Photon echo from an ensemble of (In,Ga)As quantum dots

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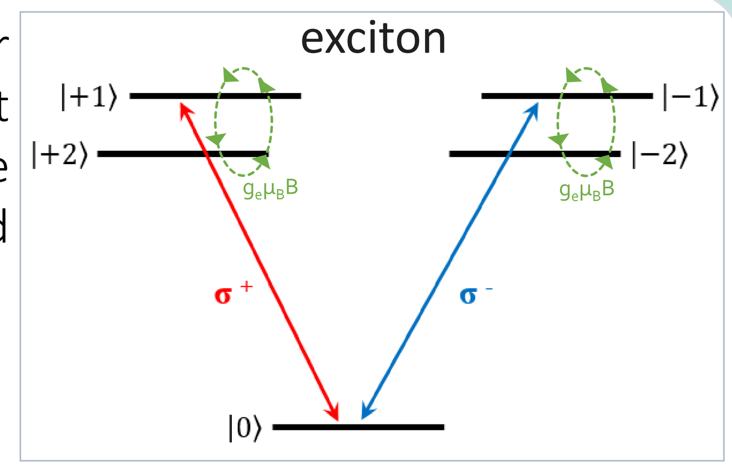
Abstract. Spontaneous photon echo from trions and excitons in (In,Ga)As/GaAs quantum dots have been studied theoretically and experimentally. Theoretical analysis allowed us to separate photon echo signals from excitons and trions measured in the same range of wavelength using specific protocols of laser excitation.

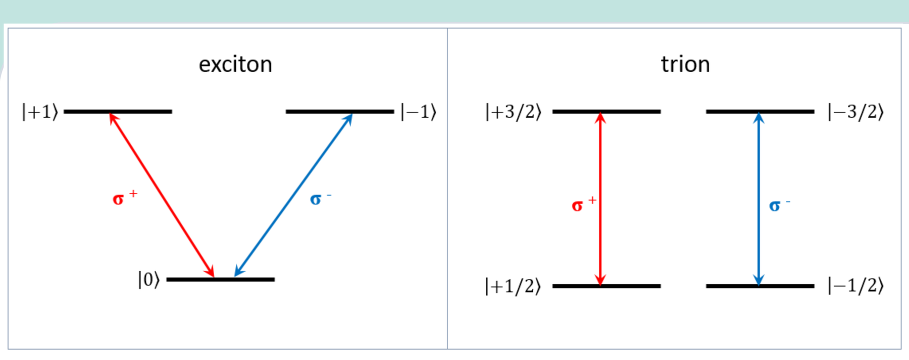
We use a 5×5 time-dependent density matrix for the basis consisting of the basic state, two bright exciton states and two dark exciton states. The temporal evolution of the density matrix is described by the Lindblad equation: $i\hbar\dot{\rho} = [\hat{H}, \rho] + \Gamma$, here $\hat{H} = \hat{H}_0 + \hat{H}_B + \hat{V}$.



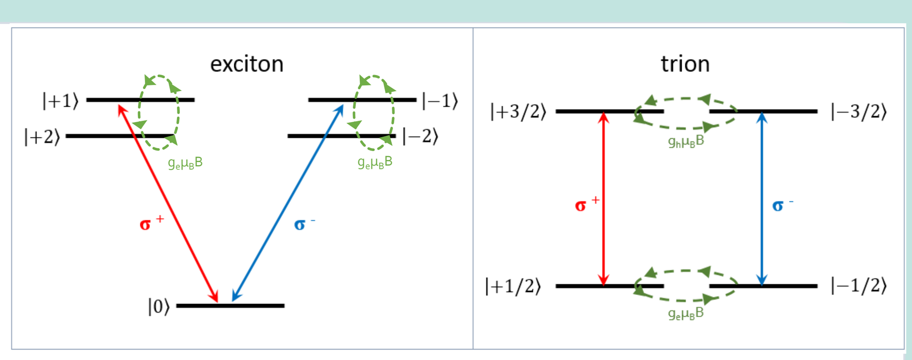
$\widehat{H}_0$ is the Hamiltonian of unperturbed system, $\widehat{H}_B$ is the Hamiltonian describing the interaction with magnetic field, and $\hat{V}$ describes the interaction with light.

