Title: Interpretation of Quantum Theory: Lecture 19

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Abstract:

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CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Experimental tests of Bell's inequalities: more ideal than ever*

Perimeter Institute, Waterloo, march 2005

Alain Aspect

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http://atomoptic.iota.u-psud.fr

A review on Bell's inequalities: AA quant-ph/0402001

* AA, Nature News and Views, 398, 189 (1999)

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The first quantum revolution (1900-)

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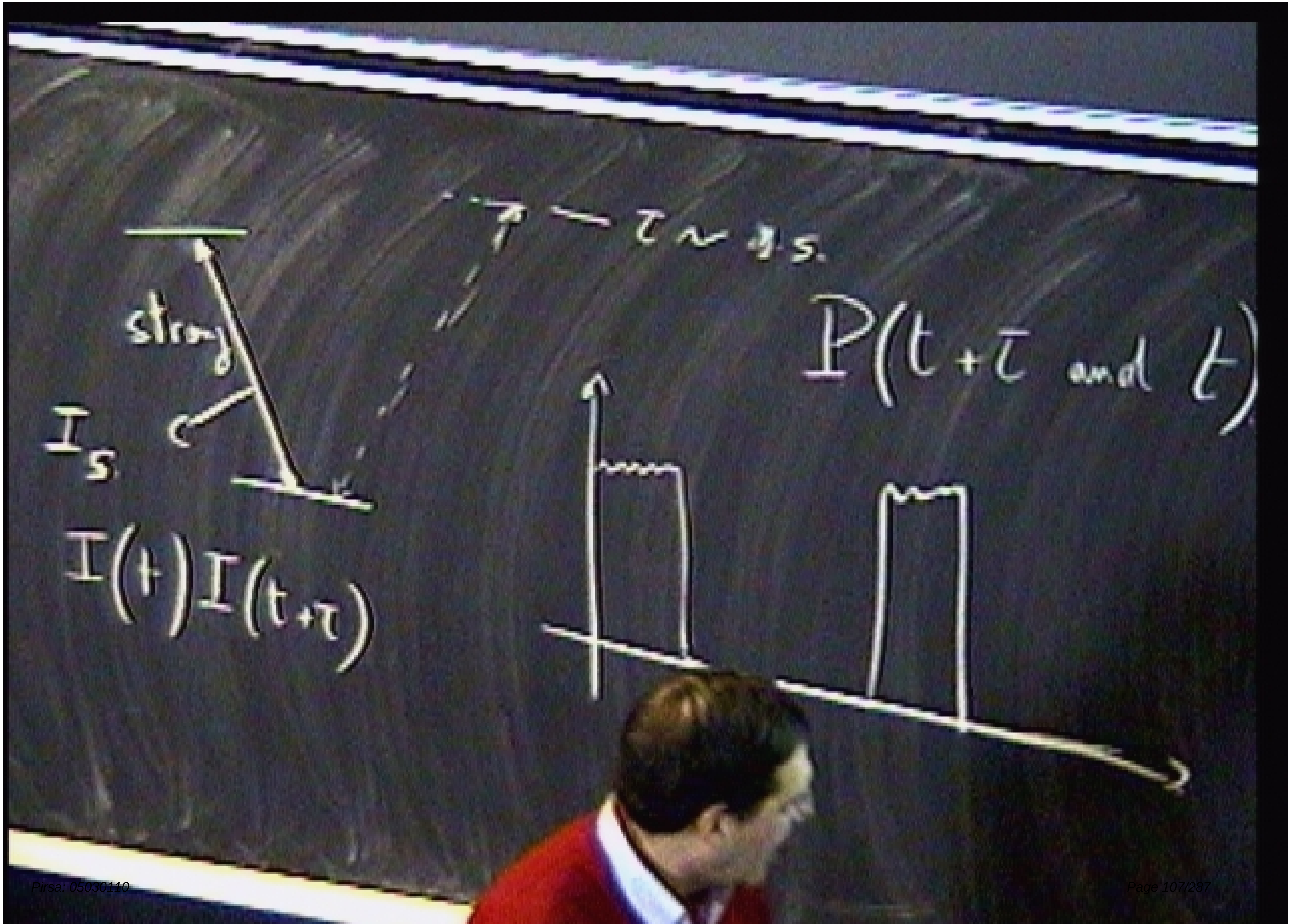
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* AA, « John Bell and the second quantum revolution »: Introduction to 2nd edition of « Speakable

ut d'Optique

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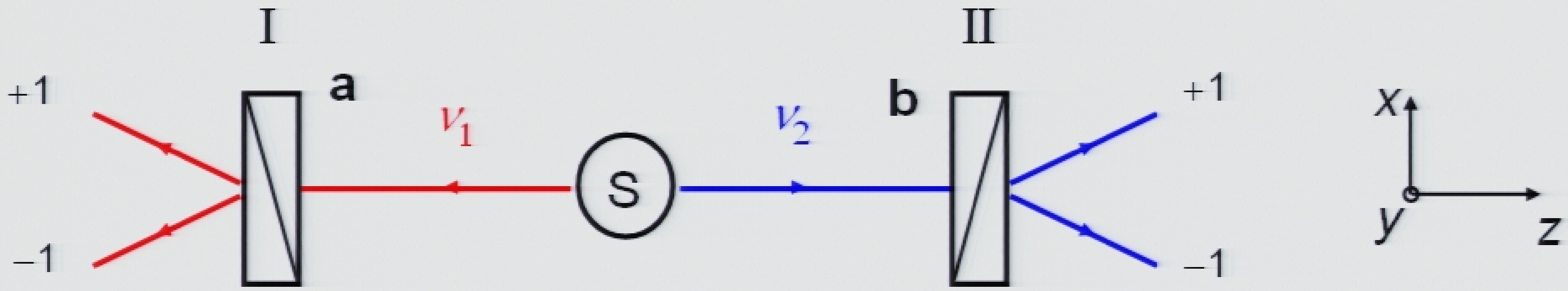
Einstein-Podolsky-Rosen GedankenExperiment with photons correlated in polarization



Measurements of linear polarization of ν_1 along **a** and of linear polarization of ν_2 along **b** : results +1 or –1

$\Rightarrow$ Probabilities of detection in channels +1 or –1 of polarizer I and in channels +1 or –1 of polarizer II (in orientations **a** and **b**).

EPR situation : entangled state $$|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\}$$

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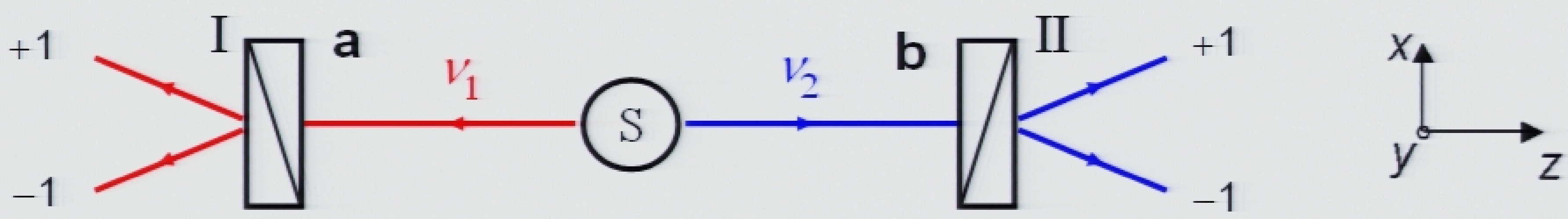

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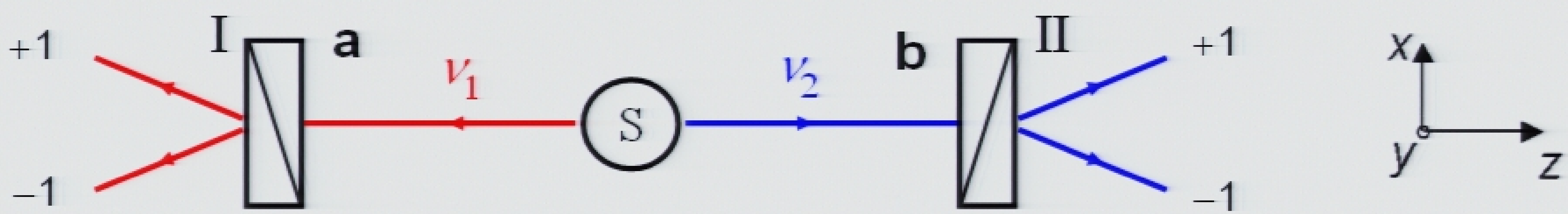

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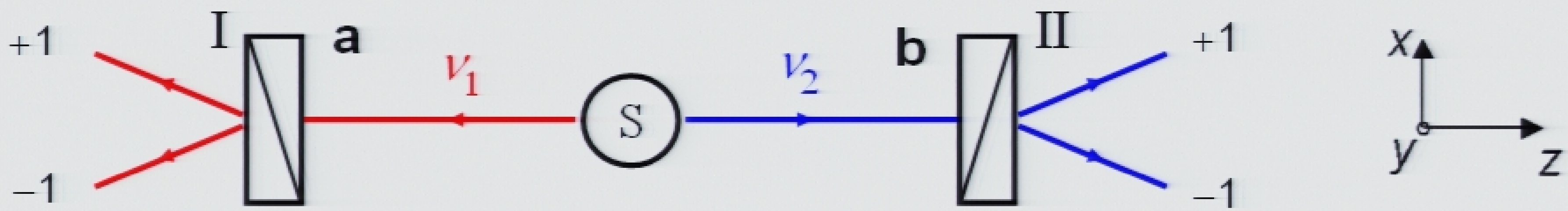

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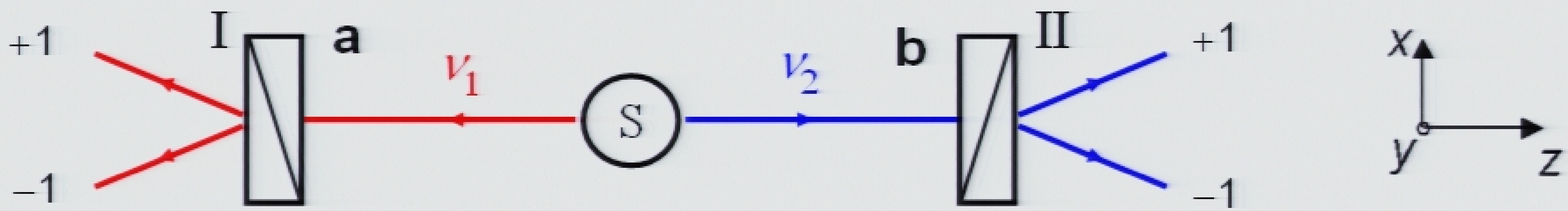

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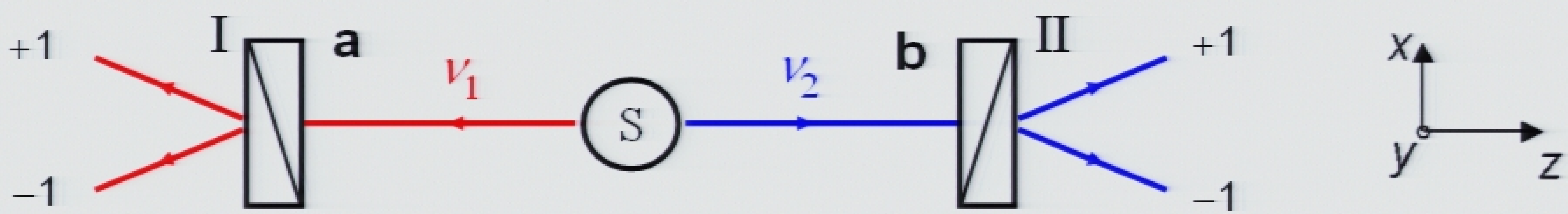

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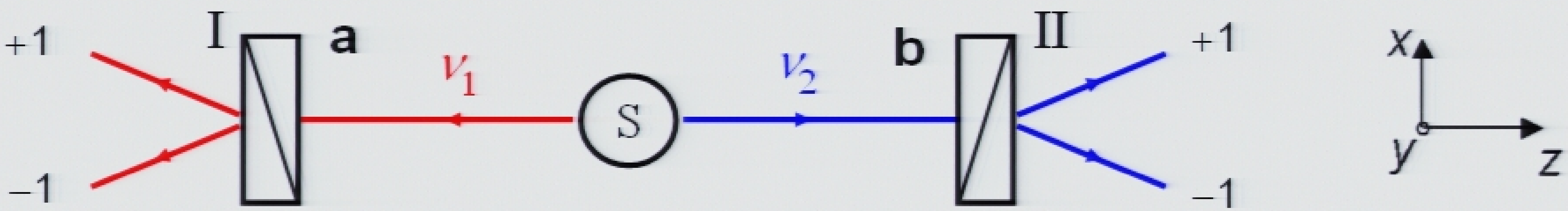

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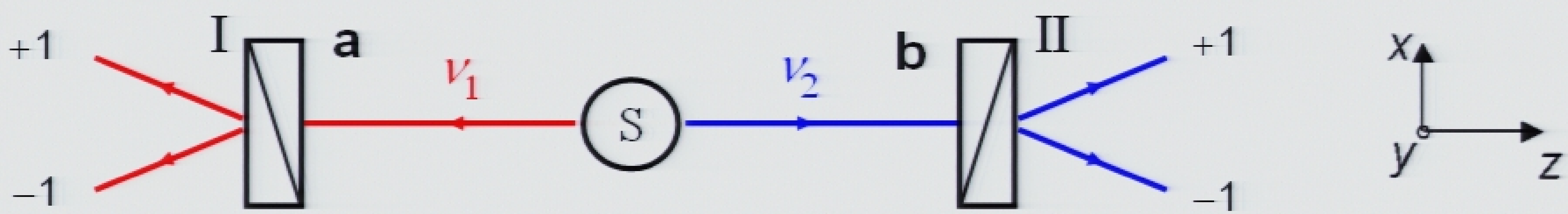

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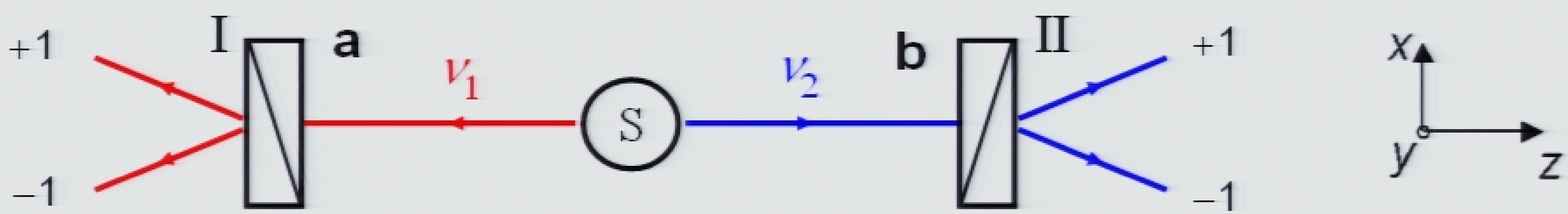

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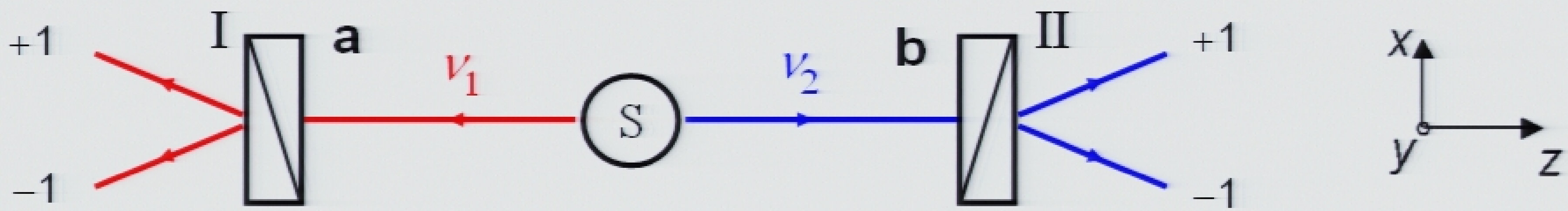

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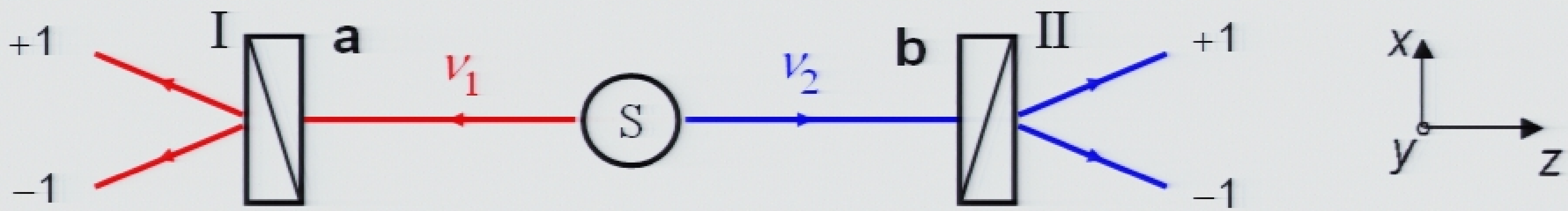

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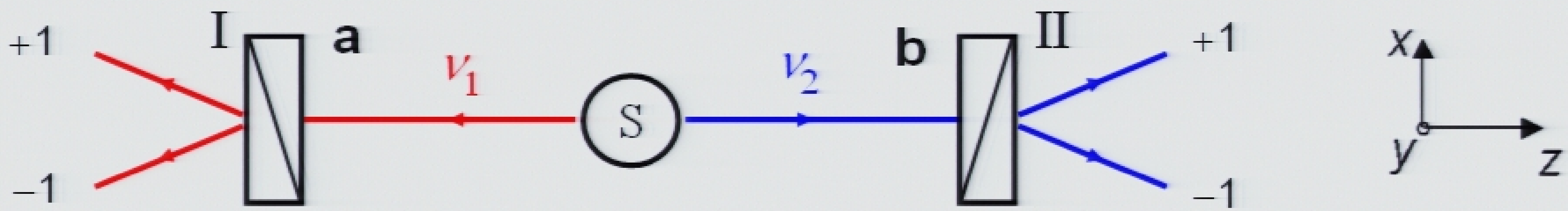

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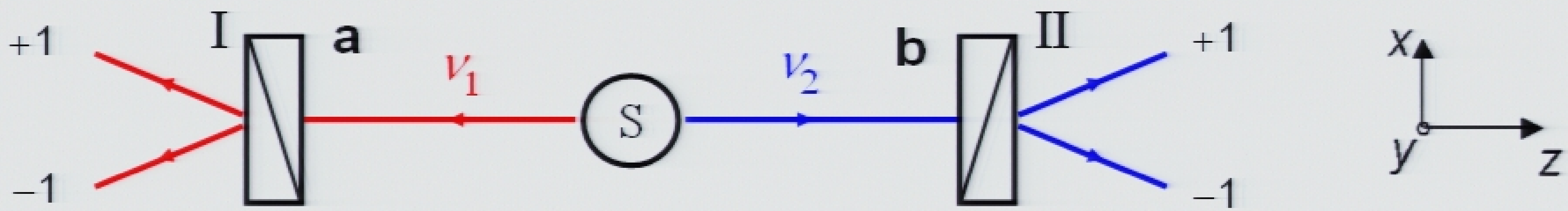

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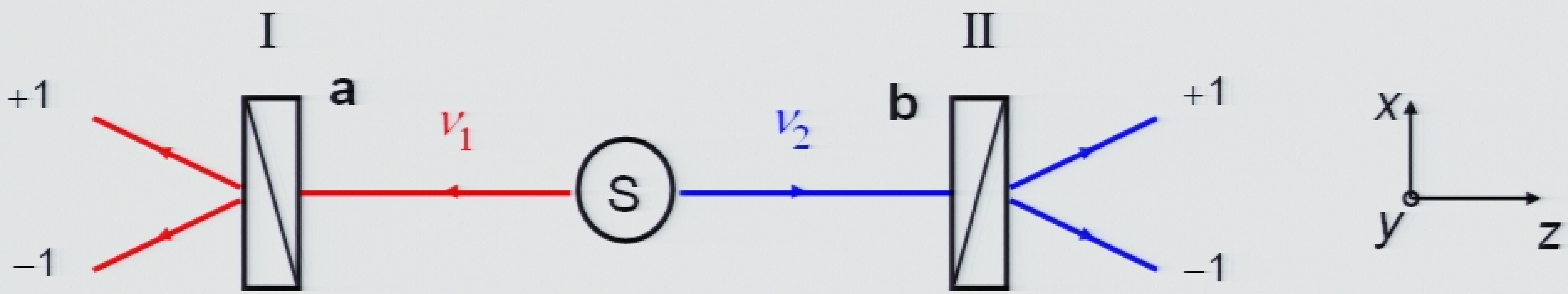

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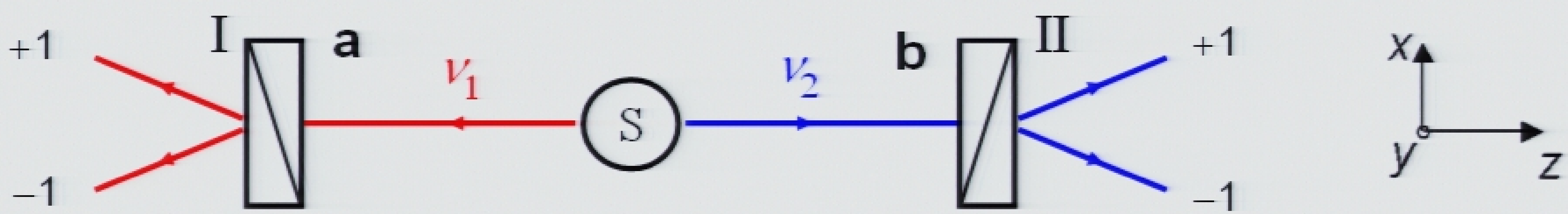
Quantum Mechanics predicts a strong polarization correlation

Correlation coefficient $E(\mathbf{a},\mathbf{b}) = P_{++} + P_{--} - P_{+-} - P_{-+}$

$E_{\mathrm{MQ}}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b}) \quad \Rightarrow \; E_{\mathrm{MQ}}(0) = 1 \; ; \; E_{\mathrm{MQ}}(90) = -1$

Einstein-Podolsky-Rosen GedankenExperiment with photons correlated in polarization



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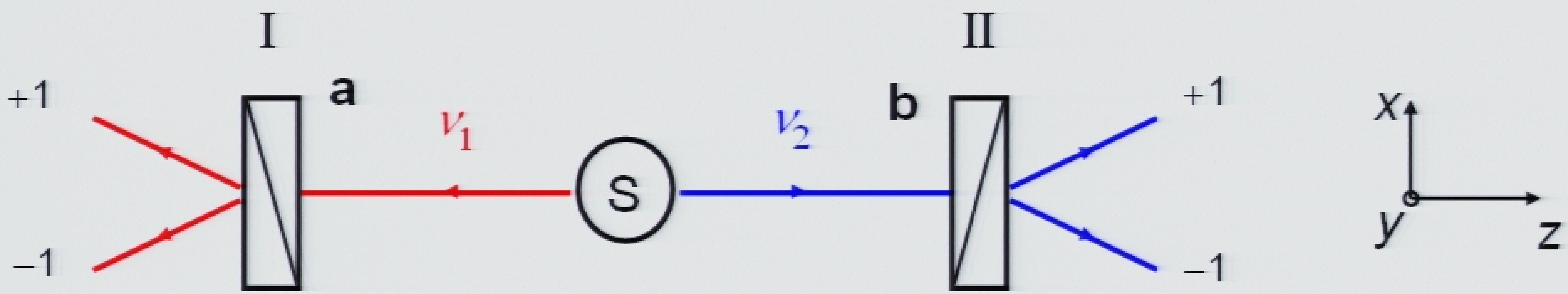

