Copenhagen Interpretation

Q.T. is about measurement of micro-systems. Apparatus is outside of description.

$|\Psi\rangle_t$ ↔ any possible measurement at t

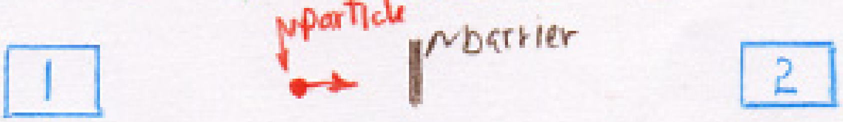
basis ↔ a particular measurement

$|a_n\rangle$ ↔ n^{th} possible measurement outcome

$|\psi(a_n)|^2$ ↔ probability of n^{th} outcome

a_n ↔ value of n^{th} outcome

example:

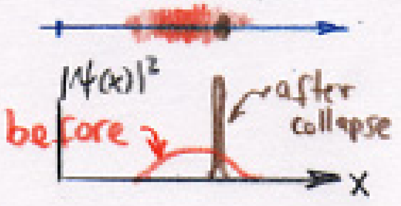


$$|\Psi\rangle_t = \sqrt{.3}\,|\text{particle in } 1\rangle + \sqrt{.7}\,|\text{particle in } 2\rangle$$

Collapse: after measurement, $|\Psi\rangle \rightarrow 1\,|\text{particle in } 1\rangle$

example: position measurement

$$|\Psi\rangle = \sum_x \psi(x)\,|\text{particle at } x\rangle$$



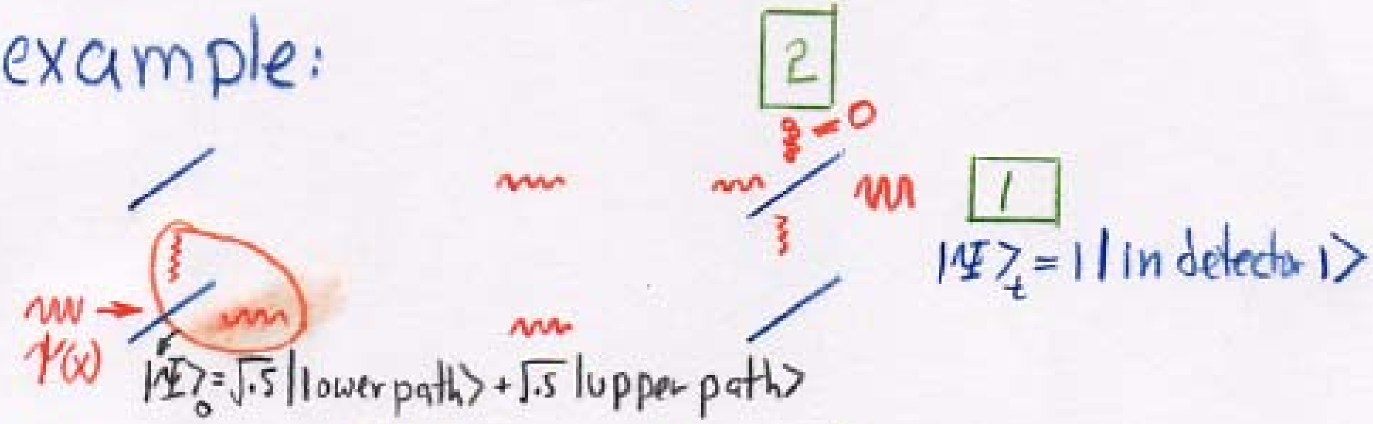
What's wrong: interpretation is ill-defined.

what's a measurement? where is micro/macro split?

when and why collapse?

Quantum ~~Strangeness~~ ~~Weirdness~~ Wonderfulness

example:



$|\Psi\rangle_t = 1|\text{in detector 1}\rangle$

$|\Psi\rangle_0 = \sqrt{.5}|\text{lower path}\rangle + \sqrt{.5}|\text{upper path}\rangle$

