QO Group meeting talk

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Quantum storage of photonic entanglement in a crystal

Christoph Clausen[1]*, Imam Usmani[1]*, Félix Bussières[1], Nicolas Sangouard[1], Mikael Afzelius[1], Hugues de Riedmatten[1,2,3] & Nicolas Gisin[1]

$$S = 2.64 \pm 0.23$$

University of Geneva

Broadband waveguide quantum memory for entangled photons

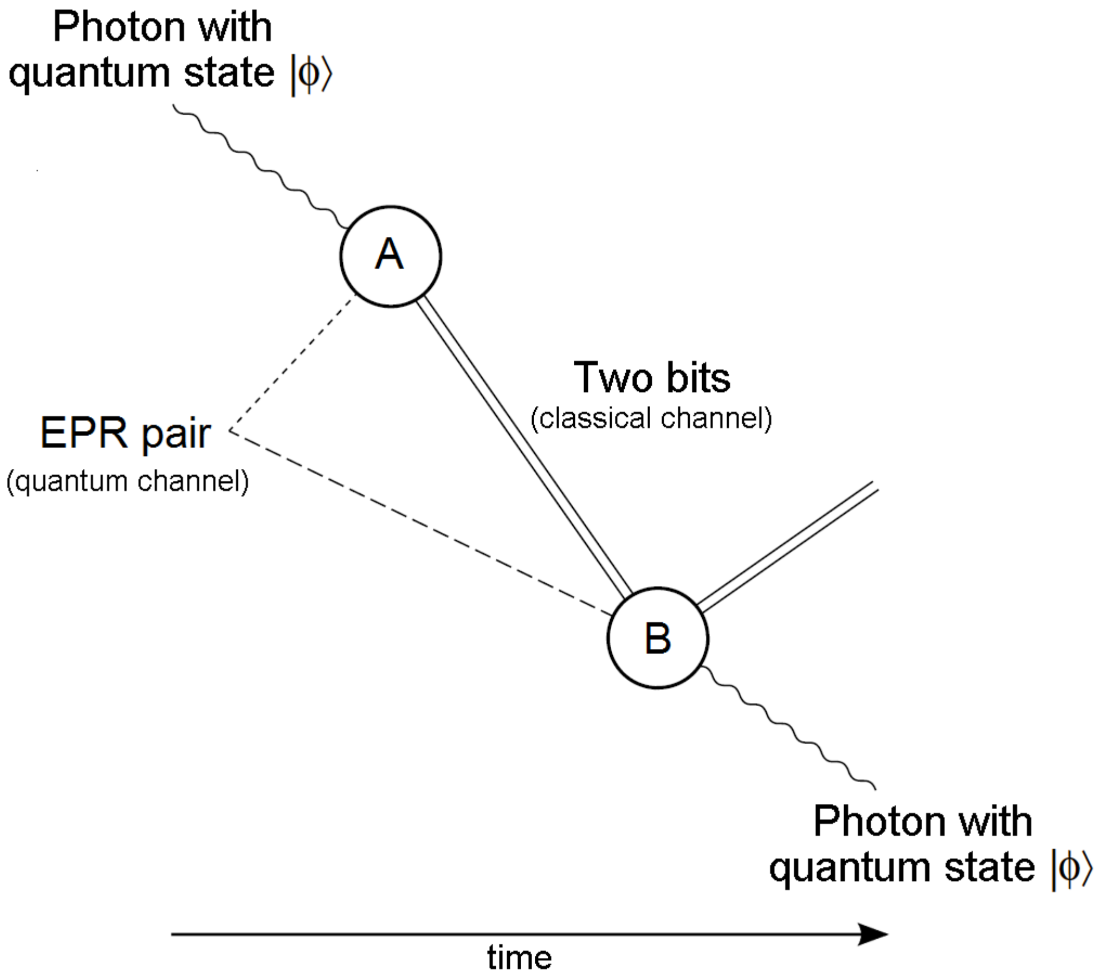
Erhan Saglamyurek[1], Neil Sinclair[1], Jeongwan Jin[1], Joshua A. Slater[1], Daniel Oblak[1], Félix Bussières[1]†, Mathew George[2], Raimund Ricken[2], Wolfgang Sohler[2] & Wolfgang Tittel[1]

$$S = 2.25 \pm 0.06$$

University of Calgary

Quantum Memories

- Quantum Teleportation



Bob needs to store the qubit before Alice does some operations on her qubit and sends information via a classical line

