Colloidal semiconductor nanocrystal quantum dots (NQDs) have remarkable optical properties, such as widely tunable emission wavelengths and high quantum efficiencies at room temperature. Due to these properties and the relatively easy fabrication method, NQDs are very promising for a broad range of applications. Surprisingly, the origin of the NQD optical transitions at low temperatures is still not clear in particular because the lowest-energy transition is associated with a dark-exciton state, i.e., an optically forbidden transition. The purpose of this work is to investigate the recombination mechanisms of dark excitons by reporting a detailed photoluminescence (PL) study of core/shell CdSe/CdS NQDs as a function of temperature, magnetic field, and shell thickness.

Three-dimensional confinement of electrons and holes in semiconductor NQDs leads to a discrete atomlike level structure. It is well established that in wurtzite NQDs the electron-hole exchange interaction and the intrinsic crystal/shape anisotropy lift the spin degeneracy of the exciton levels, leading to five distinct states, characterized by their spin projection $F$ along the NQD c axis. Evidence for this exciton fine structure has been given by the size-dependent Stokes shift from fluorescence line narrowing and the dependence of the radiative lifetime on temperature and magnetic fields. To understand the low-temperature optical properties, only the two lowest twofold-degenerate levels are important, which are lower-(higher)-energy exciton levels with $F = \pm 2$ ($F = \pm 1$) that are dipole forbidden (allowed). The separation between the two levels is given by the exchange splitting ($\Delta_{\text{ex}}$) which depends on NQD size. For typical values of $\Delta_{\text{ex}}$ of 5–20 meV, only the lowest $|F| = 2$ level is populated at low temperatures (<10 K). The radiative lifetime of this level has been found to be remarkably short for a dark state (~1 μs). This apparent brightness has been attributed to phonon-assisted transitions, supported by a redshift of the PL energy with decreasing temperature when the lower-energy phonon replicas gain importance relative to the zero-phonon line. Alternatively, the bright zero-phonon emission has been suggested to be due to mixing of the dark- and bright-exciton states, for instance as a result of unpassivated surface sites. Furthermore, it has been shown that a magnetic field mixes the dark- and bright-exciton levels and thereby decreases the radiative lifetime of the zero-phonon line, making its contribution to the total PL emission larger with respect to the phonon-assisted transitions. A magnetic field is thus a powerful tool in studying the interplay between the different phonon-assisted and zero-phonon lines.

To investigate the nature of the dark-exciton emission of wurtzite NQDs, we performed a detailed PL study, which includes temperature-dependent, resonant, and nonresonant PL spectroscopies in high magnetic fields ($B$) up to 33 T. Experiments with resonant laser excitation allowed us to determine the relative importance of zero-phonon and phonon-assisted transitions and connect changes therein to energy shifts observed in nonresonant experiments. We show that variation in temperature, magnetic field, and NQD shell thickness can shift the subtle balance between these recombination processes in either direction.

The samples were prepared by drop casting a solution of core/shell CdSe/CdS NQDs (Ref. 22) in toluene on fused silica. The CdSe core has a radius of 17.8 Å, and is either uncoated (QD0) or it is coated by a single (QD1) or triple (QD2) monolayer (ML) shell of CdS. The NQDs were capped with tri-n-octylphosphine (TOP), tri-n-octylphosphine oxide (TOPO), and hexadecylamine (HDA). The samples were mounted in Faraday geometry inside a liquid-helium bath cryostat in a 33 T Bitter-type electromagnet and cooled to 1.2–4.2 K. We measured PL of the NQDs using both nonresonant and resonant laser excitations. The nonresonant PL was excited by 2.7 eV laser light, dispersed by a single grating spectrometer, and detected by a liquid nitrogen cooled charge-coupled device (CCD) camera in 30 s exposures. For the QD1 experiments both circular polarizations were obtained simultaneously by inserting a polarizing beam splitter in the detection path. The two circular polarizations of the QD0 and QD2 PL were recorded in two consecutive sweeps with opposite current directions through the magnet.