$$\hat{V} = \frac{1}{2}\begin{pmatrix} 0 & f_+^* e^{i\omega t}\hbar & f_-^* e^{i\omega t}\hbar & 0 & 0 \\ f_+ e^{-i\omega t}\hbar & 0 & 0 & 0 & 0 \\ f_- e^{-i\omega t}\hbar & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad \widehat{H}_B = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & \delta_0 & \delta_1 & \hbar\omega_L^e & \hbar\omega_L^h \\ 0 & \delta_1 & \delta_0 & \hbar\omega_L^h & \hbar\omega_L^e \\ 0 & \hbar\omega_L^e & \hbar\omega_L^h & -\delta_0 & \delta_2 \\ 0 & \hbar\omega_L^h & \hbar\omega_L^e & \delta_2 & -\delta_0 \end{pmatrix},$$

here $f_\pm$ is proportional to the envelope of the light pulse, ω_L^e и ω_L^h are electron and hole Larmor precession frequencies respectively, and δ_0, δ_1, and δ_2 are an isotropic and anisotropic exchange constants respectively.
To obtain analytical solution, we assume that $\delta_1 = \delta_2 = 0$.

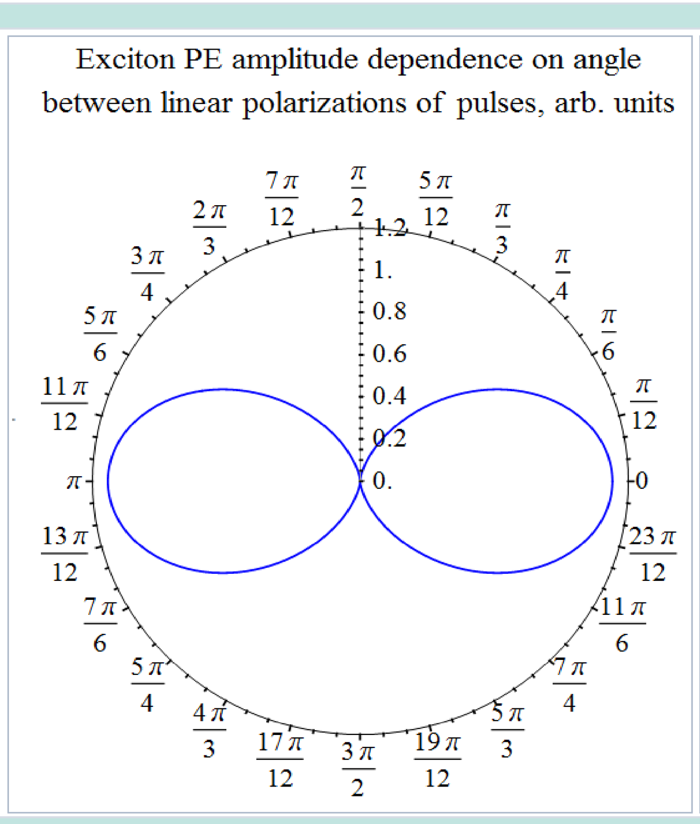


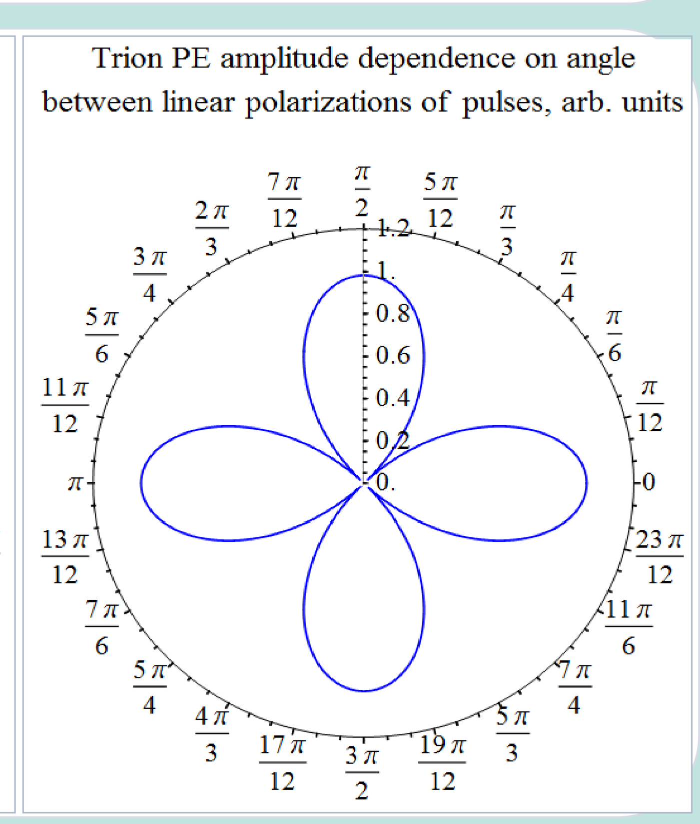
Fine structure of exciton and trion and the selection rules without magnetic field

