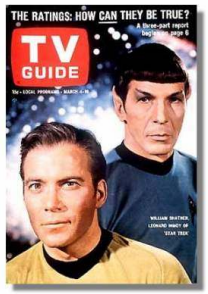
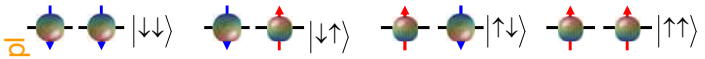
Kwantowa kryptografia i teleportacja. Splątanie kwantowe

Jacek Szczytko, Wydział Fizyki UW

a. Poplątane stany.
   i. Eksperyment EPR.
   ii. Eksperyment Bella
b. Star-Trec, czyli teleportujcie mnie!
   i. Co wlasciwie teleportujemy
   ii. Ile kosztuje ubezpieczenie
c. Kryptografia kwantowa
   i. Czy są szyfry nie do złamania
   ii. Klucze duże i małe
   iii. Alice i Bob w świecie kwantów
   iv. Ewa chce posłuchać



Opis wielu cząstek kwantowych



Stany Bella

$$|\beta_{00}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right) \qquad |\beta_{01}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle\right)$$

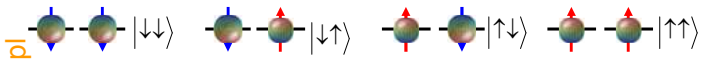
$$|\beta_{10}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle - |\uparrow\uparrow\rangle\right) \qquad |\beta_{11}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle\right)$$

Ale stanów Bella nie da się przedstawić w postaci iloczynu dwóch funkcji jednocząstkowych typu: $|\beta\rangle = |\varphi_1\rangle|\varphi_2\rangle$ gdzie $|\varphi_i\rangle = a_{i1}|\uparrow\rangle + a_{i2}|\downarrow\rangle$

Stany Bella są **SPLĄTANE**

spiny, polaryzacja fotonów, atom + foton, dwa atomy, atom w różnych stanach...

Opis wielu cząstek kwantowych



Stany Bella

$|\beta_{00}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right)$ $|\beta_{10}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle - |\uparrow\uparrow\rangle\right)$ $|\beta_{01}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle\right)$ $|\beta_{11}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle\right)$

Observation of entanglement between a single trapped atom and a single photon

B. B. Blinov, D. L. Moehring, L.-M. Duan & C. Monroe

NATURE | VOL 428 | 11 MARCH 2004 | www.nature.com/nature

PHYSICAL REVIEW A **69**, 042316 (2004)

Atom-photon entanglement generation and distribution

B. Sun, M. S. Chapman, and L. You
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
(Received 21 August 2003; published 21 April 2004)

spiny, polaryzacja fotonów, atom + foton, dwa atomy, atom w różnych stanach...

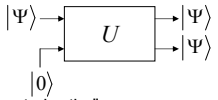
Zakaz klonowania

Źródło: Lucas Film

Zakaz klonowania

Klonowanie stanów kwantowych

$$|\Psi\rangle \rightarrow |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle ...$$

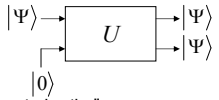


„czysta kartka"

Zakaz klonowania

Klonowanie stanów kwantowych

$$|\Psi\rangle \rightarrow |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle ...$$



„czysta kartka"

Wtedy $U|\Psi\rangle|0\rangle = |\Psi\rangle|\Psi\rangle$

$U|0\rangle|0\rangle = |0\rangle|0\rangle$

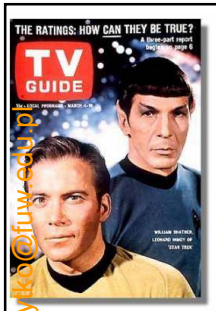
$U|1\rangle|0\rangle = |1\rangle|1\rangle$

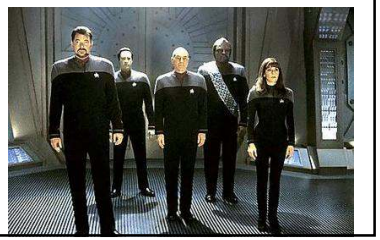
Ale dla $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$ Dostajemy sprzeczność bo:

$$U|\Psi\rangle|0\rangle = U(\alpha|0\rangle + \beta|1\rangle)|0\rangle = \alpha U|0\rangle|0\rangle + \beta U|1\rangle|0\rangle = \alpha|0\rangle|0\rangle + \beta|1\rangle|1\rangle \neq |\Psi\rangle|\Psi\rangle \quad !$$

bo $|\Psi\rangle|\Psi\rangle = \alpha^2|0\rangle|0\rangle + \alpha\beta|0\rangle|1\rangle + \beta\alpha|1\rangle|0\rangle + \beta^2|1\rangle|1\rangle$

Kwantowa teleportacja





Kwantowa teleportacja

IBM CREW Six researchers--Richard Jozsa, William K. Woolters, Charles H. Bennett *(back row, left to right)* Gilles Brassard, Claude Crepeau and Asher Peres *(front row)*--proposed quantum teleportation in 1993.

Kwantowa teleportacja

PHYSICAL REVIEW
LETTERS

VOLUME 70 29 MARCH 1993 NUMBER 13

Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

Charles H. Bennett,[1] Gilles Brassard,[2] Claude Crépeau,[2,3]
Richard Jozsa,[2] Asher Peres,[4] and William K. Wootters[5]
[1] *IBM Research Division, T.J. Watson Research Center, Yorktown Heights, New York 10598*
[2] *Département IRO, Université de Montréal, C.P. 6128, Succursale "A", Montréal, Québec, Canada H3C 3J7*
[3] *Laboratoire d'Informatique de l'École Normale Supérieure, 45 rue d'Ulm, 75230 Paris CEDEX 05, France*[a]
[4] *Department of Physics, Technion–Israel Institute of Technology, 32000 Haifa, Israel*
[5] *Department of Physics, Williams College, Williamstown, Massachusetts 01267*
(Received 2 December 1992)

An unknown quantum state $|\phi\rangle$ can be disassembled into, then later reconstructed from, purely classical information and purely nonclassical Einstein-Podolsky-Rosen (EPR) correlations. To do so the sender, "Alice," and the receiver, "Bob," must prearrange the sharing of an EPR-correlated pair of particles. Alice makes a joint measurement on her EPR particle and the unknown quantum system, and sends Bob the classical result of this measurement. Knowing this, Bob can convert the state of his EPR particle into an exact replica of the unknown state $|\phi\rangle$ which Alice destroyed.

