EXCITONS, PLASMONS, AND EXCITONIC COMPLEXES UNDER STRONG CONFINEMENT IN QUASI-1D SEMICONDUCTORS.

Theory and Perspectives

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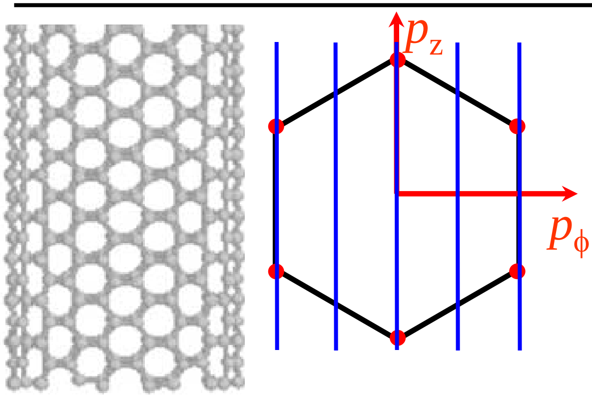
US Army Research Office – W911NF-11-1-0189
US Department of Energy – DE-SC0007117

OUTLINE

- ***Pristine Semiconducting Carbon Nanotubes: Excitons and Interband Plasmons – Brief Review***
- ***Plasmon Generation by Optically Excited Excitons, Exciton BEC Effect***
- ***Excitonic Complexes (Biexcitons & Trions) in quasi-1D: Brief Review, Landau-Herring Approach to Understand Relative Stability***
- ***Hybrid Carbon Nanotube Systems: Plasmon Enhanced Raman Scattering Effect***
- ***Summary***

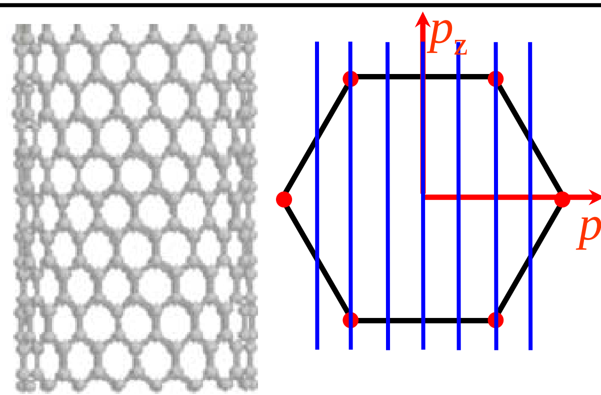
BASIC PHYSICAL PROPERTIES OF SINGLE-WALLED CNs

Brillouin zone structure and longitudinal conductivity

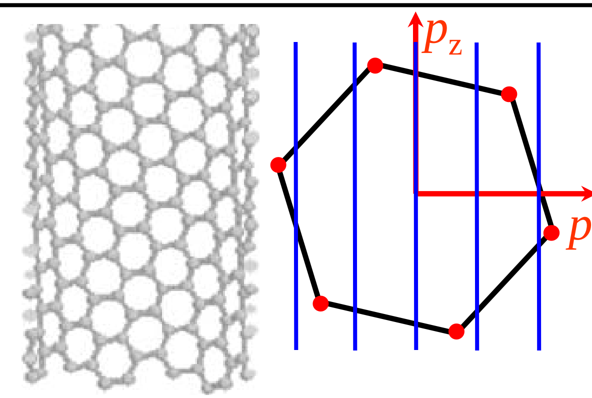


(m,m) – “Armchair”: metallic for all m

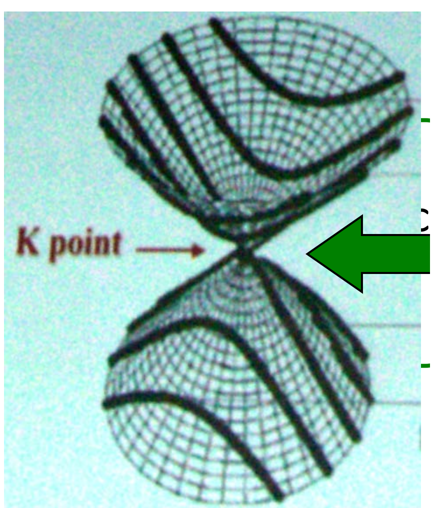
$$p_\phi = \frac{\hbar s}{R_{cn}},\ s = 1, 2, \ldots, m$$

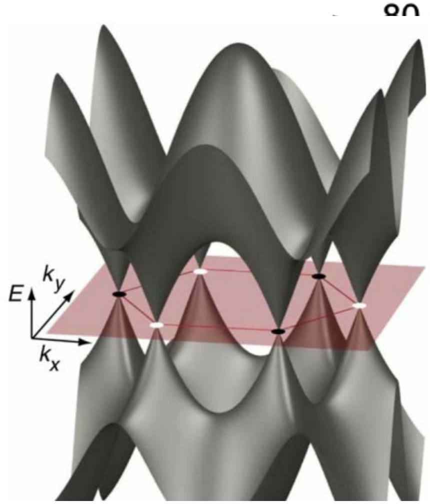


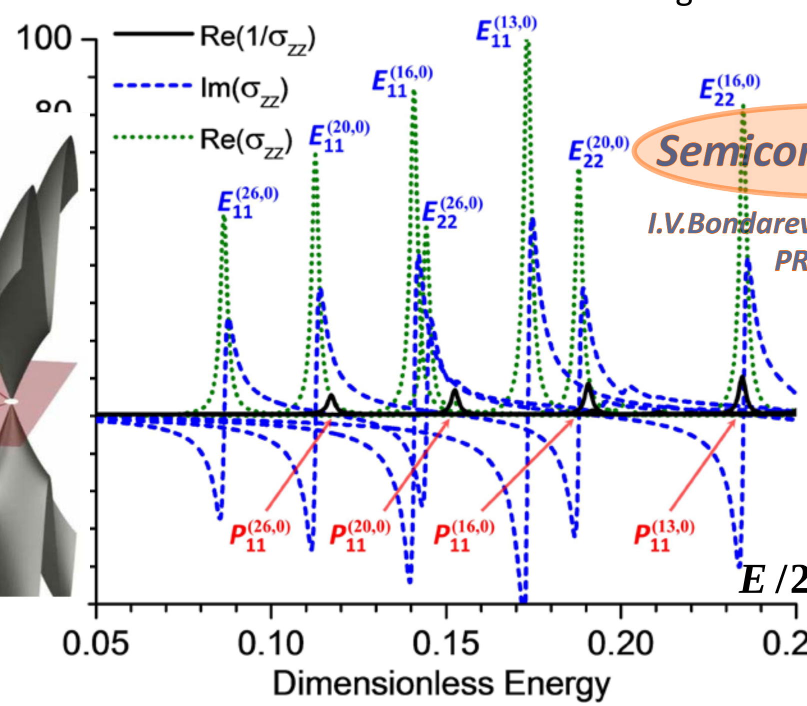
$(m,0)$ – “Zigzag”: metallic for $m=3q$, semiconducting for $m \neq 3q$ $(q=1,2,3,\ldots)$



(m,n) – chiral CN: metallic or semi-conducting depending on the radius and chiral angle





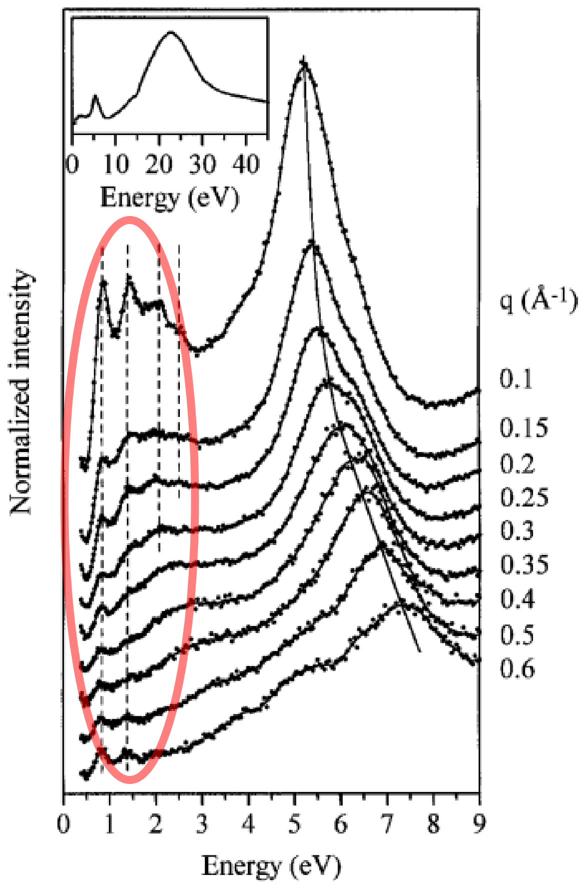


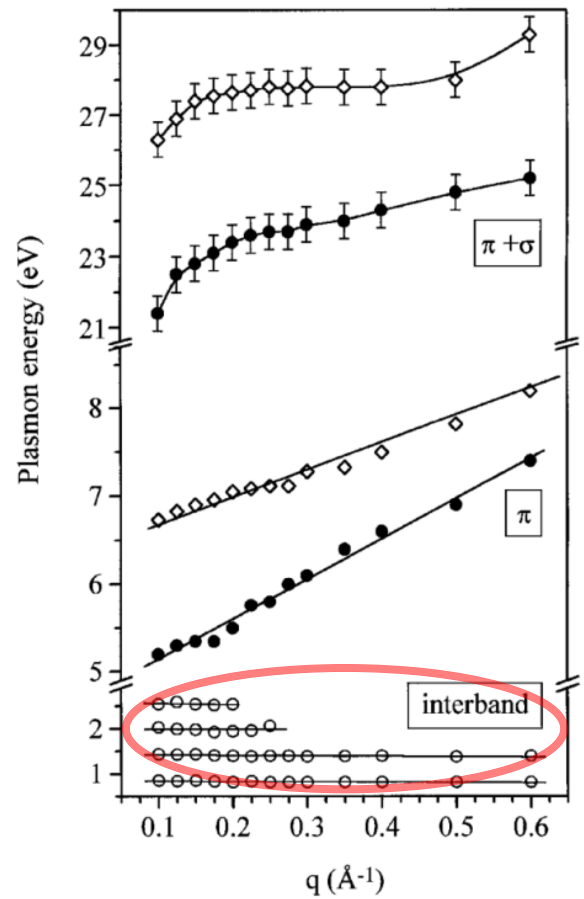
Semiconducting CNs

I.V.Bondarev & A.V.Meliksetyan, PRB 89, 045414 (2014)