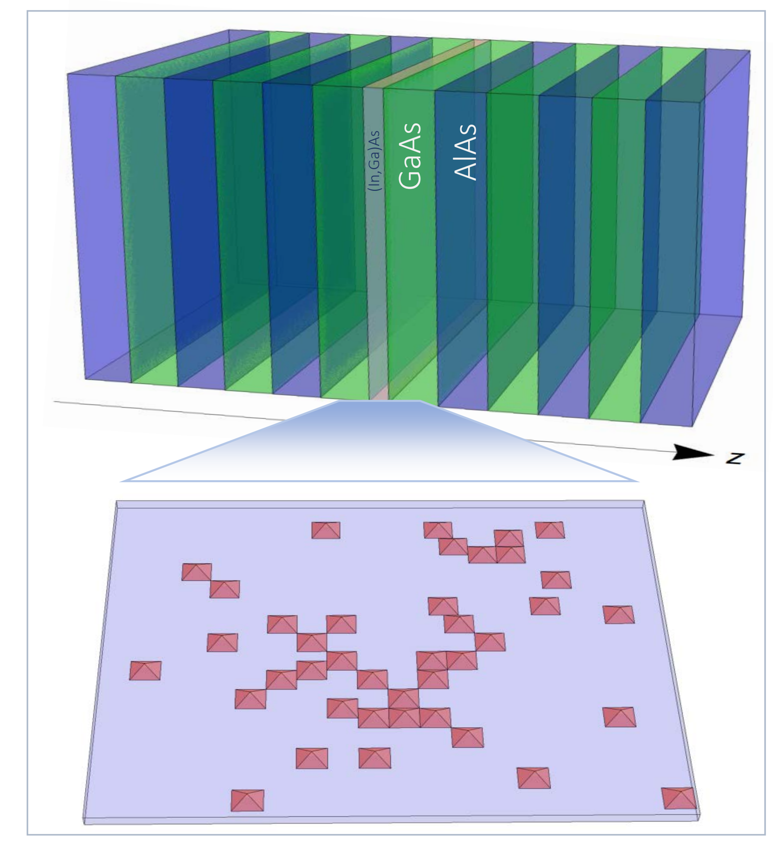


Fine structure of exciton and trion and the selection rules in transverse magnetic field

The angular dependencies of PE amplitude for excitons and trions on the angle between linear polarizations of exciting laser pulses are presented here