Kwantowa teleportacja

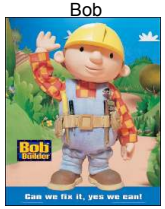
Dwucząstkowe stany splątane, baza Bella

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right) \qquad |\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle\right)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle - |\uparrow\uparrow\rangle\right) \qquad |\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle\right)$$

Alice

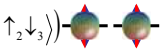
Bob



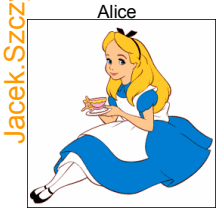
Kwantowa teleportacja

$$|\phi\rangle = a|\uparrow_1\rangle + b|\downarrow_1\rangle$$

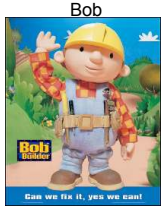
$$|\Psi^-_{2,3}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2\uparrow_3\rangle - |\uparrow_2\downarrow_3\rangle\right)$$



Alice



Bob

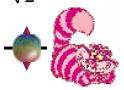


Kwantowa teleportacja

$$|\phi\rangle = a|\uparrow_1\rangle + b|\downarrow_1\rangle$$

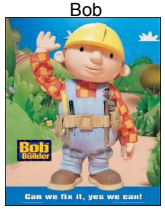
$$|\Psi^-_{2,3}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2\ \rangle - |\uparrow_2\ \rangle\right)$$

$$|\Psi^-_{2,3}\rangle = \frac{1}{\sqrt{2}}\left(|\ \uparrow_3\rangle - |\ \downarrow_3\rangle\right)$$



Alice

Bob



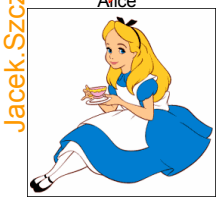
Kwantowa teleportacja

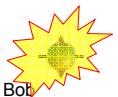
$|\phi\rangle = a|\uparrow_1\rangle + b|\downarrow_1\rangle$

$|\Psi^-_{2,3}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2 \square\rangle - |\uparrow_2 \square\rangle\right)$

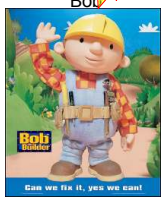
$|\Psi^-_{2,3}\rangle = \frac{1}{\sqrt{2}}\left(|\square\uparrow_3\rangle - |\square\downarrow_3\rangle\right)$

Alice





Bob



Kwantowa teleportacja

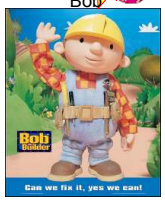
pufff...

$|\Psi^-_{2,1}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2\uparrow_1\rangle - |\uparrow_2\downarrow_1\rangle\right)$

$|\phi\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\left(a|\uparrow_3\rangle + b|\downarrow_3\rangle\right)$

Alice

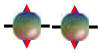
Bob



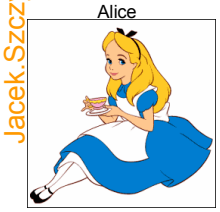
Kwantowa teleportacja

$|\Psi^-_{2,1}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2\uparrow_1\rangle - |\uparrow_2\downarrow_1\rangle\right)$

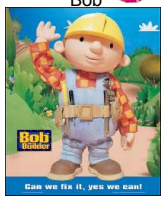
$|\phi\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\left(a|\uparrow_3\rangle + b|\downarrow_3\rangle\right)$



Alice



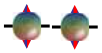
Bob



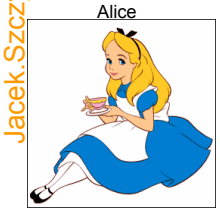
Kwantowa teleportacja

$|\Psi^-_{2,1}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow_2\uparrow_1\rangle - |\uparrow_2\downarrow_1\rangle\right)$

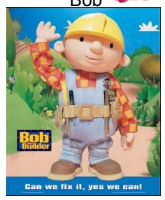
$|\phi\rangle = a|\uparrow_3\rangle + b|\downarrow_3\rangle$



Alice

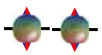


Bob

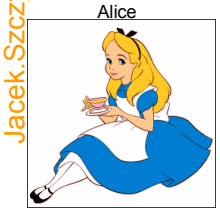


Kwantowa teleportacja

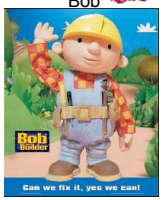
1. Przekazywana jest stan obiektu, a nie sam obiekt fizyczny.
2. Obiekt nie jest skopiowany (por. zasada Heisenberga, *zakaz klonowania*)
3. Informacja nie porusza się szybciej niż światło.
4. Trudności w pomiarze wszystkich czterech stanów Bella (wydajność).



Alice



Bob



Kwantowa teleportacja

Anton Zeilinger
Institute of Experimental Physics, University of Vienna,

Teleportacja stanów fotonowych

Nature, **390**, 575 (1997)

Experimental quantum teleportation

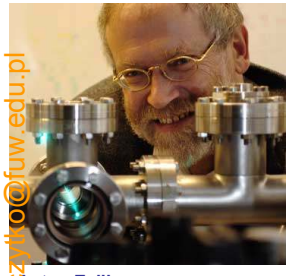
Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

1997

Quantum teleportation—the transmission and reconstruction over arbitrary distances of the state of a quantum system—is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks.

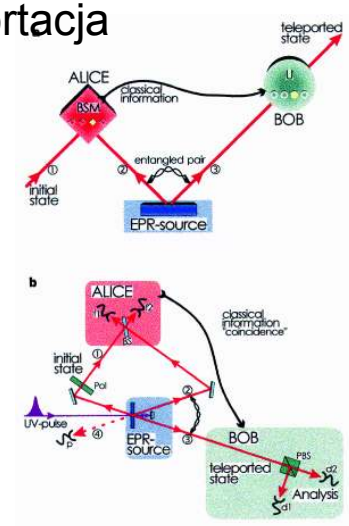
Kwantowa teleportacja



Anton Zeilinger
Institute of Experimental Physics, University of Vienna,

Teleportacja stanów fotonowych

Nature, **390**, 575 (1997)



Kwantowa teleportacja

Deterministic quantum teleportation with atoms

M. Riebe[1], H. Häffner[1], C. F. Roos[1], W. Hänsel[1], J. Benhelm[1], G. P. T. Lancaster[1], T. W. Körber[1], C. Becher[1], F. Schmidt-Kaler[1], D. F. V. James[2] & R. Blatt[1,3]

[1]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria*
[2]*Theoretical Division T-4, Los Alamos National Laboratory, Los Alamos NM 87545, USA*
[3]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 25, A-6020 Innsbruck, Austria*

Teleportacja stanów kwantowych jonów $^{40}Ca^{+}$ w pułapce jonowej

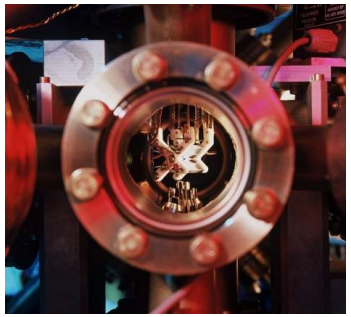
Nature, **429**, 734 (2004)

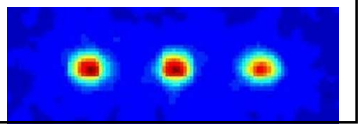
Reiner Blatt
Institute of Experimental Physics, University of Insbruck,

