

The Qubit in de Broglie-Bohm Interpretation

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How to explain spin's quantification ?

- ▶ Either by the measurement postulates of quantum theory
- ▶ Either by Pauli equation with spatial extension of the spinor

Representation of the particle with spin

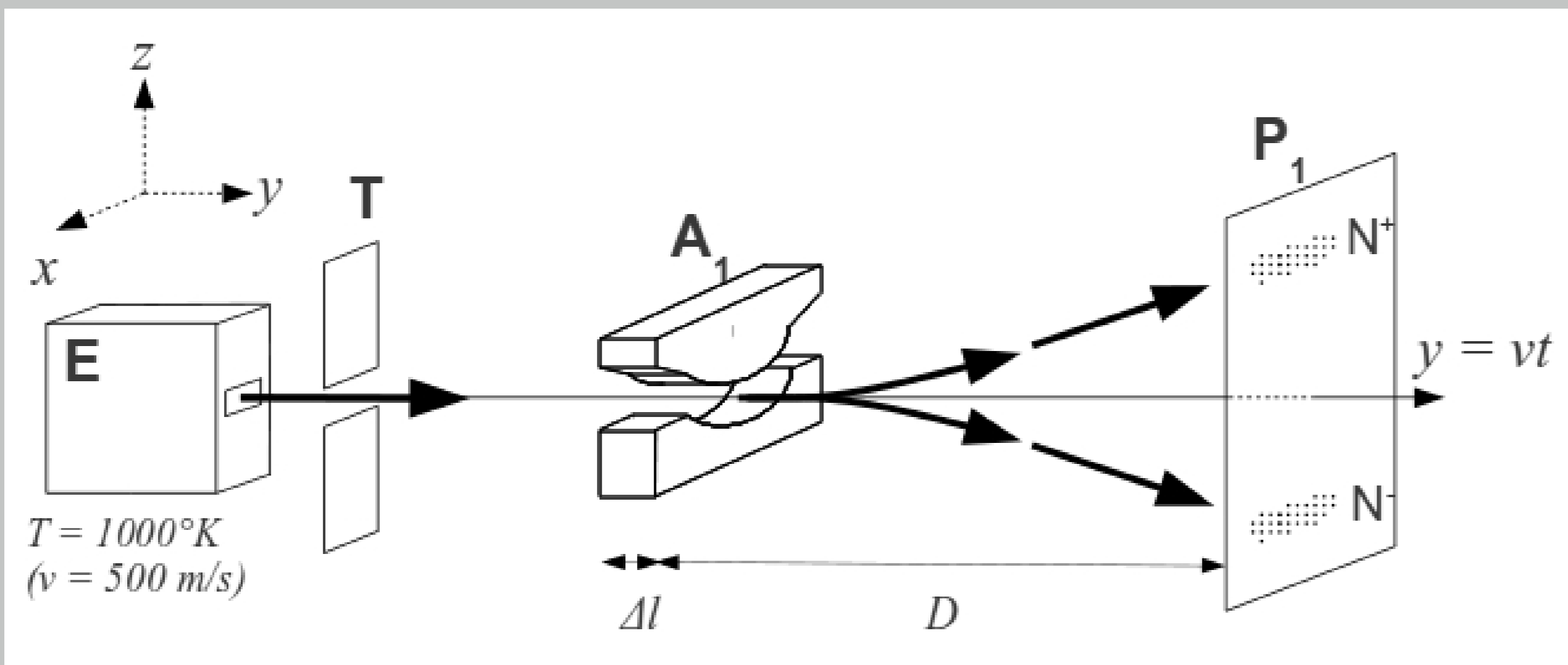
- ▶ Complete spinor with spatial extension

$$\Psi^0(z) = (2\pi\sigma_0^2)^{-\frac{1}{4}} e^{-\frac{z^2}{4\sigma_0^2}} \begin{pmatrix} \cos \frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin \frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{pmatrix}$$

- ▶ Simplified spinor used in quantum information (qubit)

$$\Psi^0 = \begin{pmatrix} \cos \frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin \frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{pmatrix}$$

Stern-Gerlach experiment



$$\Psi^0(z) = (2\pi\sigma_0^2)^{-\frac{1}{4}} e^{-\frac{z^2}{4\sigma_0^2}} \begin{pmatrix} \cos \frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin \frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{pmatrix}$$

