Spontaneous Layer Imbalance in Double-Layer Electron Systems[1]

— J. C. Díaz-Vélez, C. B. Hanna
Boise State University

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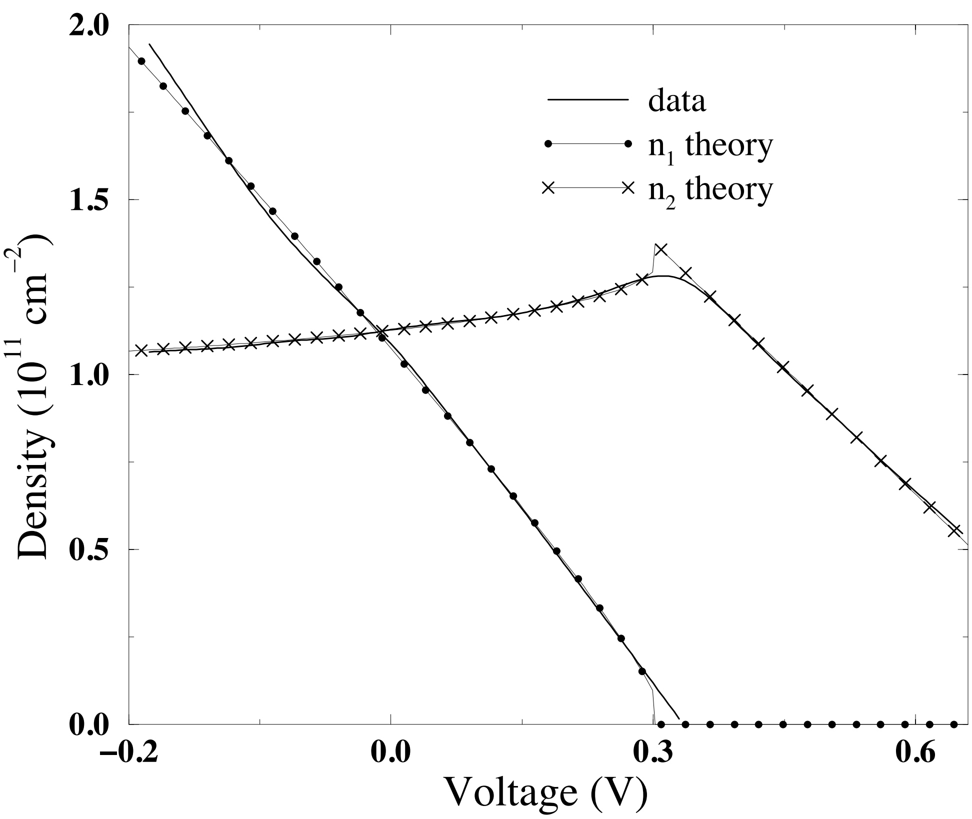
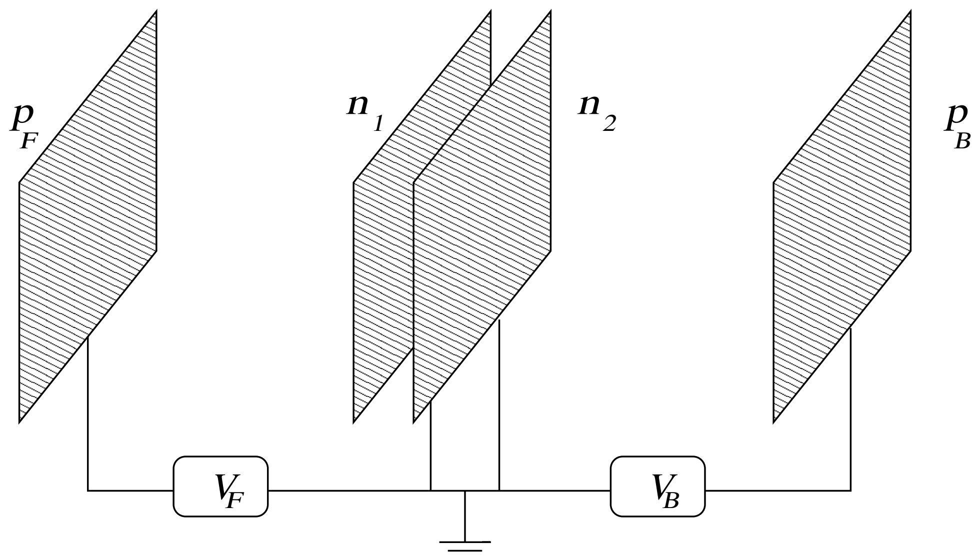
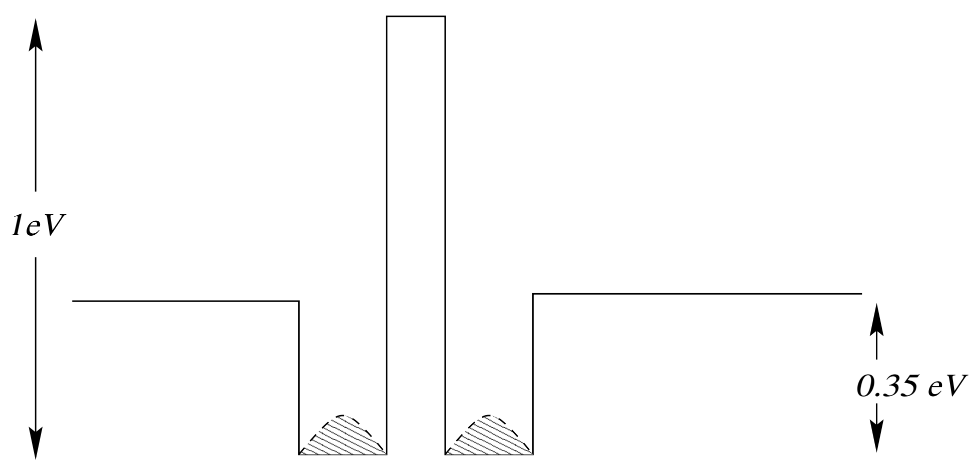
Original Motivation: SdH data

