Top

Left side

TEST

Right side

Bottom

Pulse propagation through atoms in waveguides

Rutgers Newark Physics Colloquium

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An atom interacting with light
in free space.

Dipole cross section (same result for a classical dipole or a two-level atom):

$$\sigma_0 = \frac{3\lambda_0^2}{2\pi}$$

This is the "shadow" caused by a dipole in a beam of light.

Energy due to the interaction between a dipole and an electric field.

$$H = \vec{d} \cdot \vec{E}$$

d is of the order of a_0 (Bohr radius) e (electron charge) between the ground state S and the first excited state P in alkaline atoms. (Line D2)

$$\vec{d} = e\left\langle 5S_{1/2} \left| \vec{r} \right| 5P_{3/2} \right\rangle$$

Decay rate
(Fermi's Golden Rule)

$$\gamma_{rad} \approx \frac{2\pi}{\hbar} \rho(k) \langle H_{int} \rangle^2$$

Phase space density

Interaction

Beer–Lambert law for intensity attenuation

$\frac{dI}{dz} = -\alpha I$ if α is resonant and independent of I, then $\alpha=\alpha_0$ (not saturated)

$I = I_0 \exp(-\alpha_0 l)$

where $\alpha_0 = \sigma_0 \rho$

and $\rho = N / V$ the density of atoms (absorbers) at a length *l*

Cavity Quantum Electrodynamics (QED)

Optical cavity QED

Quantum electrodynamics for pedestrians. There is no need for renormalization. One or a finite number of cavity modes.

ATOMS + CAVITY

Non-perturbative regime: coupling>>dissipation
Vacuum Rabi splitting.

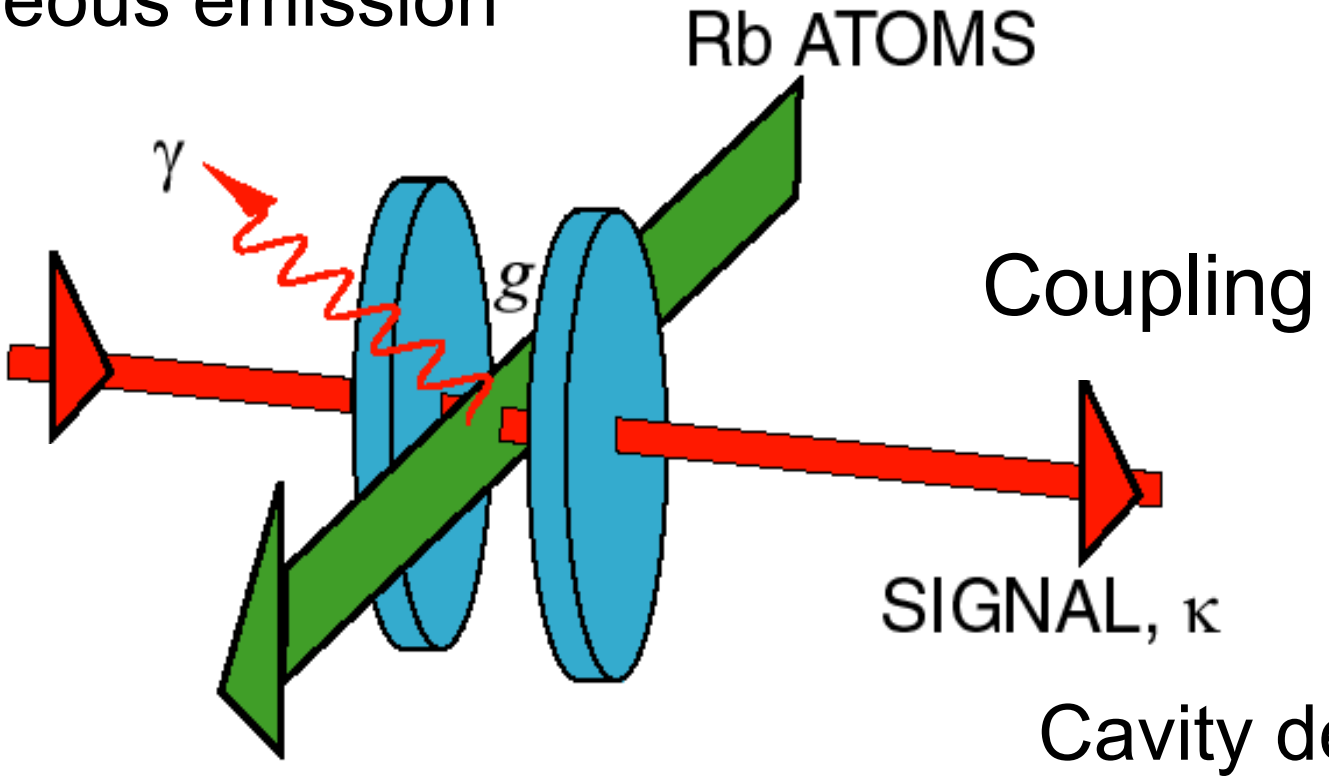
Dipole coupling between atom and cavity mode:

$$g = \frac{d \cdot E_v}{\hbar}$$

The electric field associated with a photon on average in the cavity with volume: V_{eff} is:

