



Can a Future Choice Affect a Past Measurement's Outcome?

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- In their 1964 paper Aharonov, Bergmann and Lebowitz introduced a time symmetric quantum theory.
- By performing both pre- and postselection ($|\psi(t')\rangle$ and $\langle\Phi(t'')|$ respectively) they were able to form a symmetric formula for the probability of measuring the eigenvalue c_j of the observable c :

$$P(c_j) = \frac{\langle\Phi(t'')|c_j\rangle\langle c_j|\psi(t')\rangle}{\sum_i \langle\Phi(t'')|c_i\rangle\langle c_i|\psi(t')\rangle}$$



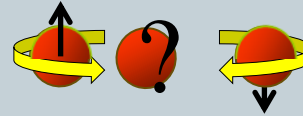
- This idea was later widened to a new formalism of quantum mechanics: the Two-State-Vector Formalism (TSVF).
- The TSVF suggests that in every moment, probabilities are determined by two state vectors which evolved (one from the past and one from the future) towards the present.
- This is a hidden variables theory, in that it completes quantum mechanics, but a very subtle one as we shall see.



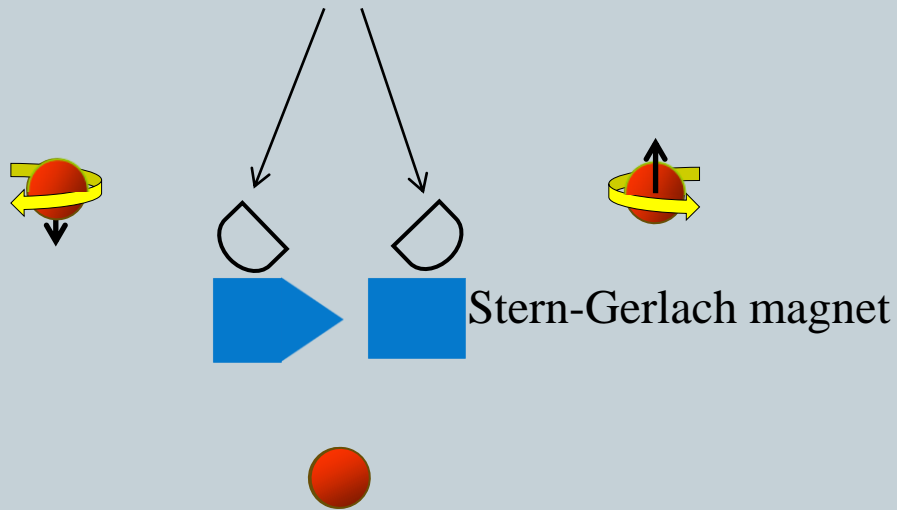
Strong Measurement



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efficient detectors
(very low momentum uncertainty)