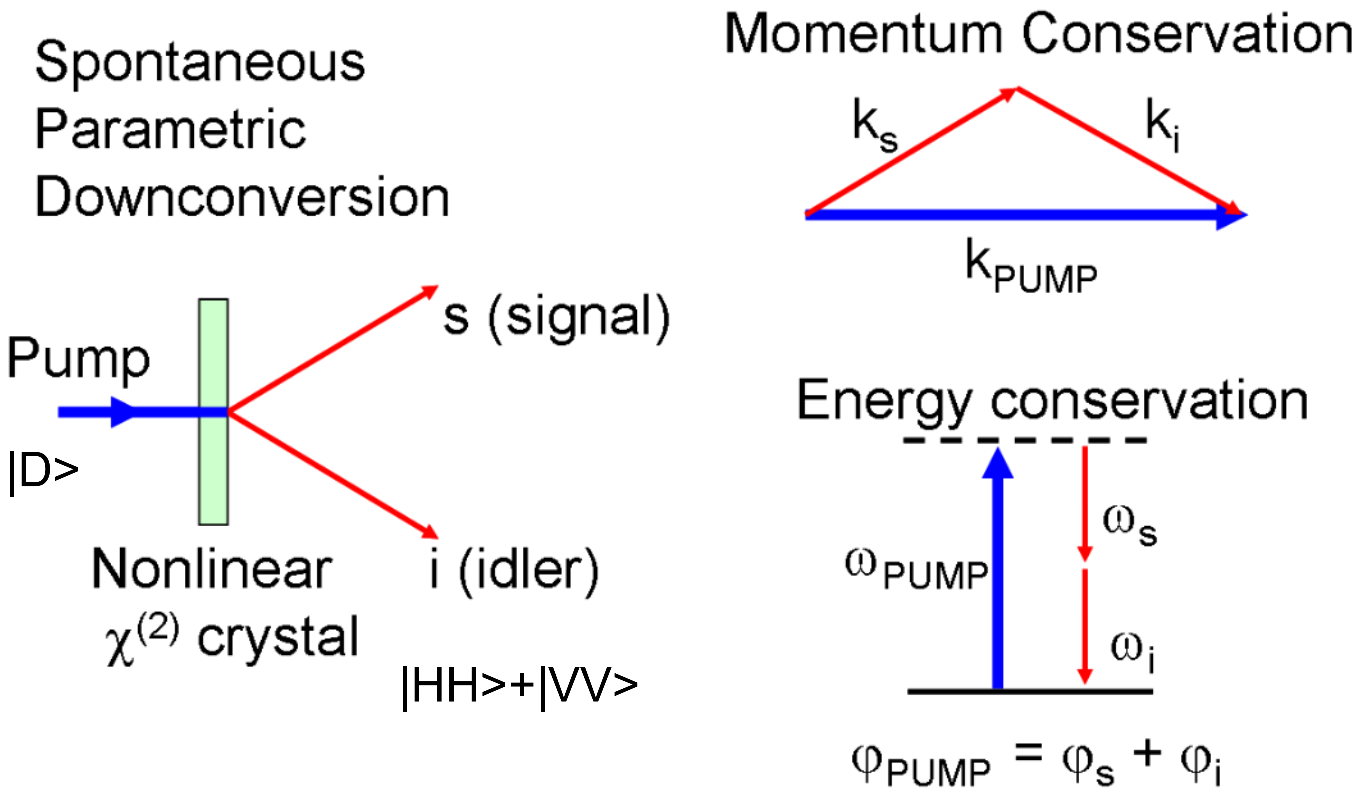
Image source: http://en.wikipedia.org/wiki/File:Quantum_teleportation_diagram.PNG

Outline

- Preparation of Entangled States
- Quantum Memory
- Measurements
- Results

Preparation of Entanglement

- Spontaneous Parametric Down-Conversion

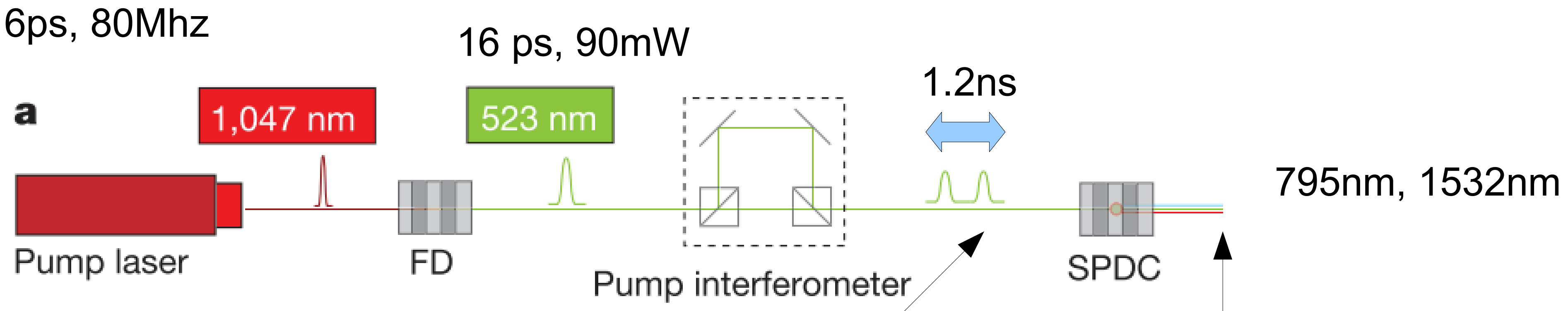


|D>

|HH>+|VV>

Image source: http://en.wikipedia.org/wiki/File:Spontaneous_Parametric_Downconversion.png

Time-bin entanglement


6ps, 80Mhz

16 ps, 90mW

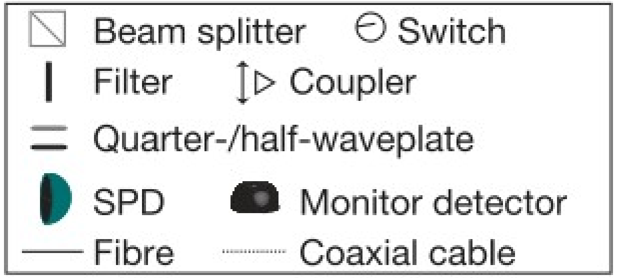
1.2ns

795nm, 1532nm

$$|\Psi\rangle_p = \frac{1}{\sqrt{2}}\left(|1,0\rangle - e^{i\varphi}|0,1\rangle\right).$$

