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Why We Should Be Skeptical of Quantum Computing

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Abstract

- Is the supremacy of QC really near?
  - On the contrary, the future of QC may be highly uncertain, for several different reasons:
- The promised performance depends on entanglement-based scaling to massive parallelism, which has not yet been verified.
- Even if the theory is correct, exponential sensitivity to noise for highly entangled states could make the technology impractical.
- “Quantum” effects in superconducting qubits may be due to nonlinear properties of classical Josephson junctions .
- Quantum effects in arrays of coupled qubits may be due to conventional energy-band theory with delocalized states.

Quotations

- Richard Feynman
  - I think I can safely say that no one understands quantum mechanics. (The Character of Physical Law, 1965)
- Carl Sagan
  - Extraordinary claims require extraordinary evidence. (Cosmos, 1980)

- ***QC is making extraordinary claims!***

Key Questions about QC

- *Are superconducting qubits really quantum?*
- *Is quantum annealing really quantum?*
- *Is gate-based QC impractical due to noise?*
- *Are interacting qubits really just energy bands?*
- *Have superposition and entanglement been proven?*
- *Can experiments answer these questions?*

Classical Bits

- Mathematical Bits
  - Single bit 0 or 1
  - 3 bits: 000 or 001 or 010 or 011 or 100 or 101 or 110 or 111
  - 2^N possible states, but only one at a time
- Physical Bits
  - Bistable physical device, with voltages V_0 or V_1, or transition between them.
  - Heavily damped system to enable fast transition with no ringing – irreversible
  - Noise and Thermal fluctuation small compared to ΔV
  - Multiple bits are completely separate with *no interactions*

Mathematical Qubits

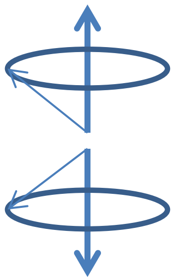
- Based on von Neumann (Hilbert space) model
  - ***Universally accepted, but see below!***
- Single qubit: Basis states |0> and |1>
  - Superposition $|\Psi> = c_0|0> + c_1|1>$, complex c_0 and c_1
- 3 interacting qubits:
  - $|\Psi_3> = c_0|000> + c_1|001> + \ldots + c_7|111>$
- Superposition of 2^N states which evolve coherently in parallel – Quantum Entanglement
  - *This extraordinary claim of 2^N parallelism has not been verified in real physical systems.*

Physical Qubits

- Real or artificial atom with ground state |0> and excited state |1>
- High-Q oscillator with negligible damping – reversible
  - Photon with energy $\Delta E = hf$ can switch $|0> \rightarrow |1>$ OR $|1> \rightarrow |0>$
- Noise and thermal fluctuations $<< \Delta E$
  - Need to maintain coherence for long time
- N qubits *must* interact and remain entangled to obtain 2^N parallelism
  - Need to maintain coherence of entire assembly

Example: Spin Qubits

- Spin of electron or nucleus acts as magnetic moment, aligns || or anti-|| with B field.
  - Nuclear spins basis for NMR (and MRI)
  - |0> = ↓, |1> = ↑



- Transition involves microwave pulse from |0> to |1> at frequency f, where hf = ΔE.
  - In semi-classical picture of spin, transition involves spiral precession of spin from one state to other.
  - State is always |0>, |1>, or precessing spin, but *not* a superposition.

Example: Superconducting Qubits

- Based on Josephson junctions rather than single spins or atoms
  - Several different types
  - Low-loss, high-Q integrated circuits
  - Operate at ultralow temp. ~ 10 mK, $<<T_c$.
- Flux qubit is bi-stable SQUID
  - Classical bit which may also exhibit quantum effects
- Phase qubits and transmons essentially tunable LC oscillators
  - Ground state and first excited state
  - No classical limit.

Are Superconducting Qubits Really Quantum?

- Early evidence for macroscopic quantum effects in Josephson junctions and circuits
  - Junction phase ϕ as macro quantum variable
- However, most "quantum effects" in JJs can be simulated using fully classical JJs.*
  - Nonlinear JJs can produce features that mimic Rabi oscillations, for example.
- This work has been virtually ignored by QC research community

*J. Blackburn, M. Cirillo, & N. Grønbech-Jensen, "Survey of Classical and Quantum Interpretations of experiments on Josephson junctions at very low temperatures", Phys. Rep. 611, 2016.

