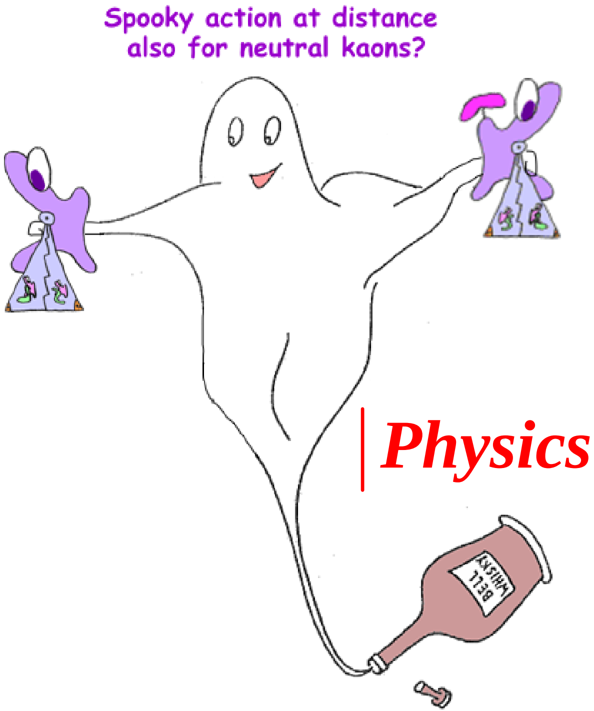
Nonlocality, Entanglement and Decoherence in High Energy Physics



by

Beatrix C. Hiesmayr

Institute for Theoretical Physics
University of Vienna
Austria

$$\left|Physics\right\rangle = \alpha \left|Particle\ Physics\right\rangle + \beta \left|Quantum\ Theory\right\rangle$$

experimental ↔ phenomenological ↔ conceptual ↔ mathematical aspects

UNIVERSITÄT WIEN

Testing QM in High Energy Physics

- **Part I: Bell inequalities 1:**

  A symmetry violation in particle physics related to nonlocality ?!

- **Part II: Bell inequalities 2/ How to describe the decay property?**
- **Part III: Entanglement witnesses and entanglement measures &**

  geometry of entanglement

- **Part IV: Complementarity/The Kaonic Quantum Eraser**

⇩

"Erasing the Past and Impacting the Future" by Aharonov & Zubairy

Testing QM in High Energy Physics

"Erasing the Past and Impacting the Future" by Aharonov & Zubairy

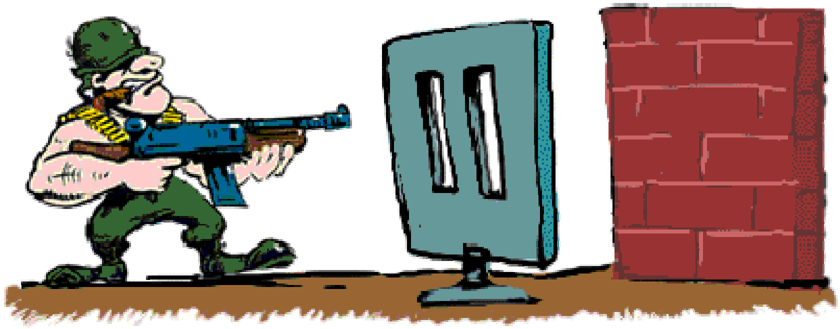
Science 307, 875 (2005)

A. Bramon, G. Garbarino and B.C. Hiesmayr. Quantum marking and quantum erasure for neutral kaons. Phys. Rev. Lett. 92, 020405 (2004);

A. Bramon, G. Garbarino and B.C. Hiesmayr. Active and passive quantum eraser for neutral kaons. Phys. Rev. A 69, 062111 (2004).

A. Bramon, G. Garbarino and B.C. Hiesmayr (2004).
Quantitative complementarity in two-path interferometry,
Phys. Rev. A 69, 022112 or quant-ph/0311179

Outline



R. Feynman:

"The double slit contains the *only* mystery."

R. Feynman about neutral kaons:

"If there is any place where we have a chance to test the main principles of quantum mechanics in the purest way---does the superposition of amplitudes work or doesn't it?---this is it."

Complementarity

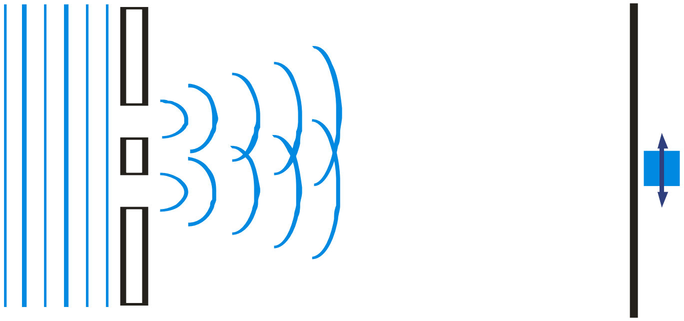
$$\left|\text{Physics}\right\rangle = \alpha\left|\text{Quantum Theory}\right\rangle + \beta\left|\text{Particle Physics}\right\rangle$$
$$+\gamma\left|\text{Nuclear Physics}\right\rangle + \delta\left|\text{Thermodynamics}\right\rangle$$

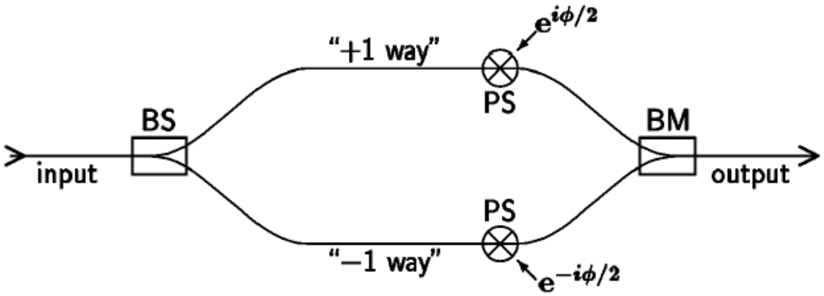
→ **unified formalism in terms of Bohr’s complementarity relation**

Outline:

- Quantitative complementarity in two-path interferometry:
  1. Double–slit-like experiments
  2. Particle oscillations
  3. Scattering of identical particles
- Complementarity in thermodynamical systems

Quantitative complementarity in two-path interferometry





Englert (1996)

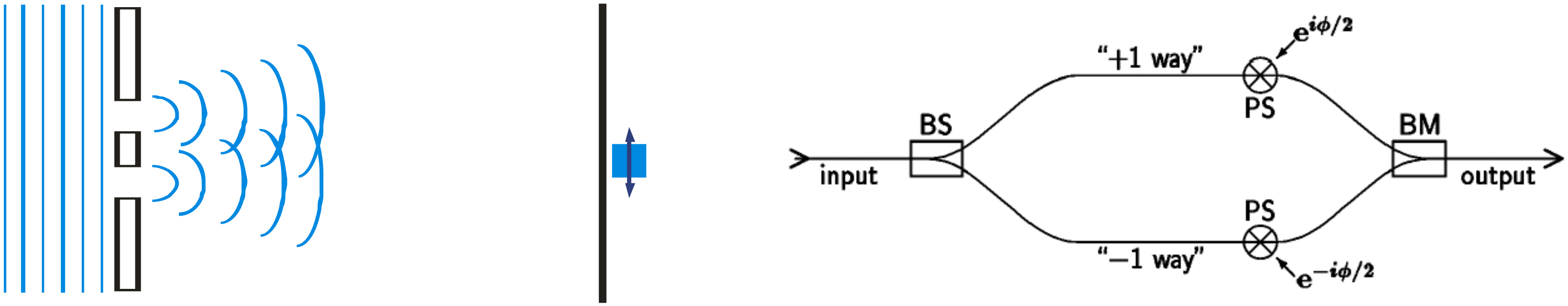
Bohr's principle of complementarity:

Quantum systems possess properties that are equally real but mutually exclusive!
→wave-particle duality

Interferometric duality:

The observation of an interference pattern and the adquisition of which-way information are mutually exclusive.

