Title: How should any quantum measuring instrument (including a quantum computer) work?

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Abstract: We will look at the axioms of quantum mechanics as expressed, for example, in the book by M. A. Nielsen and I. L. Chung ("Quantum Computation and Quantum Information"). We then take a critical look at these axioms, raising several questions as we go. In particular, we will look at the possible informational completeness property of the family of operators that we measure. We will propose physical solutions based on the results of quantum mechanics on phase space and the measurement of quantum particles by quantum mechanical means. We illustrate this with both momentum-position measurements and spin measurements.

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How Should Any Quantum Measurement Work (Including a Quantum Computer)

Dr. Franklin E. Schroeck, Jr. University of Denver

Outline

- Axioms of Quantum Mechanics (from Quantum Computation and Quantum Information by M. A. Nielsen and I. L. Chuang).
- 2) A critical look at the axioms.
- A partial solution to the questions that arose.

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Axiom 2. Execution of a closed quantum system a record by a unitary transformation. In the case of a single qubit, it is assumed that any unitary operator can be realized in realistic systems.

Axiom 3) Quantum measurements are described by a countable collection $\{M_m \mid \sum M_m M_n = 1\}$ of measurement operators, and

(a) the probability that m occurs in state was

 $\rho(m) = < \psi \mid M_m M_m \psi > - 1 M_m \psi$

(b) the state of the system after measurement is $\|M_m\psi\|^{-1} M_m\psi$.

Axiom 4) A composite system of states

 $\rho_1, \rho_2, \cdots, \rho_n$ is given by $\rho_1 \otimes \cdots \otimes \rho_n$

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There is no finite basis providing a representation of the c.c.r.'s.

Question 1) What is a basis on which to choose to truncate?

On Axiom 2) The dynamics of a particle of closed quantum system is given by a unitary operator on phase space. Given any state "localized within a certain region of phase space" it may have a slow wave packet spreading, and then we may concentrate on the spin by taking the partial trace. We may not get "any unitary operator" this way.

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Question 4) Given that you don't have projections in the game, are some or all of the "results" of the Stern-Gerlach experiment, or of quantum computing, or · · · valid? How will we proceed with positive operators?

On Axiom 3 (contin.)) If M_m is a positive state, for example?

5) Can we compute the "results" alone?

Definition We will take a set of operators $\{A_n\}$ to be informationally complete if whenever ρ and ρ' are density operators, then $Tr(\rho A_n) = Tr(\rho' A_n)$ for all a implies $\rho = \rho'$.