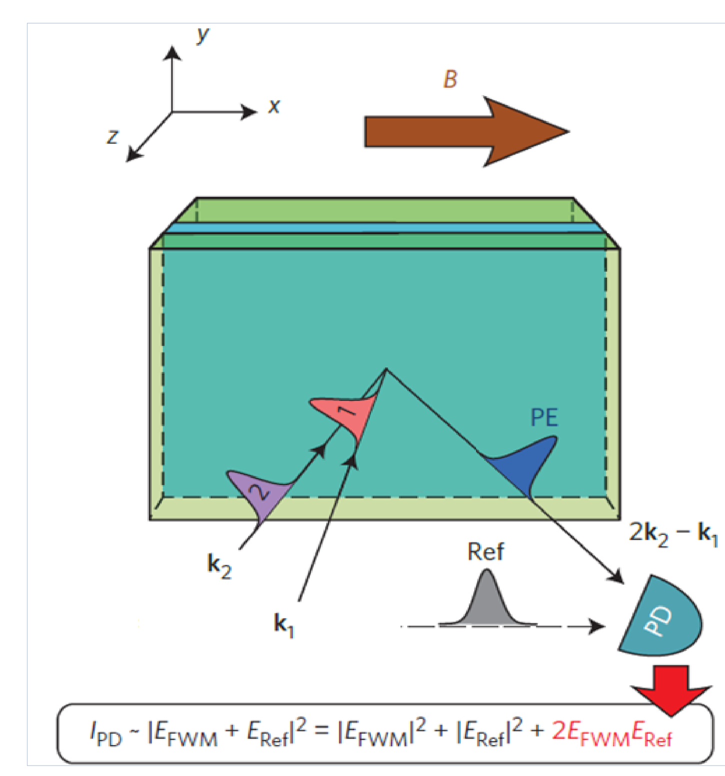




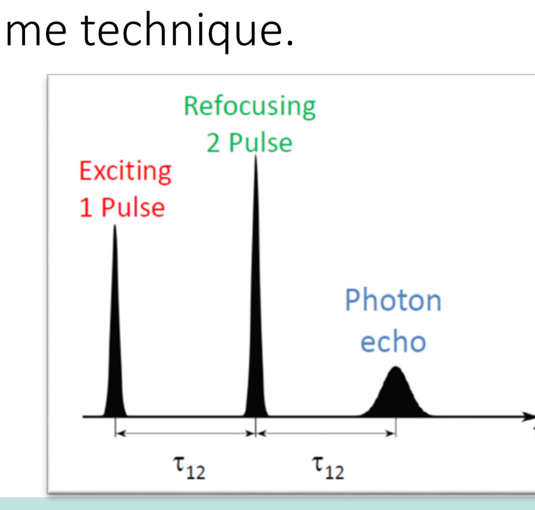


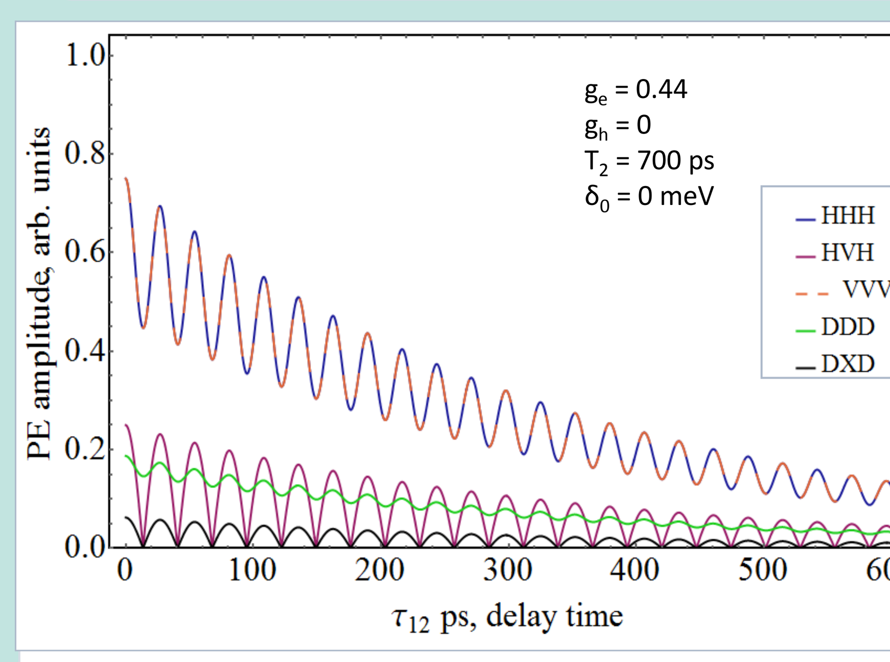
The sample is a single layer of (In,Ga)As QDs inserted into a GaAs/AlAs microcavity. The QD density is about 1.8×10^9 см$^{-2}$ and one of the GaAs barriers contains a Si-layer with donor density is about 8×10^9 см$^{-2}$.

The experiment have been performed in reflection geometry using the heterodyne detection. The sample was cooled down to about 2K into a helium bath cryostat. A mode-locked Ti:sapphire laser was a source of the pulses with duration of about 2.5 ps and repetition rate of about 76 MHz.