- Undergrad Project: apply basic Q.M. to model 2LE(H)S
- Max. simplicity: 2D layers, Gauss' Law, E_F, Exchange
- **A**brupt Interlayer **C**harge **T**ransfer (ACT)
  ...unavoidable without *interlayer* correlations

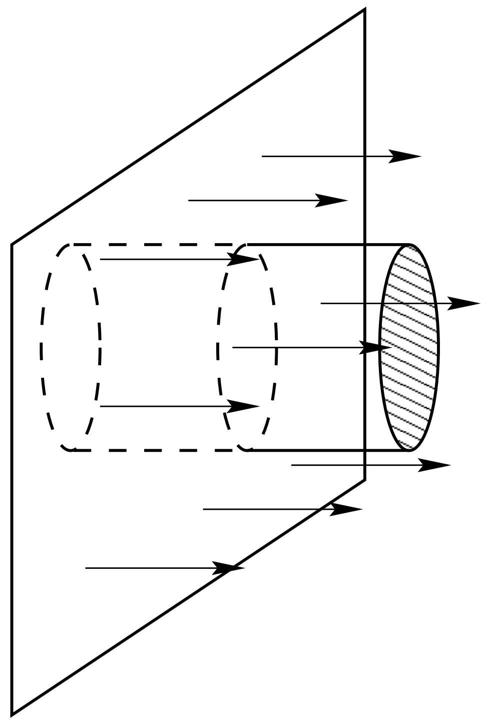


Double-Layer System:





