Interaction-free measurement for a macroscopic quantum system under decoherence

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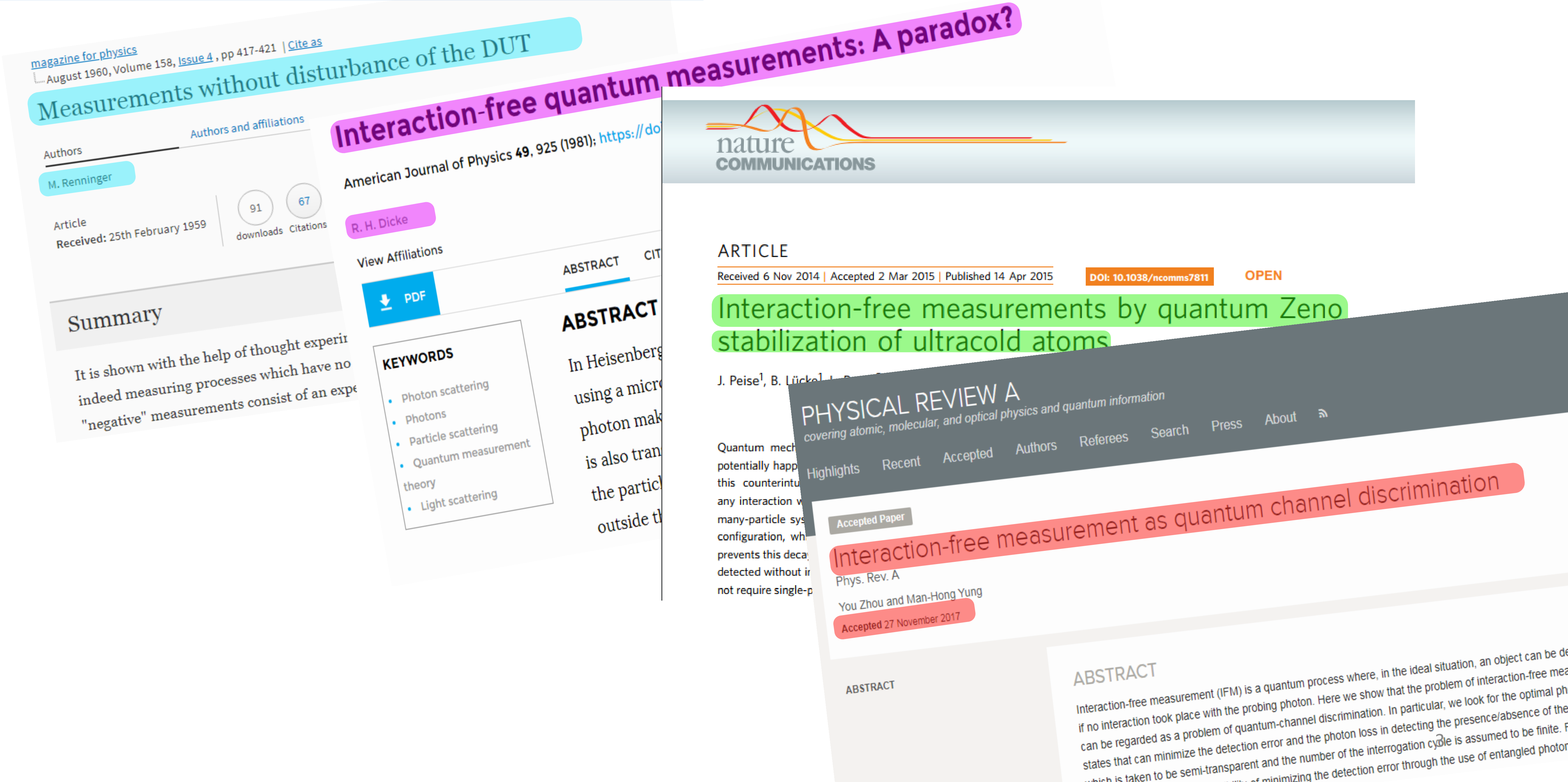
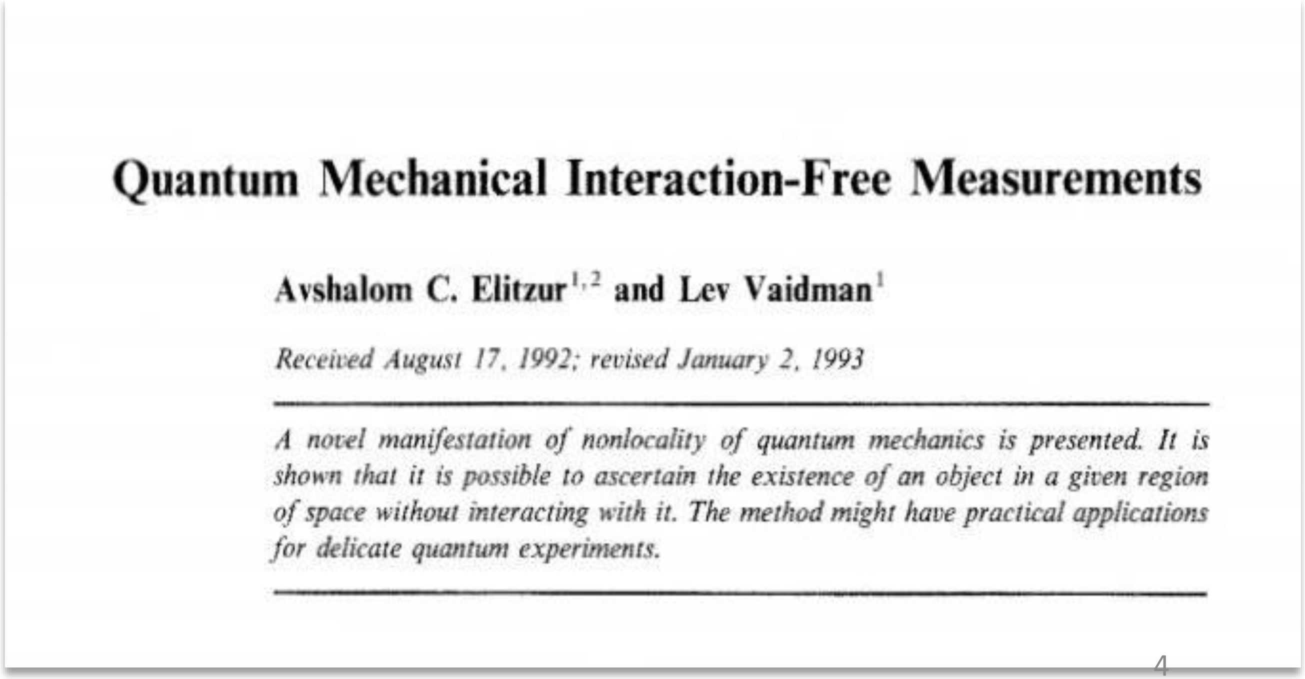
Interaction-free measurement



