Parametric Down Conversion of X-Rays

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Experiments in collaboration with:
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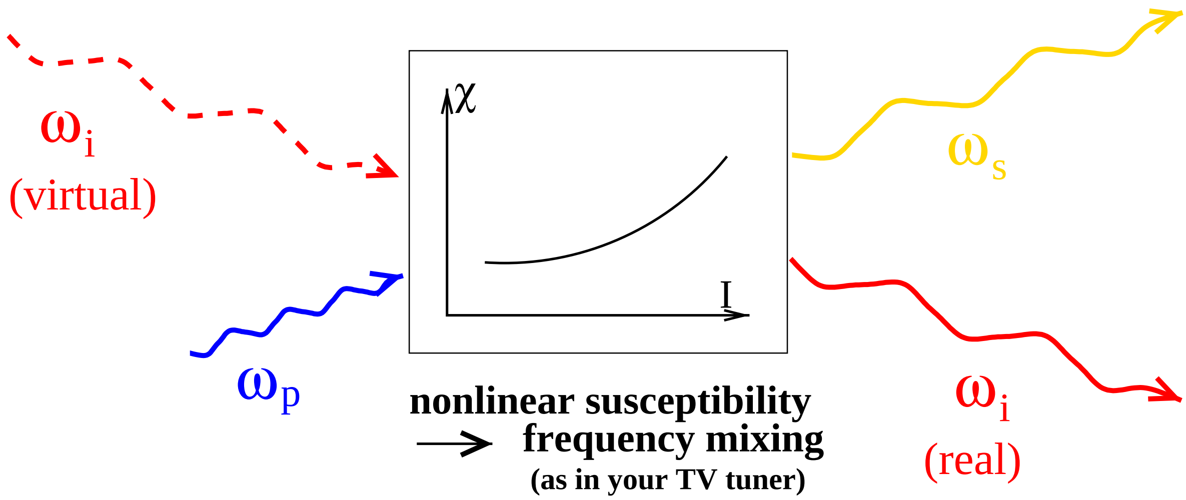
Nonlinear Optics



nonlinear susceptibility
$\longrightarrow$ **frequency mixing**
(as in your TV tuner)

Nonlinear polarization:

$$P_i = \chi^{(1)}_{ij} E_j + \chi^{(2)}_{ijk} E_j E_k + \chi^{(3)}_{ijkl} E_j E_k E_l + \ldots \qquad (1)$$

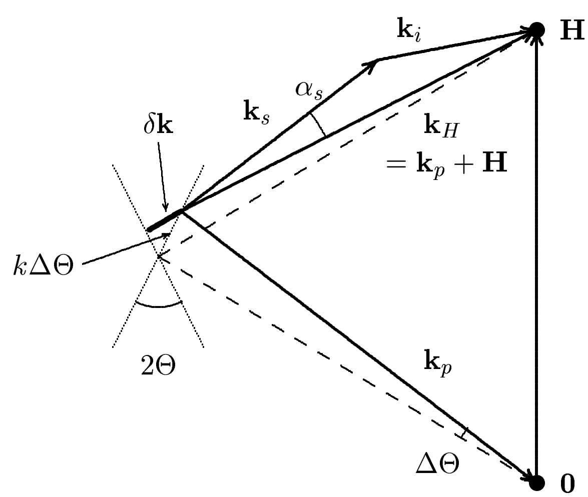
$$\chi^{(2)}_{ijk} \left(E_j(\omega_1) E_k(\omega_2) e^{i(\omega_1 \pm \omega_2)t} + \ldots \right) \qquad (2)$$

difference frequency

Here: Spontaneous decay: $\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$
Real photon & vacuum fluctuation mix $\rightarrow$ 2 real photons

