Experimental Tests of Quantum Mechanics

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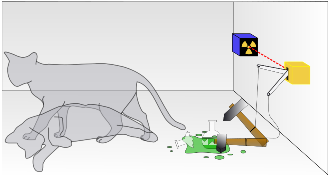
Outline

- Basics
- Bell's Inequalities
- Early Experiments
- Parametric Down-Conversion
- Advanced Topics
- Summary



➜ heated (philosophical) discussions

- relation between QM and the understanding of nature
  - ➜ mathematical structure: (mostly) accepted
  - ➜ core issue: interpretation of QM
    - ✘ causality and chance
    - ✘ relation to classical physics
- persona remarks
  - ➜ classical picture: causality in space and time
  - ➜ QM: (perhaps) theorie regarding information
    - ✘ information is intrinsically quantized
    - ✘ relevant for sufficiently small physical systems
    - ✘ QM was developed when atomic scales became accessible
  - ➜ general observation
    - ✘ information given: classical behavior
    - ✘ information missing: chance

❖ in the following:

Try to get a better understanding from comparing theory and experiment

➜ some Nobelprize awarded results. . .

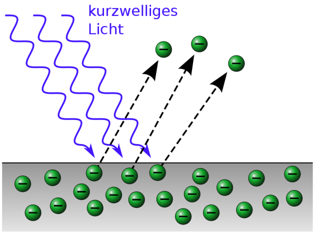
➜ Max Planck

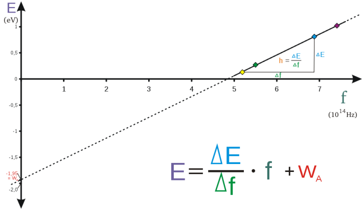
- discovery of the quantization of action $h \neq 0$
  - ➜ energy of light-waves is continuous
  - ➜ interaction with matter is quantized

$$E = h\,\nu$$

(Nobelprize 1918)

❖ experiment: photo-effect





(explanation by Einstein, Nobelprize 1921)

➜ Albert Einstein

- mass and energy are equivalent

$$E = m\,c^2$$

➜ De Broglie

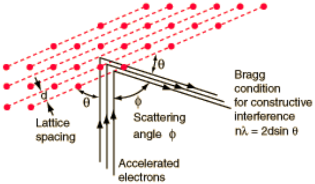
- matter has wave-like properties, too
- particles cannot be perfectly localized

$$E = h\,\nu = m\,c^2 = (mc)\,c = p\,c$$

$$\nu = \frac{c}{\lambda}$$

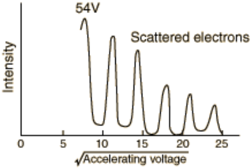
Resultat ➜ $\lambda = \dfrac{h}{p}$

(Nobelprize 1929)



❖ experiment: Davisson-Germer experiment

- diffraction in electron-scattering off crystals
- same phenomenology as X-ray scattering



(Nobelprize 1937)

Φ Formal description

Physics	$\Longleftrightarrow$	Mathematics
state of a system		**normalized wavefunction** $\mid \psi \rangle$
observable S		**hermitian operator** S
Measurement		**Eigenvalue und Eigenfunction**

➜ discussion:

- $\mid \psi \rangle$ is element of a linear vector space: wavefunctions can be linearly superposed and it exsist an inner product. The normalization is $\langle \psi \mid \psi \rangle$=1.
- On the linear space of the wavefunctions S is a matrix with real eigenvalues λ_k and an ortho-normalsystem of eigenvectors $\mid \phi_k \rangle$, i.e. $\langle \phi_k \mid \phi_l \rangle = \delta_{kl}$.
- A measurement always yields an eigenvalue λ_k of the respective operator. After the measurement the wavefunction is the eigenvector $\mid \phi_k \rangle$ (“collapse of the wavefunction”, or “decoherence”).

➜ the statistical interpretation of Quantum Mechanics

wanted: distribution of the measured values for a given state

$$|\,\psi\,\rangle = \sum_k a_k\,|\,\phi_k\,\rangle$$

with (in general) complex-valued coefficients a_k.

