Title: Lecture - Quantum Foundations, PHYS 639

Speakers: Lucien Hardy

Collection/Series: Quantum Foundations (Elective), PHYS 639, January 6 - February 5, 2025

Subject: Quantum Foundations

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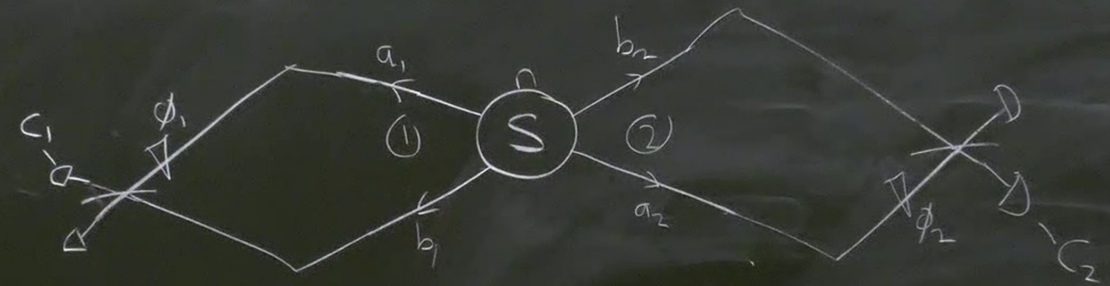
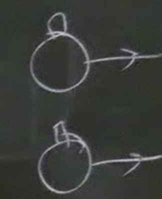
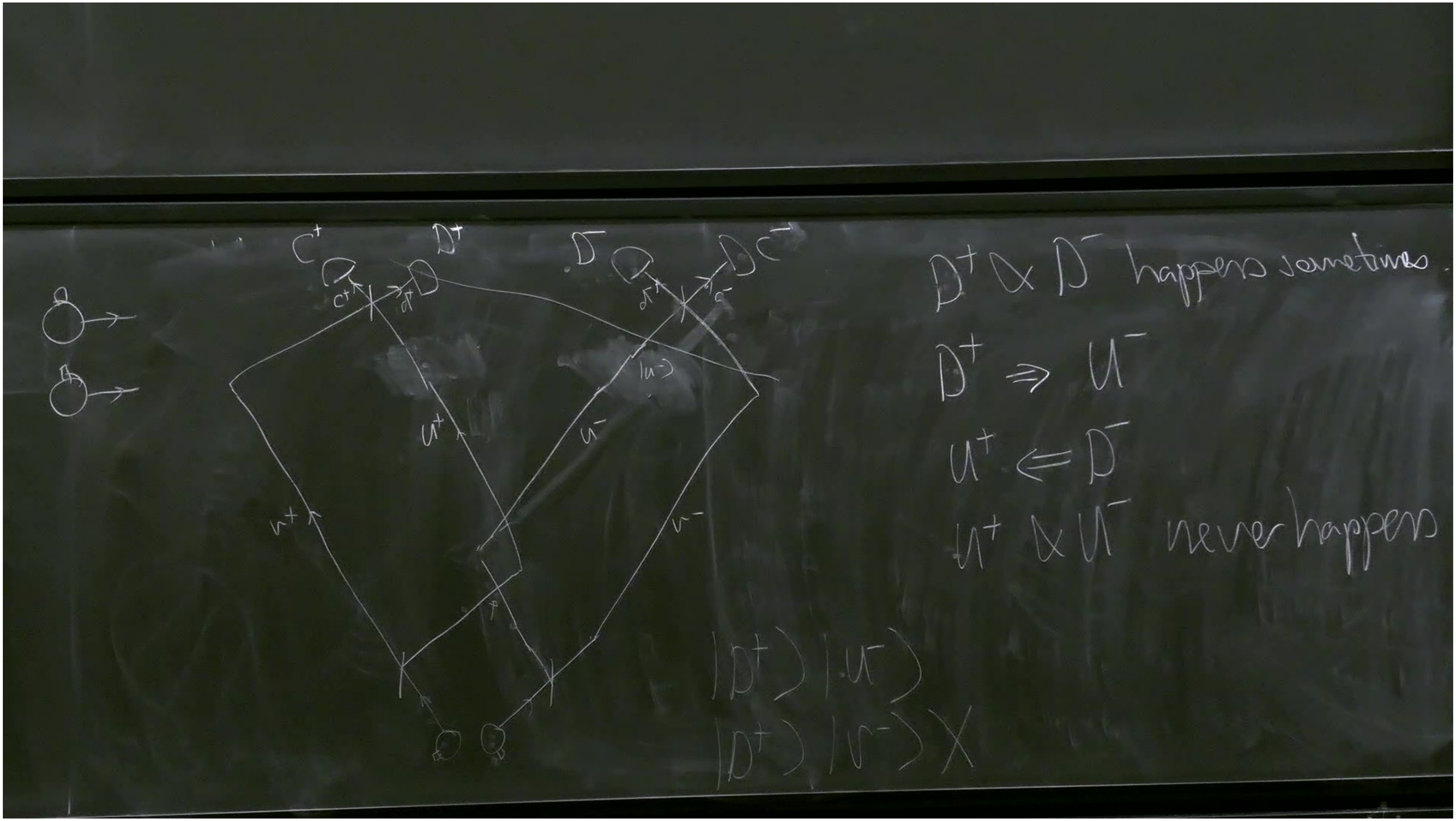