Phase matching condition:
$\mathbf{k}_p + \mathbf{H} = \mathbf{k}_s + \mathbf{k}_i$
impossible for $\mathbf{H} = \mathbf{0}$ due to dispersion

$$\Delta\Theta = \frac{\alpha_s^2/2 + 3\chi_0}{\sin 2\Theta}$$



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Details of the Nonlinearity

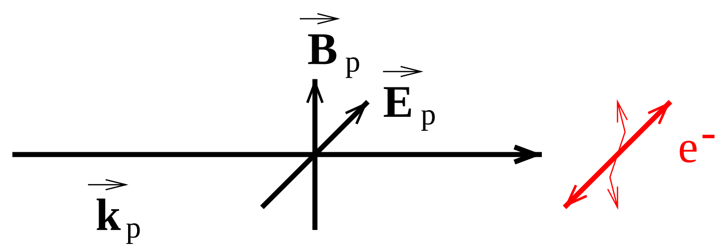
Current density, emitting radiation:

$$\mathbf{J}(\mathbf{r}) = \mathbf{v}(\mathbf{r})\rho(\mathbf{r}) \tag{3}$$

Lorentz equation:

$$\dot{\mathbf{v}}(\mathbf{r},t) = -\frac{e}{m}\left(\mathbf{E}(\mathbf{r},t) + \frac{\mathbf{v}(\mathbf{r},t)\times\mathbf{B}(\mathbf{r},t)}{c}\right) \tag{4}$$

iteration



second order part:

$$i\frac{\mathbf{E}_j\mathbf{E}_{j'}\cdot(\nabla\rho)(\mathbf{r})}{\omega_j\omega_{j'}^2}, \quad \frac{(\mathbf{k}_j\cdot\mathbf{E}_{j'})\,\mathbf{E}_j}{\omega_j^2(\omega_{j'}\pm\omega_j)}, \quad \frac{\mathbf{E}_{j'}\times(\mathbf{k}_j\times\mathbf{E}_j)}{\omega_j\omega_{j'}(\omega_{j'}\pm\omega_j)} \tag{5}$$

with γ for the vectorial products, we get:

$$\Phi_f \approx \gamma^2\frac{137c^2r_e^4}{8\pi\hbar^2\omega_f\omega_j\omega_{j'}}\left|\mathbf{E}_j\right|^2\left|\mathbf{E}_{j'}\right|^2 \tag{6}$$

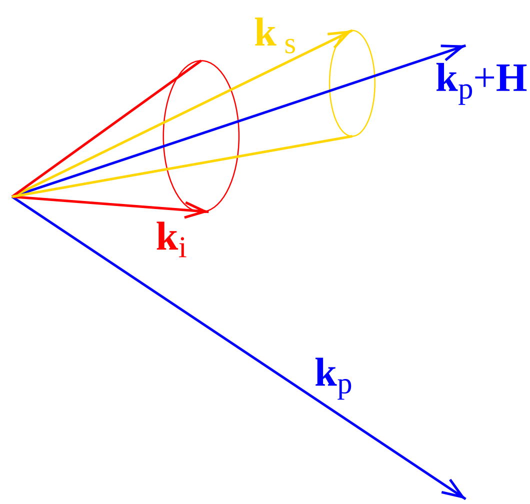
Spontaneous Down Conversion

Beating of vacuum fluctuations with incident real photons.
Bilinear in
incident intensity and
vacuum fluctuation power density: $\frac{d\langle|\mathbf{E}|^2\rangle_t}{d\omega} = \frac{2\hbar\omega^3}{\pi c^3}$

For $\omega_i \approx \omega_s$

$$\frac{d\sigma}{d\Omega} \approx \gamma^2 \frac{137 r_e^4 \omega_i^2}{2\pi c^2} dx, \qquad dx = \frac{d\omega_i}{\omega_i} \tag{7}$$