Time-bin entanglement

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle_A|1,0\rangle_B - e^{i\varphi}|0,1\rangle_A|0,1\rangle_B\right).$$



Photon wavefuntion

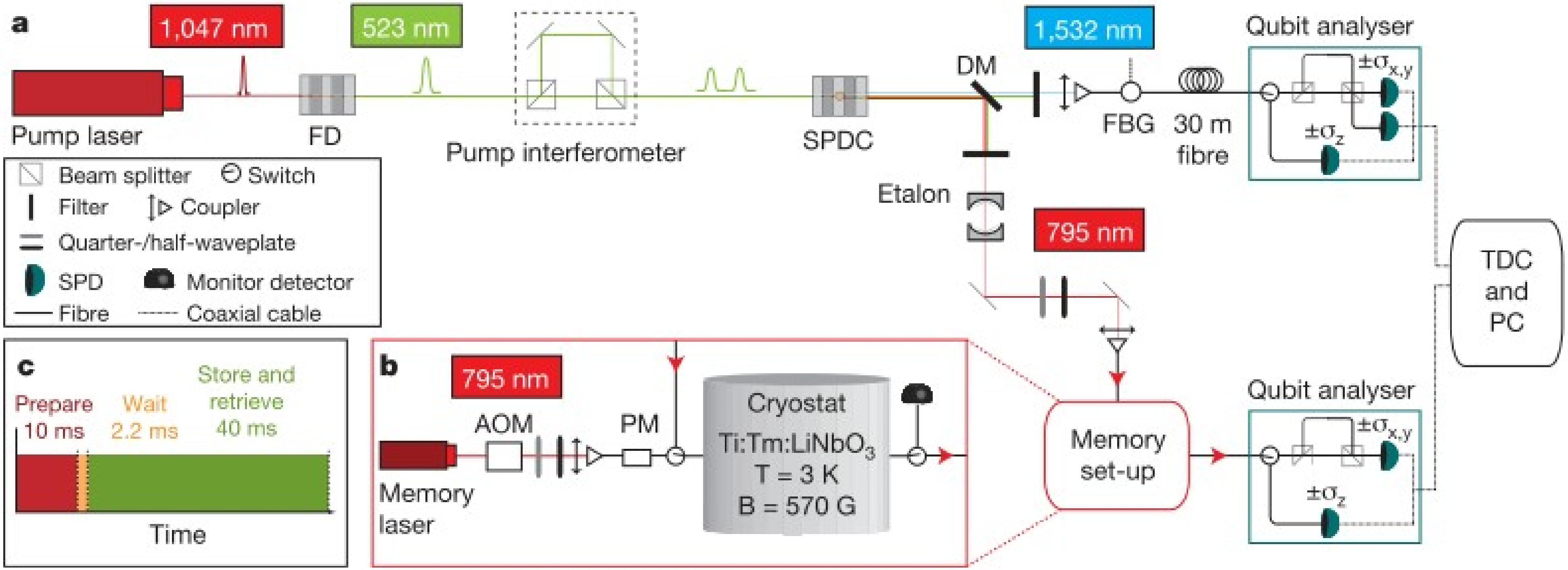
$$\mid 1\rangle = \int dk\phi\left(k\right)a_k^\dagger \mid vac\rangle$$

$$\phi\left(k\right) = \frac{\exp\left(-\left(k-k_0\right)^2/2\kappa^2\right)}{\left(\kappa\sqrt{\pi}\right)^{1/2}}$$

