

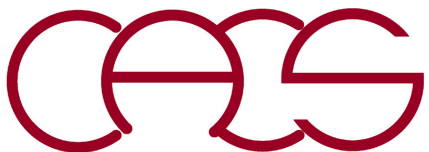
Exchange-Correlation Functional

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**How to incorporate many-electron correlations into effective
single-electron (Kohn-Sham) equations?**



Preliminary: Second Quantization (1)

- Consider a system of N electrons with the Hamiltonian

$$H = \sum_{i=1}^N h(\mathbf{r}_i) + \frac{1}{2} \sum_{i \neq j} u(\mathbf{r}_i, \mathbf{r}_j)$$
$$h(\mathbf{r}) = -\frac{\hbar^2}{2m} \nabla^2 + v(\mathbf{r}); \quad u(\mathbf{r}, \mathbf{r}') = \frac{e^2}{|\mathbf{r} - \mathbf{r}'|}$$

- Occupation-number representation:** An antisymmetric Fermionic wave function can be expanded as a linear combination of Slater determinants

$$\Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) = \sum_{n_1, \dots, n_\infty \in \{0,1\}} f(n_1, \dots, n_\infty) \Phi_{n_1, \dots, n_\infty}(\mathbf{r}_1, \dots, \mathbf{r}_N)$$

where n_κ is the occupation number of the κ -th single-electron state $\psi_\kappa(\mathbf{r})$, with the constraint $\sum_\kappa n_\kappa = N$, and each Slater determinant (which occupies states $\kappa_1 < \kappa_2 < \dots < \kappa_N$) is

$$\Phi_{\kappa_1, \dots, \kappa_N}(\mathbf{r}_1, \dots, \mathbf{r}_N) = \frac{1}{\sqrt{N!}} \begin{bmatrix} \psi_{\kappa_1}(\mathbf{r}_1) & \cdots & \psi_{\kappa_1}(\mathbf{r}_N) \\ \vdots & \ddots & \vdots \\ \psi_{\kappa_N}(\mathbf{r}_1) & \cdots & \psi_{\kappa_N}(\mathbf{r}_N) \end{bmatrix}$$

$$= \frac{1}{\sqrt{N!}} \sum_P (-1)^P \psi_{\kappa_{P(1)}}(\mathbf{r}_1) \cdots \psi_{\kappa_{P(N)}}(\mathbf{r}_N)$$

Permutation

Preliminary: Second Quantization (2)

- The quantum-dynamical system is identical to

$$\Psi = \sum_{n_1, \dots, n_\infty \in \{0,1\}} f(n_1, \dots, n_\infty) (\hat{a}_1^\dagger)^{n_1} \dots (\hat{a}_\infty^\dagger)^{n_\infty} |0\rangle$$

Vacuum

with the Hamiltonian operator

$$\hat{H} = \sum_{m,n} \hat{a}_m^\dagger \langle m|h|n\rangle \hat{a}_n + \frac{1}{2} \sum_{m,n,p,q} \hat{a}_m^\dagger \hat{a}_n^\dagger \langle mn|u|pq\rangle \hat{a}_q \hat{a}_p$$

$$\left\{ \begin{array}{l} \langle m|h|n\rangle = \int d\mathbf{r} \psi_m^*(\mathbf{r}) h(\mathbf{r}) \psi_n(\mathbf{r}) \\ \langle mn|u|pq\rangle = \int d\mathbf{r} d\mathbf{r}' \psi_m^*(\mathbf{r}) \psi_n^*(\mathbf{r}') u(\mathbf{r}, \mathbf{r}') \psi_p(\mathbf{r}) \psi_q(\mathbf{r}') = [m^*p|u|n^*q] \end{array} \right.$$

Physicist's notation Chemist's notation

and the creation (\hat{a}_m^\dagger) & annihilation (\hat{a}_p) operators anticommute

$$\left\{ \begin{array}{l} \{\hat{a}_\kappa, \hat{a}_{\kappa'}^\dagger\} = \delta_{\kappa, \kappa'} \\ \{\hat{a}_\kappa, \hat{a}_{\kappa'}\} = \{\hat{a}_\kappa^\dagger, \hat{a}_{\kappa'}^\dagger\} = 0 \end{array} \right.$$

Preliminary: Second Quantization (3)