Quantitative complementarity in two-path interferometry



How to quantify?

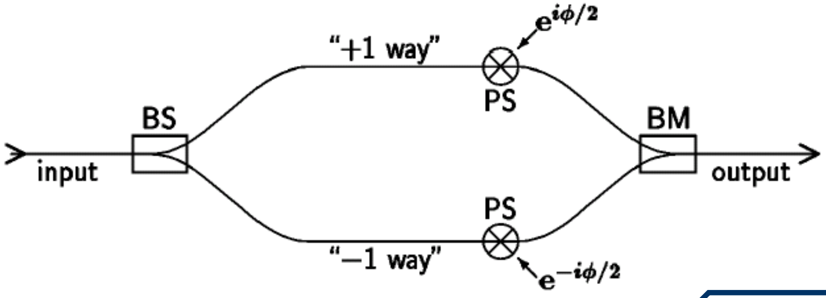
Greenberger and Yasin (1988); Englert (1996):

predictability=
***a priori* which-way knowledge**

$$\boxed{P^2 + V_0^2 \leq 1}$$

fringe visibility

Defining visibility and predictability



Initial state: $\rho_i = \frac{1}{2}\left(1 + \vec{s}_i \cdot \vec{\sigma}\right)$

Beam splitter/beam merger:

$$e^{-i\frac{\pi}{4}\sigma_y}\,\rho_i\,e^{+i\frac{\pi}{4}\sigma_y}$$

Phase shifter:

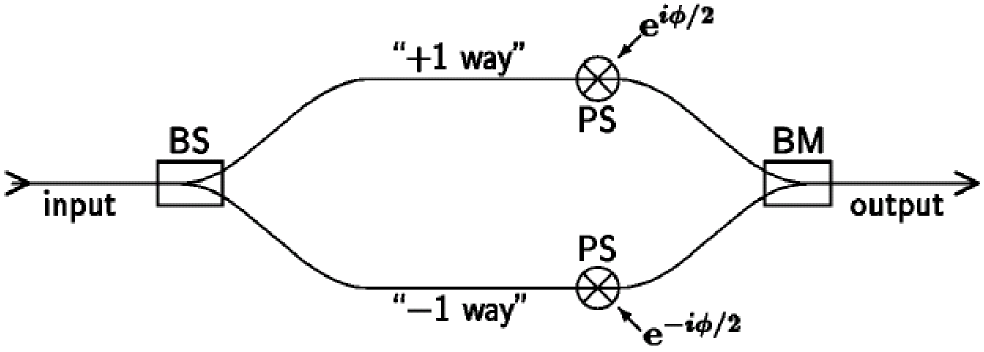
$$e^{-i\frac{\phi}{2}\sigma_z}\,\rho_i\,e^{+i\frac{\phi}{2}\sigma_z}$$

Final state: $\rho_f = \frac{1}{2}\left(1 + \vec{s}_f \cdot \vec{\sigma}\right)$

with $\vec{s}_f = \begin{pmatrix} -s_{x,i} \\ s_{y,i}\cos\phi + s_{z,i}\sin\phi \\ s_{y,i}\sin\phi - s_{z,i}\cos\phi \end{pmatrix}$

$$V_0 = \sqrt{s_{y,i}{}^2 + s_{z,i}{}^2}$$ …visibility

Defining visibility and predictability



Probability for one way:

$$w_\pm = Tr\left(\frac{1\pm\sigma_z}{2} e^{-i\frac{\pi}{4}\sigma_y} \rho_i e^{+i\frac{\pi}{4}\sigma_y}\right) = \tfrac{1}{2}\left(1\mp s_{x,i}\right)$$

Predictability:

$$\boxed{P = |w_+ - w_-| = |s_{x,i}|}$$

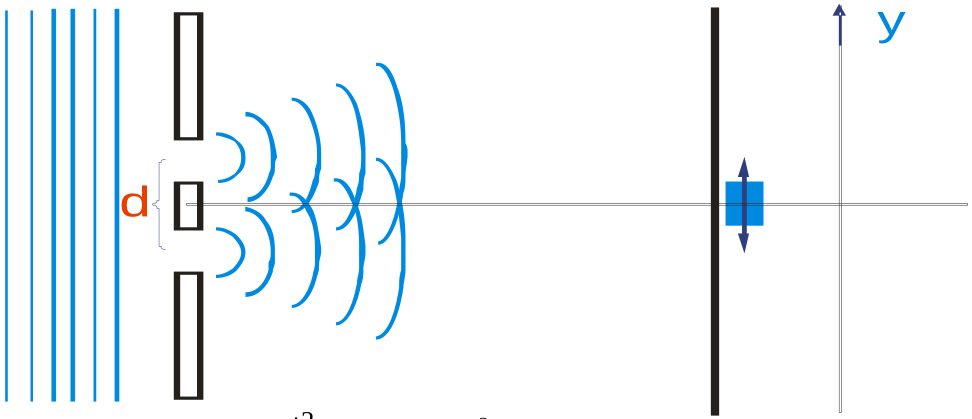
Predicting the way correctly: $(1+P)/2$

Bloch vector must not exceed unity:

$$\boxed{P^2 + V_0^2 \leq 1}$$

= for pure states

Double slit
with Gaussian transmission functions



$$I(y) \sim \left| e^{-\frac{(y-\frac{d}{2})^2}{2\sigma^2}} + e^{-\frac{(y+\frac{d}{2})^2}{2\sigma^2}} \cdot e^{i\varphi(y)} \right|^2 = e^{-\frac{(y^2+\frac{d^2}{4})}{\sigma^2}} 2\cosh(yd/\sigma^2) \left\{ 1 + \underbrace{\frac{1}{\cosh(yd/\sigma^2)}}_{\text{visibility}} \cdot \cos(\varphi(y)) \right\}$$

$$P(y) = \left| \frac{A_1(y) - A_2(y)}{A_1(y) + A_2(y)} \right| = \underbrace{\left| \tanh(yd/\sigma^2) \right|}_{\text{predictability}}$$

$$\boxed{P^2(y) + V_0^{\,2}(y) = 1 \qquad \forall y}$$

!!!! Goal !!!!

Generally:

$$P^2(y)+V_0^2(y)\leq 1$$

Intensity:

$$I(y)=N\cdot F(y)\cdot\left\{1+V_0(y)\cdot\cos(\phi(y))\right\}$$

Goal: Investigate the physical situations for which the expressions P(y), V_0(y) and ϕ(y) can be analytically computed (= only linear dependence on y) !

For all three kinds of phenomena:

unified description in terms of ``complementarity´´

+

estimation the effective number of fringes

Unified description of three kinds of phenomena

y...position, time or scattering angle → for all different situations we get the same y-dependent expressions:

pure states

$$I(y) = N \cdot F(y) \cdot \left\{ 1 + \frac{1}{\cosh(A \cdot y)} \cos(B \cdot y) \right\}$$

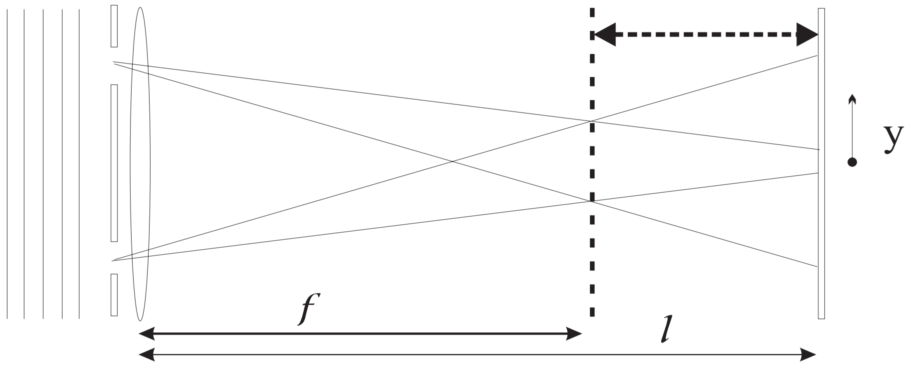
$$V_0(y) = \frac{1}{\cosh(A \cdot y)}, \quad P(y) = \left| \tanh(A \cdot y) \right|, \quad \varphi(y) = B \cdot y$$

$$\Longrightarrow \quad V_0^{\,2}(y) + P^2(y) = 1 \qquad \forall y$$

Effective number of visible fringes:

$$R = \frac{A}{B} \qquad \nu_{eff} = 0.264 / R = 0.264 \frac{B}{A}$$

Double slit like phenomena



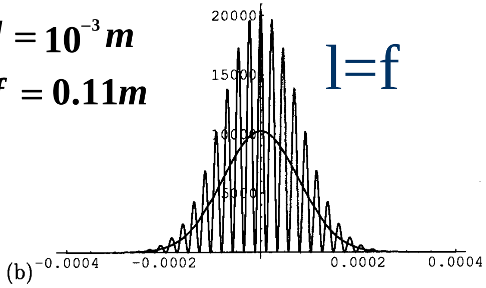
$$I(y) = N \cdot e^{-\frac{y^2}{\sigma_l^2}} \cdot \cosh(A_l \cdot y) \cdot \left\{ 1 + \frac{1}{\cosh(A_l \cdot y)} \cos(B_l \cdot y) \right\}$$

