ASPECTS OF THE QUANTUM THEORY OF NEAR-FIELD OPTICS

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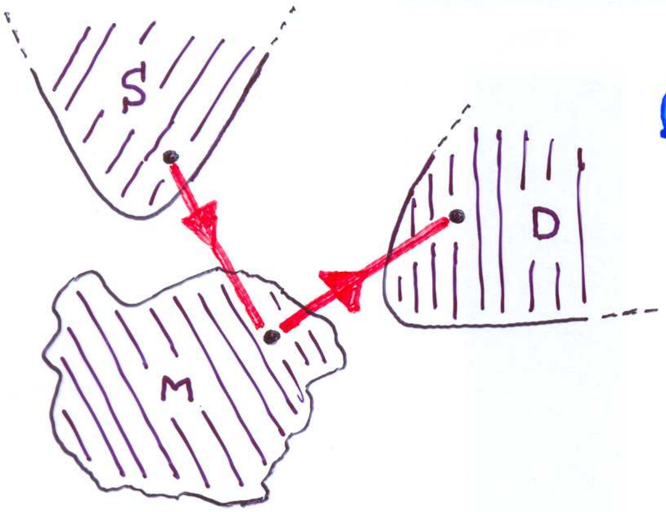
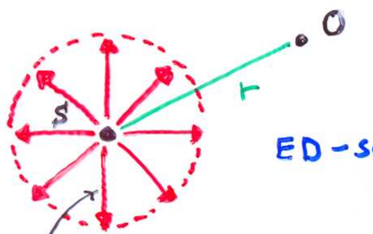


Fundamental physics

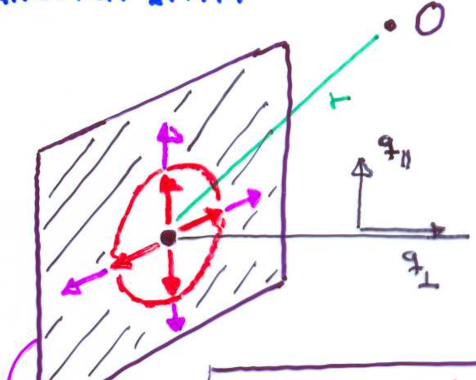
Applications

BEYOND THE CLASSICAL DIFFRACTION LIMIT



ED-source

$\boxed{q_0 = \omega / c_0} = 2\pi / \lambda_0$



$$\vec{E} \sim \int (\vec{\cdots}) \, \delta(q_0 - q) \, d^3 q = \int (\vec{\cdots}) \, d^2 q_{\parallel}$$

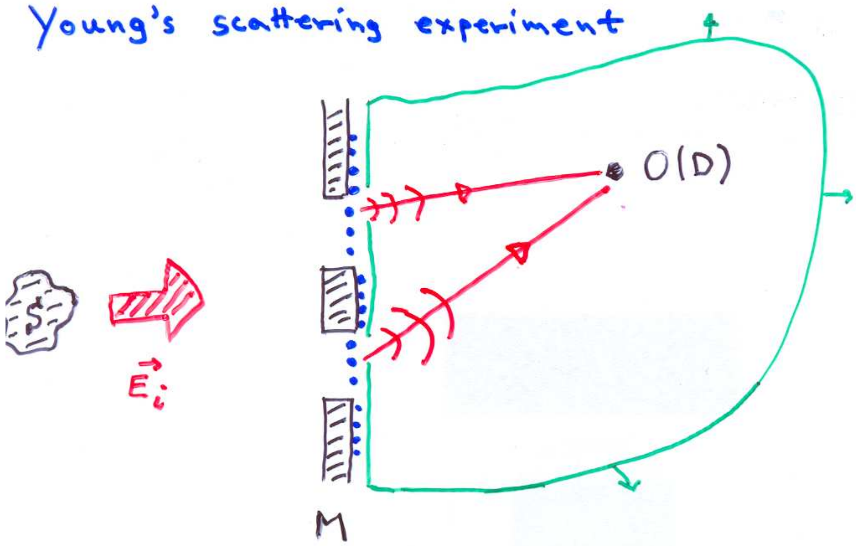
HOM. WAVES ($q_{\parallel} \leq q_0$)
INH. (EVANESCENT) WAVES ($q_{\parallel} > q_0$)

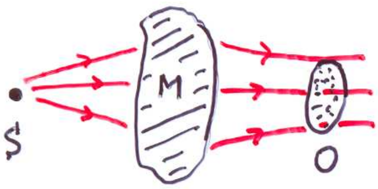
$$\left\{ \begin{array}{ll} (q_0 r)^{-1} & \text{Far,} \\ (q_0 r)^{-2} & \text{Mid-field} \\ (q_0 r)^{-3} & \text{Near} \end{array} \right.$$

Vacuum disp. rel.