Interaction-free measurement



Quantum Mechanical Interaction-Free Measurements

Avshalom C. Elitzur[1,2] and Lev Vaidman[1]

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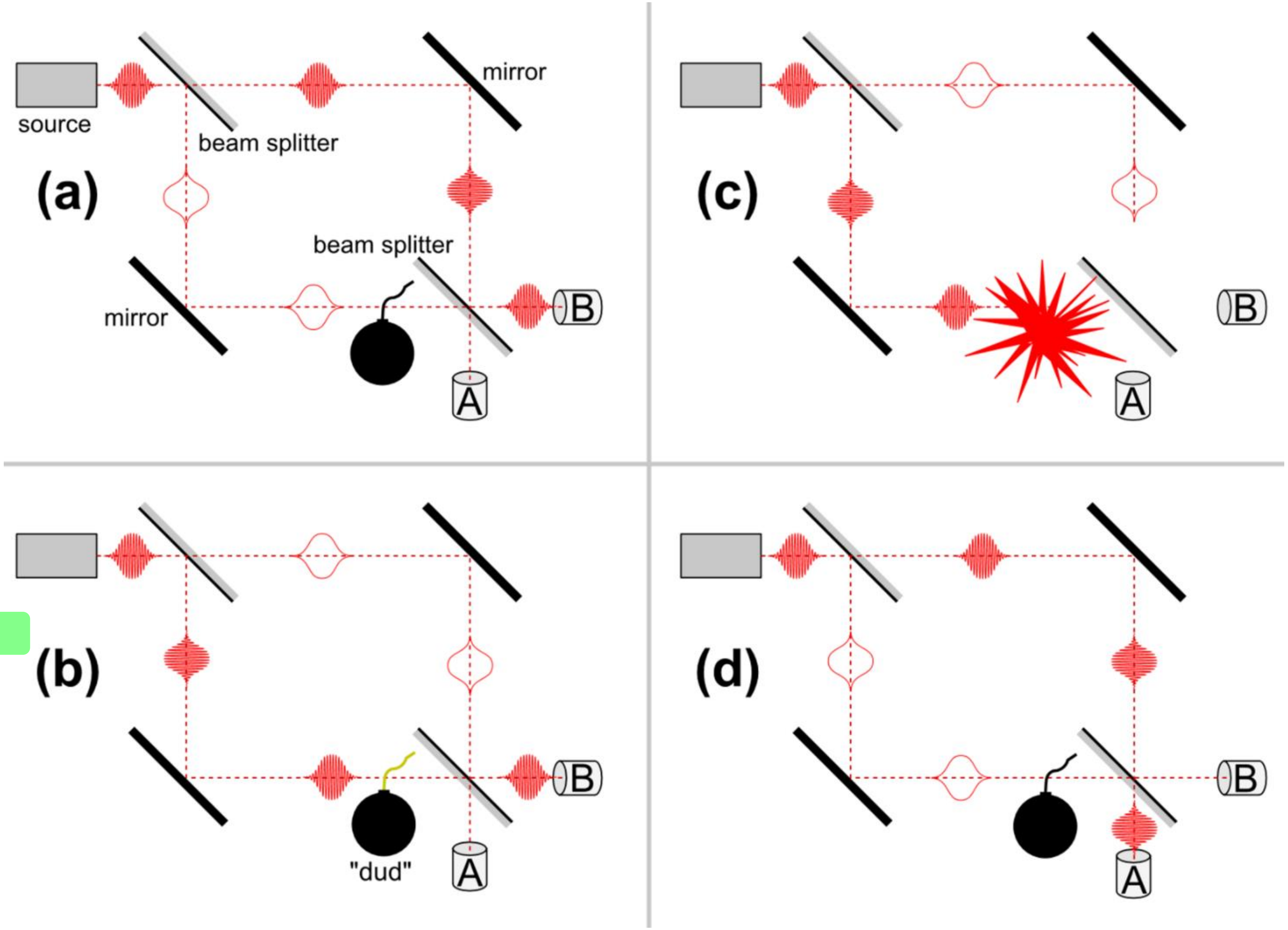
A novel manifestation of nonlocality of quantum mechanics is presented. It is shown that it is possible to ascertain the existence of an object in a given region of space without interacting with it. The method might have practical applications for delicate quantum experiments.

Elitzur-Vaidman thought experiment



a,b No bomb in the setup.

c Bomb explodes.

d Good bomb, No explosion.