A priori a measurement can return any eigenvalue λ_k, i.e. the question is what are the relative frequencies p_k (probabilities). Exploit that the wavefunction the p_k are normalized:

$$1 = \sum_k p_k = \langle\,\psi\,|\,\psi\,\rangle = \sum_{k,l} a_k\,a_l^*\,\langle\,\phi_k\,|\,\phi_l\,\rangle = \sum_{k,l} a_k\,a_l^*\,\delta_{kl} = \sum_k |a_k|^2$$

and thus $\quad p_k = |a_k|^2$ (Nobelprize 1954)

- in general the result of a measurement cannot be predicted, however . . .
- relative frequencies are fixed by the wavefunction
- only a system in the eigenstate ϕ_k deterministically yields the eigenvalue λ_k
- general predictability would contradict with relativity

Φ *Linear algebra...*

➜ determination of the expansion coefficients a_k

$$\langle \phi_k \mid \psi \rangle = \langle \phi_k \mid \left(\sum_i a_i \mid \phi_i \rangle \right) = \sum_i a_i \langle \phi_k \mid \phi_i \rangle = \sum_i a_i \delta_{ki} = a_k$$

➜ expectation values

$$\langle S \rangle \equiv \sum_k p_k \lambda_k = \langle \psi \mid S \mid \psi \rangle$$

❖ proof:

$$\langle \psi \mid S \mid \psi \rangle = \sum_{kl} a_k a_l^* \langle \phi_l \mid S \mid \phi_k \rangle = \sum_{kl} a_k a_l^* \lambda_k \langle \phi_l \mid \phi_k \rangle$$
$$= \sum_{kl} a_k a_l^* \lambda_k \delta_{kl} = \sum_k |a_k|^2 \lambda_k = \sum_k p_k \lambda_k$$

in the following: 2-state systems with $\lambda_{1,2} = \pm 1$ ➜

Spin-1/2 particles (i)

➜ operators for spin-components in x, y, z

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

➜ Eigenstates for σ_z and σ_x

$$|\uparrow\rangle_z = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \ \lambda = +1 \quad \text{und} \quad |\downarrow\rangle_z = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \ \lambda = -1$$

$$|\uparrow\rangle_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \ \lambda = +1 \quad \text{und} \quad |\downarrow\rangle_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \ \lambda = -1$$

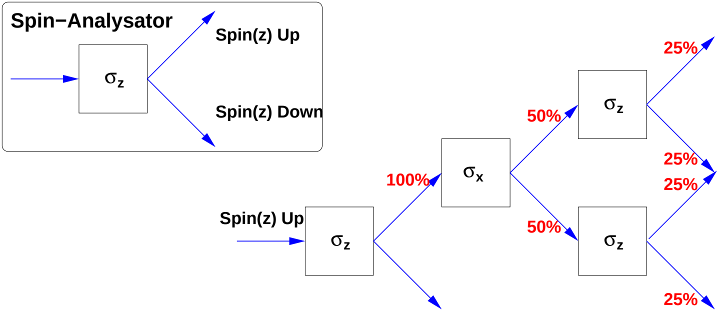
➜ transformation between the two bases

$$|\uparrow\rangle_x = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_z + |\downarrow\rangle_z\right) \quad \text{und} \quad |\downarrow\rangle_x = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_z - |\downarrow\rangle_z\right)$$

$$|\uparrow\rangle_z = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_x - |\downarrow\rangle_x\right) \quad \text{und} \quad |\downarrow\rangle_z = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_x + |\downarrow\rangle_x\right)$$

➜ example: consequence for Stern-Gerlach type experiments

- initial stat: $|\uparrow\rangle_z$
- start with measurement of the z-component of the spins
- then measure the x-component
- then measure the z-component



After a measurement all information about earlier states has been erased!