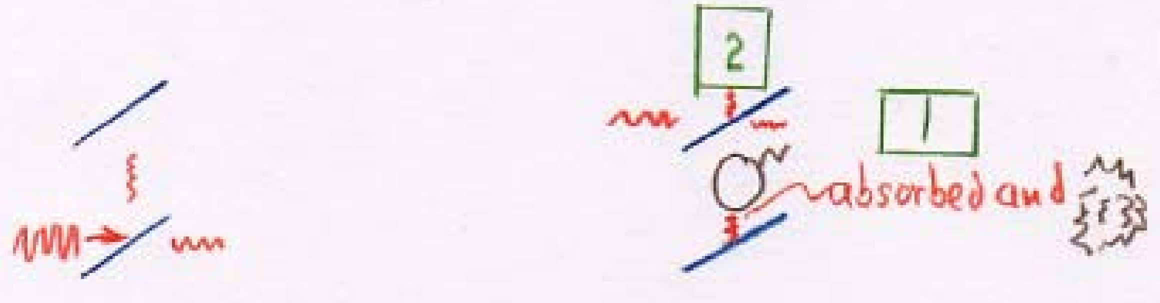
Vaidman-Elitzur Bomb

With certainty, bomb explodes if hit by photon seen

How to tell if bomb is present without :

If bomb not present, detector 1 triggers ↑

If bomb is present:



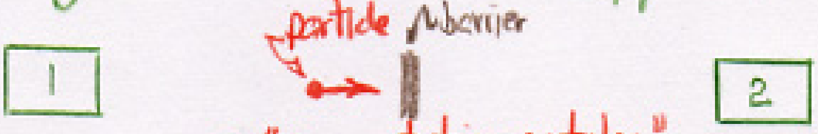
$|\Psi\rangle = \sqrt{.5}\,|\text{bomb explodes}\rangle + \sqrt{.25}\,|\text{photon in 1}\rangle + \sqrt{.25}\,|\text{photon in 2}\rangle$

With probability .25, detector 2 triggers: you then know the bomb is <u>there</u> — unexploded!

Other Interpretations

But first: Schrodinger includes the apparatus

"Entanglement":



"expectation catalog"

$$|\Psi\rangle = \sqrt{.3}\,|\text{particle in1}\rangle|\text{1 triggers}\rangle + \sqrt{.7}\,|\text{particle in2}\rangle|\text{2 triggers}\rangle$$

Einstein's favorite
no collapse

Ensemble Interp: what's the "preferred basis"?

Many-worlds Interp: replace |detector> by |observer> no collapse, all worlds are real

$$|\Psi\rangle = \sum_{\substack{\text{observer}\\ \text{states}}} \psi\,|\text{observer}\rangle|\text{world except observer}\rangle$$

ill-defined: what's an observer?

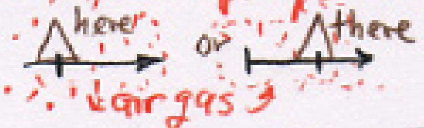
Decoherent histories Interp: replace |observer> by |environment>

each term is a history

$$|\Psi\rangle = \sum_{\substack{\text{environment}\\ \text{states}}} \psi\,|\text{environment}\rangle|\text{world except environment}\rangle$$

these rapidly become orthogonal, form a basis

example:



$$|\psi\rangle_0 = [\sqrt{.3}\,|\text{here}\rangle + .7\,|\text{there}\rangle]\,|\text{env}\rangle$$

$$|\psi\rangle_t = \sqrt{.3}\,|\text{here}\rangle|\text{env } 1\rangle + \sqrt{.7}\,|\text{there}\rangle|\text{env } 2\rangle$$

ill defined: what's an environment?

beyond the theory

None of these interpretations can say without ad hoc information, what are the realizable states of nature, and their probabilities of realization

Dynamical Collapse (CSL)

add a randomly fluctuating term

Change Schrödinger's equation to incorporate collapse

example: $|\Psi_0\rangle = \sqrt{.3}\,|1\rangle + \sqrt{.7}\,|2\rangle \rightarrow$

$|\Psi\rangle_t = |1\rangle$ prob .3

$|\Psi\rangle_t = |2\rangle$ prob .7

Analogy: gambler's ruin game

gambler 1 starts with \$30
gambler 2 starts with \$70

cointoss, etc

gambler 1 wins .3 of games
gambler 2 wins .7 of games

Theory ① $|\Psi\rangle_t = e^{t\,Op(Q.T) - \frac{t}{T} Op(\text{collapse})}\,|\Psi\rangle_0$, ② prob $= {}_t\langle\Psi|\Psi\rangle_t$

$T \approx 10^{16}$ sec $\approx 3 \times 10^{8}$ yr

Op(collapse) depends upon fluctuating field $w(\vec{x},t)$
and upon mass density

example: 