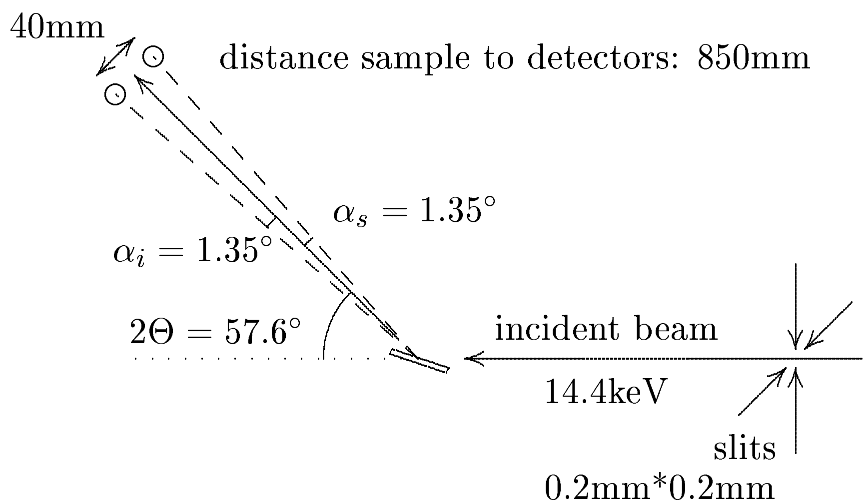
Ca. $10^{-9} r_e^2 dx$ at $\omega_i = 10keV$.
Photon pairs go anywhere on cones around $\mathbf{k}_H$.



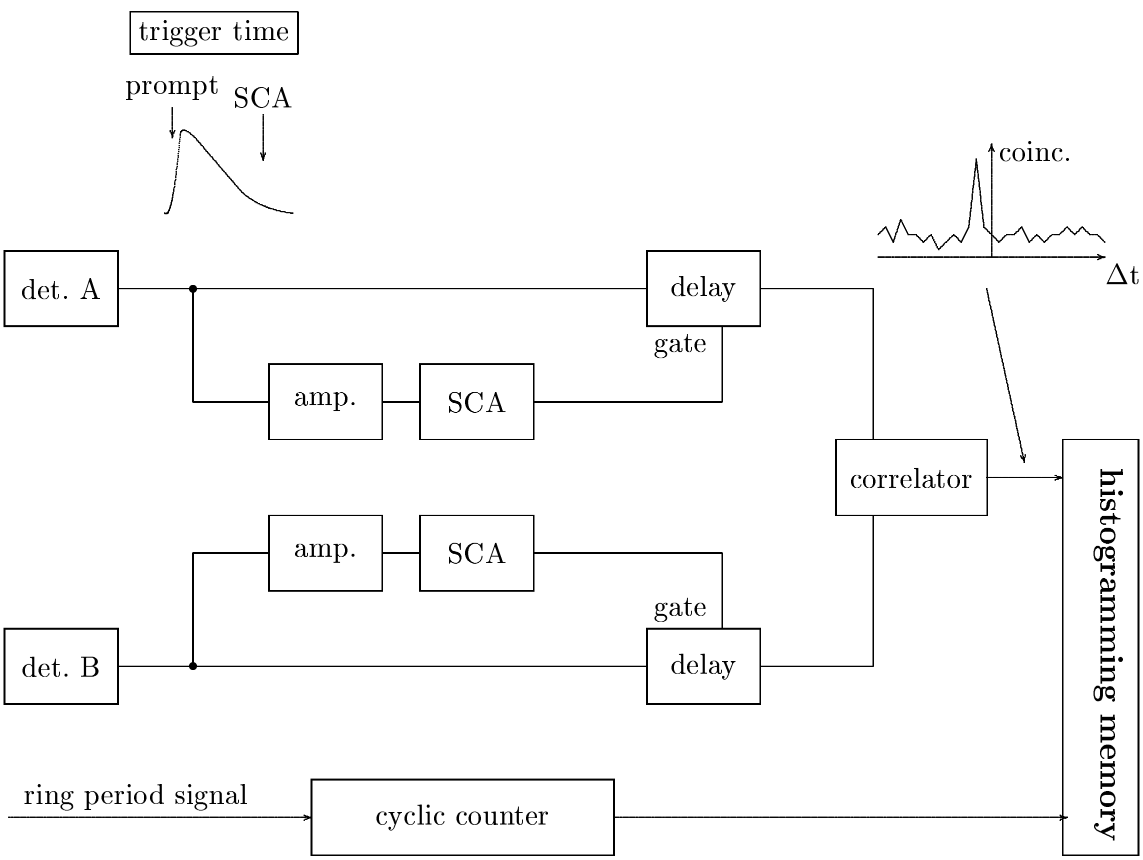
At a 3rd generation source: < 1 event / min.
Extrapolate to 10^2/s . . . 10^3/s at TESLA