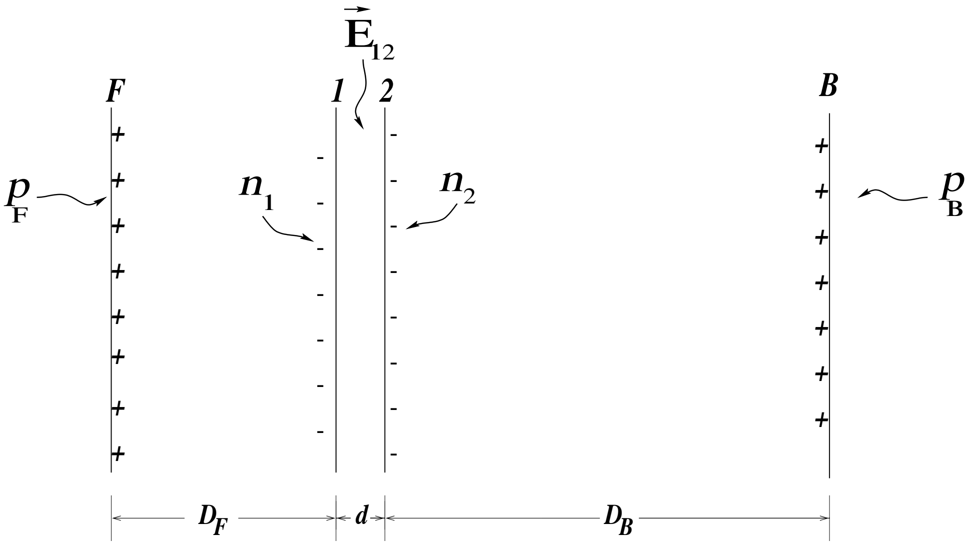
Gauss' Law:



$$\mathbf{E}\cdot d\mathbf{s} = \frac{\sigma A}{\epsilon}$$

$$E = \frac{\sigma}{\epsilon} = \frac{en}{\epsilon}$$

Classical Coulomb Energy:



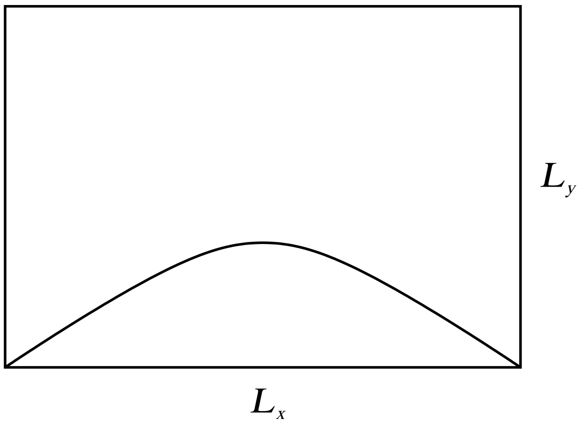
Charge neutrality: $n_1 + n_2 = p_F + p_B$.

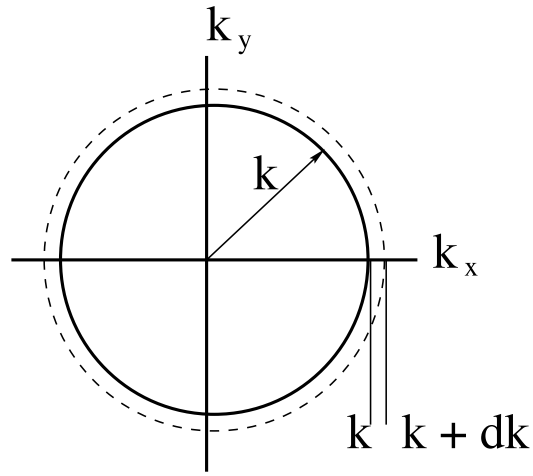
$$\frac{U}{A} = \frac{\epsilon}{2}|\vec{E}_{12}|^2 d$$

$$\text{Minimize} \quad U \;\Rightarrow\; E_{12} = 0$$

$$\Rightarrow\; n_1 = p_F, \qquad n_2 = p_B \ldots \text{“screening”}$$

Basic Q.M. (2D Electron Gas):