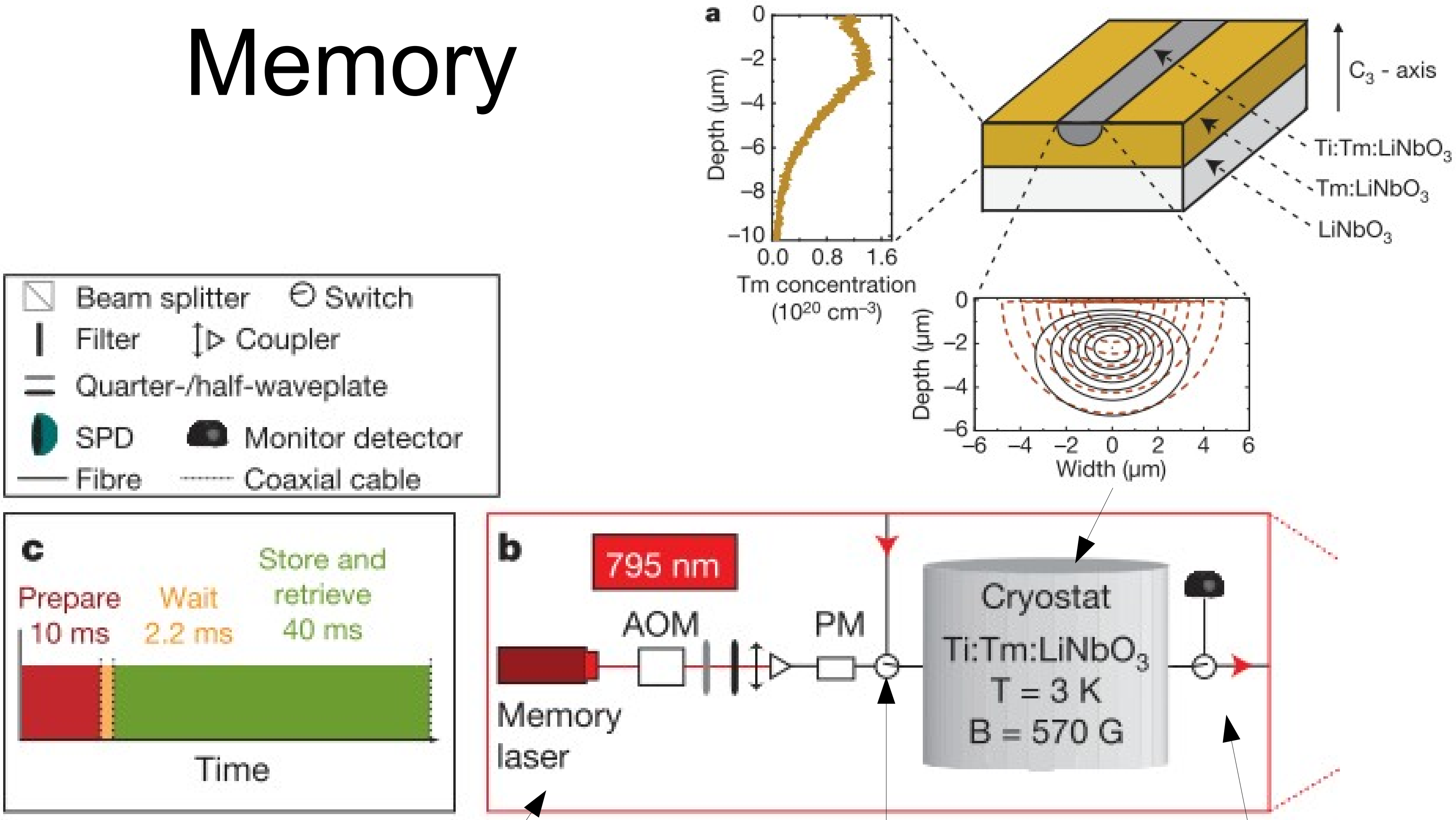
$$\mid 2\rangle = \int dk' e^{ik'x}\phi\left(k'\right)a_{k'}^\dagger \mid vac\rangle$$

$$\langle 2 \mid 1\rangle = \int dkdk' e^{ik'x}\phi\left(k\right)\phi\left(k'\right)\langle vac \mid a_{k'}a_k^\dagger|vac\rangle$$

$$= \int dke^{ikx}\phi\left(k\right) = Ce^{ik_0x}e^{-\kappa x^2/2} \sim 0 \text{ for } \kappa x \gg \cancel{0}\ 1$$


a
1,047 nm
523 nm
1,532 nm
Qubit analyser
Pump laser
FD
Pump interferometer
SPDC
DM
FBG
30 m fibre
$\pm\sigma_{x,y}$
$\pm\sigma_z$
Etalon
795 nm
Beam splitter
Switch
Filter
Coupler
Quarter-/half-waveplate
SPD
Monitor detector
Fibre
Coaxial cable
TDC and PC
c
Prepare 10 ms
Wait 2.2 ms
Store and retrieve 40 ms
Time
b
795 nm
AOM
PM
Cryostat
Ti:Tm:LiNbO$_3$
T = 3 K
B = 570 G
Memory laser
Memory set-up
Qubit analyser
$\pm\sigma_{x,y}$
$\pm\sigma_z$