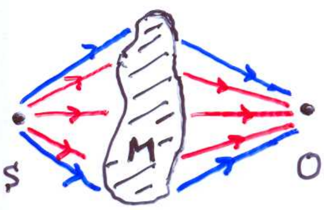
$$q_{\perp} = \pm \sqrt{q_0^2 - q_{\parallel}^2}$$

Young's scattering experiment



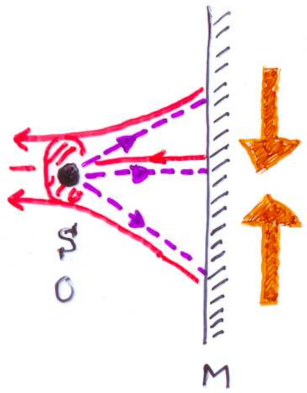


ONLY HOM. WAVES
(Farfield)

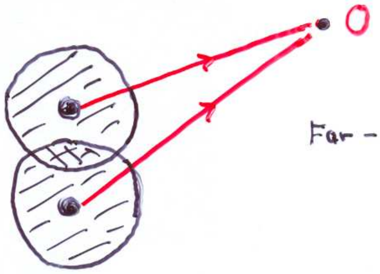


HOM. + EVAN. WAVES
(Nearfield)

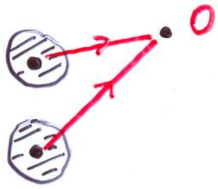
example: M = Ideal phaseconj. mirror



Spatial resolution



Far-field optics



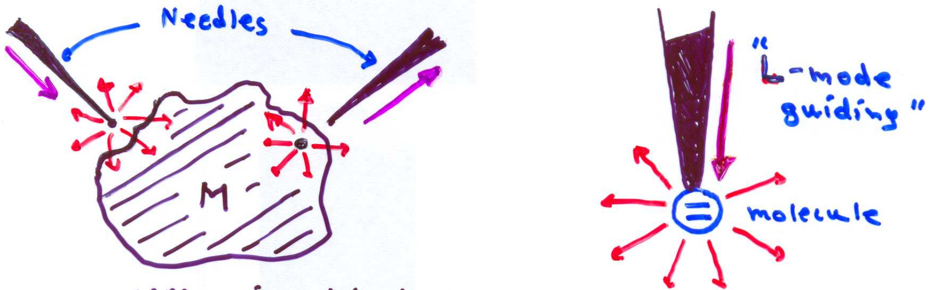
Near-field optics

$\boxed{\text{Atomic resolution ?}}$

The conclusion of (nonrelativistic) classical physics:

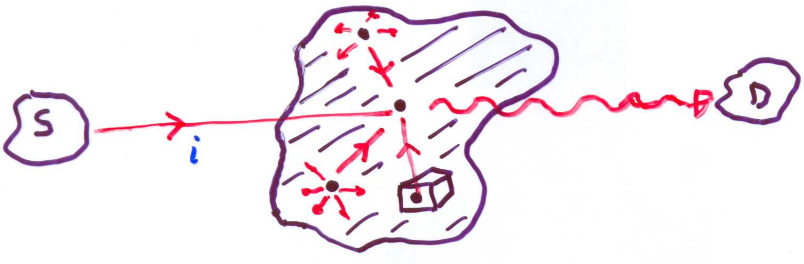
THE SPATIAL RESOLUTION PROBLEM IS "JUST" A PRACTICAL (TECHNOLOGICAL) PROBLEM

(WAVE PACKET PROBLEM; RESPONSE THEORY; ...)



mesoscopic object, e.g.