$$E_v = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V_{eff}}}$$

Spontaneous emission



Cavity decay

Cooperativity for an atom: C_1

$$C_1 = \frac{g^2}{\kappa\gamma}$$

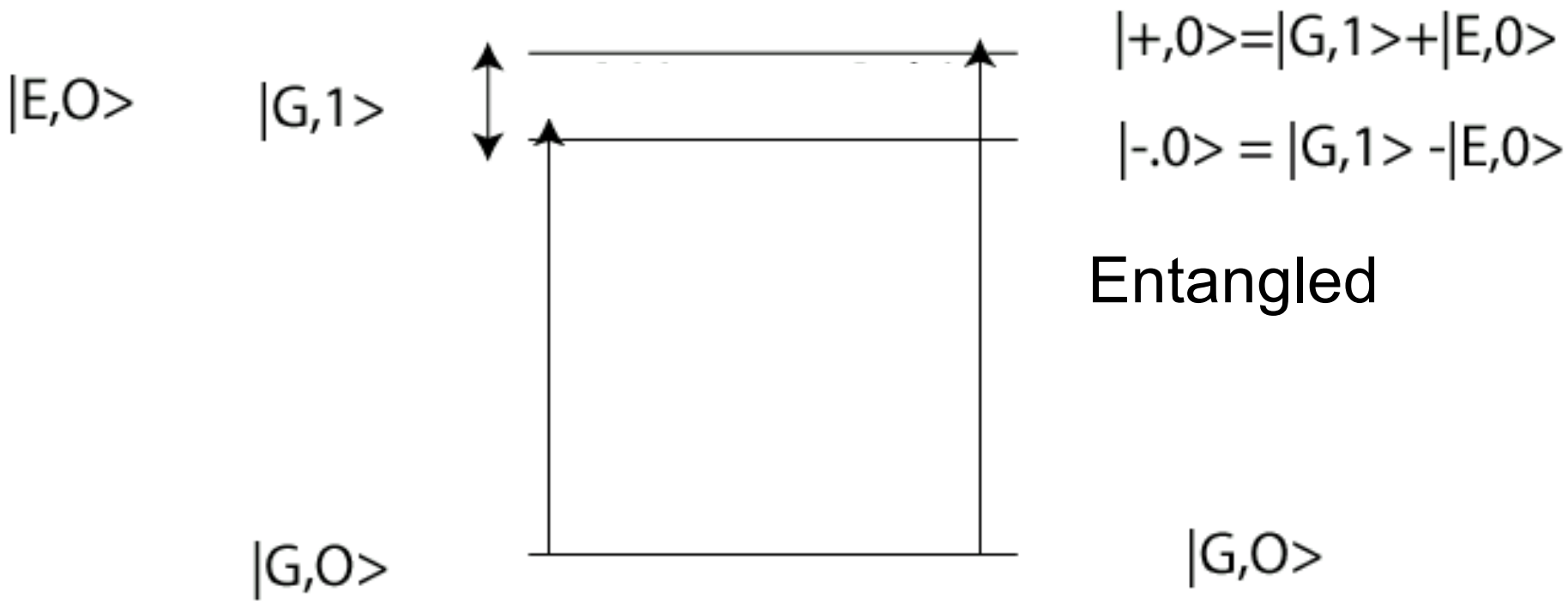
Cooperativity for N atoms: C

$$C = C_1 N$$

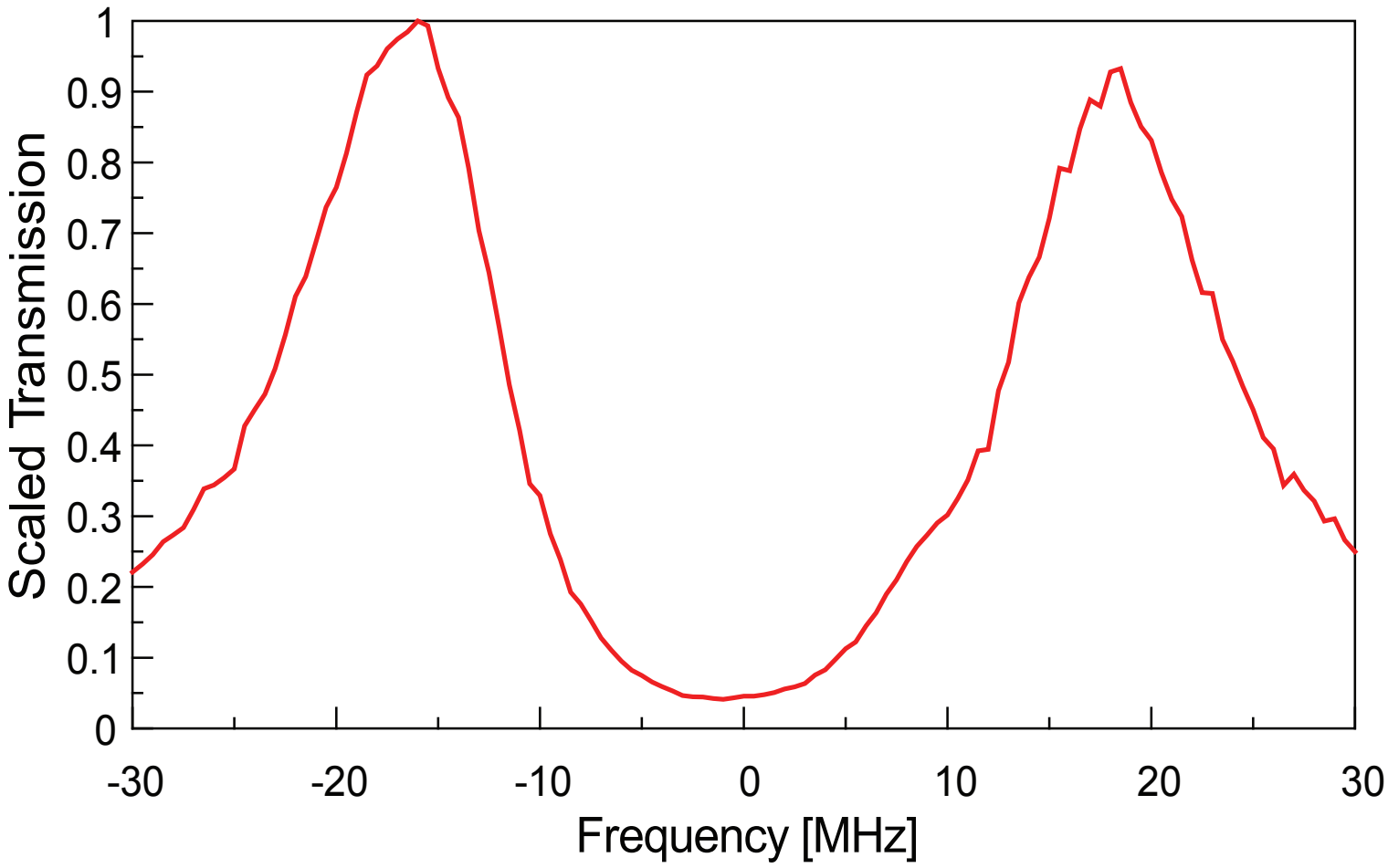
$$C_1 = \frac{\gamma_{1D}}{\gamma}$$

$$C_1 = \frac{\sigma_0}{A_{mode}} \frac{1}{T}$$

2g Vacuum Rabi Splitting



Transmission doublet different from Fabry Perot resonance

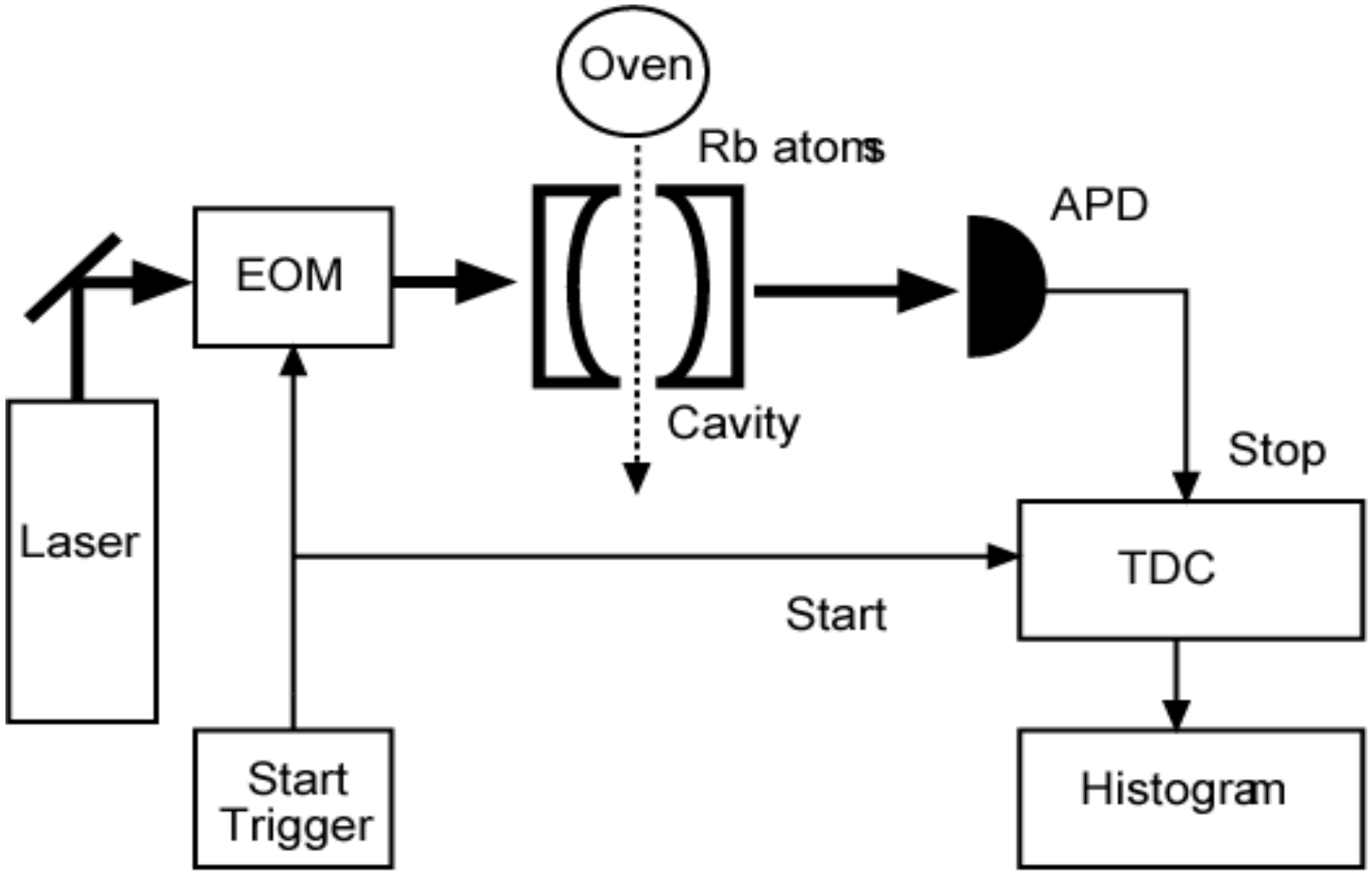


Quantum electrodynamics model of cavities
at low excitation with *N* atoms coupled g:
An electromagnetic field mode with amplitude x
atomic polarization *P.* Decays of cavity κ and átomos γ;
Excitation field (forcing) *E(t)*
Two coupled harmonic oscillators:

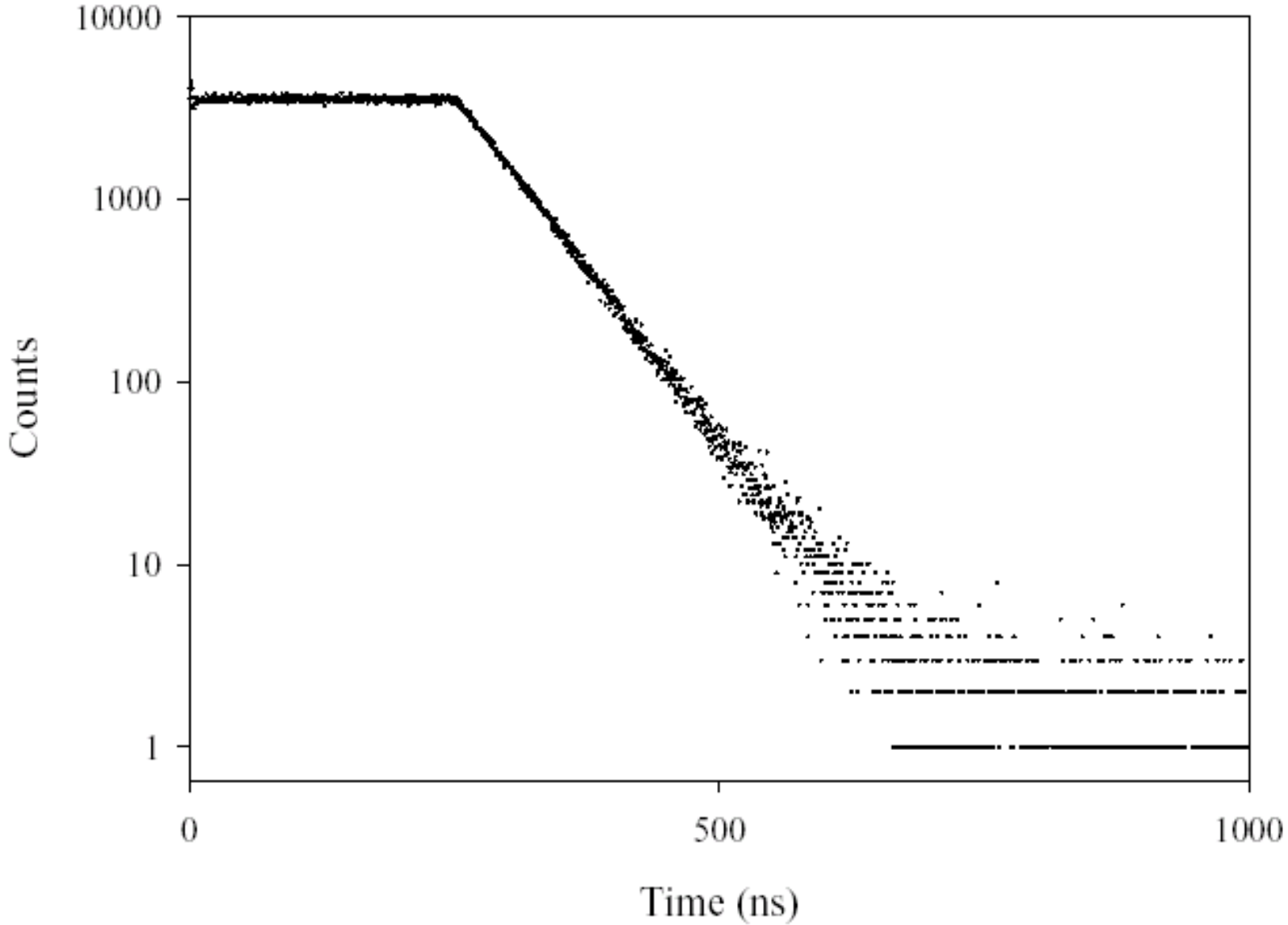
Field $$\frac{dx}{dt} = -\kappa x + g\sqrt{N}p + E(t)$$

Atomic Polarization $$\frac{dP}{dt} = -\frac{\gamma}{2}P - g\sqrt{N}x$$

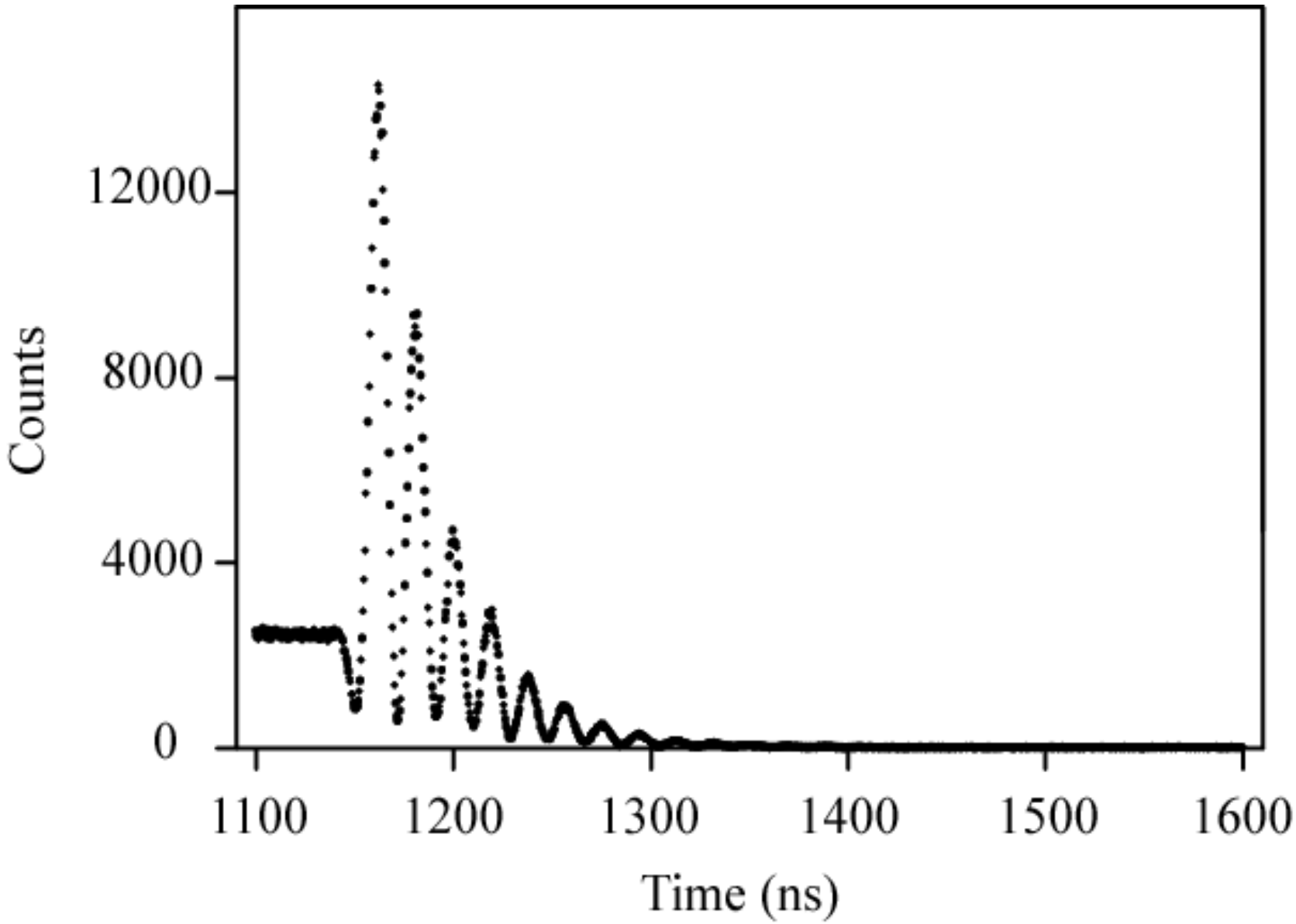
Study of the response of the system to a step excitation and de-excitation.