$$\psi_{\vec{k}}(x,y) = A sin(k_x x) sin(k_y y)$$

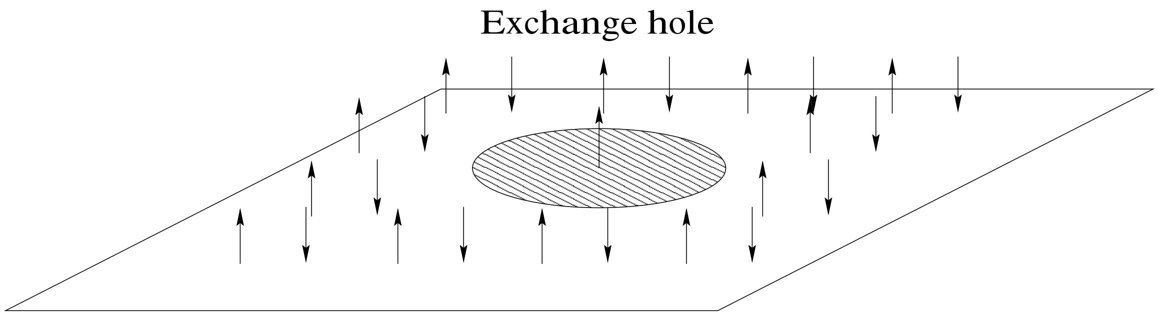
$$\mathcal{E}_k = \frac{\hbar^2 \vec{k}^2}{2m^*}, \qquad k_\alpha = n_\alpha \pi / L$$

$$k_F = \sqrt{4\pi / g_s n}$$

$$\frac{K.E.}{A} = \frac{n}{2} E_F = \frac{2}{g_s} \frac{n^2}{\nu_0}, \qquad (g_s = 1, 2)$$

where $\nu_0 = \frac{\text{D.O.S}}{\text{Area}} = \frac{m^*}{\pi \hbar^2}$.

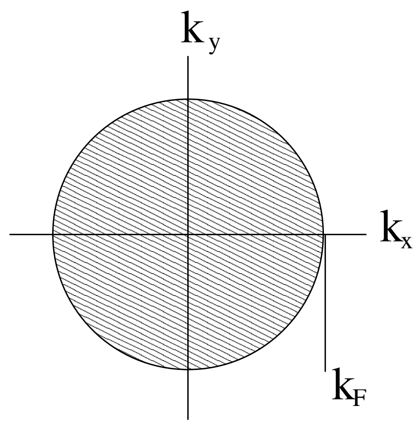
Exchange Energy:



$$\frac{U_x}{A} \propto \frac{-e^2 n}{4\pi\epsilon r_0} \propto \frac{-e^2 n^{3/2}}{4\pi\epsilon}$$

Hartree-Fock Approximation (HFA):

$$\mathcal{E} = \langle \Psi_0 | \mathcal{H} | \Psi_0 \rangle = \langle \Psi_0 | (\mathcal{H}_0 + V) | \Psi_0 \rangle$$

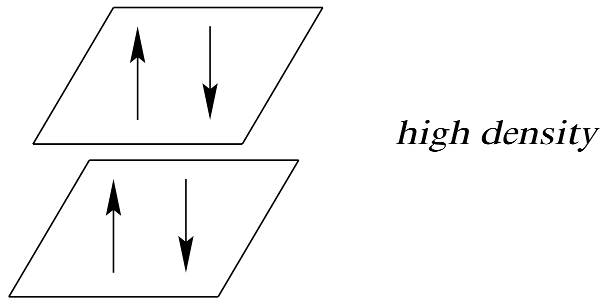
$\boldsymbol{\Psi_0} \approx$ 

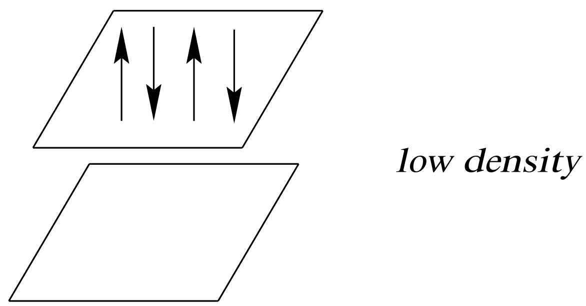
- Energy/Area:

$$\frac{\mathcal{E}}{L_x L_y} = \underbrace{\frac{e^2}{8\epsilon}(n_1 - p_F - n_2 + p_B)^2}_{\text{Coulomb}} + \underbrace{\frac{1}{\nu_0}\left(\frac{n_1^2}{g_{s_1}} + \frac{n_2^2}{g_{s_2}}\right)}_{\text{kinetic}} - \underbrace{\frac{8}{3\sqrt{\pi}}\frac{e^2}{4\pi\epsilon}\left(\frac{n_1^{3/2}}{g_{s_1}^{1/2}} + \frac{n_2^{3/2}}{g_{s_2}^{1/2}}\right)}_{\text{exchange}}$$