Φ *Two-particle systems*

➜ construction of “classical” product states

z.B. $|\,\psi\,\rangle = |\uparrow\rangle_1 \otimes |\uparrow\rangle_2 \equiv |\uparrow\uparrow\rangle$ oder $|\,\psi\,\rangle = |\uparrow\rangle_1 \otimes |\downarrow\rangle_2 \equiv |\uparrow\downarrow\rangle$

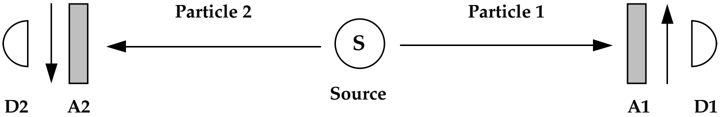
- direct product of single particle states
- use a basis (here and below) == eigenstates of σ_z

➜ new: “entagled states”

z.B. $|\,\psi\,\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$ (spin-singlet)

- possible because of the superposition principle in QM
- no classical interpretation - both particles are simultaneously “up” and “down”
- interesting phenomenology when measuring both spins . . .

➜ spin-correlation for the spin-singlet state



- xz-direction of spin measurement: particle-1: α, particle-2: β
- operators for those observables (e.g. α)

$$\sigma_\alpha = \cos\alpha \cdot \sigma_z - \sin\alpha \cdot \sigma_x$$

- effects of base-operators

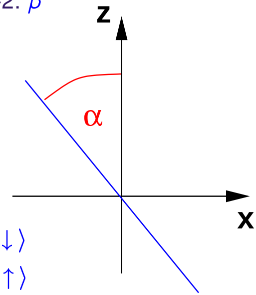
$$\sigma_z \,|\uparrow\rangle = |\uparrow\rangle \quad \text{und} \quad \sigma_z \,|\downarrow\rangle = -|\downarrow\rangle$$

$$\sigma_x \,|\uparrow\rangle = |\downarrow\rangle \quad \text{und} \quad \sigma_x \,|\downarrow\rangle = |\uparrow\rangle$$

- effects of the operators for the actual observables

$$\sigma_\alpha \,|\uparrow\rangle = \cos\alpha\,|\uparrow\rangle - \sin\alpha\,|\downarrow\rangle \equiv c_\alpha\,|\uparrow\rangle - s_\alpha\,|\downarrow\rangle$$

$$\sigma_\alpha \,|\downarrow\rangle = -\cos\alpha\,|\downarrow\rangle - \sin\alpha\,|\uparrow\rangle \equiv -c_\alpha\,|\downarrow\rangle - s_\alpha\,|\uparrow\rangle$$



then calculate. . .

Φ Quantum mechanical prediction (ii)

❖ expectation values of individual measurements

$$
\begin{aligned}
\langle\sigma_\alpha\rangle &= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right](\sigma_\alpha)\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right] \\
&= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right]\left[\sigma_\alpha|\uparrow\downarrow\rangle - \sigma_\alpha|\downarrow\uparrow\rangle\right] \\
&= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right]\left[(c_\alpha|\uparrow\downarrow\rangle - s_\alpha|\downarrow\downarrow\rangle) - (-c_\alpha|\downarrow\uparrow\rangle - s_\alpha|\uparrow\uparrow\rangle)\right] \\
&= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right]\left[c_\alpha(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) - s_\alpha(|\downarrow\downarrow\rangle - |\uparrow\uparrow\rangle)\right] \\
&= \frac{1}{2}c_\alpha\left[\langle\uparrow\downarrow|\uparrow\downarrow\rangle - \langle\downarrow\uparrow|\downarrow\uparrow\rangle\right] = 0
\end{aligned}
$$

❖ note:

- σ_α only acts on the first particle
- σ_β would only act on the other particle
- formally everything can be expressed by 4×4 matrices
- inner products of orthogonal states are zero
- single measurements are random with equal probability for $\uparrow_\alpha$ und $\downarrow_\alpha$