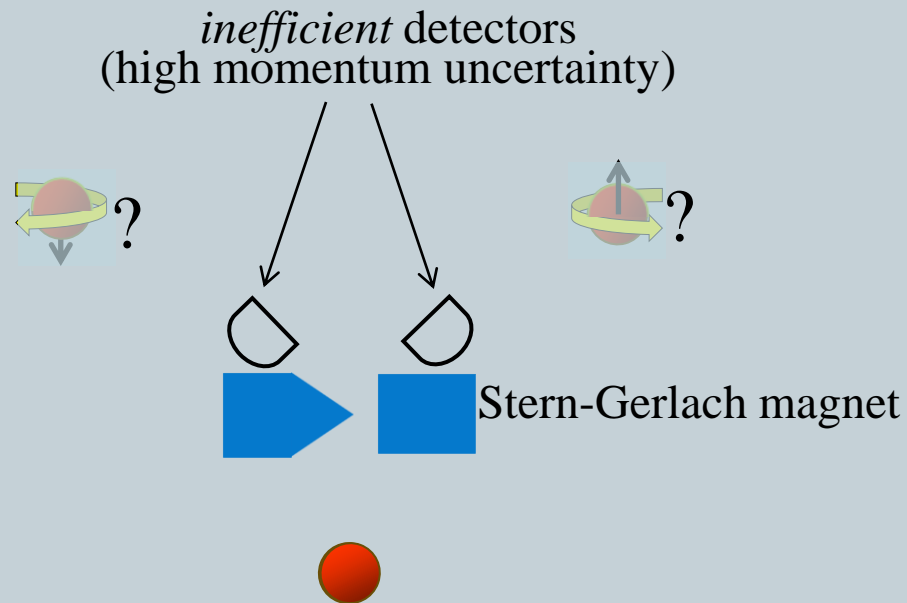




Weak Measurement - I



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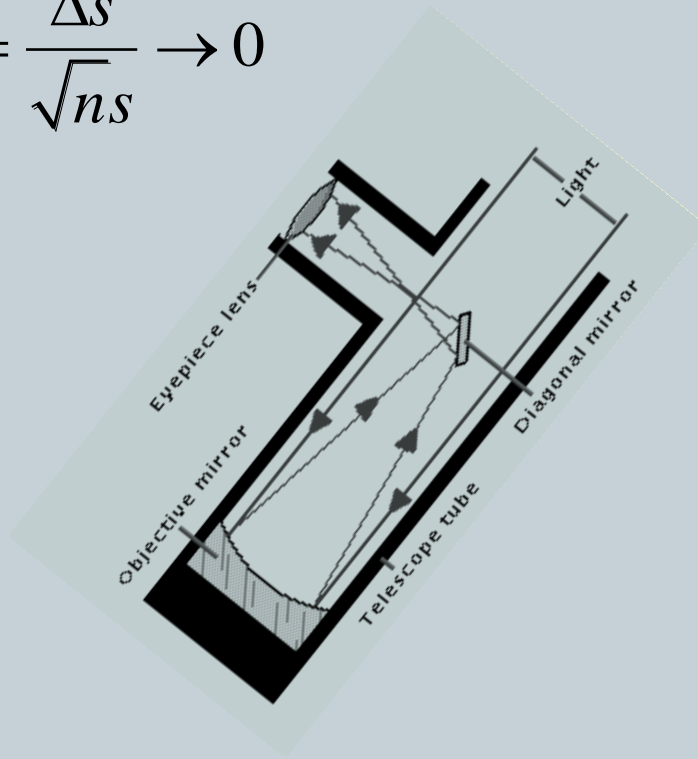


Why Weak Measurement?

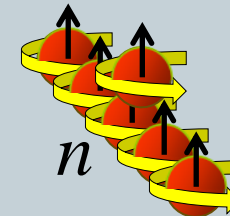
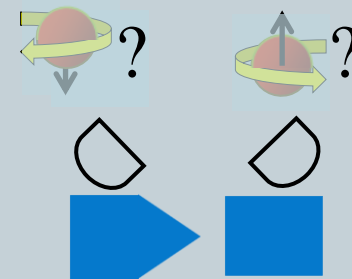


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$$\frac{\Delta s}{s} \Rightarrow \frac{\sqrt{n}\Delta s}{ns} = \frac{\Delta s}{\sqrt{ns}} \rightarrow 0$$



$$[\sigma_i, \sigma_j] = 2i\epsilon_{ijk}\sigma_k$$





Weak Measurement - II

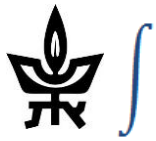


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- The Weak Measurement can be described by the Hamiltonian:

$$H(t) = \frac{\lambda}{\sqrt{N}} g(t) A_s P_d$$

- In order to get blurred results we choose a pointer with zero expectation and $\delta \gg \frac{\lambda}{\sqrt{N}}$ standard deviation.
- In that way, when measuring a single spin we get most results within the wide range $\frac{\lambda}{\sqrt{N}} \pm \delta$, but when summing up the $N/2 \uparrow$ results, most of them appear in the narrow range $\lambda\sqrt{N}/2 \pm \delta\sqrt{N}/\sqrt{2}$ agreeing with the strong results when choosing $\lambda \gg \delta$.



A Classical Experiment with Causality: Coins



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$N/2 = 500,000$

I

1=t 2=h 3=h 4=t 5=h 6=t 7=h 8=h 9=h ... n=t

II



$N/2 = 500,000$



$N/2 = 500,000$

1=h 2=t 3=h 4=t 5=t 6=t 7=h 8=h 9=t ... n=h



$N/2 = 500,000$

Weighing results on evening:
highly accurate, sliced into *I/II*



“head”
or
“tail”?