- Method: minimize $\mathcal{E}/L_x L_y$ using charge neutrality: $p_F + p_B = n_1 + n_2 \Rightarrow n_2 = p_F + p_B - n_1$.
- Here: focus on "balanced" gates: $p_F = p_B$. You might think $n_1 = n_2$ but not always so!

Ruden and Wu: [APL **59**, 2165 (1991)]

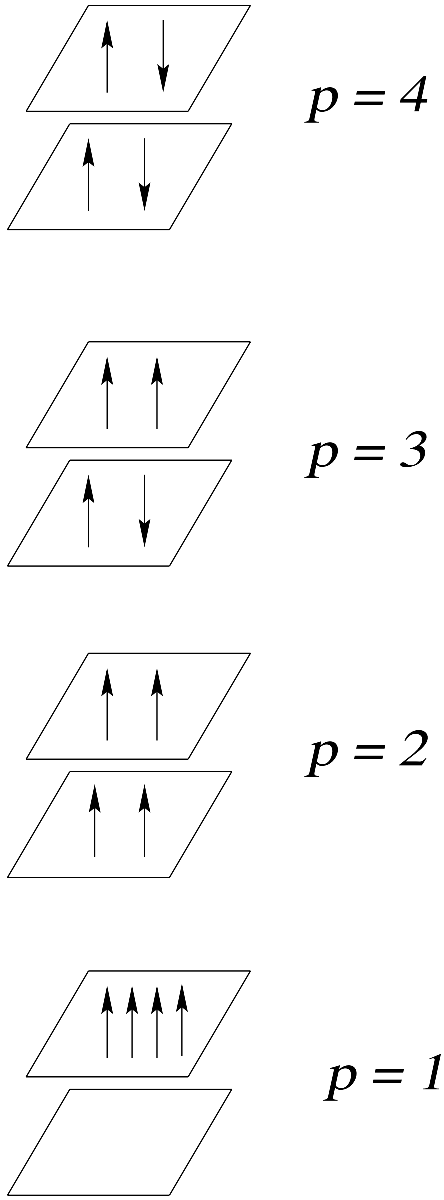




- Hartree-Fock, unpolarized real spins
- High density: "usual" $n_1 = n_2$
  Low density: "bistable" $n_1 = 0$ or $n_2 = 0$
  ... ACT
  Adding *intra*layer correlations does not eliminate ACT.
- Problem: No ↑↑↑↑
  ... real spins polarize before ACT
  ... ref. Zheng *et al.* [PRB **55**, 4506 (1997)]

