Far-infrared absorption of quantum dots; From single dots to arrays

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How to break Kohn's theorem?

FIR-absorption - Time-dependent HFA

$$\hat{H}(t) = \hat{H}_{HF} + \delta\hat{V}e^{-i(\omega+i0^+)t}$$

$$\hat{\rho}(t\to -\infty) = \hat{\rho}^0 = f(\hat{H}_{HF})$$

Linear response

$$\delta\rho_{\alpha,\beta}(t) = f^{\alpha,\beta}(\omega)\langle\alpha|\delta\hat{V}|\beta\rangle e^{-i(\omega+i0^+)t}$$

with

$$f^{\alpha,\beta}(\omega) = \left\{\frac{f(\epsilon_\beta)-f(\epsilon_\alpha)}{\hbar\omega+\epsilon_\beta-\epsilon_\alpha+i\hbar 0^+}\right\}$$

Nonlocal exchange

$$\delta V_{\alpha,\beta} = (-e)\left\{\langle\alpha|\phi_{ext}|\beta\rangle + \langle\alpha|\phi^H_{ind}|\beta\rangle + \langle\alpha|\phi^F_{ind}|\beta\rangle\right\}$$

Self-consistency $\longleftarrow \langle\alpha|\phi^{H,F}_{ind}|\beta\rangle \sim \delta\rho_{\alpha,\beta}.$

$$\sum_{\delta,\gamma}\epsilon_{\alpha\beta,\delta\gamma}(\omega)\langle\delta|\phi_{sc}|\gamma\rangle = \langle\alpha|\phi_{ext}|\beta\rangle$$

with

$$\epsilon_{\alpha\beta,\delta\gamma}(\omega) = \left\{\delta_{\delta,\alpha}\delta_{\gamma,\beta} - (H_{\gamma\delta,\beta\alpha} - F_{\gamma\delta,\beta\alpha})\, f^{\delta\gamma}(\omega)\right\}$$

$$H_{\gamma\delta,\beta\alpha} = \frac{e^2}{\kappa}\int d\mathbf{r}d\mathbf{r}'\,\frac{\psi^*_\gamma(\mathbf{r}')\psi_\delta(\mathbf{r}')\psi^*_\alpha(\mathbf{r})\psi_\beta(\mathbf{r})}{|\mathbf{r}-\mathbf{r}'|}$$

$$F_{\gamma\delta,\beta\alpha} = \frac{e^2}{\kappa}\int d\mathbf{r}d\mathbf{r}'\,\frac{\psi^*_\gamma(\mathbf{r}')\psi_\delta(\mathbf{r})\psi^*_\alpha(\mathbf{r}')\psi_\beta(\mathbf{r})}{|\mathbf{r}-\mathbf{r}'|}.$$

Now one could use

$$\det \epsilon_{\alpha\beta,\delta\gamma}(\omega) = 0, \qquad \alpha = (n, M, s)$$

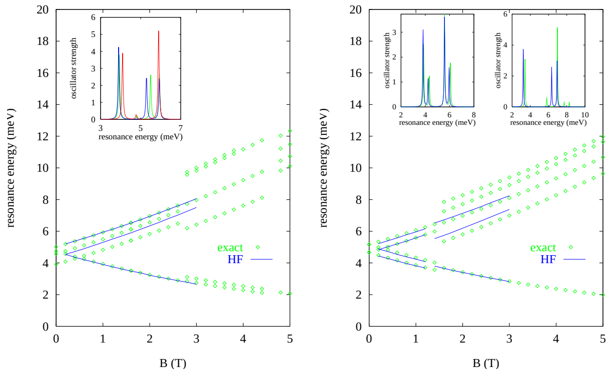
or calculate the absorption

$$P(\omega) = \frac{1}{2}\int d\mathbf{r}\ \mathrm{Re}\left[\delta\mathbf{j}(\mathbf{r})\cdot\mathbf{E}^*_{sc}(\mathbf{r})\right]$$
$$\sim \Im\sum_{\alpha\beta}\omega\langle\beta|\phi_{ext}|\alpha\rangle\langle\alpha|\phi_{sc}|\beta\rangle f^{\alpha\beta}(\omega)$$