EXPERIMENTAL ELECTRON ENERGY LOSS SPECTROSCOPY (EELS) SPECTRA OF SINGLE-WALLED CARBON NANOTUBES

T.Pichler, M.Knupher, M.Golden, J.Fink, A.Rinzler, and R.Smalley, PRL 80, 4729 (*1998*)





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SOLUTION TO THE DISPERSION EQUATION

(*exact diagonalization of the total Hamiltonian*)

I.V.Bondarev, L.M.Woods and K.Tatur, Phys. Rev. B 80, 085407 (2009)

$$x_{1,2}=\sqrt{\frac{\varepsilon_f^2+x_p^2}{2}\pm\frac{1}{2}\sqrt{(\varepsilon_f^2-x_p^2)^2+(2X_f)^2\varepsilon_f x_p}}$$

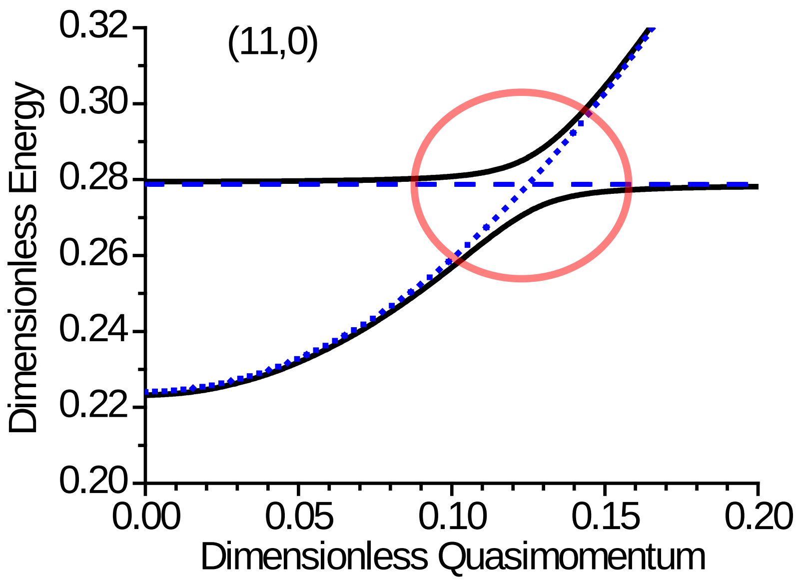
$$\varepsilon_f=E_f(\mathbf{k})/2\gamma_0,\;x_p=E_p/2\gamma_0,\;X_f=[2\Delta x_p\bar{\Gamma}_0^f(x_p)\rho(x_p)]^{1/2},\;\rho(x)\approx\rho(x_p)\Delta x_p^2/[(x-x_p)^2+\Delta x_p^2]$$

EXAMPLE:

(11,0) CN with the lowest bright exciton parameters from the Bethe-Salpeter eqn [from Spataru et al, PRL 95, 247402]

$$|d_f|^2=3\hbar\lambda^3/4\tau_{ex}^{rad}\;,\;\lambda=2\pi c\hbar/E$$

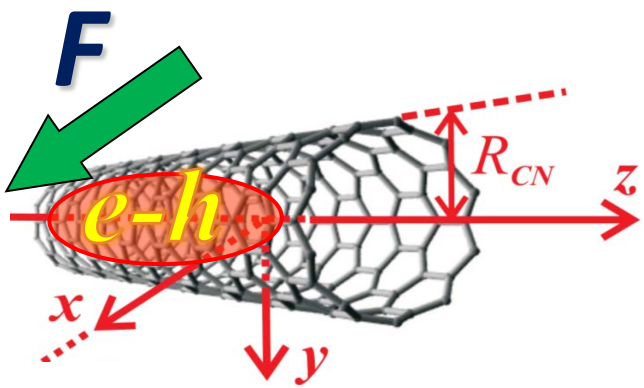
$$E=E_{exc}+(2\pi\hbar/3b)^2t^2/2M_{ex}\,,\;-1\leq t\leq 1$$



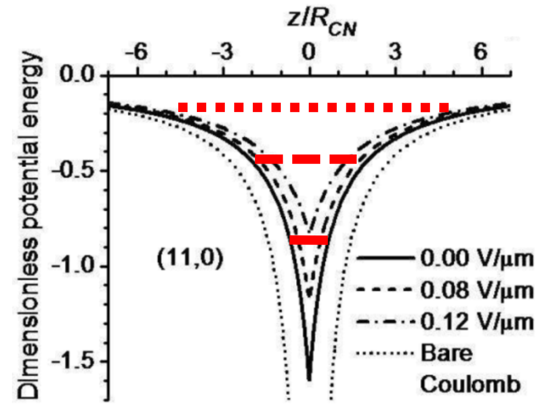
How to couple excitons to interband plasmons ?

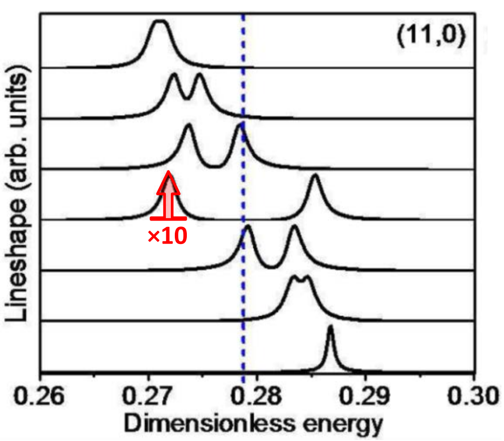
Quantum Confined Stark Effect in a Perpendicular Electrostatic Field

I.V.Bondarev, L.M.Woods, and K.Tatur, Phys. Rev. B 80, 085407 (2009)



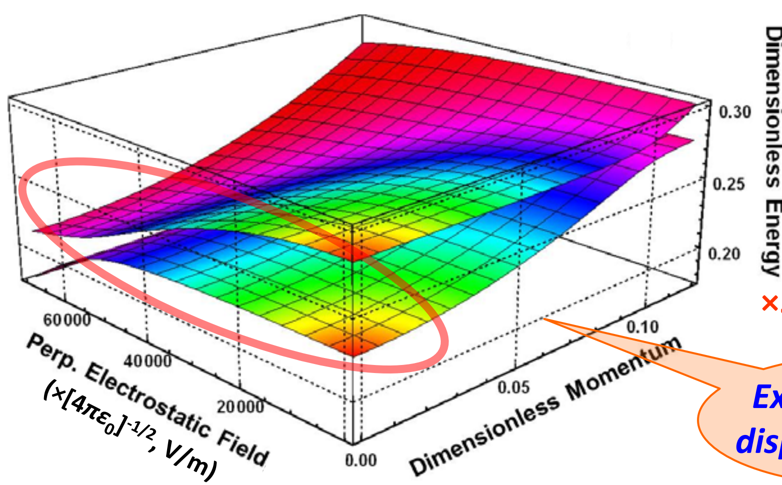
Longitudinal Coulomb potential as field increases





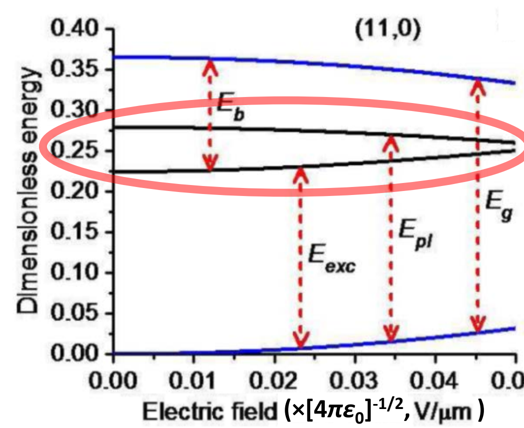
Exciton absorption when tuned to the plasmon resonance