Kwantowa teleportacja

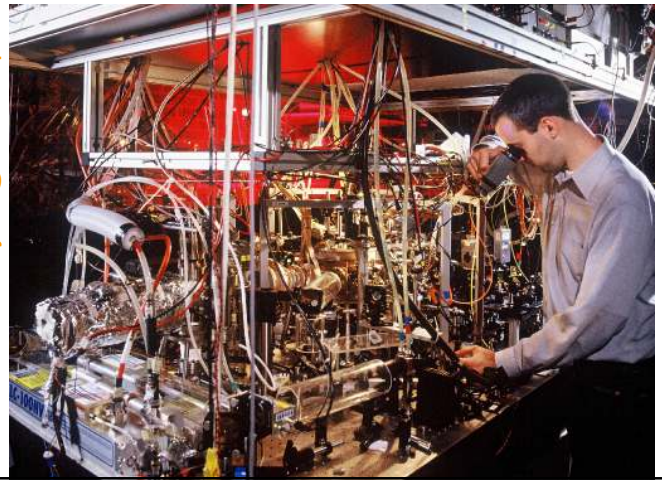
Table 1 **Pulse sequence of the teleportation protocol.**

	Action	Comment
	Light at 397 nm	Doppler preparation
2	Light at 729 nm	Sideband cooling
3	Light at 397 nm	Optical pumping
Entangle		
4	$R_3^0(\pi/2, 3\pi/2)$	Entangle ion 3 with motional qubit
5	$R_2^0(\pi, 3\pi/2)$	Prepare ion 2 for entanglement
6	$R_2^0(\pi, \pi/2)$	Entangle ion 2 with ion 3
7	Wait for 1 μs – 10,000 μs	Standby for teleportation
8	$R_1^0(\pi, 0)$	Hide target ion
9	$R_1^0(\theta_1, \varphi_1)$	Prepare source ion 1 in state χ
Rotate into Bell basis		
10	$R_3^0(\pi, 3\pi/2)$	Get motional qubit from ion 2
11	$R_1^0(\pi/\sqrt{2}, \pi/2)$	Composite pulse for phasegate
12	$R_1^0(\pi, 0)$	Composite pulse for phasegate
13	$R_1^0(\pi/\sqrt{2}, \pi/2)$	Composite pulse for phasegate
14	$R_1^0(\pi, 0)$	Composite pulse for phasegate
15	$R_2^0(\pi, \pi/2)$	Spin echo on ion 1
16	$R_3^0(\pi, \pi)$	Unhide ion 3 for spin echo
17	$R_3^0(\pi, \pi/2)$	Spin echo on ion 3
18	$R_3^0(\pi, 0)$	Hide ion 3 again
19	$R_2^0(\pi, \pi/2)$	Write motional qubit back to ion 2
20	$R_1^0(\pi/2, 3\pi/2)$	Part of rotation into Bell basis
21	$R_2^0(\pi/2, \pi/2)$	Finalize rotation into Bell basis
Read out		
22	$R_3^0(\pi, 0)$	Hide ion 2
23	PMDetection for 250 μs	Read out of ion 1 with photomultiplier
24	$R_1^0(\pi, 0)$	Hide ion 1
25	$R_2^0(\pi, \pi)$	Unhide ion 2
26	PMDetection for 250 μs	Read out of ion 2 with photomultiplier
27	$R_2^0(\pi, 0)$	Hide ion 2
28	Wait 300 μs	Let system rephase; part of spin echo
29	$R_3^0(\pi, \pi)$	Unhide ion 3
30	$R_3^0(\pi/2, 3\pi/2+\phi)$	Change basis
Reconstruction		
31	$R_3^0(\pi, \phi)$	$\left.\begin{matrix} i\sigma_x \\ -i\sigma_y \end{matrix}\right\} = -i\sigma_z$ conditioned on PM detection 1
32	$R_3^0(\pi, \pi/2+\phi)$	
33	$R_3^0(\pi, \phi)$	$i\sigma_x$ conditioned on PM detection 2
34	$R_3^0(\theta_1, \varphi_1+\pi+\phi)$	Inverse of preparation of χ with offset ϕ
35	Light at 397 nm	Read out of ion 3 with camera

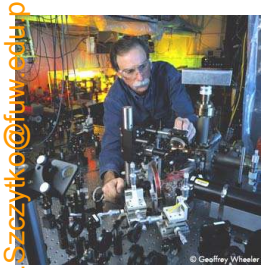




Maszyna do teleportacji



Kwantowa teleportacja



David Wineland
National Institute of Standards and Technology

Deterministic quantum teleportation of atomic qubits

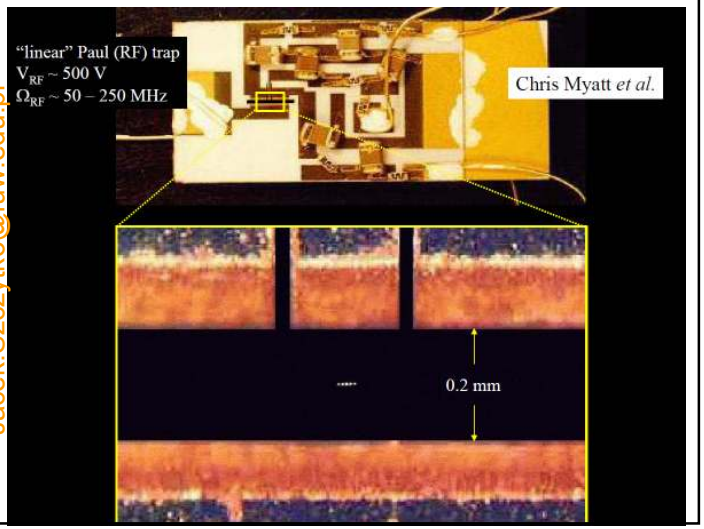
M. D. Barrett[1]*, J. Chiaverini[1], T. Schaetz[1], J. Britton[1], W. M. Itano[1], J. D. Jost[1], E. Knill[2], C. Langer[1], D. Leibfried[1], R. Ozeri[1] & D. J. Wineland[1]

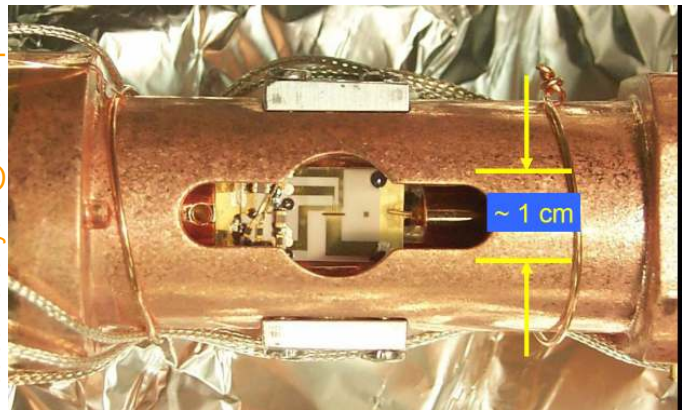
[1]*Time and Frequency Division, NIST, Boulder, Colorado 80305, USA*
[2]*Mathematical and Computational Sciences Division, NIST, Boulder, Colorado 80305, USA*