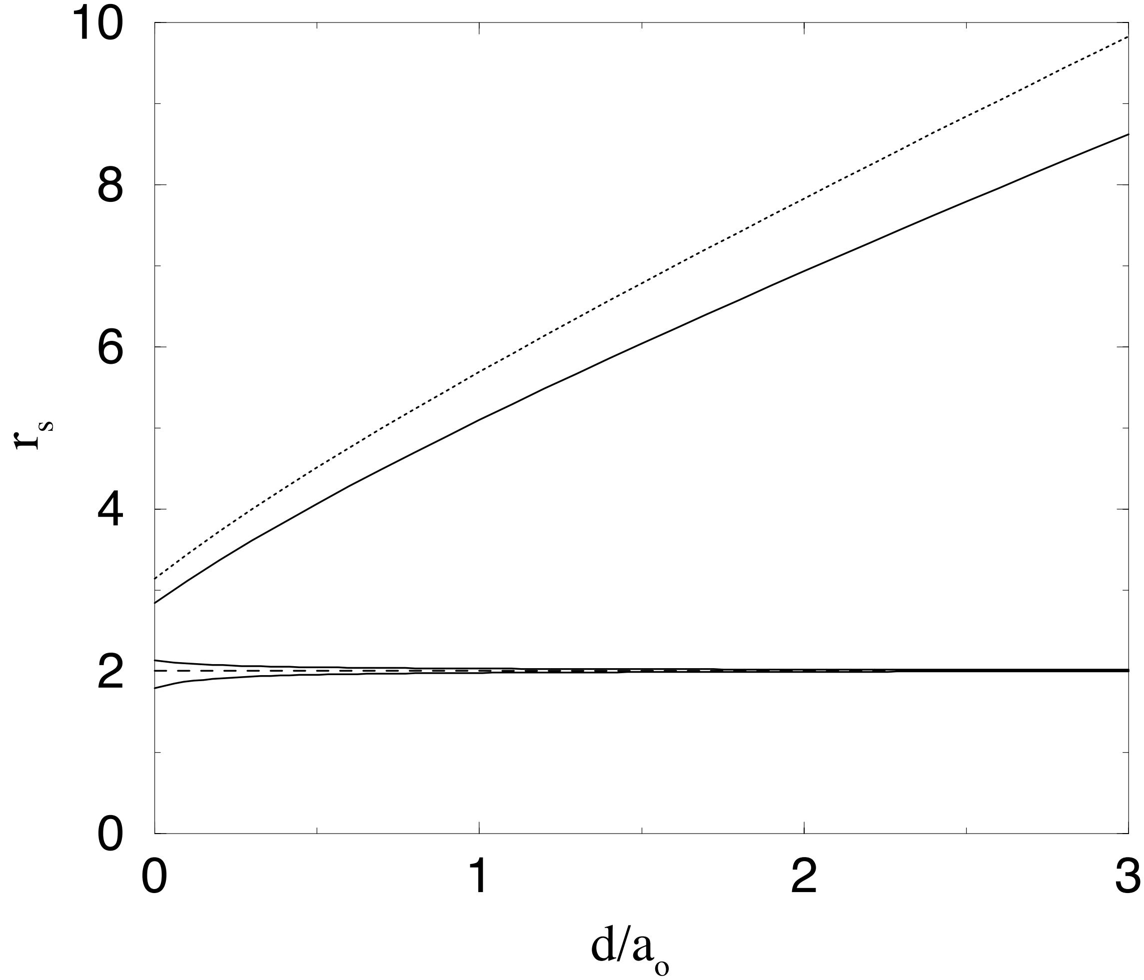
4 Noncrystalline Phases ($p_F = p_B$):

Hanna *et al.* [PRB **61** (15 June 2000)]



(For $r_s \to \infty$, expect Wigner crystal.)

