COLLAPSE MODELS

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- QUANTUM MEASUREMENT PROBLEM
- WHY NOT SOLVED BY DECOHERENCE
- EFFECTIVE THEORIES AND REQUIREMENTS FOR A COLLAPSE MODEL
- CONTINUOUS SPONTANEOUS LOCALIZATION (CSL) MODEL AND VARIANTS
- UNIQUENESS OF GENERAL FORM

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- CONSTRAINTS ON NOISE - MASS PROPORTIONAL COUPLINGS
- PHYSICAL ORIGIN OF THE NOISE - COMPLEX NUMBER FLUCTUATIONS IN $g_{\mu\nu}$?
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QUANTUM MEASUREMENT PROBLEM

TWO STATE SYSTEM $\mathcal{S}$ IN INITIAL STATE

$$|\psi_0\rangle_S = \alpha|\psi^{(A)}\rangle_S + \beta|\psi^{(B)}\rangle_S$$

INITIAL APPARATUS STATE $|\phi_0\rangle_{APP}$

INITIAL ENVIRONMENT STATE $|\phi_0\rangle_{ENV}$

EVERYTHING IN A SPHERE OF RADIUS $> cT_{MEAS}$

INITIAL STATE FOR MEASUREMENT PROCESS IS

$$|\Phi_0\rangle = |\psi_0\rangle_S\,|\phi_0\rangle_{APP}\,|\phi_0\rangle_{ENV}$$

EVOLVE WITH UNITARY EVOLUTION $e^{-iHt} = U$

FOR A WELL-DESIGNED APPARATUS EVOLVES TO

$$|\Phi(t)\rangle = \alpha\,|\psi^{(A)}\rangle_S\,|\phi^{(A)}(t)\rangle_{APP+ENV} + \beta\,|\psi^{(B)}\rangle_S\,|\phi^{(B)}(t)\rangle_{APP+ENV}$$

- SUPERPOSITION OF A AND B
- WHAT IS OBSERVED IS

$$|\psi^{(A)}\rangle_S\,|\phi^{(A)}\rangle_{APP+ENV} \quad \text{OR} \quad \text{ORTHOGONAL OUTCOMES}$$

$$|\psi^{(B)}\rangle_S\,|\phi^{(B)}\rangle_{APP+ENV}$$

- MEASUREMENT PROBLEM: HOW TO GET DEFINITE OUTCOMES SINCE

$$|A\rangle = U|0\rangle, \quad |B\rangle = U|0\rangle \Rightarrow \langle A|B\rangle = \langle 0|U^\dagger U|0\rangle = 1$$

NOT RESOLVED BY DECOHERENCE

THIS IMPLIES

$$_{APP+ENV}\langle \phi^{(A)}(t) | \phi^{(B)}(t) \rangle_{APP+ENV}$$

$$\simeq {}_{APP}\langle \phi^{(A)}(t) | \phi^{(B)}(t) \rangle_{APP} \prod_{i \atop ENV} {}_{ENV}\langle \phi_0 | S^{+}_{i(A)} S_{i(B)} | \phi_0 \rangle_{ENV}$$

$$\simeq C e^{-\Gamma t} \to 0$$

- STILL HAVE SUPERPOSITION A <u>AND</u> B

  NOT A <u>OR</u> B

- HISTORY OF PHYSICS SUGGESTS: PARADOXES RESOLVED BY <u>NEW PHYSICS</u>

EFFECTIVE THEORY FOR COLLAPSE

REQUIREMENTS:

- EXPRESSED IN STANDARD QM FRAMEWORK OF OPERATORS + STATE VECTORS IN HILBERT SPACE
- NEED NON-UNITARY, NON-LINEAR TIME EVOLUTION
- STATE VECTOR NORM PRESERVED
- NO FASTER THAN LIGHT SIGNALING
- SUPERPOSITIONS A AND B MAINTAINED FOR SMALL SYSTEMS

- DEFINITE OUTCOMES A OR B

  FOR SYSTEM + LARGE ENOUGH APPARATUS

- BORN RULE EXPLAINED, NOT POSTULATED

REMARKABLY, A CLASS OF EFFECTIVE THEORIES OBEYING THESE REQUIREMENTS EXISTS:

GRWP GHIRARDI RIMINI WEBER PEARLE

"OBJECTIVE REDUCTION MODELS"