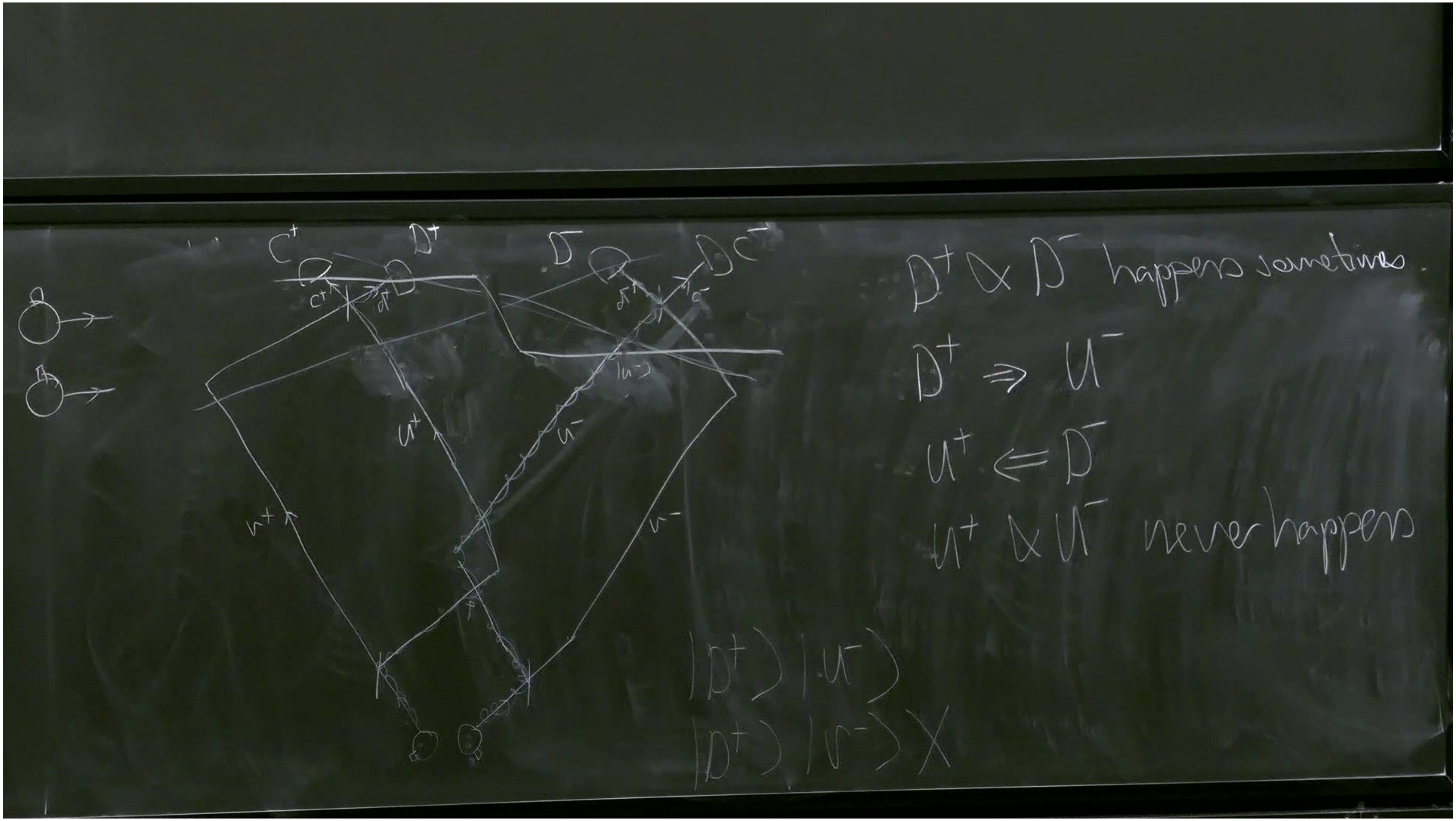


$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(|a_1\rangle|a_2\rangle + |b_1\rangle|b_2\rangle \Big)$$

$$\text{prob}(C_1 C_2) \sim \text{sinusoidal fn of } \phi_1 + \phi_2$$



D+ & D− happens sometimes
D+ ⇒ U−
U+ ⇐ D−
U+ & U− never happens
|D+⟩ |u−⟩
|D+⟩ |u−⟩ X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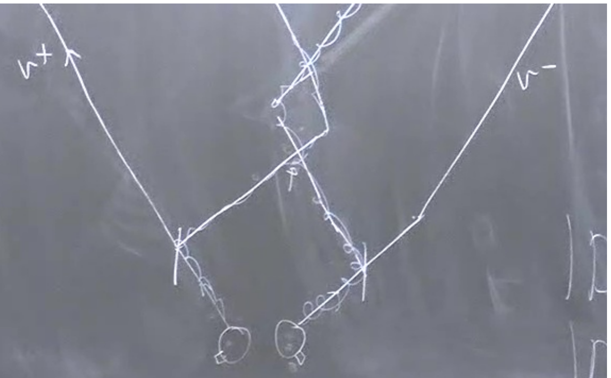
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|a_1\rangle|a_2\rangle + |b_1\rangle|b_2\rangle \right)$$

$\text{prob}(C_1 C_2) \sim$ sinusoidal fn of $\phi_1 + \phi_2$



① Associated with each system, a_1, is a Hilbert space $\mathcal{H}_{a_1}$ of dimension N_a where a is the system type and 1 is the instance.

② For a composite system ($a_1 a_2 b_3 c_4$ for example) the Hilbert space is the tensor product of the components Hilbert spaces

$$\left(\mathcal{H}_{a_1} \otimes \mathcal{H}_{a_2} \otimes \mathcal{H}_{b_3} \otimes \mathcal{H}_{c_4} \right)$$

$$\left(\mathcal{H}_{a_1} \otimes \mathcal{H}_{a_2} \otimes \mathcal{H}_{b_3} \otimes \mathcal{H}_{c_4} \right)$$

(3) The state of a system at any given time is an (initially normalized) element of the associated Hilbert space $|\psi\rangle_{a_1} \in \mathcal{H}_{a_1}$

