Effect of correlation and dielectric confinement on $1S1/2(e)nS3/2(h)$ Excitons in CdTe/CdSe and CdSe/CdTe Type-II quantum dots

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Effect of Correlation and Dielectric Confinement on 1S_{1/2}^{(h)} nS_{3/2}^{(e)} Excitons in CdTe/CdSe and CdSe/CdTe Type-II Quantum Dots

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ABSTRACT: We calculate correlated exciton states in type-II core/shell quantum dots (QDs) using a configuration interaction method combined with the k-p theory. We map the 1S_{1/2}^{(h)} nS_{3/2}^{(e)} and 1S_{1/2}^{(h)} 2S_{1/2}^{(e)} exciton correlation energy relative to the strong confinement approximation as a function of core radius, shell thickness, and dielectric confinement. The type-II confinement potentials enhance the effect of dielectric confinement which can significantly affect the wave functions and exciton energies in such heterostructures. Dielectric confinement mainly increases the correlation energy for QDs in which the corresponding single-particle hole states are delocalized. We also find that correlation leads to large changes in the optical dipole matrix element, particularly for the lowest CdSe/CdTe QD exciton, in the presence of dielectric confinement. We conclude that dielectric confinement affected the exciton properties in CdSe/CdTe QDs more than in CdTe/CdSe QDs due to the band alignment which encourages holes to localize in the shell.

1. INTRODUCTION

Semiconductor nanocrystals or quantum dots (QDs) are the subject of intensive research, due to a number of novel properties which make them attractive for both fundamental studies and technological applications.1–6 QDs are of particular interest for solar cell applications due to their ability to increase efficiency via the generation of multie excitons from a single photon.7–9 QDs can be synthesized with a high degree of control using colloidal chemistry.10–11 Much research effort has been directed toward studying QDs grown from more than one semiconductor, e.g., core/shell heterostructures.12–14 Such core/shell nanostructures provide a means to control the optical properties by tuning the electron–hole wave function overlap which is affected by the alignment of the conduction band (CB) and valence band (VB) edges, as well as the QD shape and size. In contrast to type-I band alignments, type-II alignments have staggered CB and VB edges so the lowest energy states for electrons and holes lie in different spatial regions, leading to charge separation between the carriers. Type-II core/shell QDs can be classified according to whether the band alignments tend to localize the hole in the core and electron in the shell (h/e QDs, such as CdTe/CdSe QDs) or the electron in the core and the hole in the shell (e/h QDs, such as CdSe/CdTe QDs).15 Such staggered band alignments have several useful physical consequences, including longer radiative recombination times for more efficient charge extraction in photovoltaic applications,16,17 optical gaps that can be made smaller than the bulk values of the constituent materials,12,18,19 and control of the electron–hole wave function overlap which determines the exchange interaction energy.20 Charge separation in type-II QDs can also be used to increase the repulsion between like-sign charges in biexciton states,21,22 leading to the possibility of lasing in the single exciton regime.23,24

To determine the energetics of many-body states in QDs, both the confinement potential and many-body interactions between the carriers need to be taken into account. Many-body interactions can be classified as Coulomb (charge) and Fermi (spin) correlations. Coulomb correlation arises from the electrostatic interaction of charge carriers in the many-body complex, while spin correlation occurs due to the Fermionic character of the charge carriers (i.e., the Pauli exclusion principle).25 Correlated many-body states may be calculated with the configuration interaction (CI) method which can be used in the framework of continuum or atomistic descriptions of single-particle states.26–31

Colloidal QDs are usually embedded or dispersed in media32 of lower dielectric constant than the semiconductor itself; this dielectric confinement leads to a modification of the Coulomb interaction which can be described using classical image charge theory. While atomistic calculations33 showed that dielectric confinement significantly affects the charging energies of QDs, in single-material spherical QDs the similar electron and hole charge distributions lead to a weakened dielectric confinement effect34 on exciton states which mainly increases the binding energy.26,35 It is therefore natural to wonder if the optical properties of spherical type-II core/shell QDs can be significantly affected by the dielectric environment.

The effect of dielectric confinement and many-electron correlation means that the single-particle picture is not good enough to faithfully predict exciton energetics or wave functions in colloidal QDs. The proper treatment of charges requires a many-electron description that goes beyond mean-field theories, and the configuration interaction method is one of the most accurate. However, the full configuration method becomes progressively more computationally expensive as the number of states increases. Luckily however the interpretation of physical experiments often requires detailed knowledge of...
just a few excitons of particular symmetry. To overcome unnecessary computational burden, when analyzing 1S(2s)1S(2p) excitons in core/shell QD structures, we develop a decoupled CI calculation method which only mixes the most important, \( m_s^{(2s)} \) single-particle states into the exciton wave function but accurately reproduces the full CI results with greatly reduced computational cost. This allows us to evaluate the effect of correlation on exciton energies and dipole matrix elements for many different core/shell QD geometries, and identify those designs for which correlation effects are greatest.

In this paper we examine the 1S(2s)1S(2p) and 1S(2s)2S(2p) excitons in CdTe/CdSe and CdSe/CdTe QDs using a CI approach to describe the effect of correlation between the electron and hole states. The single-particle states were described using the (2,6)-band \( k \cdot p \) theory for spherical core/shell QD heterostructures, taking into account correct operator ordering at the heterointerfaces and the complex VB structure.

II. THEORETICAL MODEL

II.A. Single-Particle States. In order to find a set of single-particle (SP) states, we use the (2,6)-band \( k \cdot p \) Hamiltonian.

To illustrate the problem and introduce basic parameters, in Figure 1 we show (a) a schematic of a spherical QD characterized by core radius \( a_c \) and shell thickness \( a_s \). (b) the staggered alignments of the CB minimum (CBM) and VB maximum (VBM) in type-II h/e CdTe/CdSe and e/h CdSe/CdTe QDs, and (c) a characteristic profile of the self-polarization potential for a colloidal CdTe/CdSe QD, with dielectric profile (inset).