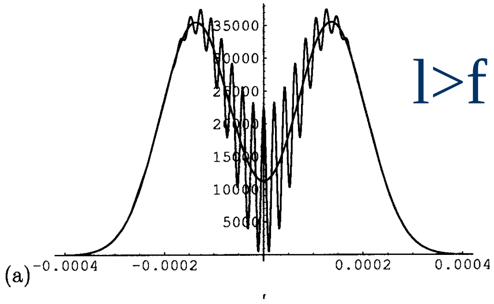
$k = 10^7 \, m^{-1}$

$x_0 = 10^{-4} \, m$

$d = 10^{-3} \, m$

$f = 0.11 m$



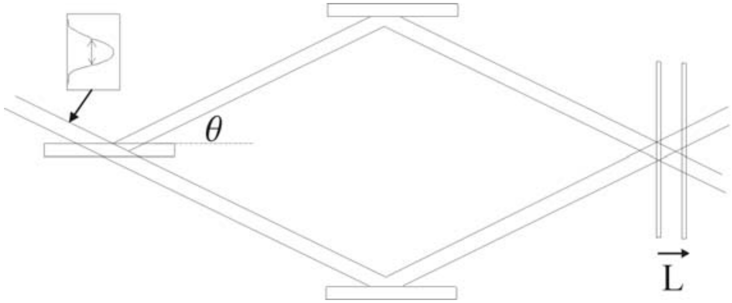


$$A_l = \frac{d}{\sigma_l^2}\left(1 - \frac{l}{f}\right) \qquad R = \frac{k x_0^2 (1 - l/f)}{l}$$

$$B_l = \frac{d}{\sigma_l^2} \cdot \frac{l}{k x_0^2} \qquad \nu_{eff} = 0.264 / R$$

Double slit like phenomena

Laser with
Gaussian profil



Experimental realizations:

Photons: **B. Dopfer, PhD thesis, Univ. of Vienna, (1998)**

Neutrons: Zeilinger &Gähler, Am. J. Phys. 59, 316 (1990)

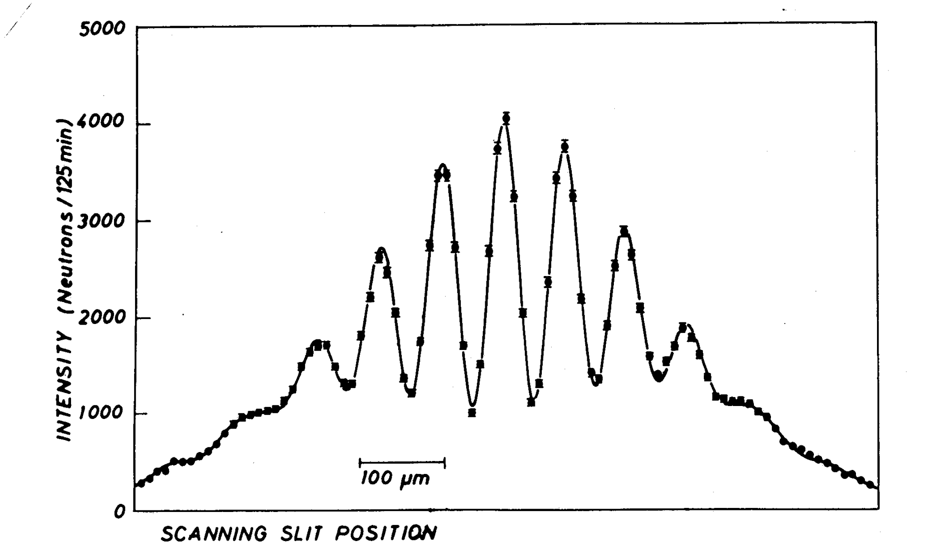
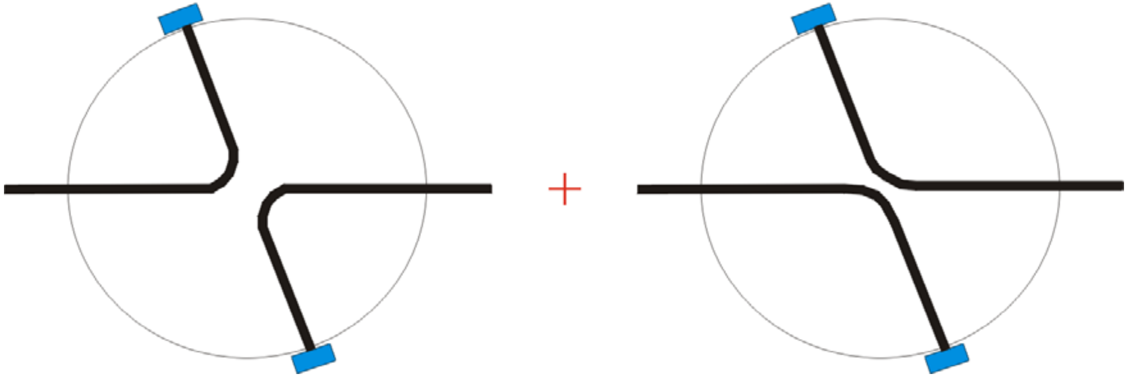


Fig. 9. Measured neutron distribution after diffraction at a double slit where a boron wire was used to define the two individual slits. The boron wire was opaque for the neutrons used in the experiment. Here, still, the solid line represents the first-principles theoretical calculation.

Mott scattering



$$I = \left| f(\theta) + f(\theta+\pi) \right|^2$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z^2 e^2}{4E}\right)^2 \left\{ \frac{1}{\sin^4(\theta/2)} + \frac{1}{\sin^4(\theta+\pi/2)} + C_s \frac{2}{\sin^2(\theta/2)\cos^2(\theta/2)} \cos\left(\eta \ln\left[\tan^2(\theta/2)\right]\right) \right\}$$

Sommerfeld parameter: $\eta = Z^2 \alpha \sqrt{\frac{M c^2}{2E}}$

$C_S = (-)^{2S} / (2S+1)$...spin effects and opposite sign for boson and fermion statistic

Mott scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z^2 e^2}{4E}\right)^2 \left\{ \frac{1}{\sin^4(\theta/2)} + \frac{1}{\sin^4(\theta+\pi/2)} + C_s \frac{2}{\sin^2(\theta/2)\cos^2(\theta/2)} \cos\left(\eta \ln\left[\tan^2(\theta/2)\right]\right) \right\}$$