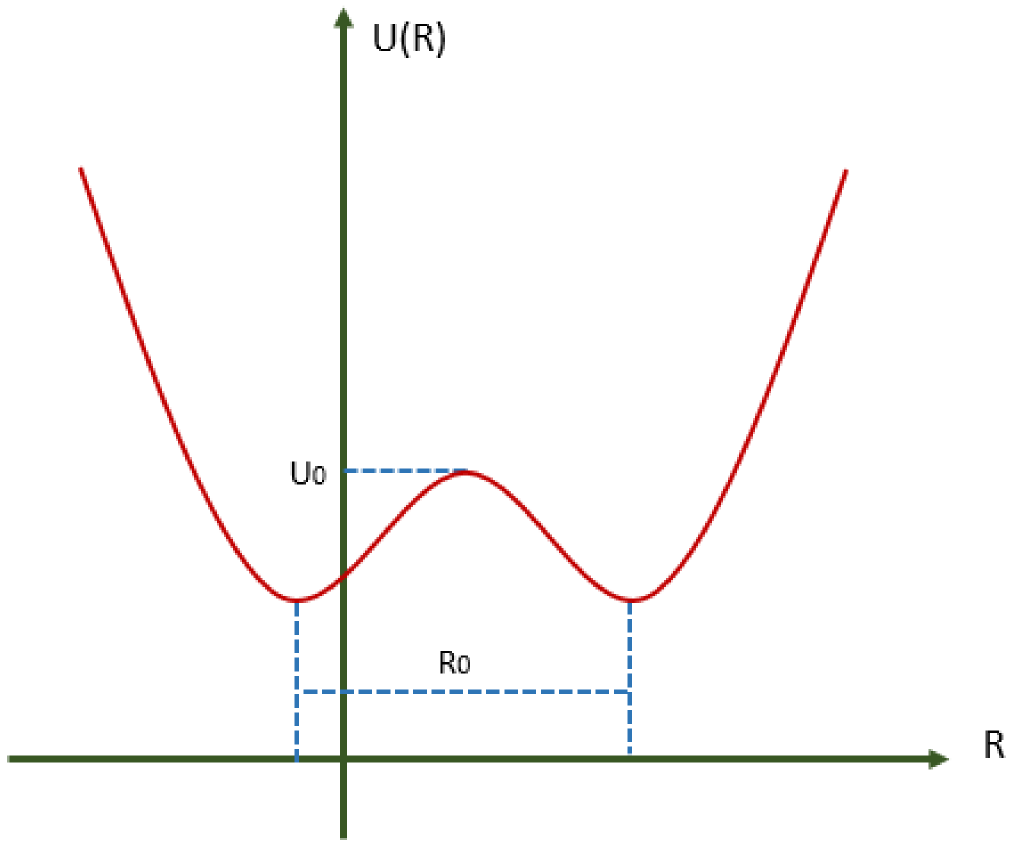
Model

System: double well potential

$$H_s = -\frac{h}{2}\Delta(|+\rangle\langle-| + |-\rangle\langle+|)$$

- Δ is a measure of the strength of the tunneling

- New parameter $h = \frac{\hbar}{R_0 P_0} = \frac{\hbar}{U_0 \tau_0}$ is a measure of the macroscopicity of the system



Model

Environment: a set of harmonic oscillators

$$H_\varepsilon = \sum_\alpha \left(\frac{1}{2}\hat{p}_\alpha^2 + \frac{1}{2}\omega_\alpha^2 \hat{x}_\alpha^2 - \frac{1}{2}\hbar\omega_\alpha\right)$$

frequency of the particle α of environment

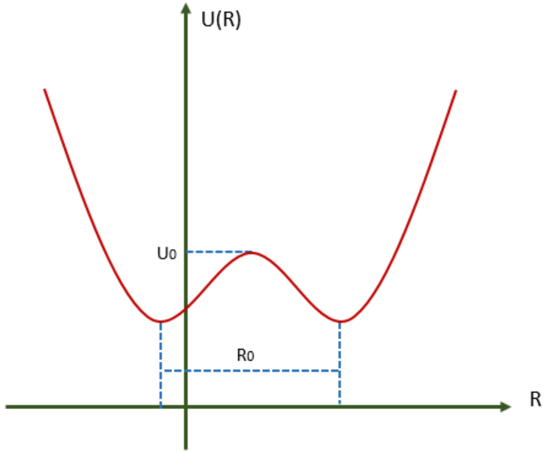
Model

Interaction Hamiltonian:

$$H_{s\varepsilon} = -\sum_{\alpha} \left(\omega_\alpha^2 f_\alpha(x) \hat{x}_\alpha + \frac{1}{2}\omega_\alpha^2 f_\alpha^2\right)$$