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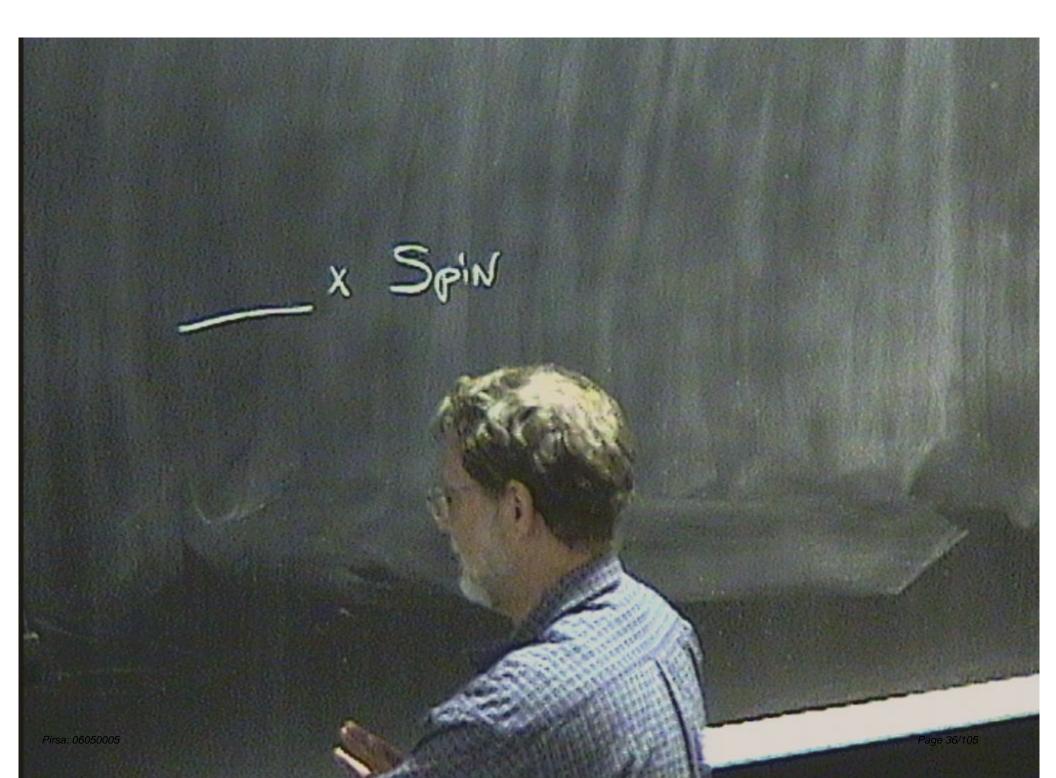
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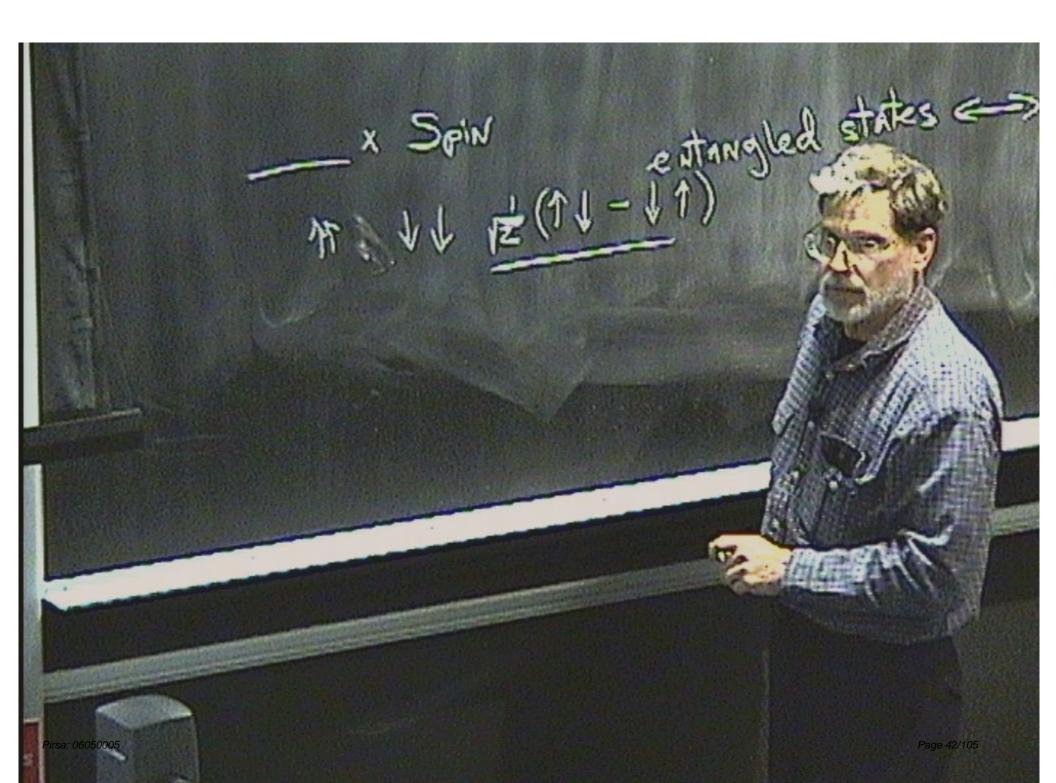
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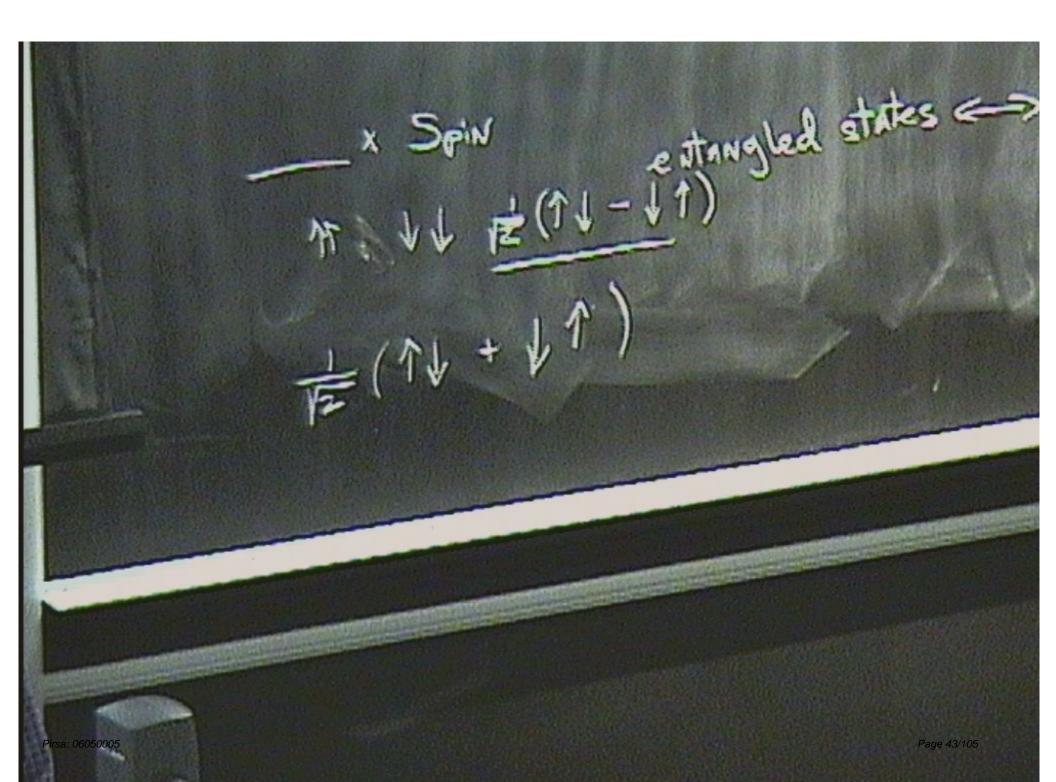
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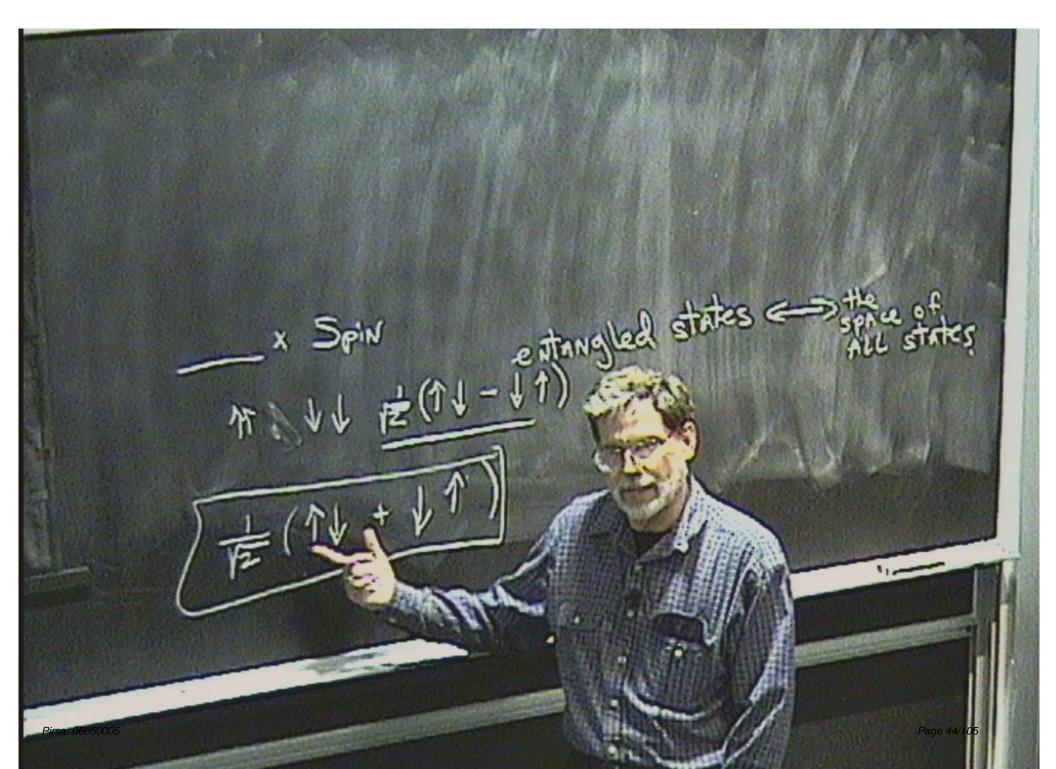
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A Possible Solution coming from Quantum Mechanics on Phase Space