- ▶ Pure state : θ_0 and φ_0 fixed
- ▶ Mixed states : θ_0 and φ_0 randomly drawn

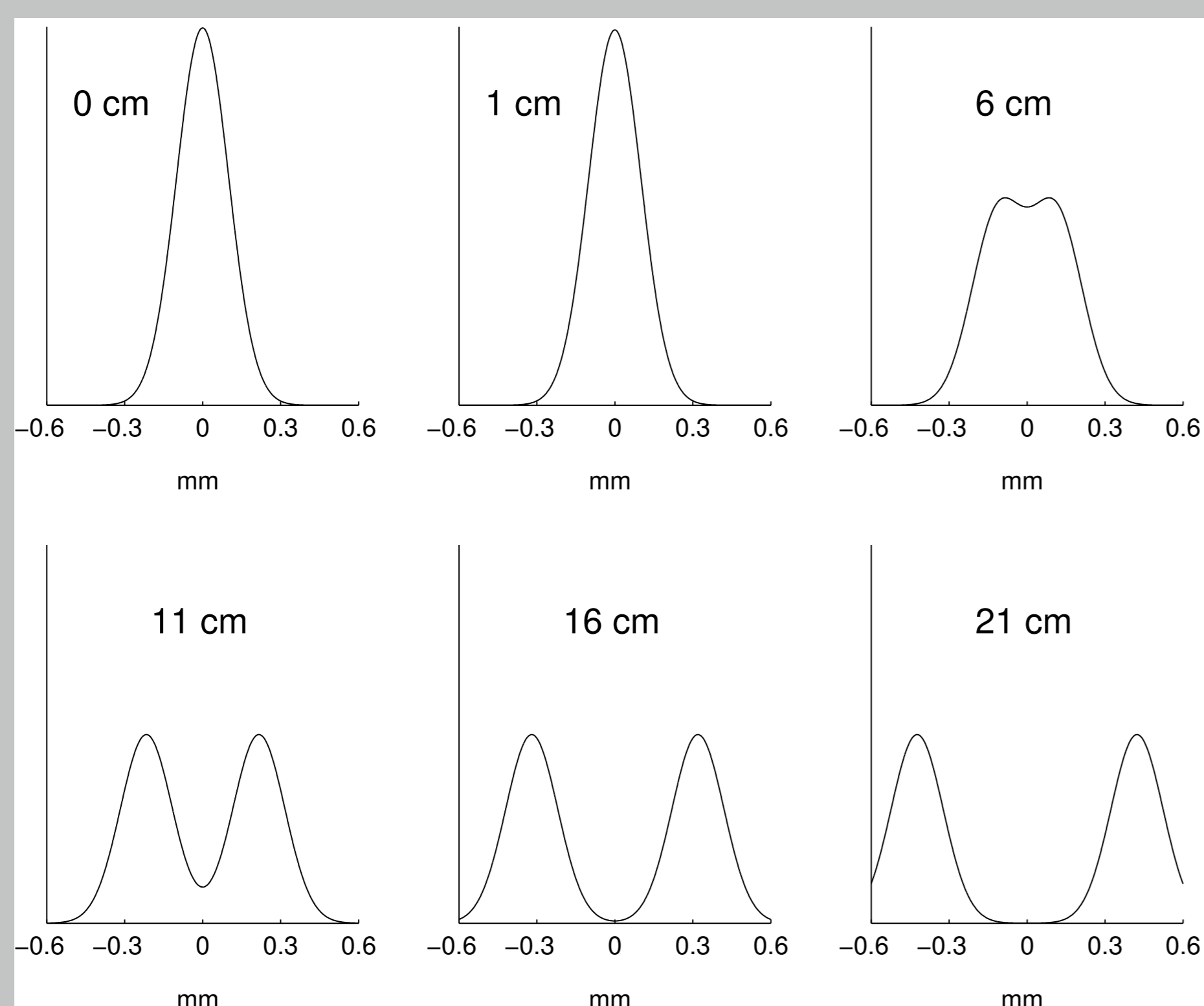
Pauli equation

- ▶ After the magnetic field: at $t + \Delta t$

$$\Psi(z, t + \Delta t) \simeq (2\pi\sigma_0^2)^{-\frac{1}{4}} \begin{pmatrix} \cos \frac{\theta_0}{2} e^{-\frac{(z-z\Delta-ut)^2}{4\sigma_0^2}} e^{i\frac{muz+h\varphi_+}{\hbar}} \\ \sin \frac{\theta_0}{2} e^{-\frac{(z+z\Delta+ut)^2}{4\sigma_0^2}} e^{i\frac{-muz+h\varphi_-}{\hbar}} \end{pmatrix}$$