**Figure 1.** (a) Cutaway view of a spherical core/shell QD; (b) CBM and VBM corresponding to type-II alignment, in (i) an h/e CdTe/CdSe QD and (ii) an e/h CdSe/CdTe QD; (c) typical self-polarization potential for a colloidal CdTe/CdSe QD, with dielectric profile (inset).

The electron (hole) SP wave function \( \psi_{j,m,p,n}^{(h)} \) satisfies the Schrödinger equation

\[
\hat{H}_e^{(h)} \psi_{j,m,p,n}^{(h)} = E_{j,m,p,n}^{(h)} \psi_{j,m,p,n}^{(h)}
\]

where \( E_{j,m,p,n}^{(h)} \) is the electron (hole) eigenenergy and \( \hat{H}_e^{(h)} \) is the \( k \cdot p \) Hamiltonian for electrons (holes). The SP quantum states are denoted using the notation \( n^{(j)} \), where \( n \) is the fundamental quantum number, \( l = s, p, d, \ldots \) represents the lowest value of the orbital angular momentum in the wave function, and \( \mu \in \{e,h\} \) denotes an electron or hole. Due to the macroscopic spherical symmetry of the QD shape and the fact that the material parameters depend on the radial coordinate \( r \) only, the states calculated according to the \( k \cdot p \) theory can be characterized by the total angular momentum \( j \) and its \( z \)-component \( m \equiv j_z \). Furthermore, the parity operator \( \hat{P} \) commutes with the Hamiltonian \( \hat{H} \) of any system possessing a spherically symmetric confining potential \( V \), so that \( \hat{H} \) and \( \hat{P} \) share the same set of eigenfunctions. As a result, SP eigenstates in spherical QDs are also characterized by the eigenvalue \( p \) of the parity operator; \( p \) takes the values \( 1 \) and \( -1 \) for even and odd states, respectively. In spherical QDs possessing spherically symmetric confinement potentials the parity is conserved. Furthermore, the radial part of the wave function can be classified according to whether it has odd or even parity. In Figures 2 and 3 we show charge densities of \( n = 1 \), \( m = 1/2 \) electron and hole SP states with (a) \( j = 1/2 \), (b) \( j = 3/2 \), and (c) \( j = 5/2 \) in CdTe/CdSe and CdSe/CdTe QDs, respectively. SP states with \( j = 1/2 \) have spherically symmetric charge densities, and all SP states with \( m = \pm 1/2 \) are symmetric about the \( z \)-axis.

II.B. Exciton States. Our SP ket notation \( |j \mu \rangle \) is defined in terms of total angular momentum \( j \) and parity \( \mu \), such that \( (r_j \mu \rangle \) is the total angular momentum \( j \) and parity \( \mu \), such that \( (r_j \mu \rangle \) is the total angular momentum \( j \) and parity \( \mu \), such that

\[
|j \mu \rangle = |j, m \rangle
\]

To construct excitonic states, we couple SP states in terms of angular momentum rather than parity, so...
we define the new ket notation $|n j m \rangle$ in terms of both total angular momentm $j$ and the lowest value of orbital angular momentum $l$. In such notation $l = j - p/2$ for electrons and $l = \min(j + p/2, jy = 3p/2l)$ for holes, where $p = \pm 1 (-1)$ for even (odd) states regardless of whether electron or hole states are considered.\textsuperscript{36}

**Exciton Hamiltonian.** In the presence of a spatially varying dielectric constant, the exciton Hamiltonian is\textsuperscript{26}

$$ \hat{H}_X = \hat{H}_e + \hat{H}_h + V(r_e, r_h) + V_e(r_e) + V_h(r_h) \quad (2) $$

where $V_e$ is the interparticle Coulomb potential and $V_h$ is the interface polarization potential.\textsuperscript{15,38} Excitonic states are diagonalized separately in different $(L,Lz)$ states regardless of whether electron or hole states are conserved for correlated exciton states, the Hamiltonian $\hat{H}_e$ can be solved separately in different $(L,Lz)$ subspaces.\textsuperscript{37}

**II.C. Correlation Energy and Momentum.** Assuming the form of excitonic wave function in eq 4, the correlation energy of the 1S|S3/2(S3/2) state is given by

$$ E_{\text{core}} = E_{X,\text{Cl}} - E_X \quad (6) $$

where $E_X$ is the exciton energy calculated according to first order perturbation theory (FOPT) inside the strong confinement approximation (SCA) for the exciton wave function.\textsuperscript{33,34,39,40} The probability of excitation from the ground state to the excited state $|\Psi_{X,L,J}^{L, Lz}\rangle$ is proportional to the square of the optical dipole matrix element: \textsuperscript{41}

$$ P_X^2 = |\langle 0 | \hat{e} \cdot \hat{p}_h | \Psi_{X,L,J}^{L, Lz}\rangle|^2 \quad (7) $$

where $\hat{e}$ is the polarization vector of incident light and $\hat{p}_h$ is the hole momentum operator. Substituting for $|\Psi_{X,L,J}^{L, Lz}\rangle$ from eq 4 gives

$$ P_{X,CL}^2 = \sum_{\beta} c_{\beta}^* \langle 0 | \hat{e} \cdot \hat{p}_h | \Psi_{X,L,J}^{L, Lz}\rangle^2 \quad (8) $$

where each term in eq 8 must obey the selection rules for electric dipole transitions. Optical dipole matrix elements of the uncorrelated states are calculated as

$$ P^2 = \sum_{\beta} \sum_{\alpha} c_{\beta}^* c_{\alpha} \langle \Psi_{X,L,J}^{L, Lz} | \hat{e} \cdot \hat{p}_h | \Psi_{X,L,J}^{L, Lz} \rangle \quad (9) $$

To assess the effect of correlation on the excitonic optical dipole matrix elements, we define \textsuperscript{51}

$$ \Delta P_X^2 = P_{X,\text{Cl}}^2 - \frac{1}{4} P^2 \quad (10) $$

The charge density of the electron (hole) in the correlated exciton is

$$ \rho_X^e(r) = \langle \Psi_{X,L,J}^{L, Lz} | \delta(r - r_e) | \Psi_{X,L,J}^{L, Lz}\rangle \quad (11) $$