Via Wigner, we treat quantum mechanics on phase space as coming from the Poincaré (or Galilei) group and then derive the phase spaces, irreducible representations, etc. as coming from the group itself. The following definition is one non-surprizing result. See F.E. Schroeck, Jr., Quantum Mechanics on

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Definition (or Theorem) In relativistic quantum mechnics, the phase space for massive spinning particle is $R^3 \oslash R^3 \oslash S(2)$. For massive, spin zero particle = $R^3 \oslash R^3$. $R^3 \oslash R^3$ denotes the momentum space times position space; S(2) is the spin space.

Spin zero case: We may want to have particles with momentum in a box Δ_1 (say

around zero) and some in a box Δ_2 . Take a particle with was suffering that has

Translate a with (%p.g) to obtain

 $= L(p,q)\eta, PU(p,q)\eta > = p.$

 $< U(p,q)\eta, QU(p,q)\eta > = q$

Take the probability for the localization operator for a general vector ψ to be in $\Delta_1 \times \Delta_2$ to be

Escaptor)

 $= \int_{\mathbb{R}^{n-1}} |\langle \psi(p,q)\eta,\psi \rangle|^2 d^{n}$

 $\int_{\mathbb{R}^n} Z_{amax}(p,q) \mid < U(p,q)\eta, \psi > 0$

Note that we have written just the transform probability for ψ with $U(p,q)\eta$ integrated over the confines of the box $\Delta_1 \times \Delta_2$. (For the interpretation of η , see my book, for example.)

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 $<\eta_{a}P\eta_{a}>0$, $|\eta_{a}Q\eta_{a}>=0$.

Translate it with the wito obtain

 $\leq U(p,q)\eta, PU(p,q)\eta > = p$

 $< U(p,q)\eta, QU(p,q)\eta > = q$

Take the probability for the localization operator for a general vector ψ to be $\Delta_1 \times \Delta_2$ to be

$$L^2_{\Delta_1 \times \Delta_2}(\psi)$$

 $\equiv \int_{\Delta_1 \times \Delta_2} |\langle U(p,q)\eta, \psi \rangle|^2 d^3 p d^3 q$

$$= \int_{\mathbb{R}^n} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid < U(p,q)\eta, \psi > \mid \quad d^* p d^* q$$

Note that we have written just the transition probability for ψ with $U(p,q)\eta$ integrated over the confines of the box $\Delta_1 \times \Delta_2$. (For the interpretation of η , see my book, for example.)