Exciton-plasmon parameters as field increases



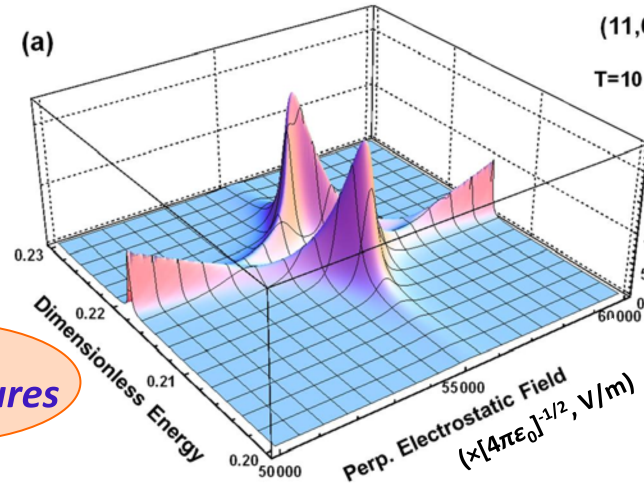
×5.4 eV

Exciton-plasmon dispersion relation

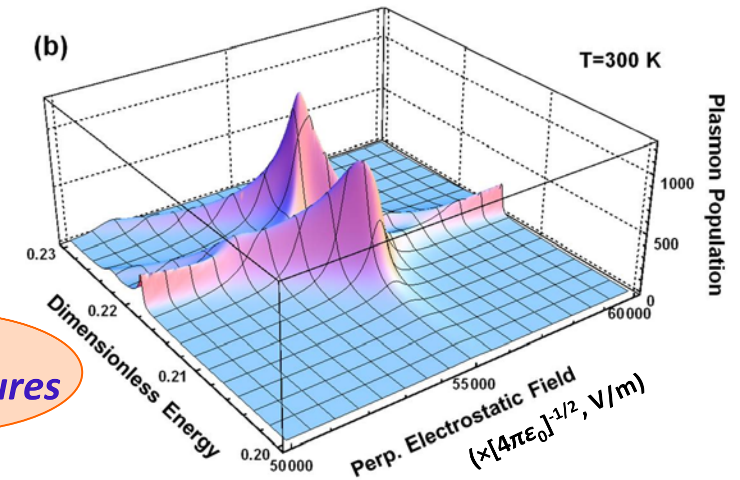


INCREASED ELECTROMAGNETIC ABSORPTION DUE TO PLASMON GENERATION BY OPTICALLY EXCITED EXCITONS

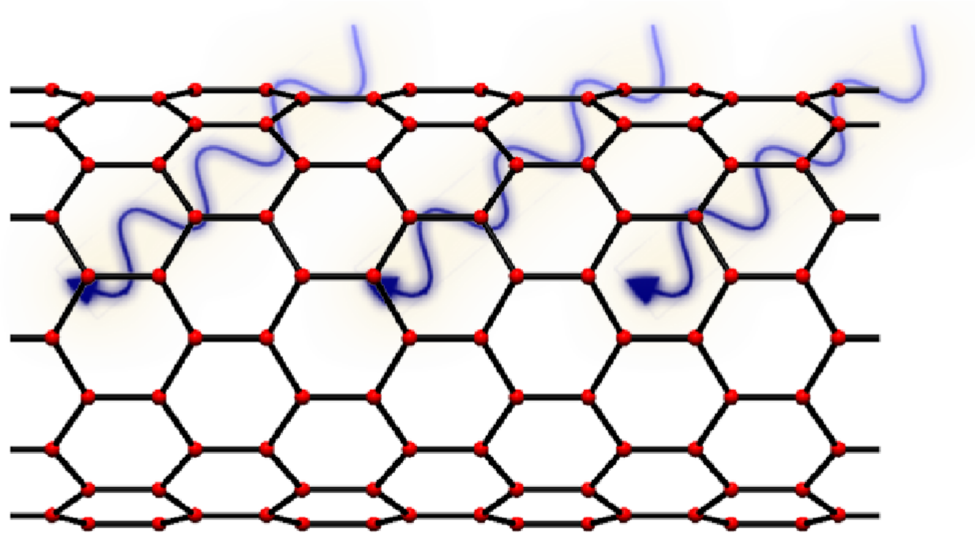
I.V.Bondarev, Phys. Rev. B 85, 035448 (2012)
I.V.Bondarev & T.Antonijevic, Phys. Stat. Sol. C 9, 1259 (2012)

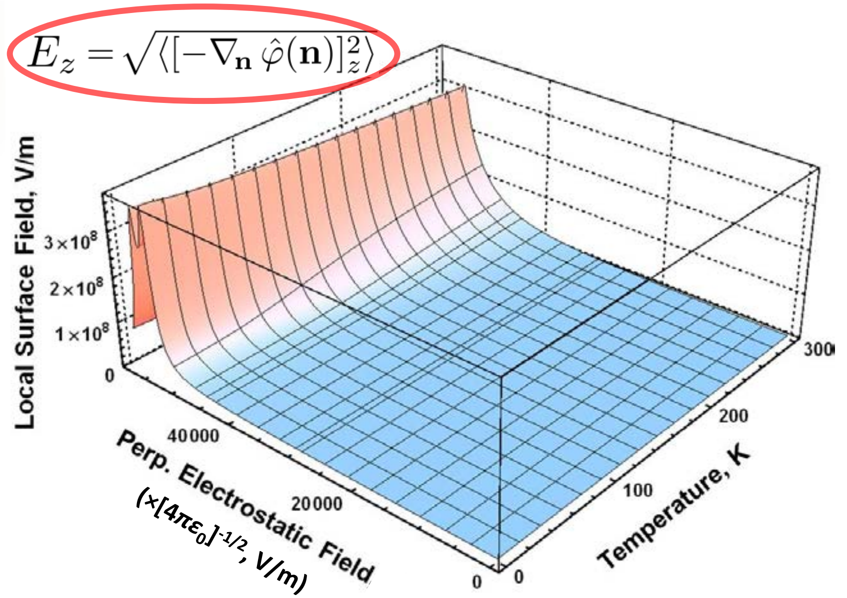


Low temperatures



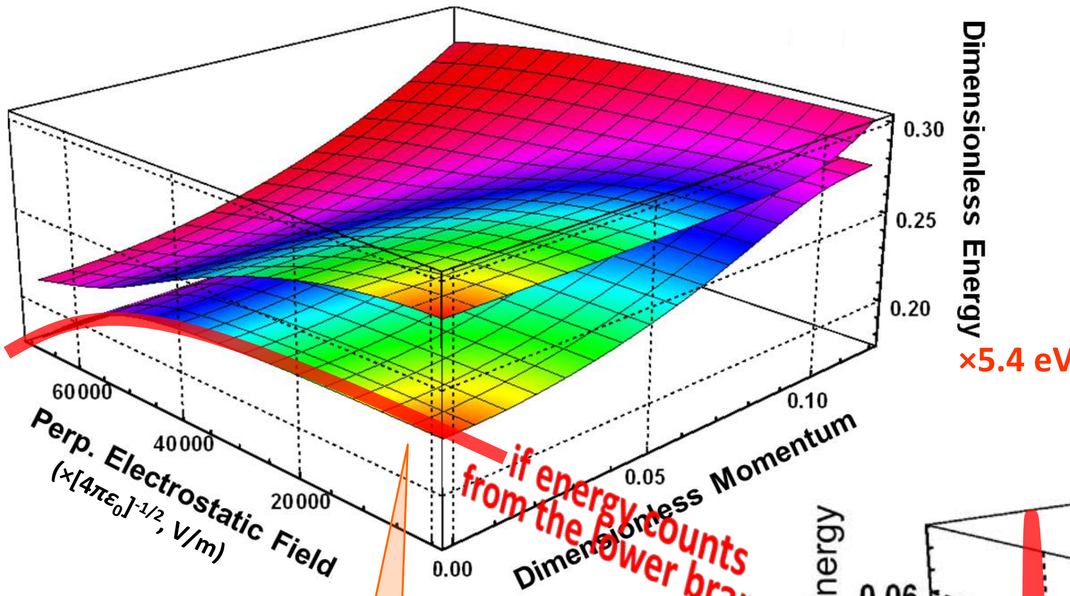
Room temperatures

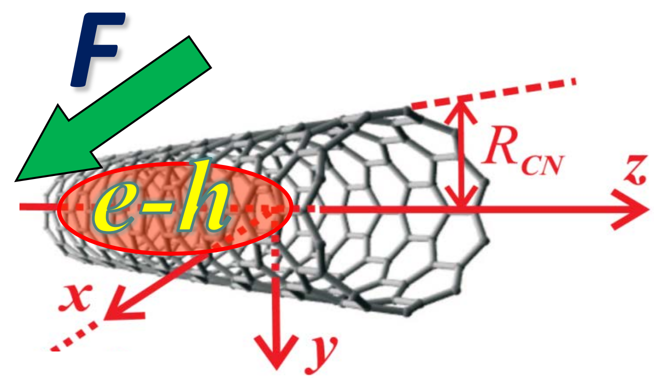




QUANTUM CONFINED STARK EFFECT AND BEC OF EXCITON-PLASMONS IN INDIVIDUAL NANOTUBES

I.V.Bondarev and A.V.Meliksetyan, Phys. Rev. B 89, 045414 (2014)

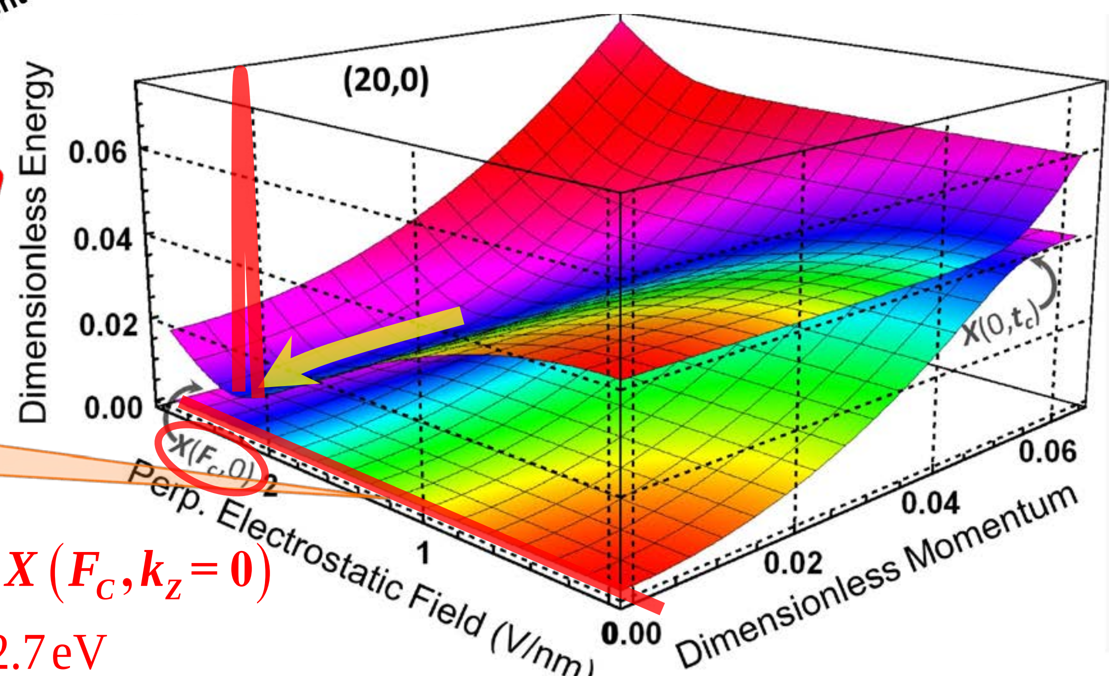




I.V.Bondarev, PRB 85, 035448 (2012)

Exciton-plasmon dispersion relation

Exciton-plasmon dispersion relation



$$T < T_C = (2\gamma_0/k_B)\,X(F_C, k_Z = 0)$$

$$\gamma_0 = 2.7\,\text{eV}$$

POSSIBILITY FOR EXCITON BEC BY MEANS OF CONTROLLED COUPLING TO INTER-BAND PLASMONS

(*via the Quantum Confined Stark Effect*)