CSL "CONTINUOUS SPONTANEOUS LOCALIZATION"

STOCHASTIC MODIFIED SCHRÖDINGER EQUATION - SIMPLE CASE FOR POINTER WITH CENTER OF MASS VARIABLE q

(LEADING SMALL DISPLACEMENT APPROXIMATION TO THE GRW AND CSL MODELS)

$$d|\psi\rangle = \frac{-i}{\hbar} H|\psi\rangle\, dt - \frac{\eta}{2}(q - \langle q\rangle)^2|\psi\rangle\, dt + \sqrt{\eta}\,(q - \langle q\rangle)\,|\psi\rangle\, dW_t$$

HERE: dt = TIME STEP

dW_t = FLUCTUATION $\sim (dt)^{1/2}$

$$\left.\begin{aligned} (dW_t)^2 &= dt \\ dW_t\, dt &= (dt)^2 = 0 \end{aligned}\right\}\ \text{ITÔ CALCULUS RULES}$$

$\langle q\rangle = \langle\psi|\, q\,|\psi\rangle$ EXPECTATION VALUE OF q IN STATE $|\psi\rangle$

BECAUSE $|\psi\rangle$ APPEARS IN $\langle q\rangle$, THIS IS A <u>NONLINEAR</u> STOCHASTIC DIFFERENTIAL EQUATION

MULTIPLYING THROUGH BY $i\hbar$,

$$i\hbar\, d|\psi\rangle = H|\psi\rangle\, dt + \cdots + \underbrace{i\hbar\sqrt{\eta}\,(q - \langle q\rangle)\,|\psi\rangle\, dW_t}_{\text{ANTI-SELF-ADJOINT}}$$

THE DETAILED STRUCTURE OF THIS EQUATION IS FIXED BY 2 REQUIREMENTS:

(1) STATE VECTOR NORMALIZATION

$$d\langle\psi|\psi\rangle = 0$$

(2) NO SUPERLUMINAL COMMUNICATION

DENSITY MATRIX $\hat{\rho} = |\psi\rangle\langle\psi|$ OBEYS

$$d\hat{\rho} = -\frac{i}{\hbar}[H, \hat{\rho}]\, dt - \frac{1}{2}\eta\,[q,[q,\hat{\rho}]]\, dt + \sqrt{\eta}\,[\hat{\rho},[\hat{\rho},q]]\, dW_t$$

ONLY NONLINEARITY IS STOCHASTIC TERM

$\Rightarrow$ STOCHASTIC EXPECTATION $\rho = E[\hat{\rho}]$ OBEYS A LINEAR EQUATION, SO SEQUENCES OF MEASUREMENTS CANNOT SEND / RECEIVE SUPERLUMINAL SIGNALS

BORN RULE

CAN NOW PROVE: WHEN THE $-\frac{i}{\hbar}[H,\rho]\,dt$ $\left(-\frac{i}{\hbar}H|\psi\rangle\,dt\right)$ TERM IS UNIMPORTANT (WHEN REDUCTION IS VERY FAST, OR WHEN THE DIFFERENT POINTER STATES ARE DEGENERATE IN ENERGY) THIS EQUATION IMPLIES THE BORN RULE!

THAT IS, DIFFERENT EVOLUTIONS OF THE STOCHASTIC PROCESS GIVE OUTCOMES $|q_\ell\rangle$ WITH PROBABILITY $|\langle\psi(0)|q_\ell\rangle|^2$

SO THE STOCHASTIC SCHRÖDINGER EQUATION GIVES A CONSISTENT EFFECTIVE THEORY FOR STATE VECTOR REDUCTION – THIS IS A REMARKABLE RESULT: SUCH AN EFFECTIVE THEORY DID NOT HAVE TO EXIST!