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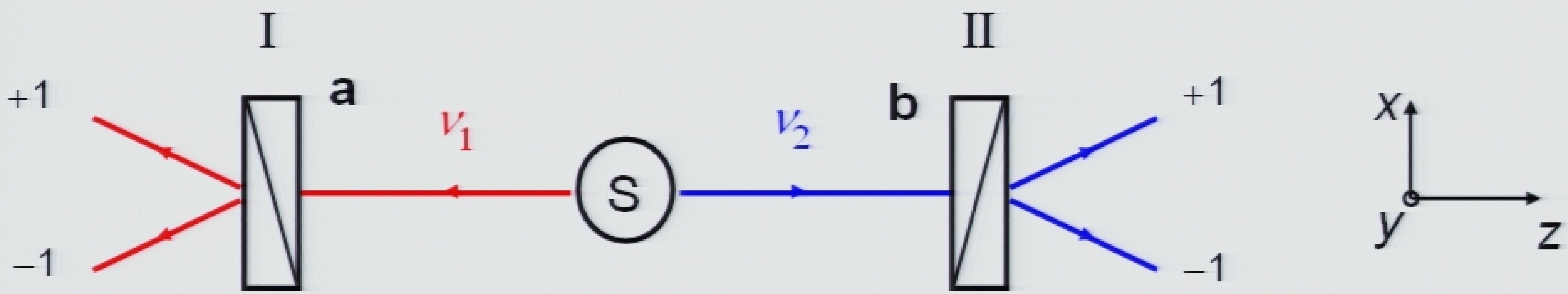
Einstein-Podolsky-Rosen GedankenExperiment with photons correlated in polarization



Photons in the EPR entangled state: $\left|\Psi(\nu_1,\nu_2)\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|x,x\right\rangle + \left|y,y\right\rangle\right\}$

Quantum Mechanics predicts a strong polarization correlation

Correlation coefficient $E(\mathbf{a},\mathbf{b}) = P_{++} + P_{--} - P_{+-} - P_{-+}$

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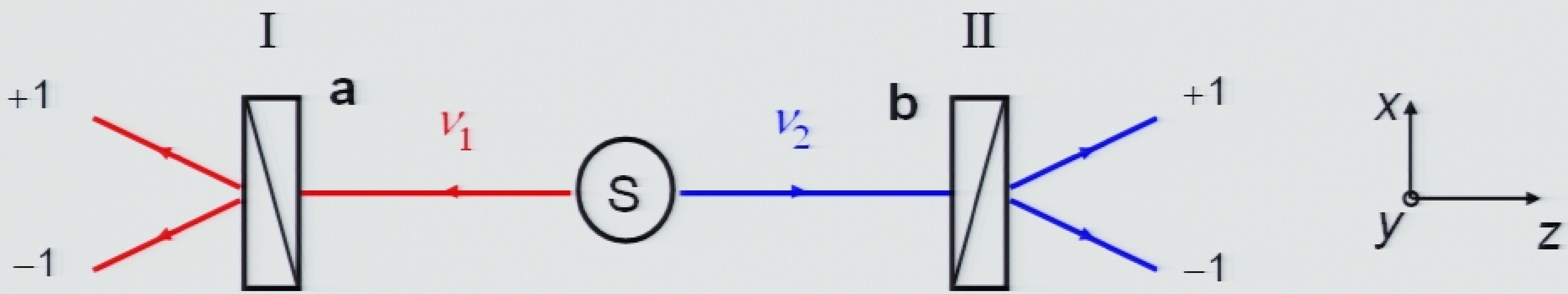

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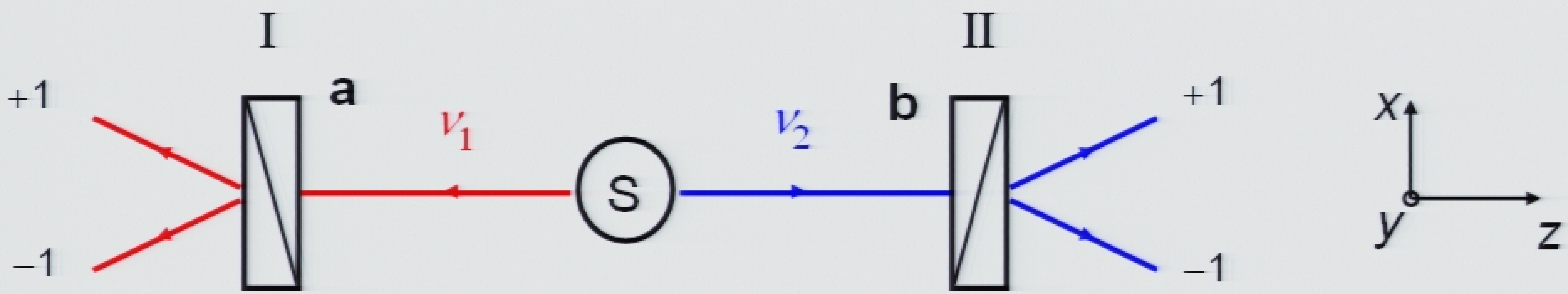

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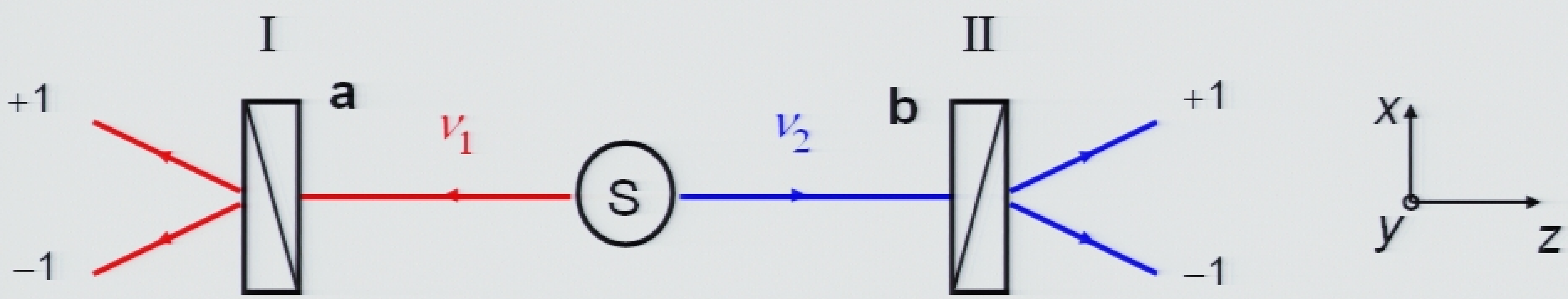

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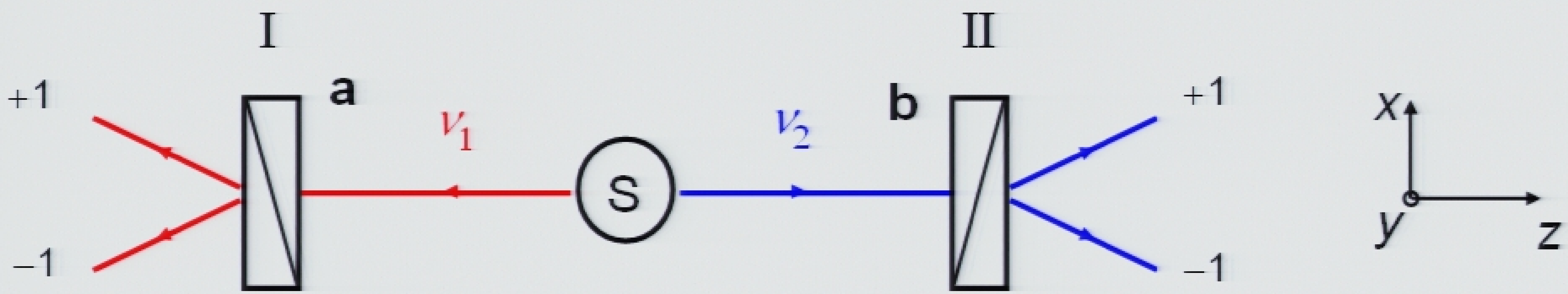

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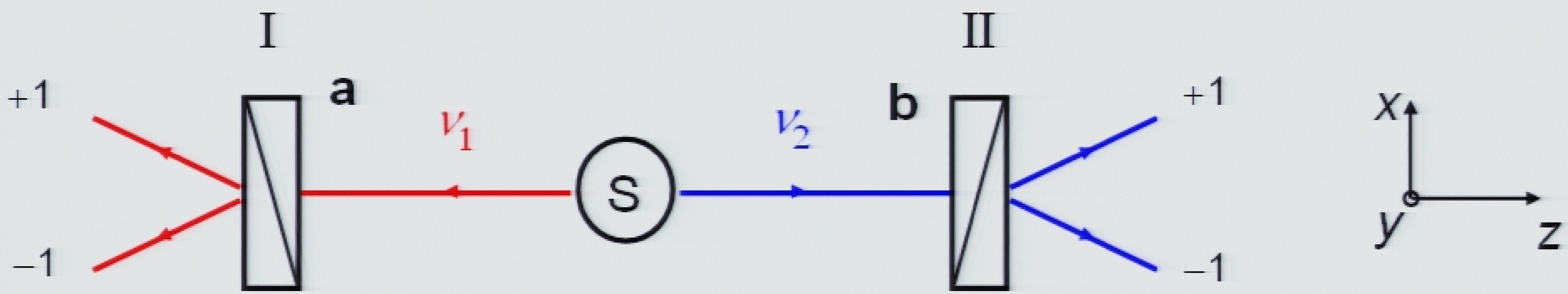

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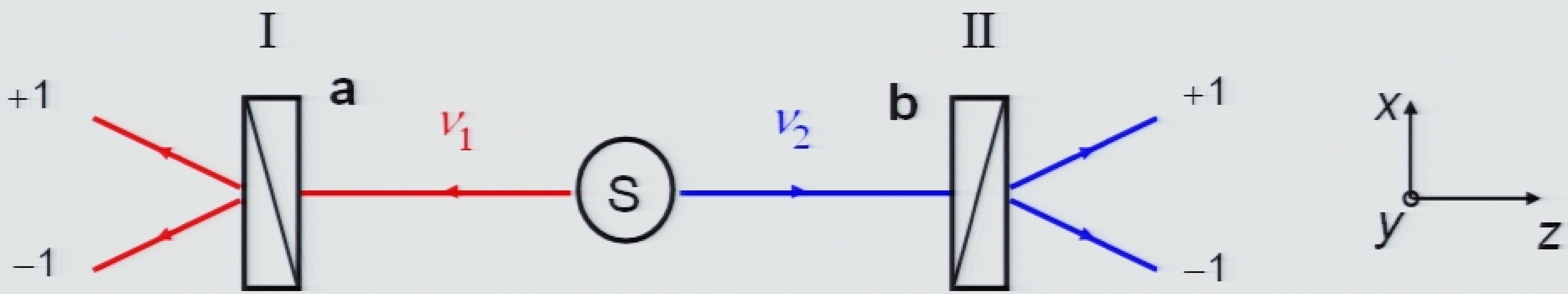

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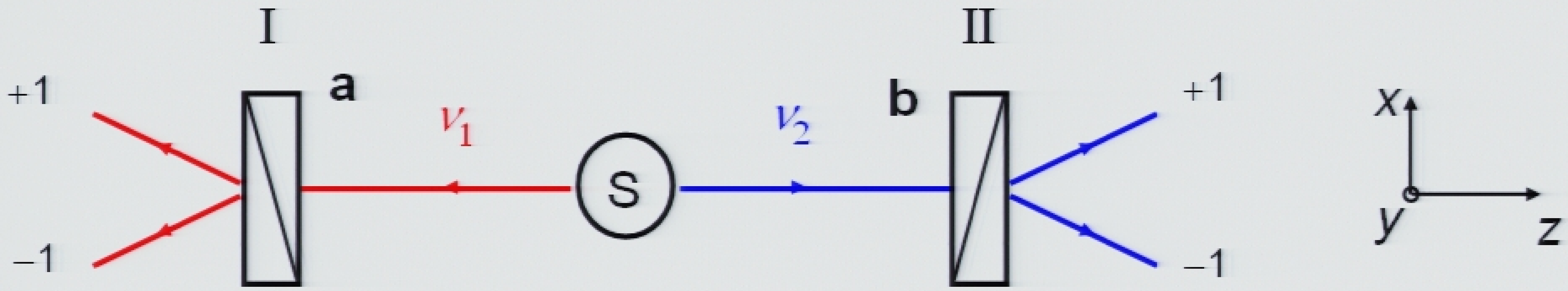

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How to understand the EPR correlations?

How to make an image?

• Derive it from the calculation algorithm?

Global (straightforward) calculation:

$$P_{++}(\mathbf{a},\mathbf{b}) = \left|\left\langle +_{\mathbf{a}}, +_{\mathbf{b}} \middle| \Psi(\nu_1,\nu_2)\right\rangle\right|^2$$

Hard to make a picture in real space:

• $\left|\Psi(\nu_1,\nu_2)\right\rangle$ is a global 2-particles wave vector

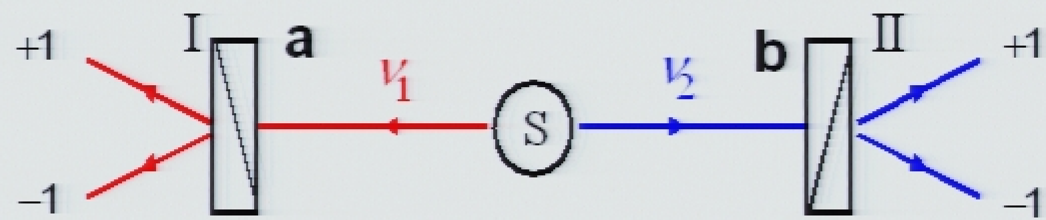
• calculation done in an abstract space, without direct correspondence in real space

How to understand the EPR correlations?

How to make an image?

·steps calculation (standard QM)

1^{rst} step: measure at polarizer I



How to understand the EPR correlations?
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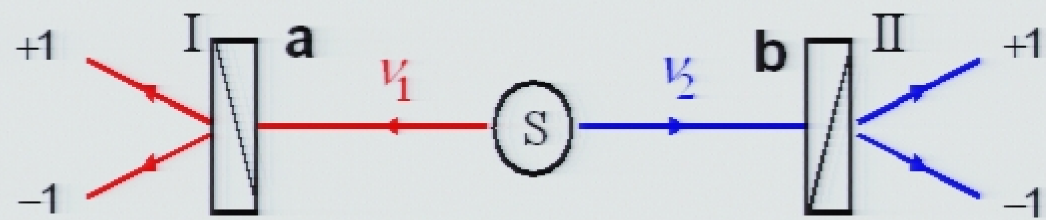


-steps calculation (standard QM)

1rst step: measure at polarizer I

⇒ result +1 (pol. along **a**)

or

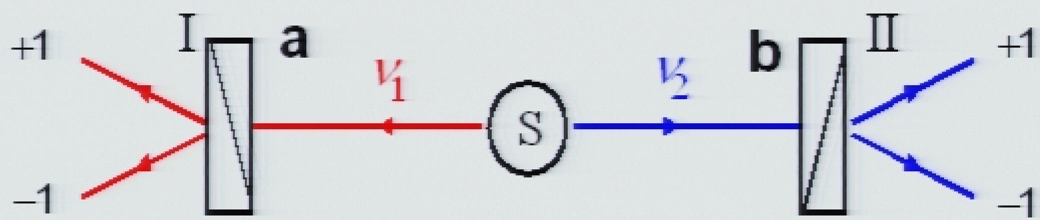
⇒ result –1 (pol. perp to **a**)

How to understand the EPR correlations?

How to make an image?

-steps calculation (standard QM)

1rst step: measure at polarizer I



⇒ result +1 (pol. along **a**) ⇒ projection of the state vector

$$\Rightarrow \quad P_{+_{\mathbf{a}}} \left|\Psi(\nu_1,\nu_2)\right\rangle = \left|+_{\mathbf{a}},+_{\mathbf{a}}\right\rangle$$

Photons polarized along **a**

How to understand the EPR correlations?

How to make an image?

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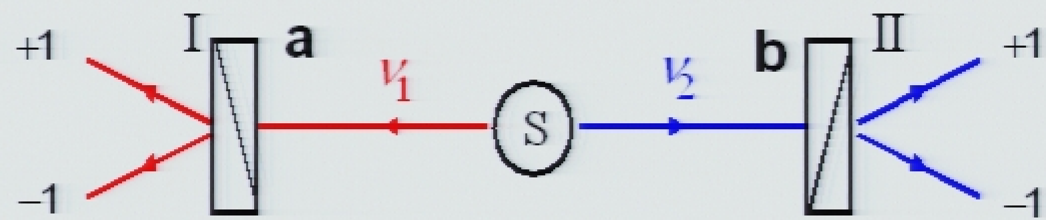
1rst step: measure at polarizer I



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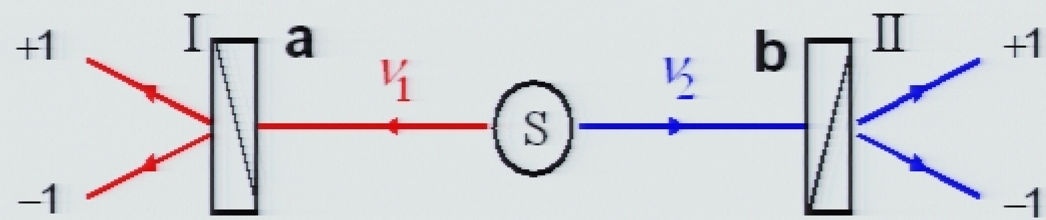

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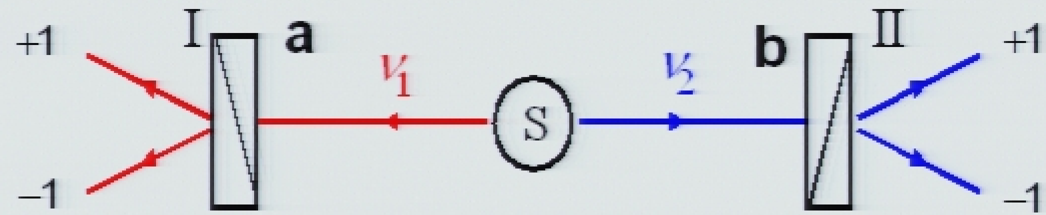

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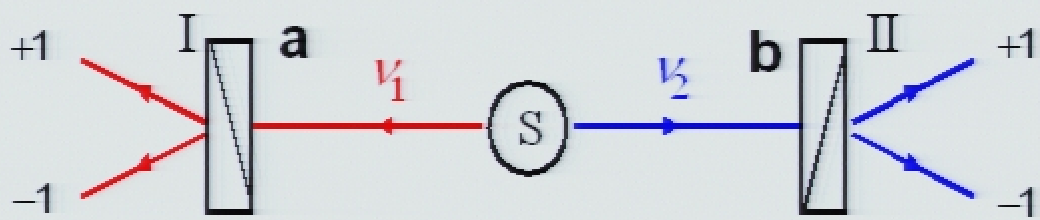

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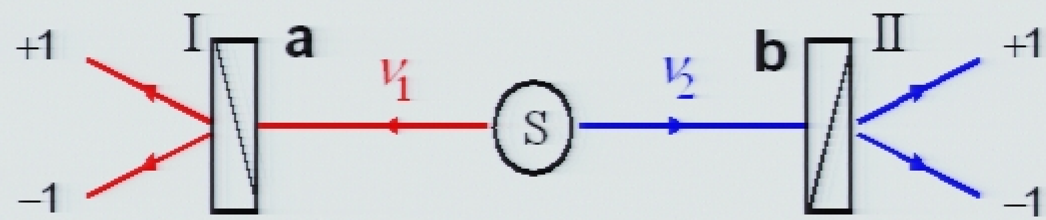

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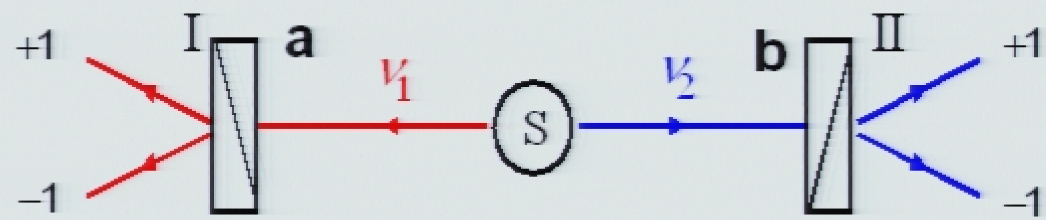
Photons polarized along **a**

- 2nd step: measure at polarizer II $\Rightarrow P_{++}(\mathbf{a},\mathbf{b}) = \frac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$

How to understand the EPR correlations?

How to make an image?

-steps calculation (standard QM)



1rst step: measure at polarizer I

$\Rightarrow$ result +1 (pol. along **a**) $\Rightarrow$ projection of the state vector

$$\Rightarrow \; P_{+_{\mathbf{a}}} \left| \Psi(\nu_1, \nu_2) \right\rangle = \left| +_{\mathbf{a}}, +_{\mathbf{a}} \right\rangle$$ Photons polarized along **a**

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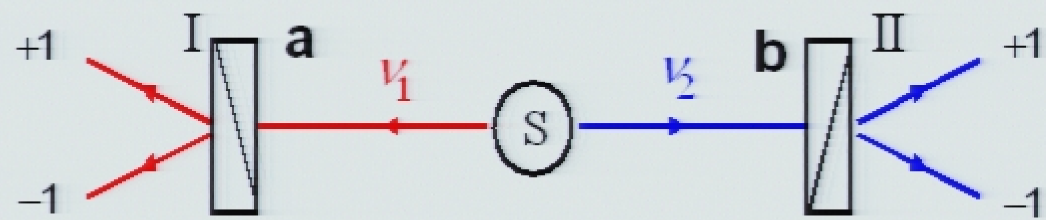
$\Rightarrow$ result -1 (pol. perp. to **a**) $\Rightarrow$ projection of the state vector

$$\Rightarrow \; P_{-_{\mathbf{a}}} \left| \Psi(\nu_1, \nu_2) \right\rangle = \left| -_{\mathbf{a}}, -_{\mathbf{a}} \right\rangle$$ Photons polarized perp to **a**

How to understand the EPR correlations?
How to make an image?

·steps calculation (standard QM)

1rst step: measure at polarizer I



⇒ result +1 (pol. along **a**) ⇒ projection of the state vector

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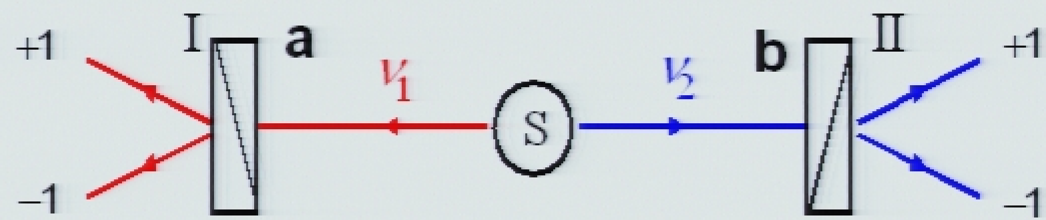
·steps calculation (standard QM)



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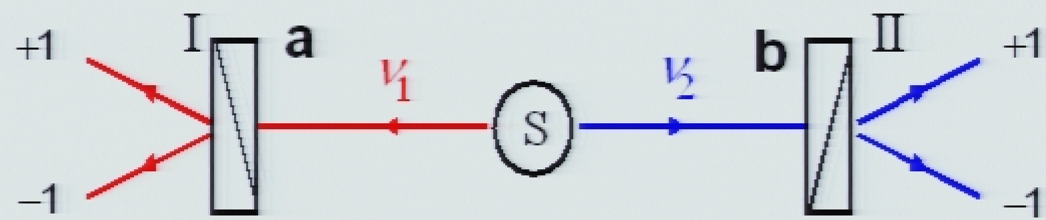

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What a picture! Polarization of ν_2 instantaneously affected by the result of measurement on ν_1 … which is far away.