Critical Temperature

$$T_C = \left(2\gamma_0/k_B\right) X\left(F, k_Z = 0\right)$$

$$\gamma_0 = 2.7\ \text{eV}$$

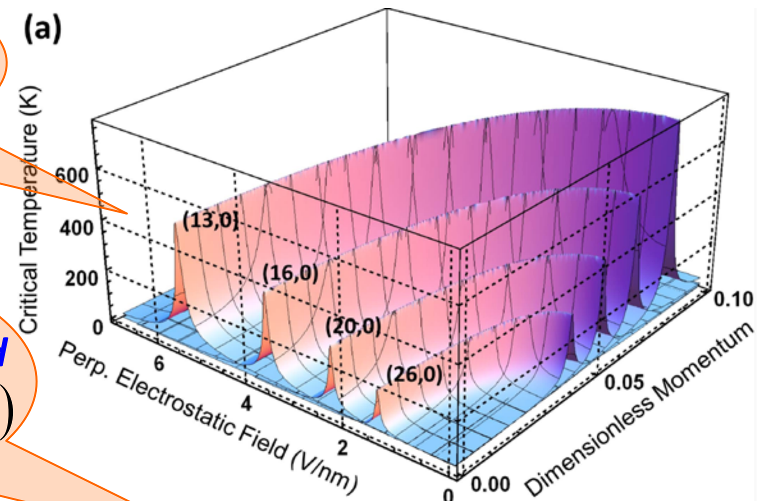
Exciton Ratio Condensed

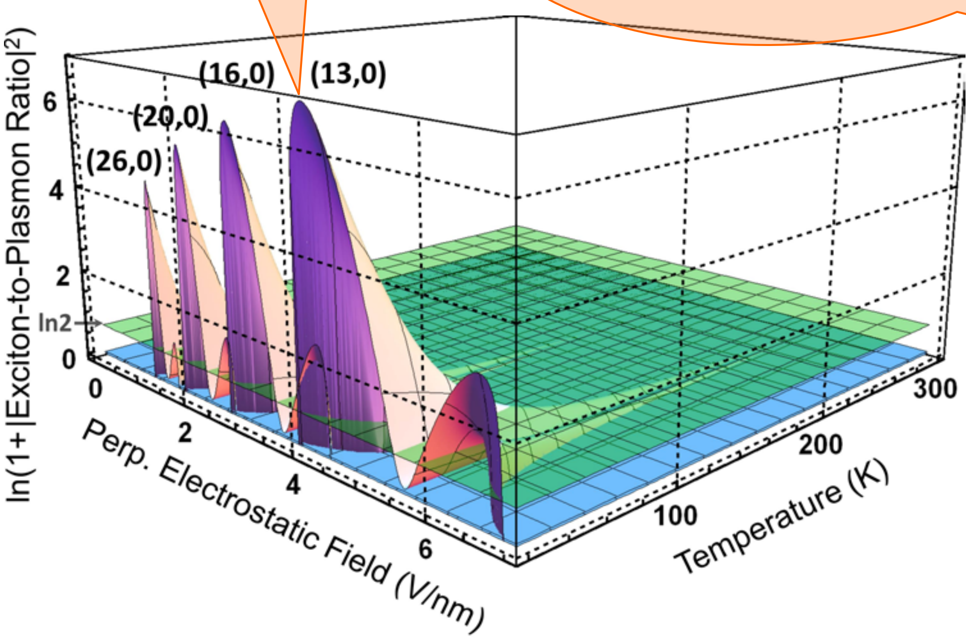
$$\left\langle n_1(k_Z = 0)\right\rangle \frac{N(Exciton)}{N(Plasmon)}$$

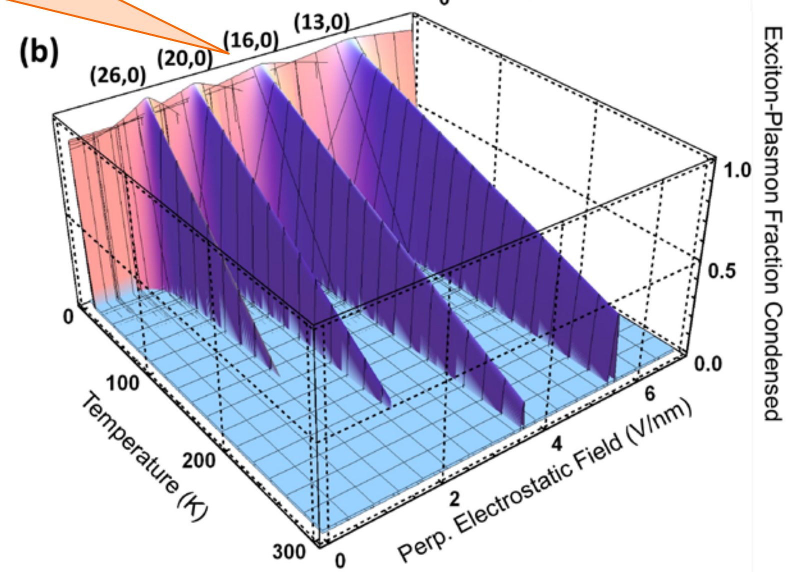
I.V.Bondarev, PRB 80, 085407 (2009)

Upper-Branch Exciton-Plasmon Fraction Condensed

$$\left\langle n_1(k_Z = 0)\right\rangle = \left\langle n_1\right\rangle\left(1 - T/T_C\right)$$







I.V.Bondarev & A.V.Meliksetyan, Phys. Rev. B 89, 045414 (2014)

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- ***Summary***

EXPERIMENT & THEORY

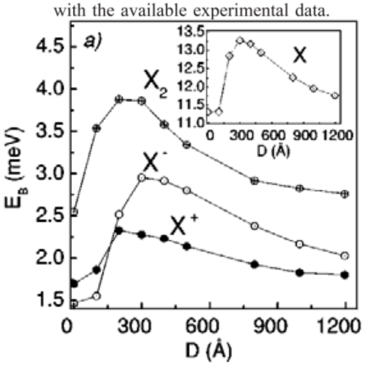
Charged and Neutral Excitonic Complexes in Confined Semiconductors
Role of Quantum Confinement

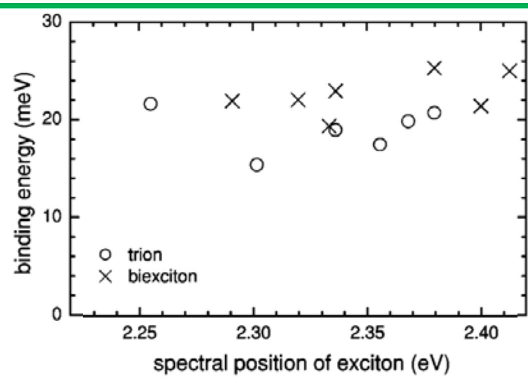
PHYSICAL REVIEW B **70**, 035323 (2004)

Influence of well-width fluctuations on the binding energy of excitons, charged excitons, and biexcitons in GaAs-based quantum wells

A. V. Filinov,[1,2,3] C. Riva,[1] F. M. Peeters,[1] Yu. E. Lozovik,[2] and M. Bonitz[3]
[1]*Departement Natuurkunde, Universiteit Antwerpen (Drie Eiken Campus), Universiteitsplein 1, B-2610 Antwerpen, Belgium*
[2]*Institute of Spectroscopy RAS, Moscow region, Troisk 142190, Russia*
hristian-Albrechts-Universität zu Kiel, Institut für Theoretische Physik und Astrophysik, Leibnizstrasse 15, 24098 Kiel, Germa
(Received 19 January 2004; revised manuscript received 8 April 2004; published 28 July 2004)

We present a first-principle path integral Monte Carlo (PIMC) study of the binding energy of excitons, trions (positively and negatively charged excitons) and biexcitons bound to single-island interface defects in quasi-two-dimensional GaAs/Al_xGa_{1-x}As quantum wells. We discuss in detail the dependence of the binding energy on the size of the well-width fluctuations and on the quantum-well width. The numerical results for the well-width dependence of the exciton, trions and biexciton binding energy are in good quantitative agreement with the available experimental data.





PHYSICAL REVIEW B **68**, 125316 (2003)

Trion, biexciton, and exciton dynamics in single self-assembled CdSe quantum dots

B. Patton, W. Langbein, and U. Woggon*
Experimentelle Physik IIb, Universität Dortmund, Otto-Hahn-Str. 4, 44221 Dortmund, Germany
(Received 7 February 2003; published 18 September 2003)

We present an analysis of time- and polarization-resolved data taken in microphotoluminescence experiments on individual CdSe/ZnSe quantum dots grown by molecular beam epitaxy. The identification of individual dots was performed by a spectral jitter correlation technique and by their polarization properties and density dependences. Decay times are given for exciton, trion, and biexciton states and evidence is shown for a spin-relaxation-limited energy relaxation of the trion. For the bright-exciton state the temperature dependence of the decay time is studied and a repopulation from the dark-exciton state is observed. Trion binding energies of 15–22 meV and biexciton binding energies of 19–26 meV are found.