Balanced Case: Four Phases

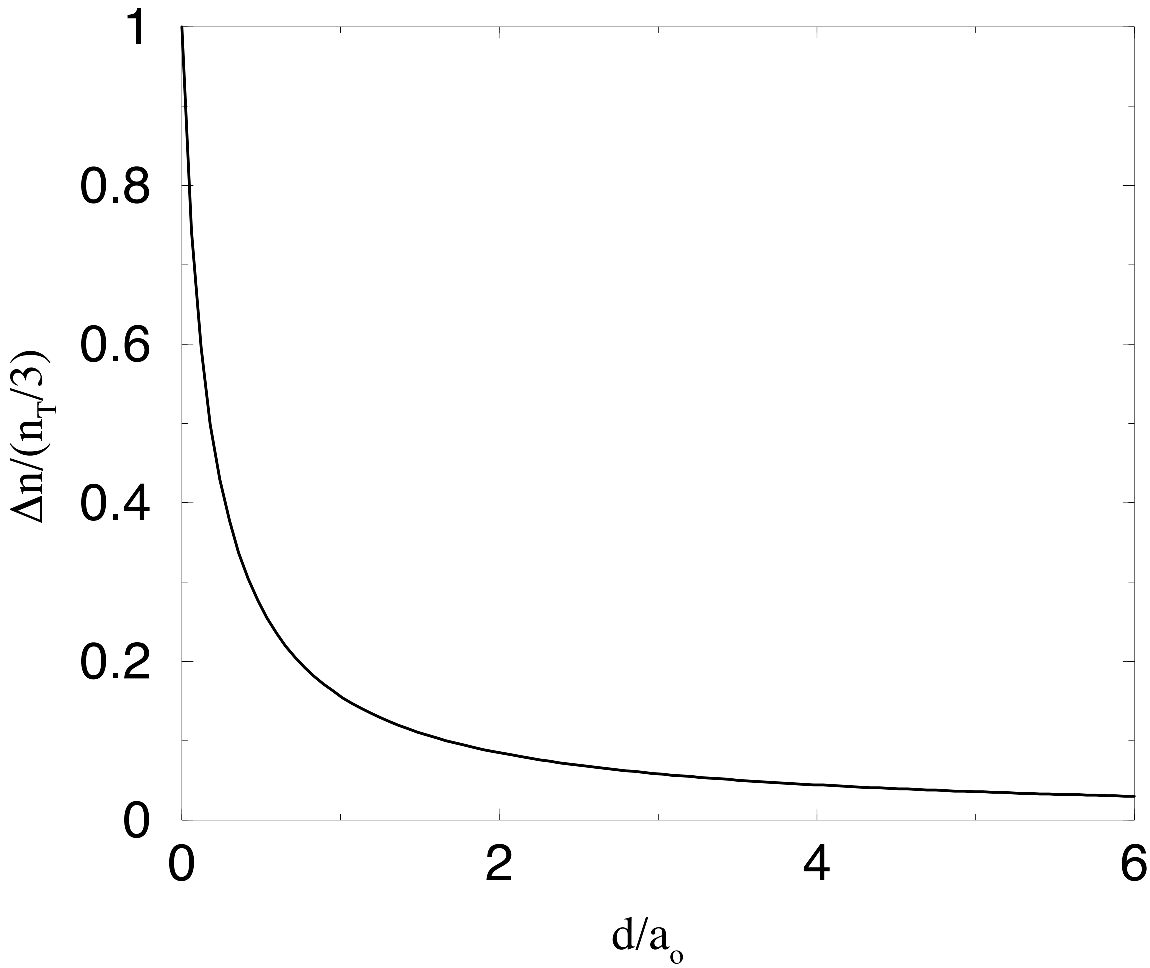


$$r_s = \frac{r_0}{a_0} \;=\; \frac{1}{\sqrt{\pi(n_T/2)a_0^2}}$$

$$a_0 \;=\; \frac{4\pi\epsilon\hbar^2}{m^* e^2}, \quad \text{(effective Bohr radius)}$$

Three-Component State: Always Unbalanced

One higher-density spin-unpolarized layer,
one lower-density spin-polarized layer . . . even when $p_F = p_B$!



For $(d/a_0 \to \infty)$,

$$\frac{U_c}{A} = \frac{\epsilon}{2}|\vec{E}_{12}|^2 d \quad \Rightarrow \quad (n_1 = n_2).$$

Summary:

- Simple HFA-based model of unpolarized spins without interlayer correlations gives good fit to SdH data.

- HFA gives 4 non-crystalline phases.

- Three-Component Phase: Unbalanced even for $p_F = p_B$. "Small" Ruden-Wu bistability, ACT, $|R_E| \to \infty$.

- Detection

  – Shubnikov-de Haas (SdH) measurements.

    R_{xx} vs. $1/B$: oscillations of period Δ.

    $$\Delta p(1/B) = \frac{e}{h}\frac{p}{n_T}.$$

  – Eisenstein Ratio: [PRL **68**, 674 (1992)]

    $$R_E = \delta E_{12}/\delta E_F = 1 - \delta n_1/\delta p_F$$

    very sensitive measure of interlayer capacitance.
    (Far more sensitive than SdH for detecting **ACT**).

- One-component phase: a superposition of both layers (see Zheng *et al.* [PRB **55**, 4506 (1997)]), no **ACT**.