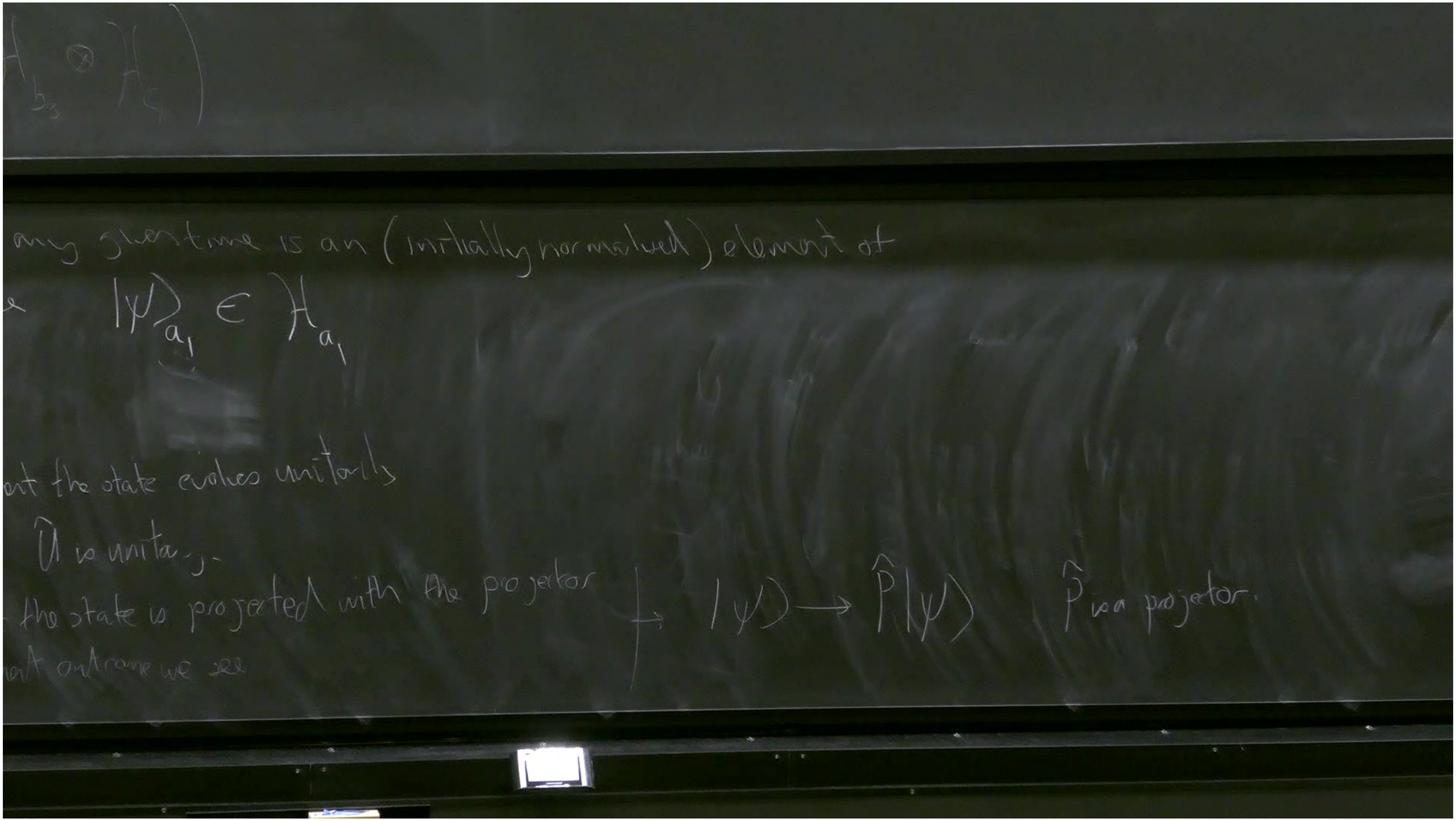
(4) Evolution. Two cases.

(a) When there is no measurement the state evolves unitarily

$$|\psi\rangle \longrightarrow \hat{U}|\psi\rangle \qquad \hat{U} \text{ is unitary.}$$

(b) When there is a measurement the state is projected with the projector associated with the measurement outcome we see

$$|\psi\rangle \longrightarrow \hat{P}|\psi\rangle$$


any given time is an (initially normalized) element of
$|\psi\rangle_{a_1} \in \mathcal{H}_{a_1}$
the state evolves unitarily
$\hat{U}$ is unitary
the state is projected with the projector
$|\psi\rangle \to \hat{P}|\psi\rangle$
$\hat{P}$ is a projector.
outcome we see