Flipping results on morning:
inaccurate but **engraved in stone**



$N = 1,000,000$



Bob



$$P(\text{1}) = P(\text{fleur-de-lis})$$



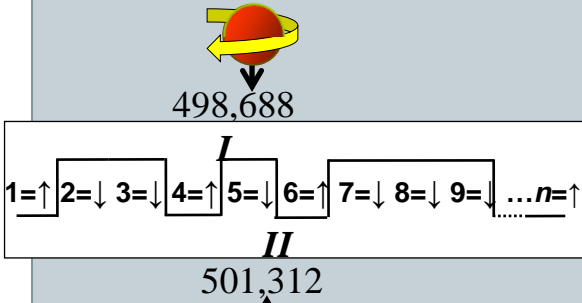
Alice



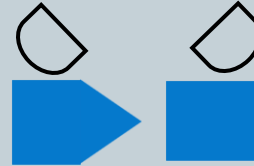
A Quantum Experiment With Causality - Spins



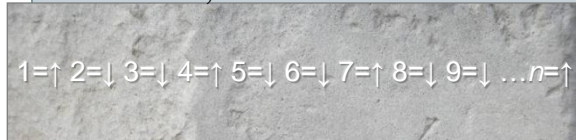
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Strong measurements' results on evening: highly accurate, sliced into I/II



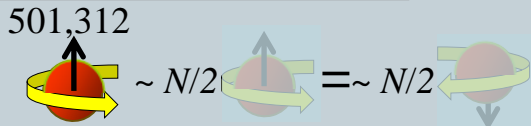
Bob



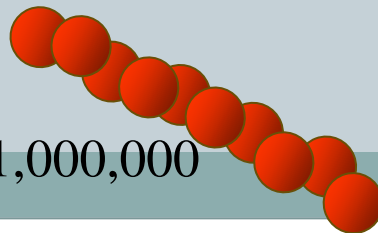
Weak measurements' results on morning: inaccurate but **engraved in stone**



Alice



$N = 1,000,000$



“up”
or
“down”?

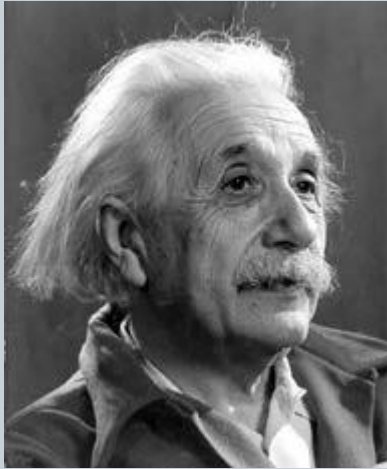




Hidden Variables?



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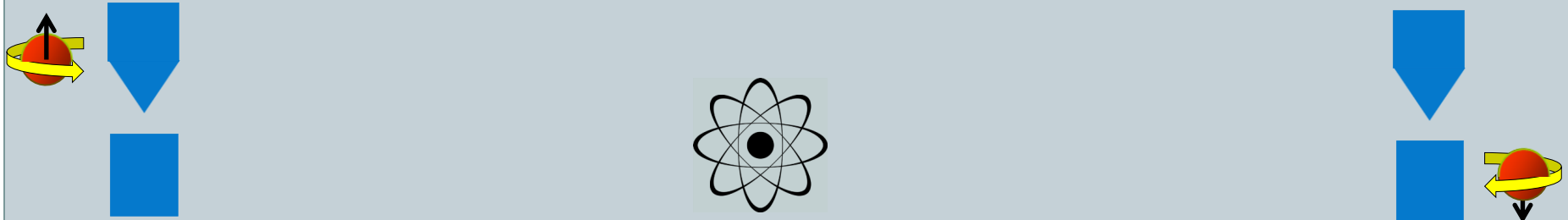
Yes, but of a very subtle kind



The EPR Experiment



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A pre-existing spin, only to be passively *detected*?

or

A superposed state,
to *become definite* upon measurement?

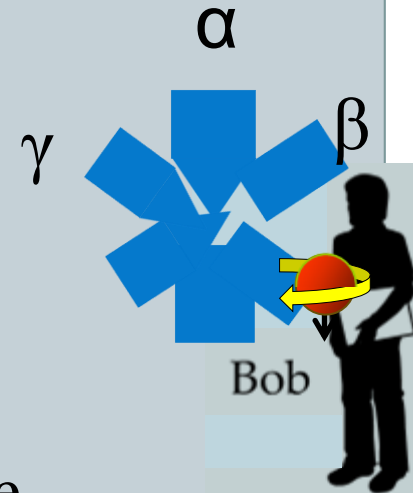
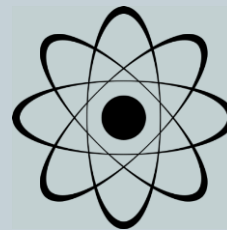
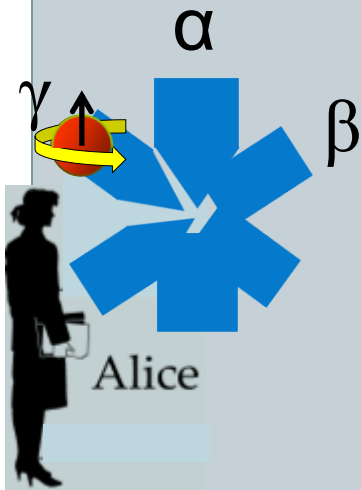