THE SELFCONSISTENT SCATTERING PROBLEM
[MULTIPLE (INFINITE ORDER)]



M

(Freq. (ω) domain calc.)

$$\vec{E}(\vec{r}) = \vec{E}_i(\vec{r}) - i\mu_0\omega \int_M \underbrace{\overleftrightarrow{D}(\vec{r}-\vec{r}\,')}_{\text{e.m. propagator}} \cdot \vec{J}(\vec{r}\,')\, d^3r'$$

Linear response theory (e.g.)

$$\vec{J}(\vec{r}) = \int_M \underbrace{\overleftrightarrow{\sigma}(\vec{r},\vec{r}\,')}_{\text{conductivity response tensor}} \cdot \vec{E}(\vec{r}\,')\, d^3r'$$

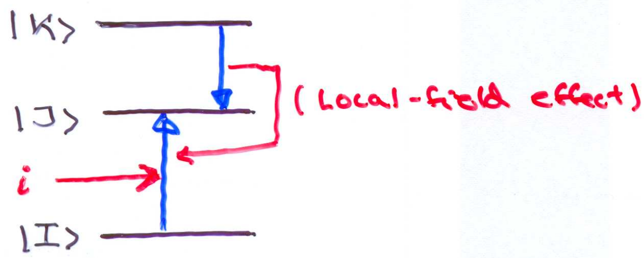
1 Field-unquantized quantum mechanical model :
(massive particle)

$$\overleftrightarrow{\sigma}(\vec{r},\vec{r}\,') = \sum_{I,J} A_{IJ}\, \vec{J}_{J\to I}(\vec{r})\, \vec{J}_{I\to J}(\vec{r}\,')$$

[summation over (many-body) quantum states]

$\Downarrow$

$\boxed{\text{Valid in the mesoscopic (nano-optical) regime}}$



2 Microscopic MAXWELL-LORENTZ theory :
(Point-particle model)

$$\overleftrightarrow{\sigma}(\vec{r},\vec{r}\,') = \sum_{n} \overleftrightarrow{\sigma}_n\, \delta(\vec{r}-\vec{r}_n)\,\delta(\vec{r}\,'-\vec{r}_n)$$

3 Macroscopic ("refractive-index") model :

Slowly varying $\vec{E}$-field
(over correlation volume)

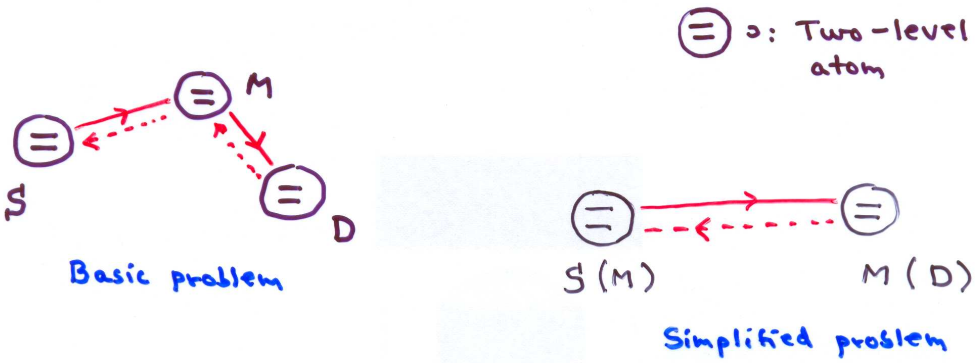
$$\vec{J}(\vec{r}) \simeq \underbrace{\int \overleftrightarrow{\sigma}(\vec{r},\vec{r}\,')\, d^3r'}_{\equiv\, \overleftrightarrow{\sigma}(\vec{r})} \cdot \vec{E}(\vec{r})$$

$$\overleftrightarrow{\sigma}(\vec{r}) \Rightarrow \overleftrightarrow{\varepsilon}(\vec{r}) \Rightarrow n(\vec{r},\omega)$$