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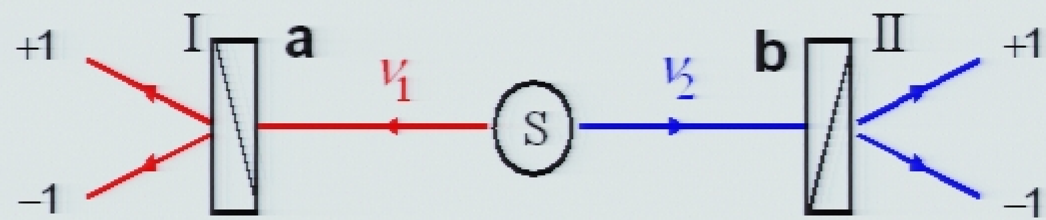

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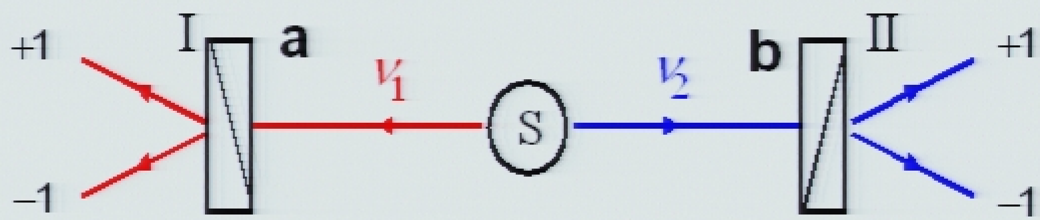

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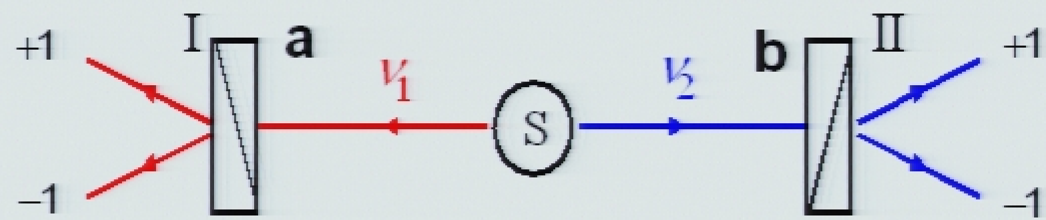

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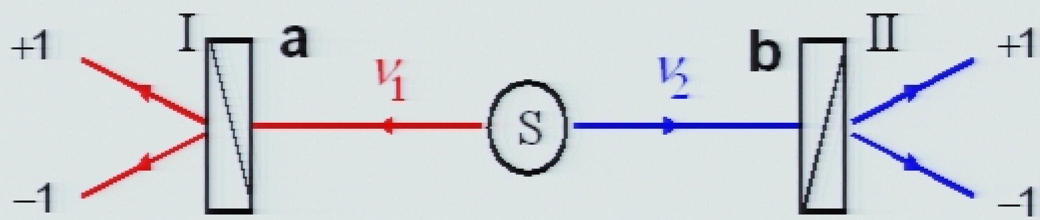

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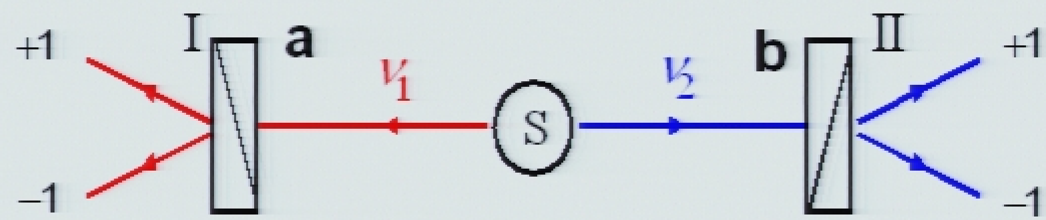

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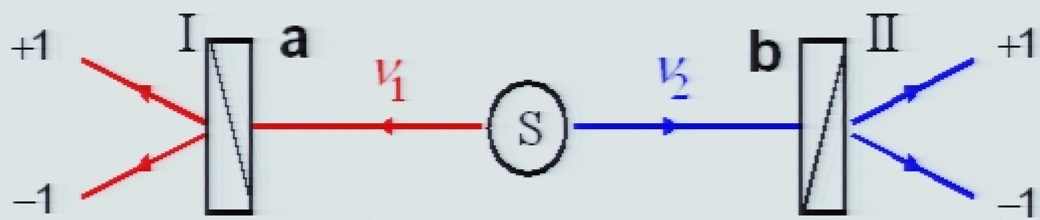

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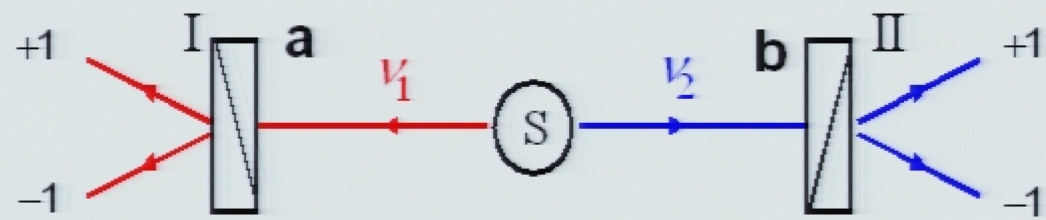

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- 2nd step: measure at polarizer II $\Rightarrow P_{++}(\mathbf{a},\mathbf{b}) = \frac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$

$\Rightarrow$ result -1 (pol. perp. to **a**) $\Rightarrow$ projection of the state vector

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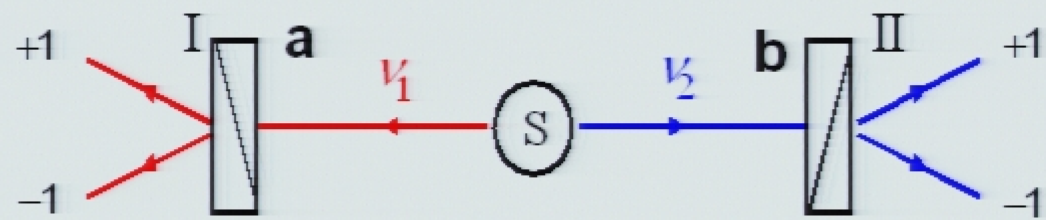
What a picture! Polarization of ν_2 instantaneously affected by the result of measurement on ν_1 … which is far away.

How to understand the EPR correlations?

How to make an image?

·steps calculation (standard QM)



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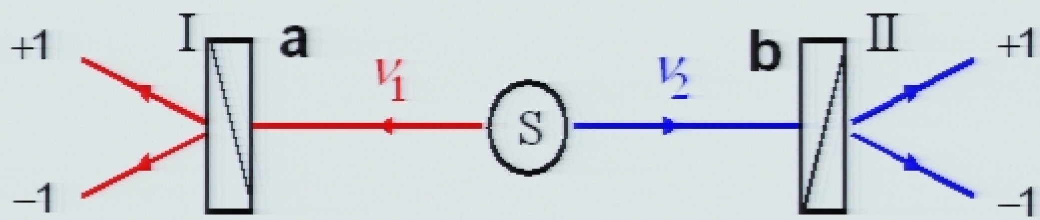

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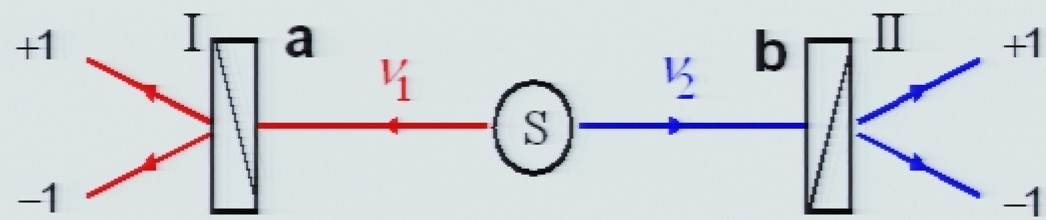

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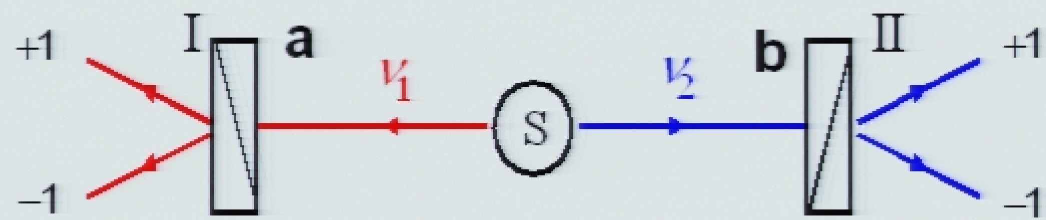

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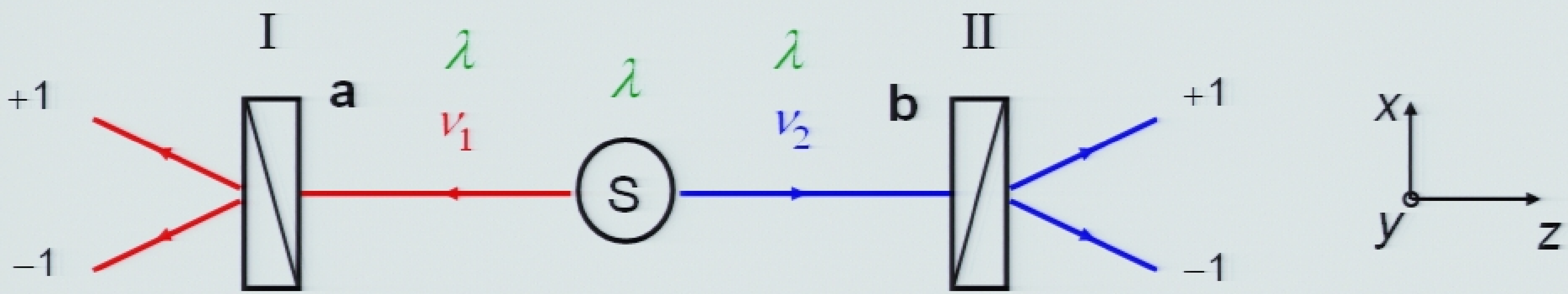
Classical explanation for correlations between distant results of measurements

- Common property λ of both particles of the same pair
- λ randomly determined in S at the emission time



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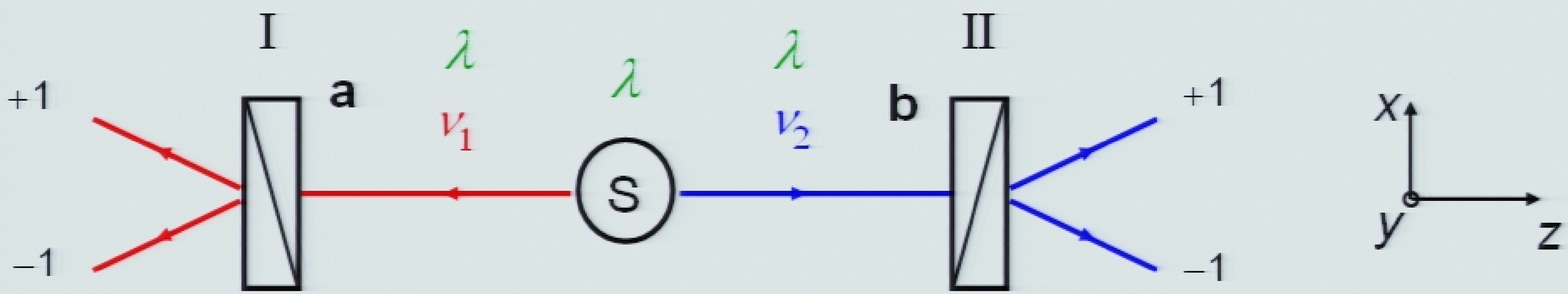

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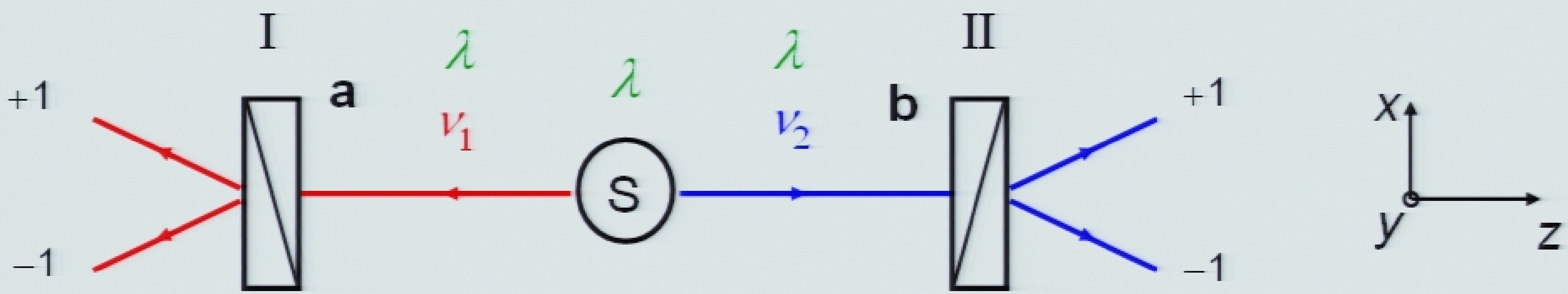

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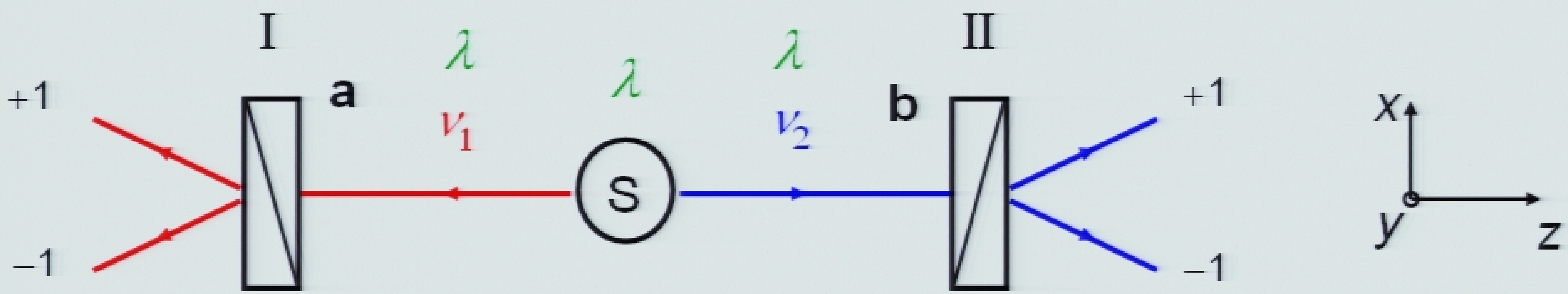


Simple image, but…

completes the formalism of quantum mechanics:

supplementary parameters λ (« hidden variables »)

From EPR to tests of Bell's inequalities: entanglement as a conceptual question

The point of view of a naive experimentalist*

- Einstein-Podolsky-Rosen correlations

  The Einstein-Bohr debate (1935-1955)

- Bell's theorem (1965)

  From epistemology back to physics

- Experimental tests: a brief review (1972-2002)

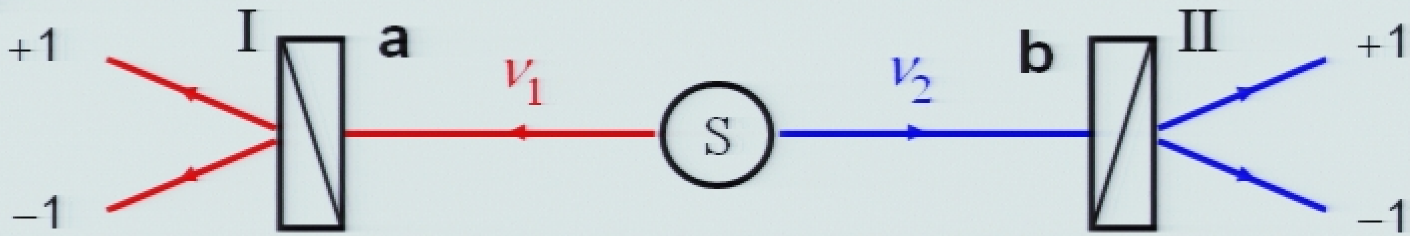
  Towards the ideal experiment

- Conclusion

  Quantum non locality: A real problem ?

* AA quant-ph/0402001

Bell's formalism



Supplementary parameters λ determine the results of measurements at I and II $\Leftrightarrow$

$$A(\lambda, \mathbf{a}) = +1 \text{ or } -1 \quad \text{at polarizer I}$$

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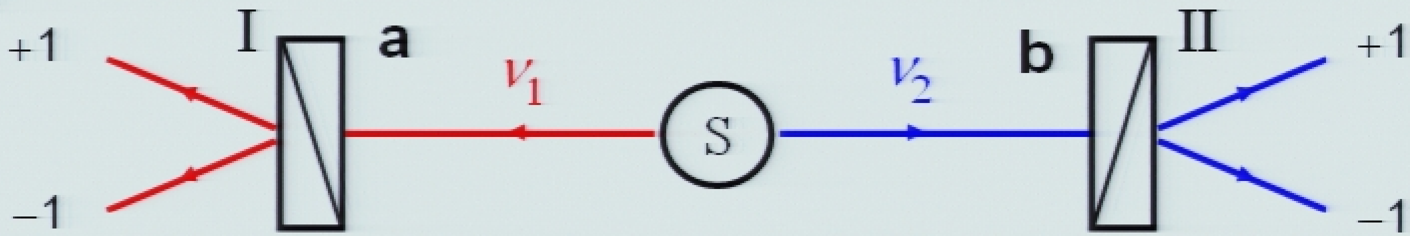

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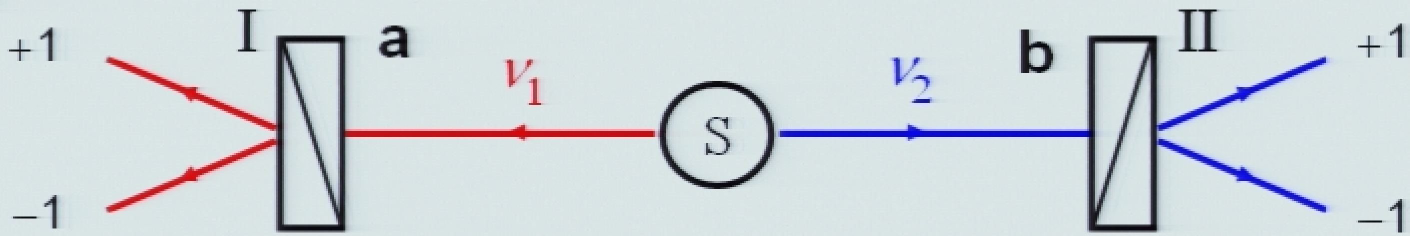

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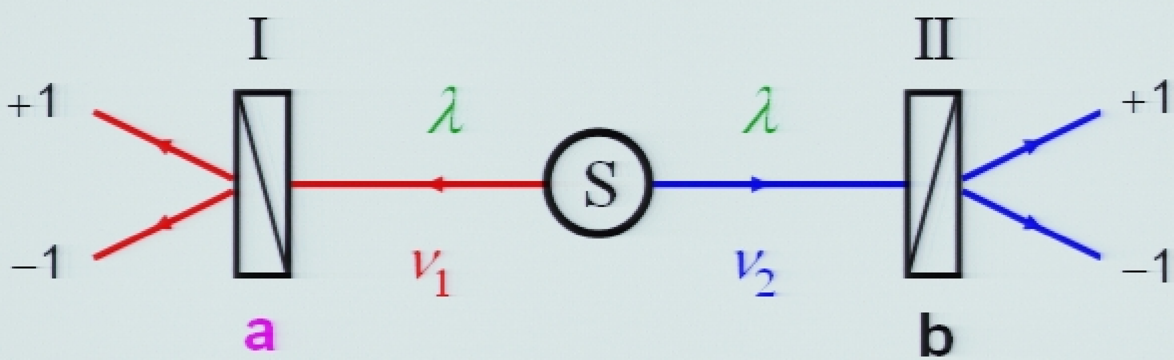
A particular hidden-variables theory gives explicit forms of A, B, ρ, and any probability can be calculated accordingly:

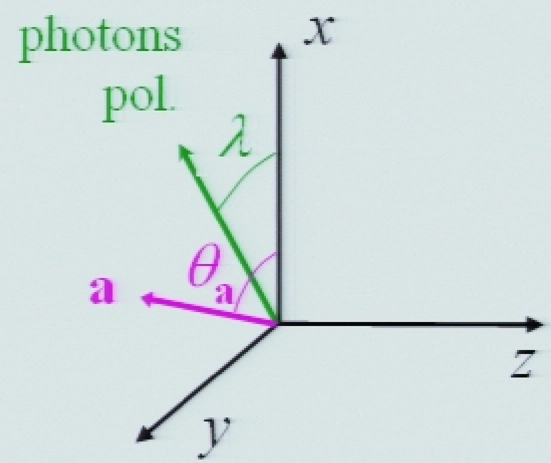
$$P_+(\mathbf{a}) = \int d\lambda\, \rho(\lambda) \left(\frac{A(\lambda,\mathbf{a})+1}{2} \right)$$

$$E(\mathbf{a},\mathbf{b}) = \int d\lambda\, \rho(\lambda) A(\lambda,\mathbf{a}) B(\lambda,\mathbf{b})$$

Naive example of LHVT

Photons polarized at an angle λ from x axis





$$\rho(\lambda) = \frac{1}{2\pi}$$

Rotational invariance

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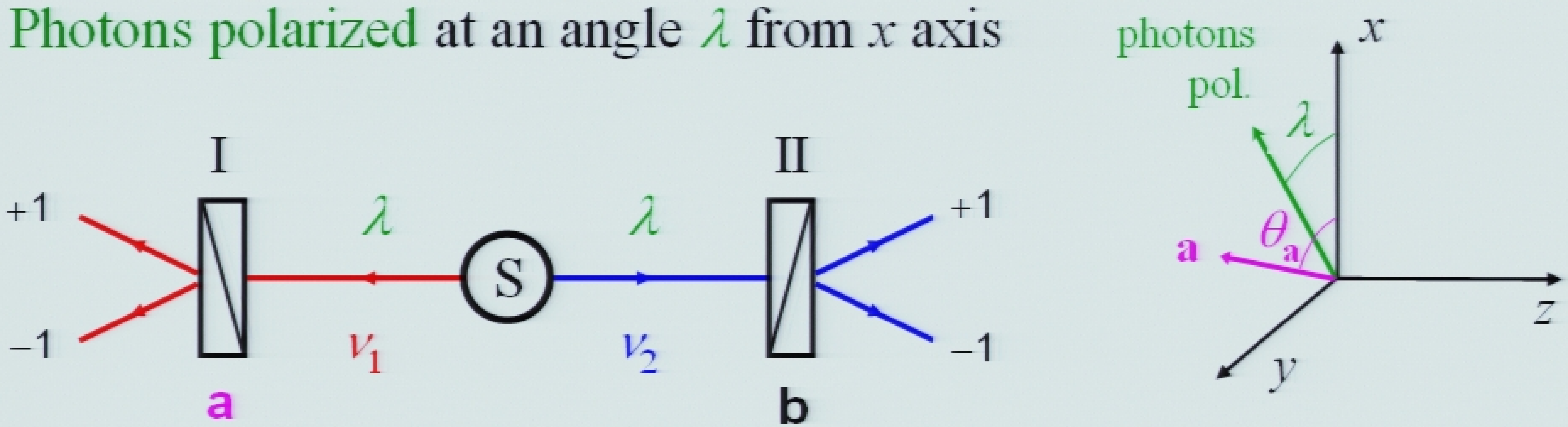

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$= +1$ if $|\theta - \lambda| \leq \pi/4$

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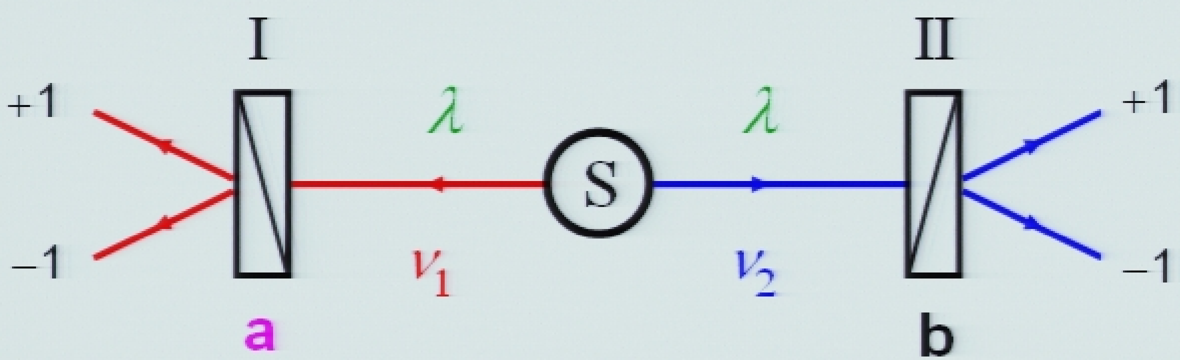