J.S Bell's Proof



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Alice and Bob can freely choose *at the last moment* the spin orientation to be measured.



Correlations or anti-correlations will emerge depending on the *relative angle* between magnets

Conclusion:

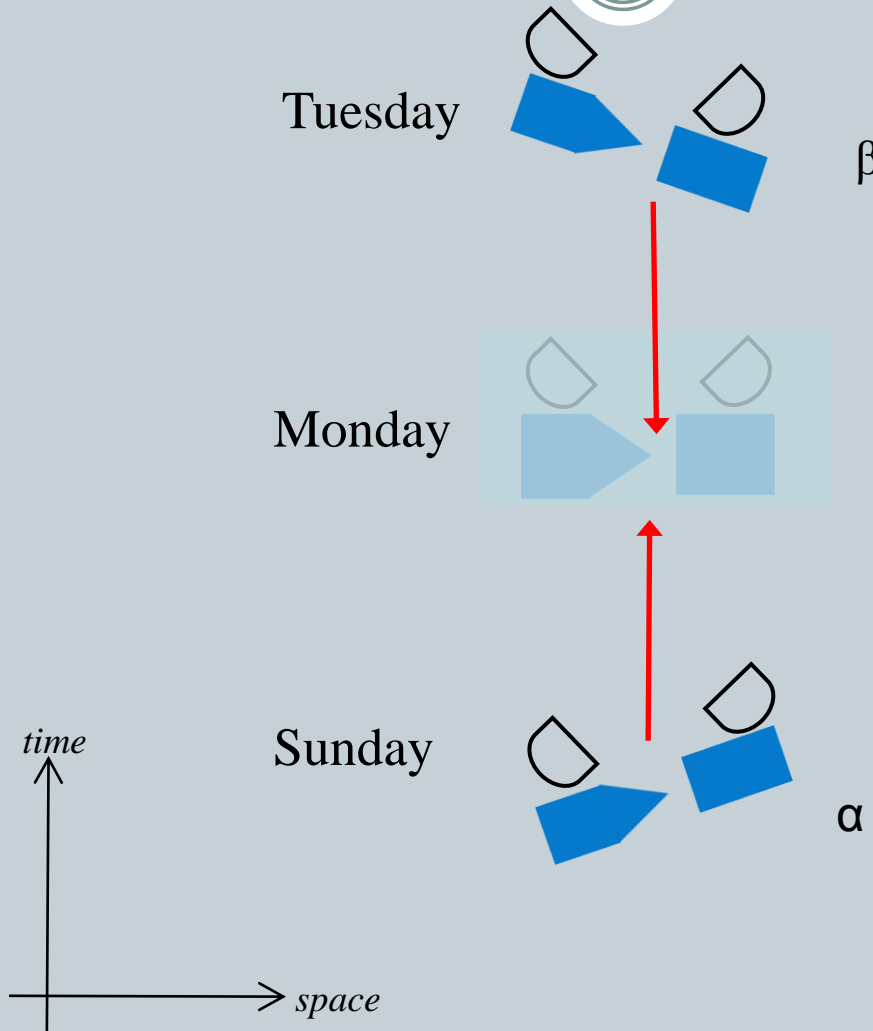
No pre-established spins can exist for every possible pair of choices