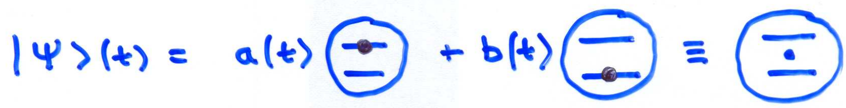
$\uparrow$
inhomogeneous medium

$\boxed{\text{Discretization in space}}$

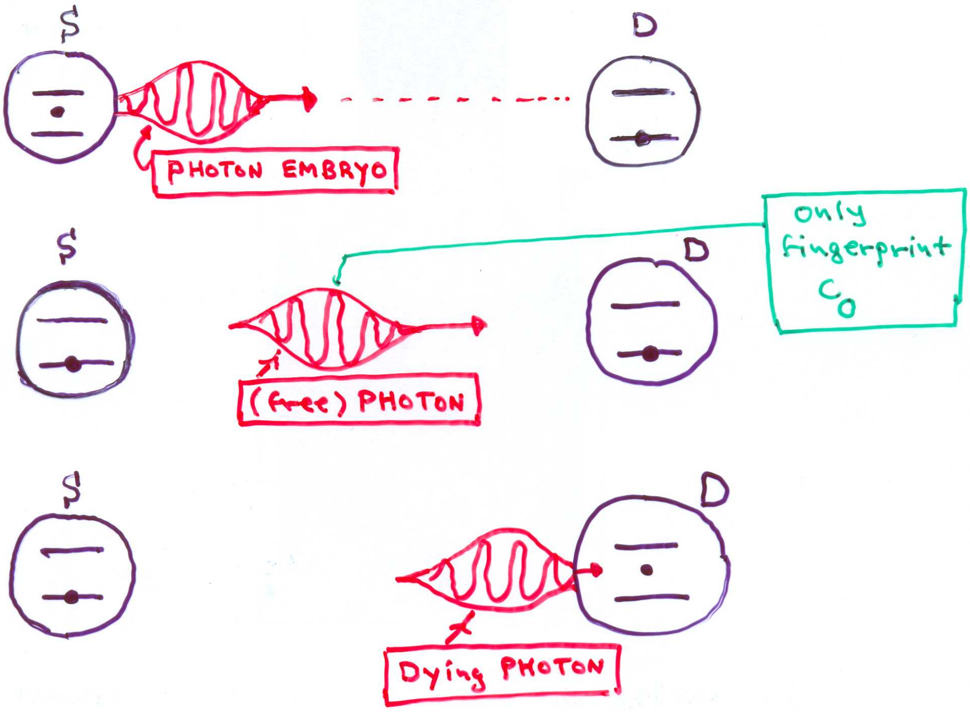
PHOTON WAVE MECHANICS, AND THE SPATIAL RESOLUTION PROBLEM (AGAIN).

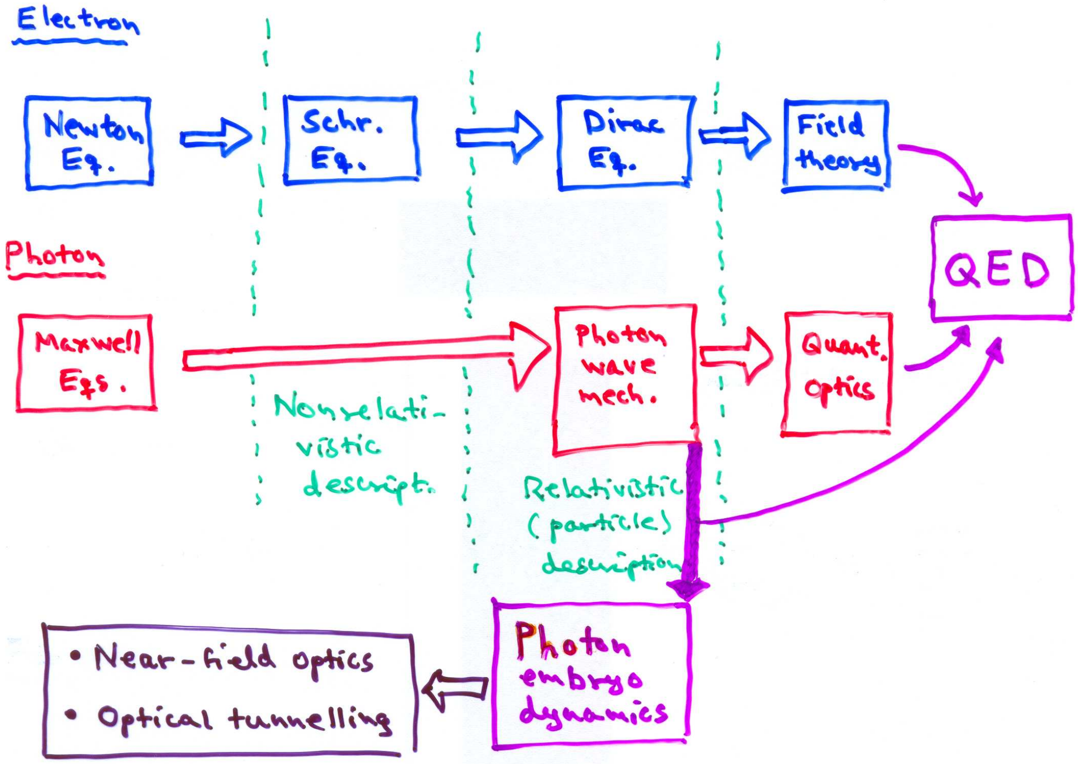


Quantum state of the atom



Far-field process





Landau – Peierls photon wave function

RIEMANN-SILBERSTEIN-OPPENHEIMER PHOTON ENERGY WAVE FUNCTION

analytical signal

$$\vec{\Phi}(\vec{r},t) = \begin{pmatrix} \vec{F}_{+}^{(+)} \\ \vec{F}_{-}^{(+)} \end{pmatrix} \qquad \vec{F}_{\pm}^{(+)} = \sqrt{\frac{\varepsilon_0}{2}}\left(\vec{e}_{T}^{(+)}(\vec{r},t) \pm i c_0 \vec{b}^{(+)}(\vec{r},t) \right)$$