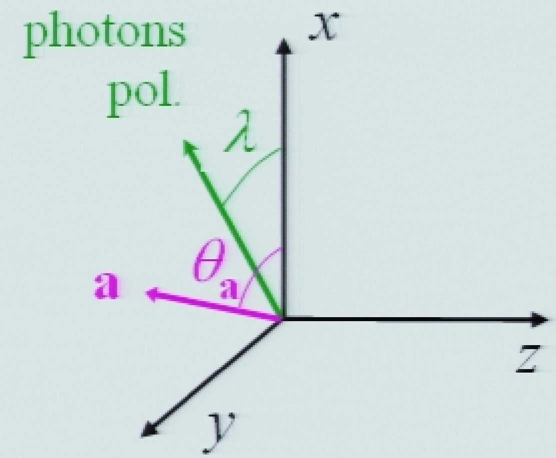

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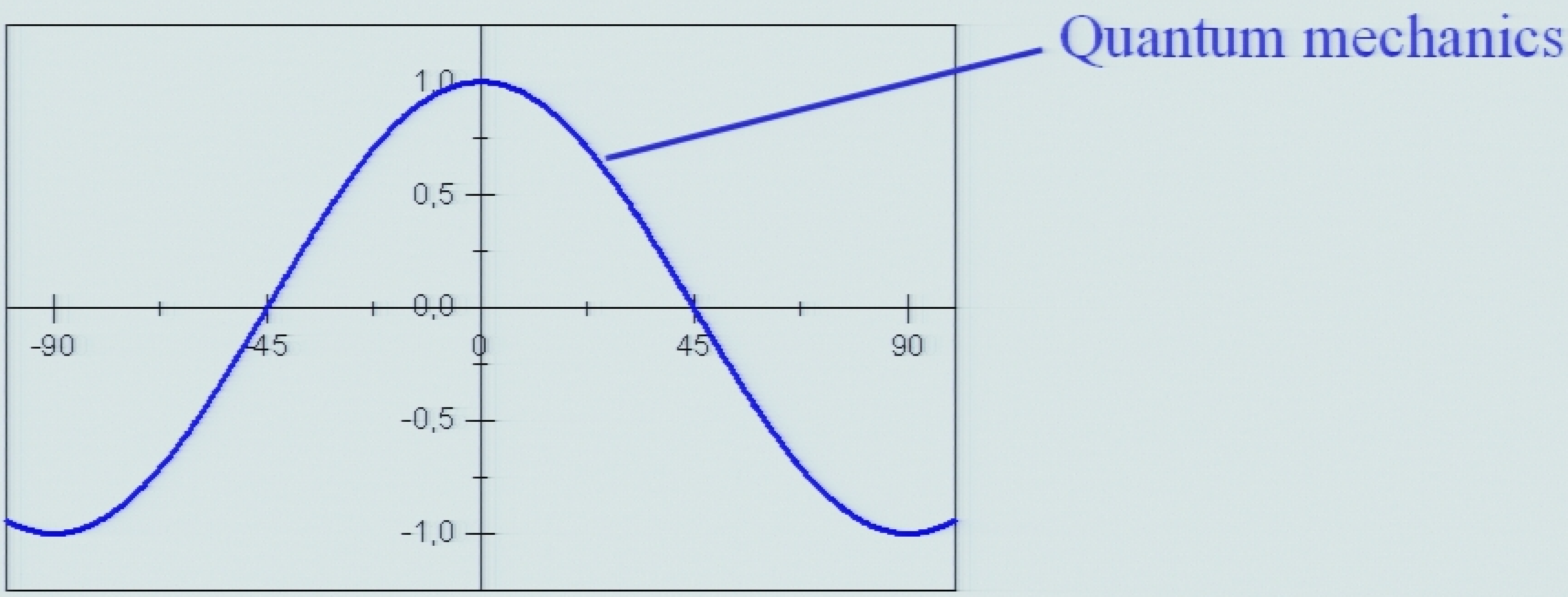
$\Rightarrow P_+(\mathbf{a}) = P_+(\mathbf{b}) = 1/2$ etc...

$\Rightarrow E(0) = 1 \;,\; E(90) = -1$

Same predictions as quantum mechanics

Naive example
Correlation coefficient *vs.* polarizers angle



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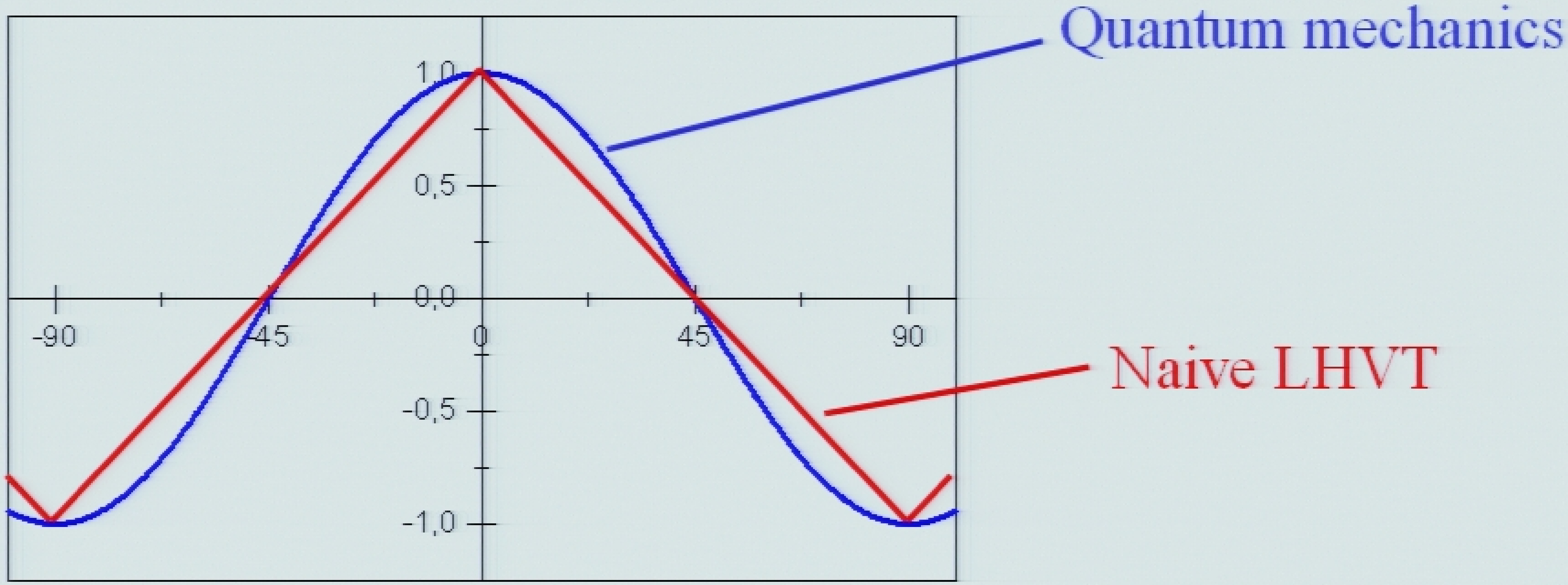

Not bad for such a simple model!

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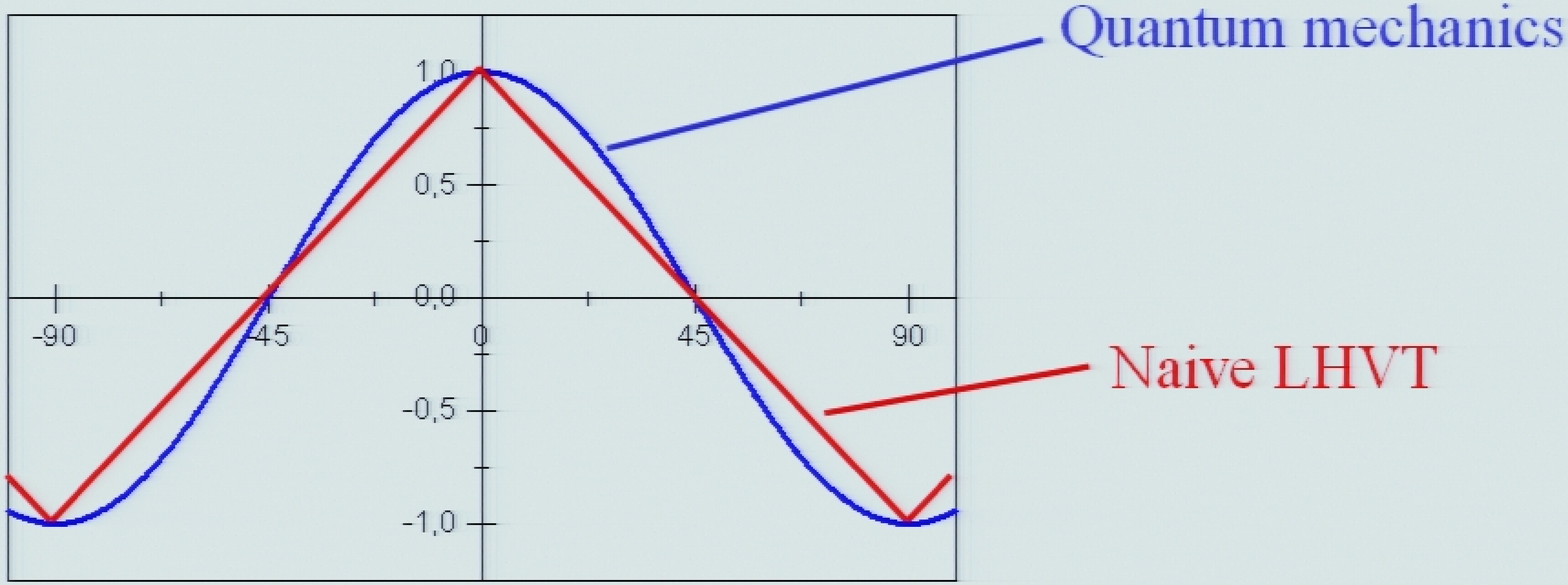

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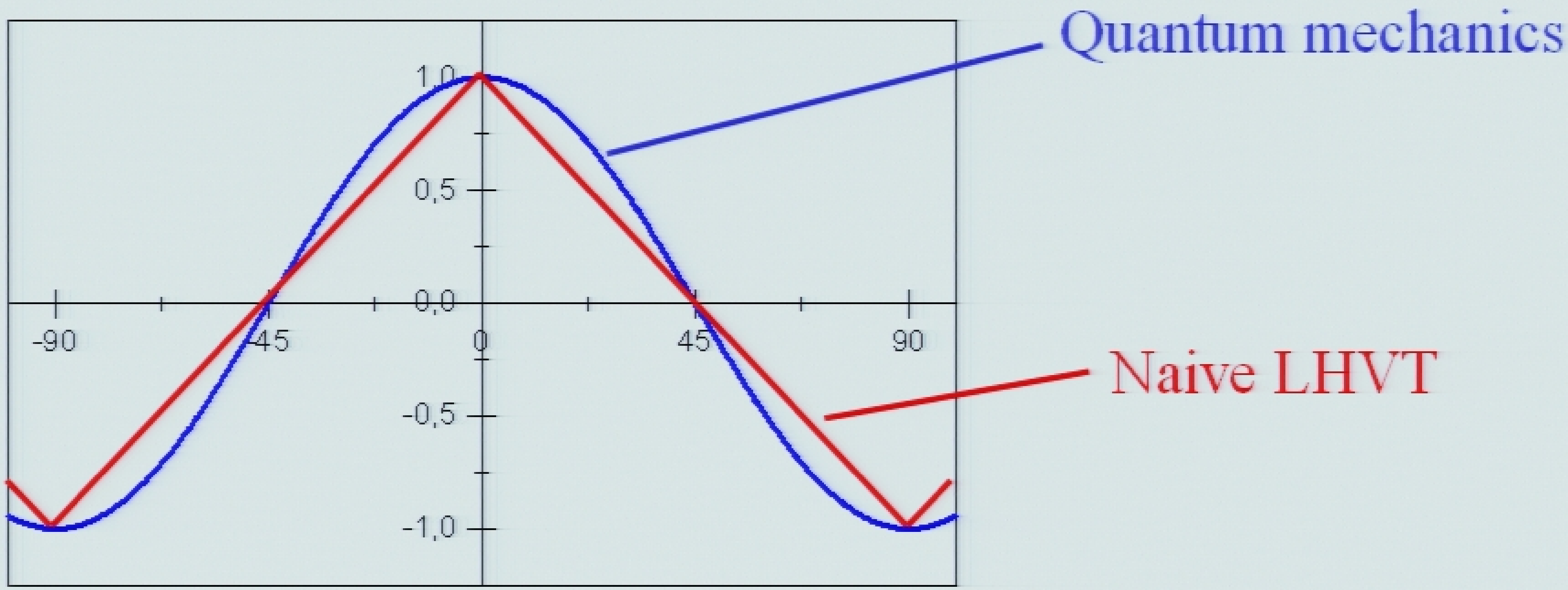

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Bell's theorem answer:

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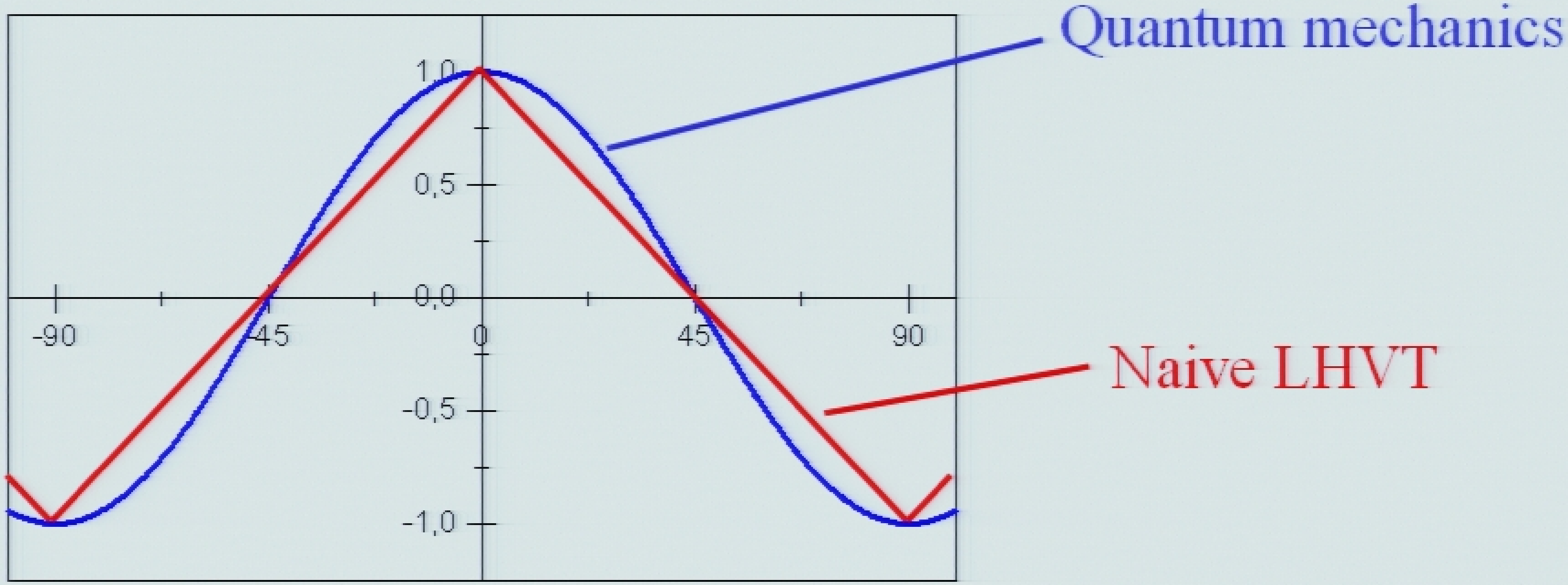

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Bell's theorem

Local Hidden Variable Theories $\Rightarrow$ Bell's inequalities

$-2 \leq S \leq 2$ with $S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$

$$|+_a, x\rangle\langle +_a, x| + |+_a, y\rangle\langle +_a, y|$$

$$|\Psi_{EPR}\rangle = \frac{1}{\sqrt{2}}\left(|x\,x\rangle + |y\,y\rangle\right)$$

$$x, x', y, y' = \pm 1 \qquad \Delta = xy - xy' +$$

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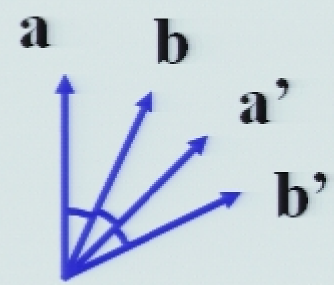
$$E_{\text{MQ}}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$$



$$S_{\text{QM}} = 2\sqrt{2}$$

CONFLICT ! The possibility of completing QM with Hidden Variables is no longer a matter of taste. It has become an experimental question.

[redacted]

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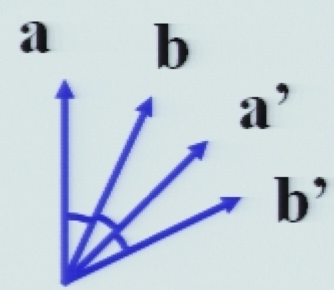

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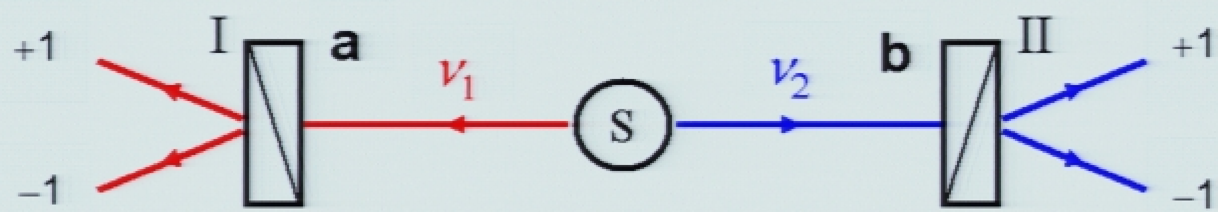
Hypotheses for Bell's inequalities
(⇒ conflict with Q. M.)



Hidden variables (supplementary parameters)

or some « classical » explanation – « à la Einstein » – for the EPR correlations, involving physical reality

Locality $A(\lambda, \mathbf{a}, \not{\mathbf{b}})$ $B(\lambda, \not{\mathbf{a}}, \mathbf{b})$ $\rho(\lambda, \not{\mathbf{a}}, \not{\mathbf{b}})$

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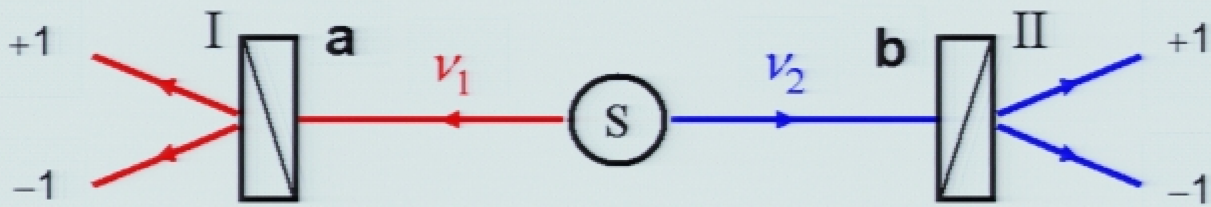

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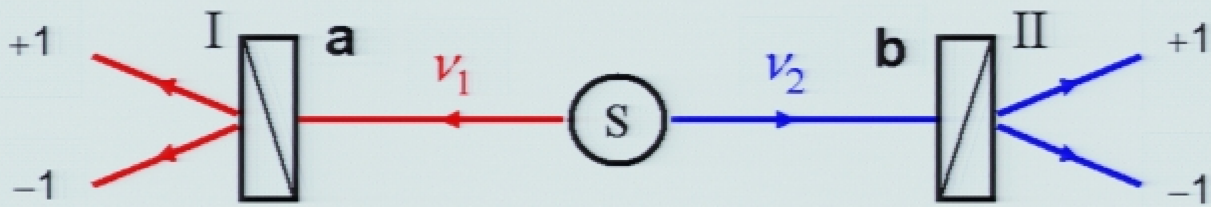

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The locality condition

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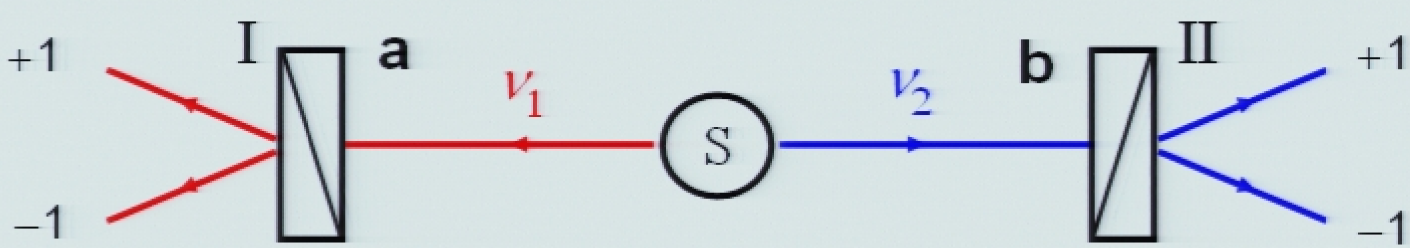
It can be stated as a reasonable assumption, but…

…in an experiment with time-variable analyzers (orientations randomly changed with a period smaller than L / c *with* L = distance between analyzers) the locality condition becomes a consequence of Einstein's causality (no faster-than-light influences)



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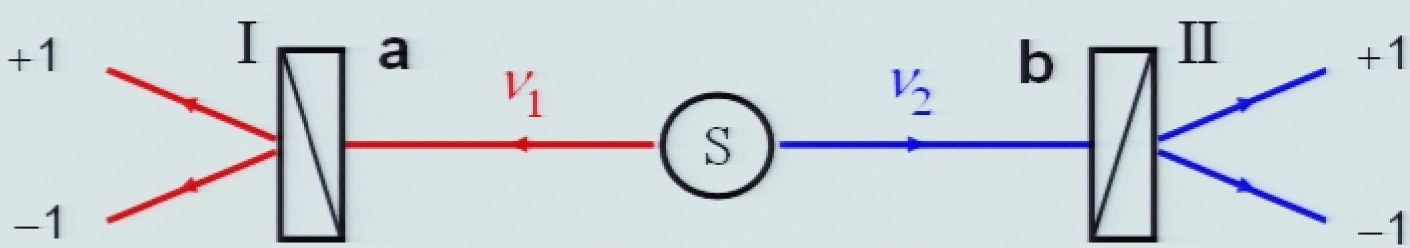

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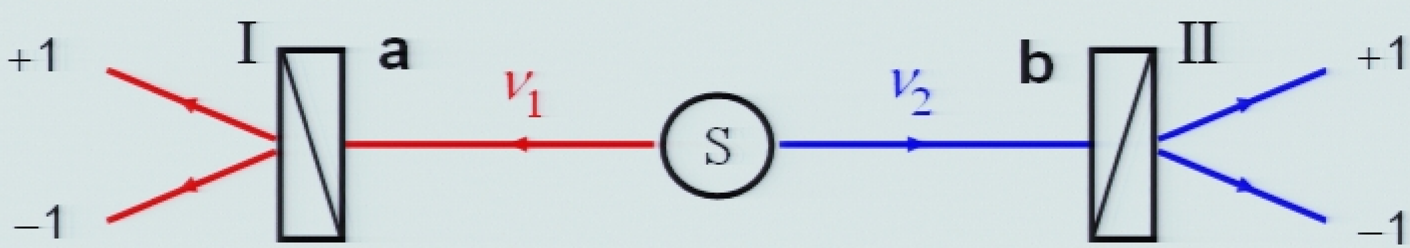

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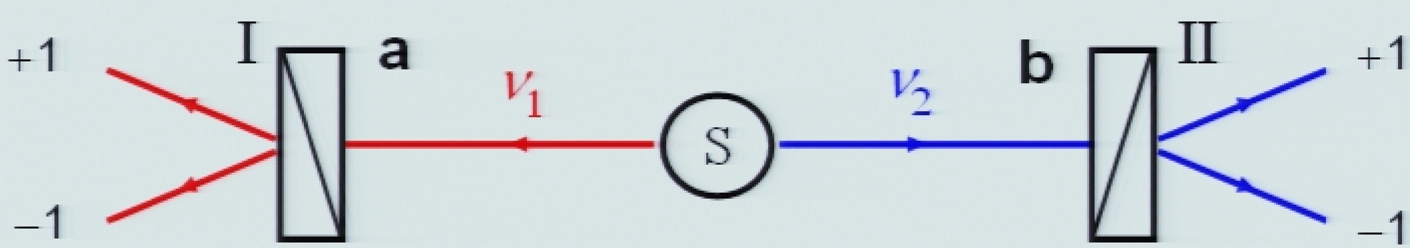