Experiment

The scattering geometry:



Data acquisition schematic:



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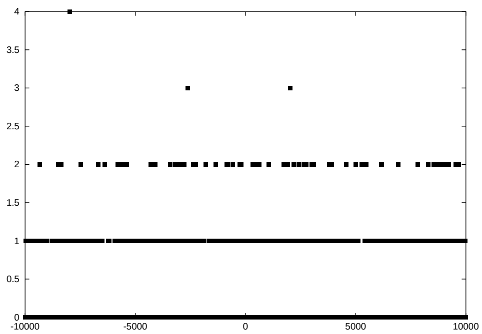
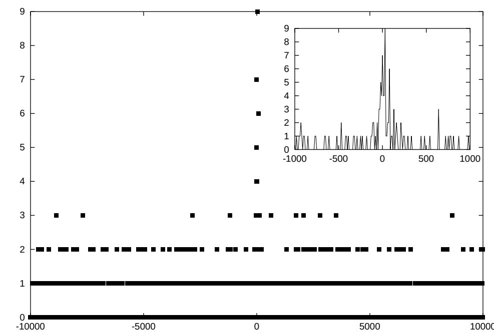
Results

Previous measurements: Eisenberger, McCall [1] at an x-ray generator, Yoda et al. [2] at a synchrotron radiation source, both only coincidence, not time correlation.

Time correlation spectra [3] show coincidence at 0 time difference above statistical background.
Shown are data from ESRF, there are also results from APS and HASYLAB

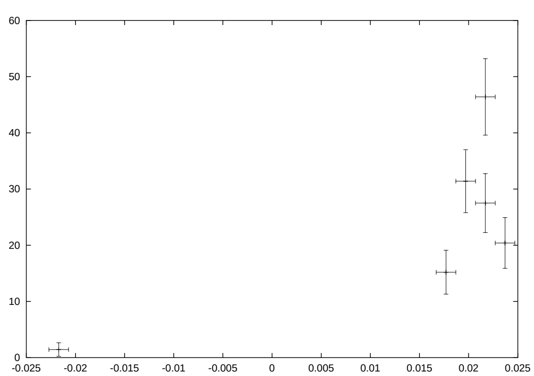




-10μs Δt $+10\mu$s -10μs Δt $+10\mu$s

not fulfilled phase matching fulfilled

events
in 3 hrs



$\Delta\Theta$

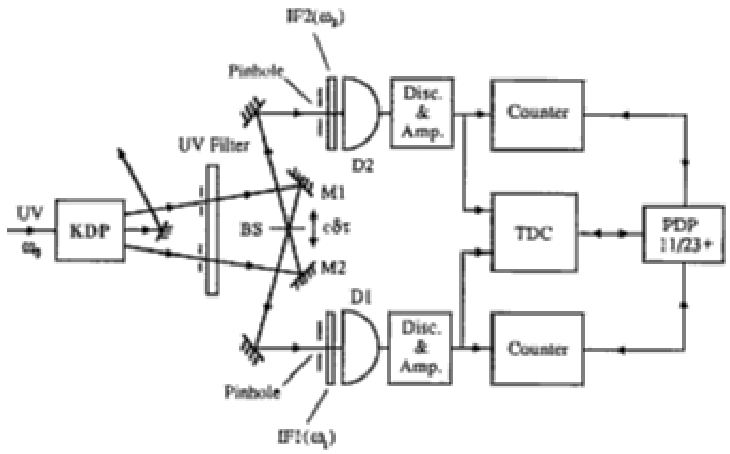
incident:
$\approx 10^{10}$ ph./s

[1] P. Eisenberger, S.L. McCall, Phys. Rev. Lett. **26**, 684 (1971)
[2] Y.Yoda et al., J. Synchrotron Rad. **5**, 980 (1998)
[3] B. Adams, P. Fernandez, W.K. Lee, G. Materlik, D.M. Mills, D.V. Novikov, submitted to J. Synchrotron Rad.