pos (+) and neg (−) helicity states

Transverse dynamics

$$\vec{\nabla}\cdot\vec{e}_{T}^{(+)}(\vec{r},t) = 0 \quad \forall\, \vec{r}$$

$$\int_{-\infty}^{\infty} \vec{\Phi}^{+}\cdot\vec{\Phi}\, d^3r = E \quad \text{(photon energy)}$$

Free-space Maxwell eqs. ⇒ **PHOTON WAVE EQUATIONS**:

$$i\hbar \frac{\partial}{\partial t} \vec{F}_{\pm}^{(+)}(\vec{r},t) = \overbrace{\pm c_0 \left(\vec{\Sigma} \cdot \underbrace{\frac{\hbar}{i} \vec{\nabla}}_{} \right)}^{\text{Hamilton operators}} \vec{F}_{\pm}^{(+)}(\vec{r},t)$$

Cartesian spin-one op. momentum ($\vec{p}$) op

In the momentum representation

Helicity op. $h = \vec{\Sigma} \cdot \frac{\vec{p}}{p}$, $ev(h) = \pm 1$

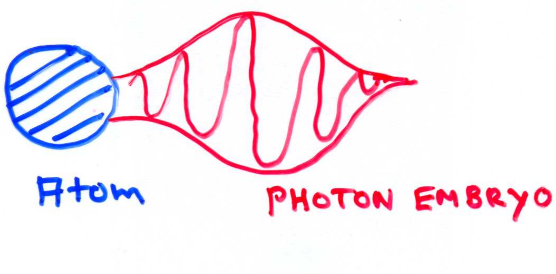
Energy op. $E = c_0 p$

$\vec{p}$ $\vec{\Sigma}$ $ev(h) = +1$

$\vec{\Sigma}$ $\vec{p}$ $ev(h) = -1$

PHOTON EMBRYO DYNAMICS

(1. quantized theory of field-matter interaction)



Forthcoming monography (and references herein)

O. Keller: "On the theory of spatial localization of photons", PHYS. REPORTS (2005).

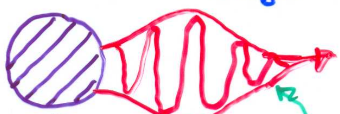
Atom Photon

$\vec{\Phi}(\vec r, t)$

$$\vec E = \vec E_L + \vec e_T$$

$$\vec{\jmath} = \vec 0$$

Photon embryo



$\vec{\Psi}(\vec r, t)$

$$\vec E = \vec E_L + \vec e_T$$

$$\vec E = -\vec{\mathcal{P}}/\varepsilon_0 + \vec d/\varepsilon_0$$

$$\vec{\jmath} = \frac{\partial \vec{\mathcal{P}}}{\partial t} + \vec\nabla \times \vec{\mathcal{M}} \neq \vec 0$$

Choice ⇓

Dynamical Eq. for the embryo state $\vec\Psi = \begin{pmatrix} \vec F_+^{(+)} \\ \vec F_-^{(+)} \end{pmatrix}$

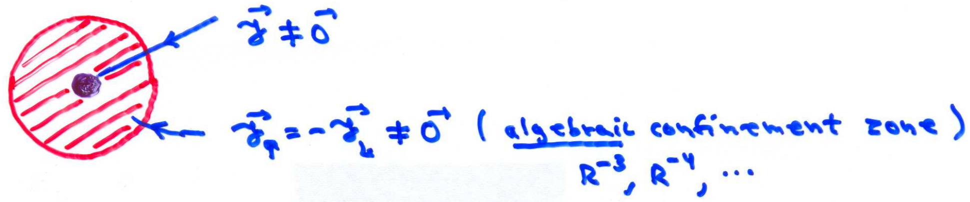
$$\boxed{i\hbar \frac{\partial}{\partial t} \vec F_\pm^{(+)}(\vec r, t) = \pm c_0 \left(\vec\Sigma \cdot \frac{\hbar}{i} \vec\nabla \right) \vec F_\pm^{(+)}(\vec r, t) - \frac{i\hbar}{\sqrt{2\varepsilon_0}} \vec{\jmath}_T^{(+)}(\vec r, t)}$$

$$\vec e_T(\vec r, t) = \mu_0 \int_{V_T} \underbrace{g_0(R, \tau)}_{\text{Huygens propagator}} \dot{\vec{\jmath}}_T(\vec r', t')\, d^3 r'\, dt'$$