Two Completely Different QC Approaches

- Gate-based QC is sequential digital logic for universal QC
  - Requires full coherent entanglement of all gates for duration of problem – incompatible with noise
  - Promises 2^N parallelism for exponential speedup
  - Addresses critical problems such as factoring large numbers (Shor’s algorithm)
- Quantum Annealing processor is *analog* computer for certain optimization problems
  - 2D array of qubits with nearest neighbor coupling
  - Compatible with noise, but degree of speedup unclear.
- These approaches have little in common and should be examined separately.

Is Quantum Annealing Really Quantum?

- The only commercial quantum computer that can solve problems
  - Superconducting system from D-Wave Systems, Inc.*
- Quantum annealer is coupled array of 2048 flux qubits operating at 20 mK.
  - Configured as analog classical solver for 2D Ising model with proposed quantum enhancement.
  - Maps onto a variety of optimization problems, such as traveling salesman problem.
  - Evidence for quantum enhancement continues to be questioned.#

*https://www.dwavesys.com/d-wave-two-system

J. Smolin and G. Smith, "Classical signature of quantum annealing," Front. Phys. (2014)

“Quantum Inspired” Classical Chips

- Classical custom processors for Ising-type machines
- Fujitsu sells a CMOS “Digital Annealer” chip and computer system*
  - Promoted as “quantum inspired”, but actually room-temperature custom silicon chip
  - Designed to simulate same kinds of problems as D-Wave machine, but with greater precision and scale.
- Quantum annealer needs to establish superior performance to CMOS annealer
  - No comparisons yet presented.

J. Boyd, “Fujitsu’s CMOS Digital Annealer Produces Quantum Computer Speeds,” IEEE Spectrum, May 2018.

Gate-Based Quantum Computing

- Mainstream approach being pursued by most researchers and several companies (IBM, Google, Intel, …)
  - Mostly based on superconducting qubits such as transmons.
- Several groups fabricated chips with >50 interacting qubits
  - Qubits and gates reported to be functional
- But no reports of significant algorithms or applications.
  - This may be due to noise issues.

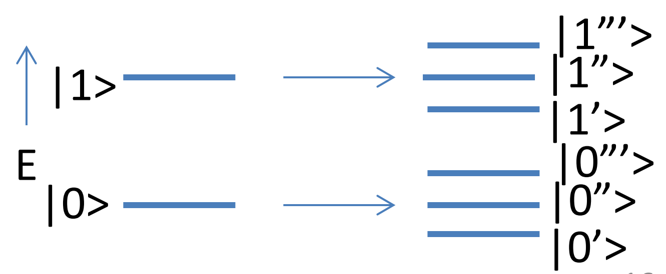
Is gate-based QC impractical due to noise?

- Current generation of gate-based QC severely limited by noise
  - Noisy Intermediate scale quantum systems (NISQ)
  - Practical NISQ applications still being identified
- Quantum Error Correction
  - Concept of correcting for noise using same technology as qubits themselves.
  - Difficult “bootstrap” problem
- Several researchers have argued* that true quantum error correction may not be possible
  - Exponential sensitivity to noise with increasing N

*G. Kilai, The Quantum Computer Puzzle (2016), https://arxiv.org/pdf/1605.00992.pdf
M. Dyakonov, “The Case Against Quantum Computing,” IEEE Spectrum, Nov. 2018.

Energy Bands in Crystals

- Consider conventional quantum theory of Bloch waves in crystals.
  - Array of identical atoms, each with ground state |0> and excited state |1>
  - When electrons interact, |0> and|1> broaden to form energy bands
  - No more localized atomic states; all states extend across crystal – Bloch Waves
  - Note that 2N initial states become 2N Bloch waves – no increase in degrees of freedom.



Are interacting qubits really just energy bands?