Spin zero case: We may want to have particles with momentum in a box Δ_1 (say around zero) and position in a box Δ_2 . Take a particle with wave function η that has

$$\langle \eta, P\eta \rangle = 0, \langle \eta, Q\eta \rangle = 0.$$

Translate it with U(p,q) to obtain

$$U(p,q) = P(i(p,q)\eta > -p)$$

$$< U(p,q)\eta, QU(p,q)\eta > = q.$$

Take the probability for the localization operator for a general vector ψ to be in $\Delta_1 \times \Delta_2$ to be

$$L^2_{\Delta_1 \times \Delta_2}(y)$$

$$= \int_{\Delta v \Delta v} |\langle U(p,q)\eta, \psi \rangle|^2 d^3p d^3p$$

$$= \int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid < U(p,q)\eta, \psi > \mid^2 d^3 p d^3 q$$

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Translate it with U(p,q) to obtain

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$$\langle U(p,q)\eta, QU(p,q)\eta \rangle = q.$$

Take the probability for the localization operator for a general vector ψ to be in

 $\Delta_1 \times \Delta_2$ to be

$$= \int_{A_{max}} | < U(p,q) \eta, \psi > |^2 d^3p d^3q$$

$$\int_{\mathbb{R}^{n}} \chi_{a_{p},a_{p}}(p,q) | < U(p,q)\eta, \psi > |^{2} d^{3}pd^{3}q$$

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$$=\int_{-\infty}^{\infty} d^3pd^3q$$

$$= \int_{\mathbb{R}^d} \chi_{\Delta_1, q, d}(p, q) | \langle U(p, q) \eta, \psi \rangle |^2 d^2 d^2$$

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$$= \int_{\mathbb{R}^{6}} \chi_{\Delta_{1} \times \Delta_{2}}(p,q) |\langle U(p,q)\eta, \psi \rangle|^{2} d^{3}pd^{3}q$$

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$$\begin{split} L^2_{\Delta_1 \times \Delta_2}(\psi) \\ &\equiv \int_{\Delta_1 \times \Delta_2} | < U(p,q) \eta, \psi > |^2 \ d^3 p d^3 q \\ &= \int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \ | < U(p,q) \eta, \psi > |^2 \ d^3 p d^3 q \end{split}$$

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$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

 $\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$

(Without general) — Jublems, you may replace $A^{\eta}(\gamma_{\Lambda^{(1)}})$ where $A^{\eta}(\gamma_{\Lambda^{(2)}})$ where $A^{\eta}(\gamma_{\Lambda^{(2)}})$ is a sublems, you may

 $f \in L^1(\mathbb{R}^n) \cap L^\infty(\mathbb{R}^n)$, real valued.)

As a function of either $\chi_{A_1 \times A_2}$ or f, these f is are informationally complete, form a set of positive operators, and take the value 1 as There are some conditions on g here.)

When you spectrum, becompose $A^{\eta}(2x-x^{\eta})$ you find that (a ray spectrum is purely discrete whenever x is compact, and ordering the spectrum in decreasing transiting drop off precipitously to just over 0. We will take "the vectors in $\Delta_1 \times \Delta_2$ " to be the eigenvectors that have eigenvalues close to

This answers questions 1, 2 and 6!

$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

$$\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$$

(Without generation and problems, you may replace $A^{\eta}(\chi_{\Delta_1 + \Delta_2})$ with $A^{\eta}(\chi_{\Delta_1 + \Delta_2})$

 $f \in L^1(\mathbb{R}^n) \cap L^{\infty}(\mathbb{R}^n)$, real valued.)

As a function of either $\chi_{A_1 A A_2}$ or f, these A''s are informationally complete, form a set of positive operators, and take the value 1 as f = 1. (There are some conditions on η here.)

When you spectrally decompose $A^*(Z_{A-1})$ you find that (i) the spectrum is purely discrete whenever Δ_2 is compact ordering the spectrum in decreasing the eigenvalues begin just below 1 and the eigenvalues begin just over 0. We was take "the vectors in $\Delta_1 \times \Delta_2$ " to be the eigenvectors that have eigenvalues close to 1.

This answers questions 1 2 and 6!

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$$\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$$

(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, freal valued.)

are informationally complete, form a set of positive operators, and take the value 1 as $f \rightarrow 1$. (There are some conditions on η here.)

When you spectrally decompose A7(Za, was) you find that (i) the spectrum is purely districte whenever A. V.A. is compact, and I ordering the spectrum or decreasing on the the enterwances make just below 1, and train drop of precipitalisty to just over 0. We will take "the vectors in $\Delta_1 \times \Delta_2$ " to be the eigenvectors that have eigenvalues close to