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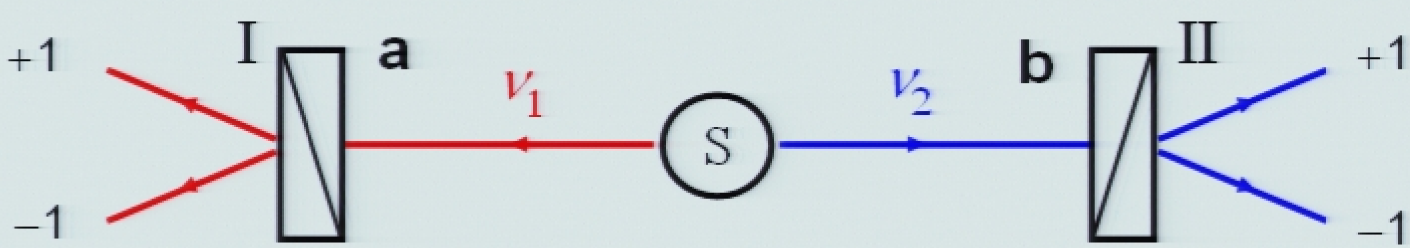

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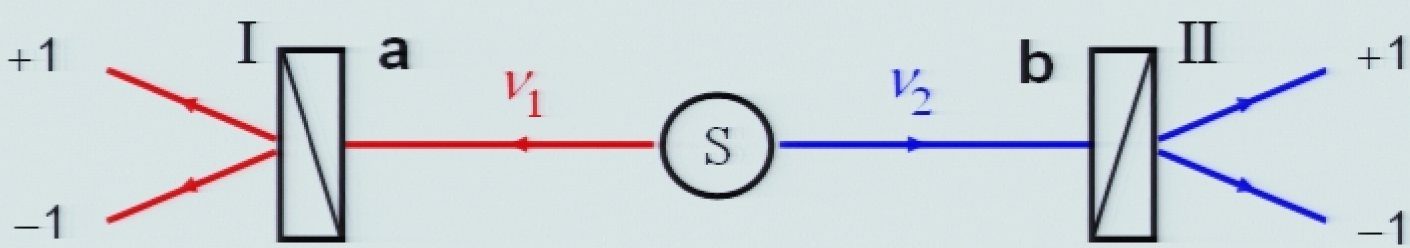

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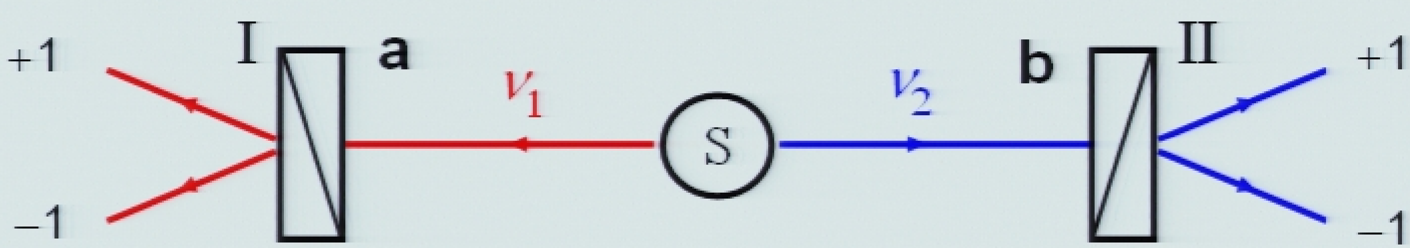

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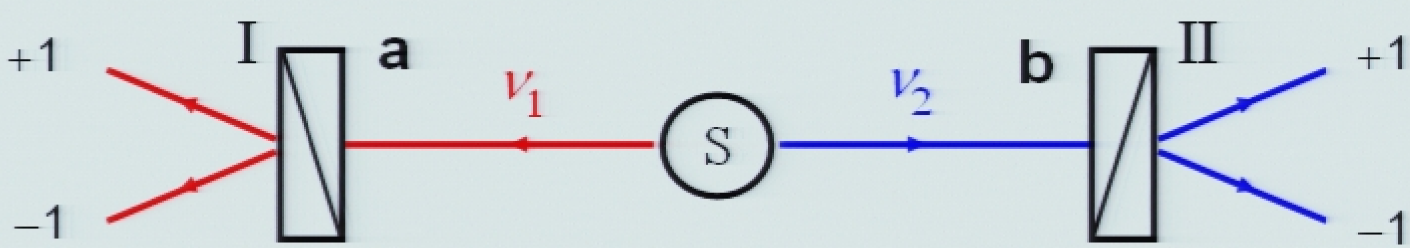

titut d'Optique

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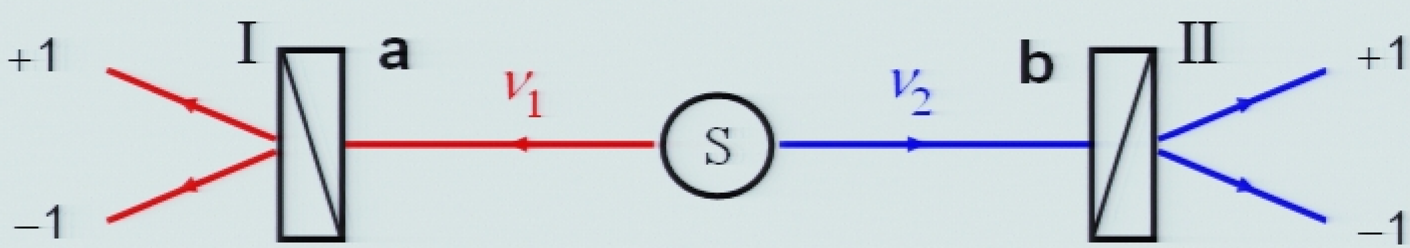

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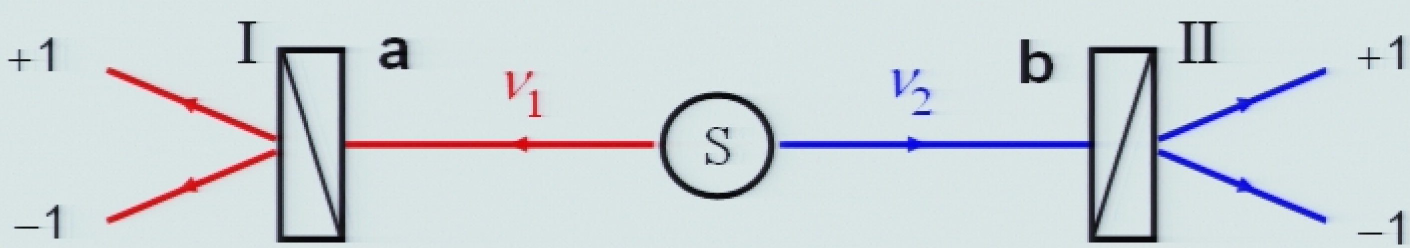

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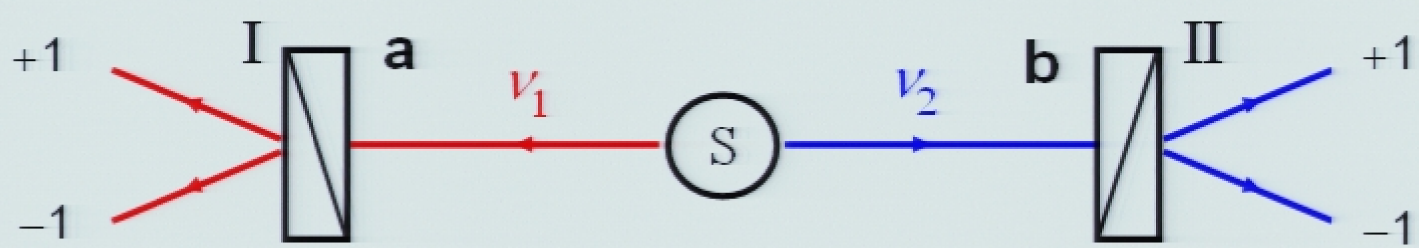

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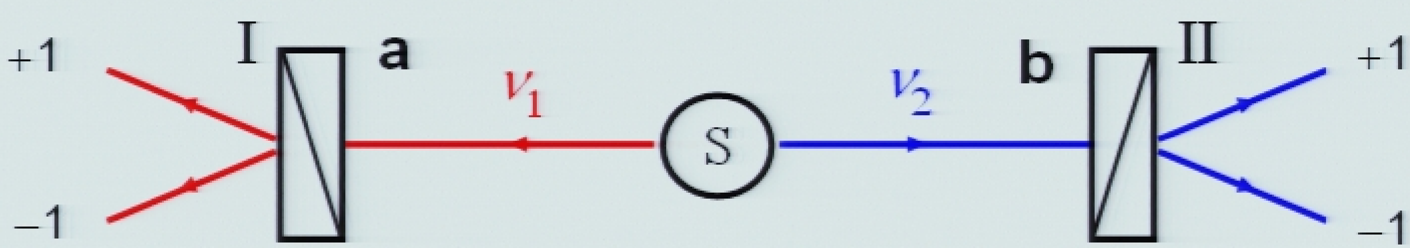

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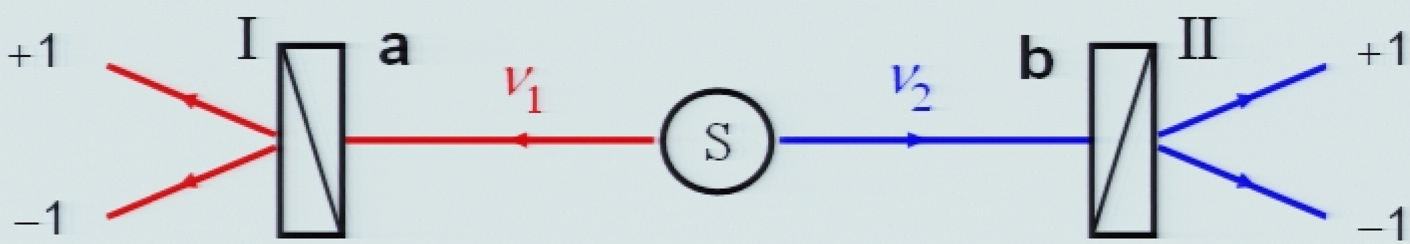

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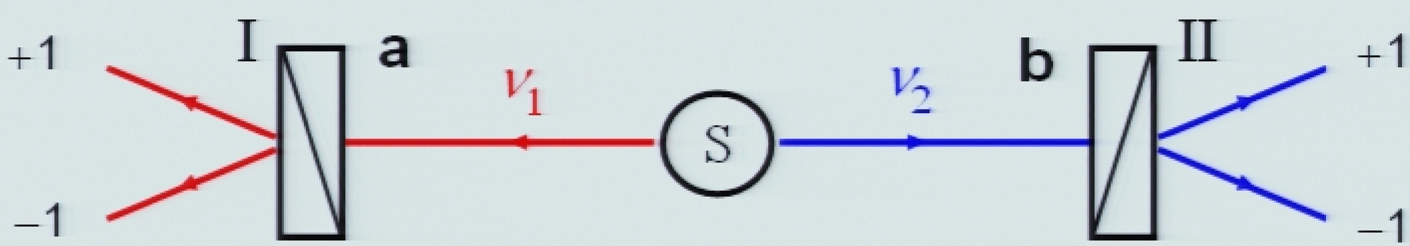

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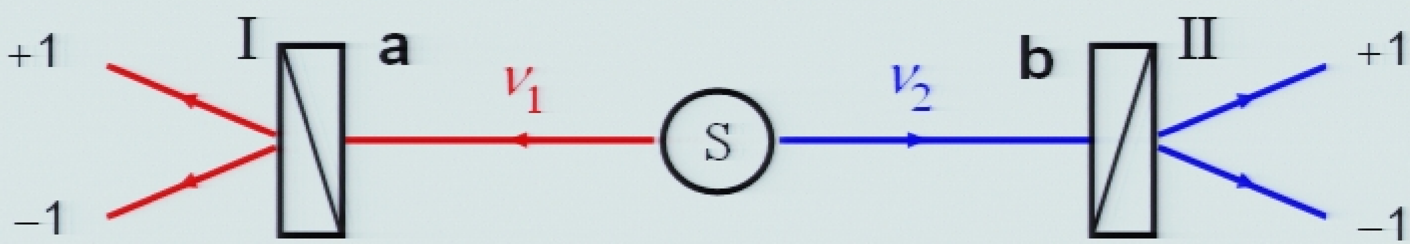

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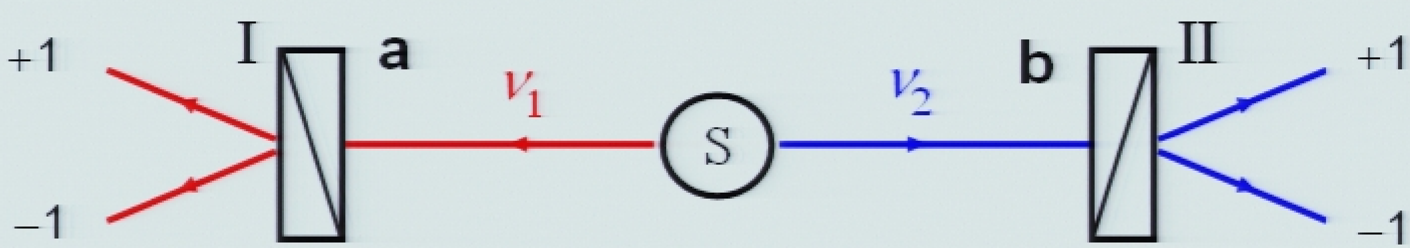

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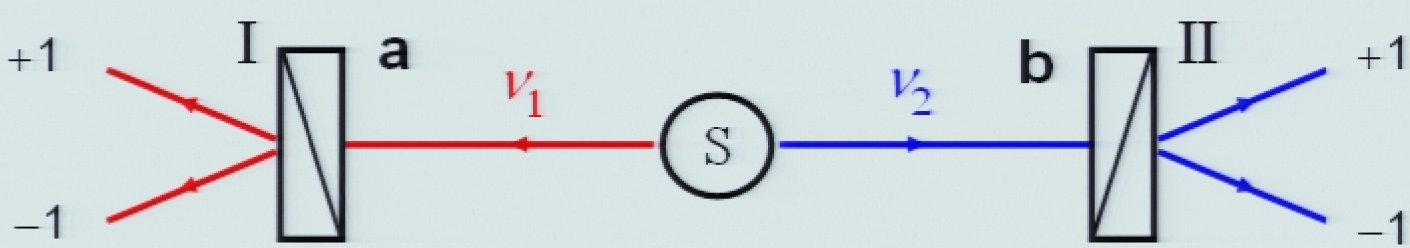

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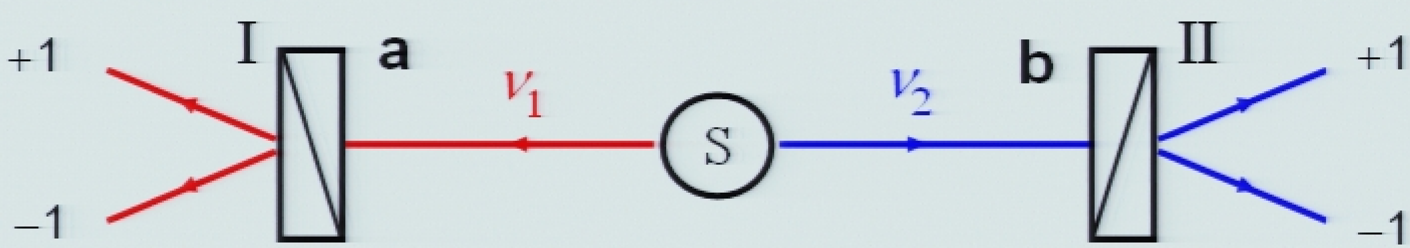

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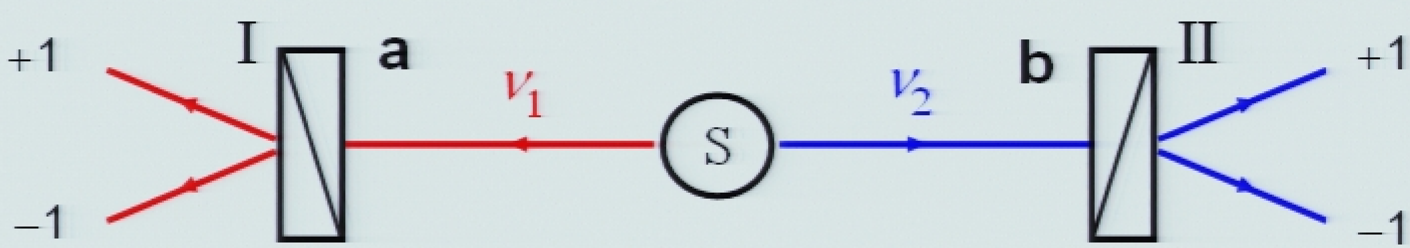
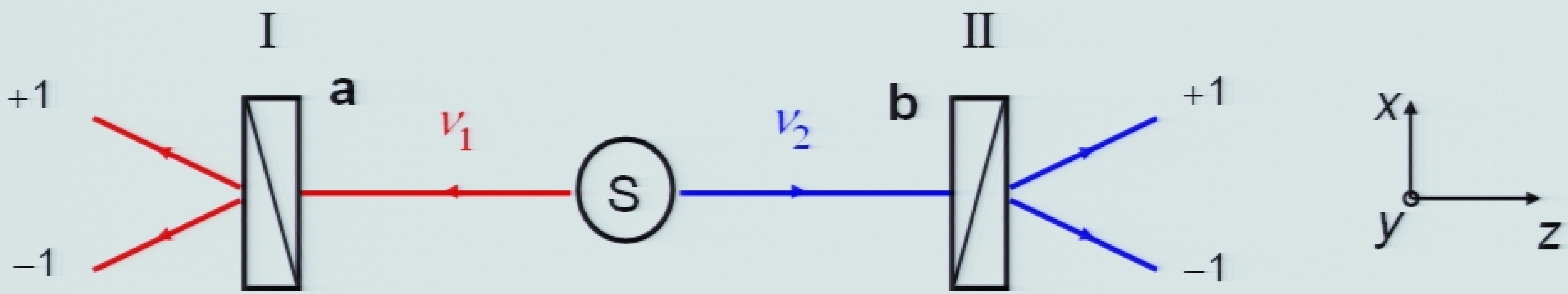


titut d'Optique

Einstein-Podolsky-Rosen GedankenExperiment
with variable polarizers



Photons in the EPR entangled state: $|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\}$

Quantum Mechanics

$E_{MQ}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$

← CONFLICT →

Bell's inequalities
(Einstein's local realism)

$-2 \leq S \leq 2$

$S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$

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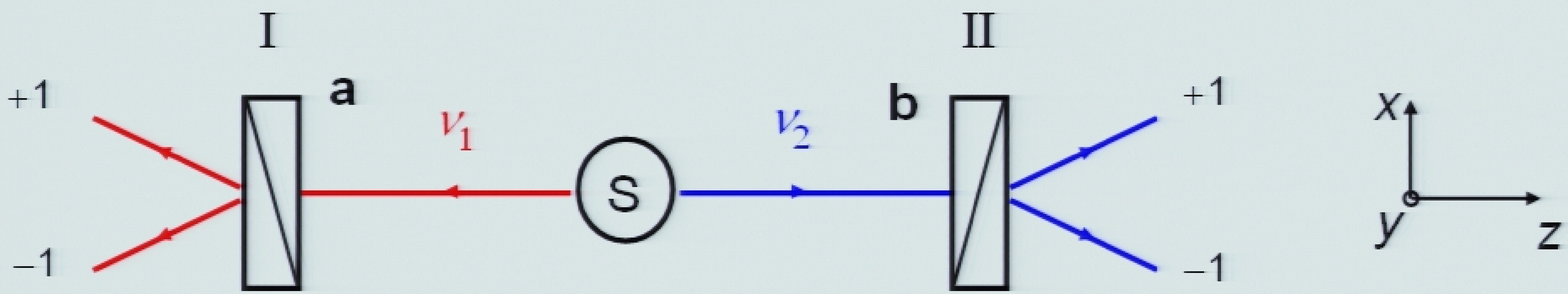

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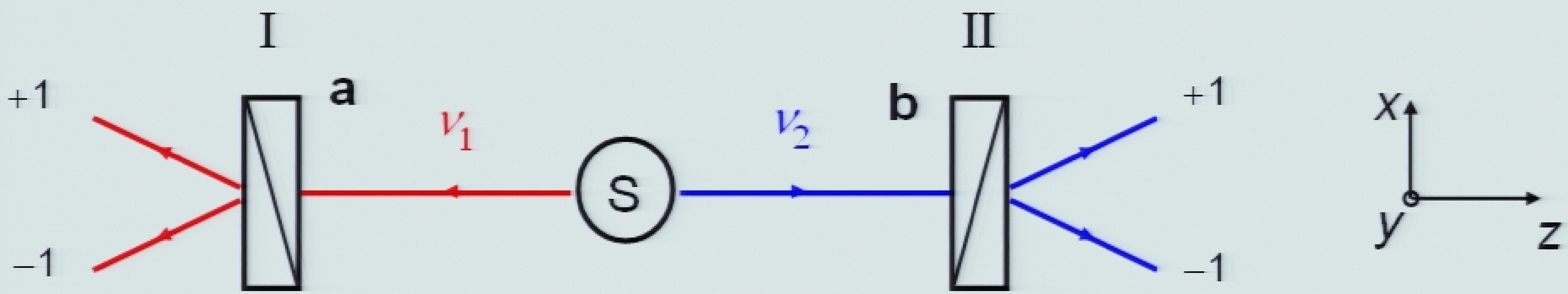

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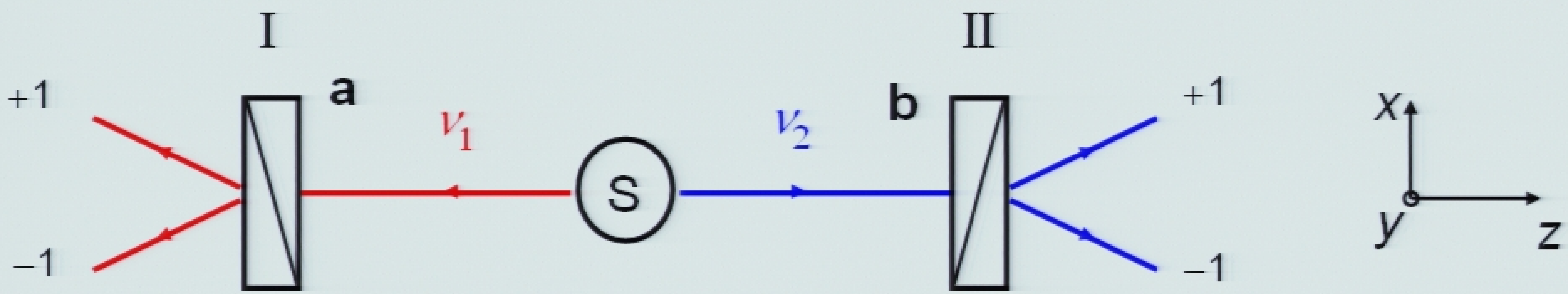

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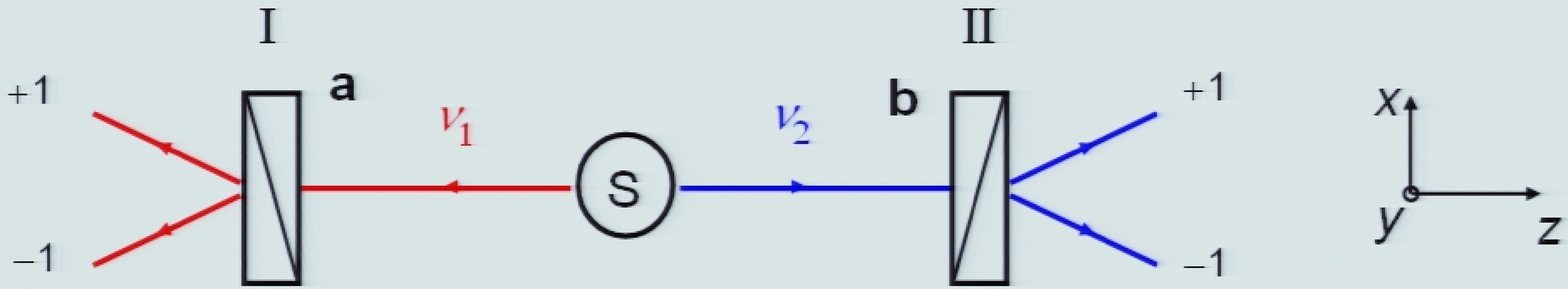