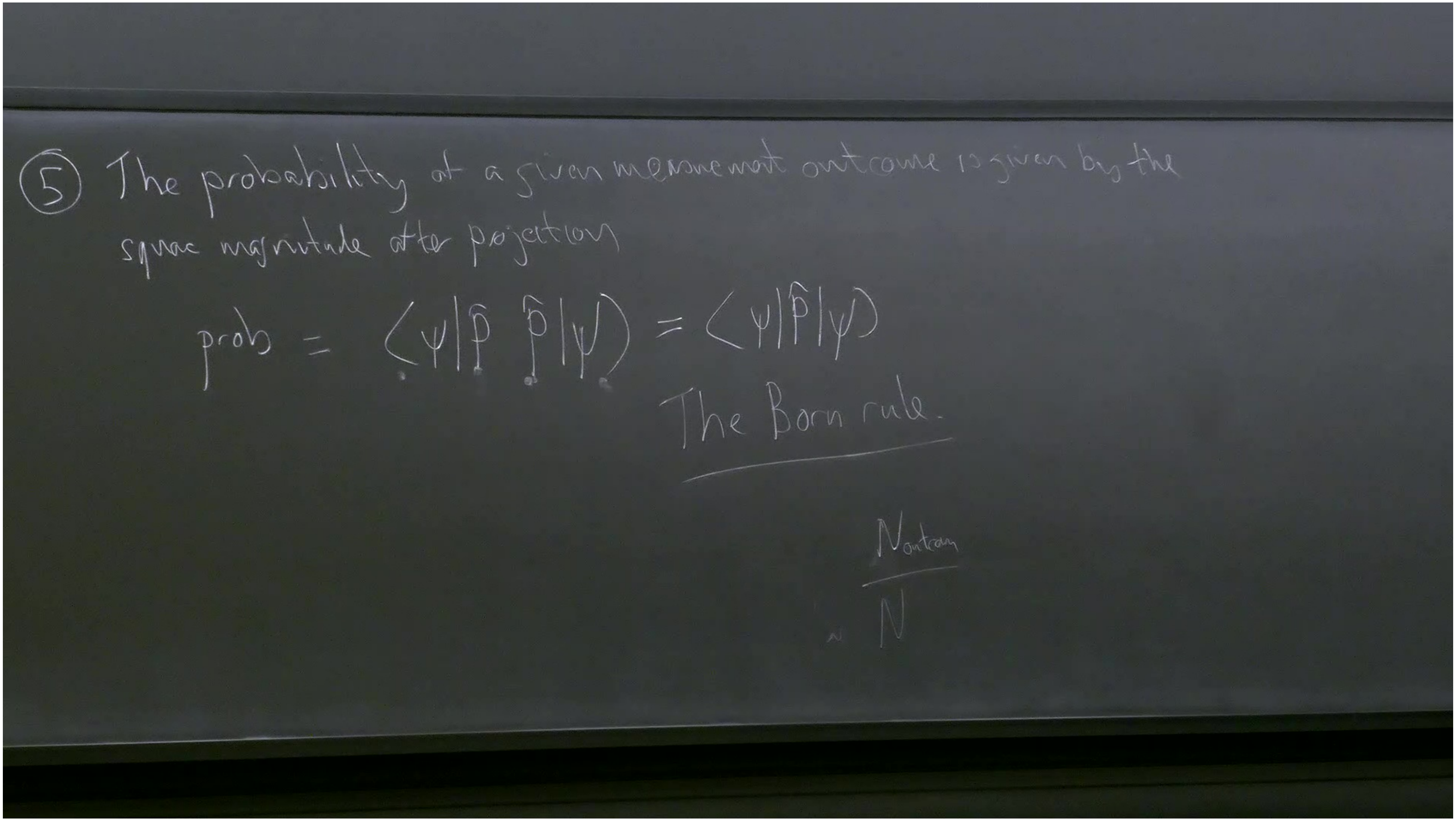
an (initially normalized) element of

a_1

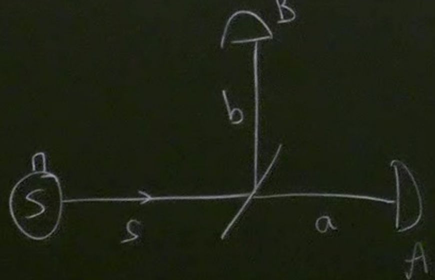
itarily

$$\hat{P}_3\left(\hat{P}_2\left(\hat{P}_1 |\psi\rangle\right)\right)$$

with the projector $\quad |\psi\rangle \longrightarrow \hat{P}|\psi\rangle \quad \hat{P}$ is a projector.


(5) The probability of a given measurement outcome is given by the square magnitude after projection
prob = ⟨ψ|P̂ P̂|ψ⟩ = ⟨ψ|P̂|ψ⟩
The Born rule.
N_outcome / N