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$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

$$\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$$

(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

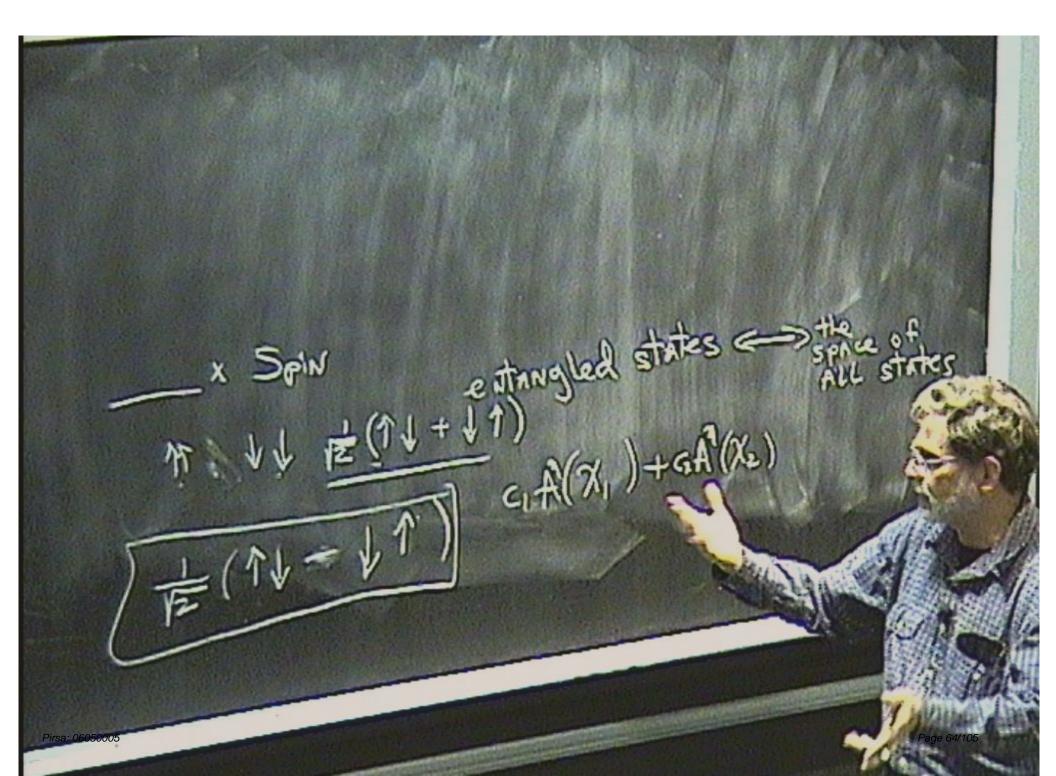
As a function of either any, these $A^{\eta}s$ are informationally complete form a set of positive operators, and take the value 1 as $f \rightarrow 1$. (There are some conditions on η here.)

When you spectrally decompose $A^n(\chi_{\Delta_1 \times \Delta_2})$ you find that it me spectrum is purely discrete where α is compact, and α ordering the spectrum of decreasing order the eigenvalues below 1, and then drop off precipitudes to just over 0. We will take "the vectors in $\Delta_1 \times \Delta_2$ " to be the eigenvectors that have eigenvalues close to 1.

This answers questions 1, 2 and 6

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$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

$$\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$$

(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

As a function of either $\chi_{\Delta_1 \times \Delta_2}$ or f, these A^{η} s are informationally complete, form a set of positive operators, and take the value 1 as $f \to 1$. (There are some conditions on n here.)

When you spectrally decrease $A^\eta(\chi_{\Delta_1 \times \Delta_2})$ you find that (i) the spectrum is purely discrete whenever $\Delta_1 \times \Delta_2$ is compact, and ii) ordering the spectrum in decreasing order, the agenvalues begin just below 1, and then drop off precipitously to just over 0. We will take the vectors in $\Delta_1 \times \Delta_2$ to be the eigenvectors that have eigenvalues close to 1.

This answers questions 1, 2 and 6

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(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

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When you spectrally $\Delta = \Delta = A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ you find that (i) the spectrum is purely discrete whenever $\Delta_1 \times \Delta_2$ is compact, and is ordering the spectrum in decreasing order. The convalues begin just below 1, and then drop off precipitously to just over 0. We will take the vectors in $\Delta_1 \times \Delta_2$ to be the eigenvectors that have eigenvalues close to

This answers questions 1, 2 and 6

$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

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(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

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When you spectrally decompose $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$

discrete whenever Δ_1 is compact, and its ordering the spectrum in decreasing order, the eigenvalues begin just below 1, and then drop off precipitously to just over 0. We will take the vectors in $\Delta_1 \times \Delta_2$ to be the eigenvectors that have eigenvalues close to

This answers questions 1; 2 and 6!