Sommerfeld parameter: $\eta = Z^2 \alpha \sqrt{\frac{M\ c^2}{2E}}$

Transformation: $$e^x \equiv \tan^2\frac{\theta}{2} = \frac{1-\cos\theta}{1+\cos\theta}$$

$$I(x) \propto 1 + \frac{C_s}{\cosh(x)} \cos(\eta\ x)$$

$A = 1$

$B = \eta$

$R = \frac{1}{\eta}$

$\nu_{eff} = 0.264\eta$

$$A = 1 \qquad R = \frac{1}{\eta} \qquad \nu_{eff} = 0.264\eta$$
$$B = \eta$$

Experiments

1961

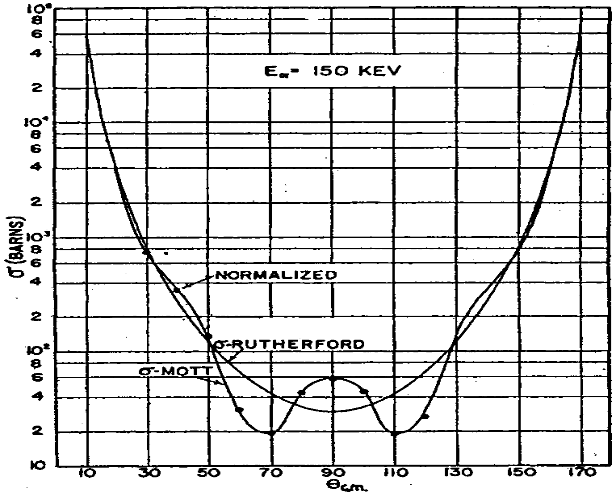


FIG. 4. Angular distribution of α—α scattering at 150 kev, owest energy. Data are normalized at 40° to the theore Mott curve. Differential cross section in the c.m. system arns. Rutherford cross section is also shown (no interfer erm). This represents the most detailed confirmation of nfluence of identity on scattering.

α-α: 150 keV
R=0.31; ν=0.85

C^{12}- C^{12}: 5 MeV
R=0.11; ν=2.4

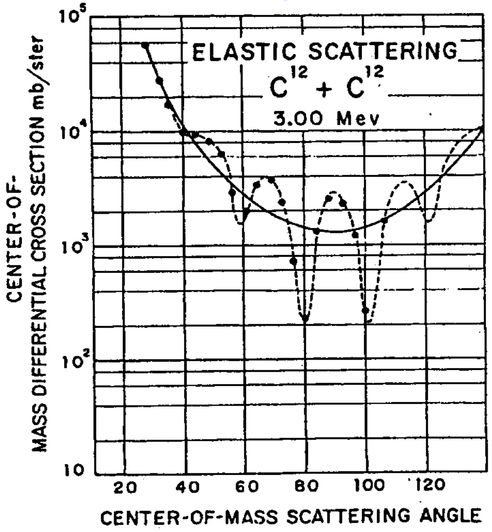


FIG. 7. Elastic scattering angular distribution for $C^{12}+C^{12}$ at $E_{c.m.}=3.00$ Mev. The solid curve is the Rutherford prediction; the dashed curve is the Mott prediction. The spot diameters encompass the statistical counting errors.

C^{12}- C^{12}: 3 MeV
R=0.09; ν~3

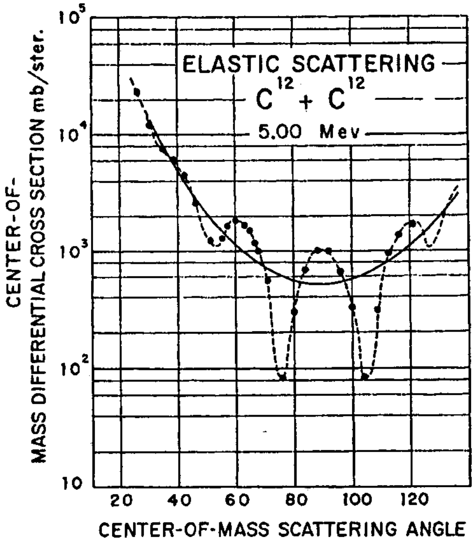
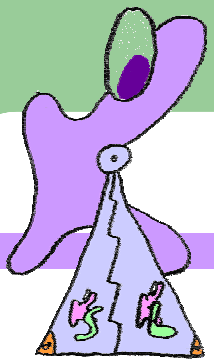


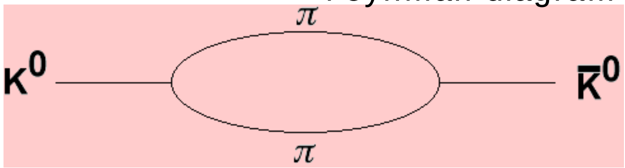
FIG. 8. Elastic scattering angular distribution for $C^{12}+C^{12}$ at $E_{c.m.}=5.00$ Mev. See caption to Fig. 7.



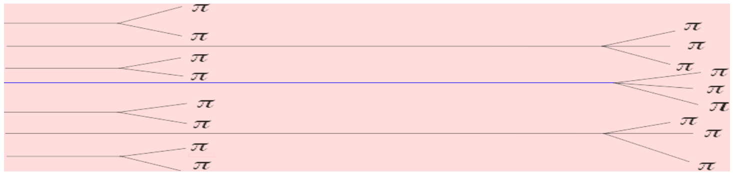
Particle oscillations (meson-antimeson systems)

Neutral kaons:

Feynman diagram



strangeness oscillation



$|K_S\rangle$ $|K_L\rangle$

Time evolution:

$$|K_S(t)\rangle = e^{-i(m_S - i\frac{\Gamma_S}{2})t}|K_S\rangle$$

$$|K_L(t)\rangle = e^{-i(m_L - i\frac{\Gamma_L}{2})t}|K_L\rangle$$

$\Delta m = m_L - m_S$

$\Delta\Gamma = \Gamma_L - \Gamma_S$

$$|K^0\rangle \to |K^0(t)\rangle_N = \frac{1}{\sqrt{1+e^{-\Delta\Gamma\, t}}}\left\{|K_S\rangle + e^{-i\Delta m t}\, e^{-\Delta\Gamma/2\, t}|K_L\rangle\right\}$$

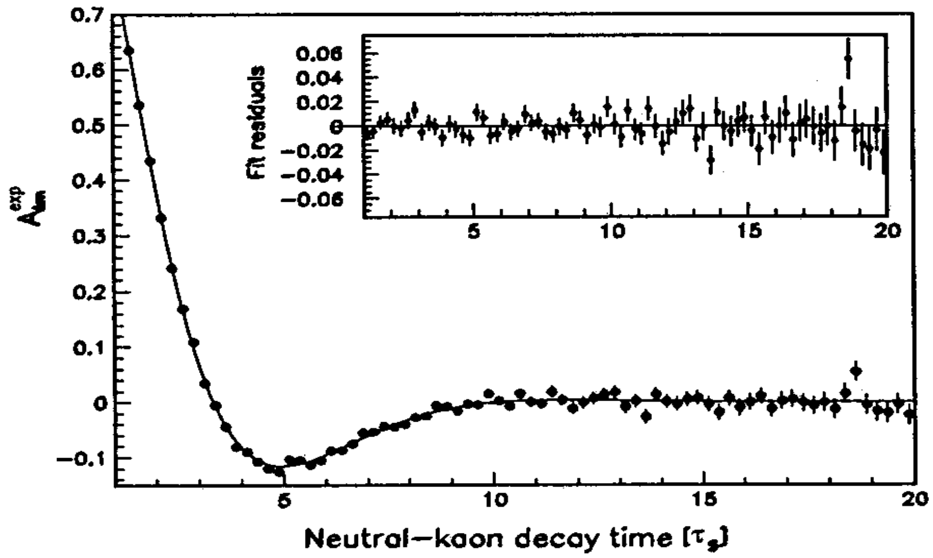
$$I(t) \propto 1 + \frac{1}{\cosh(\Delta\Gamma/2\, t)}\cdot\cos(\Delta m\, t)$$

$$A = \Delta\Gamma/2 \qquad R = \frac{|\Delta\Gamma|}{2\Delta m} \qquad \nu_{eff} = 0.264\frac{2\Delta m}{|\Delta\Gamma|}$$

$$B = \Delta m$$

Neutral kaons

A. Angelopoulos et al. / Physics Reports 374 (2003) 165–270



$R_{exp}=1$

$V_{eff}=0.26$

$$A=\Delta\Gamma/2 \qquad R=\frac{|\Delta\Gamma|}{2\Delta m} \qquad v_{eff}=0.264\frac{2\Delta m}{|\Delta\Gamma|}$$