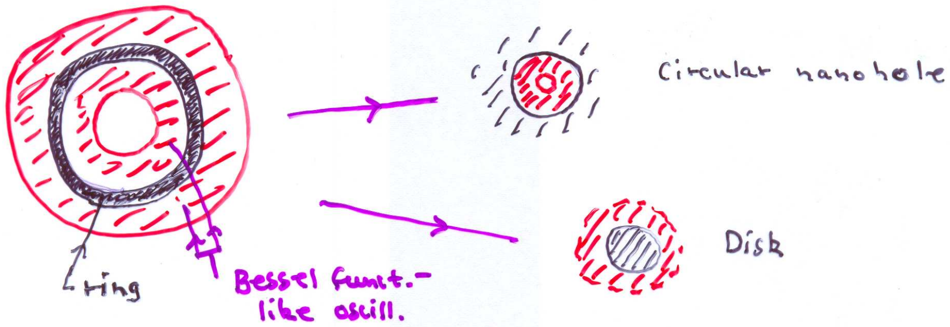
$$\vec b(\vec r, t) = \dots$$

$$g_0 = -(4\pi R)^{-1} \delta\left(\frac{R}{c_0} - \tau\right)$$

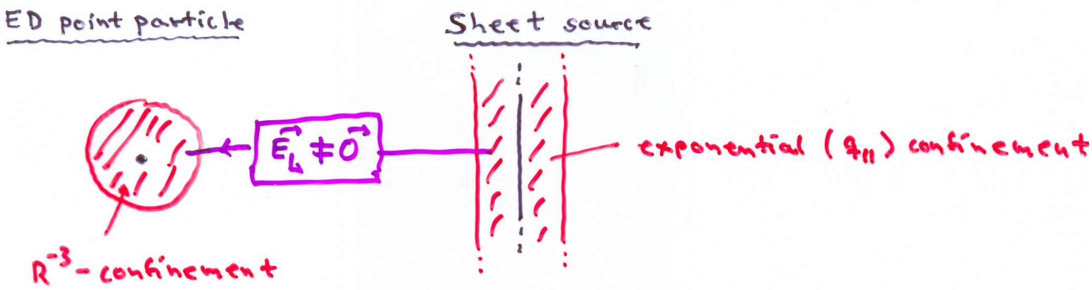
(Initial) spatial confinement of photon embryo

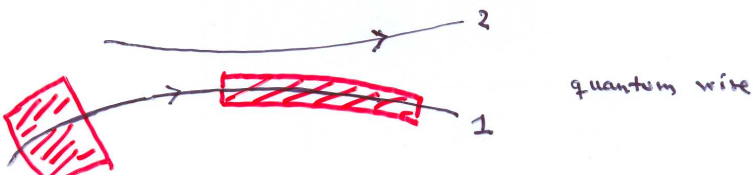


Light scatt. by a mesoscopic ring
(with Broe, Bryant ; NIST, Gaithersburg)



HEURISTIC EXAMPLES

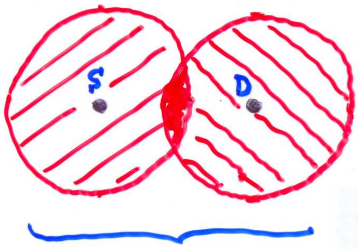




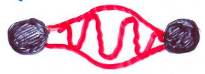
$\nabla \cdot \vec{E} = 0$ $\boxed{\vec{E}_L \neq \vec{0}}$

but still $\nabla \times \vec{E}_L = \nabla \cdot \vec{E}_L = 0$

NEAR-FIELD OPTICS : THE NIGHTMARE OF THE PHOTON



Nonlocal atomic state specification



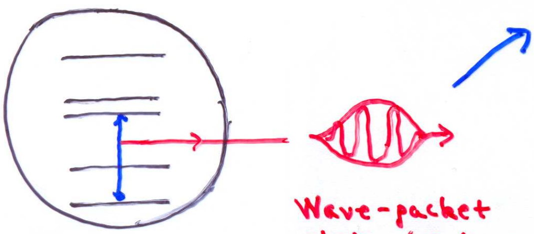
Embryo killed before the photon is born !