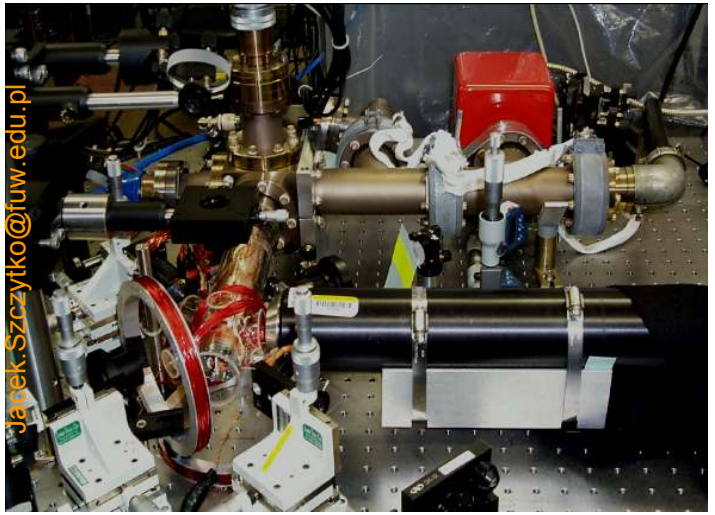
* Present address: Department of Physics, University of Otago, PO Box 56, Dunedin, New Zealand

Teleportacja stanów kwantowych jonów $^9Be^+$ w pułapce jonowej

Nature, **429**, 737 (2004)







Kwantowa teleportacja

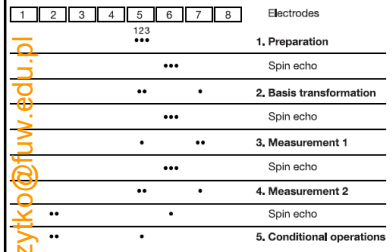
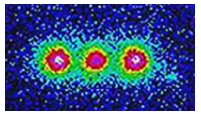


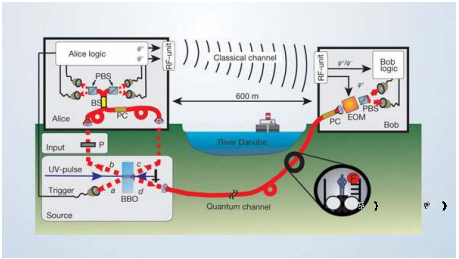
Figure 1 Schematic representation of the teleportation protocol. The ions are numbered left to right, as indicated at the top, and retain their order throughout. Positions, relative to the electrodes, are shown at each step in the protocol. The widths of the electrodes vary, with the width of the separation electrode (6) being the smallest at 100 μm. The spacing between ions in the same trap is about 3 μm, and laser-beam spot sizes (in traps 5 and 6) at the position of the ions are approximately 30 μm. In step 1 we prepare the outer ions in an entangled (singlet) state and the middle ion in an arbitrary state (equation (1)). Steps 2–4 constitute a measurement in a Bell-basis for ions 1 and 2 (Alice's qubits), teleporting the state of ion 2 onto ion 3 (Bob's qubit), up to unitary operations that depend on the measurement outcomes. In step 5 we invoke these conditional operations, recovering the initial state. Interspersed are spin-echo pulses applied in trap 6 that protect the state from de-phasing due to fluctuating magnetic fields but do not affect the teleportation protocol.



This colorized image shows the fluorescence from three trapped beryllium ions illuminated with an ultraviolet laser beam. Credit: NIST

Kwantowa teleportacja

Rupert Ursin, Thomas Jennewein, Markus Aspelmeyer, Rainer Kaltenbaek, Michael Lindenthal, Philip Walther and Anton Zeilinger Nature **430**, 849 (19 August 2004)



800 m

The quantum channel (fibre F) rests in a sewage-pipe tunnel below the river in Vienna, while the classical microwave channel passes above it. A pulsed laser (wavelength, 394 nm; rate, 76 MHz) is used to pump a -barium borate (BBO) crystal that generates the entangled photon pair *c* and *d* and photons *a* and *b* (wavelength, 788 nm) by spontaneous parametric down-conversion. The state of photon *b* after passage through polarizer P is the teleportation input; *a* serves as the trigger. Photons *b* and *c* are guided into a single-mode optical-fibre beam splitter (BS) connected to polarizing beam splitters (PBS) for Bell-state measurement. Polarization rotation in the fibres is corrected by polarization controllers (PC) before each run of measurements. The logic electronics identify the Bell state as either $|\Psi^-\rangle_{bc}$ or $|\Psi^+\rangle_{bc}$ and convey the result through the microwave channel (RF unit) to Bob's electro-optic modulator (EOM) to transform photon *d* into the input state of photon *b*.

Quantum Teleporation: The Math

Three qubit joint state of Alice, Bob, and "Victor" who prepared $|\psi\rangle$:

$$|\chi\rangle = |\psi\rangle_V \otimes |\Phi^{(+)}\rangle_{AB} = (\alpha|0\rangle_V + \beta|1\rangle_V) \otimes (|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B)$$

$$= \frac{1}{2}\left[(|0\rangle_V \otimes |0\rangle_A + |1\rangle_V \otimes |1\rangle_A) \otimes (\alpha|0\rangle_B + \beta|1\rangle_B) + (|0\rangle_V \otimes |0\rangle_A - |1\rangle_V \otimes |1\rangle_A) \otimes (\alpha|0\rangle_B - \beta|1\rangle_B)\right.$$

$$\left. + (|0\rangle_V \otimes |1\rangle_A + |1\rangle_V \otimes |0\rangle_A) \otimes (\alpha|1\rangle_B + \beta|0\rangle_B) + (|0\rangle_V \otimes |1\rangle_A - |1\rangle_V \otimes |0\rangle_A) \otimes (\alpha|1\rangle_B - \beta|0\rangle_B)\right]$$

$$|\chi\rangle = \frac{1}{2}\left(|\Phi^{(+)}\rangle_{VA} \otimes |\psi\rangle_B + |\Phi^{(-)}\rangle_{VA} \otimes Z|\psi\rangle_B + |\Psi^{(+)}\rangle_{VA} \otimes X|\psi\rangle_B - i|\Psi^{(-)}\rangle_{VA} \otimes Y|\psi\rangle_B\right)$$

A measurement by Alice in Bell-basis leaves Bob's qubit in one of four states:

$$\{|\psi\rangle_B,\ Z|\psi\rangle_B,\ X|\psi\rangle_B,\ Y|\psi\rangle_B\}$$

Alice uses the classical channel to tell Bob which Bell state she found.
Bob can then put his qubit in the unknown state, through application of a Pauli.

I. H. Deutsch, *University of New Mexico*
Short Course in Quantum Information

Kwantowa teleportacja

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Experimental Nonlocality Proof of Quantum Teleportation and Entanglement Swapping

Thomas Jennewein, Gregor Weihs, Jian-Wei Pan, and Anton Zeilinger
Institut für Experimentalphysik, Universität Wien Boltzmanngasse 5, 1090 Wien, Austria
(Received 15 August 2001; published 18 December 2001)

Quantum teleportation strikingly underlines the peculiar features of the quantum world. We present an experimental proof of its quantum nature, teleporting an entangled photon with such high quality that the nonlocal quantum correlations with its original partner photon are preserved. This procedure is also known as entanglement swapping. The nonlocality is confirmed by observing a violation of Bell's inequality by 4.5 standard deviations. Thus, by demonstrating quantum nonlocality for photons that never interacted, our results directly confirm the quantum nature of teleportation.