- Interacting qubits are typically identical qubits connected to each other or to a transmission line*
  - But these same interactions lead to collective modes in multiple qubits.
  - The relevant basis states are no longer single qubits, but are 2N Bloch waves over the entire N interacting qubits.
  - The qubit math model does not deal with delocalization, while the Bloch wave model has no entanglement.
  - This suggests that a NISQ cluster of qubits may be used for *analog* simulation of energies in crystals, interfaces, and other quantum chemistry problems.

*C. Neill et al., “Blueprint for demonstrating quantum supremacy with superconducting qubits,” Science, April 2018.

Quantum Foundations

- John Von Neumann, Mathematical Foundations of Quantum Mechanics, 1932
  - Established Hilbert space formalism with superposition and entanglement.
  - Dirac notation $|\Psi>$ added later.
- QM really hybrid of at least 3 theories:
  – Single-particle (Schrödinger Eq.) – very accurate, but no superposition or entanglement
  – Multi-particle (Pauli principle, etc.) – semi-quant.
  – Quantum measurement theory – untested.
- Prior to QC, no real applications based on quantum entanglement.
- Entanglement was questioned in 1937 by both Einstein and Schrödinger ("spooky action-at-a-distance"), but is now universally accepted.

Have superposition and entanglement been proven?

- Superposition and entanglement are central to QC, and questioning them is considered heretical.
  - But the evidence is still incomplete.
- Entanglement first proposed to explain Exclusion Principle for electrons, but other explanation compatible with local realism may be possible.
- Most experimental evidence for entanglement from Bell's Theorem tests with correlated photons (but see below).
- Model of spin without superposition has been proposed, and can be tested (see below).

Can experiments answer these questions?

- Rather than assuming that QC is correct, devise tests that can *disprove* entanglement, and exponential scaling.
- Tests on superconducting qubits should compare to classical models.
- Tests of quantum annealing should compare directly to classical Ising machines.
- Identify non-trivial problems that can be addressed with NISQ digital processors, and follow scaling.
- Analyze qubit arrays with Bloch waves, and use for analog simulation of energy levels.

*Experiments to test superposition and entanglement**

- Superposition in spins
  - The classic Stern-Gerlach experiment (1922) used atomic beams to provide the first measurement of electron spin.
  - The two-stage SG experiment, never actually done, may provide a testbed for realistic spin model.
- Entanglement in photons
  - Virtually all classic photon entanglement experiments measured linearly polarized single photons.
  - But a simple realistic model asserts that single photons must be circularly polarized, which can be tested using modern photon detectors.
- See Appendix for further information.

*A. Kadin and S. Kaplan, "Proposed experiments to test the foundations of quantum computing", 2016. http://vixra.org/abs/1607.0105

Conclusions

- Quantum computing has made extraordinary promises of exponential performance based on extrapolation of established but unproven theories.
- Proven performance thus far has been minimal.
- Need to adopt skeptical eye toward all QC claims, and develop tests for inconsistencies with orthodox theory.
- Need to develop functional performance metrics for QC that compare to classical computing.
- Given the scale of R&D, the next 5 years will be critical.
- If QC fails, that should open the door to reconsider the orthodox foundations of quantum mechanics.