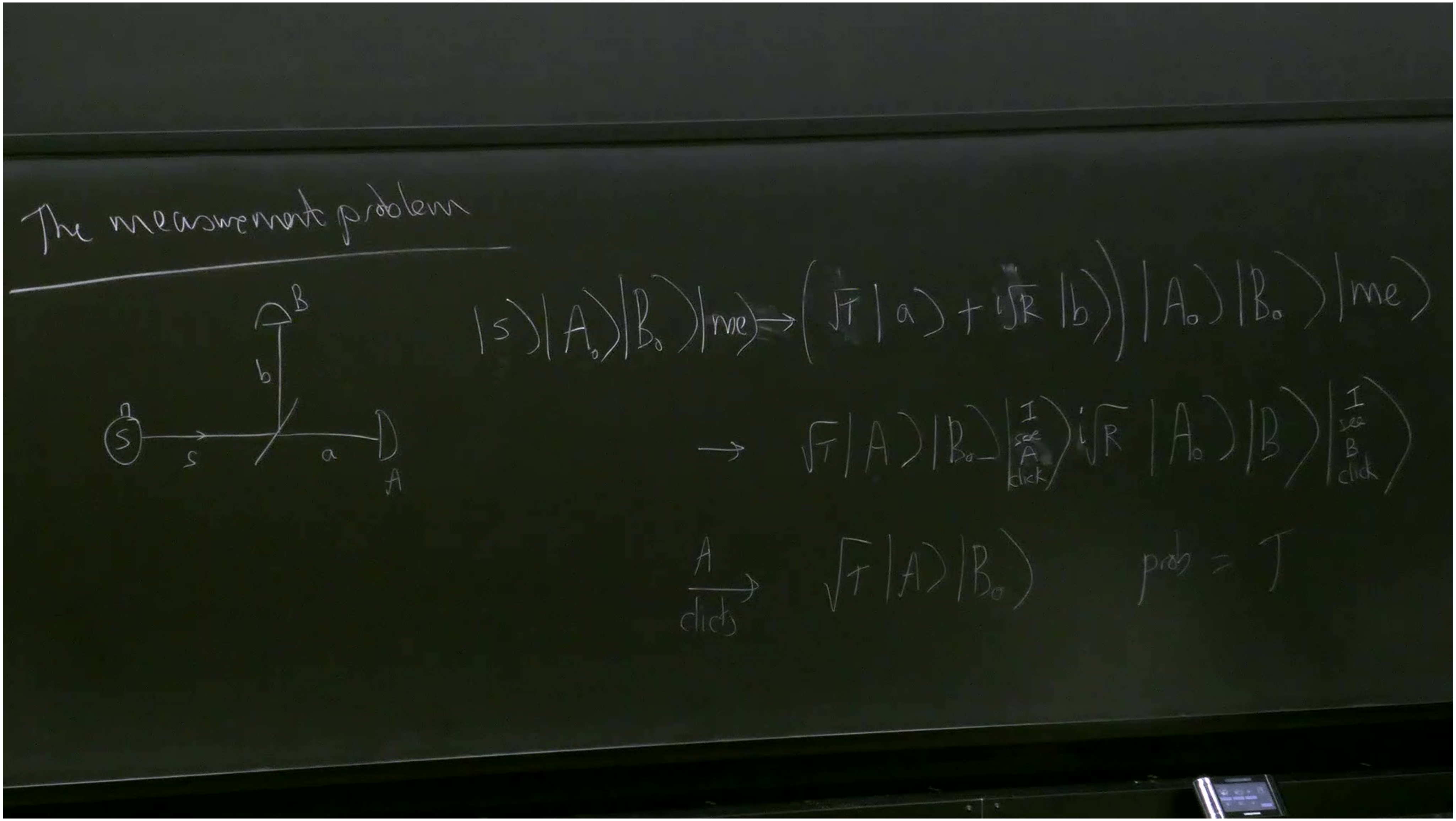
The measurement problem

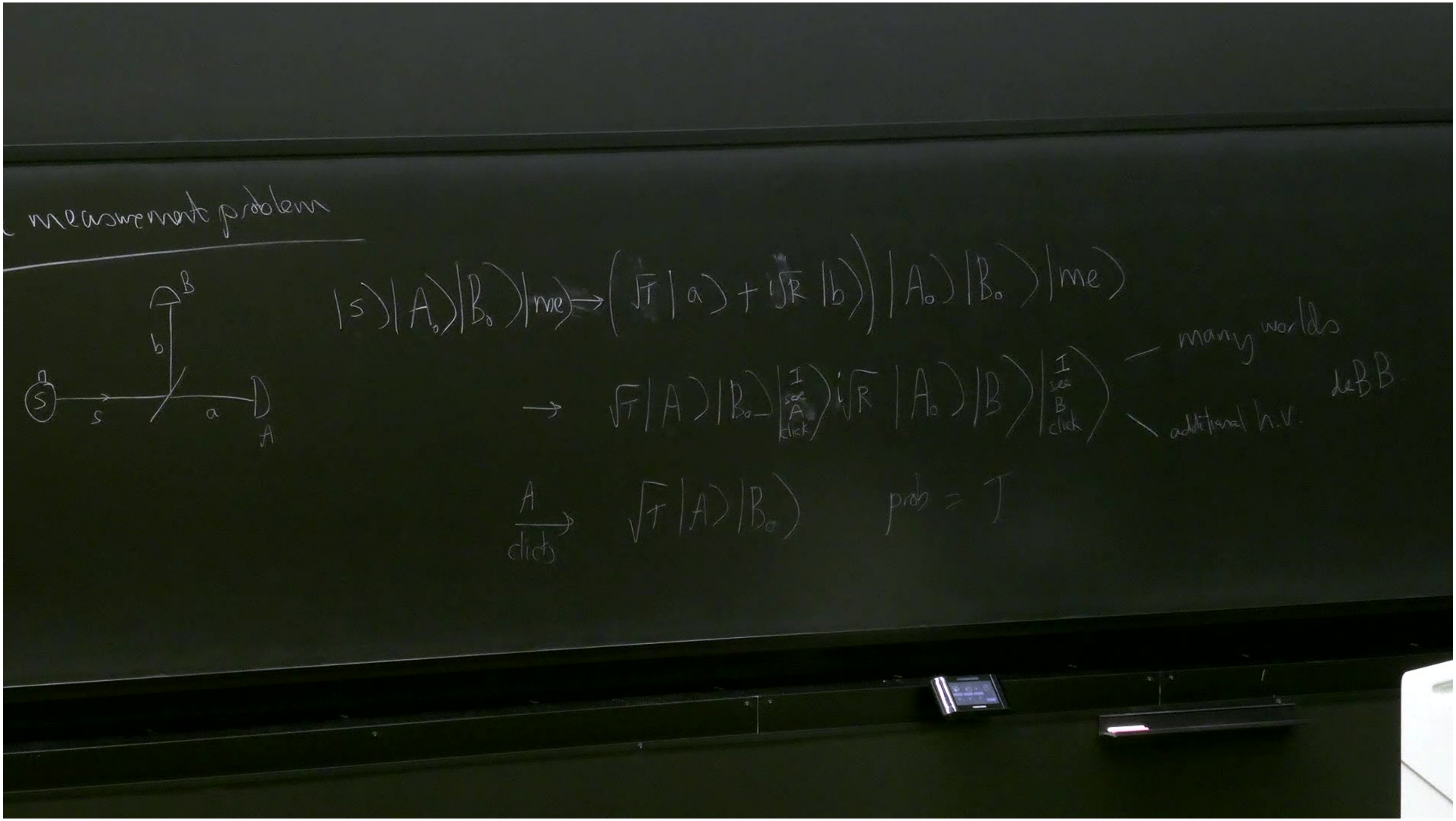


$$|s\rangle|A_0\rangle|B_0\rangle \to \left(\sqrt{T}\,|a\rangle + i\sqrt{R}\,|b\rangle\right)|A_0\rangle|B_0\rangle$$

$$\to \sqrt{T}\,|A\rangle|B_0\rangle + i\sqrt{R}\,|A_0\rangle|B\rangle$$

$$\xrightarrow[\text{clicks}]{A} \sqrt{T}\,|A\rangle|B_0\rangle \qquad \text{prob} = T$$


The measurement problem
B
b
S
s
a
A
|s⟩|A₀⟩|B₀⟩|me⟩ → (√T |a⟩ + i√R |b⟩) |A₀⟩|B₀⟩|me⟩
→ √T |A⟩|B₀⟩|I see A click⟩ i√R |A₀⟩|B⟩|I see B click⟩
A clicks → √T |A⟩|B₀⟩
prob = T


measurement problem
B
b
S
s
a
A
$|s\rangle|A_0\rangle|B_0\rangle|me\rangle \to \left(\sqrt{T}|a\rangle + i\sqrt{R}|b\rangle\right)|A_0\rangle|B_0\rangle|me\rangle$
$\to \sqrt{T}|A\rangle|B_0\rangle|\text{I see A click}\rangle + i\sqrt{R}|A_0\rangle|B\rangle|\text{I see B click}\rangle$
many worlds
additional h.v.
deBB
$\xrightarrow[\text{click}]{A} \sqrt{T}|A\rangle|B_0\rangle$ prob = T