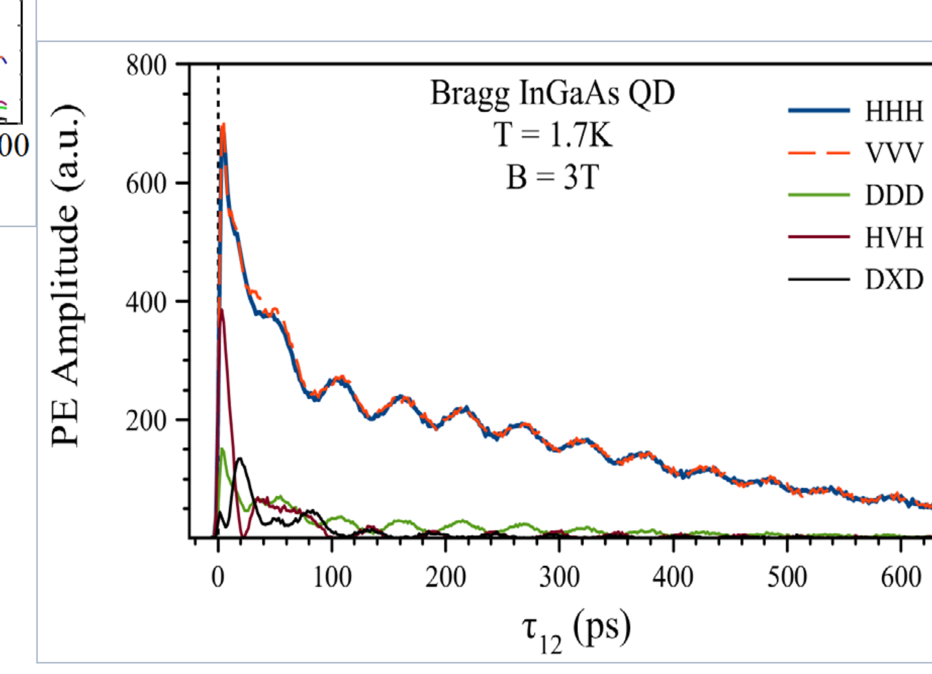
Several polarization protocols have been used: H and V for the case if the linear polarization of excitation pulses is parallel to QD axes x or y respectively (z-axis is the structure grows axis), D and X for the case if the linear polarization parallel to the axes x and y tilted on 45°. The PE signal was detected in the same technique.

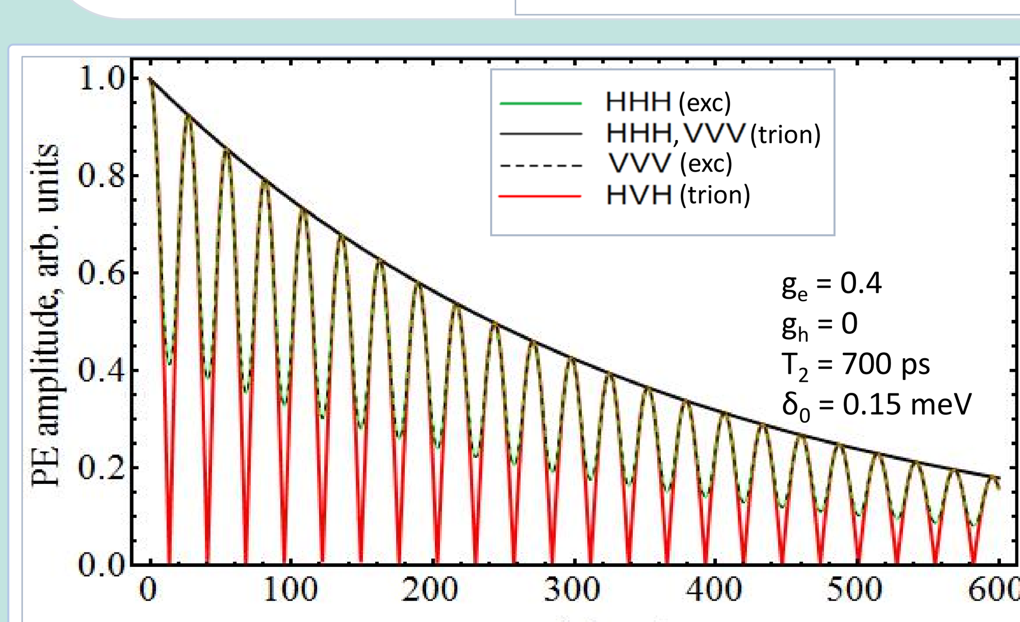




Theoretically modeled (top left picture) and experimentally obtained (bottom right) PE signals for excitons and trions in direct and tilted polarization protocols.