$$B=\Delta m$$

Summary of Part I

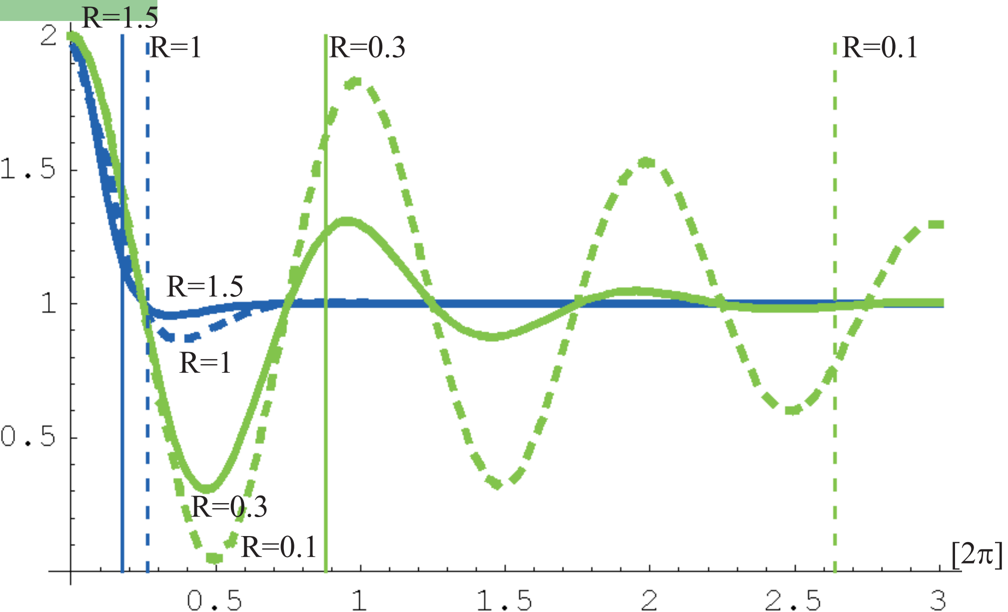
Unified description for three phenomena in terms of ``complementarity´´:

- **Double slit like experiments**
- **Particle oscillations**
- **Scattering of identical particles**

$$I(y) \propto \left\{ 1 + \frac{C}{\cosh(A \cdot y)} \cdot \cos(B \cdot y) \right\}$$

$$P^2(y) + V_0^2(y) \leq 1$$

$$R = \frac{A}{B} \qquad \nu_{eff} = 0.264 / R = 0.264 \frac{B}{A}$$



Quantum Eraser-Why is it interesting?

1982 Drühl & Scully: surprised physics community!!

“Erasing the Past and Impacting the Future”

Aharanov & Zubairy:
Science 307:875, 2005

A lot of experiments:

Neutrons: **Kawai et al. 1998; Rauch et al. 1985;...**

Atoms: **Dürr, Rempe 2000; ...**

Single photons: **Hellmuth et al. 1987; Baldzuhn 1989;...**

Entangled photons:

Ou, Wang, Zou & Mandel 1990; Zou, Wang & Mandel 1991; Herzog, Kwiat, Weinfurter & Zeilinger 1995; Kwiat, Steinberg & Chiao 1992; Kwiat et al 1994; Tsegaye and Björk 2000; Walborn, Terra Cunha, Padua & Moken 2002; Kim, Yu, Kulik, Shih & Scully 2000; Tifonov, Björk, Sönderholm & Tsegaye 2002;...

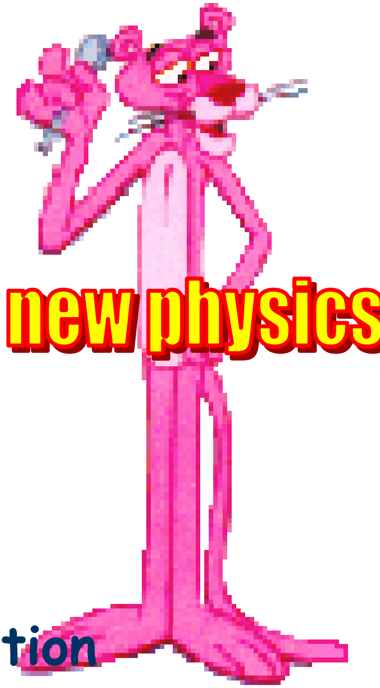
The *kaonic* quantum eraser

Bramon, Garbarino, Hiesmayr, Phys. Rev. Lett. 92 (2004) 020405
Bramon, Garbarino, Hiesmayr, Phys. Rev. A 68 (2004) 062111

→ many experiments with photons, neutrons or atoms

Why, kaons?

just another quantum system?



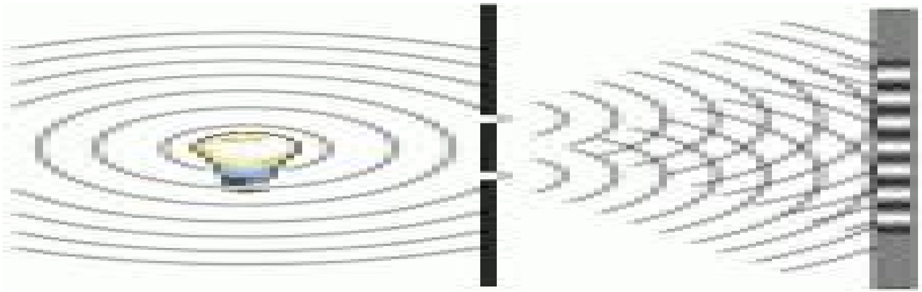
- because the working principle can be demonstrated in A NEW WAY, *!!only!! possible* with kaons

- can be performed at KLOE 2

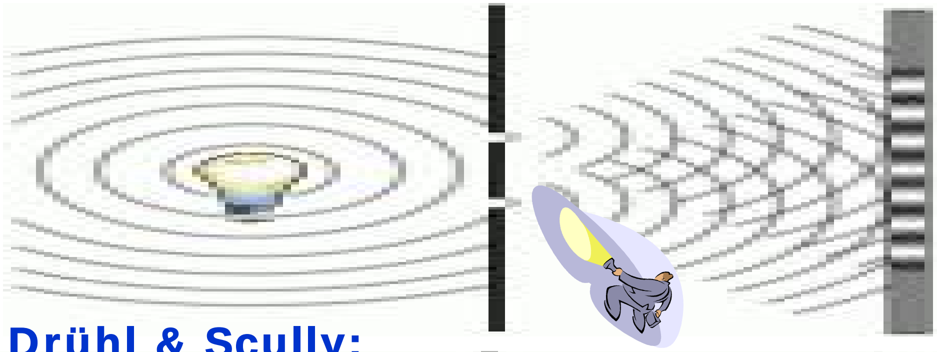
- and allows for a clear conceptual simplification

“Erasing the past and impacting the future”

1801 Thomas Young:



Photons interfere!