- ▶ Decoherence in Stern-Gerlach experiment

$$\rho(z, t + \Delta t) \simeq (2\pi\sigma_0^2)^{-\frac{1}{2}} \frac{1}{2} \left(e^{-\frac{(z-z\Delta-ut)^2}{2\sigma_0^2}} + e^{-\frac{(z+z\Delta+ut)^2}{2\sigma_0^2}} \right)$$



- ▶ The decoherence time Spots N^+ and N^- appear :

$$y = vt > 16 \text{ cm}$$

⇒ the decoherence time :

$$t_D \simeq \frac{3\sigma_0 - z_\Delta}{u} = \frac{(3\sigma_0 - z_\Delta)mv}{\mu_B B'_0 \Delta l} = 3 \times 10^{-4} \text{ s.}$$

How is the transformation done ?

Mixed states θ_0 and φ_0 randomly drawn \implies Quantized mixture $\theta_0 = \pi$ and $\theta_0 = 0$

Measure quantization's postulates

or

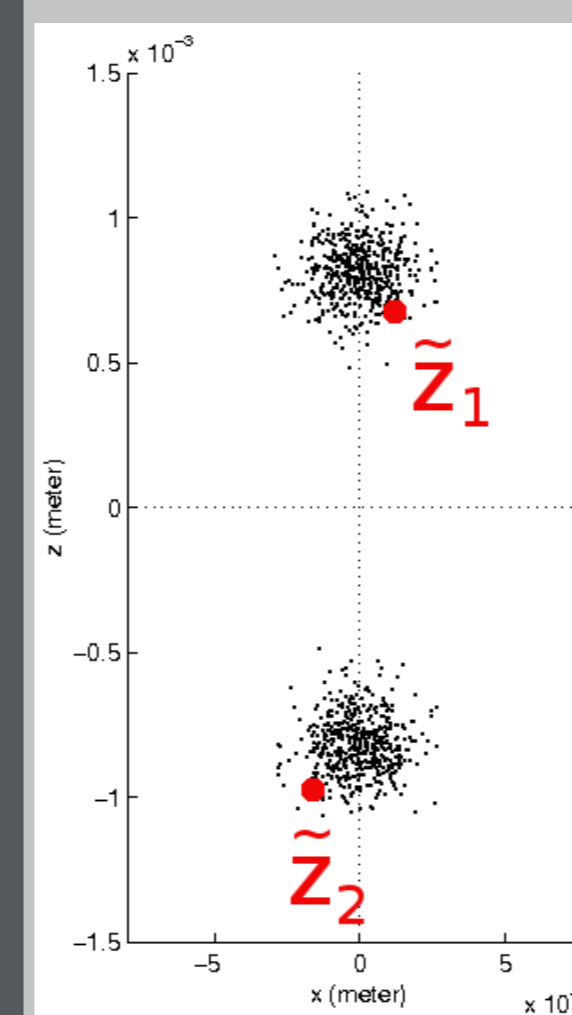
Pauli equation with spinor spatial extension

Decoherence in Stern-Gerlach experiment

Quantization postulates' proof for $S_z = \frac{\hbar}{2}\sigma_z$

$$\Psi(z, t + \Delta t) \simeq (2\pi\sigma_0^2)^{-\frac{1}{4}} \begin{pmatrix} \cos \frac{\theta_0}{2} e^{-\frac{(z-z\Delta-ut)^2}{4\sigma_0^2}} e^{i\frac{muz+h\varphi_+}{\hbar}} \\ \sin \frac{\theta_0}{2} e^{-\frac{(z+z\Delta+ut)^2}{4\sigma_0^2}} e^{i\frac{-muz+h\varphi_-}{\hbar}} \end{pmatrix}$$

Experimentally, one measures the particle position \tilde{z}



- ▶ $\tilde{z}_1 \in N^+$

$$\Psi(\tilde{z}_1, t + \Delta t) \simeq (2\pi\sigma_0^2)^{-\frac{1}{4}} \cos \frac{\theta_0}{2} e^{-\frac{(\tilde{z}_1 - z\Delta - ut)^2}{4\sigma_0^2}} e^{i\frac{m\tilde{z}_1 + h\varphi_+}{\hbar}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

- ▶ $\tilde{z}_2 \in N^-$

$$\Psi(\tilde{z}_2, t + \Delta t) \simeq (2\pi\sigma_0^2)^{-\frac{1}{4}} \sin \frac{\theta_0}{2} e^{-\frac{(\tilde{z}_2 + z\Delta + ut)^2}{4\sigma_0^2}} e^{i\frac{-m\tilde{z}_2 + h\varphi_-}{\hbar}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