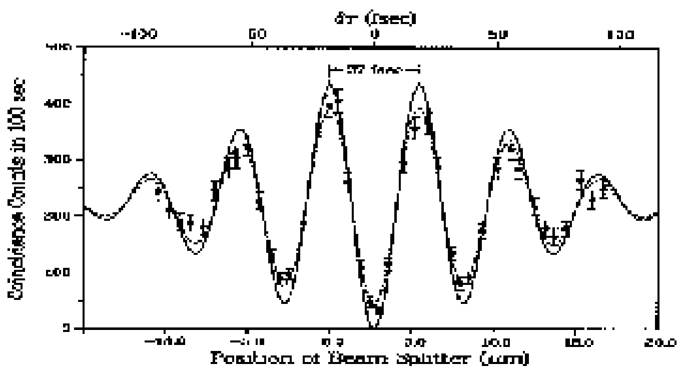
2 Photon Interferometry

Z.Y. Ou, L. Mandel, PRL **61**, 54 (1988):

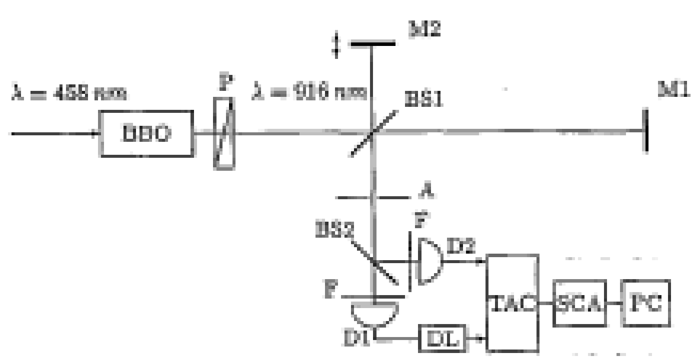
Interference of two correlated photons



Modulation:
Phase difference between photons
Envelope:
Extent of photon wavepackets



J. Brendel, E. Mohler, W. Martienssen, PRL **66**, 1142 (1991):



Michelson interferometer: 4. order interference fringes at arm length differences < incident coherence length, not necessarily < coherence lengths of converted photons

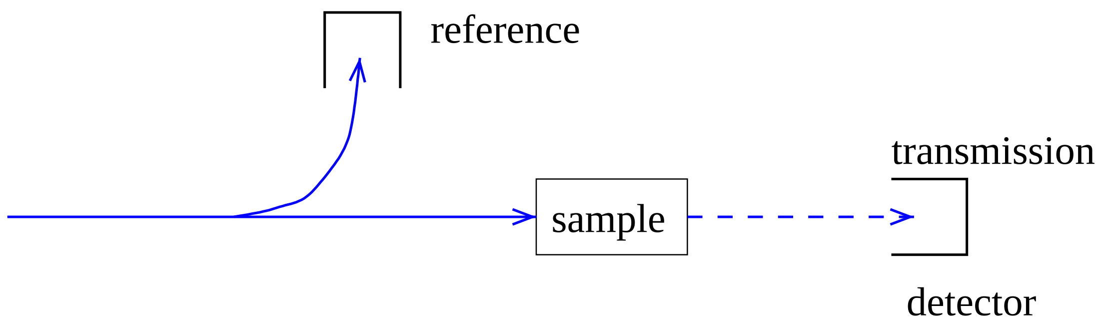
Possible applications:

- Sub-Poisson statistics: Reduced radiation dose
- Two-photon interferometry
- Tests of the quantum theory (EPR, teleportation)
- Recoil-free spectroscopy of free atoms (W. Fenzl)
- Exploit drastically different coherence lenghts of incident and converted photons - 2nd vs. 4th order correlations