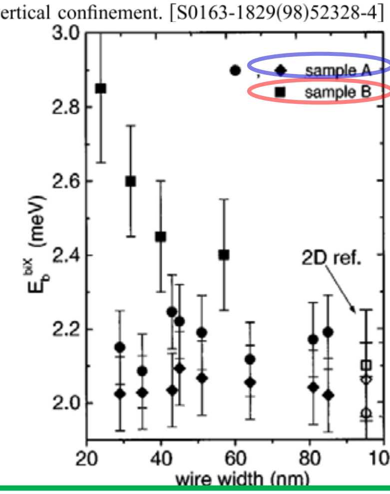
PHYSICAL REVIEW B VOLUME 58, NUMBER 4 15 JULY 1998-I

Biexcitons in semiconductor quantum wires

T. Baars, W. Braun, M. Bayer, and A. Forchel
Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
(Received 19 November 1997; revised manuscript received 4 May 1998)

We report on spectrally resolved four-wave mixing experiments on In_xGa_{1-x}As/GaAs quantum wires for a wide range of lateral sizes. Due to the polarization dependence of the four-wave mixing signal, beats in the decay of the signal and an additional emission line in the four-wave mixing spectrum can be clearly attributed to biexcitons. We find that the biexciton binding energy depends on both the vertical and lateral dimensions of the wires. For quantum wires with a large vertical confinement we observe an enhancement of the binding energy of about 40% as compared to a two-dimensional reference sample whereas the biexciton binding energy is found to be wire width independent in wires with shallow vertical confinement. [S0163-1829(98)52328-4]

	$E^B_{X^-}$	$E^B_{X^+}$
Thin (Theor.)	2.25	2.85
Thick (Theor.)	1.29	1.6



PHYSICAL REVIEW B **77**, 205413 (2008)

Influence of the shape and size of a quantum wire on the trion binding energy

Y. Sidor, B. Partoens,* and F. M. Peeters†
Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium
(Received 19 December 2007; revised manuscript received 11 April 2008; published 12 May 2008)

The binding energy for charged excitons (X^- and X^+) is calculated within the single-band effective mass approximation including effects due to strain for rectangular, triangular, and V-shaped quantum wires. Both X^- and X^+ are found to be bound in rectangular InAs/InP quantum wires and V-shaped GaAs/$Al_{0.32}Ga_{0.68}$As quantum wires. We found an appreciable dependence of the trion binding energy on the size and shape of the quantum wire. We compare with available experimental data.

RECENT EXPERIMENTS

Charged and Neutral Excitonic Complexes in CNs

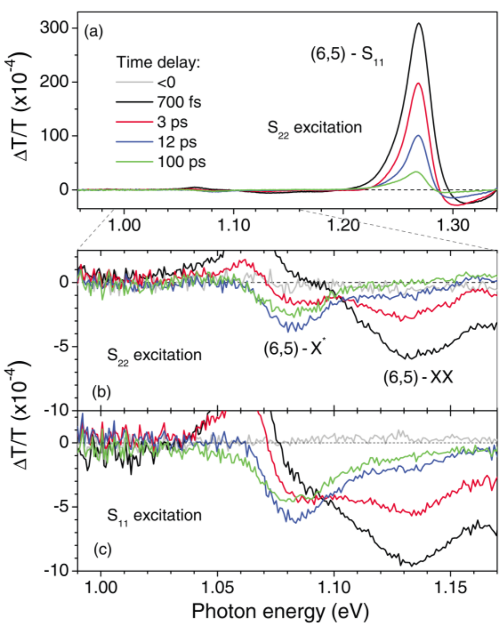
B.Yuma et al., Phys. Rev. B 87, 205412 (2013)
L.Colombier et al., Phys. Rev. Lett. 109, 197402 (2012)
R.Matsunaga et al., Phys. Rev. Lett. 106, 037404 (2011)

PHYSICAL REVIEW B **87**, 205412 (2013)

Biexciton, single carrier, and trion generation dynamics in single-walled carbon nanotubes

B. Yuma,[1] S. Berciaud,[1] J. Besbas,[1] J. Shaver,[2] S. Santos,[2] S. Ghosh,[3] R. B. Weisman,[3] L. Cognet,[2] M. Gallart,[1] M. Ziegler,[1] B. Hönerlage,[1] B. Lounis,[2] and P. Gilliot[1,*]
[1]*IPCMS, CNRS and Université de Strasbourg, 23, rue du Lœss, F-67034 Strasbourg, France*
[2]*LP2N, Université de Bordeaux, Institut d'Optique Graduate School, and CNRS, 351 cours de la Libération, F-33405 Talence, France*
[3]*Department of Chemistry and R. E. Smalley Institute for Nanoscale Science and Technology, Rice University, 6100 Main Street, Houston, Texas 77005, USA*
(Received 6 February 2013; published 8 May 2013)

We present a study of free carrier photogeneration and multicarrier bound states, such as biexcitons and trions (charged excitons), in semiconducting single-walled carbon nanotubes. Pump-and-probe measurements performed with fs pulses reveal the effects of strong Coulomb interactions between carriers on their dynamics. Biexciton formation by optical transition from exciton population results in an induced absorption line (binding energy 130 meV). Exciton-exciton annihilation process is shown to evolve at high densities towards an Auger process that can expel carriers from nanotubes. The remaining carriers give rise to an induced absorption due to trion formation (binding energy 190 meV). These features show the dynamics of exciton and free carriers populations.

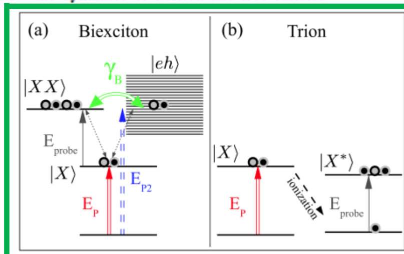


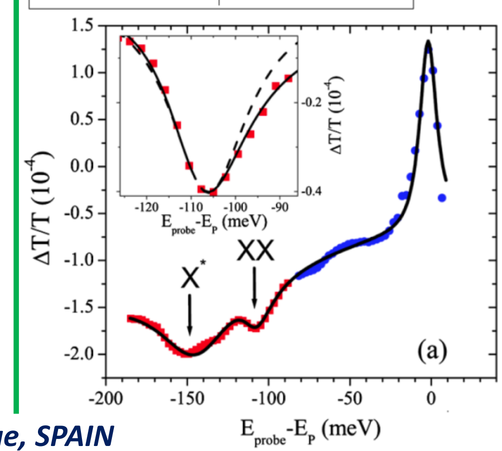
Selected for a Viewpoint in *Physics*
PRL **106**, 037404 (2011) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2011

Observation of Charged Excitons in Hole-Doped Carbon Nanotubes Using Photoluminescence and Absorption Spectroscopy

Ryusuke Matsunaga,[1] Kazunari Matsuda,[1] and Yoshihiko Kanemitsu[1,2]
[1]*Institute for Chemical Research, Kyoto University, Uji, Kyoto 611-0011, Japan*
[2]*Photonics and Electronics Science and Engineering Center, Kyoto University, Kyoto 615-8510, Japan*
(Received 13 September 2010; published 18 January 2011)

We report the first observation of trions (charged excitons), three-particle bound states consisting of one electron and two holes, in hole-doped carbon nanotubes at room temperature. When *p*-type dopants are added to carbon nanotube solutions, the photoluminescence and absorption peaks of the trions appear far below the E_{11} bright exciton peak, regardless of the dopant species. The unexpectedly large energy separation between the bright excitons and the trions is attributed to the strong electron-hole exchange interaction in carbon nanotubes.





PRL **109**, 197402 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

Detection of a Biexciton in Semiconducting Carbon Nanotubes Using Nonlinear Optical Spectroscopy

L. Colombier,[1,2] J. Selles,[1,2] E. Rousseau,[1,2] J. S. Lauret,[3] F. Vialla,[4] C. Voisin,[4] and G. Cassabois[1,2,*]
[1]*Laboratoire Charles Coulomb UMR5221, Université Montpellier 2, F-34095 Montpellier, France*
[2]*Laboratoire Charles Coulomb UMR5221, CNRS, F-34095 Montpellier, France*
[3]*LPQM-ENS-Cachan, 61 Avenue du Président Wilson, 94235 Cachan Cedex, France*
[4]*Laboratoire Pierre Aigrain, Ecole Normale Supérieure, Université Paris Diderot, CNRS UMR8551, 24 rue Lhomond, 75231 Paris Cedex 5, France*
(Received 17 July 2012; published 7 November 2012)

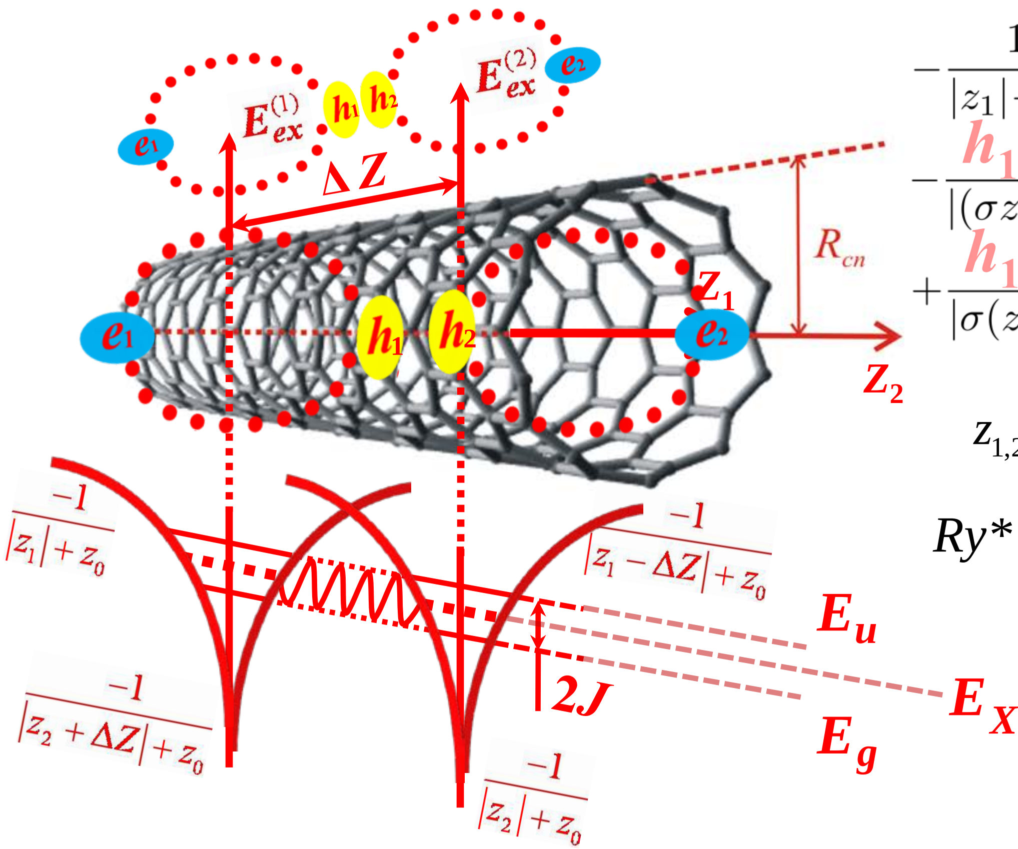
We report the observation of the biexciton in semiconducting single-wall carbon nanotubes by means of nonlinear optical spectroscopy. Our measurements reveal the universal asymmetric line shape of the Fano resonance intrinsic to the biexciton transition. For nanotubes of the (9,7) chirality, we find a biexciton binding energy of 106 meV. From the calculation of the $\chi^{(3)}$ nonlinear response, we provide a quantitative interpretation of our measurements, leading to an estimation of the characteristic Fano factor q of 7 ± 3. This value allows us to extract the first experimental information on the biexciton stability and we obtain a biexciton annihilation rate comparable to the exciton-exciton annihilation one.