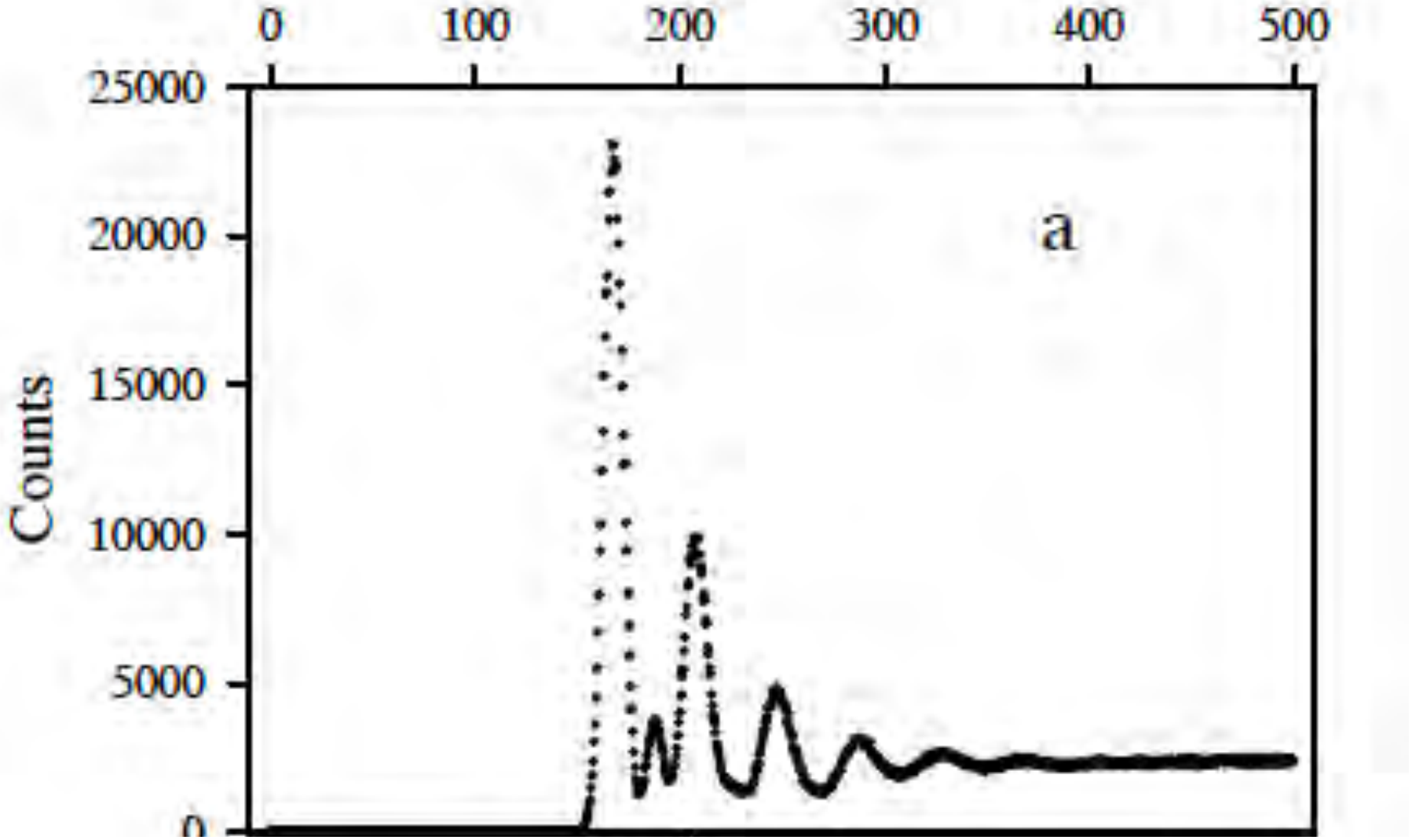
Decay of the empty cavity



Response to turning off the excitation

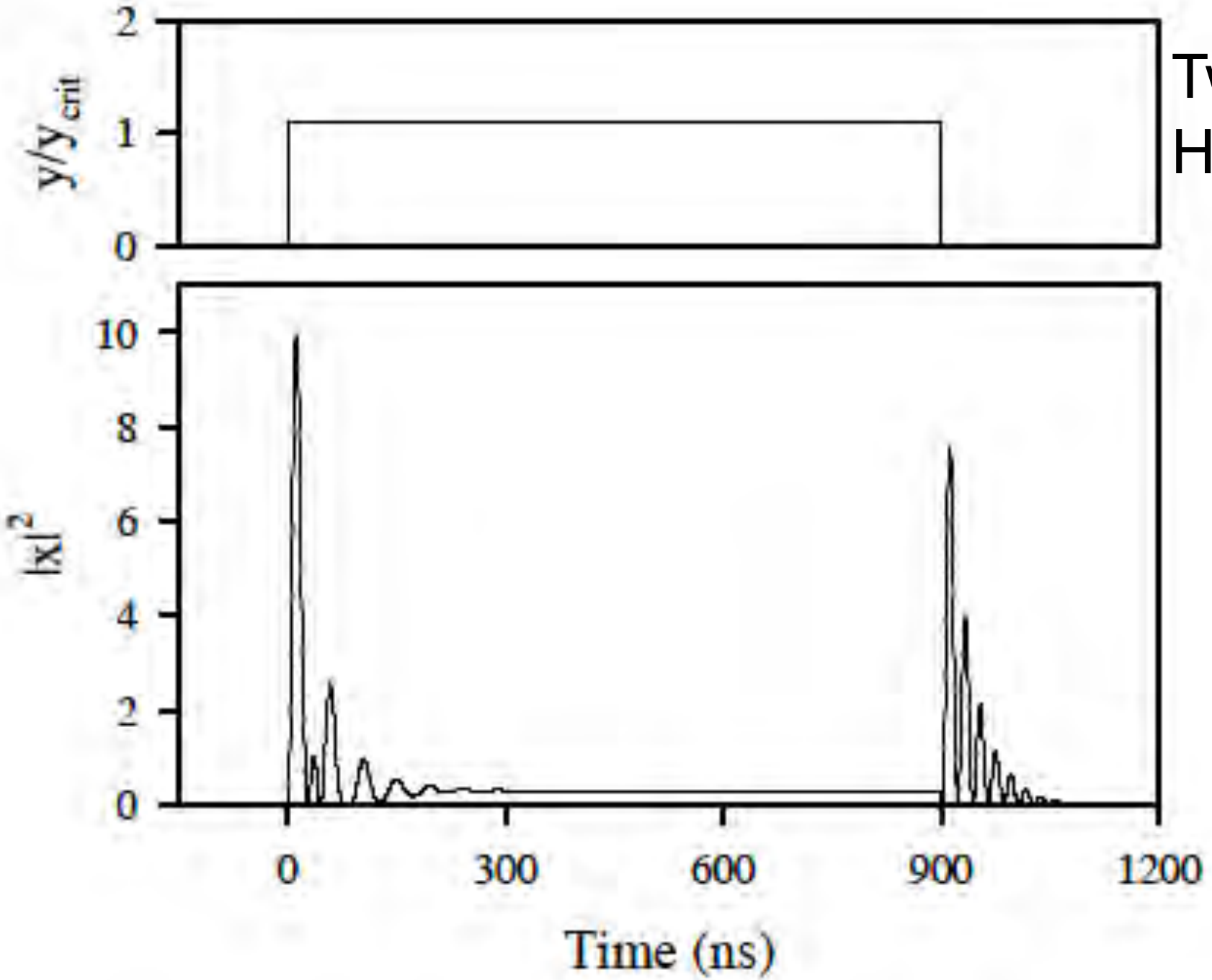


Response to turning on the excitation



Pulse

Response



Two coupled
H.O. model

Fast pulse on and of, $\tau < \kappa^{-1}, \gamma^{-1}$

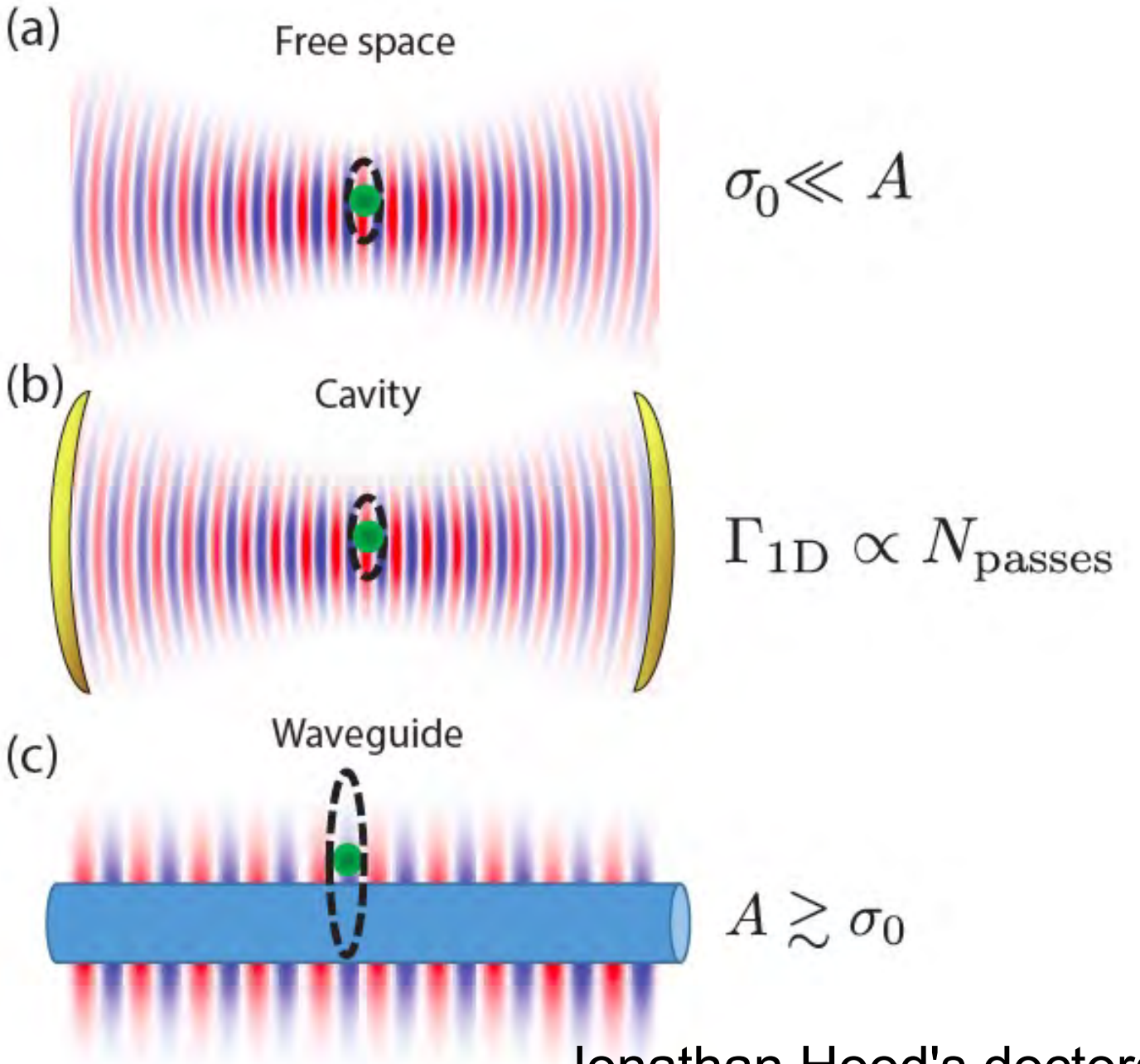
Response of coupled oscillators

Finite time for atomic polarization to respond (emit out of phase and interfere with excitation pulse)

The atoms continue to emit (half-life) and send the light into the cavity, reabsorbing it.