Here we assume that the fraction of excitons are two times larger than trions, and the isotropic exchange interaction constant for excitons δ_0 and hole g-factor are assumed to be zero.



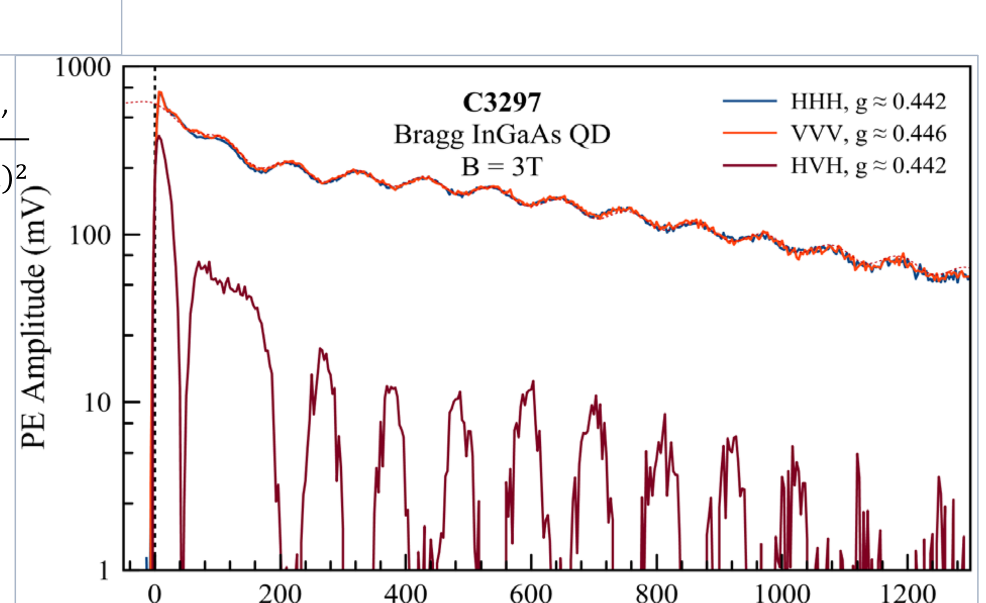


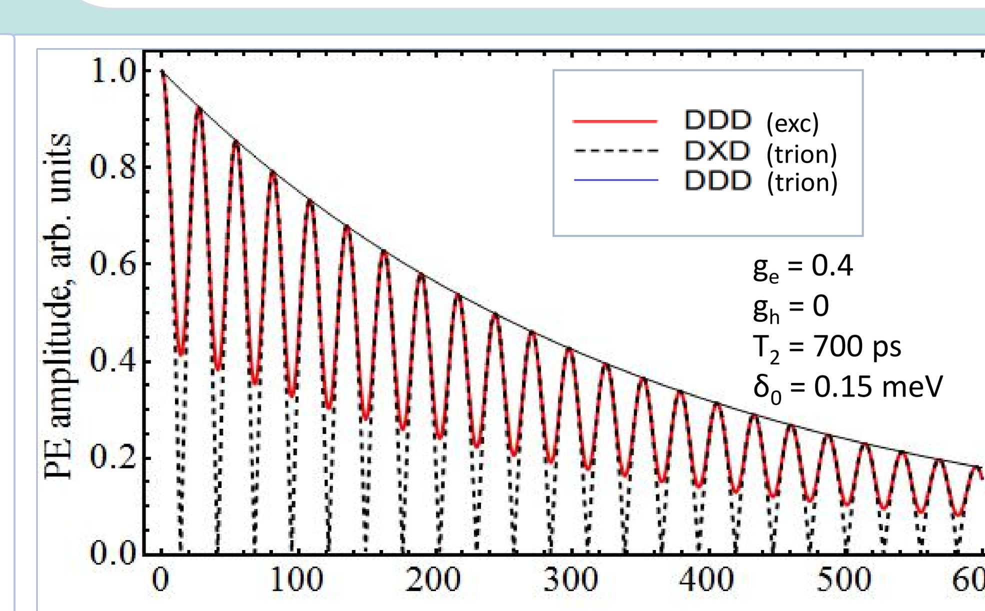
Analytically calculated PE signal from excitons and trions in H and V polarizations.