Also trion binding energy of 150 meV reported

BIEXCITON

Biexciton Binding Energy within the Landau-Herring Approach

Landau, Quantum Mechanics; C.Herring, Rev. Mod. Phys. 34, 631 (1962)
MODEL developed: I.V.Bondarev, Phys. Rev. B 83, 153409 (2011)



$$\hat{H}(z_1,z_2,\Delta Z)=-\frac{\partial^2}{\partial z_1^2}-\frac{\partial^2}{\partial z_2^2}$$

$$-\frac{1}{|z_1|+z_0}-\frac{1}{|z_1-\Delta Z|+z_0}-\frac{1}{|z_2|+z_0}-\frac{1}{|z_2+\Delta Z|+z_0}$$

$$-\frac{2}{|(\sigma z_1+z_2)/\lambda+\Delta Z|+z_0}-\frac{2}{|(z_1+\sigma z_2)/\lambda-\Delta Z|+z_0}$$

$$+\frac{2}{|\sigma(z_1-z_2)/\lambda+\Delta Z|+z_0}+\frac{2}{|(z_1-z_2)/\lambda-\Delta Z|+z_0}$$

(h_1-e_2, h_2-e_1, h_1-h_2, e_1-e_2)

$$z_{1,2}=z_{e1,2}-z_{h1,2};\ \lambda=1+\sigma;\ \sigma=m_e/m_h\rightarrow 1$$

due to the mass reversal effect

$$Ry^*=\frac{\hbar^2}{2\mu a_B^{*2}}=\frac{\mu(\text{in}\,m_0)}{\varepsilon^2}13.6\,\text{eV};\ a_B^*=\frac{\varepsilon}{\mu}0.529\,\mathring{A}$$

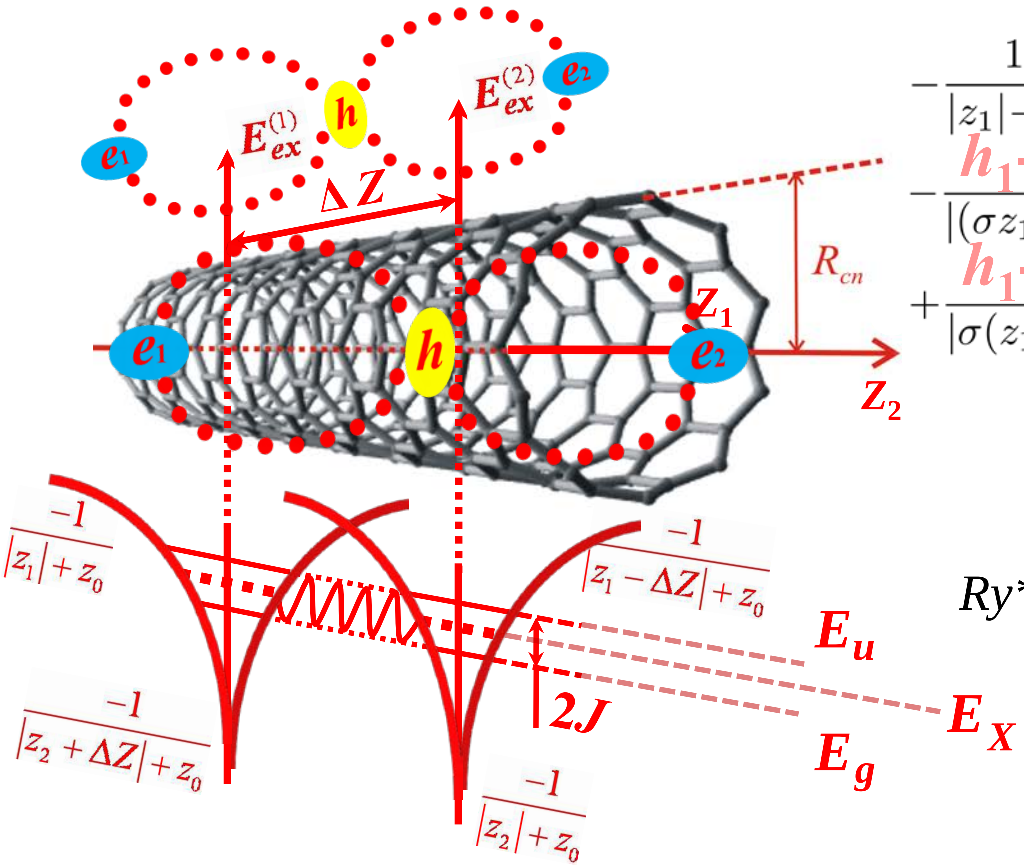
Biexciton Binding Energy

$$E_{XX}=E_g-2E_X=-J_{XX}(\Delta Z_0)$$

TRION

Trion Binding Energy within the Landau-Herring Approach

Landau, Quantum Mechanics; C.Herring, Rev. Mod. Phys. 34, 631 (1962)
MODEL developed: I.V.Bondarev, Phys. Rev. B 90, 245430 (2014)



$$\hat{H}(z_1,z_2,\Delta Z)=-\frac{\partial^2}{\partial z_1^2}-\frac{\partial^2}{\partial z_2^2}$$

$$-\frac{1}{|z_1|+z_0}-\frac{1}{|z_1-\Delta Z|+z_0}-\frac{1}{|z_2|+z_0}-\frac{1}{|z_2+\Delta Z|+z_0}$$

$$\underbrace{-\frac{2}{|(\sigma z_1+z_2)/\lambda+\Delta Z|+z_0}}_{h_1\text{-}e_2}\underbrace{-\frac{2}{|(z_1+\sigma z_2)/\lambda-\Delta Z|+z_0}}_{h_2\text{-}e_1}$$

$$\underbrace{+\frac{2}{|\sigma(z_1-z_2)/\lambda+\Delta Z|+z_0}}_{h_1\text{-}h_2}\underbrace{+\frac{2}{|(z_1-z_2)/\lambda-\Delta Z|+z_0}}_{e_1\text{-}e_2}$$

positive trion $z_{1,2}=z_e-z_{h1,2}$ **negative trion** $z_{1,2}=z_{e1,2}-z_h$

$$\lambda=1+\sigma;\quad \sigma=m_e/m_h\to 1$$

due to the mass reversal effect

$$Ry^*=\frac{\hbar^2}{2\mu a_B^{*2}}=\frac{\mu(\text{in }m_0)}{\varepsilon^2}13.6\,\text{eV};\quad a_B^*=\frac{\varepsilon}{\mu}0.529\,\mathring{A}$$

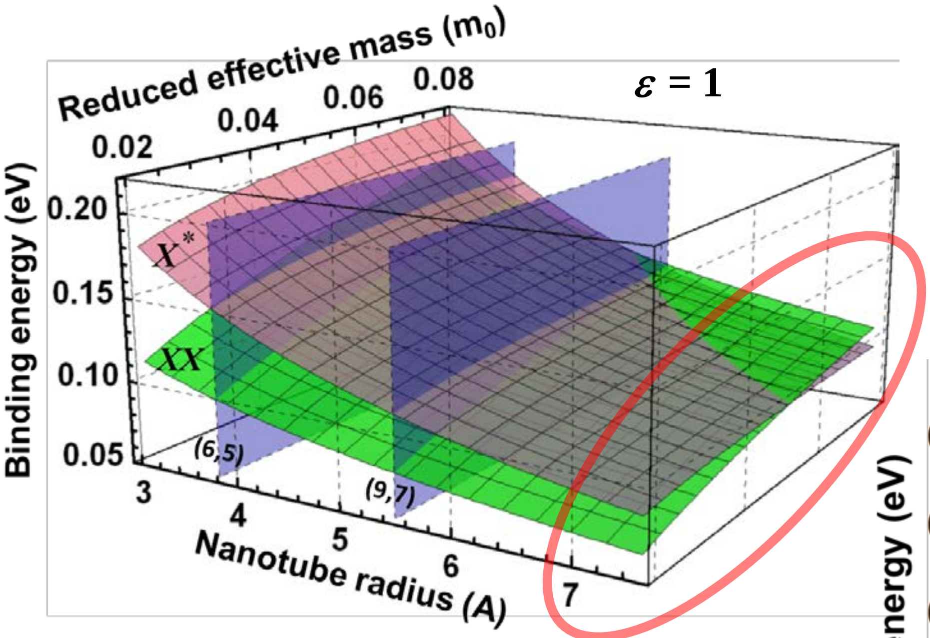
Trion Binding Energy

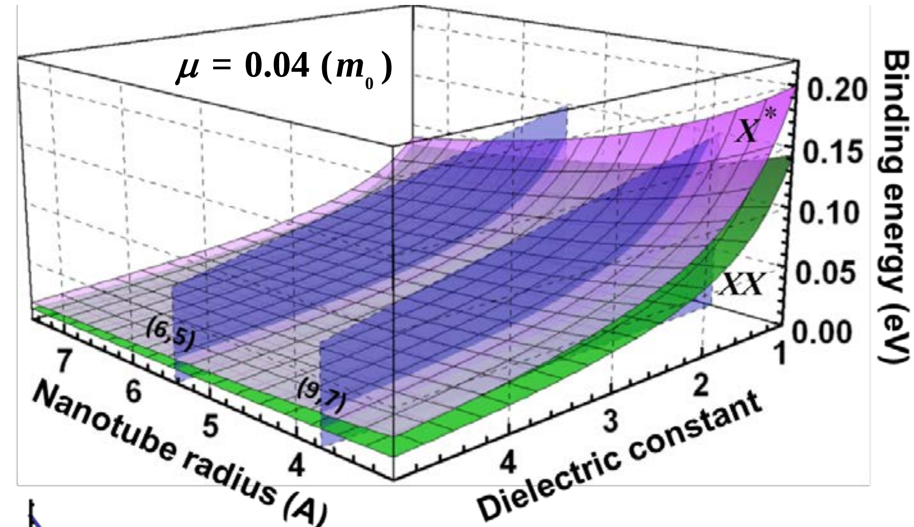
$$E_{X^*}=E_g-2E_X=-J_{X^*}(\Delta Z_0)$$