Few electrons

Radial deviations

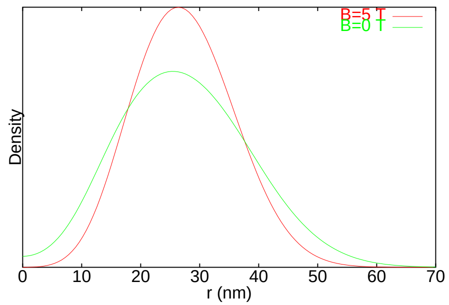
$$V_{conf}(r) = ar^2 + br^4 + cr^6$$

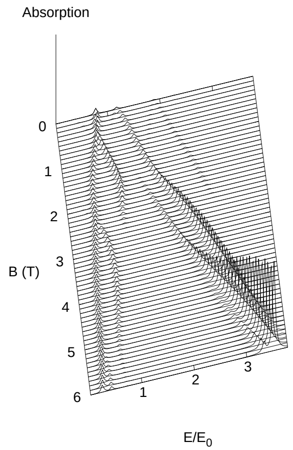


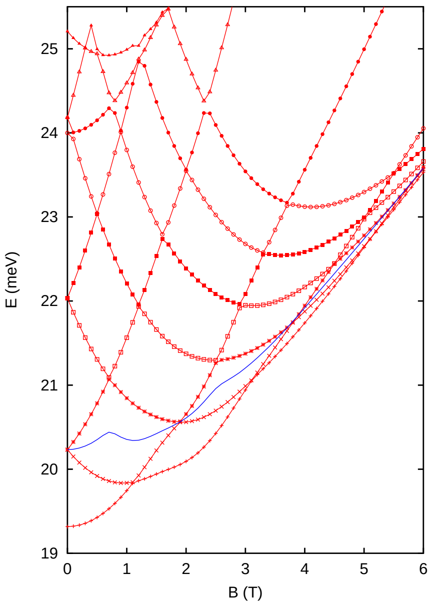
$N = 3$, spin doublet, spin quartet

Fingerprints of few electron states

Circular dot with a soft hole in the center



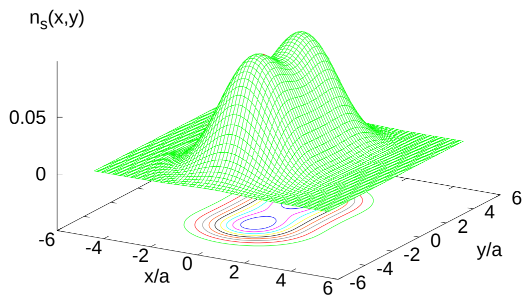




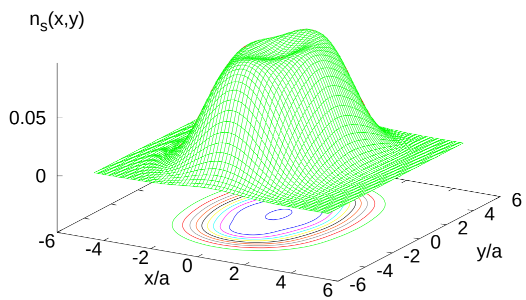
- A. Lorke and R. J. Luyken, Physica B 256-258, 424 (1998)