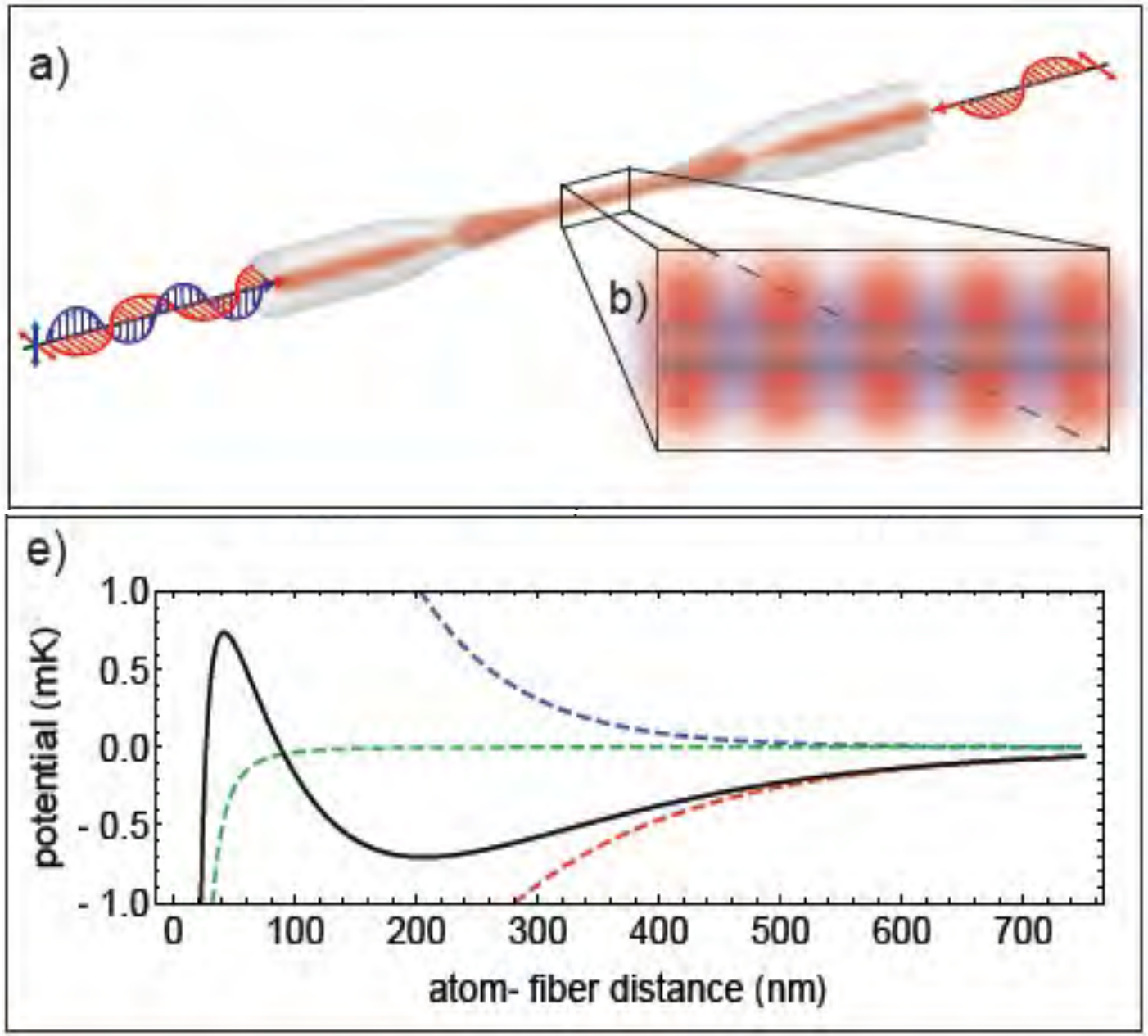
Only the light escapes from the cavity through the channel we are observing.

From cavity quantum electrodynamics to waveguide QED

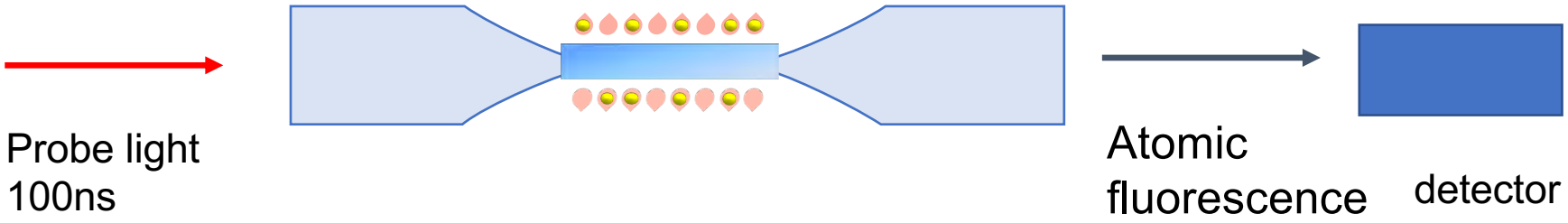


Jonathan Hood's doctoral thesis

Trapping scheme

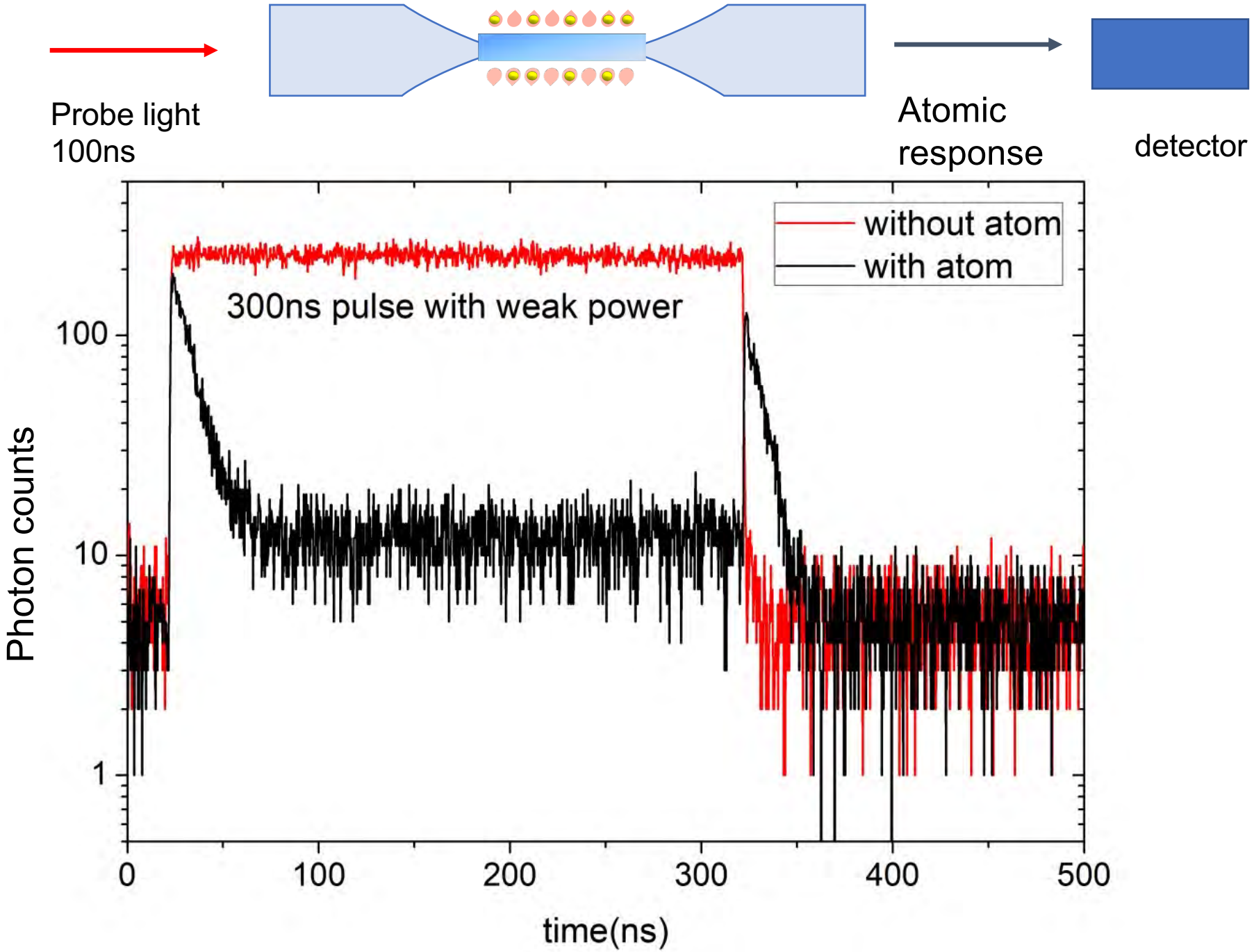


Atomic life in a transmitted direction



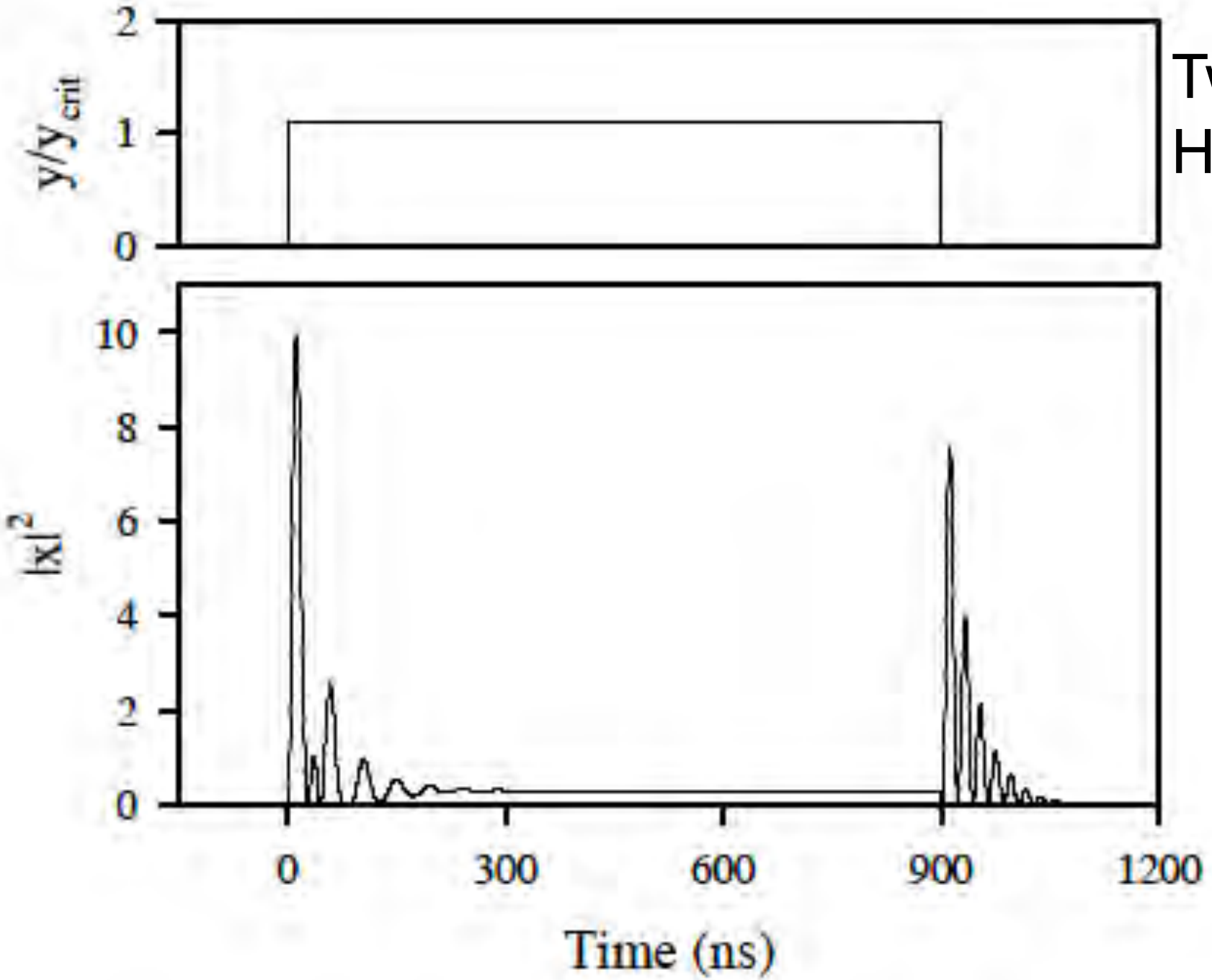
We trap the cesium atoms using almost magic wavelength lasers (~686 nm with power each beam 5 mW, 935 nm with power each beam of 0.35 mW*2).

The probe pulse of 100 to 300 ns is produced by one EOM and extinguished by another EOM at the output port. The power of the probe is about 1 pW.