BINDING ENERGY DEPENDENCE ON THE CN DIAMETER, EFFECTIVE MASS, AND DIELECTRIC CONSTANT

I.V.Bondarev, Phys. Rev. B 90, 245430 (2014)

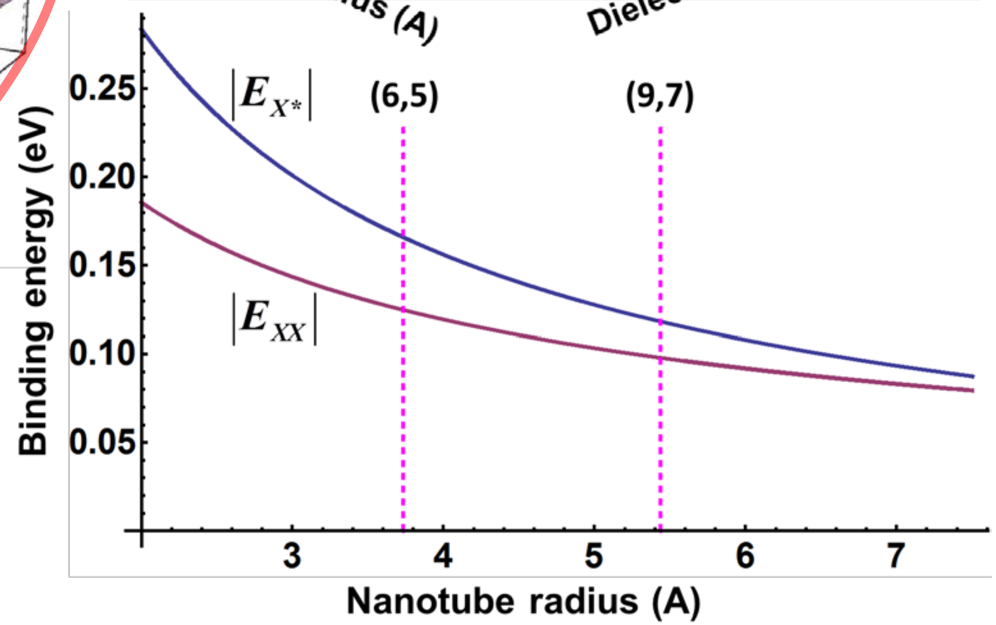
$$Ry^* = \frac{\mu}{\varepsilon^2} 13.6\,\text{eV}; \quad a_B^* = \frac{\varepsilon}{\mu} 0.529\,\mathring{A}$$





$$\varepsilon = 1, \ \mu = 0.04\,(m_0) \quad \Rightarrow$$

CNs in air [or in a dielectric, for the lowest excitation energy ground-state exciton only]

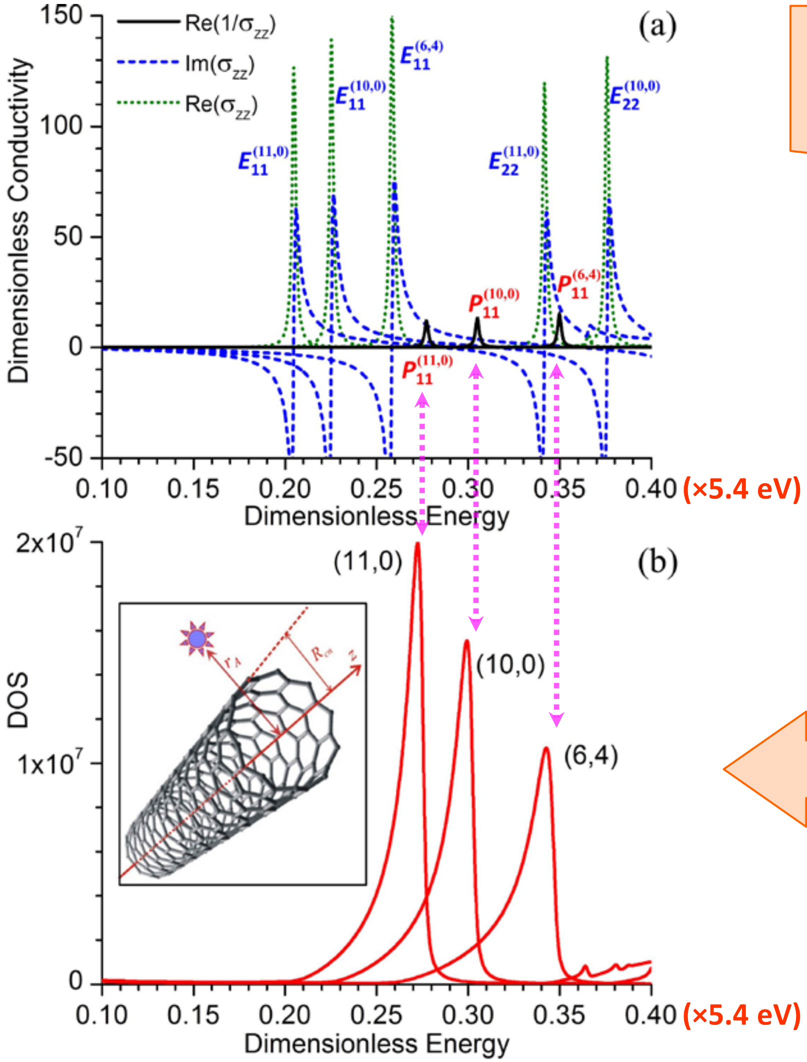


OUTLINE

- ***Pristine Semiconducting Carbon Nanotubes: Excitons and Interband Plasmons – Brief Review***
- ***Plasmon Generation by Optically Excited Excitons, Exciton BEC Effect***
- ***Excitonic Complexes (Biexcitons & Trions) in quasi-1D: Brief Review, Landau-Herring Approach to Understand Relative Stability***
- ***Hybrid Carbon Nanotube Systems: Plasmon Enhanced Raman Scattering Effect***
- ***Summary***

INTERBAND PLASMONS OF CARBON NANOTUBES ARE SIMILAR TO CAVITY PHOTONS IN MICROCAVITY SYSTEMS

I.V.Bondarev & Ph.Lambin, Phys. Rev. B 72, 035451 (2005);
also Ch.6, pp.139-183 in "Trends in Nanotubes Research" (Nova Science, 2006)

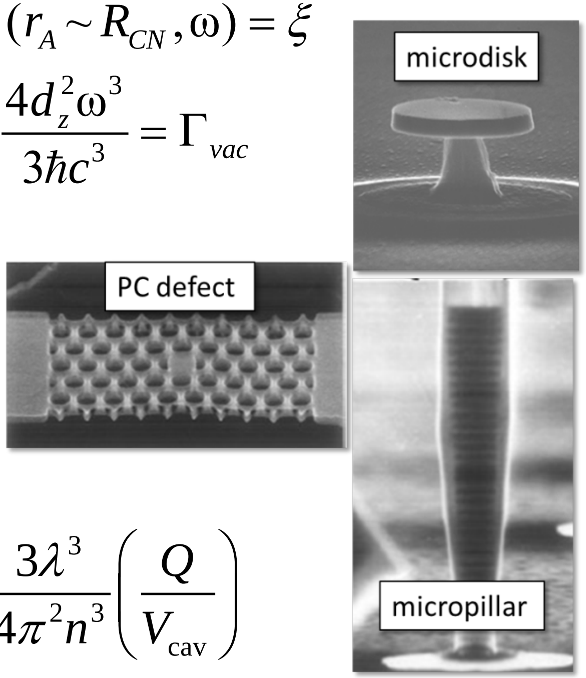


Local Density of Photonic States (DOS) for a two-level emitter coupled to ⊥ (||)-polarized electromagnetic field (same as Purcell factor)

$$\xi^{\perp(\|)}(\mathbf{r}_A,\omega)=\frac{\mathrm{Im}^{\perp(\|)}G_{zz}^{\perp(\|)}(\mathbf{r}_A,\mathbf{r}_A,\omega)}{\mathrm{Im}G_{zz}^{0}(\omega)}$$

$$\xi^{\perp}(r_A\sim R_{CN},\omega)=\xi^{\|}(r_A\sim R_{CN},\omega)=\xi$$

$$\xi=\frac{\Gamma(r_A,\omega)}{\Gamma_0(\omega)},\quad \Gamma_0=\frac{4d_z^2\omega^3}{3\hbar c^3}=\Gamma_{vac}$$



$$F_{Purcell}=\frac{\Gamma_{cav}}{\Gamma_{vac}}=\frac{3\lambda^3}{4\pi^2n^3}\left(\frac{Q}{V_{cav}}\right)$$