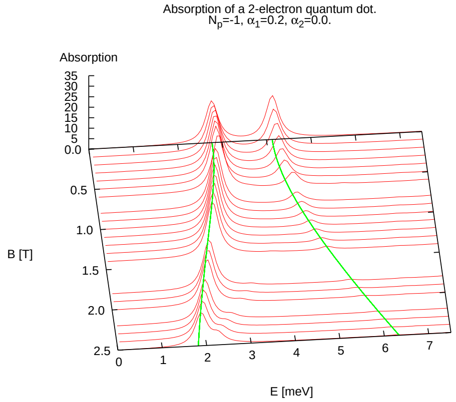
Angular deviations, elliptic

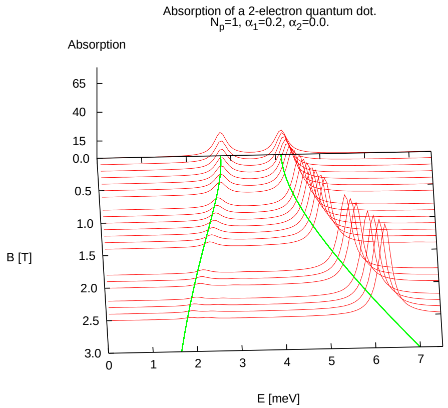
α_1=0.2, α_2=0.0, Ns=2, B=0 T.



α_1=0.2, α_2=0.0, Ns=3, B=0 T.



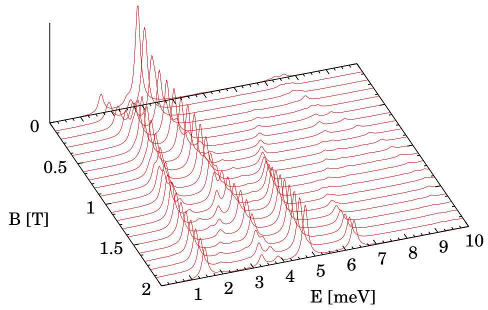




cm modes, Kohn's theorem holds

Angular deviations, square

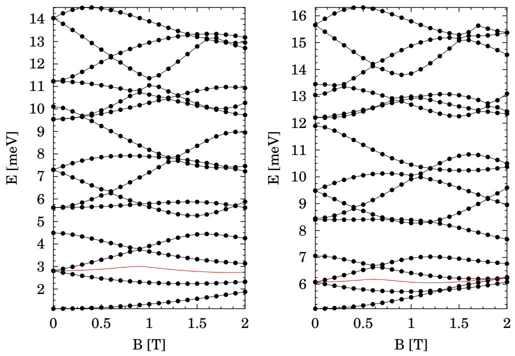
Hard wall square 100 nm×100 nm



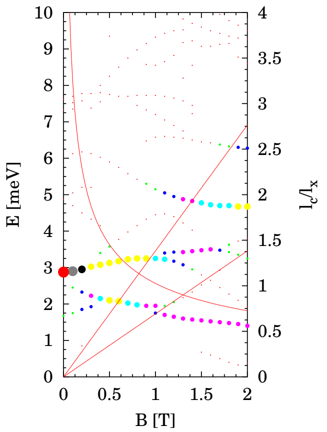
Also

- R. Ugajin, Phys. Rev. B**53**, 6963 (1996)

Noninteracting ↔ interacting



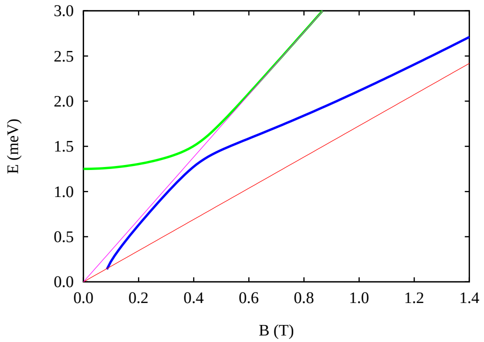
FIR dispersion, not simple perturbed cm. modes



Many electrons

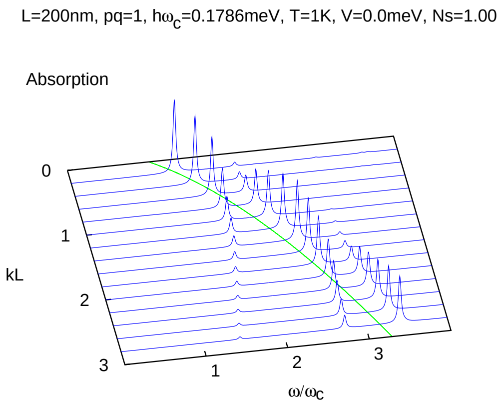
Bernstein modes

- Waves in a Plasma in a Magnetic Field, I. B. Bernstein, Phys. Rev. **109**, 10 (1958)
- N. J. M. Horing and M. M. Yildis, Annals of Physics **97**, 216 (1976).