GAMBLER'S RUIN

ALICE HAS N_A PENNIES
BOB HAS N_B PENNIES

FLIP A COIN

HEADS ALICE GIVES BOB A PENNY
TAILS BOB GIVES ALICE A PENNY

CONTINUE UNTIL ONE PLAYER HAS $N_A + N_B$
OTHER PLAYER HAS 0 (RUIN)

- PROBABILITY ALICE WINS $= \dfrac{N_A}{N_A + N_B}$

- PROBABILITY BOB WINS $= \dfrac{N_B}{N_A + N_B}$

- QM APPLICATION: $N_A \rightarrow |\langle \psi(0) | \psi_A \rangle|^2 \quad N_B \rightarrow |\langle \psi(0) | \psi_B \rangle|^2$

PHENOMENOLOGY CONTINUOUS SPONTANEOUS LOCALIZATION MODEL

GIVEN A MODEL FOR MODIFIED SCHRÖDINGER EQUATION, ONE CAN TRY TO BOUND ITS PARAMETERS. IN FULL CSL MODEL, PARAMETERS AS FOLLOWS:

$$d|\psi(t)\rangle = \left[-\frac{i}{\hbar} H dt + \int d^3x \left(M(x) - \langle M(x)\rangle \right) dB(x) - \frac{\gamma}{2} \int d^3x \left(M(x) - \langle M(x)\rangle \right)^2 dt \right] |\psi(t)\rangle$$

- $dB(x)$ BROWNIAN MOTION OBEYING

$$dt \, dB(x) = 0 \qquad dB(x) \, dB(y) = \gamma \, \delta^3(x-y) \, dt$$

- $\langle M \rangle$ IS EXPECTATION OF M IN STATE $|\psi(t)\rangle$

- $M(x)$ IS SMEARED MASS DENSITY OPERATOR

$$M(x) = m_N^{-1} \int d^3y \; g(x-y) \sum_s \underset{\text{MASS}}{m_s} \; \underset{\text{NUMBER DENSITY OPERATOR}}{N_s(y)}$$

$$g(x) = \left(\frac{\alpha}{2\pi}\right)^{3/2} e^{-(\alpha/2)x^2} \qquad \int d^3x \; g(x) = 1$$

TWO PARAMETERS

CONVENTIONAL VALUES

NOISE STRENGTH γ — $\gamma \simeq 10^{-30}\ cm^3\ s^{-1}$

CORRELATION LENGTH r_c (OR a) — $r_c \simeq 10^{-5}\ cm$

OFTEN CONVENIENT TO REPLACE γ BY RATE PARAMETER λ

$$\lambda = \gamma \left(\frac{\alpha}{4\pi}\right)^{3/2} = \frac{\gamma}{8\pi^{3/2} r_c^3}$$

CONVENTIONAL VALUE

$\lambda_c \simeq 2.2 \times 10^{-17}\ s^{-1}$

LOWER BOUND - REDUCTION MUST OCCUR IN MEASUREMENT

$$\Gamma_R \simeq \lambda n^2 N$$

n = NUMBER OF NUCLEONS WITHIN RADIUS r_c THAT MOVE BY MORE THAN r_c

N = NUMBER OF SUCH GROUPS OF n NUCLEONS

EXAMPLE: POINTER WITH 10^{15} ATOMS

$$(10^{-5}\ cm)^3 \cdot 10^{24}/cm^3 = 10^9 = n$$

$$10^{15}/10^9 = 10^6 = N$$

$$\Gamma_R \sim 2.2 \cdot 10^{-17}\ s^{-1} \times 10^{18} \times 10^6 = 2.2 \cdot 10^7\ s^{-1} \Rightarrow$$ REDUCTION IN $10^{-7}\ s$

REASON FOR MASS-PROPORTIONAL COUPLING

$$F = MA$$

IF $F \propto M$, A IS M-INDEPENDENT

⇒ FOR A BOUND SYSTEM, TO LEADING ORDER NOISE COUPLES TO CENTER OF MASS, BUT NOT INTERNAL EXCITATIONS

PROTON IS A BOUND SYSTEM OF QUARKS + GLUONS VERY STABLE

→ CSL COUPLING MUST BE MASS-PROPORTIONAL TO AVOID RAPID PROTON DECAY

GRAVITATIONAL ORIGIN OF MASS-COUPLED NOISE ?