The NQDs show asymmetric PL spectra with a full width at hal...
at half maximum of 85 meV. The spectrum was fitted by a single Gaussian to obtain the peak energy. Figure 1 shows the peak energy (a,c,e,g), integrated intensity (b,d,f,h), and the degree of circular polarization (DCP) \[ \left| \langle I_{\sigma^-} - I_{\sigma^+} \rangle / \langle I_{\sigma^-} + I_{\sigma^+} \rangle \right| \] as function of B at 1.2 and 4.2 K for QD1 and QD2. We recognize the following trends: at \( B=0 \) T the PL energy is lower at 1.2 K than at 4.2 K, namely, \( \sim 4 \) meV for QD1 [Figs. 1(a) and 1(c)], and \( \sim 2 \) meV for QD0 (not shown) and QD2 [Figs. 1(e) and 1(g)]. This redshift at 1.2 K is undone by a magnetic field of \( \sim 10 \) T [Figs. 1(a) and 1(e)]. With increasing B the PL becomes circularly polarized, where the \( \sigma^- \) emission shifts to higher energy with increasing intensity and the \( \sigma^+ \) emission shifts to lower energy with decreasing intensity. The corresponding DCP equals 0.5–0.6 at \( B=33 \) T, and only slightly depends on temperature [Figs. 1(i) and 1(j)].\(^{19,25}\) Remarkably, we measured the highest intensity at the highest energy for both temperatures, similar to an earlier report.\(^{19}\) Finally, for all samples the total normalized PL intensity only marginally increases with B from 2 (\( B=0 \) T) to 2.4 at \( B=33 \) T.

To determine the contributions of different recombination mechanisms, PL was measured under resonant excitation (FLN).\(^{14}\) The sample was mounted on a fiber coupled probe,\(^{24}\) and resonantly excited by a tunable dye laser using circularly polarized light. Excitation and detection occurred under crossed polarization to minimize scattered laser light. Spectra were recorded in 60 s exposures.

Typical FLN spectra are shown in Fig. 2(a) and can be roughly understood in terms of the exciton level scheme in Fig. 2(c). Excitons are excited by the laser into the bright \( F=\pm 1 \) levels, resulting in emission from the dark \( F=\pm 2 \) excitons, i.e., the zero-phonon line (ZPL) 6 meV below the laser energy, and several phonon replicas (1PL, 2PL), superimposed on a small nonresonant PL background. The energy positions and intensities of all resolved peaks were obtained by fitting a Lorentzian laser line and Gaussian peaks for the ZPL, 1PL, and 2PL, and the nonresonant background. Figure 2(b) shows the ZPL and 1PL intensities as a function of temperature, relative to the ZPL intensity at 4.2 K (QD2). The ZPL intensity steadily decreases with decreasing temperature, whereas the 1PL intensity slightly increases,\(^{20} \)}
The trend that is also directly visible in the FLN spectra [Fig. 2(a)].

Figure 3(a) shows the evolution of the FLN spectrum with increasing $B$ at 1.2 K, using $\sigma^+$ polarized excitation and detecting $\sigma^-$ polarized PL. The ZPL shifts to lower energy due to the Zeeman splitting and becomes more intense with field. At high fields (>15 T) an additional peak appears between the laser and the ZPL. This peak has been reported previously and is due to resonant $\sigma^+$ polarized excitation into the $+1^L$ state and subsequent $\sigma^-$ polarized emission of $-1^L$ excitons after a spin-flip process. The measured splitting increases linearly with $B$ and is directly related to the Zeeman splitting of the $F=\pm 1^L$ levels. The observation of this line is further evidence for the exciton fine-structure model.

Figure 3(b) plots the fitted ZPL and 1PL intensities as a function of $B$. The ZPL intensity increases considerably, in particular at 1.2 K where a threefold enhancement is observed. In contrast, the intensity of the phonon replica is almost constant (open diamonds).