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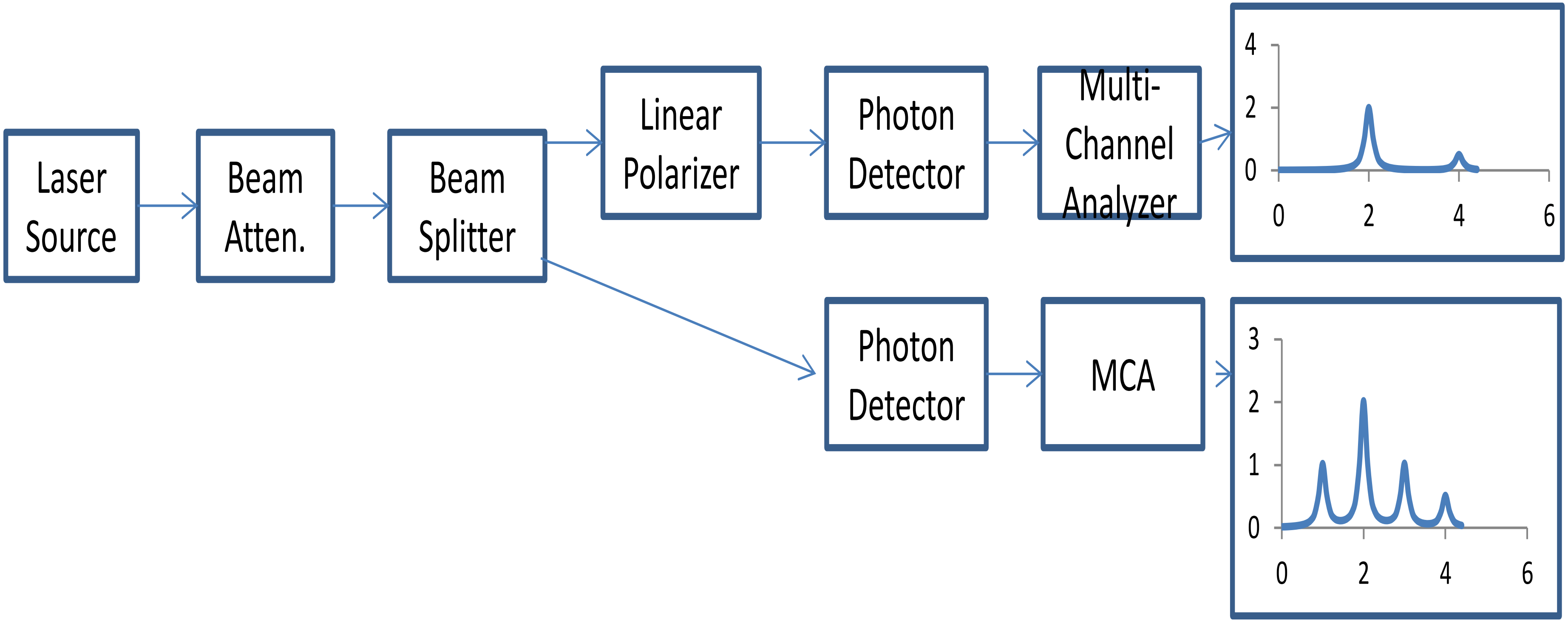
Appendix:
Experimental Tests of Quantum Foundations

- Neoclassical quantum picture predicts local reality without entanglement or indeterminacy*
- Simple experiments should show sharp deviation from orthodox quantum theory.
  - Determine whether single photon must be circularly polarized -- entanglement.
  - Determine whether spin-polarized atomic beam splits in a rotated magnetic field -- superposition.
  - Determine whether coupled qubits form delocalized energy band – scaling for quantum computing.

* A.M. Kadin, “Fundamental Waves and the Reunification of Physics”, Foundational Questions Inst. Essay Contest, 2017,

Proposed Test – LP Single Photon

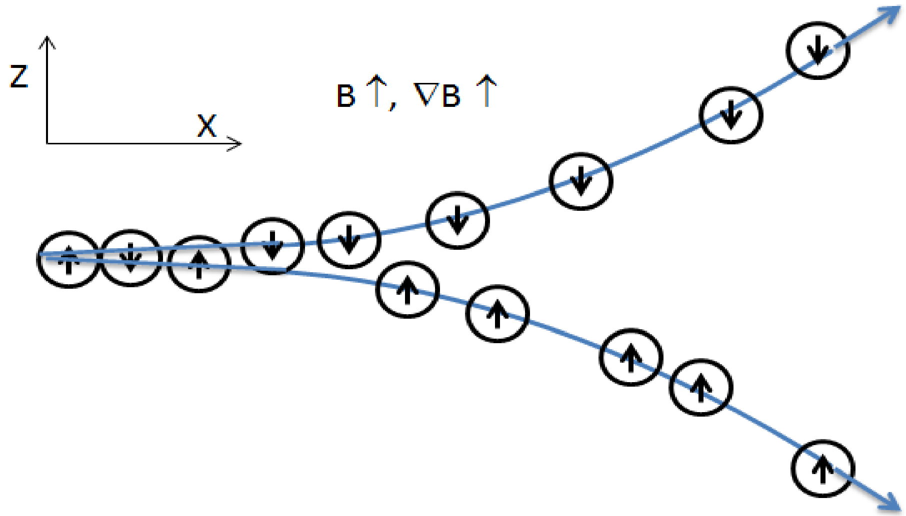
- LP single photons are central to most optical tests of quantum entanglement.
  - But neoclassical single photons are real CP wavepackets; LP fields must be photon pairs.
  - LP single photons have been observed in experiments, but with fast event detectors that cannot distinguish 1 from 2 simultaneous photons.
  - New superconducting energy-sensitive photon detectors can determine number of photons in fast pulse.
- Proposed experiment – measure photon count distribution in weak laser pulses
  - Compare results with and without linear polarizer.
  - In neoclassical picture, LP pulses should have only even number of photons.