$|\Psi\rangle_0 = \sqrt{.3}\,|\text{here}\rangle + \sqrt{.7}\,|\text{there}\rangle \rightarrow$

$|\text{here}\rangle$ prob .3

$|\text{there}\rangle$ prob .7

time $\frac{T}{N^2}$

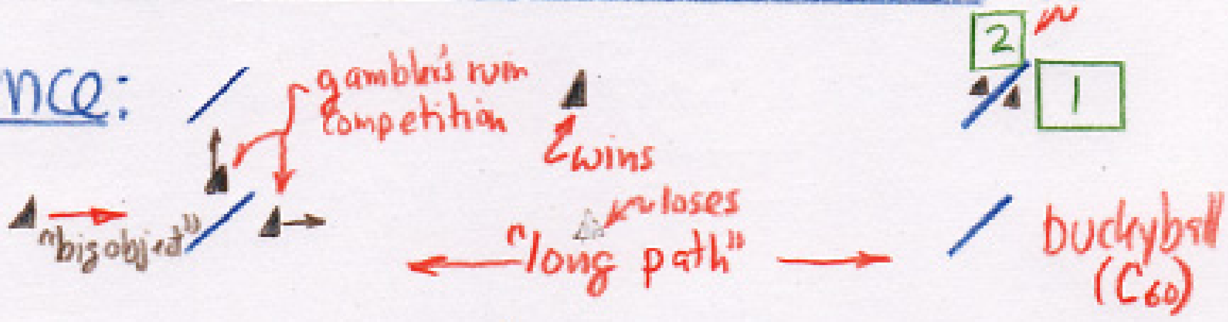
N = number of nucleons

micro-system barely affected
macro-system collapses rapidly

Interpretation: any $w(\vec{x},t) \rightarrow |\Psi\rangle_t$ is a realizable state, its probability is ${}_t\langle\Psi|\Psi\rangle_t$.

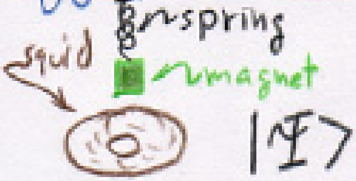
Experimental tests of CSL

Interference:



Legget's SQUID test:

$|\Psi\rangle = \sqrt{.5}\,|\circlearrowleft\rangle + \sqrt{.5}\,|\circlearrowright\rangle$



$|\Phi\rangle = \sqrt{.5}\,|\circlearrowright\rangle|\text{magnet}\uparrow\rangle + \sqrt{.5}\,|\circlearrowleft\rangle|\text{magnet}\downarrow\rangle \rightarrow |\circlearrowright\rangle|\text{magnet}\uparrow\rangle$

or $\rightarrow |\circlearrowleft\rangle|\text{magnet}\downarrow\rangle$

Atomic Excitation: electron knocked out of Ge?

Nucleer Excitation: deuterium Ⓟ Ⓝ knocked apart?

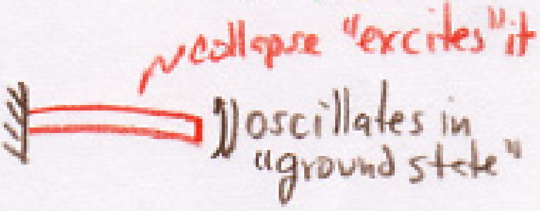
result: not seen $\Rightarrow \frac{1}{\sqrt{T}} \sim m$, collapse time depends on mass

Anomalous radiation: $w(\vec{x},t)$ shakes electrons which radiate

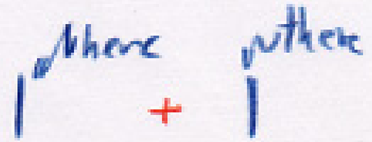
result: not seen $\Rightarrow T > 10^{11}$ sec

Random walk: a small sphere will jiggle

Cantilever excitation:



Penrose's superposition of a mirror:



We have to find a new view of the world that has to agree with everything that is known, but disagree in its predictions somewhere, otherwise it is not interesting. And in that disagreement it must agree with nature. If you can find any other view of the world which agrees over the entire range where things have already been observed, but disagrees somewhere else, you have made a great discovery. It is very nearly impossible, but not quite, to find any theory which agrees with experiments over the entire range in which all theories have been checked, and yet gives different consequences in some other range, even a theory whose different consequences do not turn out to agree with nature.

Richard Feynman, 1965