Memory



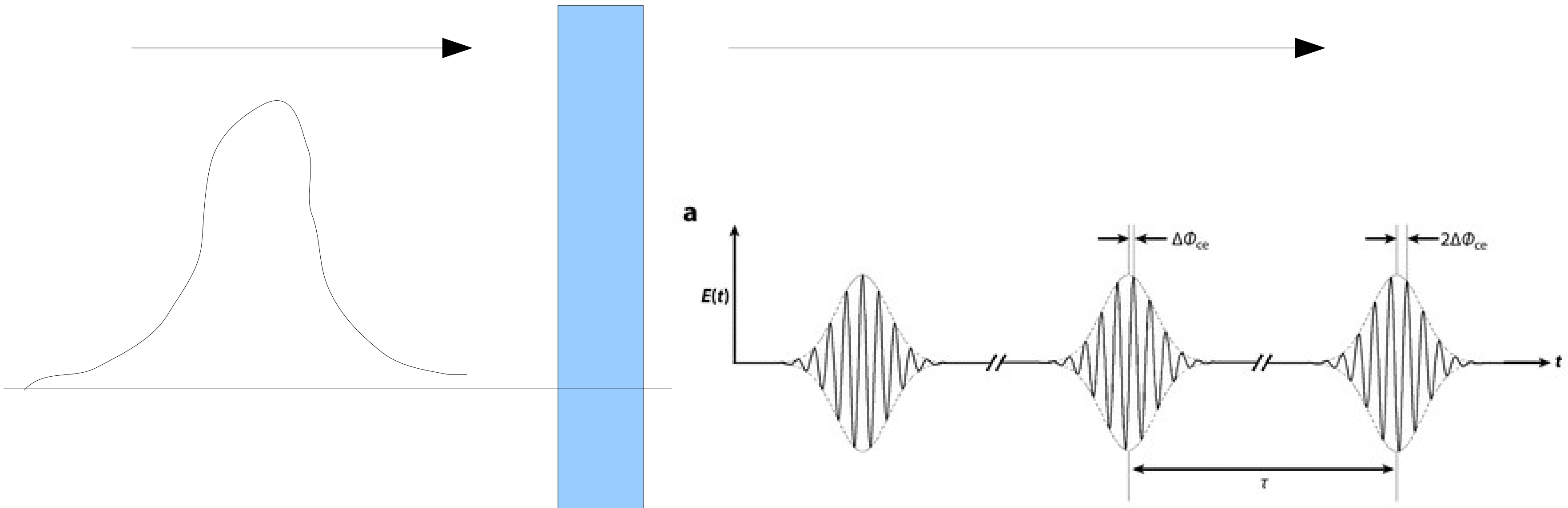
Switch

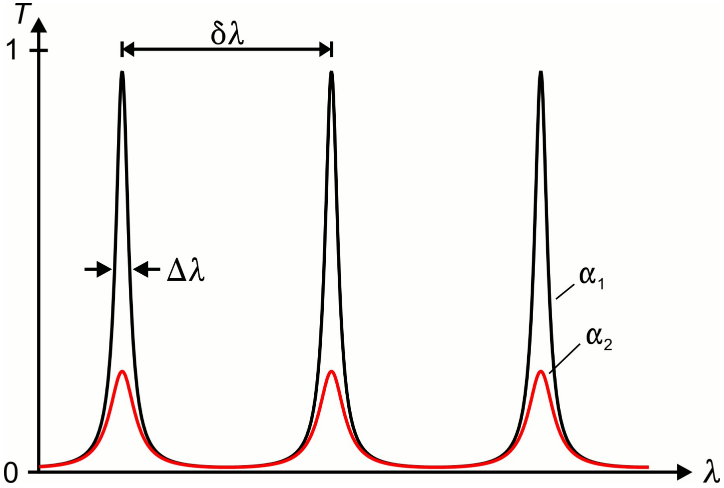
Emitted photon

Laser For Preparing memory

How does it work?

Fabry-Perot



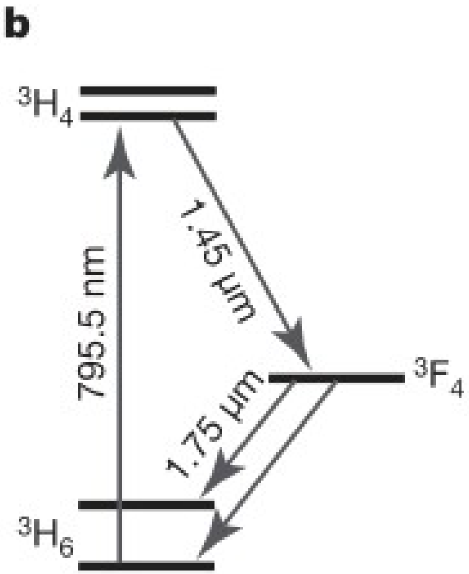


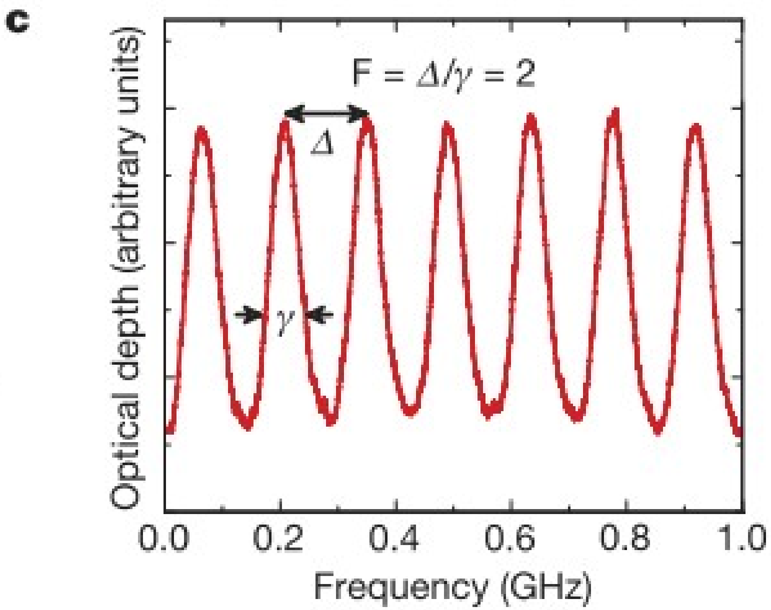
$$\omega, \omega + \delta\omega, \omega + 2\delta\omega, \ldots$$