- **Hamiltonian operator in the coordinate representation**

$$\hat{H} = \hat{T} + \hat{V} + \hat{U}$$
$$\left\{ \begin{array}{l} \hat{T} = \frac{\hbar^2}{2m} \int d\mathbf{r} \nabla \hat{\psi}^\dagger(\mathbf{r}) \cdot \nabla \hat{\psi}(\mathbf{r}) \\ \hat{V} = \int d\mathbf{r} \hat{\psi}^\dagger(\mathbf{r}) v(\mathbf{r}) \hat{\psi}(\mathbf{r}) = \int d\mathbf{r} \hat{\rho}(\mathbf{r}) v(\mathbf{r}) \\ \hat{U} = \frac{1}{2} \int d\mathbf{r} d\mathbf{r}' \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}') \frac{e^2}{|\mathbf{r} - \mathbf{r}'|} \hat{\psi}(\mathbf{r}') \hat{\psi}(\mathbf{r}) \end{array} \right.$$

- **See note on** second quantization

A. L. Fetter & J. D. Walecka, *Quantum Theory of Many-Particle Systems* (McGraw-Hill, '71)

A. Szabo & N. S. Ostlund, *Modern Quantum Chemistry* (McMillan, '82)

Preliminary: Hartree-Fock Approximation

- **Hartree-Fock approximation** determines the “best single Slater determinant” that minimizes the energy

$$\Phi = \frac{1}{\sqrt{N!}} \sum_P (-1)^P \phi_{P(1)}(\mathbf{r}_1) \cdots \phi_{P(N)}(\mathbf{r}_N)$$

$$\hat{f}(\mathbf{r})\phi_i(\mathbf{r}) = \epsilon_i \phi_i(\mathbf{r})$$

$h(\mathbf{r}) + \sum_{j=1}^N (J_j(\mathbf{r}) - K_j(\mathbf{r}))$ Fock operator

$$\begin{cases} J_j(\mathbf{r})\phi(\mathbf{r}) = \int dr \frac{e^2}{|\mathbf{r} - \mathbf{r}'|} \phi_j^*(\mathbf{r}')\phi_j(\mathbf{r}')\phi(\mathbf{r}) \\ K_j(\mathbf{r})\phi(\mathbf{r}) = \int dr \frac{e^2}{|\mathbf{r} - \mathbf{r}'|} \phi_j^*(\mathbf{r}')\phi(\mathbf{r}')\phi_j(\mathbf{r}) \end{cases}$$

- **See note on** Hartree-Fock approximation

Energy Functional

Exchange-correlation (xc) functional *via* Kohn-Sham decomposition

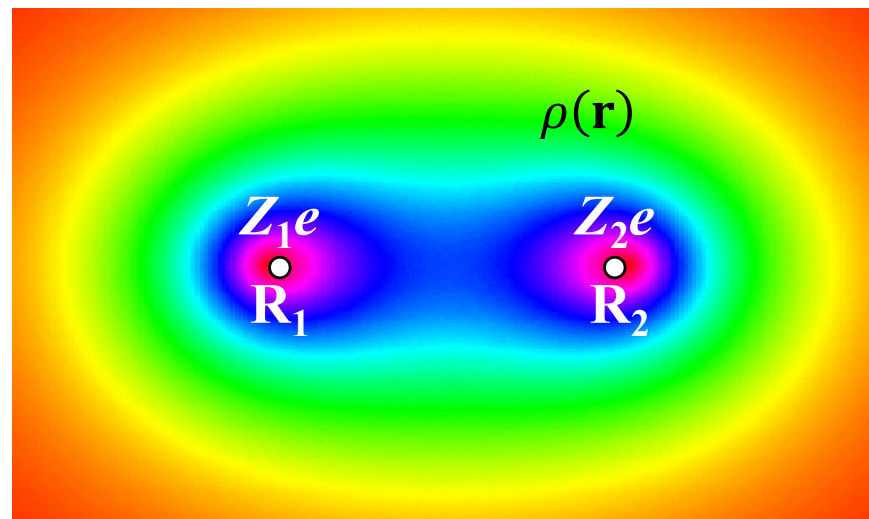
$$E[\rho(\mathbf{r})] = T_s[\rho(\mathbf{r})] + \int d\mathbf{r} v(\mathbf{r})\rho(\mathbf{r}) + \frac{1}{2} \int d\mathbf{r} d\mathbf{r}' \frac{\rho(\mathbf{r})\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + E_{xc}[\rho(\mathbf{r})]$$