However, since $s_{3/2}$ states are spherically symmetric and $s_{1/2}$ states are often approximately spheroidial (see Figures 2 and 3), it is more informative to examine the radial probability density (RPD). The electron RPD is

$$ \text{RPD}^e(r) = \frac{1}{4} \sum_{\beta \neq \beta'} c_{\beta, \beta'}^* \bar{\delta} \bar{\rho}_{\alpha, \alpha'} \left( R_{1/2, 0}^{3/2, 1} \right)^2 \left( R_{1/2, 0}^{3/2, 1} \right)^2 \quad (12) $$

Similarly we define a hole RPD as

$$ \text{RPD}^h(r) = \frac{1}{4} \sum_{\beta \neq \beta'} c_{\beta, \beta'}^* \bar{\delta} \bar{\rho}_{\alpha, \alpha'} \left( R_{1/2, 0}^{3/2, 1} \right)^2 \left( R_{1/2, 0}^{3/2, 1} \right)^2 \quad (13) $$

where $R_{1/2,0}^{3/2,1}$ is the radial part of the electron (hole) wave function\textsuperscript{26,36} and $J$ is the total Bloch function angular momentum. The corresponding SP charge densities are denoted as $\bar{\rho}_{\text{SP}}$. We also define the probability $P_{\text{SC}}$ of the SP hole being in the core (shell) region as

$$ P_{\text{SC}} = \int_0^a \rho_{\text{SP}}^h (r) \, dr, \quad P_{\text{SC}} = \int_0^{a+h} \rho_{\text{SP}}^h (r) \, dr \quad (14) $$

**II.D. Effect of Dielectric Confinement.** For colloidal QDs the dielectric constant $\varepsilon$ of the QD material is typically much larger than that of the surrounding medium. This dielectric contrast means that any free charge in the QD induces polarization charge in the QD and its surroundings. The overall effect of the induced charge on a source charge is described by the self-polarization potential $V_e(r)$ which should be ignored, Figure 1c. In colloidal core/shell QDs the self-polarization potential is characterized by a small peak and well near the core/shell interface due to the small dielectric mismatch of the core and shell materials. However, a much larger peak just inside $r = a + a_h$, and a deep well slightly outside the QD are due to the far greater dielectric mismatch of the shell and matrix material.

In order to assess the effect of dielectric confinement on the excitonic structure of CdTe/CdSe and CdSe/CdTe core/shell QDs, we performed CI calculations for two different situations: assuming a uniform dielectric constant $\varepsilon = \text{constant} = 6.65$ (i.e., the mean of the CdTe and CdSe constants so that dielectric confinement by the surrounding medium and dielectric mismatch of the core and shell were neglected) and using a realistic profile $\varepsilon = \varepsilon(r)$ with the individual dielectric constants for the core, shell, and external medium. In the former case the Coulomb interaction $V_e$ in eq 2 reduces to the direct interparticle term $V_{ij}$ only, allowing us to separate the effects of the interparticle Coulomb attraction and dielectric confinement.

**III. RESULTS AND DISCUSSION**

**III.A. Convergence Considerations.** For a general exciton state $|\Psi_{X,L,J}^{L, Lz}\rangle$ there are many combinations of SP states that
should be summed over in eq 5; this number can be reduced by considering the states that can be coupled for specific cases. Angular momentum coupling conditions mean that for optically active $L = 1$ states $|l_f − l_h| \leq 1$ and assuming $L_z = 1$ means $m_s + m_h = 1$. If incident light is polarized parallel to the z-axis, only EHPs with $m_s = m_h = 1/2$ are excited. These assumptions still leave a large number of possible basis states to calculate matrix elements for, since $I(n_e)J(n_h)j_J(n_{e,h})LL_z$ in eq 5 must be expanded over different ordinal quantum numbers $n_e$ and angular momenta $j_J$. To investigate the relative importance of different SP states, we calculate $E_X$ as a function of the number of states in the EHP basis. We include hole states up to $j = 1S/2$ and all confined electron states in a full configuration interaction (FCI) scheme.

Figure 4 shows the convergence of the exciton energy $E_X^{FCI}$ calculated in the FCI scheme for the $1S_{1/2}^{1S_{3/2}}$ exciton against (a) the number of electron states $n_e^{FCI}$ and (b) the number of hole states $n_h^{FCI}$ in the basis. We see that $E_X^{FCI}$ changes in a stepwise fashion with the addition of extra states to the basis—falling from its FOPT value of 1866.38 meV to 1856.13 meV when $n_e^{FCI} = n_h^{FCI} = 30$. For $n_h = 20$ the energy $E_X^{FCI}$ changes by ~5–6 meV at $n_e^{FCI} = 7$, while when $n_e = 20$ is fixed the energy $E_X^{FCI}$ changes by ~2 meV at $n_h^{FCI} = 5$ and by an additional ~1 meV at $n_h^{FCI} = 15$. We have identified that the seventh electron state in the FCI basis is the $2s_{3/2}^{(1)}$ state, while the fifth and fifteenth hole states are the $2s_{1/2}^{(b)}$ and $3s_{3/2}^{(b)}$ states respectively; the positions of these SP states are indicated by arrows at the top of Figure 4. These results suggest that the $1S_{1/2}^{1S_{3/2}} (n \in \mathbb{N})$ excitons are mainly composed of $m_s^{(1)}m_s^{(b)} (m, n \in \mathbb{N})$ EHPs. Therefore we developed a decoupled configuration interaction (DCI) scheme in which the EHP basis consists solely of $m_s^{(1)}m_s^{(b)} (m, n \in \mathbb{N})$ pair states. Then the calculation represented in Figure 4 is fully reproduced by the DCI scheme which includes only the first two $s_{1/2}^{(b)}$ states and first three $s_{3/2}^{(b)}$ states. The FCI calculation gave $E_X^{FCI} = 1856.13$ and 2055.88 meV for the $1S_{1/2}^{1S_{3/2}}$ and $1S_{1/2}^{2S_{3/2}}$ excitons, respectively, while the DCI calculation gave $E_X^{DCI} = 1857.00$ and 2057.29 meV for the same states (equivalent to relative errors of $−1.4 \times 10^{-2}$ and $−5.1 \times 10^{-3}$, respectively). Due to the greatly reduced computational load all relevant results are easily converged within this framework.