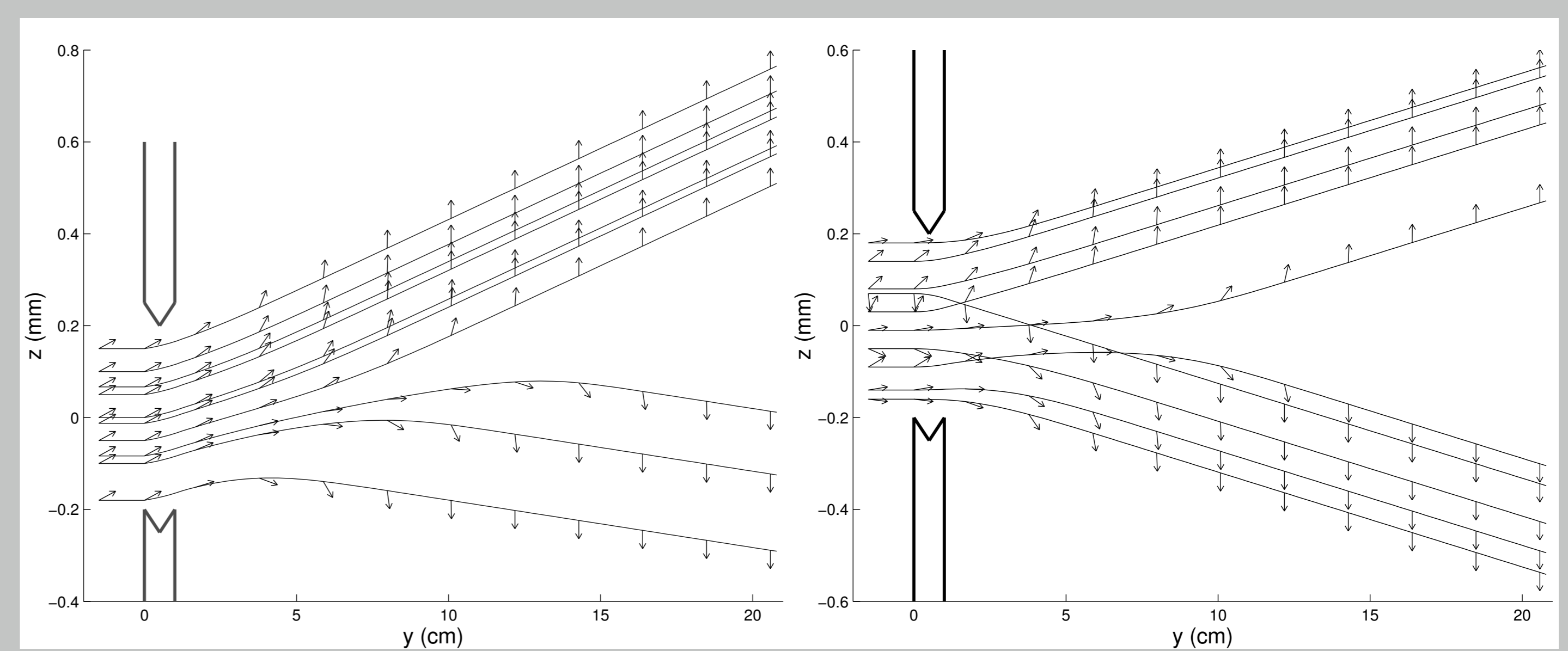
Marginal density matrix of spin variables of a pure state

$$\rho^S(z, t) = \begin{pmatrix} |\psi_+(z, t)|^2 & \psi_+(z, t)\psi_-^*(z, t) \\ \psi_-(z, t)\psi_+^*(z, t) & |\psi_-(z, t)|^2 \end{pmatrix}$$

When $t > t_D$:

$$\rho^S(z, t) \simeq \begin{pmatrix} |\psi_+(z, t)|^2 & 0 \\ 0 & |\psi_-(z, t)|^2 \end{pmatrix}$$

Experimental results : z_0 randomly drawn



Pure state (left) : $\theta_0 = \pi/3$ and $\varphi_0 = \pi/4$

Mixed states (right) : $\theta_0 \in [0; \pi]$ and $\varphi_0 \in [0; 2\pi]$ randomly drawn

Conclusion on quantum computer

- ▶ Spin-based qubit's existence? Space and spin variables are not factorizable during treatment
- ▶ Chuang NMR results' explanation Each wave function must be physically splitted because it takes at least two particles to represent the quantum system \implies Signal decay with a factor 2 for each additional qubit
- ▶ Statistical qubit (10^8 spins) exists but not individual qubit \implies Quantum mechanics is not complete