The TSVF – New Account Of Time



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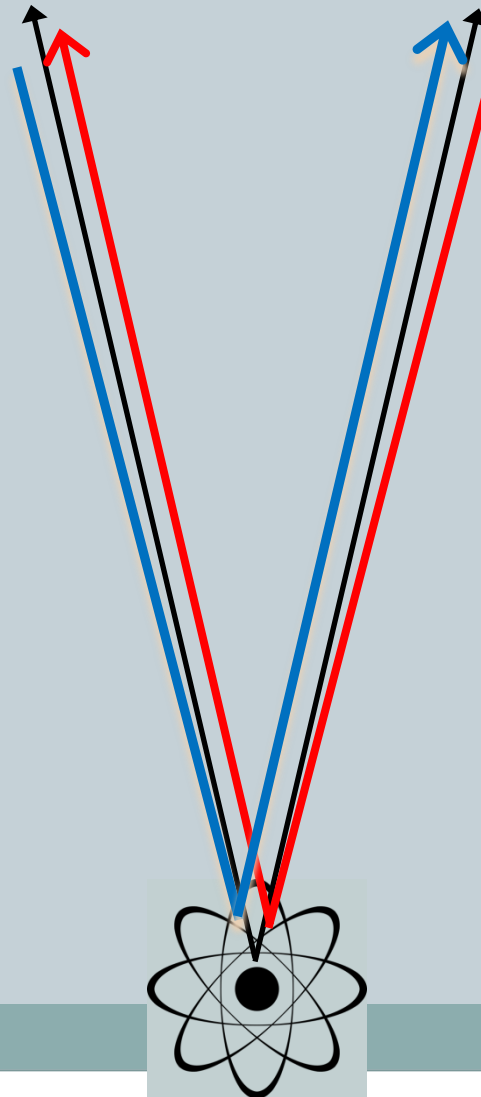
$$[\sigma_i, \sigma_j] = 2i\varepsilon_{ijk} \sigma_k$$



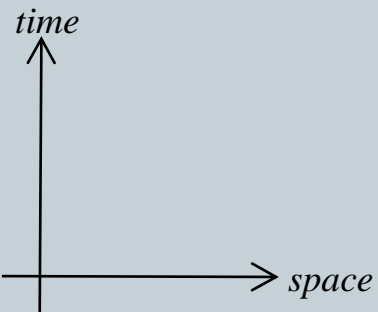
Quantum Experiment with Causality: EPR Pairs



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Non Locality?





∫

A Quantum Experiment with Causality



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γ Last minute choice! β

Evening



Bob

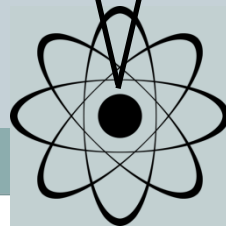
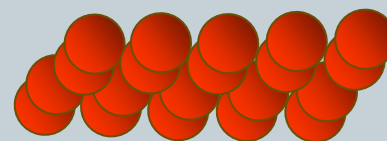
γ 50-50% γ
 α
 β 50-50% β
 α
 β 50-50% β
 α
 γ 50-50% γ
 α

No counterfactuals!

Morning



Alice



time



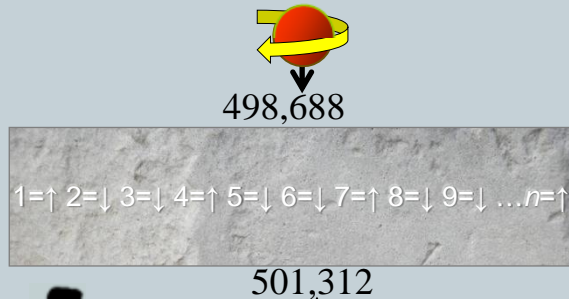
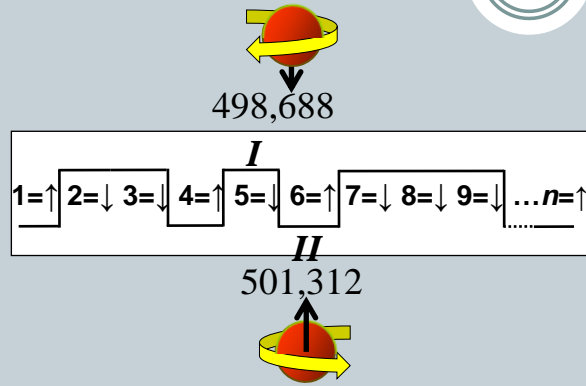
space





A Quantum Experiment with Causality

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The spins “knew” Bob’s **specific** choices and their results but couldn’t tell us!



Control Experiments



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- Time reversing the measurement's order.
- Bob tries to cheat Alice.
- Alice tries to predict Bob's results using her data.
- GHZ experiment.



Interpretation



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- Collapse???
- λ^2 Collapse??
- Subtle Collapse?
- 1-Vector?
- Superdeterminism?

• **TSVF!**

Free-Will



Thank You!





Acknowledgements



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- Prof. Marius Usher
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