Probe light
100ns
Atomic
response
detector
without atom
with atom
300ns pulse with weak power
Photon counts
100
10
1
0
100
200
300
400
500
time(ns)

Pulse

Response



Two coupled
H.O. model

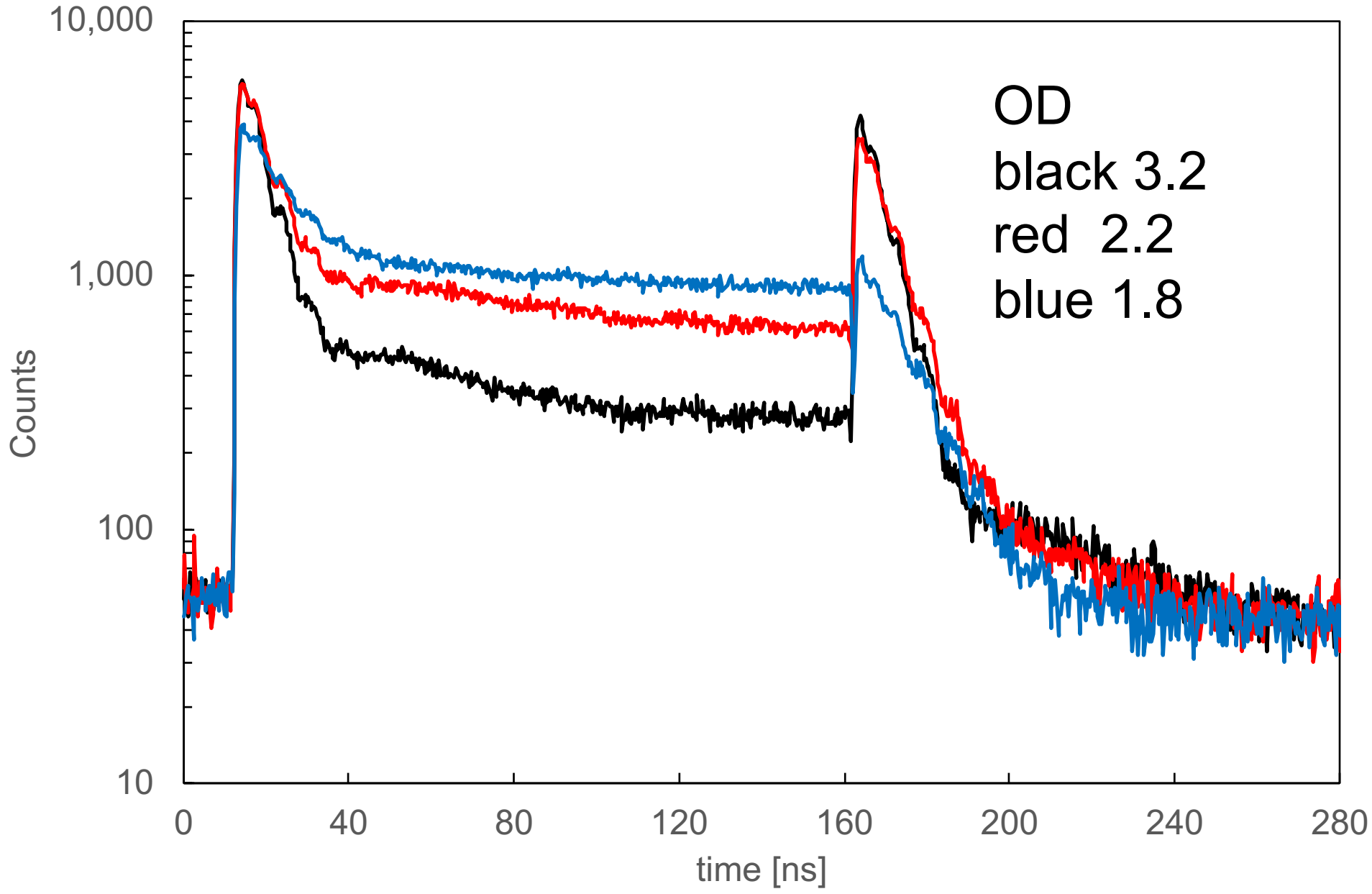
Very fast pulse on and off

Classical atomic polarization response

Finite time for atomic polarization to respond (emit out of phase and interfere with excitation pulse)

The atoms continue to emit after the light goes out.

The same thing we observe in cavity QED without oscillations


10,000
1,000
100
10
Counts
0
40
80
120
160
200
240
280
time [ns]
OD
black 3.2
red 2.2
blue 1.8

Change in the decay time as the number of atoms changes.

Some beats visible, also in the FFT

Explore dynamic beats (Mossbauer).

PHYSICAL REVIEW VOLUME 120, NUMBER 2 OCTOBER 15, 1960

Time Dependence of Resonantly Filtered Gamma Rays from Fe^{57}†

F. J. LYNCH, R. E. HOLLAND, AND M. HAMERMESH
Argonne National Laboratory, Argonne, Illinois

(Received June 6, 1960)

The time dependence of gamma rays emitted by the 14.4-kev state of Fe^{57} has been studied by delayed-coincidence measurements between a 123-kev gamma ray preceding formation of the state and the 14.4-kev gamma ray from the state. When no filter was used, the number of gamma rays decreased exponentially with the known half-life of 0.1 μsec. When a foil of Fe^{57} (which was resonant to 14.4-kev radiation) was used as a filter, the number of gamma rays observed through the filter did not decrease exponentially. Instead, the filter absorbed almost none of the gamma rays first emitted by the 14.4-kev state; at later times the absorption increased. Data were taken with three different thicknesses of absorber and with emission and absorption peaks separated by 0 to 11 times the width of the resonance. The energy separation resulted from the Doppler shift associated with a constant velocity between source and absorber. These data were, for the most part, in good accord with the prediction of a theory based on a classical model for absorber and source. In particular, the results verified the theoretical prediction that at certain times the intensity of radiation observed would be greater with the filter than without it.

PHYSICAL REVIEW VOLUME 124, NUMBER 4 NOVEMBER 15, 1961

Quantum Mechanical Calculation of Mössbauer Transmission*†

SAMUEL M. HARRIS‡§
University of Illinois, Urbana, Illinois
(Received June 26, 1961)

A quantum mechanical calculation of the time-dependent Mössbauer transmission has been performed neglecting solid-state effects. The source considered consists of nuclei which decay via a two-photon cascade, the second of which is emitted without recoil and is subject to resonant absorption by a foil whose resonance may be shifted due to a small relative velocity between source and absorber. The transmission is obtained when the transmitted recoiless photon is measured in coincidence with the first photon of the cascade. The result is in agreement with that obtained by considering the absorber as a classical dielectric slab capable of absorption and dispersion. The initial condition has been investigated in detail by considering the full cascade. In this manner, one sees that the usual simple assumption that the nucleus is in the first excited state immediately after the emission of the first photon, gives the correct boundary condition.

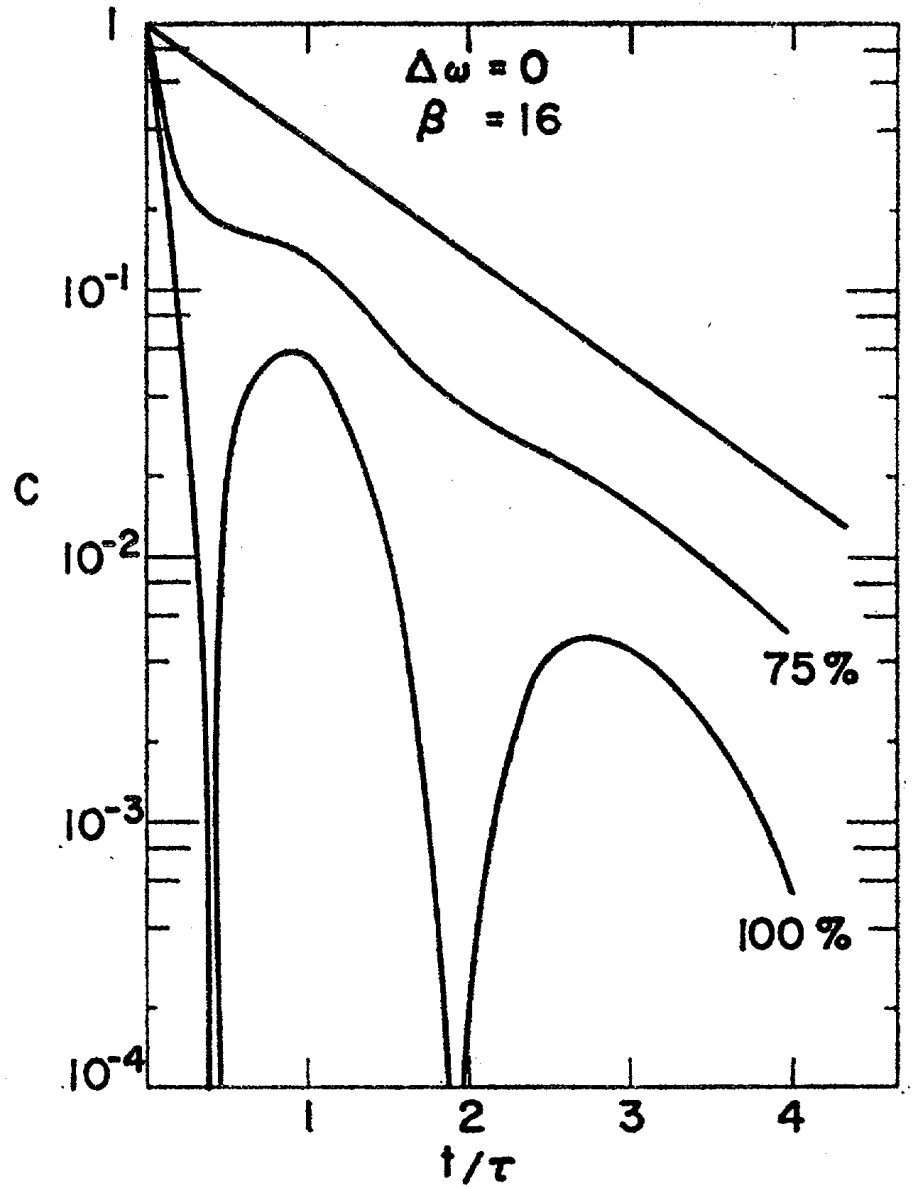


FIG. 2. Time dependence of radiation after transmission through a resonant filter according to Eq. (7), assuming all radiation is recoilless or 75% is recoilless ($\beta=16$, $\Delta\omega=0$). The straight line represents an exponential decay for comparison.

Hyperfine Interactions 123/124 (1999) 483–509

Coherent pulse propagation through resonant media

U. van Bürck

Physik-Department E15, Technische Universität München, D-85748 Garching, Germany

Resonant pulse propagation (RPP) is reviewed with special emphasis on the propagation of synchrotron radiation (SR) pulses through nuclear single-resonance media. The most remarkable feature in the time evolution of RPP is the dynamical beat (DB), a pronounced modulation with periods increasing with time and decreasing with increasing sample thickness. A comparison of RPP at γ-wavelengths (SR and Mössbauer radiation) with RPP in the infrared and visible regimes in case of molecular, atomic and excitonic resonances reveals an astonishing universality of the observed phenomena. The DB is described within the double-hump picture and the group-velocity picture, and is finally attributed to the energy exchange between radiation field and oscillator system in multiple scattering.