❖ expectation value of the product (correlation)

$$\langle\sigma_\alpha\sigma_\beta\rangle = \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right](\sigma_\alpha\sigma_\beta)\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right]$$

$$= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right]\left[|(c_\alpha\uparrow - s_\alpha\downarrow)(-c_\beta\downarrow - s_\beta\uparrow)\rangle - |(-c_\alpha\downarrow - s_\alpha\uparrow)(c_\beta\uparrow - s_\beta\downarrow)\rangle\right]$$

$$= \frac{1}{2}\left[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|\right]\left[|\uparrow\downarrow\rangle(-c_\alpha c_\beta - s_\alpha s_\beta) + |\downarrow\uparrow\rangle(s_\alpha s_\beta + c_\alpha c_\beta)\right.$$
$$\left. + |\uparrow\uparrow\rangle(-c_\alpha s_\beta - s_\alpha c_\beta) + |\downarrow\downarrow\rangle(s_\alpha c_\beta - c_\alpha s_\beta)\right]$$

$$= \frac{1}{2}(-c_\alpha c_\beta - s_\alpha s_\beta)\langle\uparrow\downarrow|\uparrow\downarrow\rangle - \frac{1}{2}(s_\alpha s_\beta + c_\alpha c_\beta)\langle\downarrow\uparrow|\downarrow\uparrow\rangle$$

$$= -(c_\alpha c_\beta + c_\alpha c_\beta) = -\cos(\alpha - \beta) \equiv -\cos(\phi)$$

➜ the correlation is only a function of the opening angle $\phi = \alpha - \beta$

spin-1/2 particles $\langle\sigma_\alpha\sigma_\beta\rangle = -\cos\phi$

photons (spin-1) $\langle\sigma_\alpha\sigma_\beta\rangle = -\cos 2\phi$

(180deg between orthogonal spin-1/2 states, 90deg between orthogonal photon polarisations)

➜ Interpretation

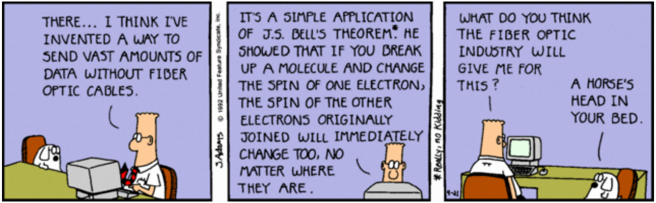
Φ *Discussion*

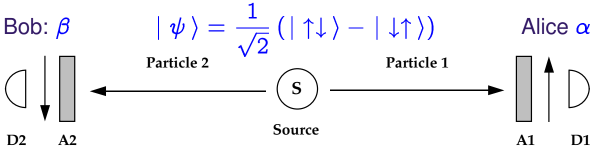
➜ $\langle \sigma_\alpha \sigma_\beta \rangle$ is only a function of ϕ

- single measurements are perfectly random
- equal probability to measure “Spin-up” or “Spin-down”
- perfect anti-correlation of both measurements refer to the same direction
- independent of space and time, i.e.
  - ➜ independent of the time ordering of the measurement
  - ➜ independent of the spatial separation

➜ obvious(?) questions:

- Is there “spooky action at a distance” which causes perfect synchronisation?
- can one use this to transmit information with $v = \infty$?





- analyzer setting $\alpha \parallel \beta$: perfect anti-correlation
- analyser setting $\alpha \perp \beta$: uncorrelated measurements

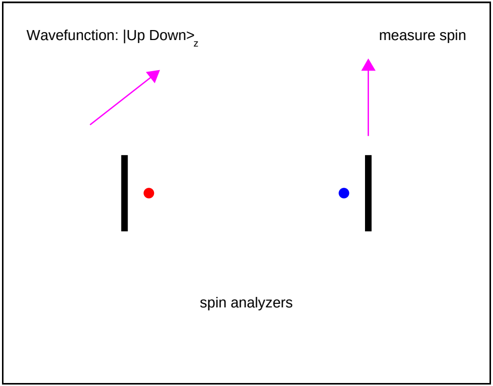
➜ Alice knows β and sends one bit to Bob by causing an excess of -1

- case 1: Alice can influence her result
  - ➜ set $\alpha \parallel \beta$ and cause an excess of $+1$ at her side
  - ➜ Bob observes the same excess of -1
- case 2: Alice kann predict her result
  - ➜ prediction $+1$: set $\alpha \parallel \beta$ and Bob always sees -1
  - ➜ prediction -1: set $\alpha \perp \beta$ and Bob measures equal numbers of ± 1

❖ insight:

If a quantum mechanical measurement is truly random, i.e. neither predictable, nor controllable then communication with $v > c$ is impossible.