**III.B. Comparison with Experiment.** The $1S_{1/2}^{1S_{3/2}} (n = 1, 2)$ states are the two lowest energy excitons observed in the absorption spectra of colloidal CdTe/CdSe nanocrystals (NCs)\textsuperscript{21,39,42} making them the most important for understanding the near band-edge absorption characteristics of such nanoparticles. Figure 5 shows the $1S_{1/2}^{1S_{3/2}}$ and $1S_{1/2}^{2S_{3/2}}$ exciton energies (solid lines) calculated in the DCI scheme as a function of shell thickness for CdTe/CdSe QDs with (a) $a_e = 1.7$ nm, (b) $a_e = 1.72$ nm, (c) $a_e = 1.75$ nm, and (d) $a_e = 1.95$ nm. Dashed lines show upper and lower limits on the exciton energies resulting from an uncertainty of 1 ML in the nominal core radii.

![Figure 4. Convergence of $E_X^{FCI}$ as a function of (a) $n_e^{FCI}$ and (b) $n_h^{FCI}$ for $a_e = 2$ nm, $a_e = 0.5$ nm CdTe/CdSe QD.](image)

![Figure 5. Energies of the $1S_{1/2}^{1S_{3/2}} (n = 1, 2)$ excitons calculated in the DCI scheme (lines) for CdTe/CdSe QDs with (a) $a_e = 1.7$ nm, (b) $a_e = 1.72$ nm, (c) $a_e = 1.75$ nm, and (d) $a_e = 1.95$ nm.](image)
but approximately constant hole confinement in the h/e heterostructure. We also find good agreement between the oscillator strength obtained by Gong et al.\textsuperscript{42} from the absorption spectra and our calculations. Calculating the oscillator strength \( f_n \) of the \( 1S_{n/2}^{(1)} \) excitons as \( f_n = 2P_{XDCD}^2/m_0E_{XCDP} \) we find that \( f_1 + f_2 \sim \text{constant} \) (inset Figure 5), confirming the validity of relevant excitonic wave functions too.

III.C. Correlation Energies. Figure 6 shows \( E_{\text{corr}} \) values for the \( 1S_{n/2}^{(1)}, 1S_{n/3}^{(2)} \), \( 1S_{n/2}^{(1)}, 2S_{n/2}^{(2)} \), \( 1S_{n/2}^{(1)}, 2S_{n/2}^{(2)} \) excitons in CdTe/CdSe and CdSe/CdTe QDs. Black and red lines represent the localization boundaries (LBs) for the electron and hole, respectively.\textsuperscript{15} In the CdTe/CdSe QD the electron is classified as shell-localized if its energy lies below the CBM of the core material, while the hole is core-localized if its energy lies above the VBM of the shell material. Similar criteria apply for the CdSe/CdTe QD. The type-I regime is defined by both carriers being delocalized over the entire QD, with their energies mainly determined by the “global confinement” provided by the potential well of radius \( a_s + a_e \). The type-II regime corresponds to the carriers being localized in different regions of the QD (i.e., the hole in the core and the electron in the shell for the h/e QD and the reverse for the e/h QD), so the SP energies are mainly determined by the dimensions of the relevant region. The quasi-type-II regime corresponds to partial charge separation; in the h/e QD this corresponds to a delocalized hole and shell-localized electron or a core-localized hole and delocalized electron in the e/h QD.

Areas of significant magnitude correlation energy in Figure 6 always roughly coincide with those associated with large optical dipole matrix elements for the corresponding uncorrelated EHPs.\textsuperscript{39} In those regions the electron–hole correlation is enhanced as the SP wave function overlap is high and the interparticle Coulomb matrix elements are increased in magnitude. In the type-II regimes \( E_{\text{corr}} \) is mainly small since the spatial separation of the electron and hole (induced by the type-II band alignment) overrides Coulomb attraction. In those regions the exciton wave function is closer to being described by the SCA. Although areas of high \( E_{\text{corr}} \) partly overlap with the type-II regions, the trend is for \( E_{\text{corr}} \to 0 \) in the type-II localization limit. The highest \( E_{\text{corr}} \) values in Figure 6 are a consequence of dielectric confinement affecting the correlated hole density [see Figure 6a(iv),b(iv)], reflected by the fact that they mainly occur in regions where the corresponding SP hole is delocalized. For example, in CdTe/CdSe QDs dielectric mismatch increases \( E_{\text{corr}} \) for the \( 1S_{1/2}^{(1)}, nS_{1/2}^{(2)} \) (\( n = 1, 2 \)) excitons in structures in which the corresponding \( nS_{1/2}^{(2)} \) states are delocalized (or approximately so) over the whole QD. Once strongly core-localized (right of the LB), such SP hole states have little or no overlap with the self-polarization potential near the QD/medium interface. Similarly dielectric mismatch mostly affects \( E_{\text{corr}} \) for the \( 1S_{1/2}^{(1)}, nS_{1/2}^{(2)} \) (\( n = 1, 2 \)) excitons in CdSe/CdTe QDs which lie below or near the hole LB (corresponding to delocalized SP holes). Figure 6a(iv),b(iv) also shows that \( E_{\text{corr}} \) has a distinct minimum as a function of \( a_s \). This minimum is due to the fact that an increase in \( a_s \) causes the hole density to shift into the shell where it starts to be affected by the self-polarization potential at the QD/medium interface. However, as \( a_s \) increases further, the hole localizes completely in the shell so that spatial confinement by the VBM overrides the repulsive effect of the self-polarization potential causing \( E_{\text{corr}} \to 0 \); see section III.D.2 for further explanations.

For the \( 1S_{1/2}^{(1)}, 1S_{1/2}^{(2)} \) exciton the area of nonzero \( E_{\text{corr}} \) in the lower right quasi-type-II regime of the CdTe/CdSe QD in Figure 6a(ii), is equivalent to the area in the upper left quasi-type-II regime of the CdSe/CdTe QD in Figure 6a(iv). Similarly, the region of large \( E_{\text{corr}} \) for the \( 1S_{1/2}^{(1)}, 2S_{1/2}^{(2)} \) exciton at \( a_s \gtrsim 2 \) nm, \( a_e \lesssim 0.5 \) nm in Figure 6b(ii) is analogous to the area at \( a_s \lesssim 2.5 \) nm, \( a_e \gtrsim 1.5 \) nm in Figure 6b(iv).