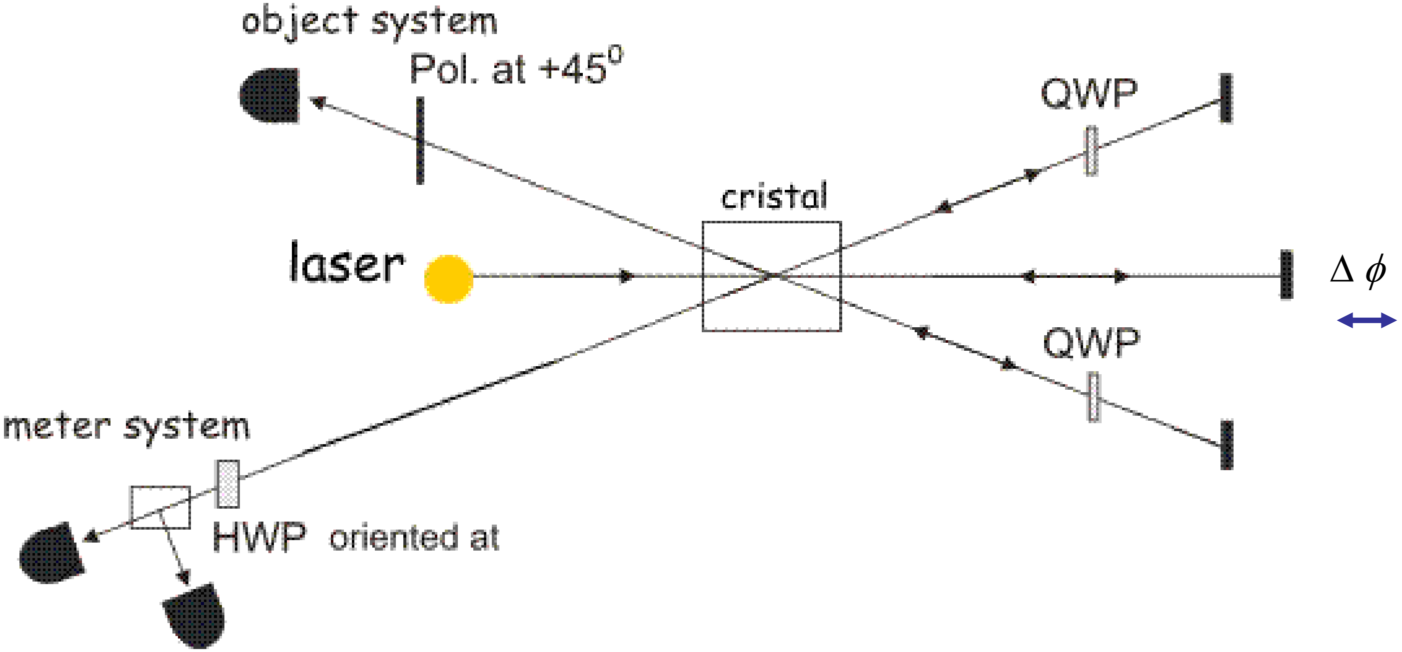
Interference lost because photon watched (gain which way info)!

1982 Drühl & Scully:

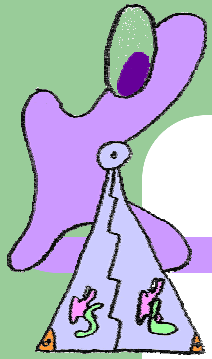
Erasing the which way info brings interference back!

No wonder Einstein would be confused!

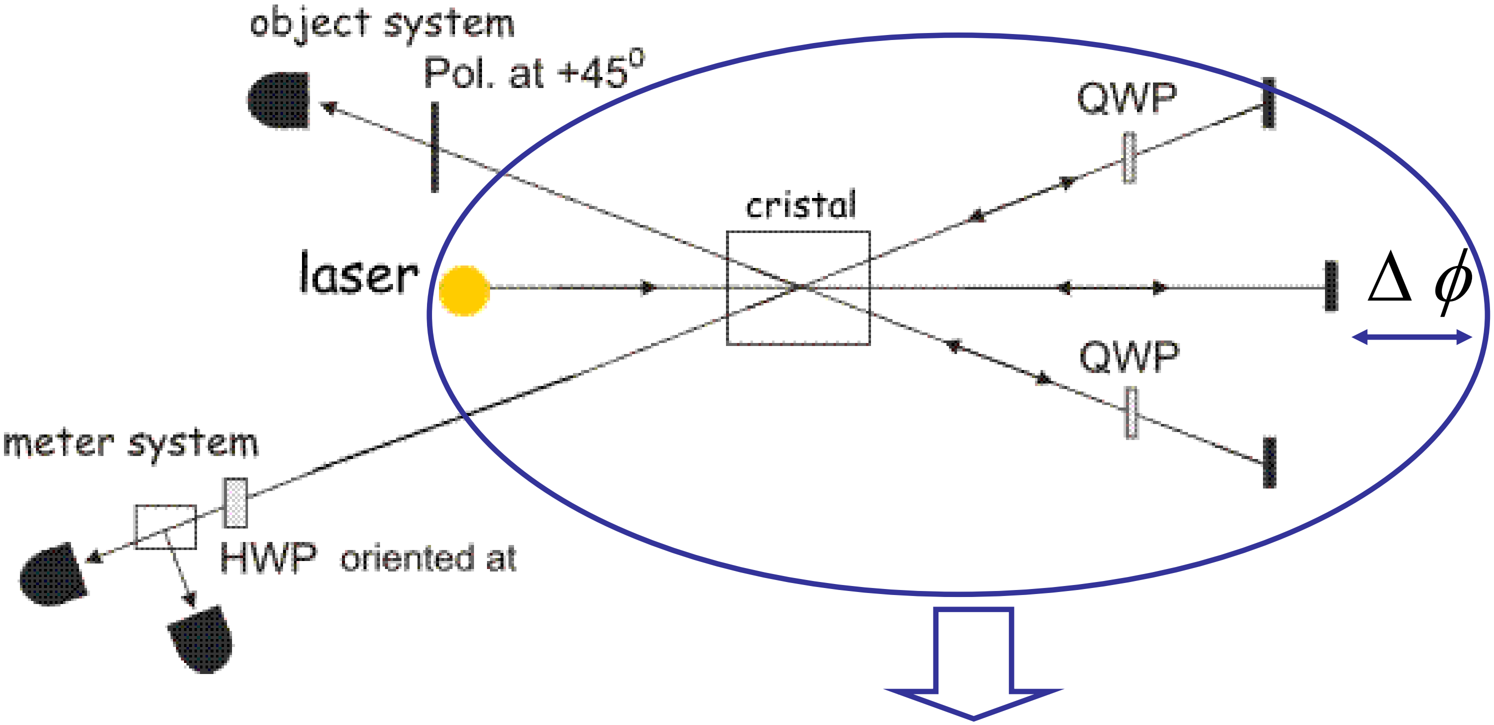
Experiment: Herzog et al.



$$|V\rangle_{object} \otimes |H\rangle_{meter}$$



Experiment: Herzog et al.

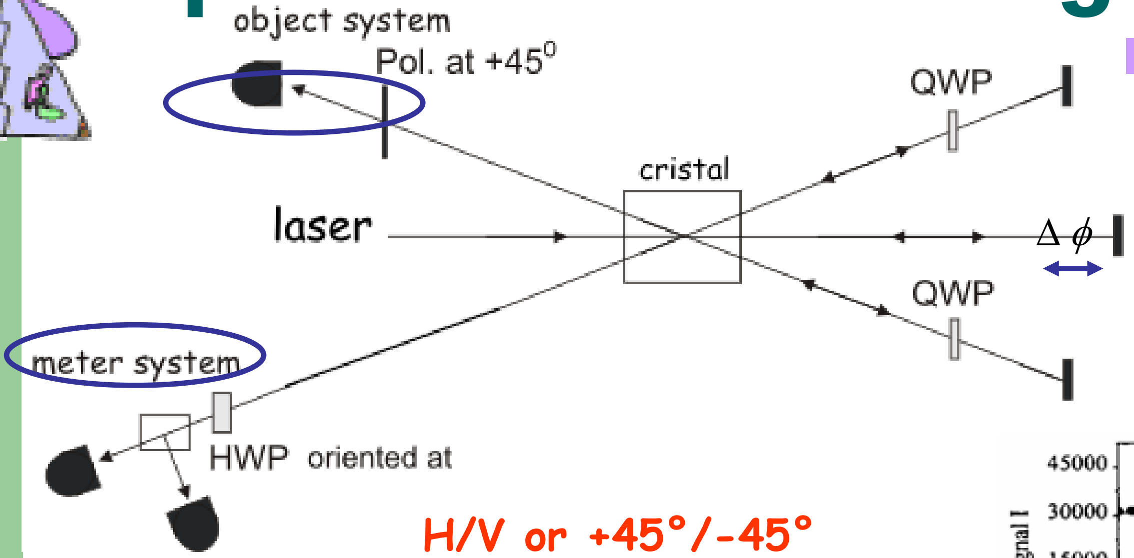


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left\{ |H\rangle_{object} \otimes |V\rangle_{meter} - e^{i\Delta\phi} |V\rangle_{object} \otimes |H\rangle_{meter} \right\}$$

$\uparrow$ **second passage**

$\uparrow$ **first passage**

Experiment: Herzog et al.