➜ measurement of spin correlations for spin-1/2 particles



- for ideal detektors and different wavefunctions consider . . .
  - ➜ measurements of spin correlations
  - ➜ coincidence measurements

➜ The EPR-paradox (Einstein, Podolski, Rosen, 1935)

❖ quantum mechanics versus physical reality

- definition: Element of reality
  There exists a certain prediction ($p = 1$) for an observable, which can be obtained without perturbing the system.
- definition: Complete theorie
  Each element of reality is represented in the theory.
- discussion:
  - ➜ plausible concepts
  - ➜ inconsistent with quantum mechanics

➜ EPR: consider the wavefunction of a two-body decay $M \to m_1 m_2$, which is an eigenstate of both $(x_1 - x_2)$ and $(p_1 + p_2)$

$$(x_1 - x_2) \mid \psi \rangle = a \mid \psi \rangle$$
$$(p_1 + p_2) \mid \psi \rangle = P \mid \psi \rangle$$

➜ allowed by quantum mechanics, since:

$$[x_1 - x_2, p_1 + p_2] = [x_1, p_1] - [x_2, p_1] + [x_1, p_2] - [x_2, p_2] = i\hbar - 0 + 0 - i\hbar = 0$$

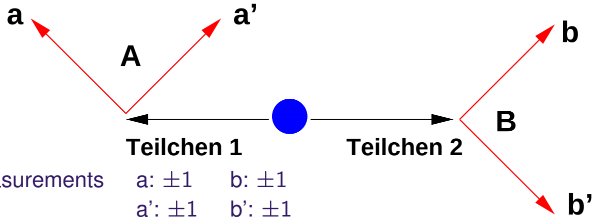
➜ measurement and interpretation

- measure x_1
  - ➜ predict $x_2 = a + x_1$
  - ➜ always found when measured
- measure p_2
  - ➜ predict $p_1 = P - p_2$
  - ➜ always found when measured
- result: A measurement of x_1 and p_2 not only determines those, but also x_2 and p_1. For each of the 4 variables one has a sure prediction.
  - ➜ x_1 AND p_1 as well as x_2 AND p_2 are elements of reality.
- quantum mechanics:
  - ➜ x_1 exclusive OR p_1 and x_2 /exclusive OR p_2 are elements of reality.
- solution to the contradiction
  - ➜ Option 1:
    Quantum mechanics is incomplete. There are additional hidden parameters which also explain the statistical properties and action at a distance.
  - ➜ Option 2:
    Einstein's concept of reality is not realized by nature.

Φ *Bell´s inequalities (i)*

➜ consider two-particle systems and 2 × 2 analyser settings

J.S. Bell: Physics 1 (1964) 195, *On the Einstein Podolski Rosen paradox*



possible measurements a: ±1 b: ±1
a': ±1 b': ±1

❖ local-deterministic assumption:

During the decay some hidden variables determine which measurements the two particles produce for given analyser settings. Each possible outcome has a fixed probability to be realized. For example:

$$\rho(a = +1, a' = -1, b = -1, b' = +1):$$

probability that particle-1 for analyzer setting a, (a') yields the measurement $+1$, (-1), and particle-2 for analyzer setting b, (b') the measurement Messwert -1, $(+1)$.

➜ configuration space and possible measurements

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+
b	−	−	−	−	+	+	+	+	−	−	−	−	+	+	+	+
a′	−	−	+	+	−	−	+	+	−	−	+	+	−	−	+	+
b′	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+

For the configurations k one has:

$$\rho_k \geq 0 \;\forall\; k \qquad \text{and} \qquad \sum_k \rho_k = 1$$

❖ measurements:

$E(x, y) = \langle x \cdot y \rangle$ expectation value of the product of the measurements x und y

$F(x, y)$ probability for $x = +1 \wedge y = +1$

The expectation values $E(x, y)$ are theoretically nice, the $F(x, y)$ are experimentally easier to determine coincidence probabilities, where $+1$ means that a particles passes the analyzer and is recorded in a detector.