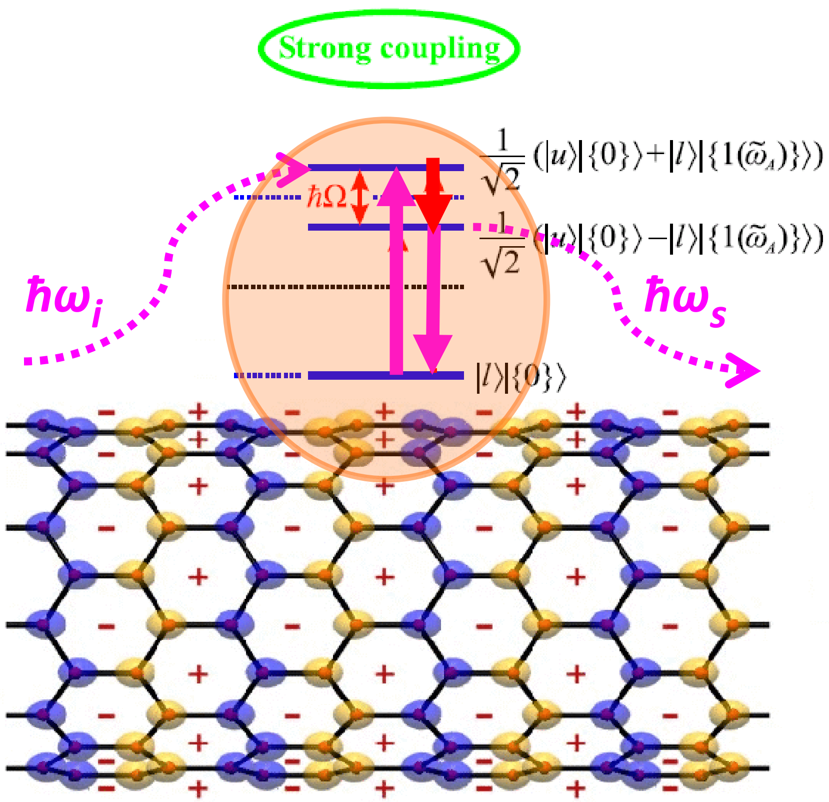
*J.M.Gerard, in: **Single Quantum Dots**, P.Michler, ed., Topics Appl. Phys. 90, 269–315 (2003)*

LIGHT SCATTERING BY A TWO-LEVEL EMITTER COUPLED TO AN INTERBAND PLASMON RESONANCE

Schematic illustration

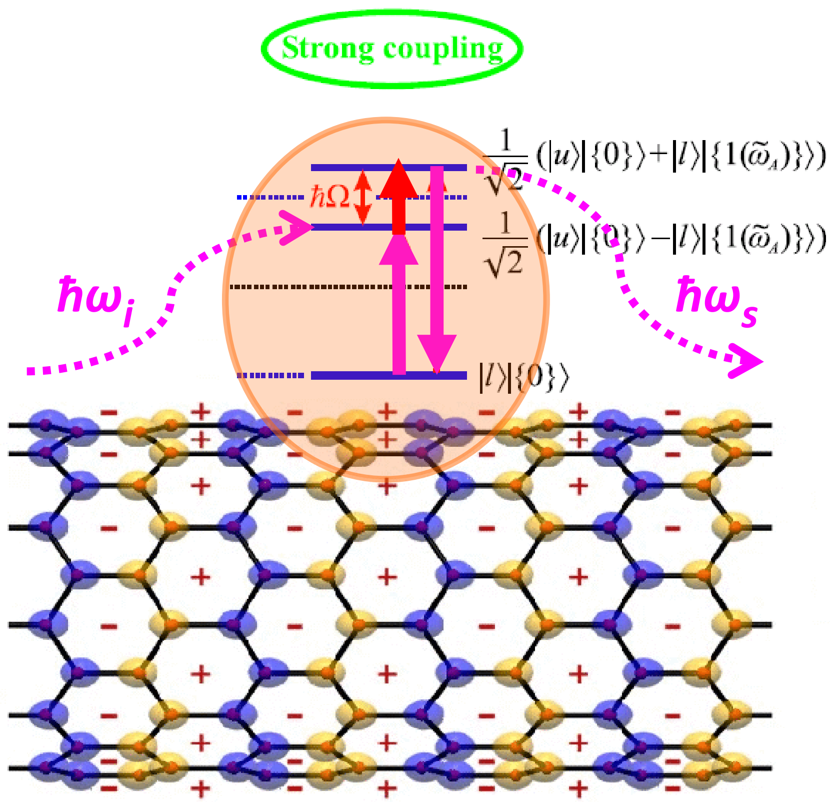
Plasmon Emission

$\hbar\omega_s = \hbar\omega_i - \hbar\omega_p$



Plasmon Absorption

$\hbar\omega_s = \hbar\omega_i + \hbar\omega_p$



$$d_z E_z^{(loc)}(\mathbf{r}_A) \sim X \propto [\Gamma_0(\omega_p)\xi(\mathbf{r}_A,\omega_p)]^{1/2}$$

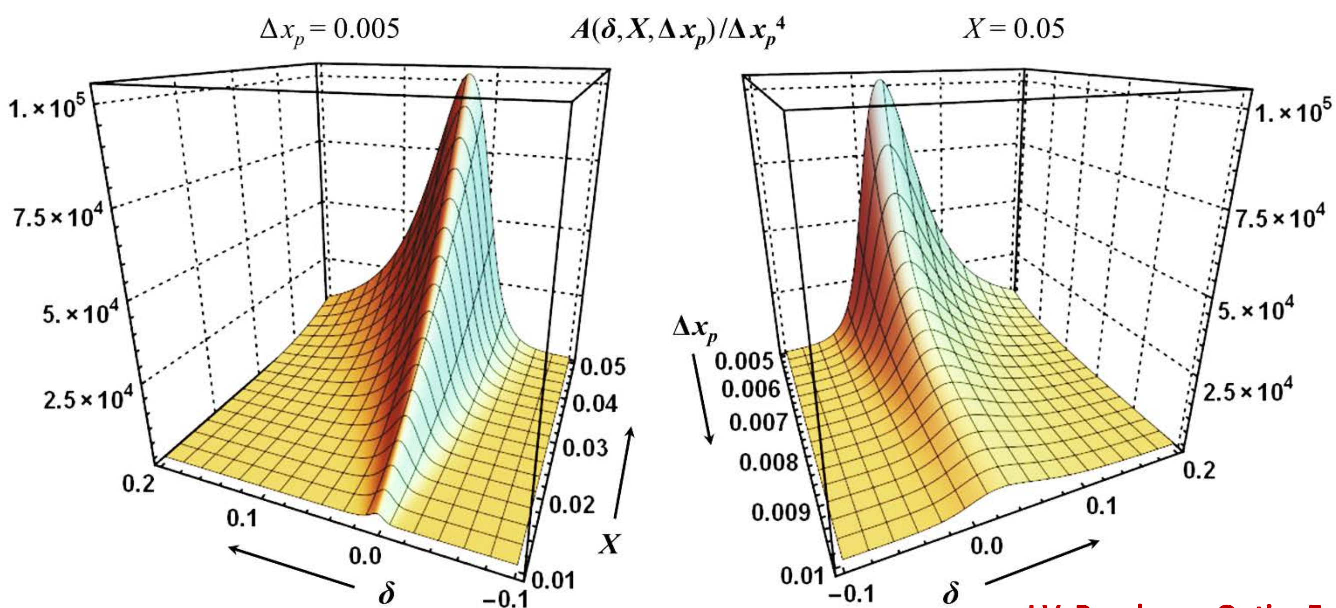
PLASMON ENHANCED RAMAN SCATTERING EFFECT FOR AN ATOM NEAR A CARBON NANOTUBE

Raman scattering cross-section. Enhancement factor

$$\frac{d\sigma}{d\Omega_s}=\frac{(2\gamma_0)^2|d_z|^4}{\hbar^4c^4}\cos^2\vartheta_i\cos^2\vartheta_s\,P(x_i,x_s)\,,\quad x_{i,s}=\hbar\omega_{i,s}/2\gamma_0,\quad \cos\theta_{i,s}=\mathbf{e}_{i,s}\cdot\mathbf{e}_z$$

$$P(x_i,x_s)\;=\;x_ix_s^3A(\delta,X,\Delta x_p)\left\{\frac{1}{[(x_i-x_p-\delta_+/2)^2+\Delta x_p^2][(x_s-x_p-\delta_-/2)^2+\Delta x_p^2]}+\frac{1}{[(x_i-x_p-\delta_-/2)^2+\Delta x_p^2][(x_s-x_p-\delta_+/2)^2+\Delta x_p^2]}\right\},\qquad \delta_\pm\;=\;\delta\pm\sqrt{\delta^2+X^2}$$

$$A(\delta,X,\Delta x_p)=\frac{X^8}{2^6(\delta^2+X^2)^2(\delta_-^2+\Delta x_p^2)}\sim[d_zE_z^{(loc)}(\mathbf{r}_A)]^4\propto\xi^2(\mathbf{r}_A,\omega_p)$$



I.V. Bondarev, Optics Express 23, 3971 (2015)

SUMMARY

- **NANOOPTOPLASMONICS WITH PRISTINE AND HYBRID QUASI-1D SYSTEMS. Examples outlined:**
  (1) controlled absorption due to plasmon generation by optically excited excitons in individual CNs;
  (2) quasi-1D exciton BEC in individual semiconducting CNs due to the exciton-plasmon coupling controlled by a perpendicular electrostatic field applied *[~1 V/nm, T<100 K experimentally accessible, opens up perspectives to develop coherent polarized light source with CNs]*;
  (3) Landau-Herring approach to uncover relative stability peculiarities for lowest energy excitonic complexes in quasi-1D semiconductors: trions are more stable in strongly confined quasi-1D structures with small reduced electron-hole masses; biexcitons are more stable in less confined structures with large reduced electron-hole masses *[spintronics & nonlinear optics in quasi-1D]*;
  (4) plasmon enhanced Raman scattering near CNs *[single molecule/atom/ion detection, precision spontaneous emission control, optical manipulation, …]*;
  (5) *more to come (optical nonlinearities & transport in hybrid CNs, BEC in double wall CNs, CN arrays)…*

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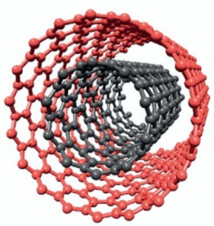
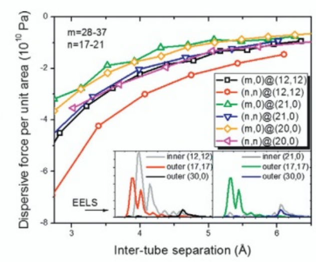
Guest Editors
Tobias Hertel and Igor Bondarev





FROM L.M. WOODS, GRAPHICAL ABSTRACT, CONTENTS LIST, PAGES 116–122, IN THIS ISSUE.

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