$$A^{\eta}(\chi_{\Delta_1 \times \Delta_2}) =$$

$$\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$$

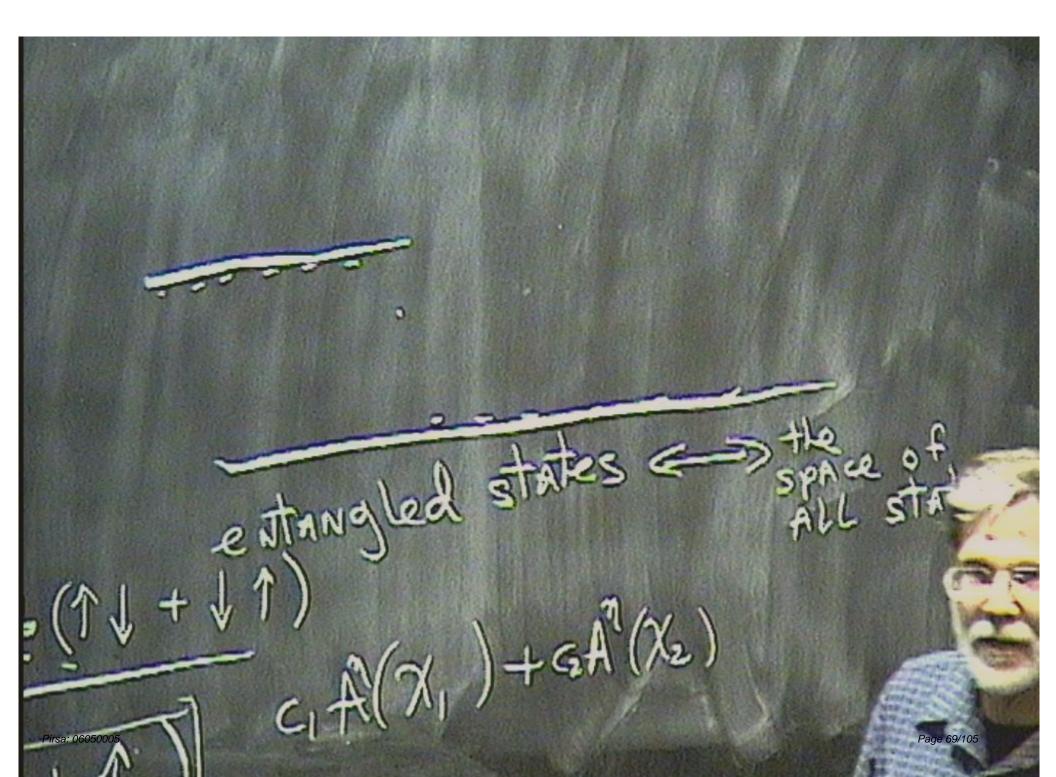
(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

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When you spectrally decompose $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ you find that (i) the spectrum is purely discrete whenever $\Delta_1 \times \Delta_2$ is compact, and ii) ordering the spectrum in decreasing order, the eigenvalues begin just below 1, and then

take "the vectors in $\Delta_1 \times \Delta_2$ to be the eigenvectors that have eigenvalues close to 1.

This answers questions 1, 2 and 6!



 $\int_{\mathbb{R}^6} \chi_{\Delta_1 \times \Delta_2}(p,q) \mid U(p,q)\eta > < U(p,q)\eta \mid d^3pd^3q$

(Without generating any problems, you may replace $A^{\eta}(\chi_{\Delta_1 \times \Delta_2})$ with $A^{\eta}(f)$, $f \in L^1(\mathbb{R}^6) \cap L^{\infty}(\mathbb{R}^6)$, f real valued.)

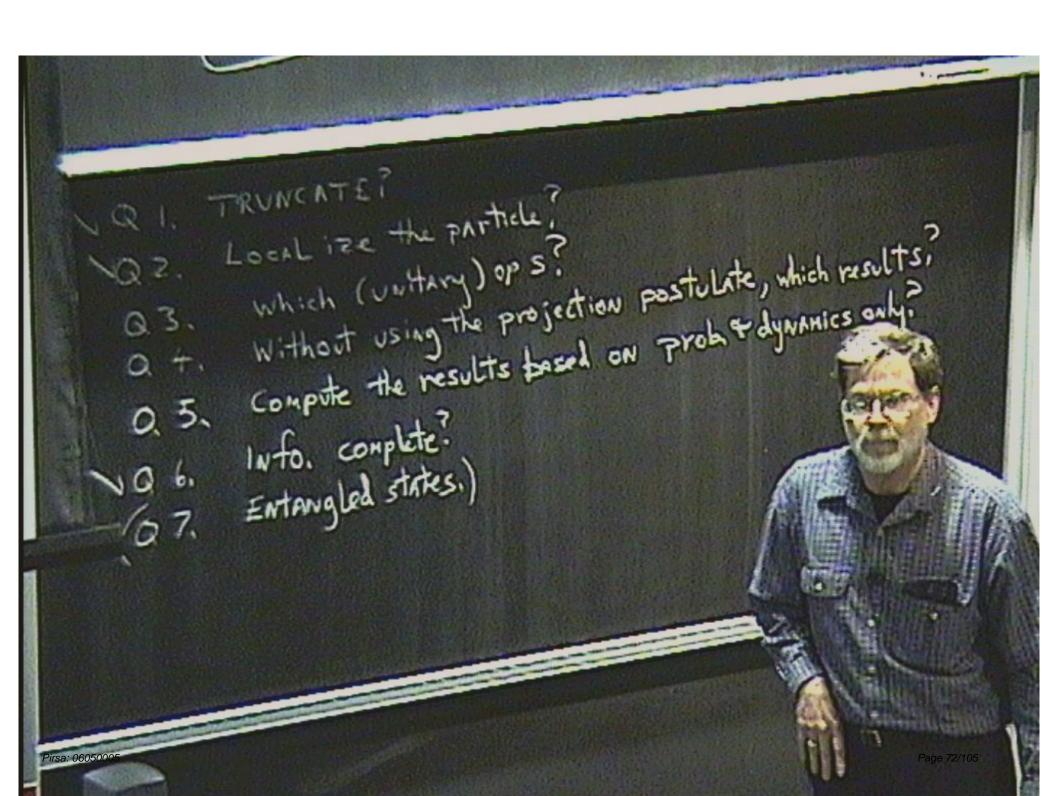
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TRUNCATE LOCAL ize the PArticle, Without using the projection postulate, which results, compute the results based on Prob & dynamics only. 0, 5, INFO. complete?