$$T = 2\pi / \delta\omega$$

Frequency Comb

Atomic Frequency Comb





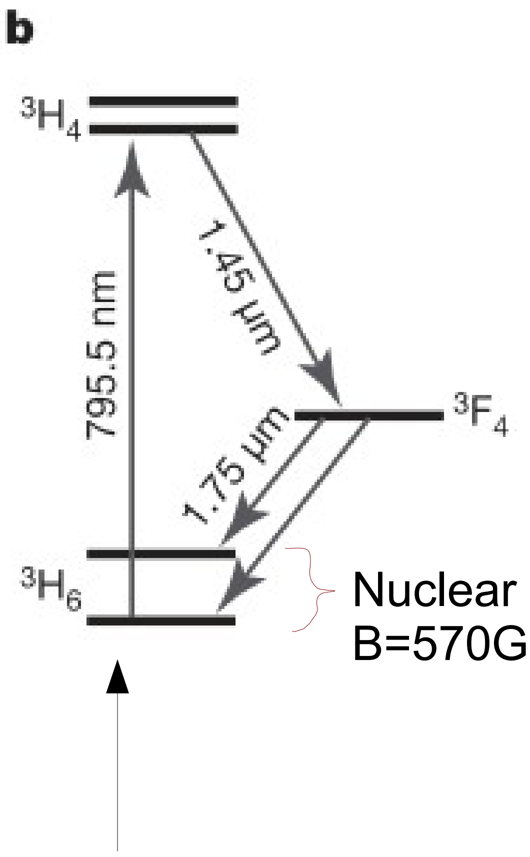
$$\gamma = 75MHz$$

$$\Delta = 143MHz$$

Storage time of approx 7ns

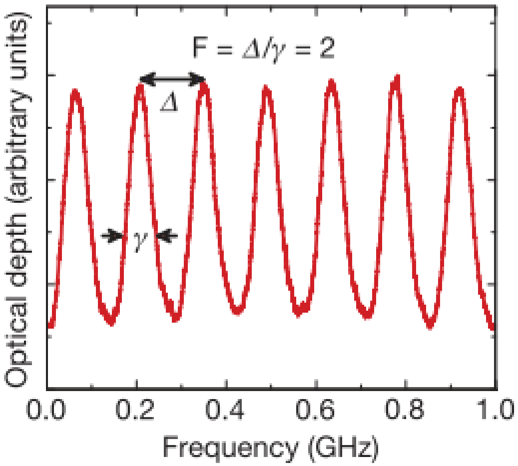
Hole burning

- Hole burning laser: Memory laser
- Frequency sweep
- Modulate amplitude while frequency sweeping
- Selectively pump to 3F4 state
- Repeat 100 times to prepare memory
- Wait 2.4ms, lifetime of 3H4 state