Kinetic energy of
non-interacting
electrons

External potential

Hartree energy (mean-
field approximation to
the electron-electron
interaction energy)

Exchange-correlation
energy



Electron-Electron Interaction Energy

$$U = \frac{1}{2} \sum_{i=1}^N \sum_{j \neq i}^N \langle \Psi | \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} | \Psi \rangle = \int d\mathbf{r} \int d\mathbf{r}' \frac{\rho_2(\mathbf{r}, \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}$$

$$\rho_2(\mathbf{r}, \mathbf{r}') = \frac{1}{2} \sum_{\sigma, \sigma'} \langle \Psi | \hat{\psi}_{\sigma}^{\dagger}(\mathbf{r}) \hat{\psi}_{\sigma'}^{\dagger}(\mathbf{r}') \hat{\psi}_{\sigma'}(\mathbf{r}') \hat{\psi}_{\sigma}(\mathbf{r}) | \Psi \rangle$$

Two-body
density matrix

Creation operator

Annihilation operator

$e = \hbar = 1$

- **Two-body correlation function** $g(\mathbf{r}, \mathbf{r}')$

$$\rho_2(\mathbf{r}, \mathbf{r}') = \frac{1}{2} \rho(\mathbf{r}) \rho(\mathbf{r}') g(\mathbf{r}, \mathbf{r}')$$

$$\rho(\mathbf{r}) = \rho_1(\mathbf{r}, \mathbf{r}) \quad \rho_1(\mathbf{r}, \mathbf{r}') = \sum_{\sigma} \langle \Psi | \hat{\psi}_{\sigma}^{\dagger}(\mathbf{r}) \hat{\psi}_{\sigma}(\mathbf{r}') | \Psi \rangle$$

One-body density matrix

$$U = \underbrace{\int d\mathbf{r} \int d\mathbf{r}' \frac{\rho(\mathbf{r}) \rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}}_{E_{\text{H}}} + \underbrace{\int d\mathbf{r} \int d\mathbf{r}' \frac{\rho(\mathbf{r}) \rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} [g(\mathbf{r}, \mathbf{r}') - 1]}_{E_{\text{xc}}}$$

- **See note on** second quantization

Electron Correlation vs. Density Response

- **Information on two-body correlation is encoded in the density response function χ through fluctuation-dissipation theorem; see note on time-dependent perturbation**