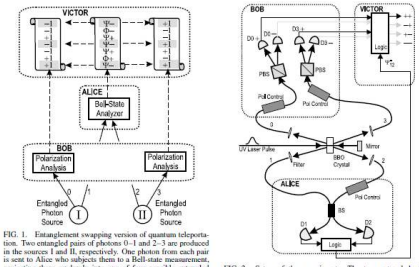


FIG. 1. Entanglement swapping version of quantum teleportation. Two entangled pairs of photons 0–1 and 2–3 are produced in the sources I and II, respectively. One photon from each pair is sent to Alice who subjects them to a Bell-state measurement, projecting them randomly into one of four possible entangled

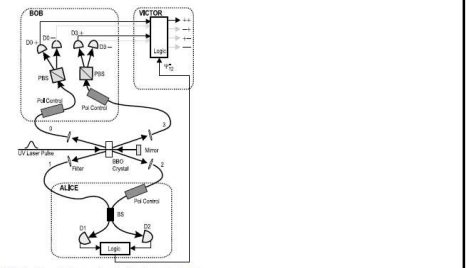


FIG. 2. Setup of the experiment. The two entangled pho-

Kwantowa teleportacja

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Experimental Nonlocality Proof of Quantum Teleportation and Entanglement Swapping

Thomas Jennewein, Gregor Weihs, Jian-Wei Pan, and Anton Zeilinger
Institut für Experimentalphysik, Universität Wien Boltzmanngasse 5, 1090 Wien, Austria
(Received 15 August 2001; published 18 December 2001)

Quantum teleportation strikingly underlines the peculiar features of the quantum world. We present an experimental proof of its quantum nature, teleporting an entangled photon with such high quality that the nonlocal quantum correlations with its original partner
also known as entanglement swapping. The nonlocality is con
inequality by 4.5 standard deviations. Thus, by demonstrati
never interacted, our results directly confirm the quantum natu

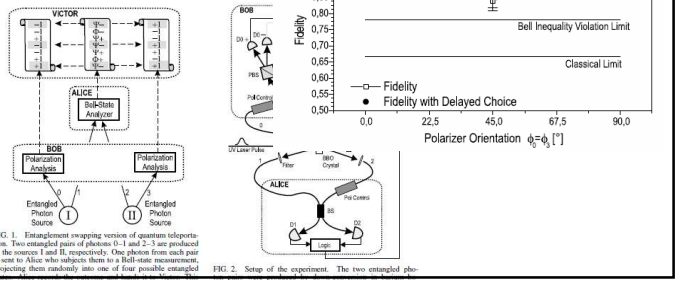


FIG. 1. Entanglement swapping version of quantum teleportation. Two entangled pairs of photons 0–1 and 2–3 are produced in the sources I and II, respectively. One photon from each pair is sent to Alice who subjects them to a Bell-state measurement, projecting them randomly into one of four possible entangled

FIG. 2. Setup of the experiment. The two entangled pho-

Kryptografia Kwantowa

Kryptografia Kwantowa

Jacek.Szczytko@fuw.edu.pl

- http://zon8.physd.amu.edu.pl/~tanas/

Kryptografia Kwantowa

Jacek.Szczytko@fuw.edu.pl
•http://zon8.physd.amu.edu.pl/~tanas/

1.4 Proste szyfry

Szyfr Cezara

szyfr podstawieniowy monoalfabetyczny

ABCDEFGHIJKLMNOPRSTUVWXYZ
DEFGHIJKLMNOPRSTUVWXYZABC

tekst jawny ⟶ KRYPTOGRAFIA
kryptogram ⟶ NUBTWSJUDILD

Kryptografia Kwantowa

Jacek.Szczytko@fuw.edu.pl
•http://zon8.physd.amu.edu.pl/~tanas/

Szyfr Vigenère'a

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	K	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	L	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	M	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	N	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	O	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	P	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
R	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
S	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R
T	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S
U	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T
V	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U
W	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V
X	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W
Y	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X
Z	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	W	X	Y

klucz ⟶ SZYMPANSSZYM
tekst ⟶ KRYPTOGRAFIA
krypt. ⟶ CPWCIOUISEGM

Kryptografia Kwantowa

Jacek.Szczytko@fuw.edu.pl
•http://zon8.physd.amu.edu.pl/~tanas/

Szyfr Vernama (one-time pad)

	S	Z	Y	F	R
tekst jawny ⟶					
binarnie ⟶	01010011	01011010	01011001	01000110	01010010
klucz ⟶	01110010	01010101	11011100	10110011	00101011
kryptogram ⟶	00100001	00001111	10000101	11110101	01111001

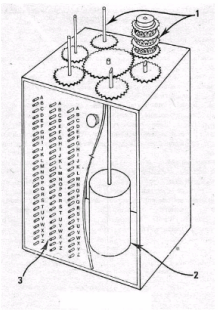
- Klucz jest losowym ciągiem bitów.
- Kryptogram jest także losowym ciągiem bitów i jeśli nie znamy klucza to nie dowiemy się niczego o tekście jawnym.
- Jeśli klucz jest tak długi jak wiadomość i użyty tylko raz, to szyfr ten gwarantuje bezpieczeństwo absolutne.
- Współczesne metody kryptograficzne sprowadzają się do obliczeń w systemie binarnym, czyli operacji na bitach.

Kryptografia i kryptoanaliza


Jerzy Różycki


Marian Rejewski


Henryk Zygalski



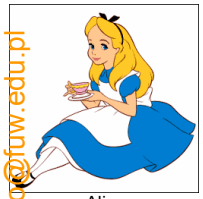
Enigma 1918/1923

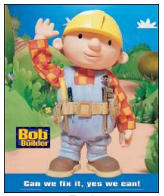
images from http://www.armyradio.com/publish/Articles/The_Enigma_Code_Breach/

Szyfry nie do złamania

Klucze jednorazowe – nie do złamania!

Kryptografia

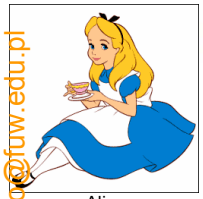

Alice

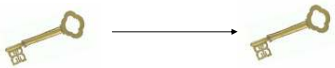


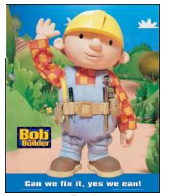
Bob

Eve (eavesdropper)

Kryptografia


Alice

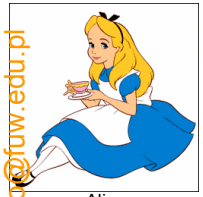




Bob

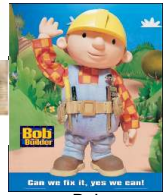
Eve

Kryptografia



Alice

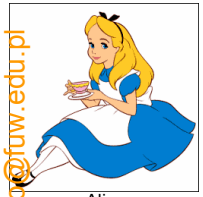
Aby mieć bezpieczny kanał łączności trzeba mieć bezpieczny kanał łączności...