Overall we find that dielectric confinement affects the correlated hole density more than the correlated electron density for two reasons. First, the larger effective mass and
deeper potential well experienced by SP hole states compared to electron states allow the former to localize more fully in the shell, closer to the peak in $V(r)$ at $r \approx a_c + a$. Second, the smaller energy spacing between the hole SP basis states (i.e., the larger density of hole states) compared to electron SP basis states means that the resulting correlated hole density has more “degrees of freedom” to adjust to the effects of dielectric confinement.

III.D. Correlated Exciton States. III.D.1. CdTe/CdSe QD: Effect of Electron Shell Localization. In Figure 7 we present $E_{\text{corr}}$ values for the $1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ and $1S_{1/2}^{(e)}|2S_{3/2}^{(h)}$ excitons as a function of core radius for fixed shell $a_s = 2$ nm CdTe/CdSe QDs (line $l_1$ in Figure 6).

We see that in the presence of dielectric confinement $|E_{\text{corr}}| \leq 20$ meV for both excitons and that $E_{\text{corr}}$ exhibits at least one minimum as a function of $a_c$ in the $\epsilon = \text{const.}$ and $\epsilon = \epsilon(r)$ cases. $|E_{\text{corr}}|$ is up to 4 times greater in the presence of dielectric confinement ($\epsilon = \epsilon(r)$) compared to the $\epsilon = \text{const.}$ case. This result highlights the importance of a proper treatment of the dielectric environment in such nanostructures. The minimum in $E_{\text{corr}}$ for the $1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ exciton, Figure 7a, is a consequence of two competing effects: proximity of the self-polarization potential peak which tends to reduce the electron–hole separation and the effect of the type-II confinement profile which tends to separate the carriers as $a_c$ increases. However, for the $1S_{3/2}^{(e)}|2S_{3/2}^{(h)}$ exciton $E_{\text{corr}}$ is not a monotonic function of $a_c$ for either $\epsilon = \epsilon(r)$ or $\epsilon = \text{const.}$ Insight into the QD size dependence of $E_{\text{corr}}$ can be gained by considering the amount of probability density in the core and shell associated with the dominant SP hole state that the correlated exciton originates from. The inset in Figure 7b shows the amount of $2S_{3/2}^{(h)}$ hole probability density in the core as a function of $a_c$, demonstrating a similar qualitative $a_c$ dependence to $E_{\text{corr}}$ in the dielectric mismatch case. We expect an increase in $p_s$ to cause a decrease in $|E_{\text{corr}}|$ since a greater amount of hole density in the core leads to less overlap with electron density in the shell and less correlation.

$1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ Exciton. In the absence of dielectric confinement $E_{\text{corr}}$ is always small ($\leq 3$ meV) because the exciton state is very close to the $1S_{3/2}^{(e)}|2S_{3/2}^{(h)} (\beta = 2)$ EHP state and $|c|^2 \approx 1$. When $\epsilon = \epsilon(r)$ the trend is very similar to the $1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ exciton, except different EHP characters are involved. For example, in the $a_s = 1$ nm QD the correlated exciton wave function is mainly composed of the $\beta = 3, 4$, and $23 (1s_{3/2}^{(e)}3s_{3/2}^{(h)}|2s_{3/2}^{(e)}3p_{3/2}^{(h)}$) EHPs, while in the $a_s = 1.5$ nm QD, the $\beta = 3$ and $26 (1s_{3/2}^{(e)}3s_{3/2}^{(h)}|2s_{3/2}^{(e)}2p_{3/2}^{(h)}$) EHPs are dominant. Again, when the hole localizes in the core, only the exciton is significantly affected by dielectric mismatch.

III.D.2. CdSe/CdTe QD: Effect of Hole Shell Localization. In Figure 9 we present $E_{\text{corr}}$ values for the $1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ and $1S_{1/2}^{(e)}|2S_{3/2}^{(h)}$ excitons as a function of shell thickness for an $a_s = 3.5$ nm fixed core in CdSe/CdTe QDs (line $l_1$ in Figure 6). A similar qualitative behavior to the electron case is observed. The magnitude of $|E_{\text{corr}}|$ is also significantly smaller, with the $1S_{3/2}^{(e)}|1S_{1/2}^{(h)}$ exciton being less than 20 meV. This is because of the smaller amount of electron density in the core. In the presence of dielectric confinement, Figure 9 shows the qualitative behavior of $E_{\text{corr}}$ for both holes and electrons is similar, with a minimum at $a_s = 0.5$ nm for the $1S_{1/2}^{(e)}|2S_{3/2}^{(h)}$ exciton and $a_s = 1.5$ nm for the $1S_{1/2}^{(e)}|1S_{1/2}^{(h)}$ exciton.
nm QD, Figure 9a. This value is more than 6 times larger than the corresponding value for the $\epsilon = \text{const.}$ case, highlighting the particularly strong effect of the dielectric environment on this exciton. It can be observed from Figure 9 that the effect of dielectric mismatch on $E_{\text{corr}}$ is strongest in the vicinity of the 1s$^{(b)}$ SP QD, i.e., once the SP hole becomes delocalized over the QD.

We found the second largest $|E_{\text{corr}}|$ value for the CdSe/CdTe QD 1S$^{(a)}$/2S$^{(b)}$ exciton, with $E_{\text{corr}} = -36$ meV for an $a_s = 0.5$ nm QD. Again, this minimum is observed in the vicinity of the 1s$^{(b)}$ and 2s$^{(b)}$ LBs where those two hole states become delocalized over the QD. The maximum value of $|E_{\text{corr}}|$ is almost 9 times larger in the presence of dielectric confinement compared to its absence. We note that the curves for $E_{\text{corr}}$ and the amount of hole RPD in the shell $p_s$ have qualitatively similar $a_s$ dependences to the right of the 1s$^{(b)}$ LB; see the inset in Figure 9b. An increase in $p_s$ is associated with a decrease in the amount of hole RPD that overlaps with the core-localized electron leading to a decrease of electron–hole correlation and causing $E_{\text{corr}} \to 0$.