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To answer questions 3 and 4, we first look at the full phase space (momentum, position, and spin) on which we have some Hamiltonian dynamics. Then we will take the projection of that unitary operator onto the part of phase space being considered, and then take the partial trace to get what we have to discuss for a theory based on just momentum, or just position, or just spin. We

discrete spectrum at all.

page of the space (monomorphic spectrum) on which we have the page of that unitary of the page of the spectrum of the partial trace in the spectrum of the page of the p

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To arswer questions 3 and 4, we the full phase space (momentum, and spin) on which we have some Hamiltonian dynamics. Then we very projection of that unitary operator part of phase space being considered then take the partial trace to get whave toget a unitary dynamics by the have toget a unitary dynamics by the Atternative of the eigenbar obtained from localizing; then trund basis, and then look at the relevance of the experiment by marginality.

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To answer questions 3 and 4, we first look at the full phase space (momentum, position, and spin) on which we have some Hamiltonian dynamics. Then we will take the projection of that unitary operator onto the part of phase space being considered, and then take the partial trace to get what we have to discuss for a theory based on just momentum, or just position, or just spin. We don't get a unitary dynamics by this means.

Alternatively, we may expand the Hamiltonian dynamics in terms of the eigenbasis we obtained from localizing; then truncate the basis; and then look at the relevant variables for the experiment by marginality. Again we won't get a unitary operator.

Page 76/105

How far do the operators we get diverge from the measurement of unitary operators? Well, for the position and momentum, we don't get much divergence in general practically

The spin a sufferent story. You can or record a spin by comparing it with a spin in a known direction. This will lead you to the transition probabilities that describe the thing that gives you the Law of Malus (or its generalization to take care of leakage through crossed polarizers. Here, the importance of quantum mechanics enormous for deviations from alternations and positive operator velocities a positive operator velocities (POVM) rather than a projection assure (PVM).

Page 77/10k

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Page 78/105

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Page 80/105

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a projection value

Page 81/105

Stern-Gerlach devise: If you take the beam of (hound) electrons as collumated (which they

are), then place the sear Gerlach device in the beam, and the beam particles as functions of momentum, position, and spin, you find that the "upper" transmitted beam has a great deal of spin "up" all. It may be as much as 1 in 25 spin (P. Busch and F. Schroeck, Found 19 (1989), 807-872.) Spin is a quantities

is physically not an eigenfunction of projection in this experiment, as you can not allign the direction of measurement of the spin perfectly. We may have an eigenfunction of a positive operator with eigenvalue near but not equal to one, obtained in a manner similar to our formulation of $A^n(\chi_{\Delta t \Delta t})$.

The discussion of beam splitters is similar.
See P. Busch, M. Grabowski, and P. J. Lantii.
Operational Quantum Physics, Springer.
1995, pp. 174 - 177.

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Page 84/10:

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Quantum computing: A CNOT gate:

take a control qubit and a target the control is in state |0>, then the control is in state |10>, then |

But, having a system with only ust an approximation, and the seator you have on that two states system doesn't come from any Hamiltonian dynamics.

You consider the states of the character target as functions of p. q. and s. Hamiltonian as function of P. Q. and S.

Pirsa: 06050005 Page 88/10

Quantum computing: A CNOT gate is

the larget is left alone; if the control is in state |0>, then the larget is left alone; if the control is in state |1>, the target is flipped.

This transition may be described by a unitary operator in H₀. But, having a system with only two states is just an approximation, and the unitary operator you have on that two state system doesn't come from any Hamiltonian dynamical

You consider the states of the communitarget as functions of p, q, and s.

Hamiltonian as function of P, Q, and S.

Pirsa: 06050005

Quantum computing: A CNOT gate is supposed to take a control qubit and a target qubit, and if the control is in state |0>, then the target is left alone; if the control is in state

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You consider the states of the control and/or target as functions of p, q, and s, and the Hamiltonian as function of P, Q, and S.

