New Horizons in Quantum Theory

APS Forum on International Physics

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Sharif University of Technology,
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IICQI-21 talk: Quantum Simulations with Analog and Digital Quantum Computers
Speaker: Ignacio Cirac
Date-time: Thu, 13 May 2021, 06:30 PM +0430
Event: IICQI 2020-21

IICQI-21 talk: From Structured Photons to Structured Electrons
Speaker: Ebrahim Karimi
Date-time: Thu, 8 Apr 2021, 06:00 PM +0430
Event: IICQI 2020-21

IICQI-21 talk: Qubit sensors in correlated quantum noise environments: advances in noisy quantum metrology
Speaker: Lorenza Viola
Date-time: Thu, 4 Mar 2021, 06:00 PM +0330
Event: IICQI 2020-21

IICQI-20 talk: Reframing SU(1,1) Interferometry
Speaker: Carlton Caves
Date-time: Thu, 17 Dec 2020, 06:30 PM +0330
Event: IICQI 2020-21

IICQI-20 talk: Probing the quantumness of states and channels with truncated moment sequences
Resurgence of Quantum Mechanics, after 100 years

Simple ideas + elegant experiments
The present century: Manipulation of single atomic entities.
Extremely cold temperatures

Temperature

Speed

Laser Cooling

10^{-9} \text{ Kelvin}

1 \text{ mm/s}
Extremely precise frequencies  

Precision 1 in $10^{17}$

Extremely short laser pulses  

$10^{-18}$ Seconds
$n = 52$ in 2.5 V/cm

Circular states

52 $F m = 2$

1.26 $\mu$m

5D

250 MHz

776 nm

5P

780 nm

5S
Rydberg Atoms

\[ \Psi_{n,l,m} \]

n=52, l=51, m=51
Rydberg Atoms
Quantum Information Science

Immediate applications in technology

Fundamental questions in physics
The No-Cloning theorem (1981-82)

Asher Peres

William Wootters
Quantum Process

\[ |\psi\rangle \otimes |b\rangle \rightarrow |\psi\rangle \otimes |\psi\rangle \]

\[ |0\rangle \otimes |b\rangle \rightarrow |0\rangle \otimes |0\rangle \]

\[ |1\rangle \otimes |b\rangle \rightarrow |1\rangle \otimes |1\rangle \quad |+_\rangle := |0\rangle + |1\rangle \]

\[ |+_\rangle \otimes |b\rangle \rightarrow |0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle \neq |+_\rangle \otimes |+_\rangle \]
Quantum Process

$|\psi\rangle \otimes |b\rangle \otimes |world\rangle \quad \text{Quantum Process} \quad |\psi\rangle \otimes |\psi\rangle \otimes |World_\psi\rangle$
Everybody can hear you, but only one person understands you.
If we have a cloning machine, we can violate Heisenberg Uncertainty Principle.
$|\psi\rangle$  Quantum Cloner  $|\psi\rangle \otimes |\psi\rangle \otimes \cdots \otimes |\psi\rangle$

$x$  $p$
If we have a cloning machine, we can violate Special Theory of Relativity
\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) \]

**Alice**

**Bob**

**Measurement in the \{ |0\rangle, |1\rangle \} basis.**
$|\psi\rangle = \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle)$

Measurement in the $\{|+, -\rangle\}$ basis.
What kind of measurement Alice has done?

Measurement in the X or Z basis
Cloning states make them more distinguishable.

\[ \langle a | b \rangle = \frac{1}{2} \]

\[ \langle a^\otimes 2 | b^\otimes 2 \rangle = \frac{1}{4} \]
Bob can now distinguish between $|0\rangle^\otimes$, $|1\rangle^\otimes^n$, $|+\rangle^\otimes^n$ and $|-\rangle^\otimes^n$. Measurement in the $X$ or $Z$ basis.
Superposition

David Deutsch

Bit

0
1

Qubit

$\alpha |0\rangle + \beta |1\rangle$
Constant Function

Balanced Function

<table>
<thead>
<tr>
<th>x</th>
<th>C(x)</th>
<th>C(x)</th>
<th>B(x)</th>
<th>B(x)</th>
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<tbody>
<tr>
<td>0</td>
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</tr>
</tbody>
</table>
Two calls are necessary