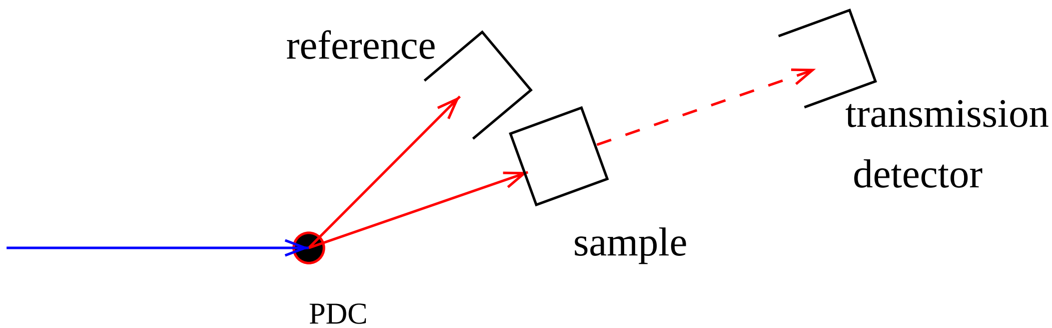
Sub-Poisson Statistics

In absorption spectroscopy, the number of incident photons is known only within Poisson statistics.

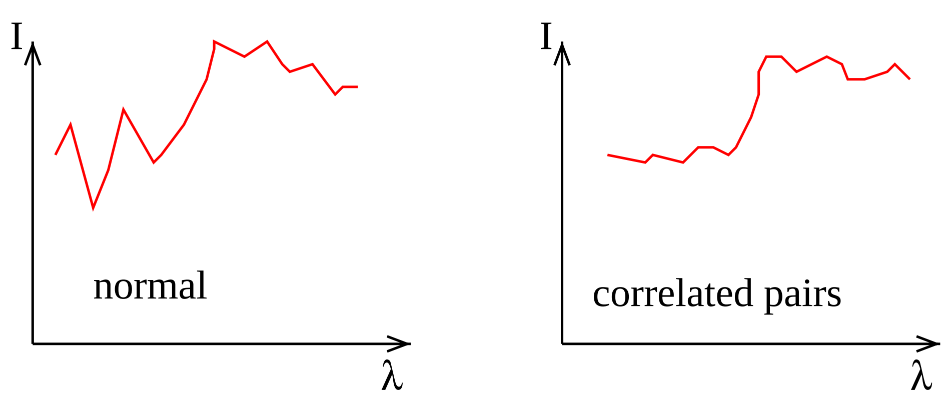
Schematic of absorption spectroscopy:



With pairs of correlated photons, the number of incident photons is known almost exactly - statistics only in the absorption process.



Possible field of application: Dilute and radiation sensitive samples.



EXAFS at same radiation dose

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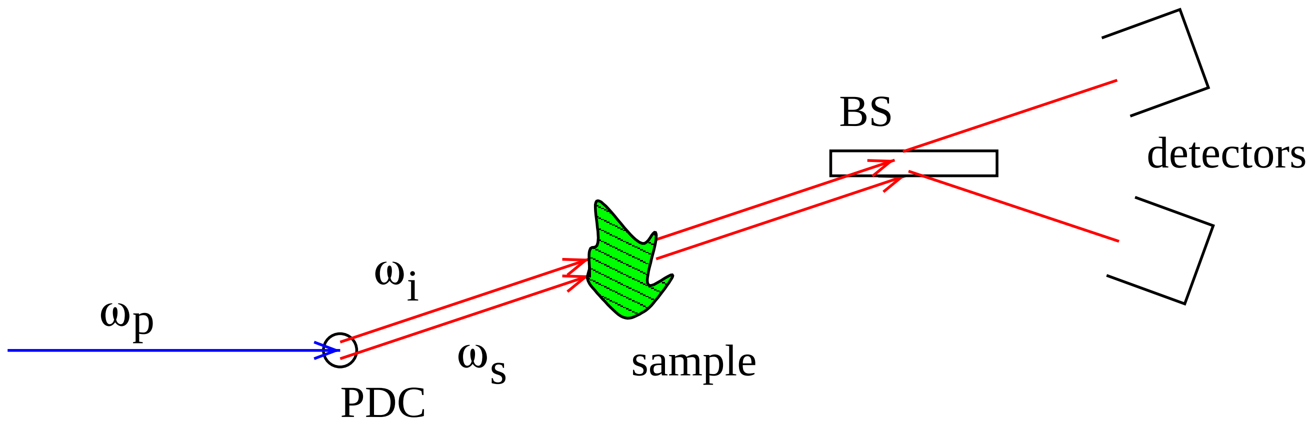
In-Line Interferometry