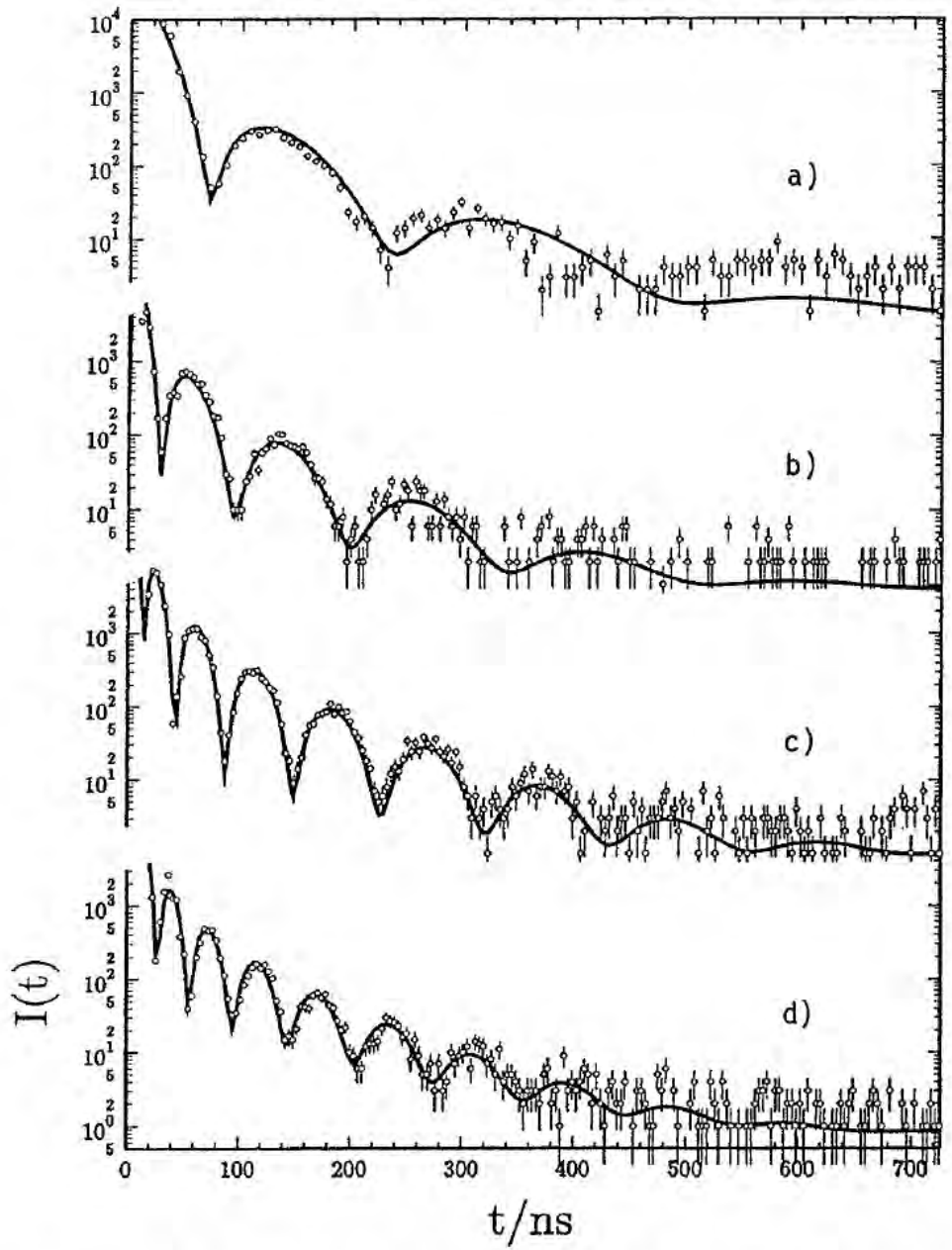


Figure 2. Time evolution of NFSSR through enriched SS metal foils of different effective thicknesses $T \approx 35$ (a), 90 (b), 210 (c), and 330 (d) [41]. The aperiodic modulation is the DB, with apparent periods increasing with time and decreasing with increasing effective thickness. The solid lines are fits using the NFS theory via Motif [83].

Transmitted Pulse

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathcal{T}(\omega) E_0(\omega) e^{-i\omega t} d\omega.$$

Transmission Function

$$\mathcal{T}(\omega) = \mathrm{Exp}\left\{-\frac{\mathrm{iN}\Gamma_{1\mathrm{D}}}{2}\frac{1}{\omega - \omega_0 + \mathrm{i}\Gamma'/2}\right\}.$$

Γ_{1D} and Γ' are the decay rates into and out of the nanofiber, and ω_0 is the atomic resonance frequency. The optical density is $OD = 2N\,\Gamma_{1\mathrm{D}}/\Gamma'$.

For Gaussian pulse

$$\frac{I_d(t)}{I_0} = \left| \frac{1}{2\pi} \int_{-\infty}^{\infty} \mathrm{Exp}\left[\frac{-\mathrm{iN}\Gamma_{1\mathrm{D}}}{2} \frac{1}{\mathrm{z} + \Delta + \mathrm{i}\Gamma'/2} \right] \mathrm{Exp}\left[-\frac{1}{2}\sigma^2 \mathrm{z}^2 \right] \mathrm{Exp}\left[-\mathrm{izt} \right] \mathrm{dz} \right|^2$$

Bessel generating function

$$\mathrm{Exp}\left[\frac{-\mathrm{iN}\Gamma_{1\mathrm{D}}}{2} \frac{1}{\mathrm{z} + \Delta + \mathrm{i}\Gamma'/2} - \mathrm{izt} \right] = \mathrm{Exp}\left[(\mathrm{i}\Delta - \Gamma'/2)\,\mathrm{t} \right]$$
$$\times \sum_{m=-\infty}^{\infty} \left(-i \left(z + \Delta + i\frac{\Gamma'}{2} \right) \sqrt{\frac{2t}{N\Gamma_{1D}}} \right)^m J_m\left(\sqrt{2N\Gamma_{1D}t} \right)$$

For $m > 0$, $$A_m = \sqrt{\pi} i^m \left(\frac{2}{\sigma^2}\right)^{\frac{m+1}{2}} U\left(-\frac{1}{2}m; \frac{1}{2}; -\frac{\sigma^2(\Delta + i\frac{\Gamma'}{2})^2}{2}\right).$$

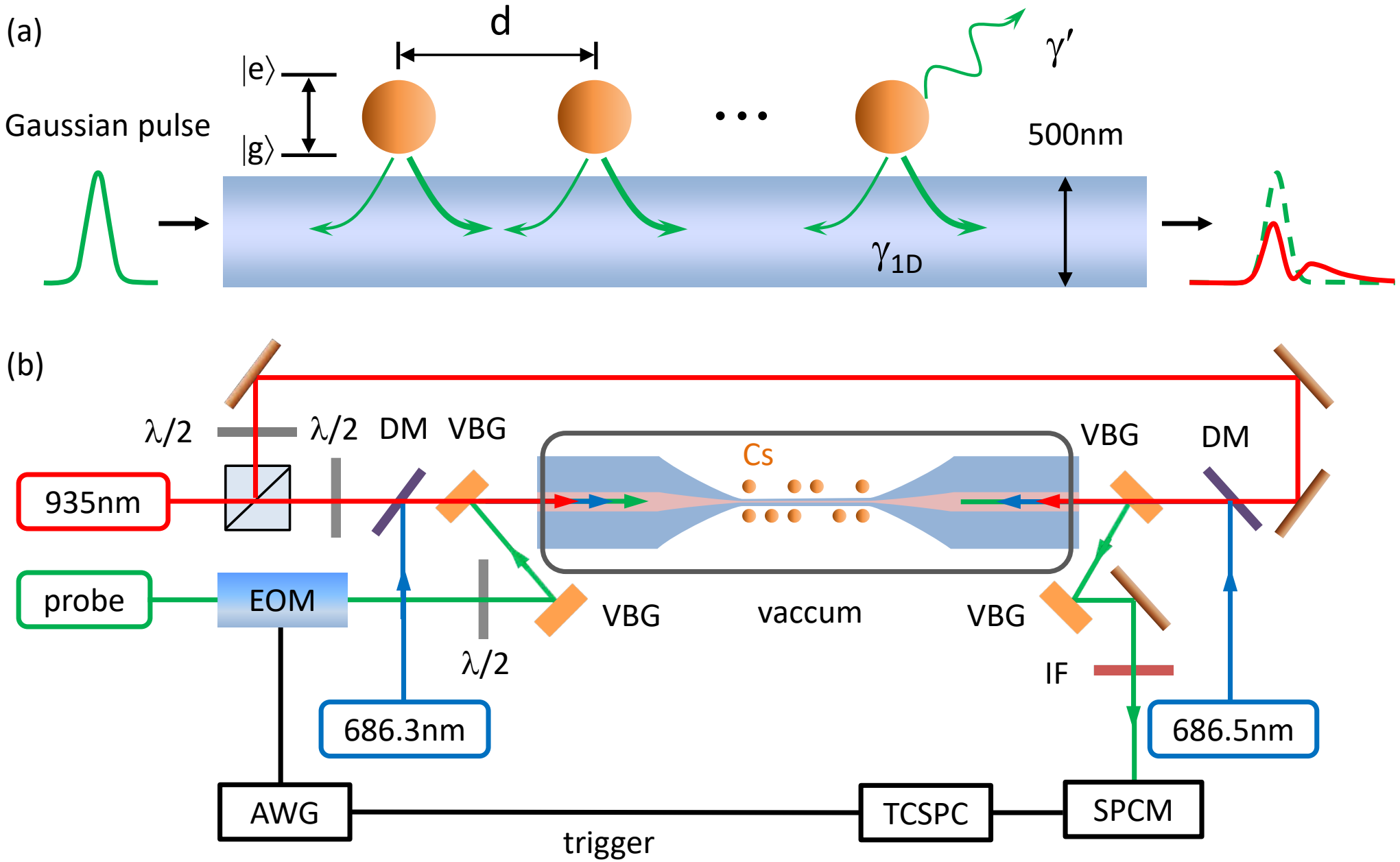
For $m < 0$, $$A_m = \frac{(-1)^{m-1}}{(m-1)!} \partial_\alpha^{m-1} F(\alpha, \sigma)\big|_{\alpha=\Delta+i\frac{\Gamma'}{2}},$$

$$F(\alpha, \sigma) = -i\pi e^{-\frac{1}{2}\sigma^2\alpha^2}\left(\mathrm{erf}(i\frac{\alpha\sigma}{\sqrt{2}}) + 1\right).$$

Multi mode model for Gaussian Pulse input

$$\frac{I_d(t)}{I_0} = e^{-\Gamma' t} \left| \sum_{m=-\infty}^{\infty} A_m \left(-2i\sqrt{\frac{t}{OD\Gamma'}} \right)^m J_m \left(\sqrt{OD\Gamma' t} \right) \right|^2 \qquad (4)$$

Propagation of a short “Gausssian” pulse in the waveguide with atoms

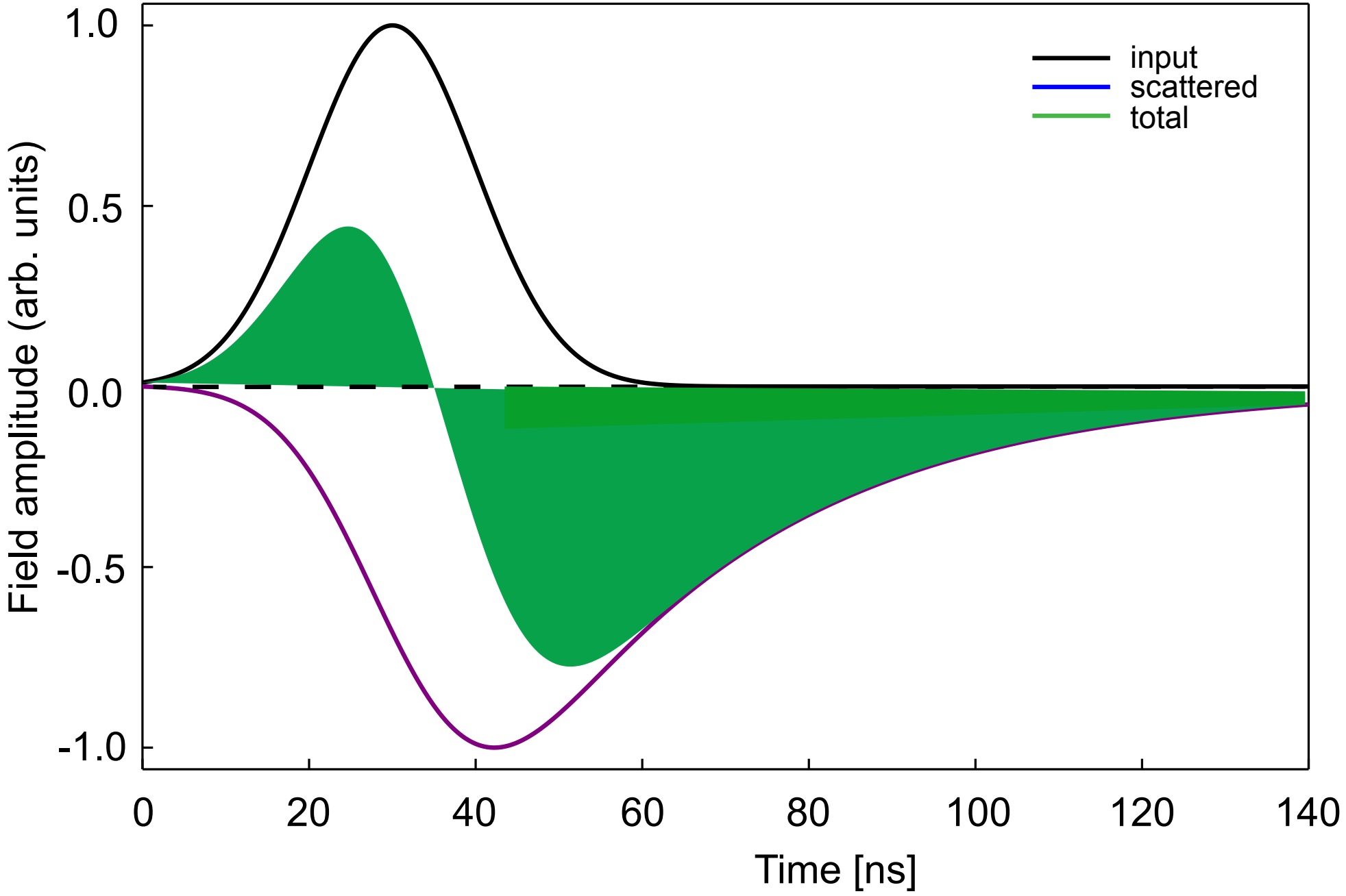

(a)
d
|e⟩
|g⟩
Gaussian pulse
γ′
500nm
γ1D
(b)
λ/2
λ/2
DM
VBG
Cs
VBG
DM
935nm
probe
EOM
VBG
vaccum
VBG
λ/2
IF
686.3nm
686.5nm
AWG
trigger
TCSPC
SPCM