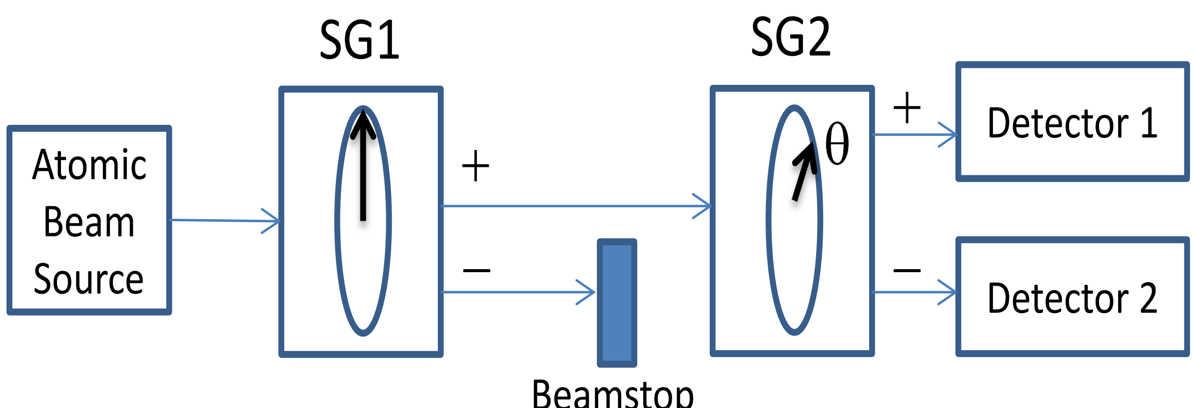
Counting Photons in a Light Pulse using Energy-Resolving Detector with and without Polarizer

Proposed Test – Magnetic Spin Superposition

- Stern-Gerlach experiment (1922) provided first evidence for spin quantization of electrons.
  - Univalent atomic beam placed in magnetic field gradient
  - Assumed to be in superposition of $\downarrow$ and $\uparrow$ spins.
  - Split into two sub-beams, corresponding to $\uparrow$ and $\downarrow$
- Two-stage SG experiment used in many textbooks to illustrate quantum measurement
  - One sub-beam is sent to 2nd SG analyzer, rotated by angle θ.
  - Expected statistical distribution as $\cos^2\theta$ and $\sin^2\theta$.
  - But this experiment was never done – admitted by Feynman, ignored by others.
- Proposed experiment – carry out 2-stage SG experiment
  - In neoclassical picture, no superposition states; spins rotate to new field direction.
  - Expected result – 0 or 100%, with no distribution.