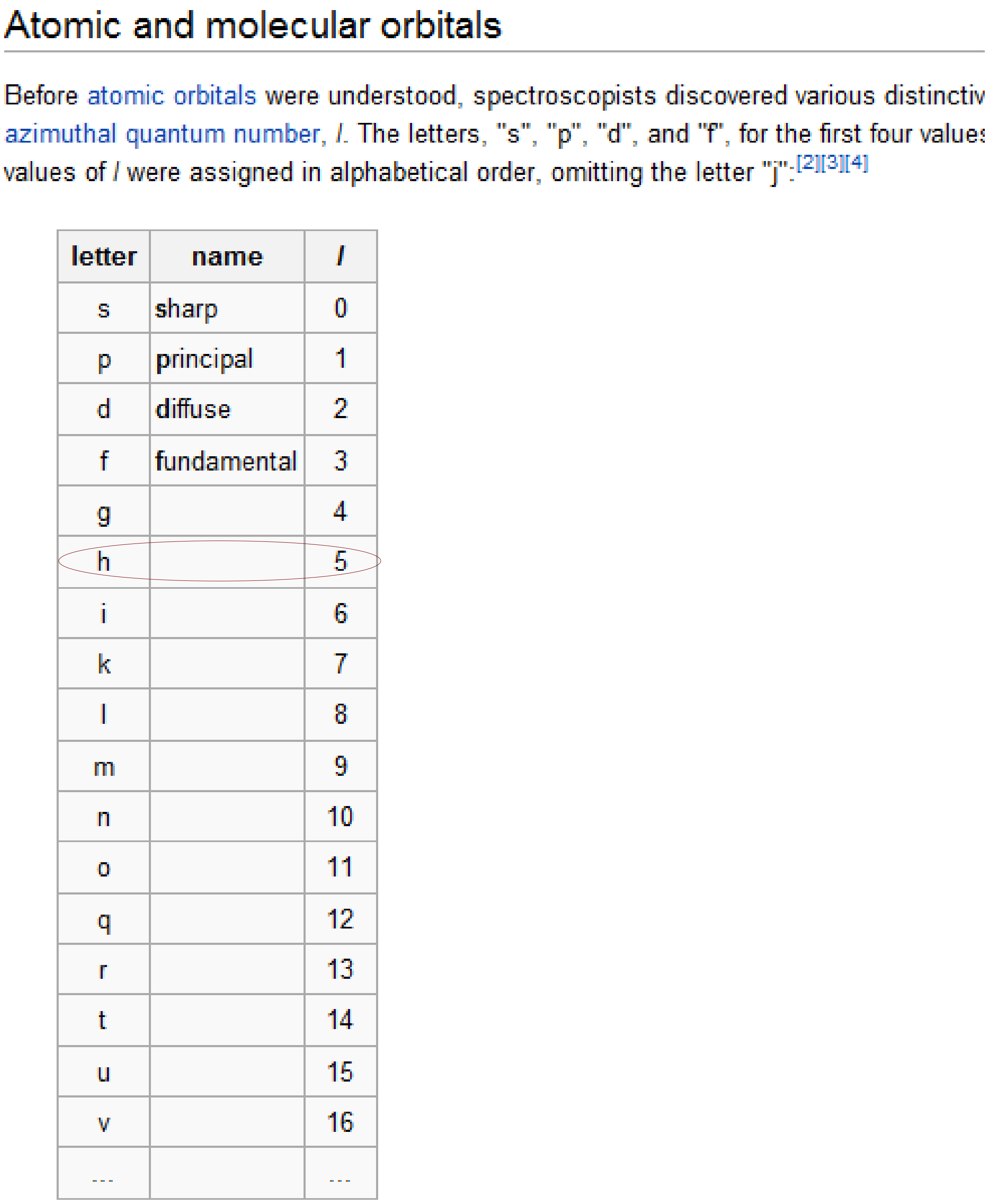


Nuclear Zeeman levels
B=570G

Inhomogeneously broadened, 5GHz bandwidth



Aside



Atomic and molecular orbitals

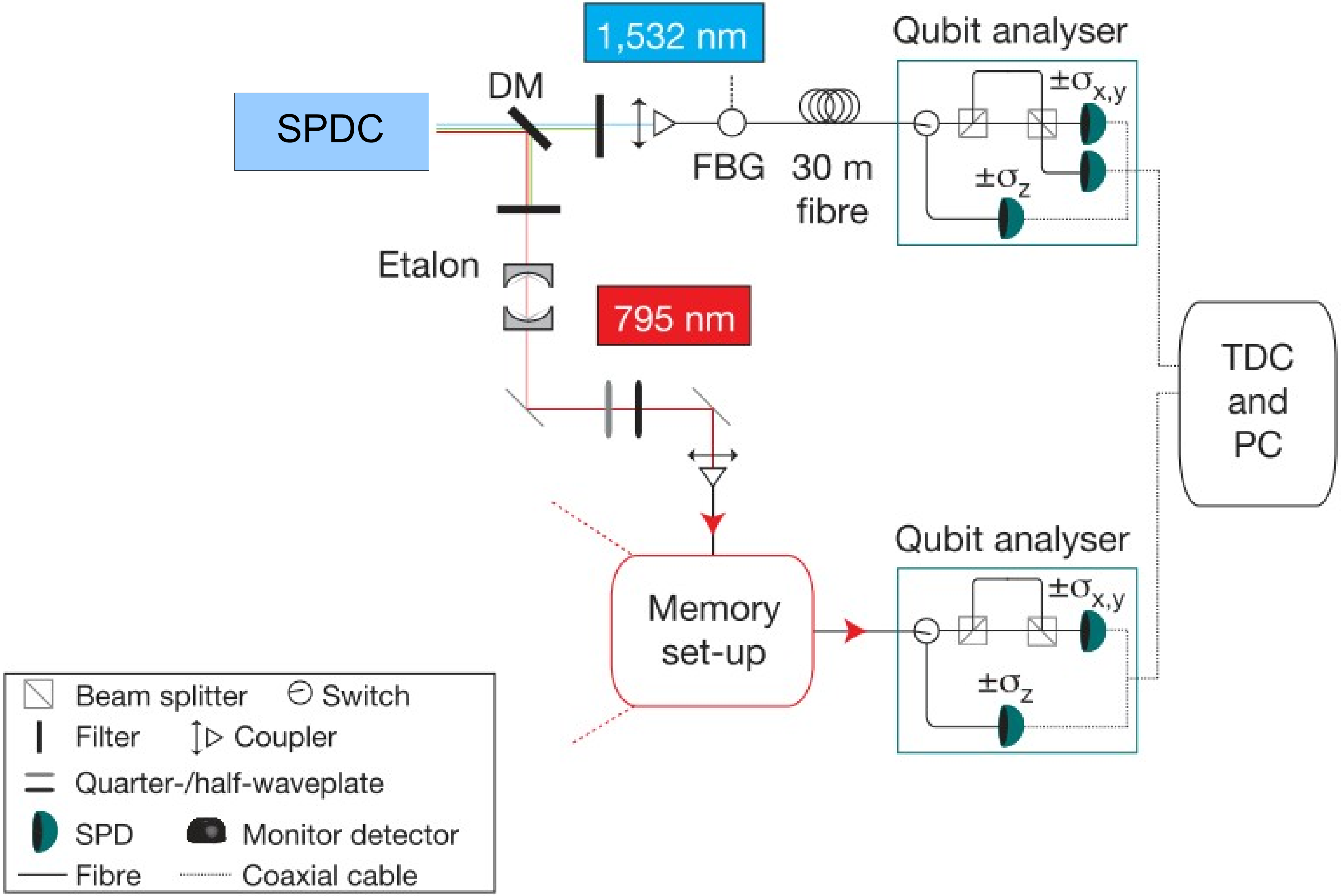
Before atomic orbitals were understood, spectroscopists discovered various distinctiv
azimuthal quantum number, *l*. The letters, "s", "p", "d", and "f", for the first four value
values of *l* were assigned in alphabetical order, omitting the letter "j":[2][3][4]

letter	name	*l*
s	sharp	0
p	principal	1
d	diffuse	2
f	fundamental	3
g		4
h		5
i		6
k		7
l		8
m		9
n		10
o		11
q		12
r		13
t		14
u		15
v		16
...		...