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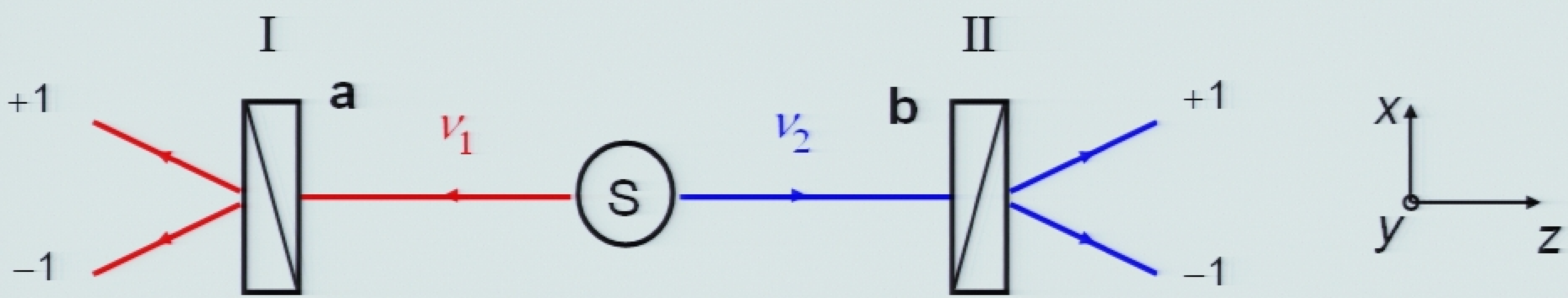

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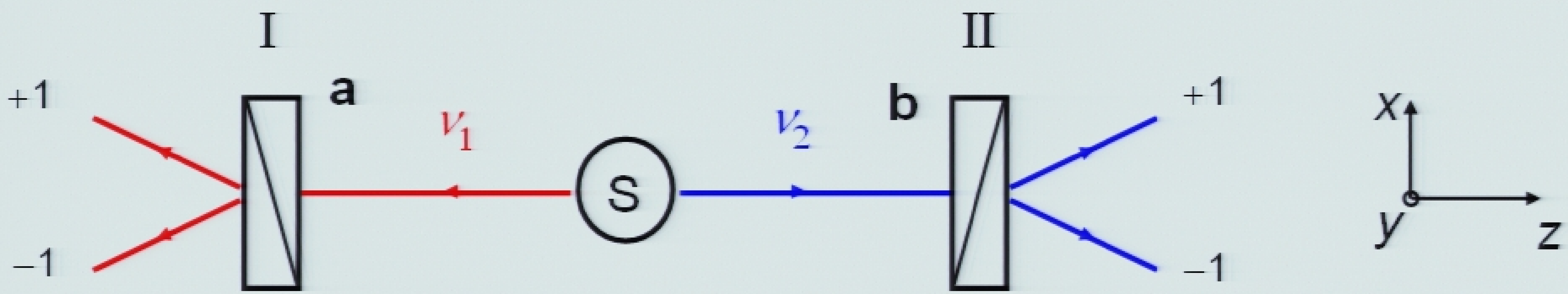

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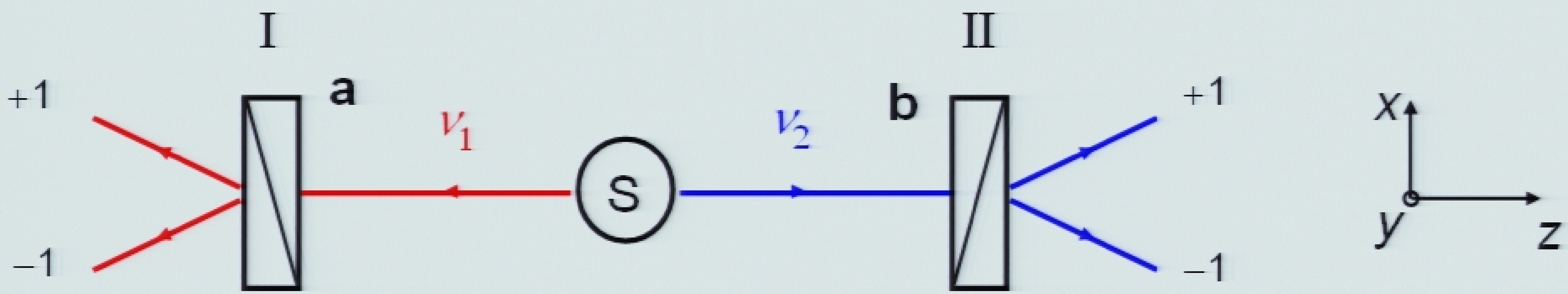

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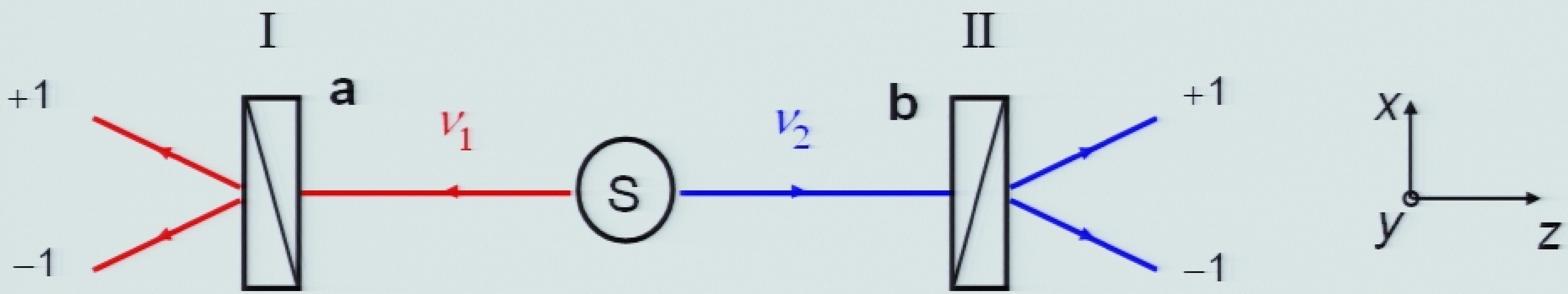

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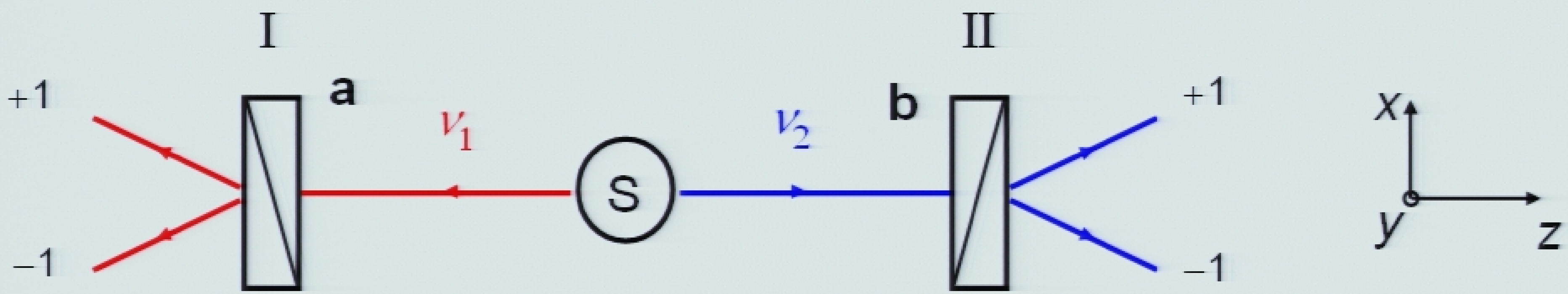

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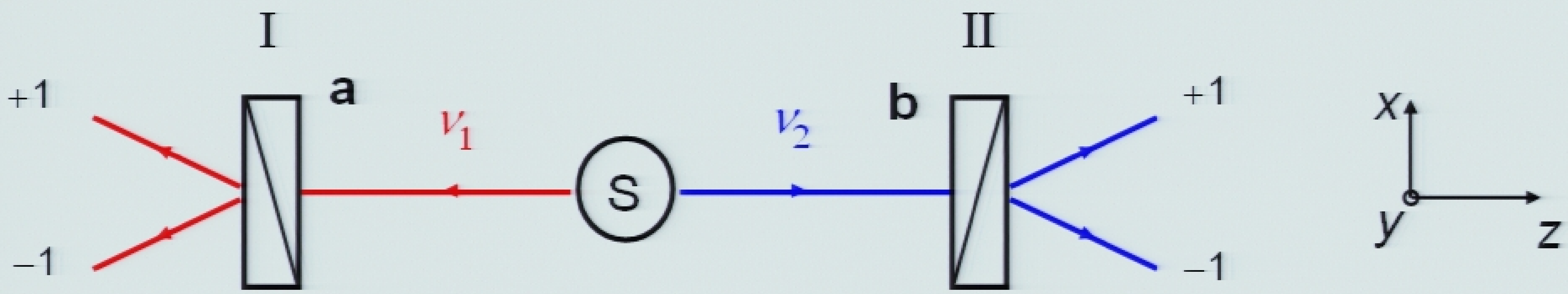

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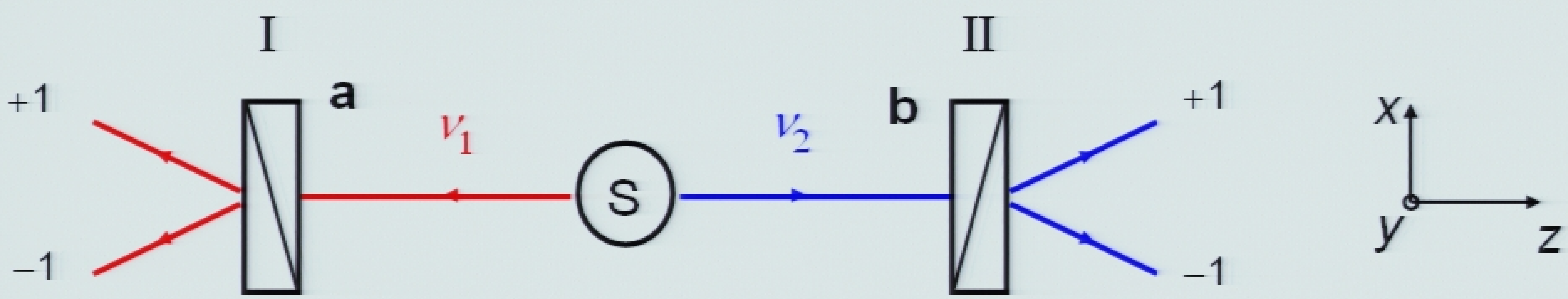

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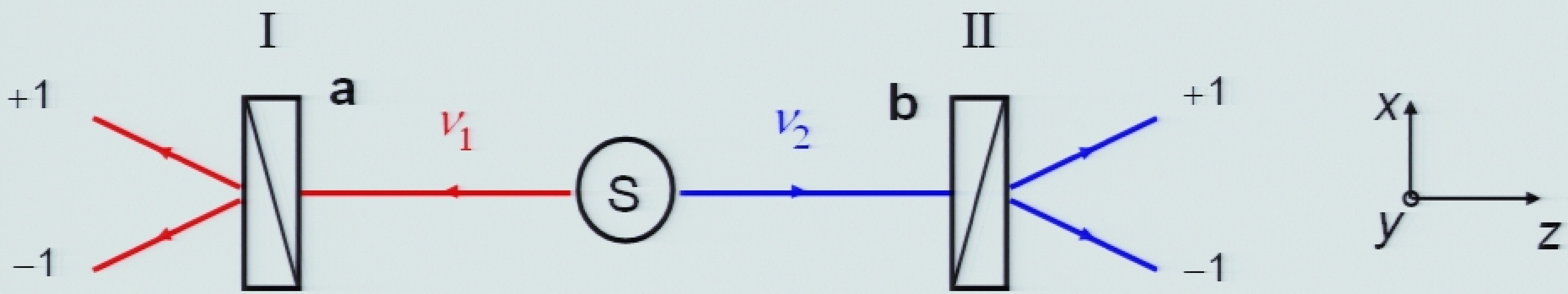

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Bell's theorem

Some predictions of Quantum Mechanics (in EPR situations) can not be mimicked by a « reasonable classical-like model » in the spirit of Einstein's ideas.

What about nature ?

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When Bell's theorem appeared, there was no experimental result available for testing Bell's inequalities vs. Quantum Mechanics.

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CNRS

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Couldn't it be that the violation of Bell's inequalities indicates a limit of the validity of Quantum Mechanics ?

From EPR to tests of Bell's inequalities: entanglement as a conceptual question

The point of view of a naive experimentalist*

- Einstein-Podolsky-Rosen correlations

  The Einstein-Bohr debate (1935-1955)

- Bell's theorem (1965)

  From epistemology back to physics

- Experimental tests: a brief review (1972-2002)

  Towards the ideal experiment

- Conclusion

  Quantum non locality: A real problem ?

* AA quant-ph/0402001

First experiments with EPR pairs

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Experiments with γ photons (0.5 MeV) produced in positronium desintegration

Experiments with protons (proton scattering on a target)

Agreement with QM, but not a test of Bell's inequalities

There are no polarizers (apparatus with 2 outcome). The polarization is inferred from a Compton scattering, by use of a QM calculation.

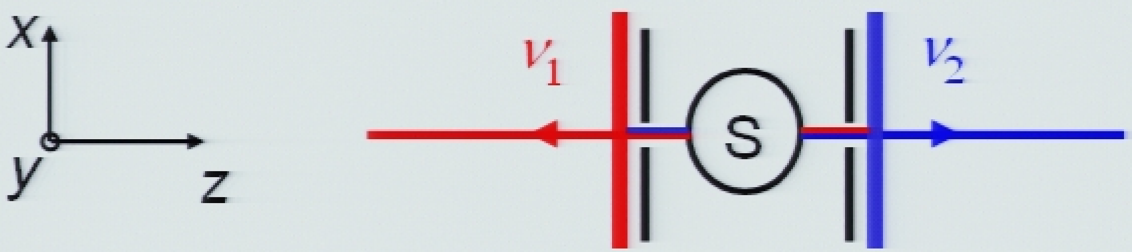
Visible photons EPR pairs produced in some atomic radiative cascades

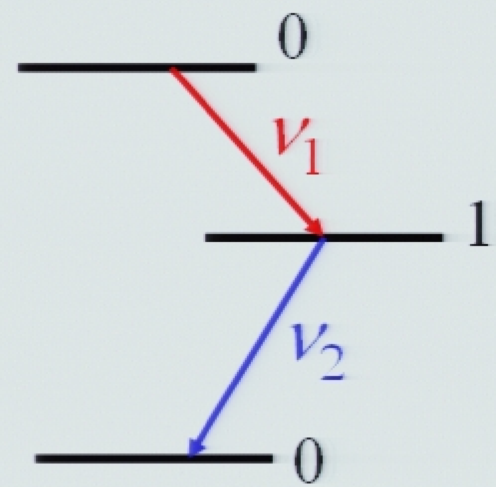
titut d'Optique

Polarizers do exist for visible photons

EPR pairs produced in radiative cascades
(Clauser, Horne, Shimony, Holt, 1969)