Original Stern-Gerlach Experiment – spin separation

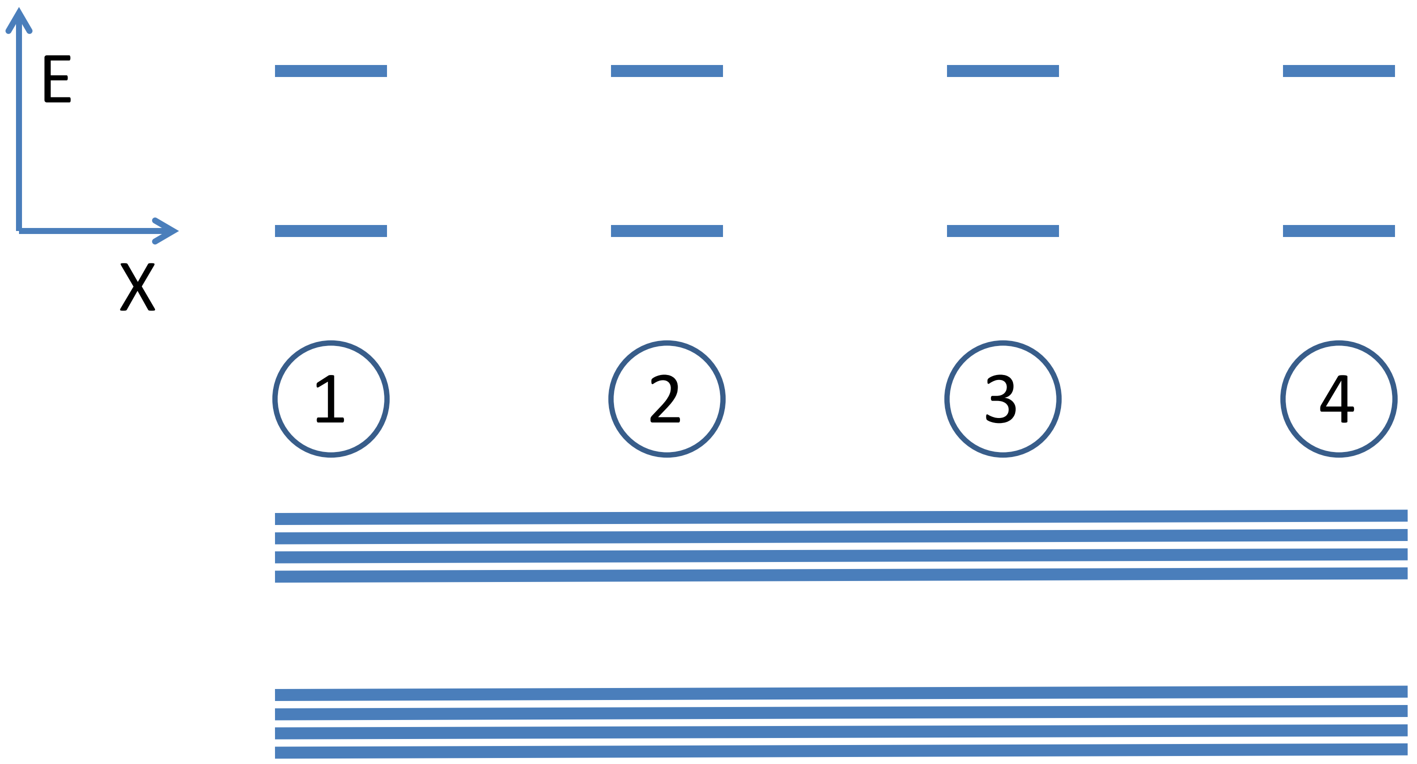


2-stage Stern-Gerlach Experiment

Proposed Test – Interacting Qubits

- Quantum computing is first major application critically dependent on quantum entanglement
  - 2^N effective parallelism for N qubits due to expansion of Hilbert space.
  - Massive parallelism enables QC to solve difficult problems with finite resources.
- But neoclassical model has no entanglement and no Hilbert space.
  - Quantum computing should not work at all!
- Example of N coupled quantum oscillators
  - Orthodox picture predicts 2^N entangled states
  - Neoclassical picture predicts 2N delocalized states (band theory)
- Similar to interacting superconducting qubits (Neill 2018)
  - Delocalized band model should work better than model of entangled localized qubits.

Energy Levels of Coupled and Uncoupled Qubits



- Localized states broaden into extended bands
- No increased degrees of freedom

More References

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You may be interested in another poster on Thursday!

APS March Meeting, Boston, MA
Thursday, March 7, 2019
Poster T70.002

A Neoclassical Framework That Reunifies Modern Physics

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