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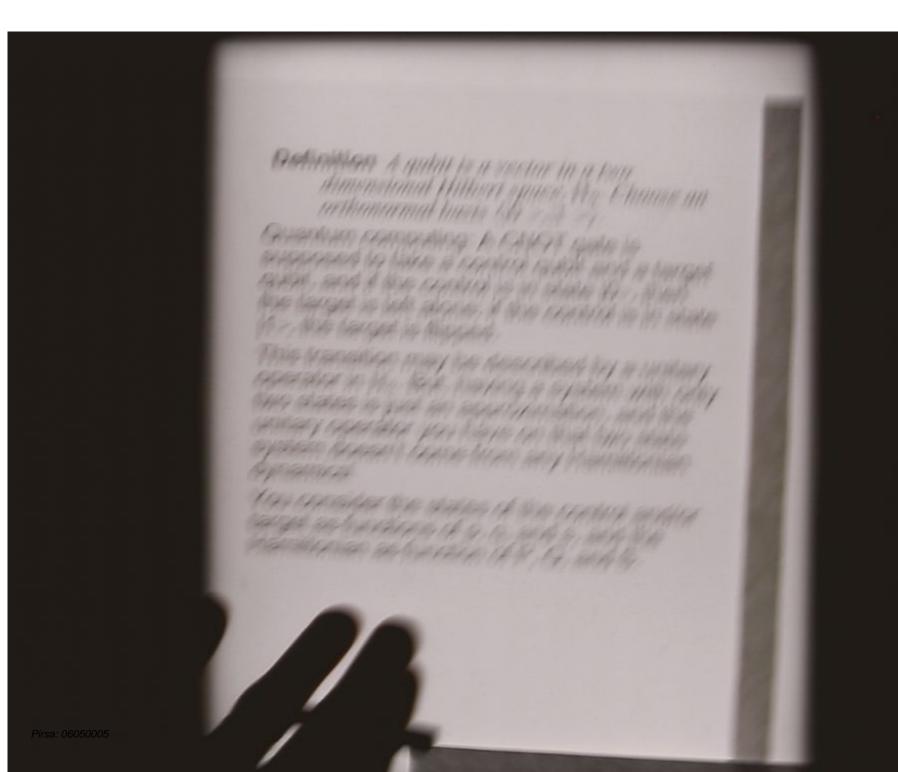
Pirsa: 06050005 Page 92/105

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As states evolve, they undergo wave-function spreading. This is a small spreading in terms

of q, but it will change the direction of p slightly, and thus change the spin which have a drastic effect if the angle of change appreciable. Said another way, as the evolution takes place, the state goes from an eigenvector of localization with makes place a state that is a mixture and action of the state of the state of the state of the actions; you don't expect it to an action of the state of the stat

The banadion is

 $y \rightarrow A^{\alpha}(\chi_{\alpha})y \rightarrow U(\Delta t)A^{\alpha}(\chi_{\alpha})y$

 $\rightarrow A^{\eta}(\chi_{S})U(\Delta t)A^{\eta}(\chi_{\gamma})V$

where $U(\Delta t)$ is the unitary time evolution the set for localizing the particle in the function phase space before the evolution and a for localizing after the evolution, which may be different. Then $M = A^{\eta}(\chi_{\Delta'})U(\Delta t)A^{\eta}(\chi_{\Delta'})$ which is not a unitary operator on the original Hibert space.

It was answers question 4 for this example.

Pirsa: 06050005 Page 95/108

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The transition is

 $= -A^{*}(\chi_{\Delta})\psi + U(\Delta t)A^{*}(\chi_{\Delta})\psi$ $-A^{*}(\chi_{\Delta})U(\Delta t)A^{*}(\chi_{\Delta})\psi$

where $U(\Delta t)$ is the unitary time evolution, Δ is the set for localizing the particle in the full phase space before the evolution and Δ is for localizing after the evolution, which may be different. Then $M_n = A^n(\chi_\Delta)U(\Delta t)A^n(\chi_\Delta)$ which is not a unitary operator on the original Hilbert space.

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 $\psi \mapsto A^{\eta}(\chi_{\Lambda})\psi \mapsto U(\Delta t)A^{\eta}(\chi_{\Lambda})\psi$ $\mapsto A^{\eta}(\chi_{\Lambda})U(\Delta t)A^{\eta}(\chi_{\Lambda})\psi$

where M is the unitary time evolution, Λ is the set to localizing the particle in the full phase space before the evolution and Λ' is for localizing after the evolution, which may be different. Then $M_* = A^\eta(\chi_{\Lambda'})U(\Lambda)M'(\chi_{\Lambda})$ which is not a unitary operator on the original Hilbert space.

This answers question 4 for this example.

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where $U(\Delta t)$ is the unitary time evolution, Δ is the set for localizing the evolution and Δ' is for localizing after the evolution, which may be different. Then $U_{+}=U(\Delta t)A'(x)$ which is not a unitary operator on the original Hilbert space.

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Pirsa: 06050005 Page 99/10

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We have question 5 to contemplate. Take the Stern-Gerlach example, and consider the collumation descibed by $A^{\eta}(\chi_{\Delta})$. Consider placing a hole in the screen around one of the bright spots, and place another Stern Collach device in the direction of fice offer the hole. You have an operator (75) hal describes the hole. You will get $g \rightarrow A^{*}(\chi_{N'})U(\Delta t)A^{*}(\chi_{N'})U(\Delta t)A^{*}(\chi$ lescribe the process. You may then compute me probabilities independent of what we secide to do with the final electrons. All we only record where the electrons he time if impact by recording flashers where they were approximately

Pirsa: 06050005 Page 102/10

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Conclusion

In order to get a truely quantum mechanical theory of measurement we must look a little deeper into the theory of measurement. We may take the previous "results" as just mathematical, and not necessarily physical. For example, we take the unitary operators of time propagation and look at the resultant when we "project" by means of a positive operator. What then will be the analog of Shor's theorem, for example?

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