CLASSICAL METRIC $g_{\mu\nu} = \bar{g}_{\mu\nu} + \phi_{\mu\nu}$

LINE ELEMENT $(ds)^2 = \bar{g}_{\mu\nu}\, dx^\mu\, dx^\nu$

$\phi_{\mu\nu}$ COMPLEX NUMBER FLUCTUATION TERM

WITH EXPECTATIONS $\mathcal{E}$

$$\mathcal{E}[\phi_{\mu\nu}] = 0$$

$$\mathcal{E}[\phi_{\mu\nu}(\vec{x},t_1)\,\phi^*_{\lambda\sigma}(\vec{y},t_2)] = D_{\mu\nu\lambda\sigma}(\vec{x}-\vec{y},\, t_1-t_2)$$

$$\mathcal{E}[\phi_{\mu\nu}(\vec{x},t_1)\,\phi_{\lambda\sigma}(\vec{y},t_2)] = U_{\mu\nu\lambda\sigma}(\vec{x}-\vec{y},\, t_1-t_2)$$

VARIATION OF MATTER INTERACTION ACTION K

$$\delta S_{int} = -\frac{1}{2}\int d^4x\,\sqrt{g}\,T^{\mu\nu}\phi_{\mu\nu} \Rightarrow \delta H_{int} = \frac{1}{2}\int d^3x\,\sqrt{g}\,T^{\mu\nu}\phi_{\mu\nu}$$

GRAVITATIONAL ORIGIN ...

FOR NON-RELATIVISTIC MATTER, DOMINANT TERM IS

$$\delta H_{int} = \frac{1}{2}\int d^3x \sqrt{g}\, T^{00}(\vec{x},t)\, \phi_{00}(\vec{x},t)$$

$$\mathcal{E}\left[\phi_{00}(\vec{x},t_1)\,\phi^*_{00}(\vec{y},t_2)\right] = D_{0000}(\vec{x}-\vec{y}, t_1-t_2)$$

$$\mathcal{E}\left[\phi_{00}(\vec{x},t_1)\,\phi_{00}(\vec{y},t_2)\right] = U_{0000}(\vec{x}-\vec{y}, t_1-t_2)$$

GIVES THE ANTI-SELF-ADJOINT HAMILTONIAN TERM NEEDED FOR COLLAPSE MODEL

HOW BIG IS THE NOISE STRENGTH λ ?

UPPER BOUNDS

- SECULAR ENERGY GAIN OF BODY OF MASS M — IGM HEATING

$$\frac{dE}{dt} = \frac{3}{4}\lambda \frac{\hbar^2}{r_c^2} \frac{M}{m_N^2}$$

- FULLERENE DIFFRACTION
- DECAY OF SUPERCURRENTS
- EXCITATION OF BOUND ATOMIC AND NUCLEAR SYSTEMS
- RADIATION BY FREE OR ATOMIC ELECTRONS

ENHANCED LOWER BOUND ?

MOTT: α EMITTER IN EMULSION

SPHERICAL WAVE $\frac{e^{ikr}}{r}$

TRACK PICKS ONE COMPONENT FROM SUPERPOSITION IN SPHERICAL WAVE

LATENT IMAGE FORMATION IN
PHOTOGRAPHIC EMULSIONS
ETCHED TRACK DETECTORS

FEW ATOMS MOVE ON CONVENTIONAL MODELS OF THESE PROCESSES

IF LATENT IMAGE FORMATION (AND NOT SUBSEQUENT DEVELOPMENT, ETCHING, ETC) CONSTITUTES MEASUREMENT, NEED $\lambda \sim 10^{9\pm2}$ TIMES "CONVENTIONAL" VALUE λ_c. IGM HEATING REQUIRES $\lambda \lesssim 10^{8\pm1}\lambda_c$

EXPERIMENTAL STATUS

SPONTANEOUS X-RAY EMISSION FROM GERMANIUM

IGEX (Ge DETECTORS - DOUBLE β DECAY
WIMP SEARCHES)

BOUNDS ON X-RAY EMISSION $\rightarrow$

$\lambda \leq 6.8 \cdot 10^{-12}\ s^{-1}$ MASS-PROPORTIONAL

$\lambda \leq 2.0 \cdot 10^{-18}\ s^{-1}$ NON- " " "

SO ENHANCED λ RULED OUT FOR

WHITE NOISE WITH 14.5 TO 48.5 keV

SPECTRAL COMPONENTS;

NON-WHITE NOISE WITH $E_{max} \ll$ keV ALLOWED

EXPERIMENT - LARGE MOLECULE DIFFRACTION

GRATING 10^{-5} cm $\sim r_c = 10^{-7}$ m (recall $\lambda_c = 2.2 \cdot 10^{-17} s^{-1}$)