$$P_{HHH}^{exc} \sim \left[\cos^2(\Omega\tau_{12}) + \frac{\delta_0^2 \sin^2(\Omega\tau_{12})}{4\Omega^2}\right] e^{-\frac{2\tau_{12}}{T_2}}$$
$$P_{HVH}^{exc} = 0$$
$$P_{HHH}^{tr} = P_{VVV}^{tr} \sim e^{-\frac{2\tau_{12}}{T_2}}$$
$$P_{HVH}^{tr} \sim e^{-\frac{2\tau_{12}}{T_2}} \cos(\omega_L^e \tau_{12})$$

Here we assume that $g_h = 0$, so $\omega_L^h = 0$, and $\Omega_p = \Omega_m = \Omega$,
$\Omega_p \equiv \sqrt{(\omega_L^e + \omega_L^h)^2 + (\delta_0/\hbar)^2}$, $\Omega_m \equiv \sqrt{(\omega_L^e - \omega_L^h)^2 + (\delta_0/\hbar)^2}$

Experimental dependencies of PE signal in direct polarization protocols.

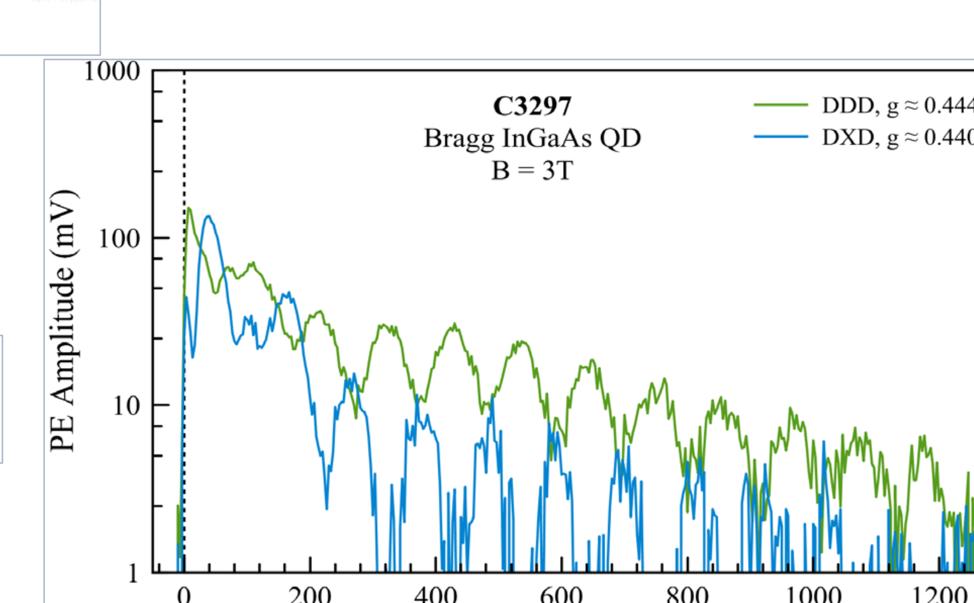




Analytically calculated PE signal from excitons and trions in D and X polarizations.

$$P_{DDD}^{exc} \sim \left[\cos^2(\Omega\tau_{12}) + \frac{\delta_0^2 \sin^2(\Omega\tau_{12})}{4\Omega^2}\right] e^{-\frac{2\tau_{12}}{T_2}}$$
$$P_{DDD}^{tr} \sim e^{-\frac{2\tau_{12}}{T_2}}$$
$$P_{DXD}^{tr} \sim e^{-\frac{2\tau_{12}}{T_2}} \cos(\omega_L^e \tau_{12})$$
$$P_{DXD}^{exc} = 0$$

Experimental dependencies of PE signal in tilted polarization protocols.



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