The pulse is less than the half-life of the excited state.
The pulse does not saturate the atoms
The pulse is not distorted by the nanofiber

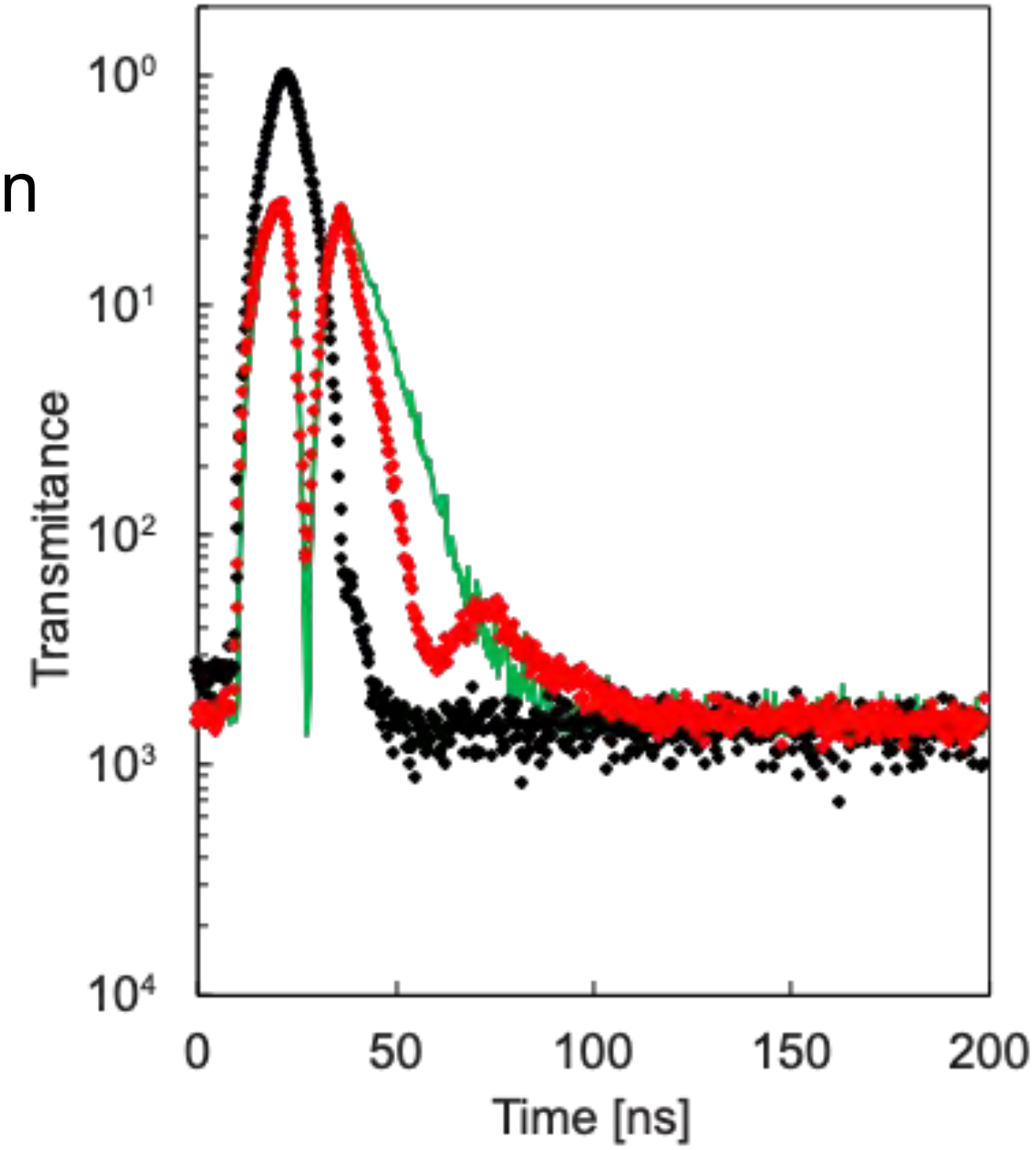
Waveguide quantum electrodynamics model
at low excitation with *N* atoms coupled to the mode by γ_{1D}:

atomic polarization P atoms; pulse excitation field (forcing) *E(t)* :

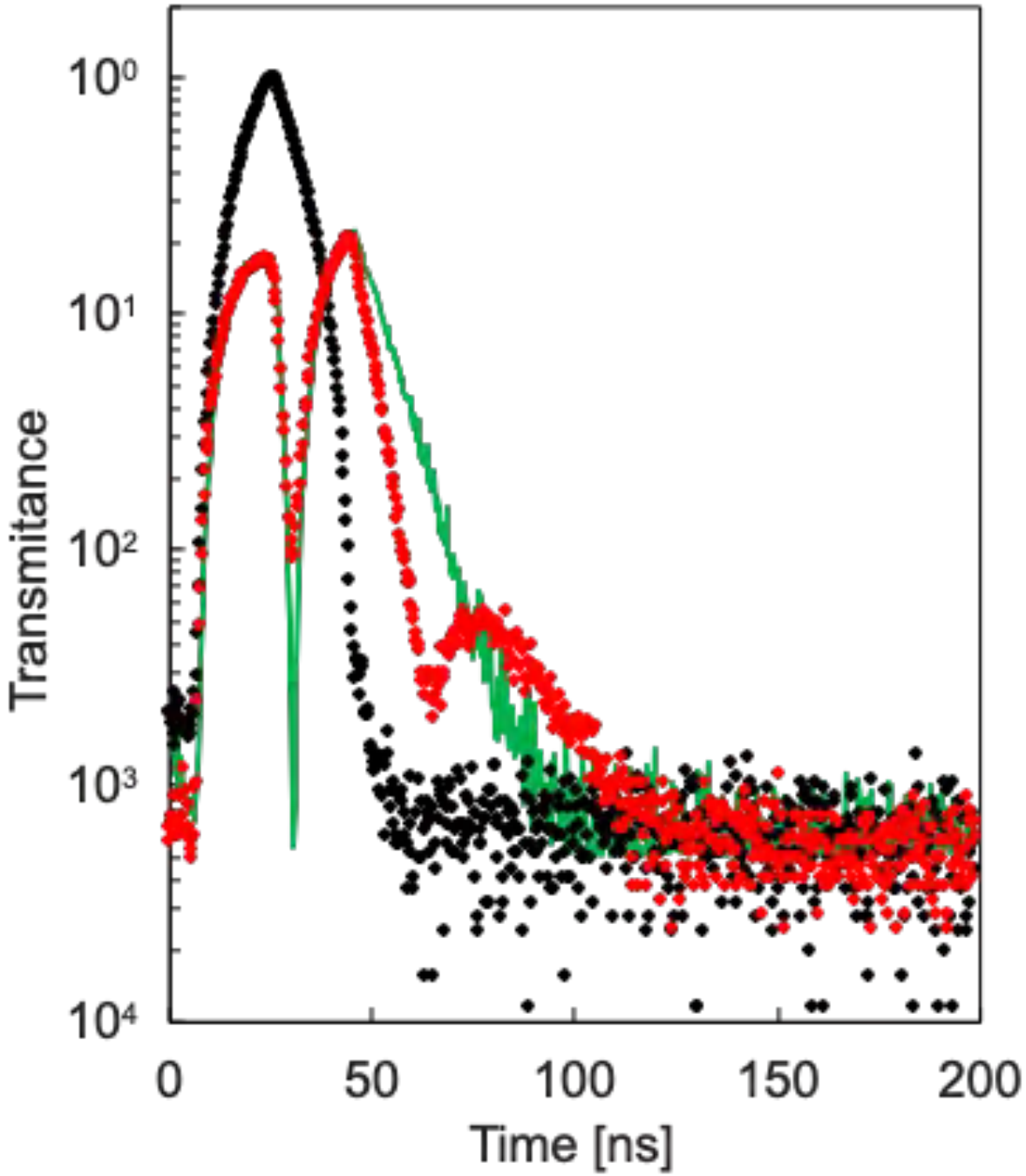
$$\frac{d\tilde{P}}{dt} + \frac{\Gamma}{2}\tilde{P} = \eta\widetilde{E(t)}$$


1.0
0.5
0.0
-0.5
-1.0
Field amplitude (arb. units)
0
20
40
60
80
100
120
140
Time [ns]
input
scattered
total

