S}_2$

Used in many metabolic reactions including energy transport in photosynthesis

Classical algorithm

Quantum algorithm 2012

Quantum algorithm 2015

!  ~24  ~1

INTRACTABLE  BILLION YEARS  HOUR

with less than 200 ideal qubits

Slide: Dave Wecker (Microsoft)
Quantum Computing and Quantum Information

- Qubits
- Entanglement and Superposition
- Unitary Operations and Measurements
“First Qubits” for Applications

- In cases:
- Tech companies, national laboratories and universities are working together to develop hardware
- Technology companies are making their quantum devices available for computations via the cloud
- Laboratories and companies are making their hardware available through collaboration
Quantum Communication
Recent

EU Awards Ten Million Euro to European Quantum Internet Alliance to Speed up Development of Quantum Internet

October (2018)

U.S. National Labs Team Up to Build a Quantum Network

A 48-kilometer quantum network will test whether solid-state qubits are more reliable and scalable than photonic qubits

By Jeremy Heu

U.S. National Labs Team Up to Build a Quantum Network

October (2018)

FNAL to ANL

October (2018)

STEPPANNE WEHNER

COMPUTER NETWORKS AND QUANTUM PROTOCOL DESIGN - ALLIANCE COORDINATOR

To create a link, Alice can emit a photon towards Bob from her qubit. Bob does the same towards Alice. Because the photons are entangled with their original qubits, when they interact, Alice’s and Bob’s qubits become entangled, too.

LONG-DISTANCE LINKS

If Alice and Bob are far away from one another or not directly connected, one or more quantum repeaters will be needed to establish entanglement. Here, one qubit in the repeater is entangled with Alice’s qubit, and the other with Bob’s. By performing an operation on the two qubits it holds, the repeater creates entanglement between Alice’s and Bob’s qubits.

Illustration: iStockphoto

FNAL to ANL

October (2018)
House Approves the National Quantum Initiative Act

Sep 13, 2018  | Press Release

WASHINGTON – The House of Representatives unanimously approved legislation today that will leverage the expertise and resources of U.S. industry, academia, and government to move Quantum Information Science (QIS) to the next level of research and development.

Motivation(s) for Nuclear Physics

Quantum Information and Quantum Computing has the potential

• to provide improvements in sensing and detection.

• to perform fully-controlled large-scale simulations of quantum many-body systems and of the standard model. To integrate with and complement classical computing (not replace).

• for transforming the handling of data.

Currently there is no explicitly demonstrated Quantum Advantage for any scientific application, but ....
Quantum Many-Body Systems

Finite Density Systems
- Quantum Monte Carlo
- Sign Problem(s) in Sampling

Nuclear Many-Body Problem
- Schrödinger Eqn.
- Hilbert space grows exponentially with particles

Classical Computing
- Exponentially large resources
- Exponentially growing memory for large nuclei

Quantum Computing
- No sign problem (naively)
- Real-time evolution
- Hilbert space grows exponentially with number of qubits
  - i.e. 1 qubit doubles size
The Standard Model

Quantum Field Theories and Fundamental Symmetries
- indefinite particle number
- gauge symmetries and constraints

Real-Time Evolution
- Integrals over phases
- Fragmentation
- Neutrinos in dense matter

Classical Computing
- Euclidean space
- high-lying states difficult
- Signal-to-noise
- Severe limitations for real-time or inelastic collisions or fragmentation

Quantum Computing
- Real-time evolution
- S-matrix
- No sign problem(s) (naively)
Sensing and Detection

Classical Computing
  e.g.
  Classical Sensing : precision $\sim \frac{1}{\sqrt{N}}$
  Classical DataBase Searching : time $\sim N$

Quantum Computing
  e.g.
  Quantum Sensing : precision $\sim \frac{1}{N}$
  Quantum DataBase Searching : time $\sim \sqrt{N}$
QC and QIS for Scientific Applications
Highlights of Trajectory to the Present

1980 - 2000
Benioff, Manin, Feynman, Deutsch, IBM and reversability
First quantum algorithms

2000 - 2010
Proof-of-principle demonstrations
Initial QC hardware
Error correction and control theory
Spin-chains and scalar field theories