Environment oscillator α is displaced by $f_\alpha(x)$

Environment



Perturbation

Thought Experiment

We use operators

$$|-\rangle \xrightarrow{S_1 or S_2} (A|-\rangle + iB|+\rangle)$$

$$|+\rangle \xrightarrow{S_1 or S_2} (A|+\rangle + iB|-\rangle)$$

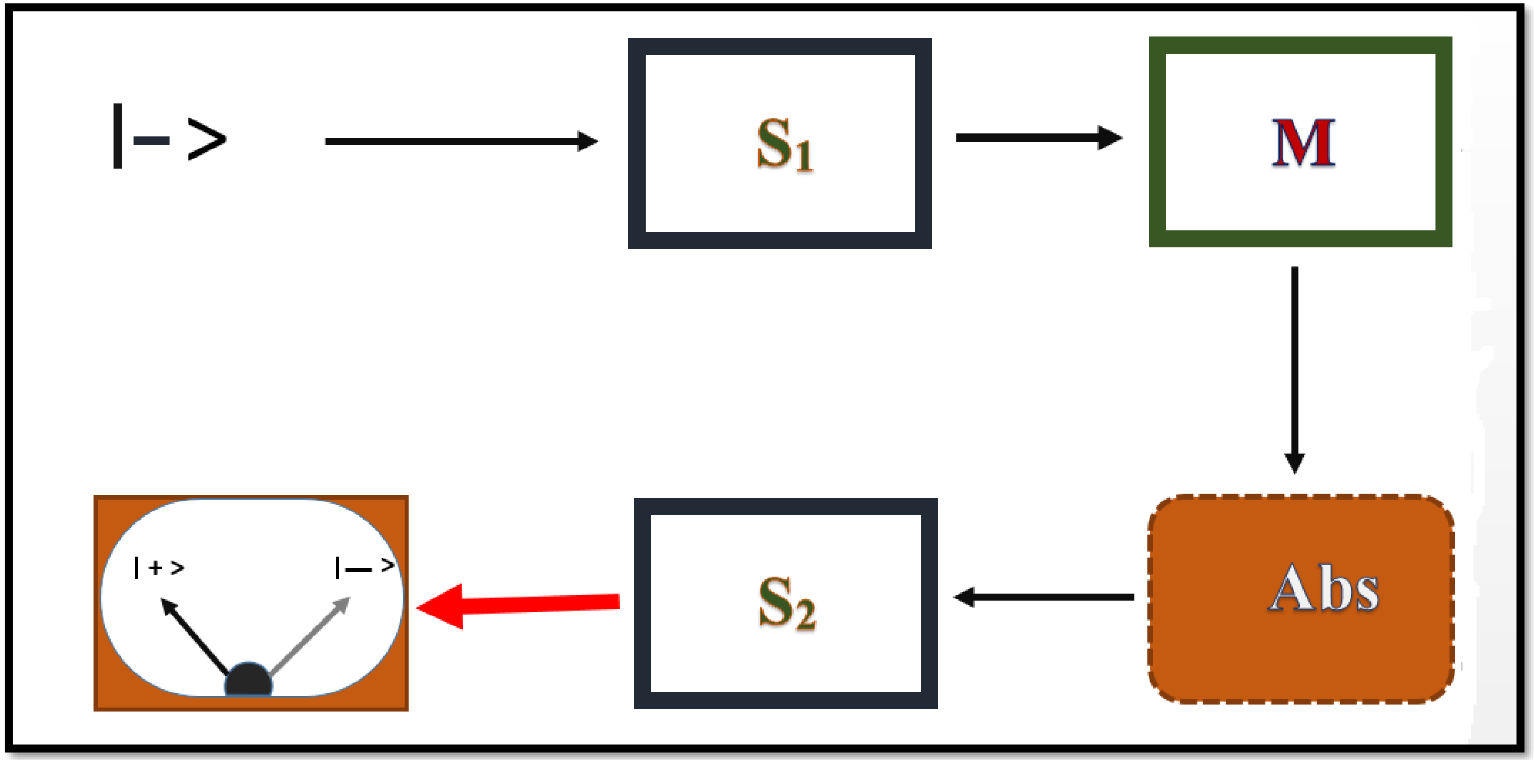
$$|-\rangle \xrightarrow{M} i|+\rangle$$