1S$^{(a)}$/1S$^{(b)}$ Exciton. In the case of a core-only CdSe QD and no dielectric confinement, correlation causes both carriers to move toward the center of the QD compared to their SP counterparts, Figure 10a(i). This is purely a result of the direct interparticle Coulomb interaction, giving correlation energies of approximately $-5$ meV. Introduction of the self-polarization potential, i.e., $\epsilon = \epsilon(r)$, further enhances this move of RPDs of both carriers away from the QD surface in the core-only CdSe QD, Figure 10a(ii). This effect increases localization of both carriers near the center of QD, increasing their overlap and giving correlation energies $E_{\text{corr}} = -18$ meV. For the 1S$^{(a)}$/1S$^{(b)}$ exciton in the CdSe QD, the shift in RPD is mainly due to an increase in $2s^{(a)}$ (2s$^{(b)}$) $\beta = 26$ character.

To assess the effect of dielectric confinement on the correlated carriers in the CdSe QD, we consider the expectation value of the 1s electron (hole) radial coordinate, denoted $\langle r_\mu \rangle$. When $\epsilon = \text{const.}$ (no self-polarization) we find $\langle r_\mu \rangle = 1.55$ nm, compared to $\langle r_\mu \rangle = 1.44$ nm when $\epsilon = \epsilon(r)$ for the 1s$^{(b)}$ state. In contrast, the effect of dielectric confinement moves the 1s$^{(a)}$ electron from $\langle r_\mu \rangle = 2.01$ nm to $\langle r_\mu \rangle = 1.89$. Although the SP 1s$^{(a)}$/2s$^{(b)}$ RPD has significantly greater overlap with the repulsive peak in self-polarization potential near the QD surface than the SP 1s$^{(b)}$ hole RPD, the correlated electron is shifted by dielectric confinement by almost the same distance as the correlated hole. These results reflect the larger sensitivity of the correlated hole wave function to the dielectric environment compared to the electron in the CdSe core-only QD.

In Figure 10b(i) we see that the introduction of a thin CdTe shell allows the uncorrelated hole to start to localize near the QD surface at $r = a_s + a_h$, dramatically reducing its overlap with the uncorrelated electron. However, when $\epsilon = \text{const.}$ the introduction of correlation alone is strong enough to pull the hole back toward the center of the QD, mainly due to the addition of the 1s$^{(s)}$/2s$^{(b)}$ ( $\beta = 2$) EHP to the exciton wave function. We see that the introduction of dielectric confinement again enhances this move of the carriers further away from the QD surface compared to the $\epsilon = \text{const.}$ case. The effect of dielectric confinement is particularly strong in this case because $\langle r_\mu \rangle$ for the 1s$^{(b)}$ state is close to the value of QD’s outermost radius, $a_h + a_s$.

The close proximity of the hole to QD surface reduces the distance $\xi = \langle r^{(h)} \rangle - \langle r^{(\text{map})} \rangle$ between the hole in the QD and its mirror image in the colloid, dramatically increasing the Coulombic repulsion between them which scales as $1/\xi$. Such repulsion causes the hole to be pushed back toward the center of the QD, thereby dramatically increasing overlap with the correlated electron wave function. The presence of dielectric confinement means the exciton wave function is an almost equal superposition of the 1s$^{(s)}$/2s$^{(b)}$ ( $n = 1, 2$) states, with $|c_1|^2 = 0.449$ and $|c_2|^2 = 0.458$ (inset in Figure 10b(ii)). For comparison, when $\epsilon = \text{const.}$ the 1s$^{(a)}$/2s$^{(b)}$ $\beta = 26$ character amounts to only $|c_2|^2 = 0.019$. The much stronger configuration mixing in the dielectric confinement case allows $E_{\text{corr}}$ to reach $-62$ meV, compared to $-9$ meV without dielectric confinement.

Further increase of the CdSe/CdTe QD shell thickness to $a_s = 1$ nm allows the SP hole to fully localize in the shell while the
SP electron stays in the core, reaching the type-II localization limit. The carriers effectively enter the strong confinement regime in which the Coulomb effects are overridden by the effects of the type-II spatial confinement. In the SCA $\rho^{\theta}_{e} \approx \rho^{\theta}_{h}$ and the effect of correlations is lost. Again, $E_{\text{core}}$ is only nonzero when the hole is delocalized; once it localizes in the shell, the effect of VBM confinement overrides the interparticle Coulomb attraction. Dielectric confinement only slightly shifts the hole density toward the core, resisted by the opposing effect of spatial confinement with $E_{\text{core}} \approx -3$ meV for $a_s > 1.5$ nm. $1S_{1/2}^0 \rightarrow 2S_{3/2}^0$ Exciton. In the absence of dielectric mismatch ($\epsilon = \text{const.}$) the interparticle Coulomb interaction mainly causes the hole to move toward the core while the electron is nearly unaffected, Figure 11a(i)–c(i). Introducing dielectric confinement systematically moves the hole RPD toward the center of the QD, while the electron is again minimally affected, Figure 11a(ii)–c(ii). Dielectric confinement has the most pronounced effect on the $a_s = 0.5$ nm QD for which the self-polarization potential is able to almost completely repel the hole RPD from the shell to the core region, Figure 11b(ii); this is associated with an increase of $\Delta P_{\text{corr}}$ to 36 meV. The movement of the correlated hole RPD to the center of the QD upon introduction of dielectric confinement is due to the mixing of $1S_{1/2}^0 \rightarrow nS_{1/2}^0 \rightarrow 1S_{3/2}^0 \rightarrow 2S_{3/2}^0$ EHPs into the exciton wave function. For the $a_s = 1$ nm QD the competing effects of type-II VBM profile, interparticle Coulomb attraction, and self-polarization potential lead to the correlated hole RPD being delocalized across the whole QD with a local maximum in both the core and shell. When $a_s$ is increased to 1.5 nm and beyond, the SCA regime is reached and the correlated RPDs are very close to those of the uncorrelated states (not shown).