2010-2018
Focus on practicality and improving quality and control
Circuit design and synthesis
Cloud-based access to NISQ hardware
First simulations of light nuclei and simple quantum field theories
Entanglement and improving algorithms

Based on a slide by David Dean
At the Heart of Quantum Computing
Massively Parallel Processing, Nonlocality and Entanglement

e.g., for a 3-bit computer \(2^3\) states
Classical computer in 1 of 8 possible states

\[
|\psi\rangle = |000\rangle \text{ or } |001\rangle \text{ or } |010\rangle \text{ or } |100\rangle \text{ or } |011\rangle \text{ or } |101\rangle \text{ or } |110\rangle \text{ or } |111\rangle
\]

Quantum computer can be in a combination of all states at once

\[
|\psi\rangle = \alpha_1|000\rangle + \alpha_2|001\rangle + \alpha_3|010\rangle + \alpha_4|100\rangle + \alpha_5|011\rangle + \alpha_6|101\rangle + \alpha_7|110\rangle + \alpha_8|111\rangle
\]

Once system mapped onto qubits, unitary operations used to compute and process information
At the Heart of Quantum Computing
Massively Parallel Processing, Nonlocality and Entanglement

e.g. 2-qubits, unitary transformations between 4 states: U(4) transformations

\[ \hat{U}_4(\theta_1, \ldots \theta_{16}) \ket{00} = \alpha \ket{00} + \beta \ket{01} + \gamma \ket{10} + \rho \ket{11} \]
Quantum Sensing, Metrology and Lithography
Nonlocality and Entanglement

e.g., $H \sim \beta \sigma_z$  a new type of coupling

20th Century Detection
``independent qudits”

21st Century Detection
entangled ``qudits”

Uncertainty in measurement scales as

$\Delta \beta \sim 1/(t \sqrt{N})$

$\Delta \beta \sim 1/(t N)$
Space-Based Quantum Keys

**e.g., Quantum Teleportation**


Entangled qubit pair created in Satellite

- One sent to earth station
- Entangled by CNOT gate and Hadamard Gate
- Pair is measured
- Measure. The classical "number" of the collapsed state, N=1,2,3, or 4 from |00⟩, |01⟩, |10⟩ or |11⟩ is sent back to satellite

Classical Number(s)

- N dictates the applied unitary operation 1=I, 2=X, 3=Y, 4=Z

Quantum State demolished on Earth BUT teleported to the Satellite

9/17: Quantum secure video call between China and Austria
The Noise Intermediate-Scale Quantum (NISQ) Era

John Preskill - Jan 2018

• No or little error correction in hardware or software [requires > x10 qubits]

• Expect to have a few hundred qubits with modest gate depth (decoherence of devices)

• Imperfect quantum gates/operations

• NISQ-era ~ several years  Not going to be a near term magic bullet
  • will not replace classical computing

• Searching to find Quantum Advantage(s) for one or more systems

• Understanding the application of ``Quantum” to Scientific Applications, and identifying attributes of future quantum devices.
Efforts at National Laboratories, Technology Companies and Universities developing such devices and other types, e.g. cold atoms, qudits.
Quantum coherence time of superconducting qubits has improved analogously to Moore’s Law.
Quantum Computing
Examples of Available Hardware and Technology Companies - US + Ca

**D-wave**: ~ 2000 superconducting qubits, quantum annealing

**Google**: 72 superconducting qubits - 2-qubit error < 0.5%

**IBM**: superconducting - 5, 14, 16, 20 qubits systems - cloud access

**Intel**: 49 superconducting qubits, progress in silicon

**IonQ**: trapped ions, 53 qubit system, cloud access coming

**Microsoft**: Majorana (topological) - in development

**Rigetti**: 8, 19 superconducting qubits with 128 coming
e.g. IBM’s Calculations of Ground States of Molecules

How to measure a molecule's energy using a quantum computer

September 14, 2017, IBM
A First Quantum Computation in Quantum Field Theory
1+1-Dim QED

Based upon a string of $^{40}\text{Ca}^+$ trapped-ion quantum system

Simulates 4 qubit system with long-range couplings = 2-spatial-site Schwinger Model