H/V or +45°/-45°

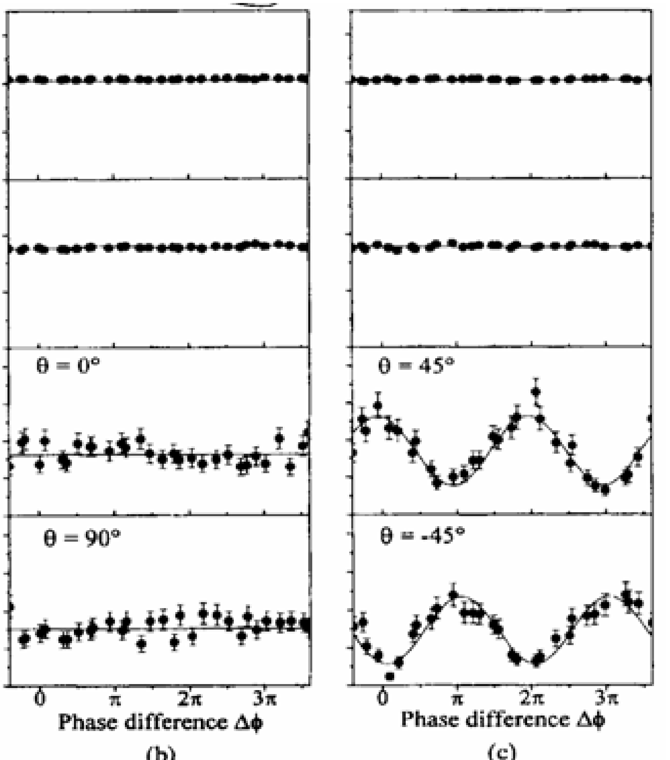
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left\{ |H\rangle_{object} \otimes |V\rangle_{meter} - e^{i\Delta\phi} |V\rangle_{object} \otimes |H\rangle_{meter} \right\}$$

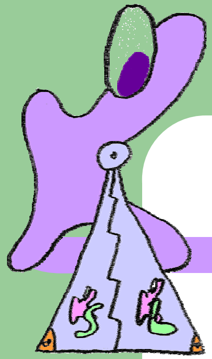
$$\Downarrow$$

$$|\Psi\rangle = |+45\rangle_{object} \otimes \frac{1}{\sqrt{2}}\left\{ |V\rangle_{meter} - e^{i\Delta\phi} \otimes |H\rangle_{meter} \right\}$$

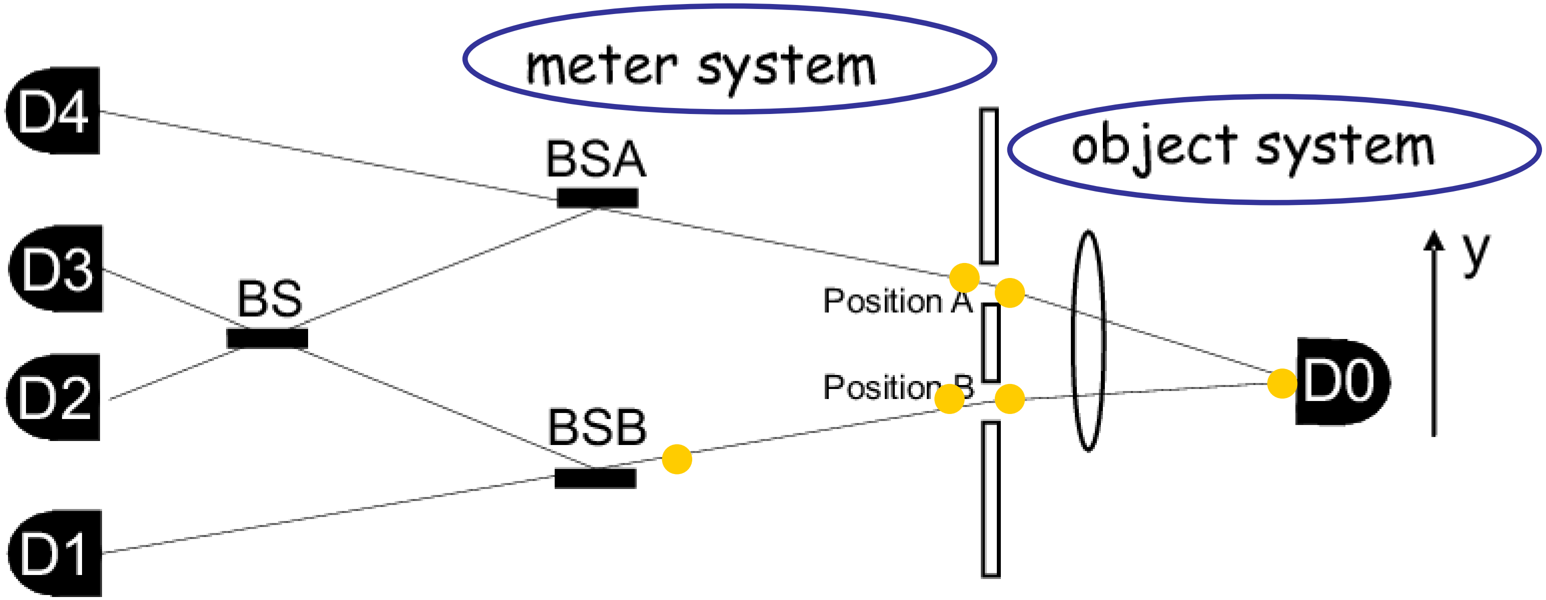
$$|\Psi\rangle = \frac{1}{\sqrt{1+e^{\Delta\Gamma\cdot\Delta\tau}}}\left\{ |K_L\rangle_l \otimes |K_S\rangle_r - e^{i\Delta m\Delta\tau} \cdot e^{\frac{1}{2}\Delta\Gamma\Delta\tau} |K_S\rangle_l \otimes |K_L\rangle_r \right\}$$

normalized to surviving kaon pairs





Experiment: Kim et al.



→ **choice to show which way info or not is *partially active* !**

Measurements: active & passive

Strangeness basis: $\langle K^0 | \bar{K}^0 \rangle = 0$

“Active” measurement:

Strong interactions:

$K^0 + p \rightarrow K^+ + n$

$\bar{K}^0 + p \rightarrow \Lambda + \pi^+$

$\bar{K}^0 + n \rightarrow K^- + p,\ \Lambda + \pi^0$

“Passive” measurement:

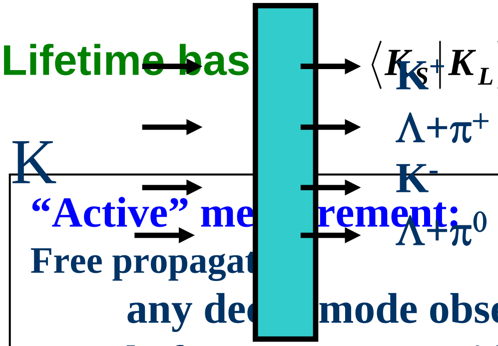
Semileptonic decay modes $\Delta Q = \Delta S$:

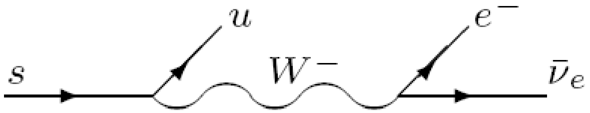
$K^0(\bar{s}d) \rightarrow \pi^-(\bar{u}d) + l^+ + \nu_l$

$\bar{K}^0(s\bar{d}) \rightarrow \pi^+(u\bar{d}) + l^- + \bar{\nu}_l$

Lifetime bas

$\langle K_S | K_L \rangle = \frac{2\,\mathrm{Re}\{\varepsilon\}}{1+|\varepsilon|^2} \cong 3.2\cdot 10^{-3}$





“Active” me rement:

Free propagat

any de mode observed

before t+4.8 τ_S are identified

as K_S at time t

Misidentification: few parts in 10^{-3}!