Generally we have observed when the correlated wave functions are in the type-II localization regime the charge that localizes in the QD’s shell is affected more by the interparticle Coulomb attraction while the innermost confined charge carrier is barely affected. We explain this behavior from the fact that $s_1^0$ electron states are largely spherically symmetric (see Figure 2a) and core-localized $s_1^0$ hole states are approximately spheroidal (see Figure 2b). Gauss’s law means that hole charge density $\rho_h$ at some radius $r_h$ is not affected any more by electron charge density $\rho_e$ situated at $r > r_h$.

### III.E. Exciton Optical Dipole Matrix Elements.

The regions of largest $\Delta P_{X}^2$ in Figure 12 closely coincide with the regions of largest $1E_{\text{corr}}$ in Figure 6 since the greater the change in carrier density due to correlation the greater the change in electron–hole wave function overlap. However, the correlation can increase or decrease the dipole matrix element of a particular exciton state relative to the SCA depending on the localization regime of the uncorrelated charge carriers.

Correlation only slightly changes the dipole matrix elements of the $1S_{1/2}^0 \rightarrow 1S_{1/2}^0$ CdTe/CdSe QD exciton, which is consistent with the similarity of the correlated and uncorrelated carrier RPDs in Figure 8. For the CdTe/CdSe QD we see that when $\epsilon = \text{const.}$ the $\Delta P_{X}^2 = 0$ contour closely follows the $1S_{1/2}^0 \text{LB}$ (see Figure 12a(i)), indicating that the $1S_{1/2}^0$ hole should be delocalized (or approximately so) for correlation to reduce the dipole matrix element relative to the uncorrelated EHP. Once the hole localizes in the core, $\Delta P_{X}^2$ becomes positive. Similar behavior is seen when $\epsilon = \epsilon(r)$, except that $\Delta P_{X}^2$ can be slightly negative for QDs with thin shells, $a_s \lesssim 0.5$ nm.

Figure 12a(iii,iv) shows a similar trend for the CdSe/CdTe QD, with $\Delta P_{X}^2$ only being negative when the $1S_{1/2}^0$ hole is delocalized; this is particularly noticeable for CdSe/CdTe QDs with $a_s \gtrsim 1.5$ nm when $\epsilon = \epsilon(r)$ in Figure 12a(iv). As the shell width increases for a particular core radius $\Delta P_{X}^2$ increases dramatically near the $1S_{1/2}^0$ LB; this is due to the interparticle Coulomb interaction that prevents the hole wave function localizing in the shell and dramatically increases its overlap with the electron wave function in the core, Figure 10b. This effect is enhanced by dielectric confinement, shown by the larger brighter area in Figure 12a(iv) above the hole LB. The difference $\Delta P_{X}^2$ reaches a maximum value of 0.15 for an $a_s = 3.5$ nm, $a_s = 0.75$ nm QD when $\epsilon = \epsilon(r)$, compared to a maximum value of 0.042 (for an $a_s = 3$ nm, $a_s = 0.625$ nm QD) when $\epsilon = \text{const.}$. These shifts represent an increase by a factor of 7.29 and 1.5 in the dipole matrix element respectively relative to the SCA results found using FOPT. Both regions of positive $\Delta P_{X}^2$ seen in Figure 12a(iii,iv) near the hole LB are mainly due to the mixing of the $1S_{1/2}^0 \rightarrow 2S_{1/2}^0 \rightarrow 1S_{3/2}^0 \rightarrow 2S_{3/2}^0$ EHP which becomes a large component of the exciton wave function.

The effect of correlation in the $1S_{1/2}^0 \rightarrow 2S_{3/2}^0$ exciton leads to a reduction of dipole matrix element near the $2S_{3/2}^0$ LB in both the CdTe/CdSe and CdSe/CdTe QD. This is most clearly seen for the CdSe/CdTe QD in Figure 12b(iii,iv), for which the reduction in the contribution of the $1S_{1/2}^0 \rightarrow 2S_{1/2}^0$ EHP leads to an area of negative $\Delta P_{X}^2$. These areas roughly coincide with the regions of positive $\Delta P_{X}^2$ seen in Figure 12a(iii,iv), suggesting a transfer of oscillator strength from the $1S_{1/2}^0 \rightarrow 1S_{1/2}^0 \rightarrow 2S_{1/2}^0 \rightarrow 2S_{3/2}^0$ CdSe/CdTe QD exciton.

The $\Delta P_{X}^2$ reaches its maximum value for an $a_s = 3.5$ nm and $a_s = 0.75$ nm QD, Figure 13. At this point the radiative recombination time of the $1S_{1/2}^0 \rightarrow 1S_{1/2}^0$ exciton calculated with FOPT ($\tau_{\text{rad}}^{\text{FOPT}} = 13.4$ ns) is about 1 order of magnitude larger than that calculated with DCF ($\tau_{\text{rad}}^{\text{DCF}} = 2.85$ ns). This reflects the need for a proper treatment of correlation effects in the design.
of optoelectronic devices that rely on dynamic processes between charges.

We also found that the effect of correlation on the CdSe/CdTe QD exciton dipoles and radiative lifetimes strongly depends on the dielectric properties of the external medium. In Table 1 we list radiative times calculated with and without correlation for several values of $\varepsilon_3$. The first two rows correspond to $\varepsilon = \text{const.}$, while (iii) and (iv) correspond to $\varepsilon = \varepsilon(r)$, respectively. Electron (hole) LBs are shown as blue (red) lines.

### Table 1. Radiative Lifetimes of CdSe/CdTe QDs with $a_c = 3.5$ nm and Different Dielectric Environments

<table>
<thead>
<tr>
<th>$\varepsilon_3$</th>
<th>$a_s$ (nm)</th>
<th>$\tau_{\text{rad}}$ (FOPT) (ns)</th>
<th>$\tau_{\text{rad}}$ (DCI) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.80</td>
<td>38.6</td>
<td>7.66</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
<td>13.4</td>
<td>2.85</td>
</tr>
<tr>
<td>6.65</td>
<td>0.55</td>
<td>1.55</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The second column shows shell widths for which $\Delta P^2_X$ reaches its maximum: $\tau_{\text{rad}}$ (FOPT) obtained neglecting the correlation effects and $\tau_{\text{rad}}$ (DCI) obtained including them.