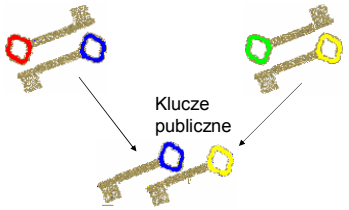
Bob

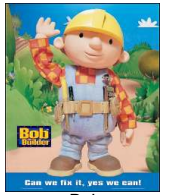
Eve

Kryptografia klucza publicznego



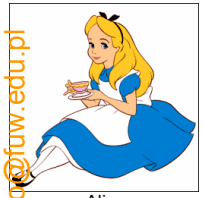
Alice



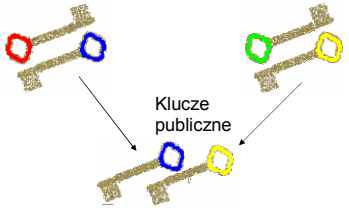


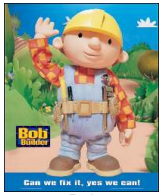
Bob

Kryptografia klucza publicznego



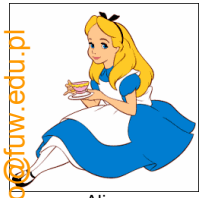
Alice



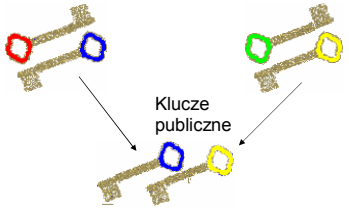


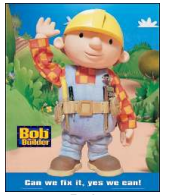
Bob

Kryptografia klucza publicznego

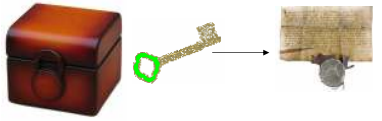


Alice





Bob



Kryptografia klucza publicznego

Jacek.Szczytko@fuw.edu.pl

•Bezpieczenstwo systemu kryptograficznego z kluczem publicznym jest oparte na istnieniu funkcji jednostronnych, dla których znalezienie wartosci samej funkcji jest łatwe zas znalezienie argumentu funkcji kiedy znamy jej wartosc jest obliczeniowo trudne (jak trudne to zalezy od aktualnego stanu wiedzy i rozwoju techniki)

•Najbardziej znany kryptosystem z kluczem publicznym, RSA, opiera sie na trudnosci z rozkładem liczby na czynniki (faktoryzacja)

•Systemy takie nie gwarantuja pełnego bezpieczenstwa. Nie mozna wykluczyc, ze ktoś znajdzie efektywny algorytm faktoryzacji liczb.
W istocie taki algorytm juz istnieje. Jest to algorytm Shora! Wymaga on jednak komputera kwantowego!.

http://zon8.physd.amu.edu.pl/~tanas/

Kryptografia klucza publicznego

Jacek.Szczytko@fuw.edu.pl

W 1994 r. RSA 129 został złamany na 1600 stacjach roboczych w ciagu 8 miesiecy

Eve

http://zon8.physd.amu.edu.pl/~tanas/

Kryptografia kwantowa

Jacek.Szczytko@fuw.edu.pl

Wielokrotna i bezpieczna procedura uzgadniania klucza jednorazowego

http://wug.physics.uiuc.edu/courses/phys214/fall04/

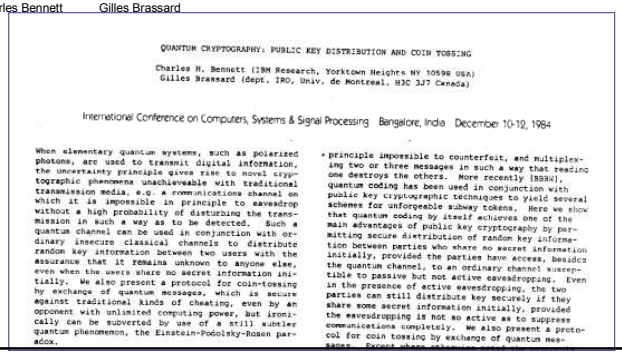
Kryptografia kwantowa

Jacek.Szczytko@fuw.edu.pl

Charles Bennett

Gilles Brassard

Wielokrotna i bezpieczna procedura uzgadniania klucza jednorazowego



QUANTUM CRYPTOGRAPHY: PUBLIC KEY DISTRIBUTION AND COIN TOSSING

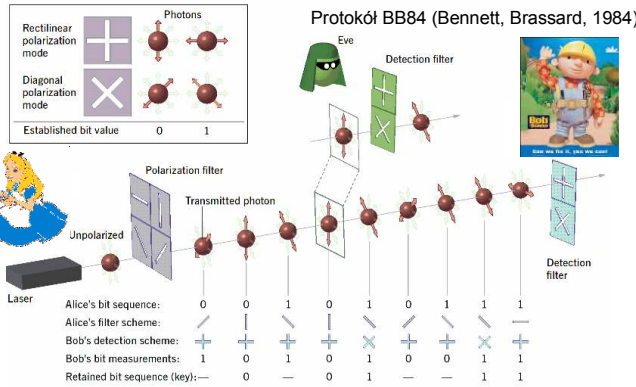
Charles H. Bennett (IBM Research, Yorktown Heights NY 10598 USA)
Gilles Brassard (dept. IRO, Univ. de Montreal, H3C 3J7 Canada)

International Conference on Computers, Systems & Signal Processing Bangalore, India December 10-12, 1984

When elementary quantum systems, such as polarized photons, are used to transmit digital information, the uncertainty principle gives rise to novel cryptographic phenomena unachieveable with traditional transmission media, e.g. a communications channel on which it is impossible in principle to eavesdrop without a high probability of disturbing the transmission in such a way as to be detected. Such a quantum channel can be used in conjunction with ordinary insecure classical channels to distribute random key information between two users with the assurance that it remains unknown to anyone else, even when the users share no secret information initially. We also present a protocol for coin-tossing by exchange of quantum messages, which is secure against traditional kinds of cheating, even by an opponent with unlimited computing power, but ironically can be subverted by use of a still subtler quantum phenomenon, the Einstein-Podolsky-Rosen paradox.

principle impossible to counterfeit, and multiplexing two or three messages in such a way that reading one destroys the others. More recently [BBBW], quantum coding has been used in conjunction with public key cryptographic techniques to yield several schemes for unforgeable subway tokens. Here we show that quantum coding by itself achieves one of the main advantages of public key cryptography by permitting secure distribution of random key information between parties who share no secret information initially, provided the parties have access, besides the quantum channel, to an ordinary channel susceptible to passive but not active eavesdropping. Even in the presence of active eavesdropping, the two parties can still distribute key securely if they share some secret information initially, provided the eavesdropping is not so active as to suppress communications completely. We also present a protocol for coin tossing by exchange of quantum mes-

Kryptografia kwantowa



Bolek publicznie informuje Alicje jakiej bazy uzywał, zaś Alicja informuje go czy była to baza właściwa czy nie.