$$J = 0 \rightarrow J = 1 \rightarrow J = 0$$





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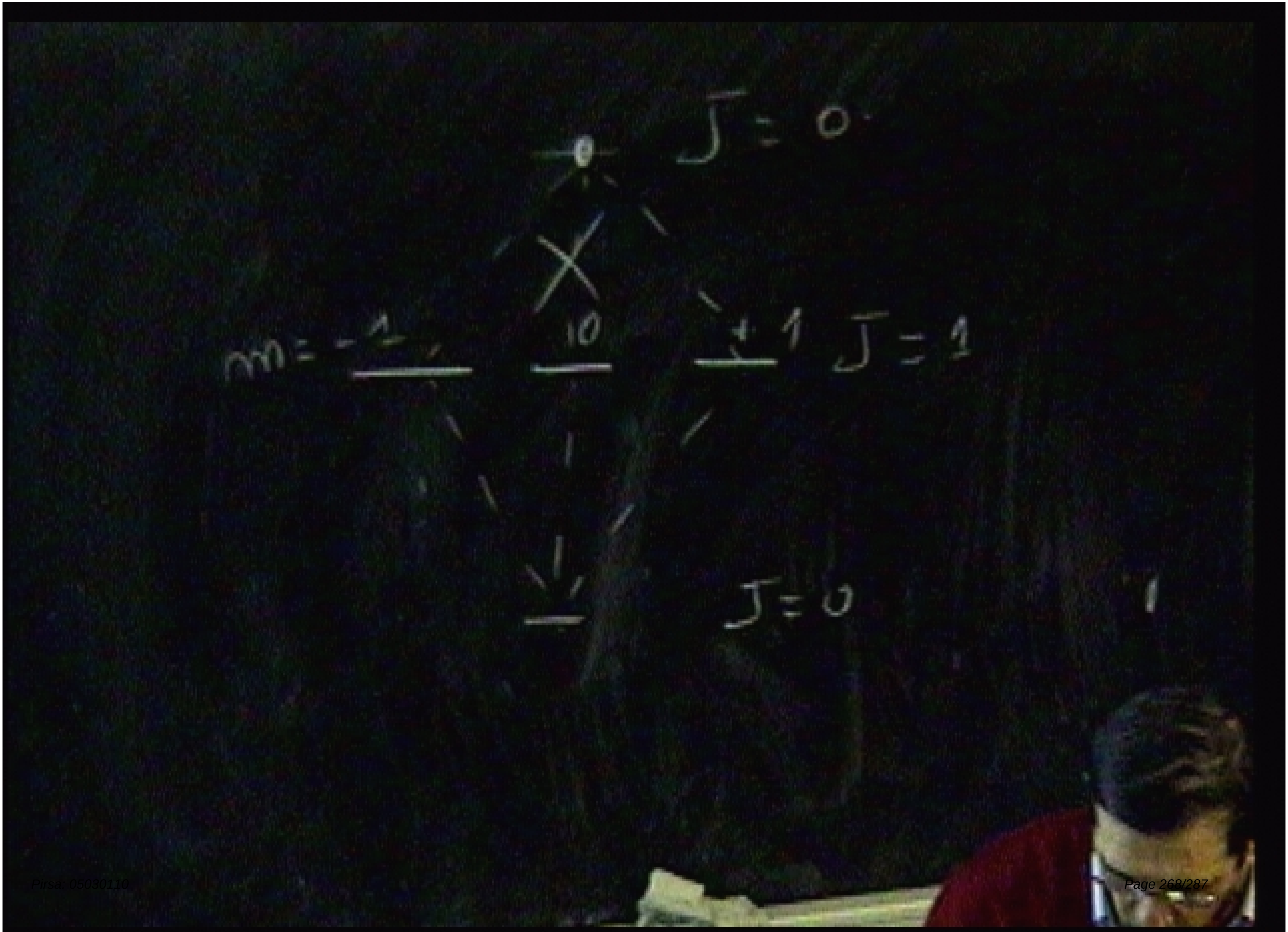
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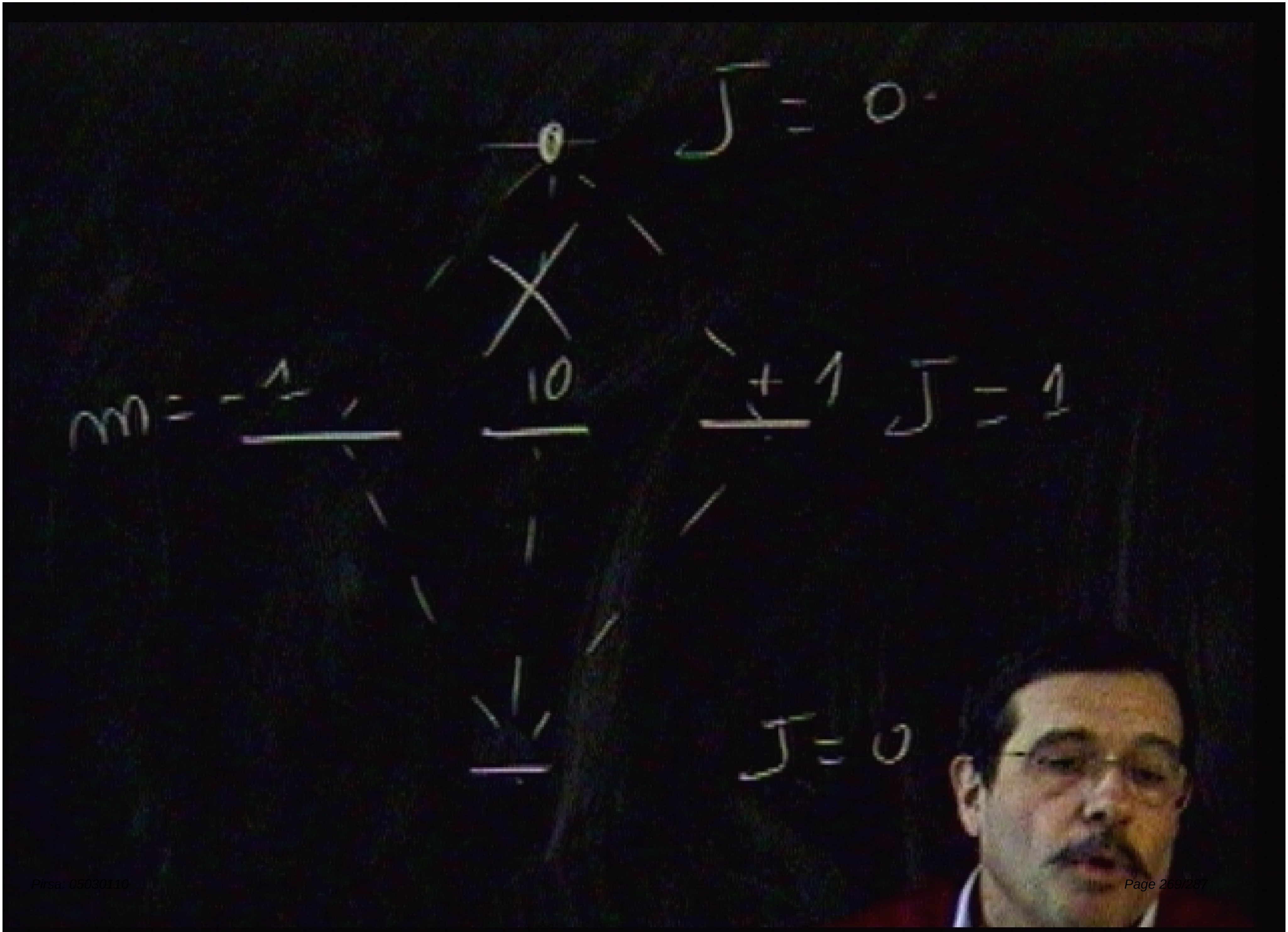
m = -1
0
+1
J = 1
J = 0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m = -1
10
+1
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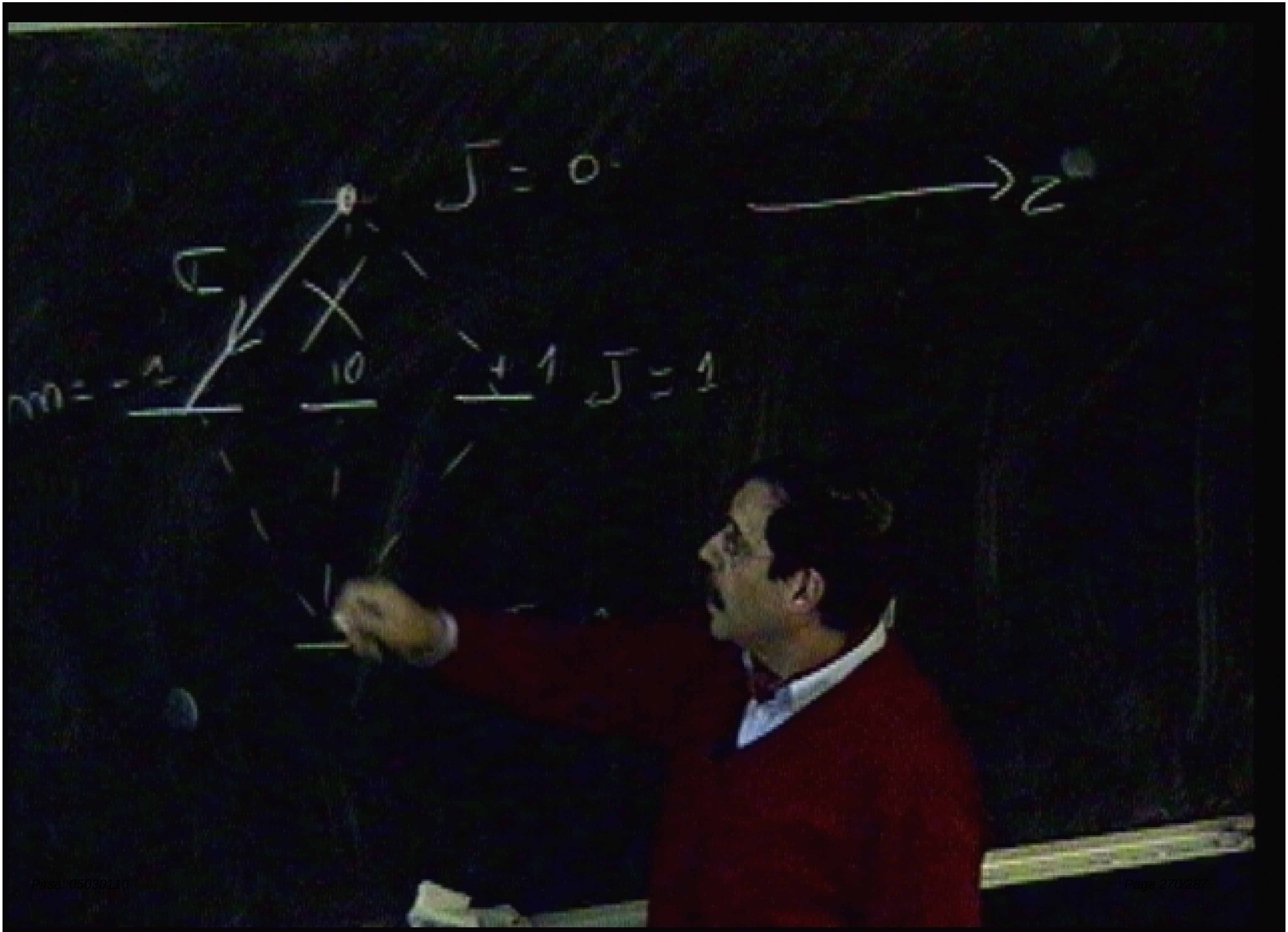
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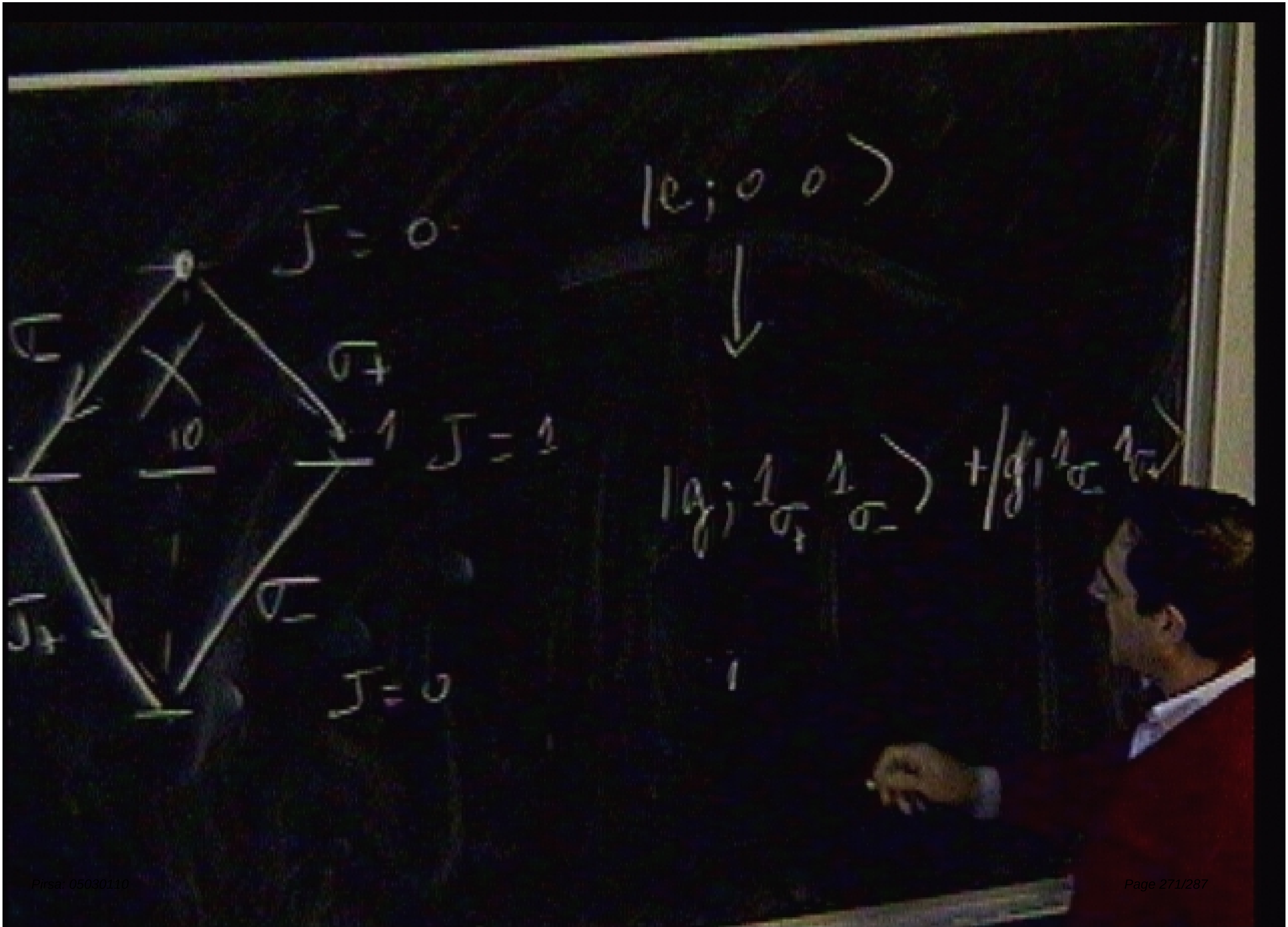
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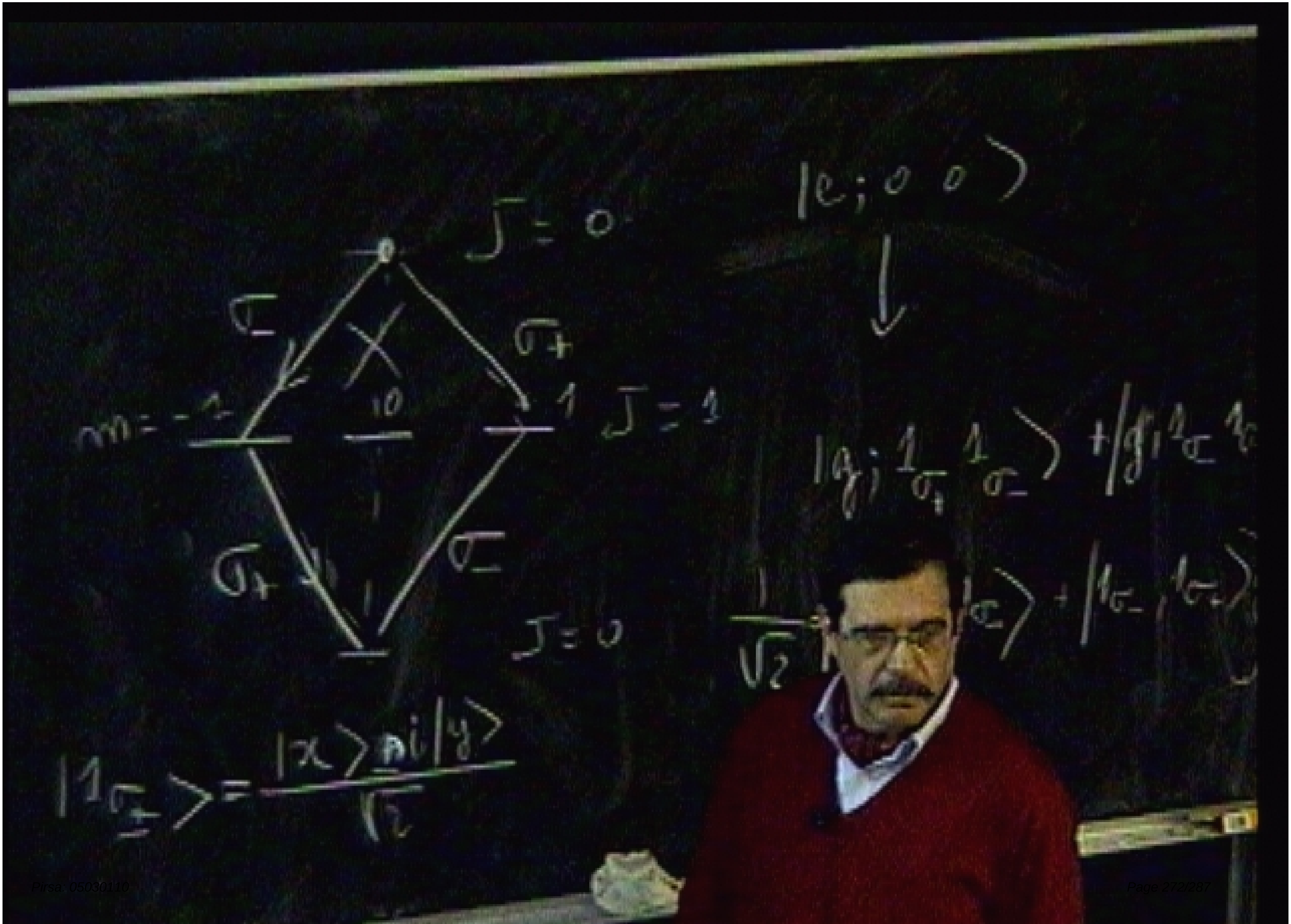
|e; 0 0⟩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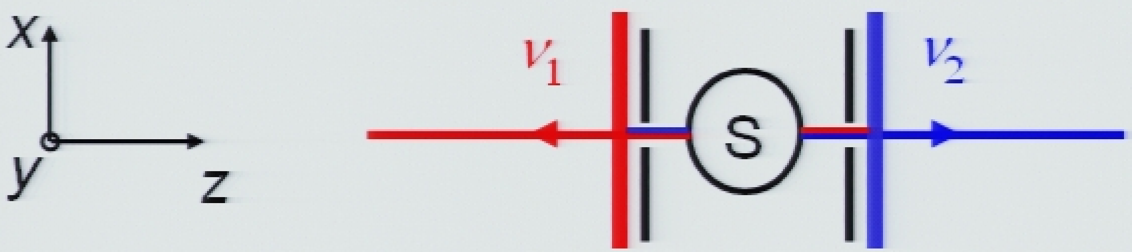
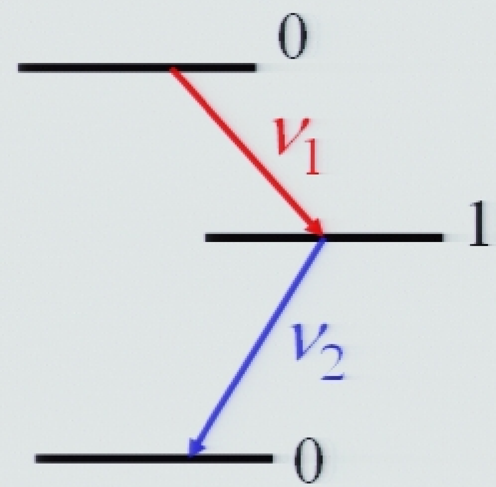
EPR pairs produced in radiative cascades
(Clauser, Horne, Shimony, Holt, 1969)

$$J=0 \rightarrow J=1 \rightarrow J=0$$





$$\left|\Psi(\nu_1,\nu_2)\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|x,x\right\rangle + \left|y,y\right\rangle\right\}$$

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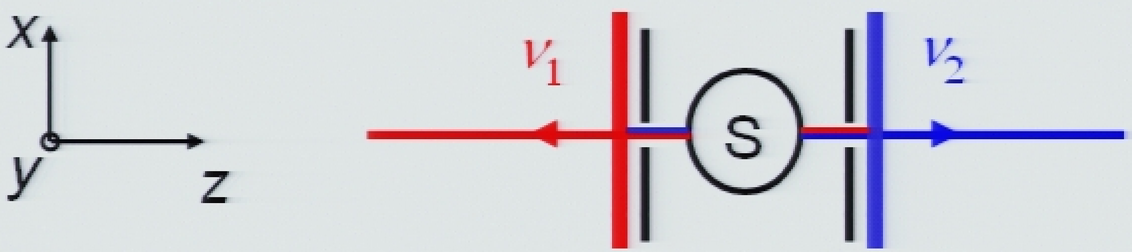

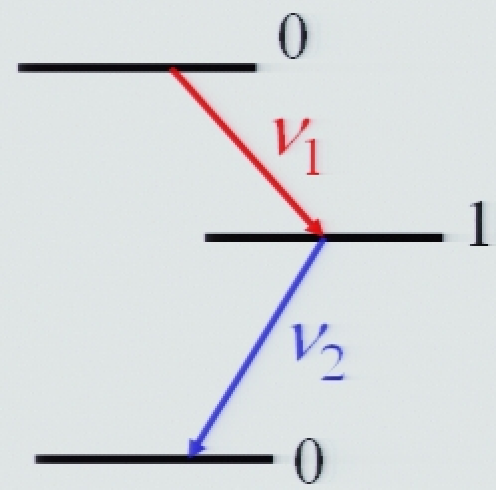

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Any computable extra effect (finite solid angle, hyperfine structure…) leads to a decrease or even a cancellation of the conflict between Bell's inequalities and Quantum Mechanics.

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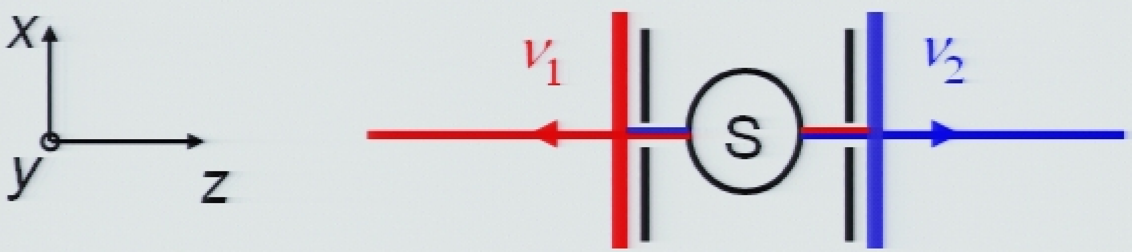

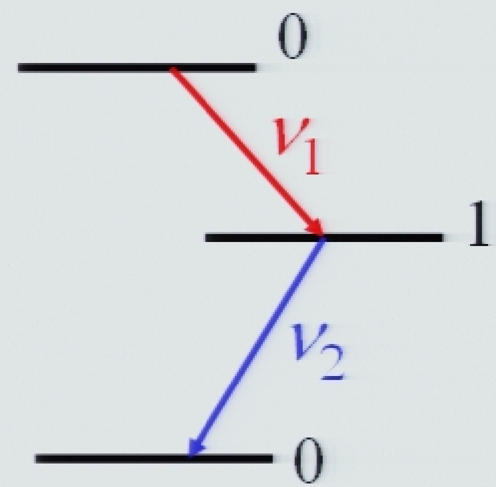

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The experiment must be as ideal as possible

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First experiments with visible photons produced in atomic radiative cascades

1rst generation

- Clauser & Freedman (Berkeley, 1972)
  ^{40}Ca 200 hours M. Q.
- Holt & Pipkin (Harvard, 1973)
  ^{200}Hg 200 hours B. I.

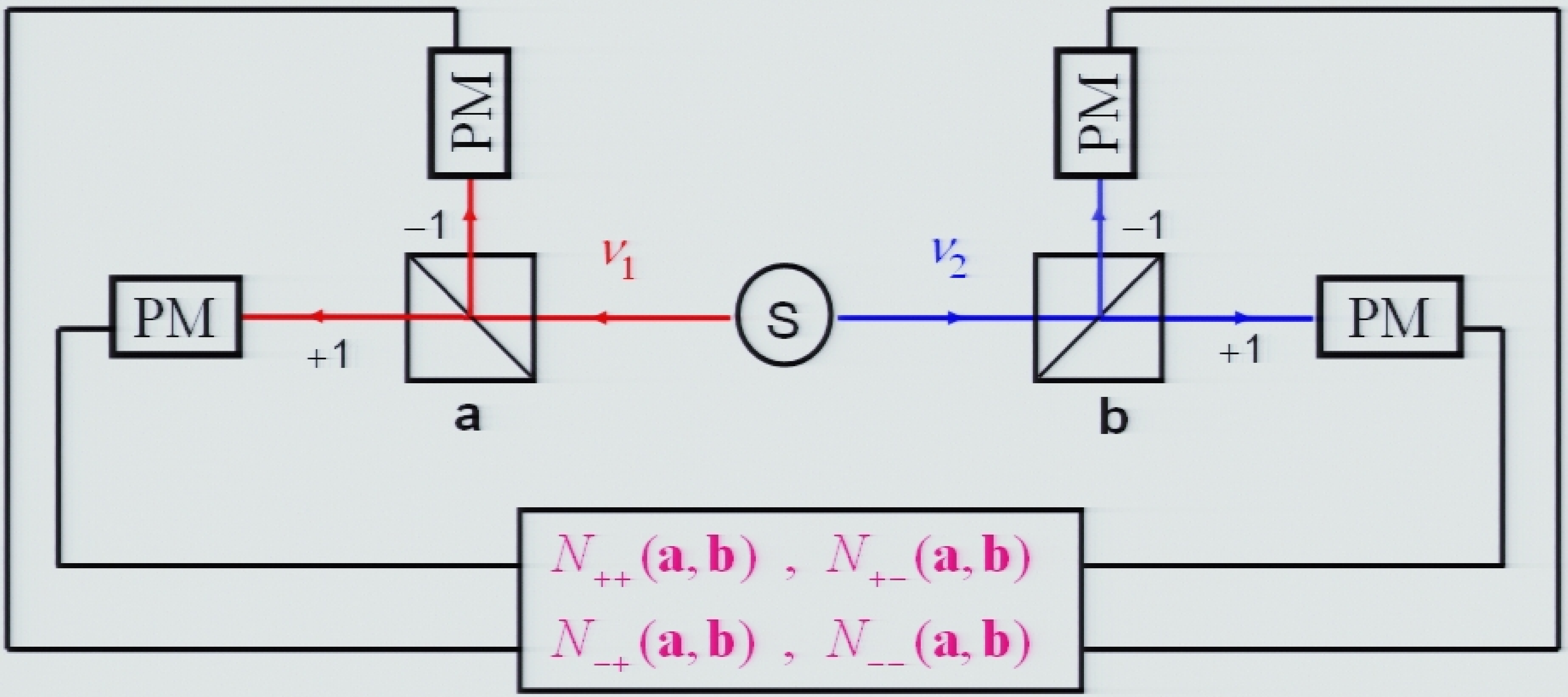
2nd generation (laser excitation ***)

- Fry & Thompson (Texas A&M, 1976)
  ^{200}Hg 80 mn M. Q.

In these experiments, single channel polarizers : indirect reasoning, auxiliary calibrations required.

Experiment with 2- channels polarizers

AA, P. Grangier, G. Roger, PRL 1982



Fourfold coincidence system: the 4 coincidence rates are measured during the same run $\Rightarrow$ coefficient of correlation

$$E(\mathbf{a},\mathbf{b}) = \frac{N_{++}(\mathbf{a},\mathbf{b}) - N_{+-}(\mathbf{a},\mathbf{b}) - N_{-+}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b})}{N_{++}(\mathbf{a},\mathbf{b}) + N_{+-}(\mathbf{a},\mathbf{b}) + N_{-+}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b})}$$

Experiment with 1- channel polarizers

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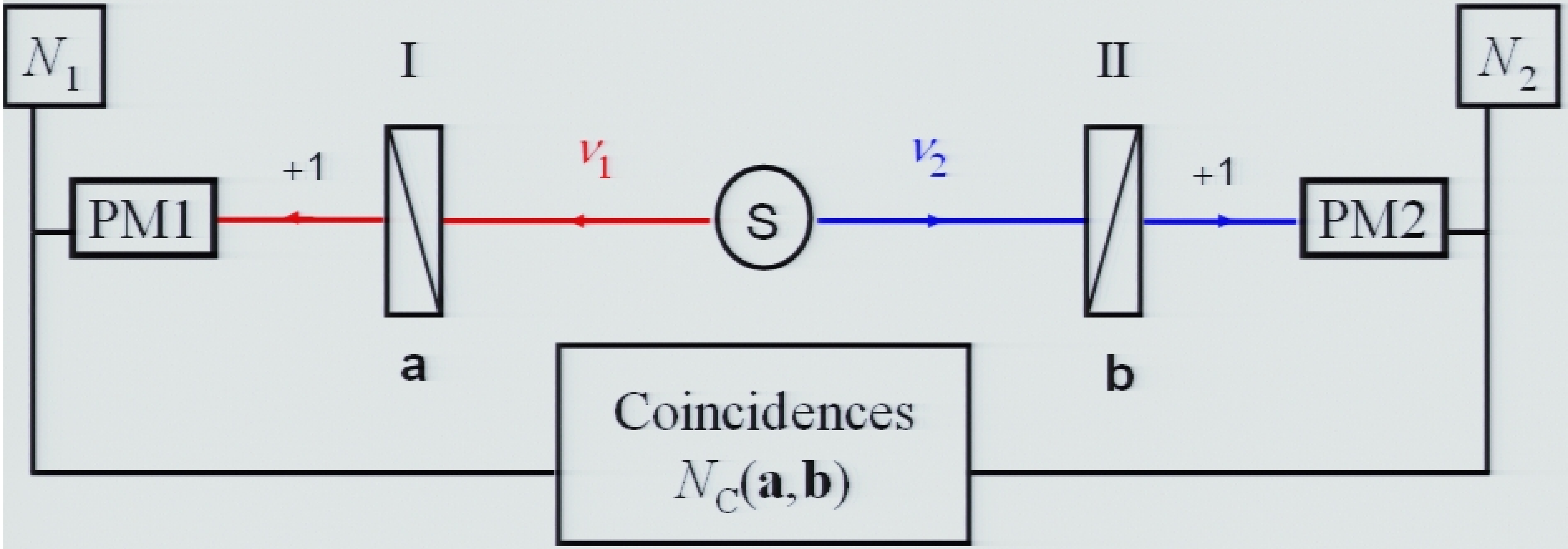

High grade pile of plates polarizers, but only one channel (+1)

- Excellent agreement with QM.
- Violation of Bell's inequalities by 9 σ
- No change in the results with polarizers at a distance (6 m) larger than the coherence length of ν_2 (1.5 m)

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First experiments with visible photons produced in atomic radiative cascades

CNRS

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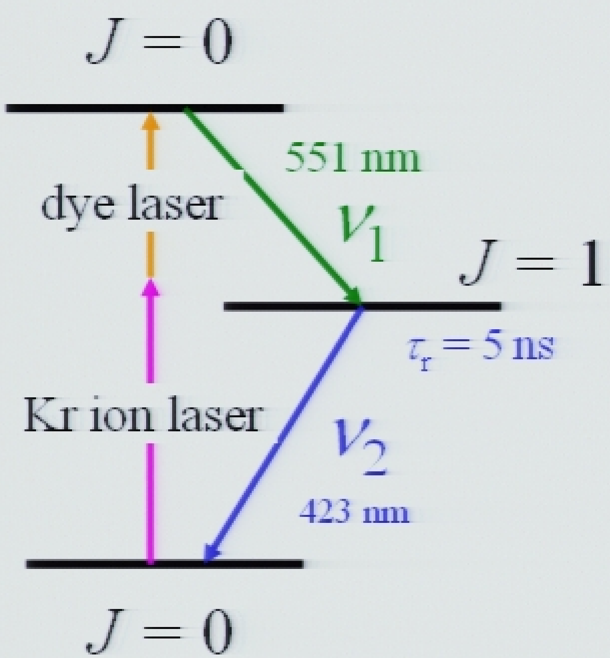
Orsay source of entangled photons