Real-Time evolution of the quantum fields, implementing > 200 gates per Trotter step
``Time = 0`` for Quantum Computing in Nuclear Physics

Cloud Quantum Computing of an Atomic Nucleus


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2 Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
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We report a quantum simulation of the deuteron binding energy on quantum processors accessed via cloud servers. We use a Hamiltonian from pioneer effective field theory at leading order. We design a low-depth version of the unitary coupled-cluster ansatz, use the variational quantum eigensolver algorithm, and compute the binding energy to within a few percent. Our work is the first step towards scalable nuclear structure computations on a quantum processor via the cloud, and it sheds light on how to map scientific computing applications onto nascent quantum devices.

http://arxiv.org/abs/1801.03897

FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle $\theta$ around the Y axis, and the two-qubit CNOT gates.

of a Hamiltonian is to use UCC ansatz in tandem with the VQE algorithm [12, 15, 21]. We adopt this strategy for the Hamiltonians described by Eqs. (4) and (5). We define unitary operators entangling two and three orbitals,

$$U(\theta) \equiv e^{i \theta (a_0^\dagger a_1 - a_1^\dagger a_0)} = e^{i \theta (X_0 Y_1 - X_1 Y_0)},$$
First Demonstrations in Nuclear Many-Body Systems

Many-Body Studies

Ovrum, Hjorth-Jensen (2007)

Energy measurement probability

\[ \alpha \left| \langle \psi_f | \psi_i \rangle \right|^2 \]

Linear Response Functions

Carlson, Roggero (2018)

\[ \sum \left| \langle \psi_i | \delta | \psi_0 \rangle \right|^2 \delta(E_v - E_0 - \omega) \]

dynamic linear response and exclusive information

Spectral Combing

Kaplan, Klco, Roggero (2017)

Time-dependent auxiliary system = comb

Exponential level crossings send target system to ground state

The Deuteron

Cloud Quantum Computing of an Atomic Nucleus


published 23 May 2018

Variational Quantum Eigensolver

Slide by Natalie Klco (Oct 2018)
Developments in Field Theory for QC/QIS
(many more than are shown)

Simulating lattice gauge theories on a quantum computer
Tim Byrnes* Yoshihisa Yamamoto

Quantum Computation of Scattering in Scalar Quantum Field Theories
Stephen P. Jordan,* Keith S. M. Lee,* and John Preskill § *

Atomic Quantum Simulation of $U(N)$ and $SU(N)$ Non-Abelian Lattice Gauge Theories
D. Banerjee¹, M. Bögli¹, M. Dalmonte², E. Rico²,³, P. Stebler¹, U.-J. Wiese¹, and P. Zoller²,³

Towards Quantum Simulating QCD
Uwe-Jens Wiese

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices
Erez Zohar J. Ignacio Cirac Benni Reznik

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer
Esteban A. Martinez,¹,* Christine Muschik,²,³,* Philipp Schindler,¹ Daniel Nigg,¹ Alexander Erhard,¹ Markus Heyl,²,⁴ Philipp Hauke,²,³ Marcello Dalmonte,²,³ Thomas Monz,¹ Peter Zoller,²,³ and Rainer Blatt¹,²

Quantum Sensors for the Generating Functional of Interacting Quantum Field Theories
A. Bermudez,¹,²,* G. Aarts,¹ and M. Müller¹

Gauss’s Law, Duality, and the Hamiltonian Formulation of U(1) Lattice Gauge Theory
David B. Kaplan* and Jesse R. Stryker¹
Institute for Nuclear Theory, Box 351550, University of Washington, Seattle, WA 98195-1550

Slide by Natalie Klco (Oct 2018)
Quantum Field Theory on Superconducting Qubits
1+1-Dim QED

Hybrid Classical-Quantum ``System''

Quantum-classical computation of Schwinger model dynamics using quantum computers

Trotterized time evolution

Discretized time evolution requires long coherence

\[ e^{-iHt} = e^{-i \sum_j H_j t} \approx \left( \prod_j e^{-i H_j \frac{t}{N}} \right)^N \]

3.6 QPU·s

Only 15 angles define arbitrary SU(4) matrix


Vidal, Dawson (2003)

12.3 QPU·s

ArXiv:1803.03326
Lattice QCD application **chroma** code written by Savage (2012) for NPLQCD, adapted from other **chroma** codes written by Robert Edwards and Balint Joo [JLab, USQCD, SciDAC].