Scientific American, January 2005

Kryptografia kwantowa

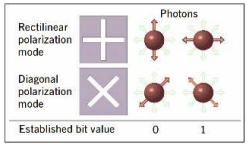
Uwagi:

Porównując bity wysłane przez Alicję z bitami zarejestrowanymi przez Bolka możemy podzielić bity zarejestrowane przez Bolka na trzy kategorie:

- bity pewne (średnio 50 %) — te dla których Bolek wybrał prawidłową bazę i które mogą być traktowane jako klucz kryptograficzny;
- bity prawidłowe pomimo złego wyboru bazy (średnio 25 %);
- bity nieprawidłowe (srednio 25 %).

Zatem prawdopodobieństwo tego, że zarejestrowany bit będzie prawidłowy (taki sam jak bit wysłany) jest równe 3/4

Prawdopodobieństwo zarejestrowania bitu nieprawidłowego wynosi wiec 1/4



Kryptografia kwantowa

Uwagi:

Jeśli Ewa podsłuchuje stosując strategię tzw. *nieprzezroczystego podsłuchu*, to wybiera losowo bazę prostą lub ukośną, dokonuje pomiaru polaryzacji w tej bazie i następnie przesyła do Bolka foton o takiej polaryzacji jaką zmierzyła.

- Dokonywane przez Ewę pomiary muszą wprowadzić błędy, które Alicja i Bolek mogą wykryć przy uzgadnianiu klucza.

Takie błedy Alicja i Bolek mogą wykryć wybierając losowo pewną liczbę bitów klucza i porównując publicznym kanałem ich wartości. Te bity oczywiście następnie się wyrzuca.

- Jeśli liczba błędów przekracza założony poziom to uznaje się, że kanał był podsłuchiwany i procedurę uzgadniania klucza rozpoczyna się od nowa.

- **Mechanika kwantowa nie dopuszcza możliwości pasywnego podsłuchu. Bezpieczeństwo kwantowego systemu kryptograficznego gwarantowane jest przez prawa fizyki!**

Alice's bit sequence:	0	0	1	0	1	0	1	1	1
Alice's filter scheme:	⟋	|	⟍	|	⟍	⟋	⟍	⟍	—
Bob's detection scheme:	+	+	+	+	×	+	+	×	+
Bob's bit measurements:	1	0	1	0	1	0	0	1	1
Retained bit sequence (key):	—	0	—	0	1	—	—	1	1

Produkty

Produkty

Kryptografia kwantowa

Artur Ekert

PHYSICAL REVIEW LETTERS

VOLUME 67 — 5 AUGUST 1991 — NUMBER 6

Quantum Cryptography Based on Bell's Theorem

Artur K. Ekert

Merton College and Physics Department, Oxford University, Oxford OX1 3PU, United Kingdom
(Received 18 April 1991)

Practical application of the generalized Bell's theorem in the so-called key distribution process in cryptography is reported. The proposed scheme is based on the Bohm's version of the Einstein-Podolsky-Rosen *gedanken experiment* and Bell's theorem is used to test for eavesdropping.

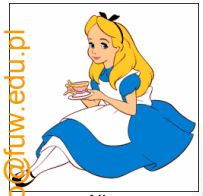
Kryptografia kwantowa

Artur Ekert

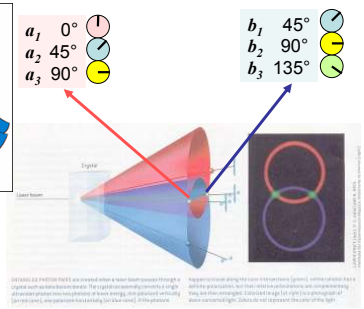
Artur Ekert

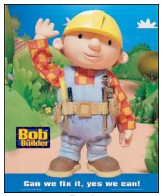
Kryptografia kwantowa

Artur Ekert



Alice

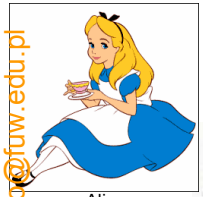




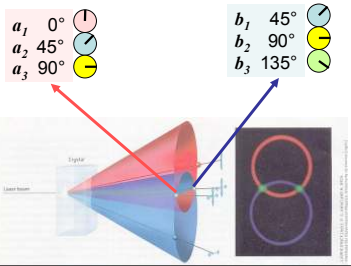
Bob

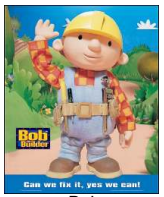
Kryptografia kwantowa

Artur Ekert



Alice





Bob

a																					
	1	0	1	1	0	0	0	1	0	1	x	1	0	1	1	0	0	1	1	1	0
b																					
	1	0	0	0	1	1	0	1	1	1	0	0	0	0	0	1	0	1	0	1	1
	t	0	1	t	0	0	t	1	0	1	x	t	0	1	t	t	t	1	t	t	t

jawne

jawne

test (jawny)

Klucz: 0100101011…

Kryptografia kwantowa

Artur Ekert

After the transmission has taken place, Alice and Bob can announce in public the orientations of the analyzers they have chosen for each particular measurement and divide the measurements into two separate groups: a first group for which they used different orientation of analyzers, and a second group for which they used the same orientation of their analyzers. They discard all measurements in which either or both of them failed to register a particle at all. Subsequently, Alice and Bob can reveal publicly the results they obtained but within the first group of measurements only. This allows them to establish the value of S, which, if the particles were not directly or indirectly "disturbed," should reproduce the result of Eq. (4). This assures the legitimate users that the results they obtained within the second group of measurements are anticorrelated and can be converted into a secret string of bits—the key. This secret key may be then used in a conventional cryptographic communication between Alice and Bob.

$$S = E(\mathbf{a}_1,\mathbf{b}_1) - E(\mathbf{a}_1,\mathbf{b}_3) + E(\mathbf{a}_3,\mathbf{b}_1) + E(\mathbf{a}_3,\mathbf{b}_3) . \quad (3)$$

Again, quantum mechanics requires

$$S = -2\sqrt{2} . \quad (4)$$

The eavesdropper cannot elicit any information from the particles while in transit from the source to the legitimate users, simply because there is no information encoded there. The information "comes into being" only after the legitimate users perform measurements and communicate in public afterwards. The eavesdropper may try to substitute his own prepared data for Alice and Bob to misguide them, but as he does not know which orientation of the analyzers will be chosen for a given pair of particles, there is no good strategy to escape from being detected.

$$S = \int \rho(\mathbf{n}_a,\mathbf{n}_b)\, d\mathbf{n}_a\, d\mathbf{n}_b [\sqrt{2}\mathbf{n}_a \cdot \mathbf{n}_b] , \quad (6)$$

which implies

$$-\sqrt{2} \le S \le \sqrt{2} , \quad (7)$$

Kryptografia kwantowa

PHYSICAL REVIEW A VOLUME 56, NUMBER 2 AUGUST 1997

Optimal eavesdropping in quantum cryptography. I. Information bound and optimal strategy