EINSTEIN CAUSALITY : No sharp questions possible !

THE FERMI PROBLEM

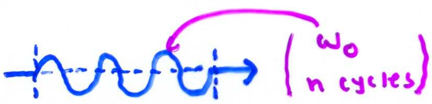
CORRECT INTERPRETATION OF EXP. DATA BECOMES MORE DIFFICULT WITH DECREASIN $R_{inter\text{-}atomic}$

FROM PHOTON WAVE MECHANICS TO QED



Wave-packet photon (embryo

WAVE-TRAIN PHOTONS



⇓

MODE FUNCTIONS (COMPLETE SET)

⇓

SECOND QUANTIZATION

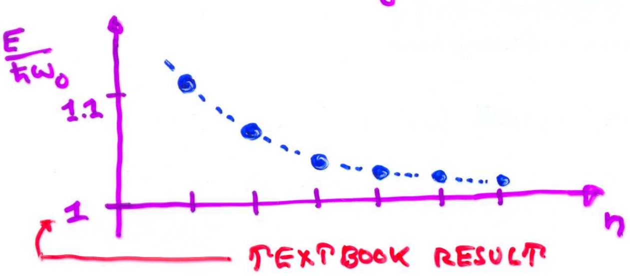
⇓

WAVE-TRAIN QUANTA (Many-photon descrip.)

Energy of wave-train photon

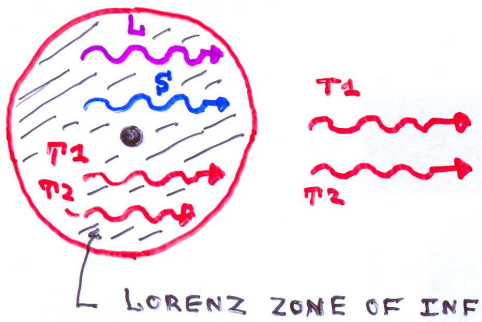
(limit $a_0 \ll \lambda_0$)

$$E = \hbar\omega_0 \left[\frac{2}{\pi} \int_0^{2\pi n} \frac{\sin x}{x} dx \right]^{-1}$$



COVARIANT (LORENZ GAUGE) DESCRIPTION

not Lorentz !



long. photon — $L + S =$ — scalar photon

$d + g$ (gauge photon)

"d-photon"

NEAR-FIELD PHOTON !

EXPONENTIAL PHOTON LOCALIZATION (IN 3D)

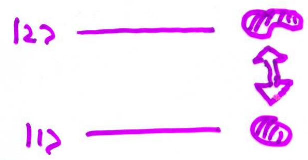
$\boxed{\text{(EMBRYO)}}$

$\vec{\gamma} = \vec{\gamma}_T + \vec{\gamma}_L$ Is $\underline{\vec{\gamma} = \vec{\gamma}_T}$ possible ?

<u>Electronic transition</u> $\dot{\rho}\ (= -\vec{\nabla}\cdot\vec{\gamma}_L) \neq 0$ always !

<u>Pure spin transition</u>

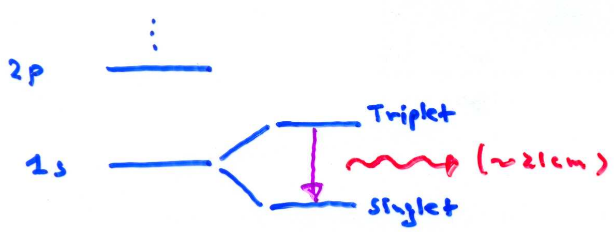
$\vec{\gamma} = \vec{\gamma}_{spin} = \vec{\gamma}_{T,spin}$!