**C++**

Displaced propagator sources generate hadronic blocks projected onto cubic irreps. to access meson-meson scattering amplitudes in L>0 partial waves.

**Python3** code written by Savage (2018) to access IBM quantum devices through "the cloud" (through ORNL). IBM templates and example codes.

Calculates Trotter evolution of +ve parity sector of the 2-spatial-site Schwinger Model.
Entanglement and Fragmentation

Deep inelastic scattering as a probe of entanglement
Dmitri E. Kharzeev (RIKEN BNL & SUNY, Stony Brook), Eugene M. Levin (Santa Maria U., Valparaiso & Tel Aviv U.). Feb 12, 2017.
Published in Phys.Rev. D95 (2017) no.11, 114008

Dynamics of entanglement in expanding quantum fields
Published in JHEP 1804 (2018) 145
QC and QIS in the International Community

2 significant examples

Europe

Investing heavily in all related areas of QIS and QC
* e.g., Alibaba - qubits/devices and QIS

China

Generally:
* Investments in field theory and sensors
* Other efforts Nuclear Physics are beginning
QC and QIS in Broader Community

Caltech

U of Maryland

Lattice QCD consortium

DOE Study Group Report

Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (co-

Mikhail Lukin, Juan Maldacena, John Preskill (co-

Peter Shor, Jacob Taylor, Carl Williams

17 January 2015

Quantum Sensing for High Energy Physics

Report of the first workshop to identify approaches and techniques to the physics of quantum sensing that can be utilized for high energy physics. Convened by the U.S. scientific community for high energy physics.

Organized by the Coordinating Panel for Advanced Detection of the Division of Particles and Fields of the American Physical Society.

March 27, 2018

HEP funds QIS

Field Theory

Neutrinos

Dark Matter Ints.
Activities in Nuclear Physics

Workshop on Computational Complexity and High Energy Physics
July-31 — August 2, 2017

Quantum Computing for Nuclear Physics
November 14-15, 2017

Intersections Between Nuclear Physics and Quantum Information
Argonne National Laboratory
March 28-30, 2018

Near-term Applications of Quantum Computing
December 6-7, 2017

David Dean as Head of Physics Division
ahead of all others in NP

DOE NP funds a modest number of proposals in 2018
Activities in Nuclear Theory

A broad, multi-institutional program has been funded by DOE to hold two community-wide meetings, and to partially-support 2 junior scientists.

First meeting: January 23-25 in Santa Fe (Los Alamos)
Expertise in other domains will be important for Nuclear Physics

- Chemistry
- Quantum Information and Computing
- High-Energy Physics
- Condensed Matter
- ASCR
- Photonics
- Computer Science
- Technology Companies
- ...

International expertise will be valuable

Workforce development/adaptation just starting
Broader Impacts

e.g.
- Quantum many-body systems
  - Error correction
  - Topological structures
- Sensors
- Device design
- Workforce development
  - undergraduate and graduate students are excited and engaged

Anticipated to be of benefit to
- QIS + QC
- Technology companies
- High-Energy Physics
- Condensed matter
- Chemistry
- Quantum communication
- Quantum encryption
  - …
Summary

QC and QIS are now entering Nuclear Physics

• Significant potential to disruptively enhance the NP research program
  • address exponentially difficult challenges
• A limited fraction of community is actively engaged
• Community is starting to organize
• Workforce training critical
• NP has broad systemic fundamental knowledge of quantum many-body systems - anticipated to be valuable in QC and QIS development and other scientific applications

Charge to NSAC related to QC+QIS is timely
FIN
Simulations of Subatomic Many-Body Physics on a Quantum Frequency Processor

Hsuan-Hao Lu¹, Natalie Kloc², Joseph M. Lukens³, Titus D. Morris³, Aaina Bansal⁴, Andreas Ekström⁵, Gaute Hagen⁶,⁷, Thomas Papenbrock⁸,⁹, Andrew M. Weiner¹, Martin J. Savage², and Pavel Lougovski¹