0, 1

B or C function

Classical Computer

One call is enough

\[ \alpha|0\rangle + \beta|1\rangle \]

B or C function

Quantum Computer
Factoring Large Numbers

Reducing thousands of years to hundreds of seconds

Peter Shor
Quantum Circuit for Factoring
Does it have anything to do with deep science?
We enter a new era for solving scientific problems.
Entanglement

Quantum Key Distribution

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) \]

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|++\rangle + |--\rangle) \]
Does it have anything to do with deep science?
Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto and V. Vedral
Phys. Rev. Lett. 119, 240402 – Published 13 December 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn
Phys. Rev. Lett. 119, 240401 – Published 13 December 2017
A classical field cannot create entanglement between two objects.
C being a classical system, doesn’t have two non-commuting operators!

\[
[H_{c,1}, H_{c,2}] = 0
\]

\[
U = U_{c,1} U_{c,2}
\]
Let $M_1$ and $M_2$ interact via gravitational field and measure their entanglement after a while.

If $M_1$ and $M_2$ are not entangled Gravitation is classical.
The proposed experiment:

Interferometry
\[ |0\rangle \otimes |0\rangle \]

\[ (|0\rangle + |1\rangle) \otimes (|0\rangle + |1\rangle) \]

Example: \[ |0\rangle |0\rangle \xrightarrow{e^{-i \frac{Gm^2}{\hbar d_2} t}} e^{i \phi_2} |0\rangle |0\rangle \]
\[ |1\rangle |1\rangle \quad \rightarrow \quad e^{-i \frac{G m^2}{\hbar d_2} t} |1\rangle |1\rangle = e^{i \phi_2} |1\rangle |1\rangle \]
\[ |1\rangle|0\rangle \quad \xrightarrow{e^{-i\frac{Gm^2}{\hbar d_1}t}} \quad e^{i\phi_1}|1\rangle|0\rangle \]
By measuring the probability of detecting the masses at D0 and D1 we can detect entanglement.

Estimates for achieving maximal entanglement:

\[ m \approx 10^{-12} \text{ Kg} \quad \quad t \approx 10^{-6} \text{ s} \quad \quad d \approx 10^{-6} \text{ m} \]
Entanglement Again

| 0⟩ → |0⟩ = \frac{1}{\sqrt{2}}(|00⟩ + |11⟩)

| 1⟩ → |1⟩ = \frac{1}{\sqrt{2}}(|01⟩ + |10⟩)
Quantum State Sharing

\[|\psi\rangle = \alpha |0\rangle + \beta |1\rangle \quad \rightarrow \quad |\psi\rangle = \alpha |\bar{0}\rangle + \beta |\bar{1}\rangle\]

In the end Bob and Charlie can collaborate to retrieve the original state \(|\psi\rangle\).
A more complicated schemes: (2,3)
\[|0\rangle \rightarrow \quad |\bar{0}\rangle = |000\rangle + |111\rangle + |222\rangle\]

\[|1\rangle \rightarrow \quad |\bar{1}\rangle = |012\rangle + |120\rangle + |201\rangle\]

\[|2\rangle \rightarrow \quad |\bar{2}\rangle = |021\rangle + |102\rangle + |210\rangle\]
\[
|\bar{0}\rangle = |000\rangle + |111\rangle + |222\rangle
\]

Bob adds to Charlie

\[
\rightarrow |000\rangle + |121\rangle + |212\rangle
\]

Charlie adds to Bob.

\[
\rightarrow |000\rangle + |021\rangle + |012\rangle = |0\rangle \otimes (|00\rangle + |21\rangle + |12\rangle)
\]
Another scheme: (3,5)
Two levels of encoding
A quantum mechanical description of the Holographic Principle.
Regular Article - Theoretical Physics | Open Access | Published: 23 June 2015

Holographic quantum error-correcting codes: toy models for the bulk/boundary correspondence

Fernando Pastawski ☰, Beni Yoshida, Daniel Harlow & John Preskill

Journal of High Energy Physics 2015, Article number: 149 (2015) | Cite this article

5893 Accesses | 341 Citations | 103 Altmetric | Metrics

ℹ️ A preprint version of the article is available at arXiv.
Thank you for your attention