MEASUREMENT TIME 10^{-2} s $\Rightarrow$ NEED $\Gamma_R \sim 10^{2} s^{-1}$

$$\Gamma_R = \lambda n^2$$

FOR $\lambda = \lambda_c$ NEED $n \sim 2 \times 10^9$

FOR $\lambda = 2 \times 10^7 \lambda_c$ NEED $n \sim 5 \times 10^5$ = 500 x MASS OF FULLERENE

ACHIEVED SO FAR

C284.H190.F320.N4.S12
PERFLUOROALKYL CHAIN

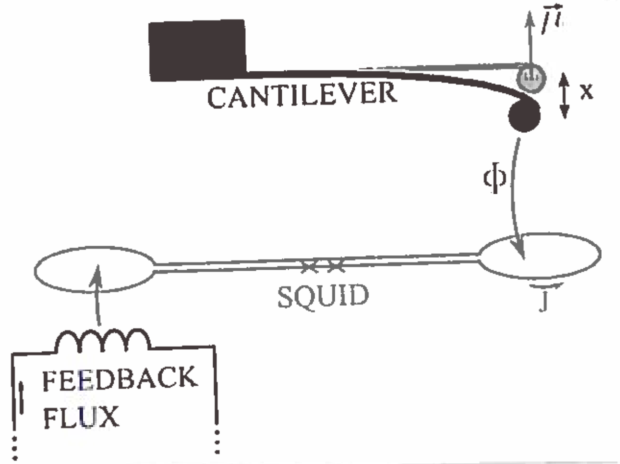
$n \sim 10^4$

NEED 1 TO 2 ORDERS OF MAGNITUDE MORE

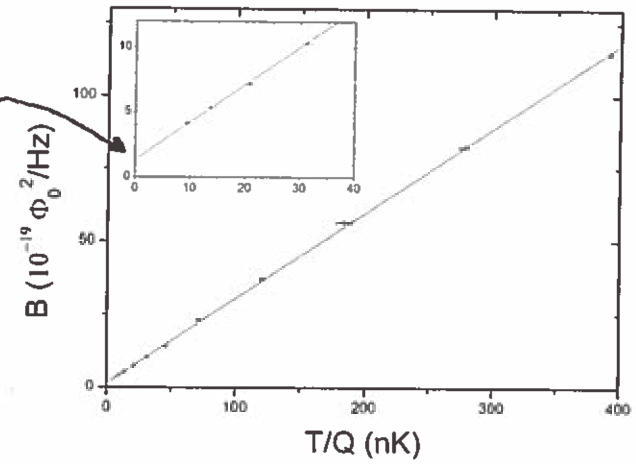
CANTILEVER EXPERIMENT - VINANTE ET AL

CANTILEVER WITH FERROMAGNETIC BEAD MONITORED BY SQUID AT MILLIKELVIN TEMPERATURES

SETUP:



PLOT OF NOISE FROM LORENTZIAN FIT VERSUS TEMPERATURE HAS A NONZERO INTERCEPT



IF THE EXCESS NOISE WERE DUE TO CSL,

WOULD CORRESPOND TO $\lambda = 10^{-7.7}\, s^{-1}$ (for $r_c = 10^{-7}$ m)

$$= 10^{9} \lambda_c$$

COMPATIBLE WITH ENHANCED λ VALUE

THERMAL EFFECTS

CRYOGENIC EXPERIMENTS AND EARTH HEATING

BOTH IMPLY $\lambda_{eff} \lesssim 10^{-11}\ s^{-1}$

SO IF VINANTE ET AL. EXCESS NOISE IS CSL NOISE,

NOISE MUST BE NON-WHITE

FOR NON-WHITE NOISE WITH POWER SPECTRUM $\lambda(\omega)$

HEATING A SOLID BY PHONON EXCITATION

$$\frac{dE}{dt\,dM} = \frac{3}{4}\lambda_{eff}\frac{\hbar^2}{r_C^2}\frac{1}{m_N^2}$$

$$\lambda_{eff} = \frac{2}{3\pi^{3/2}}\int d^3w\, e^{-\vec{w}^2}\,\vec{w}^2\,\lambda(\omega_L(\vec{w}/r_C))$$

$\omega_L(\vec{q})$ IS LONGITUDINAL ACOUSTIC PHONON FREQUENCY

AT WAVE NUMBER $\vec{q}$

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