$4p^2\,{}^1S_0 - 4s4p\,{}^1P_1 - 4p^2\,{}^1S_0$

radiative cascade in calcium 40

Already used in Berkeley experiment

New : 2 photon laser excitation

⇒ Selective excitation (isotope, level)

⇒ Small source : 0.5 x 0.05 mm^2

⇒ Optimum cascade rate ($4 \times 10^7\ s^{-1}$) easily achieved

1% accuracy on coincidence rate in 100 s

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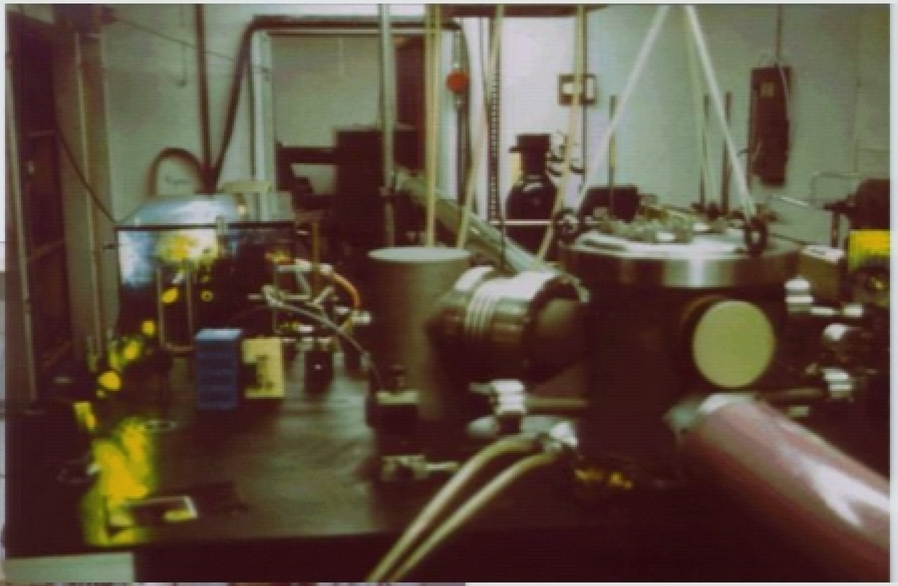
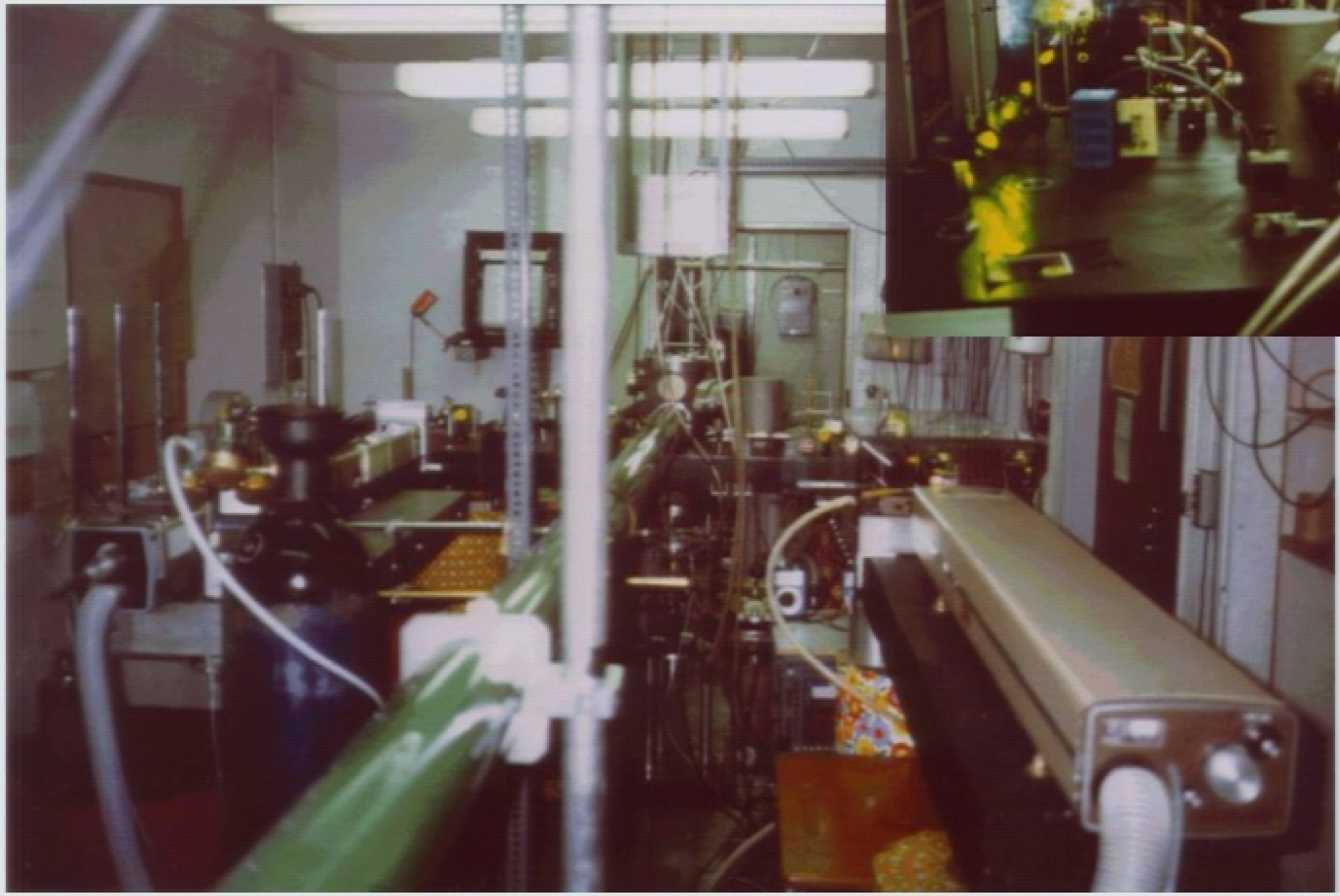
The Orsay source of entangled photons





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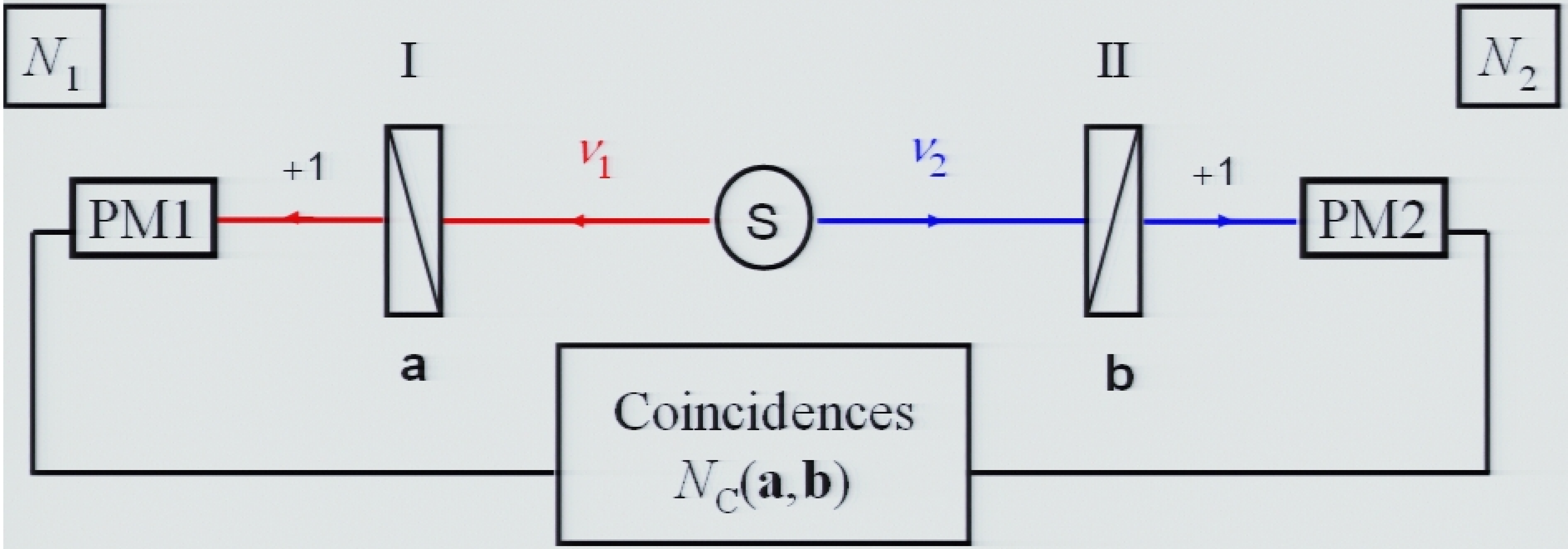

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Experiment with 2- channels polarizers

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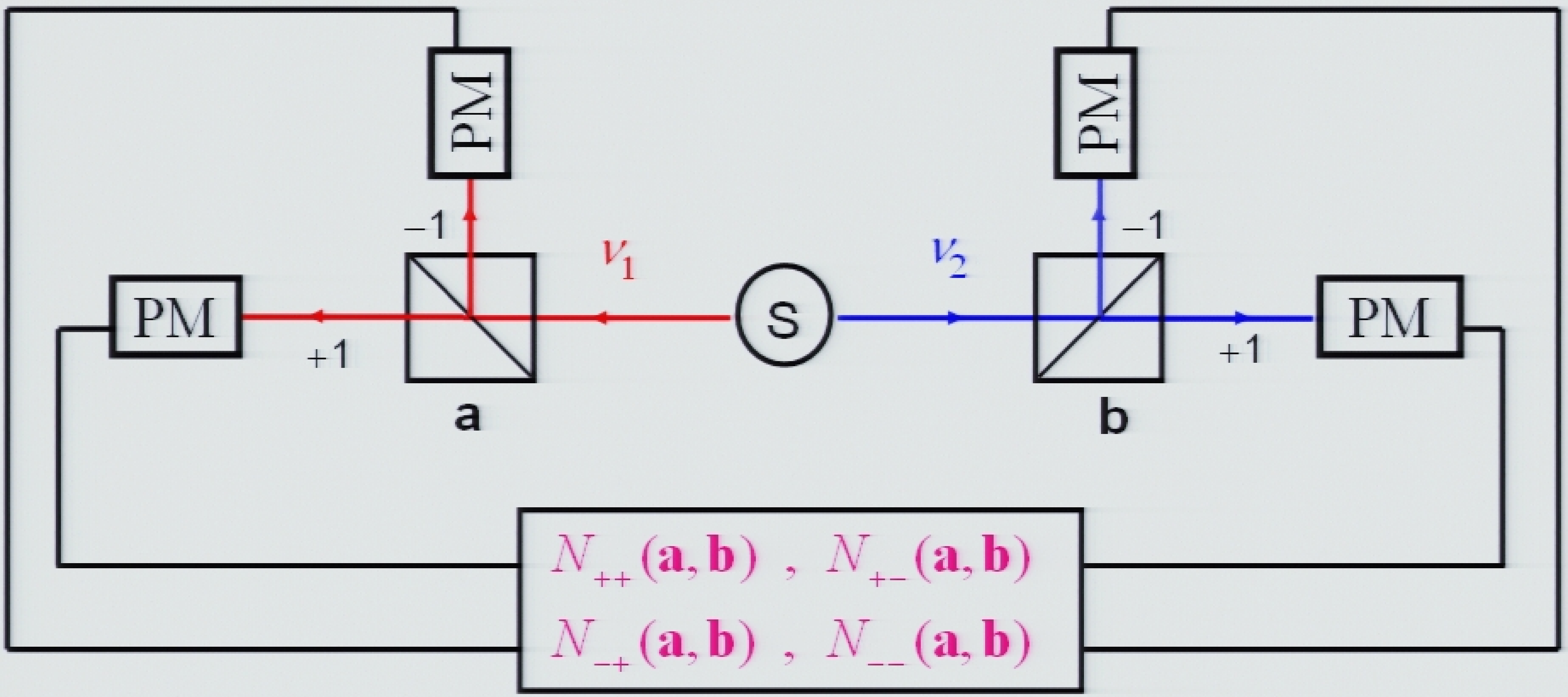
AA, P. Grangier, G. Roger, PRL 1982



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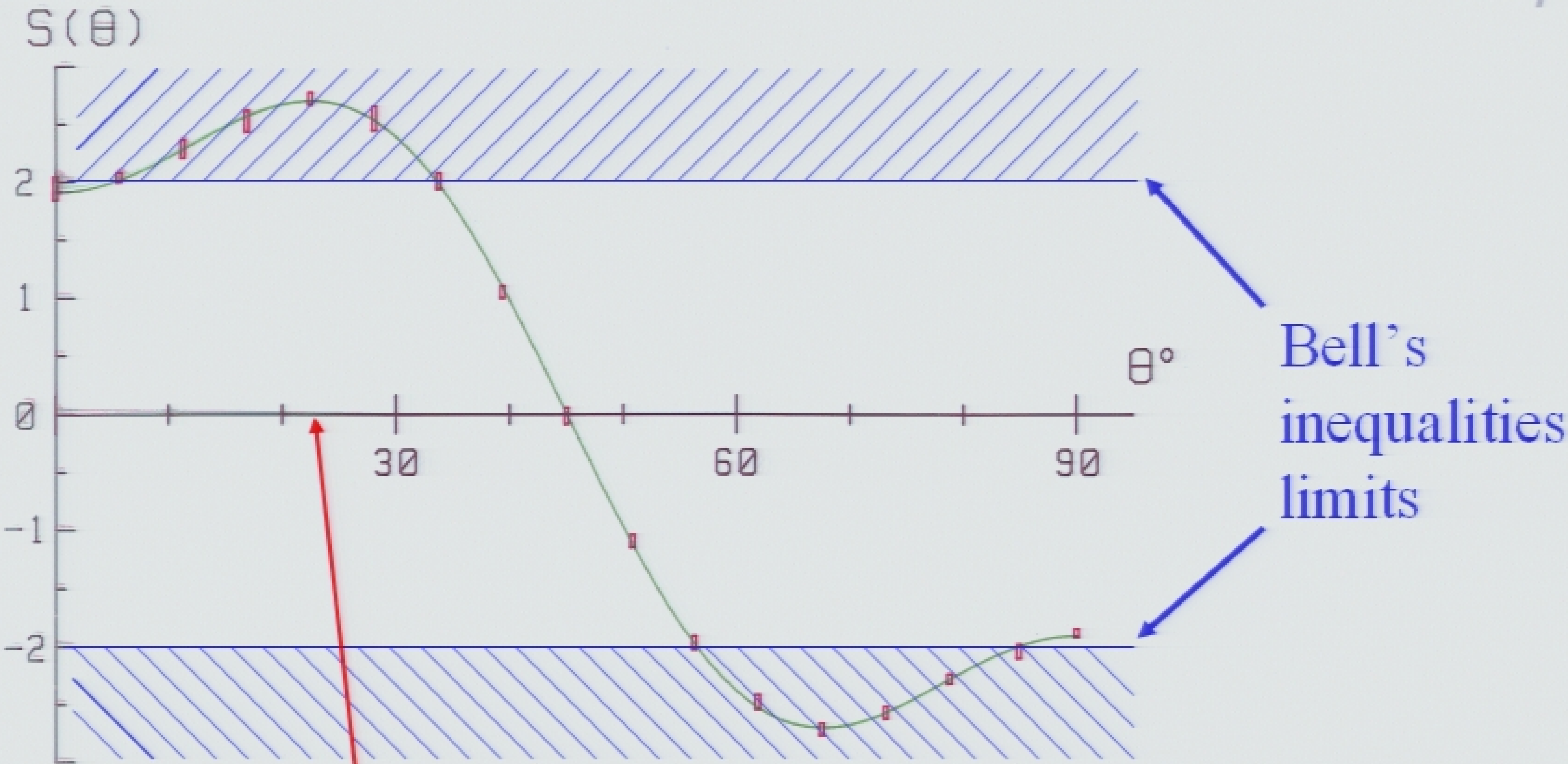
Experiment with 2- channels polarizers

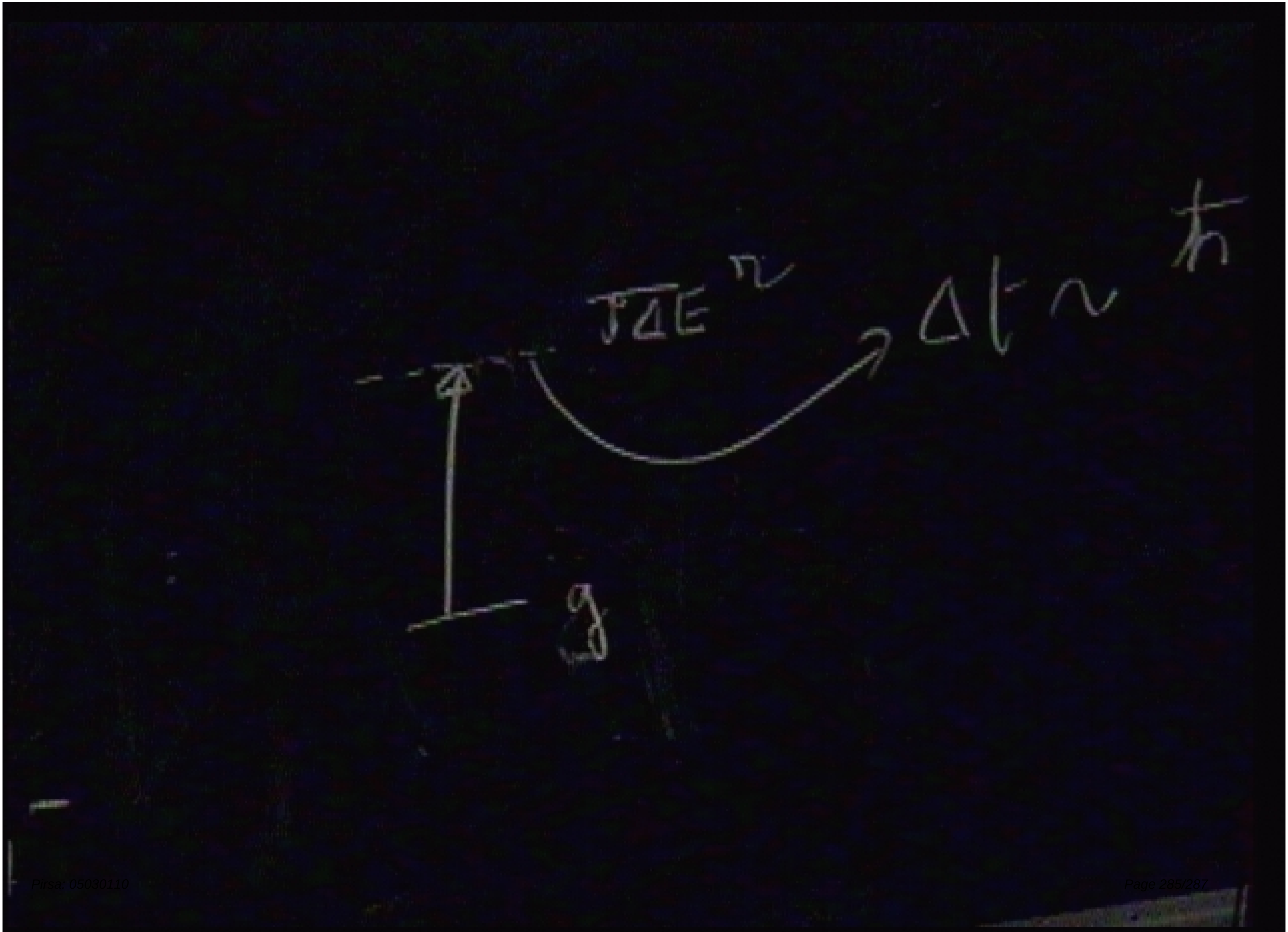


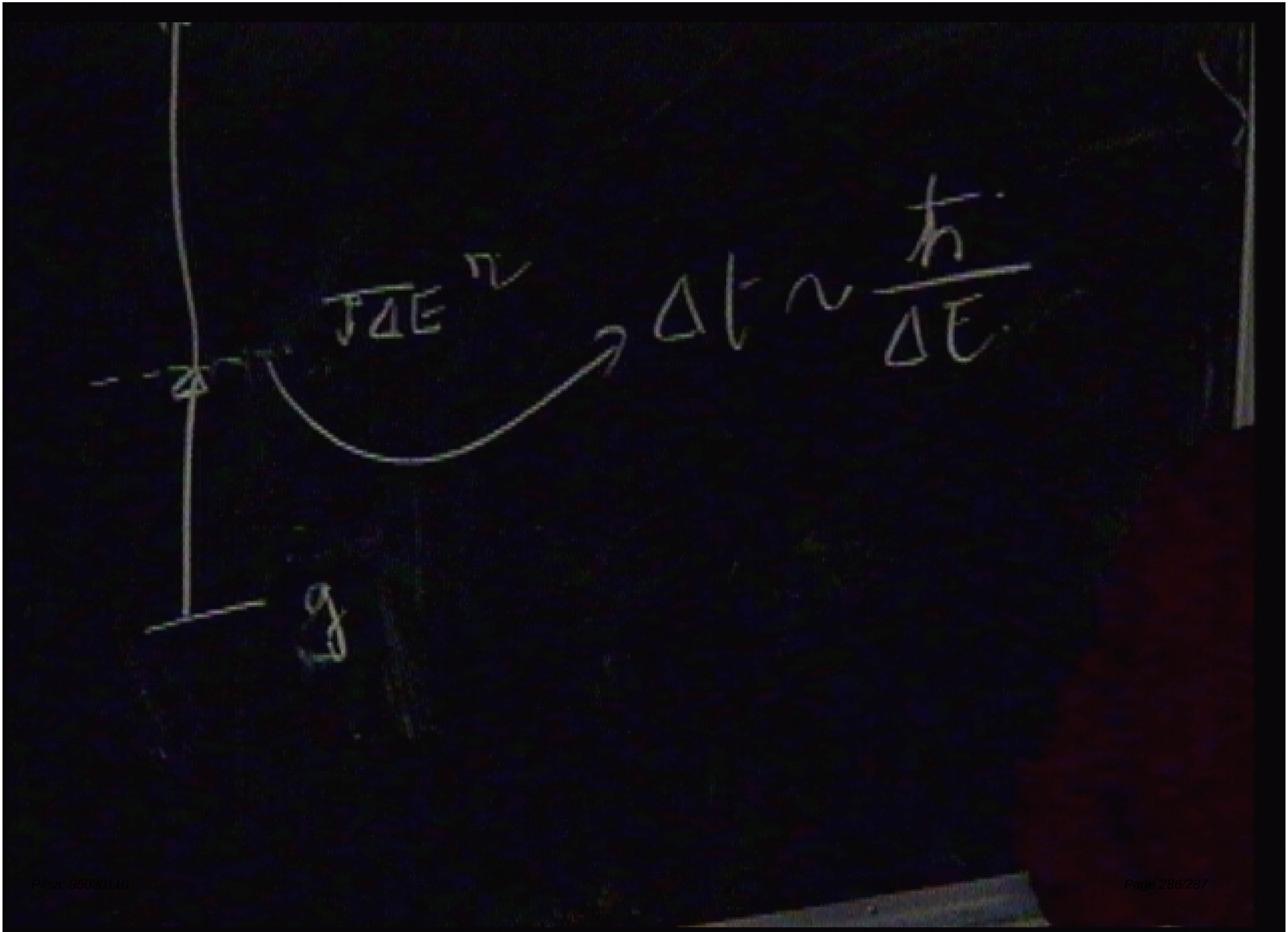
For $\theta = (\mathbf{a},\mathbf{b}) = (\mathbf{b},\mathbf{a}') = (\mathbf{a}',\mathbf{b}) = \frac{\pi}{8}$ $\quad S_{\text{exp}}(\theta) = 2.697 \pm 0.015$

Violates Bell's inequality $(S \leq 2)$ by $> 40\,\sigma$

No auxiliary calibration necessary.

Excellent agreement with Q.M. $S_{QM} = 2.70$


Δt ~
g


ΔE
Δt ~ ħ/ΔE
g