Single mode model green
~10 ns pulse

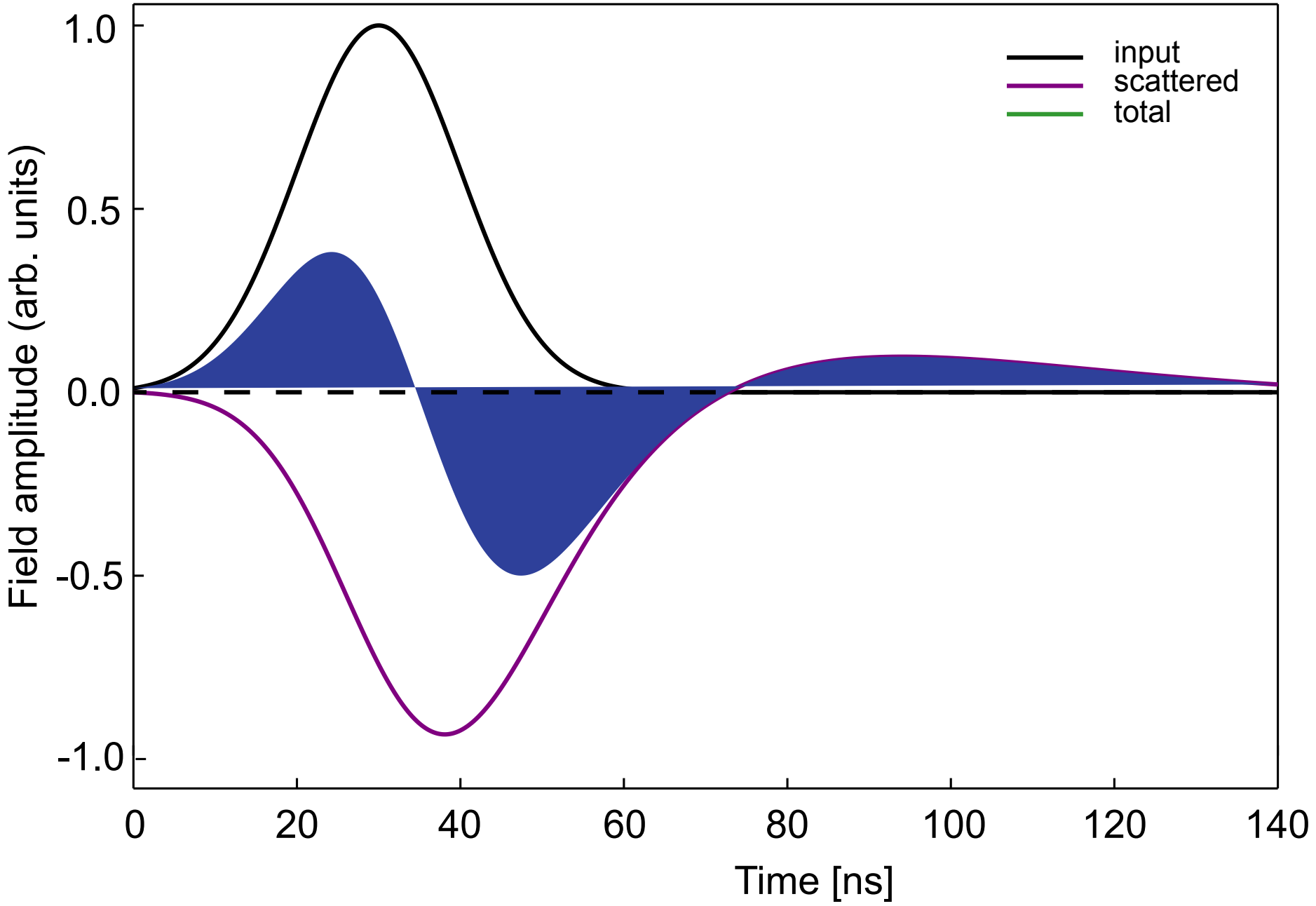


Single mode model green
~15 ns pulse

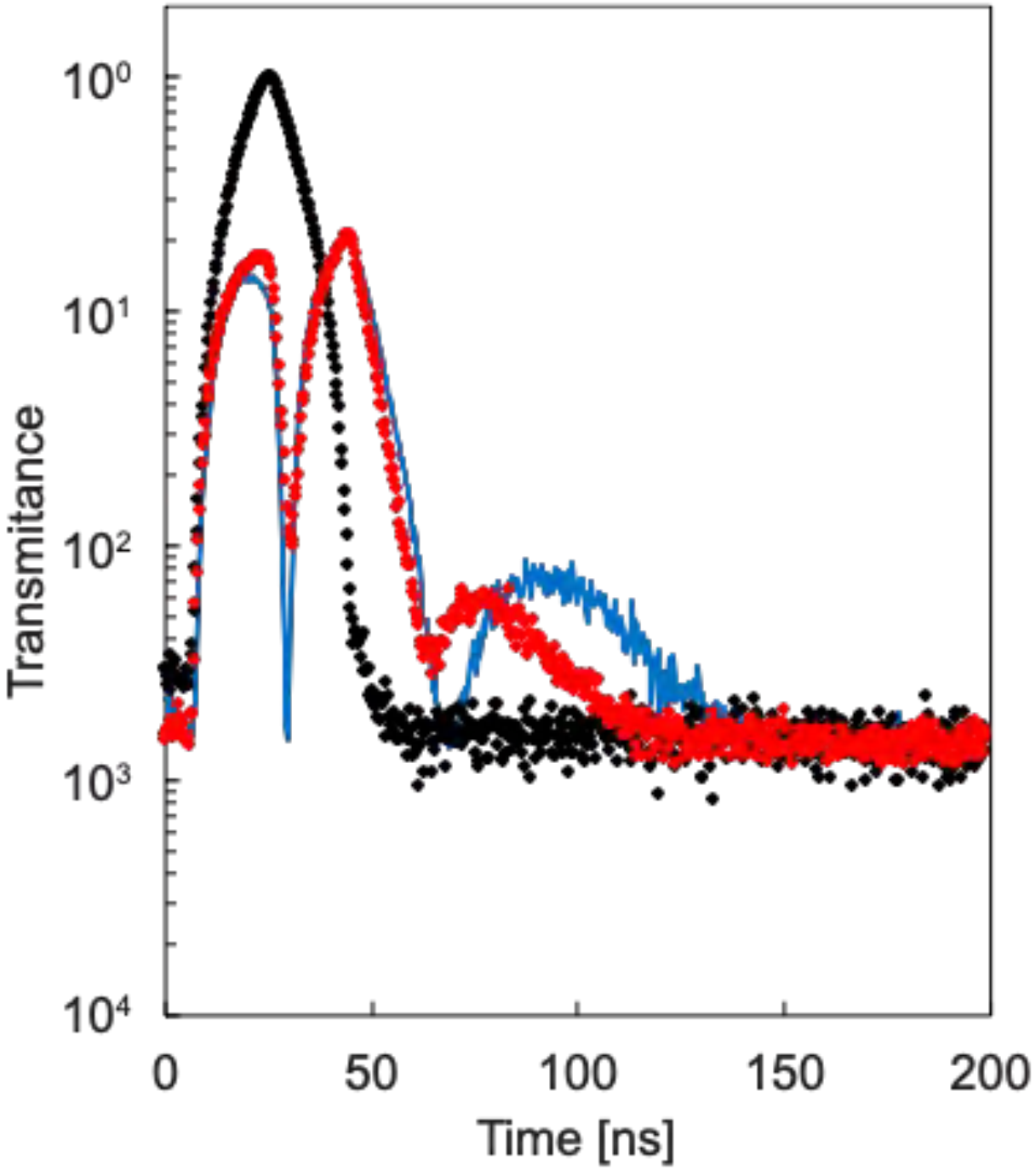


Dynamical beats

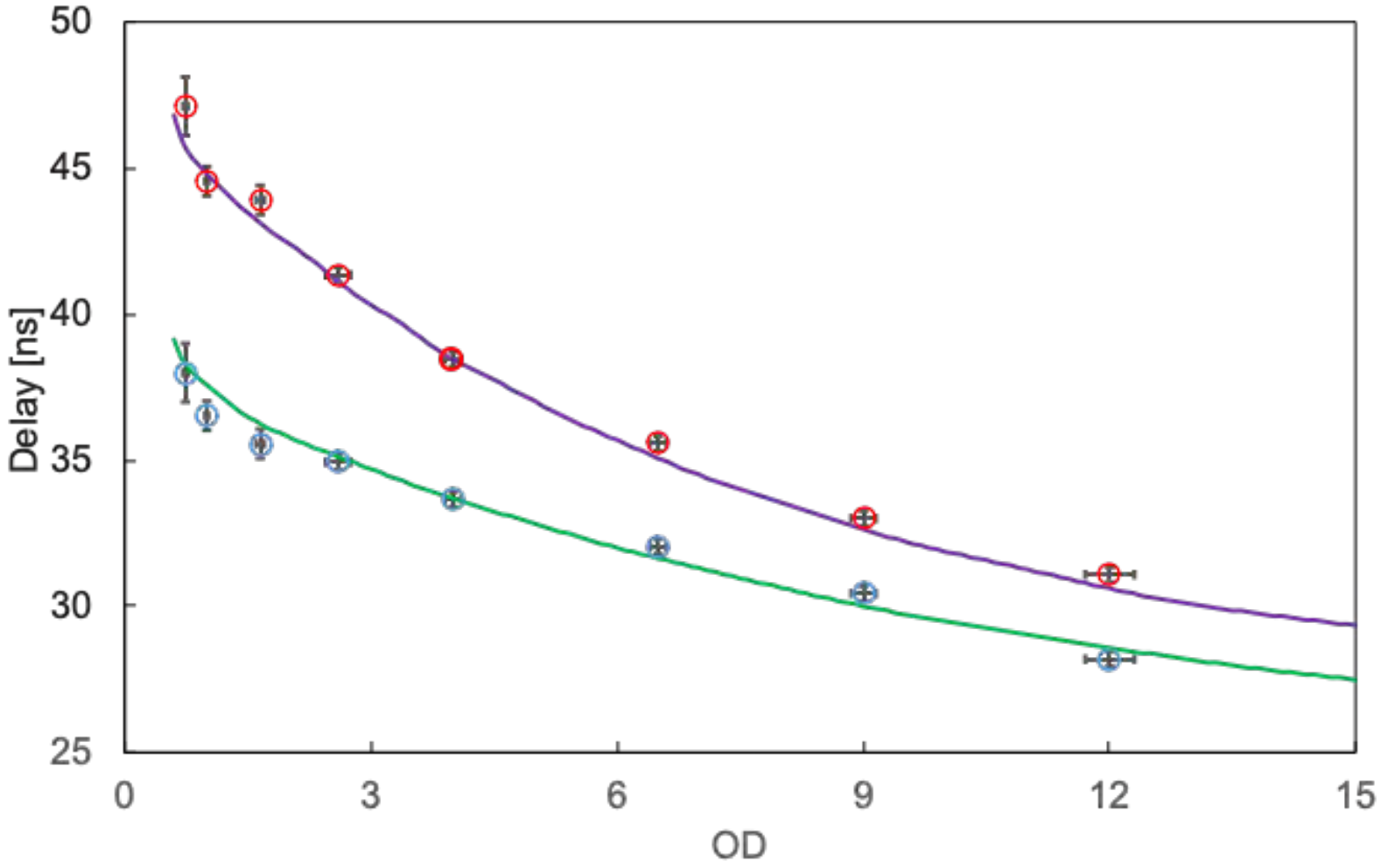
$$I_{out}(\tau) = I_0 e^{-\gamma_{in}\tau} \left| \sum_{n=0}^{\infty} \left[\frac{-2i\Delta\tau}{\sqrt{OD\gamma_0\tau}} \right]^n J_n \left[\sqrt{OD\gamma_0\tau} \right] \right|^2$$


input
scattered
total
Field amplitude (arb. units)
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
Time [ns]

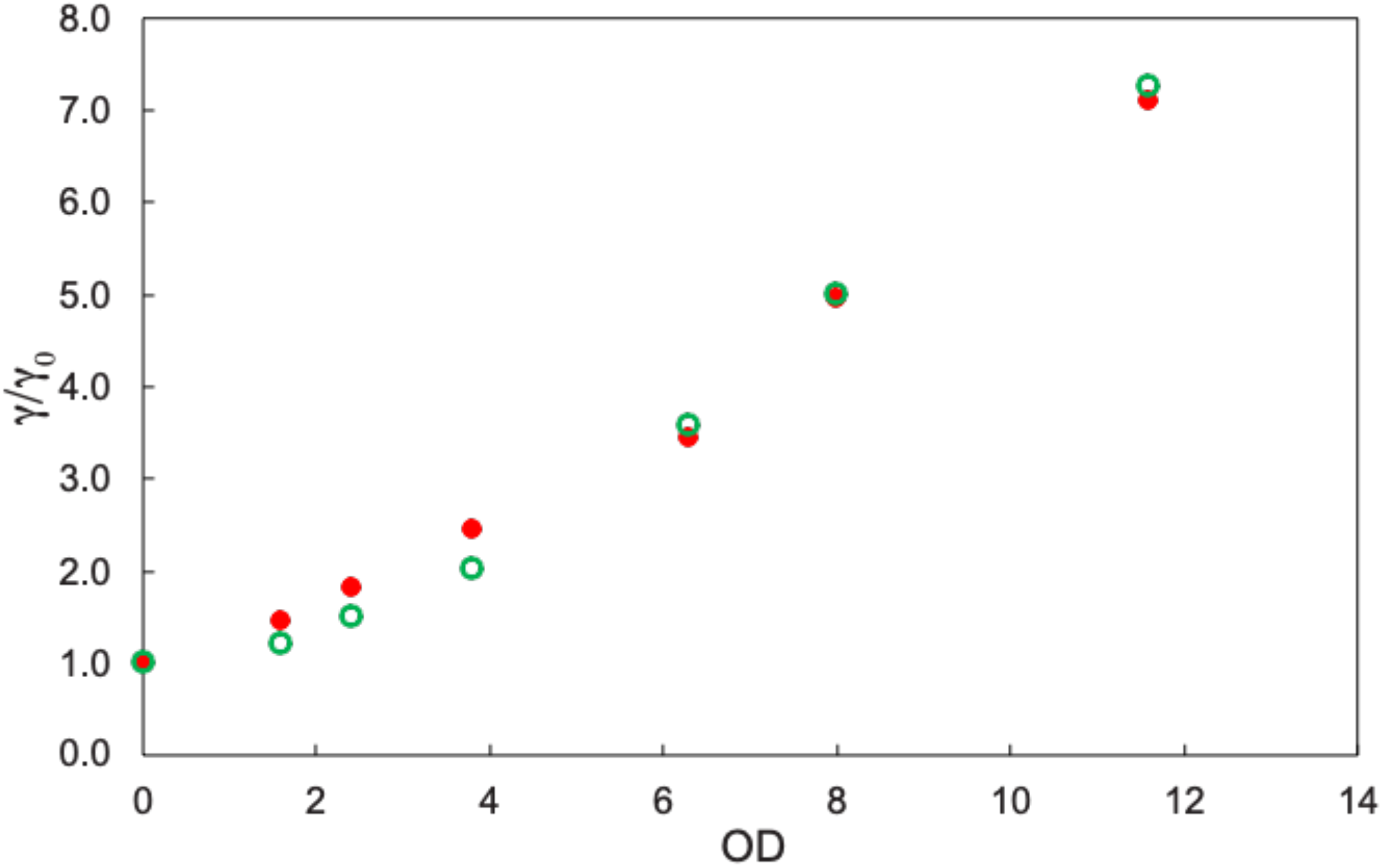
Multi mode model blue
~15 ns pulse



Delay of the first zero in transmission as a function of optical density for different pulse width: blue red 10 ns, red 15 ns.



“Decay” second peak. Red data green multimode model



Simple model of pulse filed and atomic polarization. Explains precursors and first zero.

The interaction of atoms with the field of the waveguide completely modifies the dynamics (Dynamic beats).

This requires a multimode theory.

The change in lifetime due to the atoms, second peak, is agrees with multimode theory.

Thanks