Christopher A. Fuchs,[1] Nicolas Gisin,[2] Robert B. Griffiths,[3] Chi-Sheng Niu,[3] and Asher Peres[4,*]
[1]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125*
[2]*Group of Applied Physics, University of Geneva, CH 1211 Geneva 4, Switzerland*
[3]*Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[4]*Institute for Theoretical Physics, University of California, Santa Barbara, California 93106*
(Received 31 January 1997)

We consider the Bennett-Brassard cryptographic scheme, which uses two conjugate quantum bases. An eavesdropper who attempts to obtain information on qubits sent in one of the bases causes a disturbance to qubits sent in the other basis. We derive an upper bound to the accessible information in one basis, for a given error rate in the conjugate basis. Independently fixing the error rates in the conjugate bases, we show that both bounds can be attained simultaneously by an optimal eavesdropping probe. The probe interaction and its subsequent measurement are described explicitly. These results are combined to give an expression for the optimal information an eavesdropper can obtain for a given average disturbance when her interaction and measurements are performed signal by signal. Finally, the relation between quantum cryptography and violations of Bell's inequalities is discussed. [S1050-2947(97)01708-5]

Kryptografia kwantowa

We take the framework for our problem directly from quantum cryptography. In order to take advantage of Alice's delayed information on the basis that was used, Eve's optimal strategy is the following: she lets a probe, initially in some standard state $|\psi_0\rangle$, interact unitarily with the qubit sent by Alice. (There is no loss of generality in this, because any physical nonunitary interaction is equivalent to a unitary one with a higher dimensional probe.) Eve's probe is then stored until Alice announces the basis that was used, and only after that is it measured by Eve.

In a convenient notation, if Alice sends state $|x\rangle$, the result may be written as

$$|x\rangle \otimes |\psi_0\rangle \rightarrow |X\rangle, \quad (1)$$

where $|X\rangle$ is an entangled state of the probe and the photon that Alice sent to Bob. Likewise, for the other signals that Alice may send, the results of Eve's intervention are entangled states, $|Y\rangle$, $|U\rangle$, and $|V\rangle$. Since the interaction is unitary, it follows from

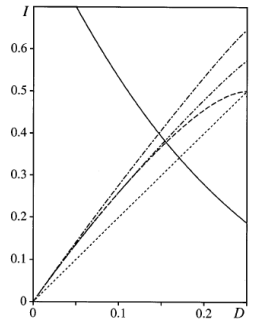
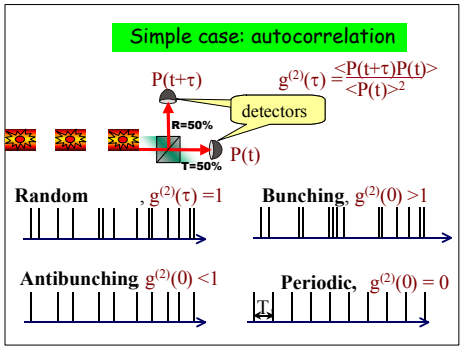


FIG. 2. Information vs disturbance for various eavesdropping methods.

Badania na Hożej
pojedyncze fotony na żądanie

Jacek.Szczytko@fuw.edu.pl



prof. J. A. Gaj
prof. M. Nawrocki
dr hab. A. Golnik
dr P. Kossacki

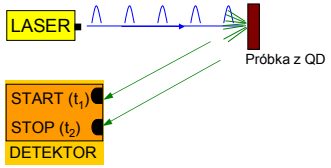
mgr W. Maślana
mgr J. Suffczyński
mgr K. Kowalik
mgr W. Pacuski

mgr A. Trajnerowicz
mgr B. Piechal
M. Goryca
T. Kazimierczuk

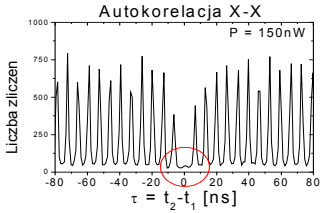
Problemy

Jacek.Szczytko@fuw.edu.pl

Pojednyncze fotony na żądanie

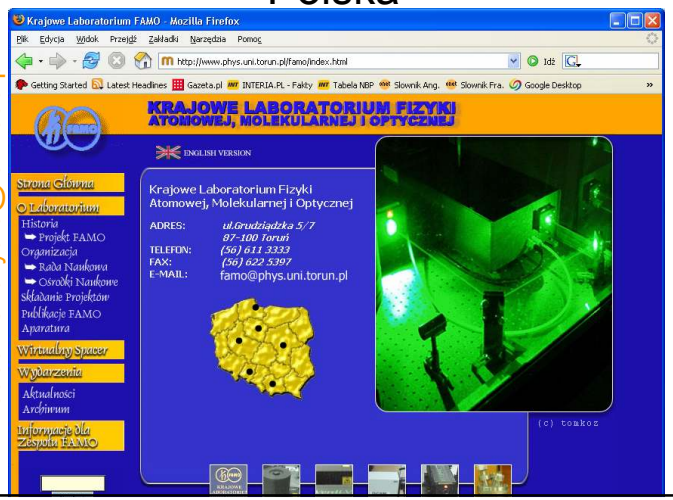


prof. J. A. Gaj
prof. M. Nawrocki
dr hab. A. Golnik
dr P. Kossacki
mgr W. Maślana
mgr J. Suffczyński
mgr K. Kowalik
mgr W. Pacuski
mgr A. Trajnerowicz
mgr B. Piechal
M. Goryca
T. Kazimierczuk



Polska

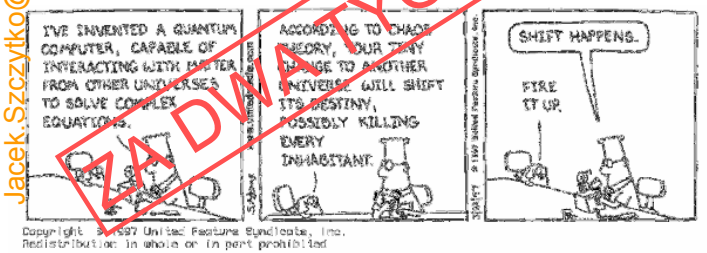
Jacek.Szczytko@fuw.edu.pl



Quantum Computer I (QC)

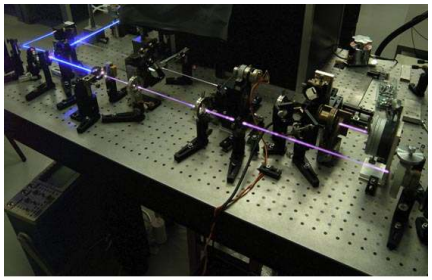
Jacek.Szczytko@fuw.edu.pl

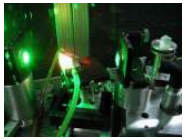
1. Komputery kwantowe
   a. Logika bramek
   b. Kwantowe algorytmy
   c. Jak zbudować taki komputer?



Dr Piotr Wasylczyk

Nieliniowo, adaptacyjnie i femtosekundowo, czyli ekstremalnie w optyce.





Jacek.Szczytko@fuw.edu.pl

Jacek.Szczytko@fuw.edu.pl