➜ linear combination of expectation values

$$T = E(a,b) - E(a,b') + E(a',b) + E(a',b') \equiv E_1 - E_2 + E_3 + E_4$$

❖ straightforward calculation:

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+
b	−	−	−	−	+	+	+	+	−	−	−	−	+	+	+	+
a′	−	−	+	+	−	−	+	+	−	−	+	+	−	−	+	+
b′	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+

$E_1 : \rho_0 + \rho_1 + \rho_2 + \rho_3 - \rho_4 - \rho_5 - \rho_6 - \rho_7 - \rho_8 - \rho_9 - \rho_{10} - \rho_{11} + \rho_{12} + \rho_{13} + \rho_{14} + \rho_{15}$

$E_2 : \rho_0 - \rho_1 + \rho_2 - \rho_3 + \rho_4 - \rho_5 + \rho_6 - \rho_7 - \rho_8 + \rho_9 - \rho_{10} + \rho_{11} - \rho_{12} + \rho_{13} - \rho_{14} + \rho_{15}$

$E_3 : \rho_0 + \rho_1 - \rho_2 - \rho_3 - \rho_4 - \rho_5 + \rho_6 + \rho_7 + \rho_8 + \rho_9 - \rho_{10} - \rho_{11} - \rho_{12} - \rho_{13} + \rho_{14} + \rho_{15}$

$E_4 : \rho_0 - \rho_1 - \rho_2 + \rho_3 + \rho_4 - \rho_5 - \rho_6 + \rho_7 + \rho_8 - \rho_9 - \rho_{10} + \rho_{11} + \rho_{12} - \rho_{13} - \rho_{14} + \rho_{15}$

collecting all terms:

$$T = 2 \cdot (\rho_0 + \rho_1 + \rho_3 + \rho_7 + \rho_8 + \rho_{12} + \rho_{14} + \rho_{15})$$
$$- 2 \cdot (\rho_2 + \rho_4 + \rho_5 + \rho_6 + \rho_9 + \rho_{10} + \rho_{11} + \rho_{13})$$

and using $\sum \rho_k \leq 1$ one finds:

$$-2 \leq T \leq 2$$

➜ linear combination of coincidence probabilities

$$S = F(a,b) - F(a,b') + F(a',b) + F(a',b') - F(a') - F(b)$$

❖ straightforward calculation:

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+
b	−	−	−	−	+	+	+	+	−	−	−	−	+	+	+	+
a′	−	−	+	+	−	−	+	+	−	−	+	+	−	−	+	+
b′	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+

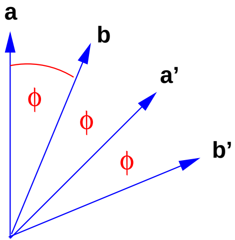
$$F(a,b) = \rho_{12} + \rho_{13} + \rho_{14} + \rho_{15}$$
$$F(a,b') = \rho_9 + \rho_{11} + \rho_{13} + \rho_{15}$$
$$F(a',b) = \rho_6 + \rho_7 + \rho_{14} + \rho_{15}$$
$$F(a',b') = \rho_3 + \rho_7 + \rho_{11} + \rho_{15}$$
$$F(a') = \rho_2 + \rho_3 + \rho_6 + \rho_7 + \rho_{10} + \rho_{11} + \rho_{14} + \rho_{15}$$
$$F(b) = \rho_4 + \rho_5 + \rho_6 + \rho_7 + \rho_{12} + \rho_{13} + \rho_{14} + \rho_{15}$$

collecting all terms:

$$S = -\rho_2 - \rho_3 - \rho_4 - \rho_5 - \rho_6 - \rho_9 - \rho_{11} - \rho_{13} \quad \text{and thus} \quad S \leq 0$$

Predictions of quantum mechanics (i)