Classical effect, blocked by Kohn's theorem

2DEG - no modulation

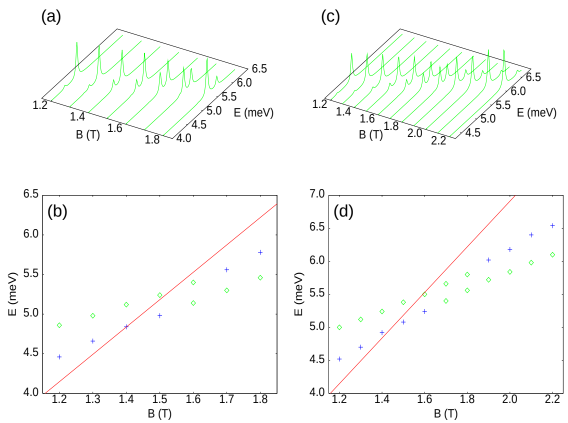


- **k** $\neq 0$ breaks Kohn's theorem
- Magnetoplasmon interacts with harmonics of the cyclotron resonance
- Cyclotron resonance seen in longitudinal excitation due to density modulation by the magnetoplasmon

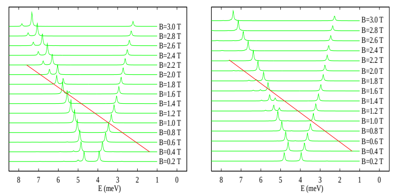
Quantum dots

3D↔2D↔1D↔0D

br^4-deviation ↔ cr^6-deviation



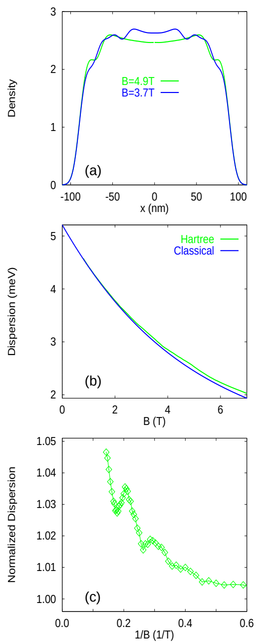
$N = 16$, HA ↔ HFA



Not seen for few electrons!

ω_- oscillations

br^4-deviation



- K. Bollweg, T. Kurth, D. Heitmann, V. Gudmundsson,...
  Phys. Rev. Lett. **76**, 2774 (1996)
- T. Darnhofer, M. Suhrke, U. Rössler, Europhys. Lett. **35**, 591 (1996)

Ground state

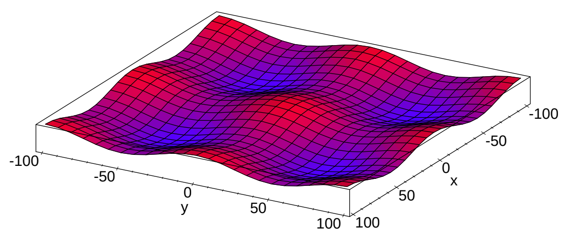
2DEG in a periodic potential

$$V(x,y) = V\{\cos(gx) + \cos(gy)\}$$

$g = 2\pi/L$, with the periodic length L

Perpendicular magnetic field $\mathbf{B} = B\hat{\mathbf{z}}$

Integer number pq of flux units $\Phi_0 = hc/e$ flows through a lattice unit cell with area $A = L^2 \longrightarrow B = pq\Phi_0/A$