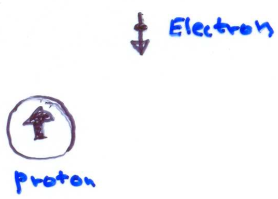


Spin flip

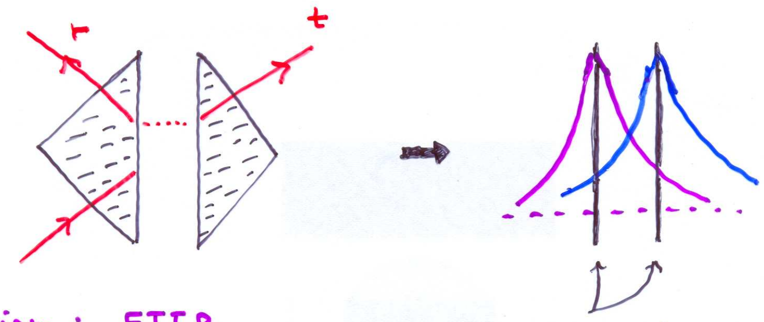
<u>Avoid spin-orbit couplings</u>

<u>Example</u> : HYPERFINE GROUND STATE TRANSITION (in hydrogen)





OPTICAL TUNNELLING
(always a near-field phenomenon)



Paradigm : FTIR

$\theta_i > \theta_c$

Current den. sheets (possible with QW-enhancement)

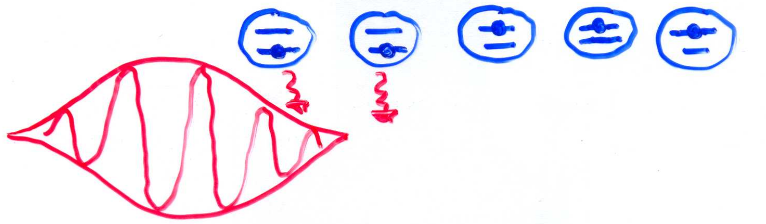
Decay const. $q_{\parallel}$ and not $\varkappa_{\perp} = \sqrt{q_{\parallel}^2 - (\omega/c_0)^2}$

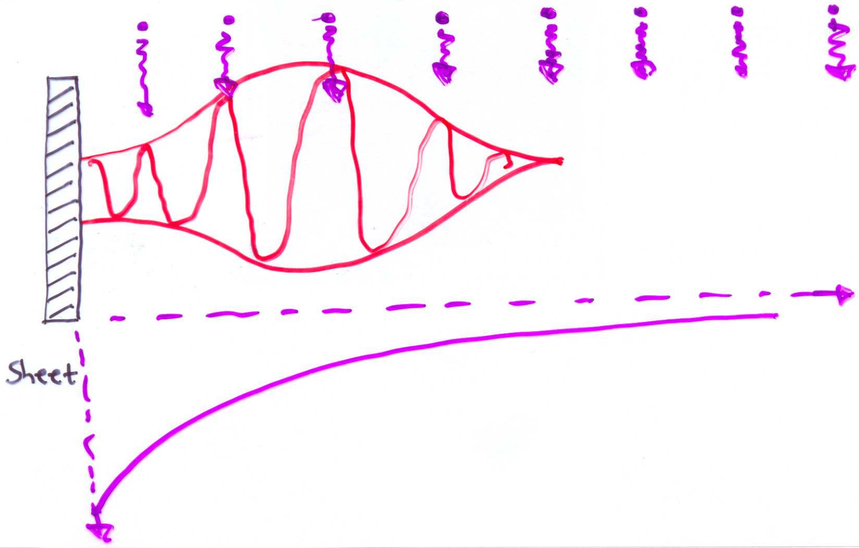
c_0 (!)

$\Downarrow$

APPARENT SUPERLUMINALITY ("FAST" LIGHT)

= <u>EINSTEIN CAUSAL PROP.</u> + <u>PHOTON DELOCALIZATION</u>





- Photon wave function (prior to 1997)

  I. Bialynicki-Birula in:
  Progress in Optics, Vol. 36, ch. 5; ed. E. Wolf
  (Elsevier, 1996)
  (REVIE

- On the theory of spatial localization of light

  O. Keller, Phys. Rep. (upcoming) (REVIEW)

- Articles on photon embryo, 2nd quantized theory, tunnelling

  O. Keller, Phys. Rev. A58, 3407 (1998).
  Phys. Rev. A60, 1652 (1999).
  Phys. Rev. A62, 022111 (2000).
  J. Opt. Soc. Amer. B18, 206 (2001).
  J. Opt. Soc. Amer. B16, 835 (1999).
  J. Nonl. Opt. Phys. and Mat. 12, 393 (2003)

HEURISTIC WORKS:

O. Keller, Single Mol. 3, 5 (2002).

"Concepts and aspects of near-field optics"
to appear in
Minerva Biotechnologica
(special issue on biological (optical) imaging)

Historical article

O. Keller, "Optical works of L.V. Lorenz"
in Progress in Optics, ~~ch~~ Vol. 43, ch. 3; ed. E. Wolf (Elsevier, 2002).