➜ consider symmetric configurations



❖ predictions

Spin-1/2 particles: $E(x,y) = -\cos\phi_{xy}$

Photons: $E(x,y) = -\cos 2\phi_{xy}$

experimental: $E(x,y) \to V \cdot E(x,y)$

attenuation of the correlation by Visibility $V < 1$

➜ predictions for T

$$\begin{aligned} T(\text{Spin 1/2}) &= E(a,b) - E(a,b') + E(a',b) + E(a',b') \\ &= V \cdot (-\cos(\phi) + \cos(3\phi) - \cos(\phi) - \cos(\phi)) \\ &= V \cdot (\cos(3\phi) - 3\cos(\phi)) \end{aligned}$$

$$T(\text{Spin 1}) = V \cdot (\cos(6\phi) - 3\cos(2\phi))$$

➜ result: QM: $|T| \le V \cdot 2\sqrt{2}$ vs Bell: $|T| < 2$

Φ Predictions of quantum mechanics (ii)

➜ predictions for S

relation between coincidence probability $F(x,y)$ and $E(x,y)$:

$$E(x,y) = F^{++}(x,y) + F^{--}(x,y) - F^{+-}(x,y) - F^{-+}(x,y)$$

with F^{ab} the probability to observe simultaneously a at analyzer setting x for particle 1, and b at analyzer setting y for particle 2. Using

$$F = F^{++} = F^{--} \quad , \quad F^{+-} = F^{-+} \quad , \quad F^{++} + F^{+-} = \frac{1}{2}$$

one finds

$$E(x,y) = 2 \cdot F(x,y) - 2 \cdot \left(\frac{1}{2} - F(x,y)\right) \quad \text{or} \quad F(x,y) = \frac{1}{4}(1 - E(x,y))$$

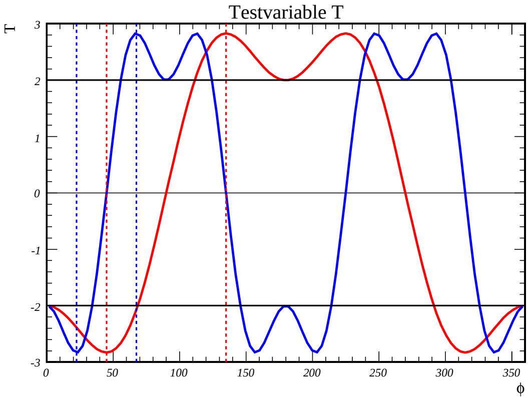
and with $F(a') = F(b) = 1/2$ finally

$$\begin{aligned} S &= F(a,b) - F(a,b') + F(a',b) + F(a',b') - F(a') - F(b) \\ &= -\frac{1}{2} + \frac{1}{4}\left(E(a,b) - E(a,b') + E(a',b) + E(a',b')\right) = -\frac{1}{2} + \frac{T}{4} \end{aligned}$$

➜ result: QM: $S < (\sqrt{2} - 1)/2 \approx 0.207$ vs Bell: $S < 0$

Φ Discussion

➜ the test variables S and T are equivalent:



❖ most sensitive settings

Photons $\phi = 22.5^\circ, 67.5^\circ$

spin 1/2 $\phi = 45^\circ, 135^\circ$

➜ blue: QM-prediction for photons

➜ red: QM-prediction for Spin-1/2 particles

Φ Loopholes

➜ quantum mechanics permits violations of Bell's inequalities

❖ consequences of experimental confirmation

- local-realistic theories are falsified
  - ➜ there are no hidden variables
  - ➜ nature is non-local
- the experiments did not really test quantum mechanics

❖ Loopholes

- static experimental setup affects hidden parameters
  - ➜ decide on analyser setting only after emission of the particles
- analyser are not spacial separated (i.e. within light cone)
  - ➜ use large distanced
  - ➜ measure in moving reference frames (each observer sees his particle first)
- das "Detection Loophole"
  - ➜ only a small fraction of all particles is recorded
  - ➜ this fraction is not a fair sampling of the total

➜ (increasingly better) experiments. . .