“Passive” measurement:

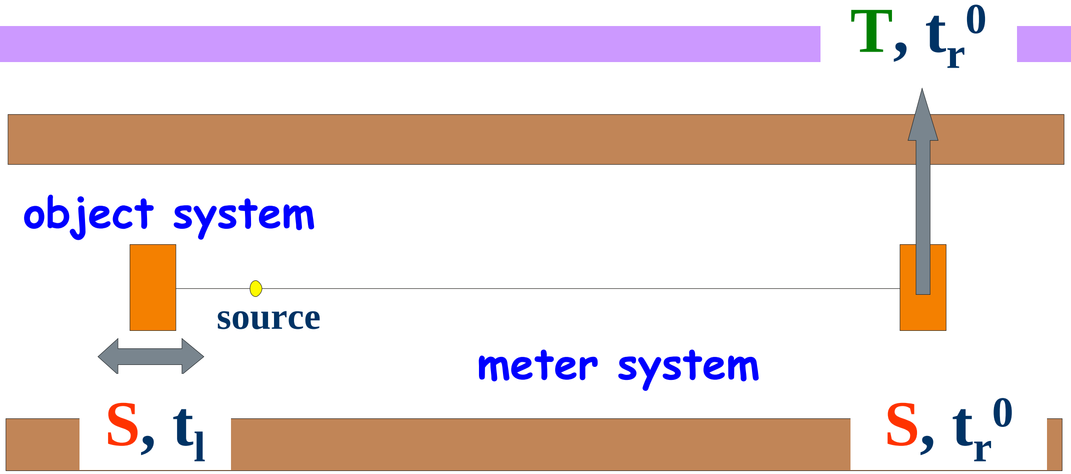
Sensitive to the decay modes:

2 π’s are identified as K_S

3 π’s are identified as K_L

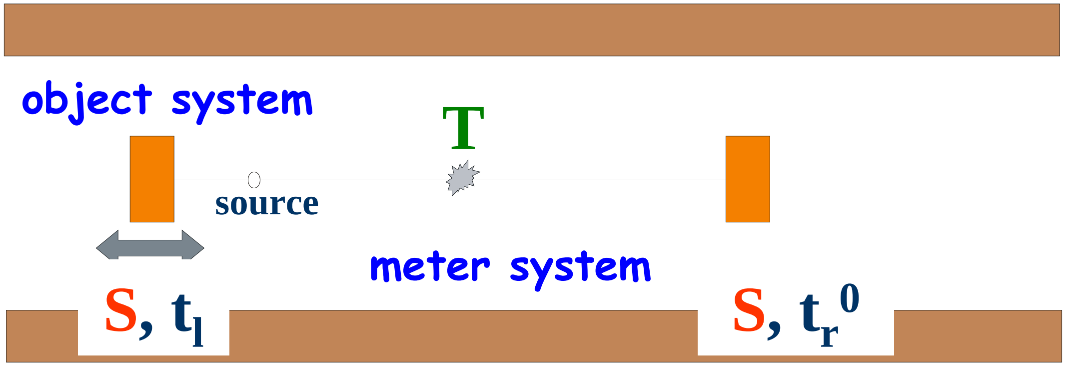
Misidentification: few parts in 10^{-3}!

(A) Active Eraser with active measurements



	left (object)	right (meter)
1.Setup (matter block remove):	*active* **S**	*active* **T**
2.Setup (matter block inserted):	*active* **S**	*active* **S**

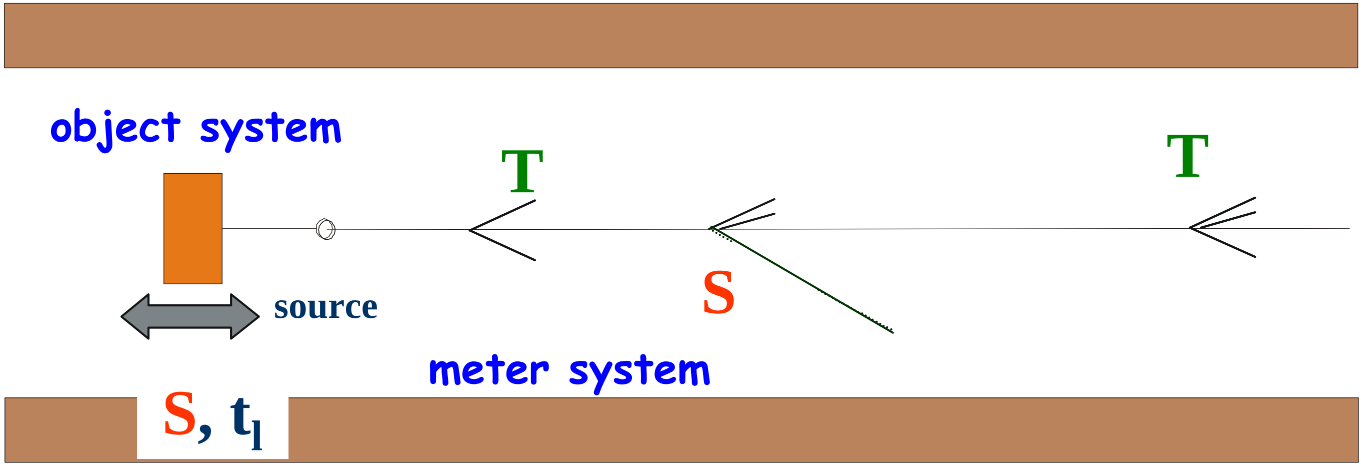
(B) Partially active eraser with *active* measurements



left (object)	right (meter)
active S	*active* T, *active* S

→ partially active choice due to instability of kaon

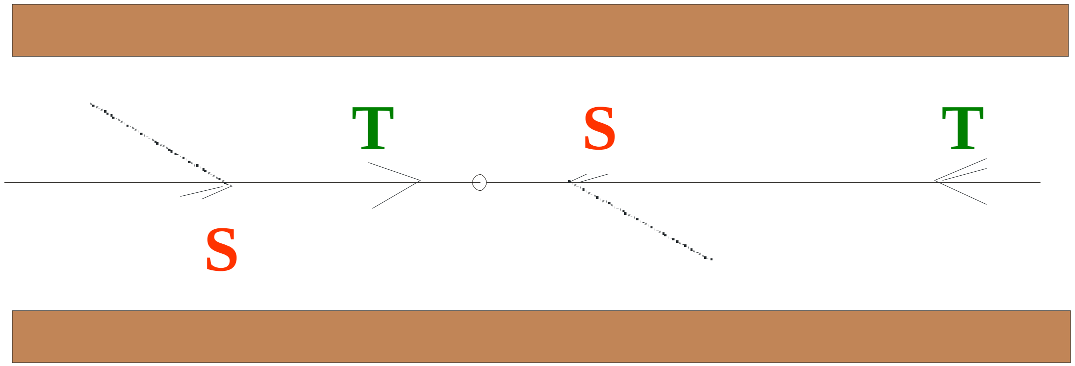
(C) Passive eraser with *passive* measurements on the meter



left (object)	right (meter)
active S	*passive* T, *passive* S

Not available for usual quantum systems

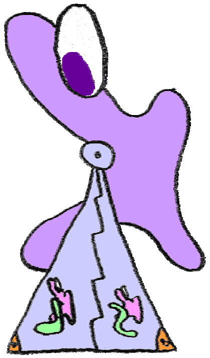
(D) Passive eraser with *passive* measurements



left (??object??)	right (??meter??)
passive T, *passive* S	*passive* T, *passive* S

Not available for usual quantum systems

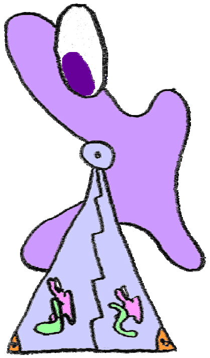
Summary of “kaonic” eraser



- remarkably all these QE options lead to the same probabilities!
- this is even true regardless the temporal ordering (delayed choice)
- demonstrates nicely the very nature of QE: sorting events; or differently: the way, in which joint events are classified according to the available information

→ should be possible to test it at DAΦNE!

→ contributes to clarify the working principle of a QE



THANK YOU HISHAM!

THANKS to co-Organizers, students, drivers!