Efficiencies

- Currently 0.2%
- Partly due to 90% loss during fiber to waveguide coupling
- Comb efficiency ~ 2%
- By tailoring AFC spectrum and reabsorbing backward scattered photons, and optimizing mode overlap, total efficiency can be increased to 15%

Analysis


1,532 nm
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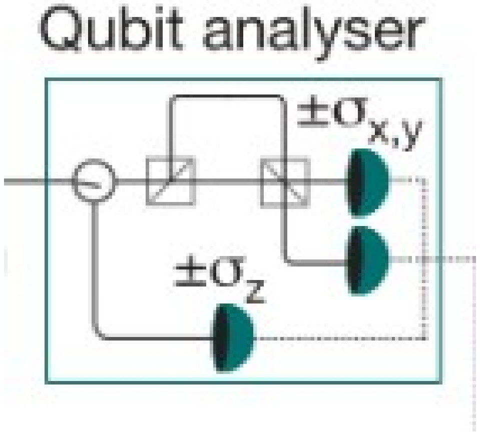
Memory
set-up
$\pm\sigma_{x,y}$
$\pm\sigma_z$
Beam splitter
Switch
Filter
Coupler
Quarter-/half-waveplate
SPD
Monitor detector
Fibre
Coaxial cable

Example: σ_z

- Monitor time of arrival using TDC – 2 bins
- Corresponding to + and -
- From these counts, calculate joint detection probability
- Use delay line instead of memory, and calculate ρ_{in}
- Use memory, ρ_{out}



Measures of Entanglement

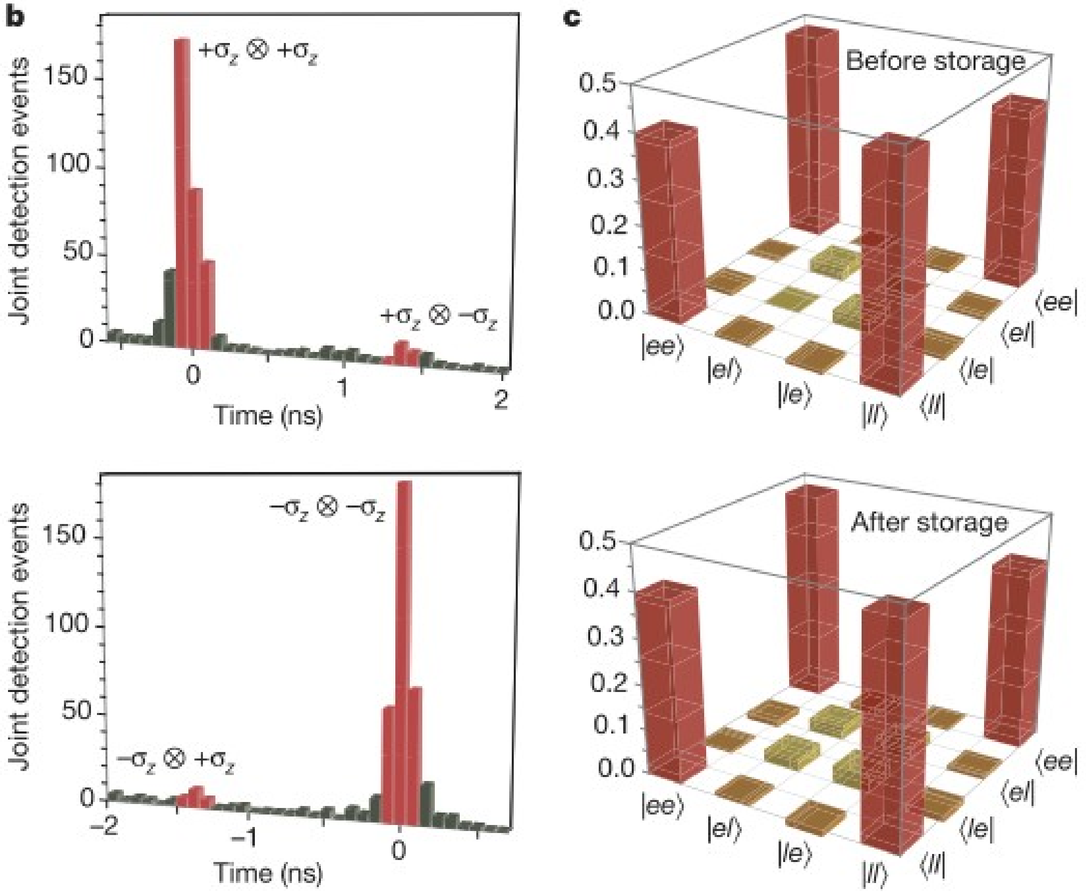


Table 1 | Entanglement measures, purities and fidelities

	Entanglement of formation (%)	Purity (%)	Fidelity with $\|\phi^+\rangle$ (%)	Input/output fidelity (%)	Expected S_{th}	Measured S
ρ_{in}	64.4 ± 4.2	75.7 ± 2.4	86.2 ± 1.5		2.235 ± 0.085	2.379 ± 0.034
ρ_{out}	65 ± 11	76.3 ± 5.9	86.6 ± 3.9	95.4 ± 2.9	2.2 ± 0.22	2.25 ± 0.06

CHSH Bell inequality (measured for $\mathbf{a} = \sigma_x$, $\mathbf{a}' = \sigma_y$, $\mathbf{b} = \sigma_x + \sigma_y$, and $\mathbf{b}' = \sigma_x - \sigma_y$).

Thank you!

Questions

- Why time-bin entanglement?
  - Multimode possible
  - Polarization errors reduced

- Numbers – Efficiency, fidelity,
- How to measure?
- Uniform absorption
- Readout