To describe the data we consider the different recombination channels of neutral excitons that are schematically shown in Fig. 2(c), taking into account bright $F=\pm 1^L$ and dark $F=\pm 2$ levels. Note that for sake of clarity the Zeeman splittings of the exciton lines have been omitted in this figure. Given the measured exchange splitting $\Delta_{\text{eff}}=6$ meV, the $F=\pm 1^L$ levels are not populated at the low temperatures used here. Therefore, we only need to include recombination from the $F=\pm 2$ levels, where we distinguish three recombination processes: surface-state assisted transitions, phonon-assisted transitions, and direct zero-phonon transitions.

The optical phonon-assisted 1PL lies typically $\hbar \omega_{LO} = 25–26$ meV below the $F=\pm 2$ level [Fig. 2(a)], and is characterized by a recombination lifetime $\tau_{\text{phonon}}$. Direct recombination of the dark excitons can only occur through mixing with the bright excitons, either due to a magnetic field $\Delta_{\text{eff}}$ (Refs. 14, 15, 19, and 25) or due to unpassivated surface states $\tau_{\text{surface}}$. Clearly, this schematic model ignores recombination of charged excitons or biexcitons, as well as the chemical details of the actual states at the NQD surface, which might lead to modifications of the exciton fine structure and the optical recombination.

The actual dark-exciton recombination is governed by the competition between the different transitions, depending on temperature, magnetic field, and surface passivation. Let us first consider the temperature dependence of the NQD emission. In the FLN experiment we observed a reduced ZPL emission with decreasing temperature, whereas the intensity of the phonon replicas only marginally increases [Fig. 2(b)]. This redistribution among the ZPL and 1PL lines is responsible for the temperature dependence of the nonresonant PL.

The nonresonant spectrum is the averaged PL emission of an ensemble of NQDs with slightly different sizes. For typical size variations of about 5%, the ensemble PL linewidth is larger than the LO phonon energy, which implies that the nonresonant PL spectrum is an average of nonphonon and phonon-assisted lines. We simulate this average PL by combining the extracted energies and intensities of the ZPL and 1PL emissions in the FLN spectra [Fig. 2(b)] to calculate the
The competition between zero-phonon and phonon-assisted emission, leading to an increased quantum yield with an optimal mixing of the ZPL and 1PL emissions, is sample dependent. A magnetic field has several effects on the exciton recombination scheme of Fig. 2, which is repeatedly used to support this model. However, with the parameters used to fit the DCP, the model fails to describe three other characteristic features: (i) the peculiar polarization of the PL emission, (ii) the actual value of the observed energy splitting, and (iii) the non-zero intensity of the low-temperature PL. Therefore, we find that the exciton fine-structure model cannot fully describe the high magnetic-field experiments, which confirm that a complete description of the dark-exciton PL should include multiple recombination channels.

A complete theory for dark-exciton recombination that is capable of explaining all experimental observations is still lacking. Therefore, we propose the schematic dark-exciton recombination scheme of Fig. 2, which combines ingredients from several different theoretical descriptions. The starting point is an exciton fine structure, in which bright-
dark-exciton levels are split due to exchange interactions. This fine structure has been calculated by either an effective-mass approximation model\textsuperscript{15} or atomistic pseudopotential calculations.\textsuperscript{11} To explain the finite lifetime of the dark-exciton PL polarization. This confirms the crucial role of phonon-assisted transitions explains the redshift of the dark-exciton levels are split due to exchange interactions. This lifetime, however, is still very long needed, for instance due to unpassivated surface states.\textsuperscript{11} This competition between these direct and phonon-assisted transitions should also be taken into account.\textsuperscript{13,17,20} The competition between zero-phonon and phonon-assisted processes depends strongly on internal factors, such as shell thickness and surface passivation, and on external factors, such as temperature and a magnetic field. Our results prove that any model that attempts to fully describe the optical properties of CdSe QD heterojunctions should include, besides the exciton fine structure, also phonon-assisted and surface-state assisted recombinations.

In conclusion, we have found that the low-temperature dark-exciton emission of CdSe/CdS QDs is determined by the competition between phonon-assisted and zero-phonon recombination. This work was partly sponsored by DeNUF and EU FP6 Contract No. 011760, and is part of the research program of the “Stichting voor Fundamenteel Onderzoek der Materie (FOM),” financially supported by the “Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).”