$$\phi_{n_l}^{\mu\nu}(\mathbf{r}) = \frac{1}{\sqrt{pq}} \sum_{\substack{m,n \\ =-\infty}}^{\infty} \left[S(\mathbf{c})e^{-i\mu}\right]^m \left[S(\mathbf{d})e^{-i\nu}\right]^n \phi_{n_l}(\mathbf{r})$$

$$\mu = \frac{\theta_1 + 2\pi n_1}{p}, \quad n_1 \in I_1 = \{0, \ldots, p-1\}$$

$$\nu = \frac{\theta_2 + 2\pi n_2}{q}, \quad n_2 \in I_2 = \{0, \ldots, q-1\}$$

$$\phi_{n_l}(\mathbf{r}) = \frac{1}{\sqrt{2\pi n_l! l^2}} \left(\frac{x+iy}{\sqrt{2}l}\right)^{n_l} \exp\left(-\frac{r^2}{4l^2}\right)$$

Complete orthogonal basis in $\mathcal{H}_{\theta_1\theta_2}$ if $(\mu,\nu) \neq (\pi,\pi)$ for all $(n_1,n_2) \in I_1 \times I_2$

Periodic on the finer lattice

$$S(\mathbf{c})\phi_{n_l}^{\mu\nu} = e^{i\mu}\phi_{n_l}^{\mu\nu}, \quad S(\mathbf{d})\phi_{n_l}^{\mu\nu} = e^{i\nu}\phi_{n_l}^{\mu\nu}$$

$$\mathbf{c} = \frac{\mathbf{l}_1}{p}, \quad \mathbf{d} = \frac{\mathbf{l}_2}{q}, \quad pq \in \mathbf{N}$$

FIR-absorption, THFA

Self-consistent response to the in-field

$$\mathbf{E}_{ext}(\mathbf{r},t) = -i\mathcal{E}_0 \frac{\mathbf{k}+\mathbf{G}}{|\mathbf{k}+\mathbf{G}|} \exp\{i(\mathbf{k}+\mathbf{G})\cdot\mathbf{r} - i\omega t\}$$

System properties $\rightarrow$ $\epsilon_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\omega)$ $\rightarrow$ self-consistent field $-\nabla\phi_{sc}$

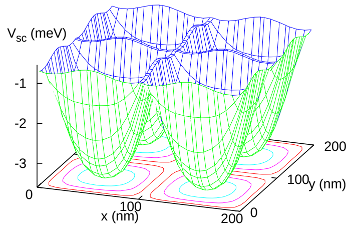
$$\sum_{\mathbf{G}'} \epsilon_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\omega)\phi_{sc}(\mathbf{k}+\mathbf{G}',\omega) = \phi_{ext}(\mathbf{k}+\mathbf{G},\omega)$$

Joule heating $\rightarrow$ power absorption

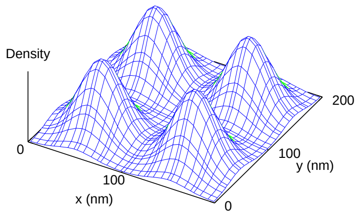
$$P(\mathbf{k}+\mathbf{G},\omega) = -\frac{\omega}{4\pi}\Im\{\mathcal{E}_0\phi_{sc}(\mathbf{k}+\mathbf{G},\omega)\}$$