4th order correlations of photon pairs from PDC for novel interferometry



$\mathbf{k}_i, \mathbf{k}_s$ are almost collinear
normal refraction effects do not influence coincidence contrast
coincidence signal modulation due to difference in propagation phase for different energies, wavevectors and/or polarization states

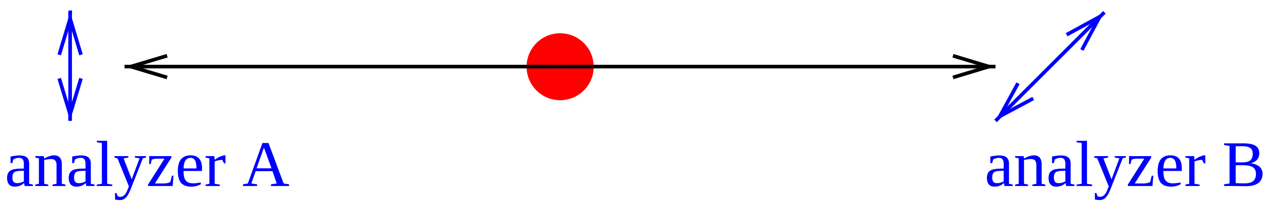
- energy differential interferometry,
  for example $\omega_{i,s}$ above/below absorption edge
- polarization differential interferometry with crossed linear or opposite circular polarizations (magnetism)
- almost collinear case: $|\mathbf{k}_i| = |\mathbf{k}_s|$, $0 < |\mathbf{k}_i - \mathbf{k}_s| \ll |\mathbf{k}_i|$: Probe structural correlations in sample (critical phenomena)

EPR

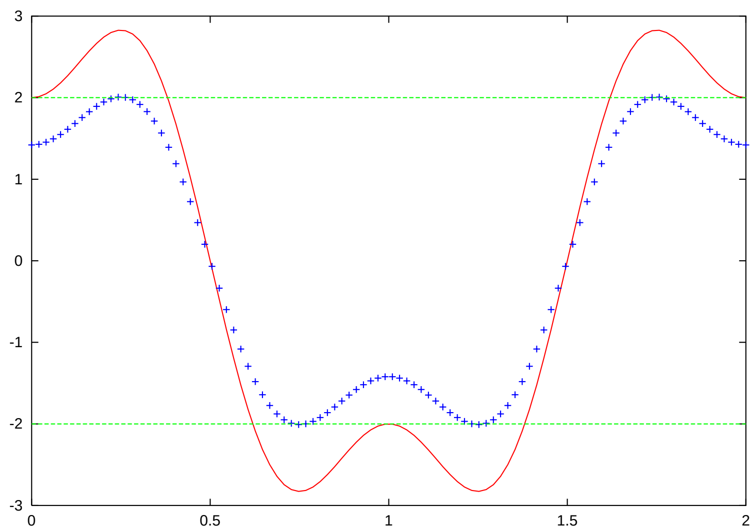
Entangled state:

$$| \quad \rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_1 \, |\downarrow\rangle_2 - |\downarrow\rangle_1 \, |\uparrow\rangle_2 \right) \tag{8}$$

can not be decomposed into a product of single particle states.



Can't measure both x- and y-components of spin:
Bell's inequality: $|3E(\Phi) - E(3\Phi)| \leq 2$



Experimental tests of Bell's inequality are being made in the visible light regime. Problem: The limited quantum efficiency of light detectors. X-rays are at an advantage there.