$$|+\rangle \xrightarrow{M} i|-\rangle$$

There is an absorber of state $|-\rangle$ in the setup (Abs)

Thought Experiment

The state $|-\rangle$ first experiences operator S_1 and then M. Then, if there were an object the state $|-\rangle$ would be absorbed and finally, the resulting state would encounter S_2. After S_2 we let the environment interact with the system. At the end, the Final state would be detected by detectors



Thought Experiment

No Environment, No Abs.

Only D_- clicks

The environment effects on the system

$$P_-^{\varepsilon}(t) = \frac{1}{2}(1 + e^{-\Gamma t/2}\cos\Omega t)$$

$$P_+^{\varepsilon} = \frac{1}{2}(1 - e^{-\Gamma t/2}\cos\Omega t)$$

Γ^{-1} is the life time of the shifted energy $E_1 + \delta E_1$.

$$\Omega = (\delta E_1 - \delta E_0)/h$$

The environment effects on the system and Abs. is present in the setup.

$$P_-^{Abs,\varepsilon} = A^4\{\frac{1}{2} + \frac{1}{2}e^{-\Gamma t/2}\cos\Omega t\} + A^2B^2\{\frac{1}{2} - \frac{1}{2}e^{-\Gamma t/2}\cos\Omega t\}$$

$$P_+^{Abs,\varepsilon} = A^4\{\frac{1}{2} - \frac{1}{2}e^{-\Gamma t/2}\cos\Omega t\} + A^2B^2\{\frac{1}{2} + \frac{1}{2}e^{-\Gamma t/2}\cos\Omega t\}$$

Results & Discussion

The true contribution of free-measurement in $P_+^{Abs,\varepsilon}$ is not obvious

$$
\begin{cases}
P_+^{Abs} = P_+^{Abs,\varepsilon} - P_+^{Abs,\varepsilon} P_+^{\varepsilon} \\
\quad = \frac{1}{4} - \frac{1}{4} P_+^{\varepsilon} \\
\text{We used } P_+^{Abs,\varepsilon} = \frac{1}{4} \text{ for } A = B = \frac{1}{\sqrt{2}}
\end{cases}
$$

It holds always true → It is logically possible to have free-measurement

when $P_+^{\varepsilon} \to 0, P_+^{Abs,\varepsilon} \to \frac{1}{4}$ → It is possible to see interaction-free measurement for 25% of detections

Results & Discussion

For an isolated system $\Gamma \to 0$

$$P_{+}^{Abs,\varepsilon} \to A^4 sin^2\Omega t/2 + A^2B^2 cos^2\Omega t/2$$
$$P_{-}^{Abs,\varepsilon} \to A^2B^2 sin^2\Omega t/2 + A^4 cos^2\Omega t/2$$

Elitzur-Vaidman results

For a fully decohered system we have $\Gamma \gg 1,\ Q = e^{-\Gamma t/2}\cos\Omega t \to 0$

$$P_{+}^{\varepsilon} \to \frac{1}{2}, P_{+}^{Abs} = \frac{1}{8}$$

Free-measurement could be imagined principally

For a macroscopic quantum system $h = 0.1$

$$Q \to 1, P_{+}^{\varepsilon} \to 0$$

All the detections at D_{-} refer to free-measurement

Conclusion

The dissipative effects of environment cause some detections at D_-

It is possible to distinguish between the effects of environment and interaction-free measurement.

For a macroscopic quantum system in interaction with the environment, it is possible to see interaction-free measurement.

Is it possible to describe a physical reality without direct measurement?

Thank you