Quantum dots

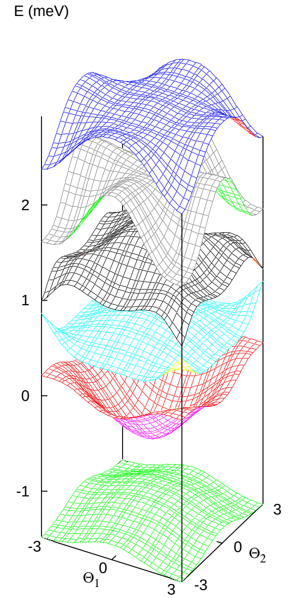
Potential



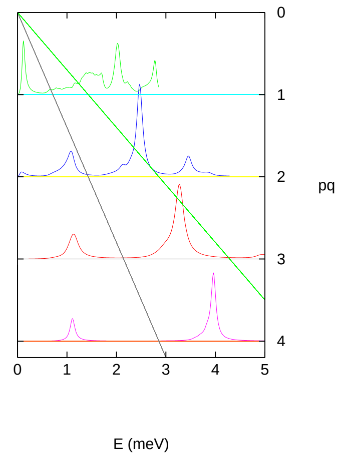
Density



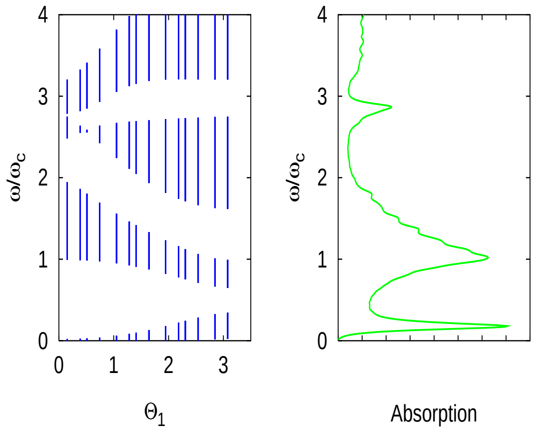
Energy spectrum, $pq = 1$, $N_s = \frac{1}{2}$, $L = 100$ nm



Absorption, $L = 100$, $V = -5$ meV, $N_s = \frac{1}{2}$

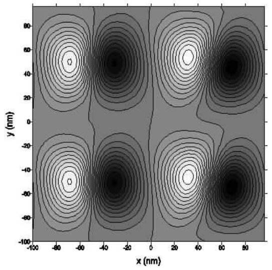


$pq = 1$

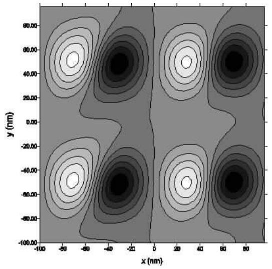


- $\hbar\omega_c = 0.714$ meV, $V = -5$ meV
- Intra-band transitions
- Single-particle transitions

Induced density, $pq = 3$, $N_s = \frac{1}{2}$, $l = 23$ nm



$E = \hbar\omega = 1.13$ meV



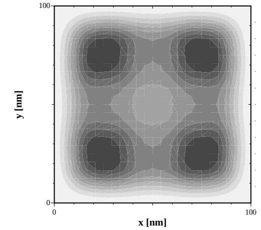
$E = \hbar\omega = 3.27$ meV

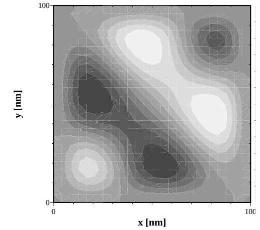
Finite system, 2×2 dots

Short "lattice" constant $L = 50$ nm

Weak modulation $V_0 = -5$ meV

Density $\leftrightarrow$ Induced density





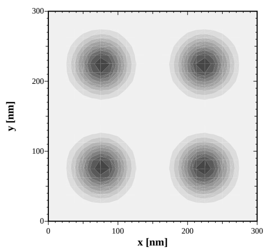
Overlapping density, $B = 0$T

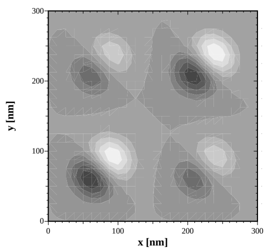
Finite system 2×2 dots

$L = 150$ nm

$V_0 = -10$ meV

Density $\leftrightarrow$ Induced density





Vanishing density overlap, Coulomb coupling

Also found for the infinite periodic system

Conclusion

- We can see inside quantum dots with FIR spectroscopy
- Experiments on dots with few electrons will be refined
- Coupled dots
- Microscopic picture of the Bernstein modes?
- Antidots