### IV. CONCLUSIONS

We developed a computationally efficient decoupled CI scheme to examine the correlation energy $E_{\text{corr}}$ and the change in optical dipole matrix element $\Delta P^2_X$ of the $1S_{1/2}^{(1)} 1S_{3/2}^{(0)}$ excitons as a function of core radius and shell width in type-II CdTe/CdSe and CdSe/CdTe core/shell QDs. We have found the following: (i) The QD designs which gave the largest magnitude $E_{\text{corr}}$ values for the $1S_{1/2}^{(1)} 1S_{3/2}^{(0)}$ excitons were associated with delocalized $n_{3/2}$ hole states. In CdSe/CdTe QDs the largest magnitude correlation energy found is the consequence of strong configuration mixing of the $1S_{1/2}^{(1)} 1S_{3/2}^{(0)}$ and $1S_{1/2}^{(1)} 2S_{3/2}^{(0)}$ EHPs in the excitonic wave function caused by dielectric mismatch. (ii) The dielectric confinement mainly affected QDs in the type-I and quasi-type-II localization regimes, particularly those QDs for which the corresponding SP solvents like toluene or hexane ($\varepsilon_3 \approx 2$), the effect of correlations on the radiative lifetime cannot be neglected.

Type-II QD heterostructures have smaller dipole matrix elements than core-only QDs of the same ground state exciton energy. Such reduced dipole matrix elements could be beneficial for solar cell applications due to the longer radiative recombination times (and better charge extraction efficiencies) of photoexcited charges compared to core-only QDs.45

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**Figure 12.** Change $\Delta P^2_X$ in the optical dipole matrix element due to correlation for the (a) $1S_{1/2}^{(1)} 1S_{3/2}^{(0)}$ and (b) $1S_{1/2}^{(1)} 2S_{3/2}^{(0)}$ excitons in CdTe/CdSe and CdSe/CdTe QDs. (i) and (iii) correspond to $\varepsilon = \text{const.}$, while (ii) and (iv) correspond to $\varepsilon = \varepsilon(r)$, respectively. Electron (hole) LBs are shown as blue (red) lines.

**Figure 13.** Dipole matrix elements calculated in FOPT (open circles) and the DCI scheme (solid squares) for CdSe/CdTe QDs with $a_c = 3.5$ nm as a function of the shell thickness for the $1S_{1/2}^{(1)} 1S_{3/2}^{(0)}$ exciton. The shaded area shows the region of $a_s$ in which correlation has the greatest effect.
hole states are delocalized. (iii) Overall CdSe/CdTe QDs were affected more by dielectric environment than CdTe/CdSe QDs, as they tend to localize holes in the shell closer to the repulsive peak in the self-polarization potential that arises from dielectric mismatch. We conclude that the correlated holes are more affected by dielectric confinement than the electrons due to the much larger density of states in the VB. (iv) The regions of \((a_s,a_d)\) space with the largest \(\Delta P_{2}\) corresponded to regions in which \(I_{2}(\sigma)\) was greatest. The dipole matrix elements of the \(1S^{(0)}(2S^{(0)})\) \((n = 1, 2)\) excitons can be significantly changed by the dielectric environment in CdSe/CdTe QDs, in contrast to CdTe/CdSe QDs in which they are only slightly affected. These results suggest that changing the dielectric environment could be another way in which to control the oscillator strength and radiative lifetime of excitons in CdSe/CdTe core/shell QDs.

In contrast to epitaxially grown QDs\(^{35}\) which largely correspond to the \(e \approx \) const. case in our analysis, our results show that the charge separation due to the type-II band alignments and by dielectric mismatch induces self-polarization in core/shell colloidal QDs leads to strong deviations from the SCA for the exciton wave function.

### APPENDIX

The SP and excitonic states were calculated using the parameters in Table 2, where \(E_s\) denotes the bulk band gap.

<table>
<thead>
<tr>
<th>(E_s) (eV)</th>
<th>(E_v) (eV)</th>
<th>(\Delta) (eV)</th>
<th>(\gamma) ((\text{eV}))</th>
<th>(\alpha)</th>
<th>(m^*) ((\text{m}_0))</th>
<th>(\epsilon) ((\text{e}_0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe</td>
<td>CdSe</td>
<td>matrix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.56(^a)</td>
<td>1.75(^b)</td>
<td>8</td>
<td>3.77(^c)</td>
<td>0.965</td>
<td>0.091 (\epsilon) (e0)</td>
<td></td>
</tr>
<tr>
<td>17.9(^d)</td>
<td>17.5(^e)</td>
<td>0</td>
<td>1.67(^h)</td>
<td></td>
<td>0.12 (\epsilon) (e0)</td>
<td></td>
</tr>
<tr>
<td>(0 \sim -0.4)</td>
<td>(-0.4 \sim 0)</td>
<td>(-3.525 \sim -3.22)</td>
<td>1.98(^g)</td>
<td>6.2(^f)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) \(E_s\) values correspond to the CdTe/CdSe (CdSe/CdTe) VB offsets. \(^{b}\) Reference 46. \(^{c}\) Reference 37. \(^{d}\) Reference 47. \(^{e}\) Reference 48. \(^{f}\) Reference 50.

The Kane energy is \(E_K = 2m_0P_0^2/\hbar^2\), \(P_0\) is the bulk interband momentum matrix element, \(m_0\) is the free electron mass, \(^{41}\) \(\Delta\) is the spin–orbit splitting, and \(E_v\) is the VBM energy. The Luttinger parameters are \(\gamma_i\) \((i = 1, 2, 3)\), \(\alpha\) is a CB parameter, and \(m^*\) represents the electron effective mass at the bottom of the CB.\(^{37}\) \(\epsilon\) is the dielectric constant given in the units of free space permittivity, \(\epsilon_0\). Modified Luttinger parameters for the VB were calculated in the spherical approximation.\(^{36}\)

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**Notes**

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