$$\hat{H}_{\text{tot}} = \hat{H} + \hat{V}(t)$$

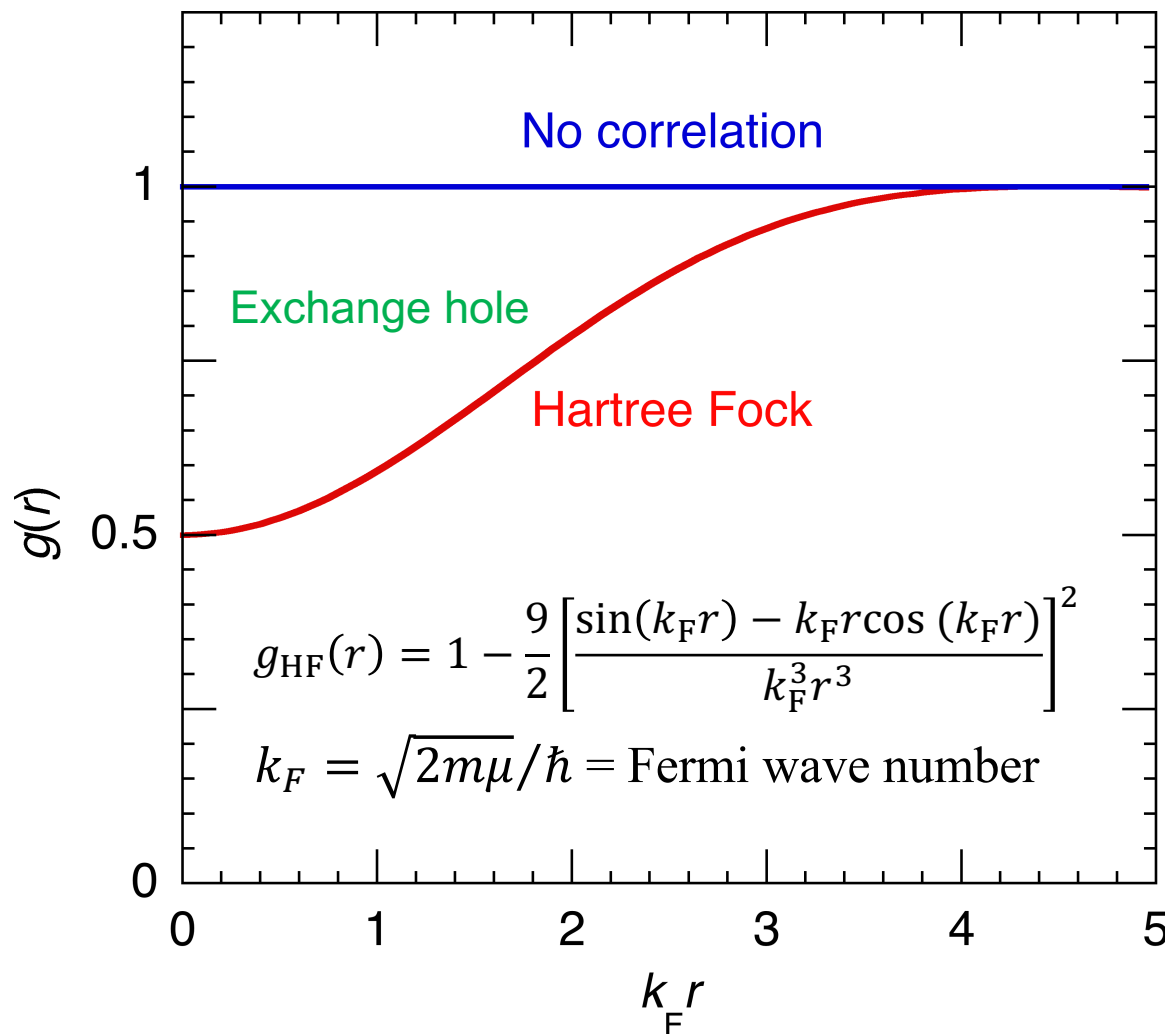
$$\left\{ \begin{aligned} \hat{H} = \hat{T} + \hat{U} &= \frac{\hbar^2}{2m} \int d\mathbf{r} \nabla \hat{\psi}^\dagger(\mathbf{r}) \cdot \nabla \hat{\psi}(\mathbf{r}) + \frac{1}{2} \int d\mathbf{r} d\mathbf{r}' \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}') \frac{e^2}{|\mathbf{r} - \mathbf{r}'|} \hat{\psi}(\mathbf{r}') \hat{\psi}(\mathbf{r}) \\ \hat{V}(t) &= \int d\mathbf{r} \hat{\psi}^\dagger(\mathbf{r}) v(\mathbf{r}, t) \hat{\psi}(\mathbf{r}) = \int d\mathbf{r} \hat{\rho}(\mathbf{r}) v(\mathbf{r}, t) \end{aligned} \right.$$

$$\begin{aligned} \chi(\mathbf{r} - \mathbf{r}', t - t') &\equiv \frac{\delta \langle \hat{\rho}(\mathbf{r}, t) \rangle}{\delta v(\mathbf{r}', t')} \\ &= -\frac{i}{\hbar} \Theta(t - t') \langle \Psi_0 | [\hat{\rho}_H(\mathbf{r}, t), \hat{\rho}_H(\mathbf{r}', t')] | \Psi_0 \rangle \\ &= -\frac{i}{\hbar} \Theta(t - t') \langle \Psi_0 | [\hat{\psi}_H^\dagger(\mathbf{r}, t) \hat{\psi}_H(\mathbf{r}, t), \hat{\psi}_H^\dagger(\mathbf{r}', t') \hat{\psi}_H(\mathbf{r}', t')] | \Psi_0 \rangle \end{aligned}$$

- **Equation-of-motion & functional derivative to derive approximate χ ; see A. Nakano & S. Ichimaru, *Phys. Rev. B* **39**, 4930 ('89); *ibid.* **39**, 4938 ('89)**

Pair Correlation: Exchange Hole

- Radial distribution function $g(|\mathbf{r} - \mathbf{r}'|)$ in a homogeneous system
- **Hartree-Fock (HF) approximation:** Ground state is a Slater determinant of plane waves occupied up to the chemical potential μ
- $g(r)$ is analytically calculated for homogeneous electron gas with HF

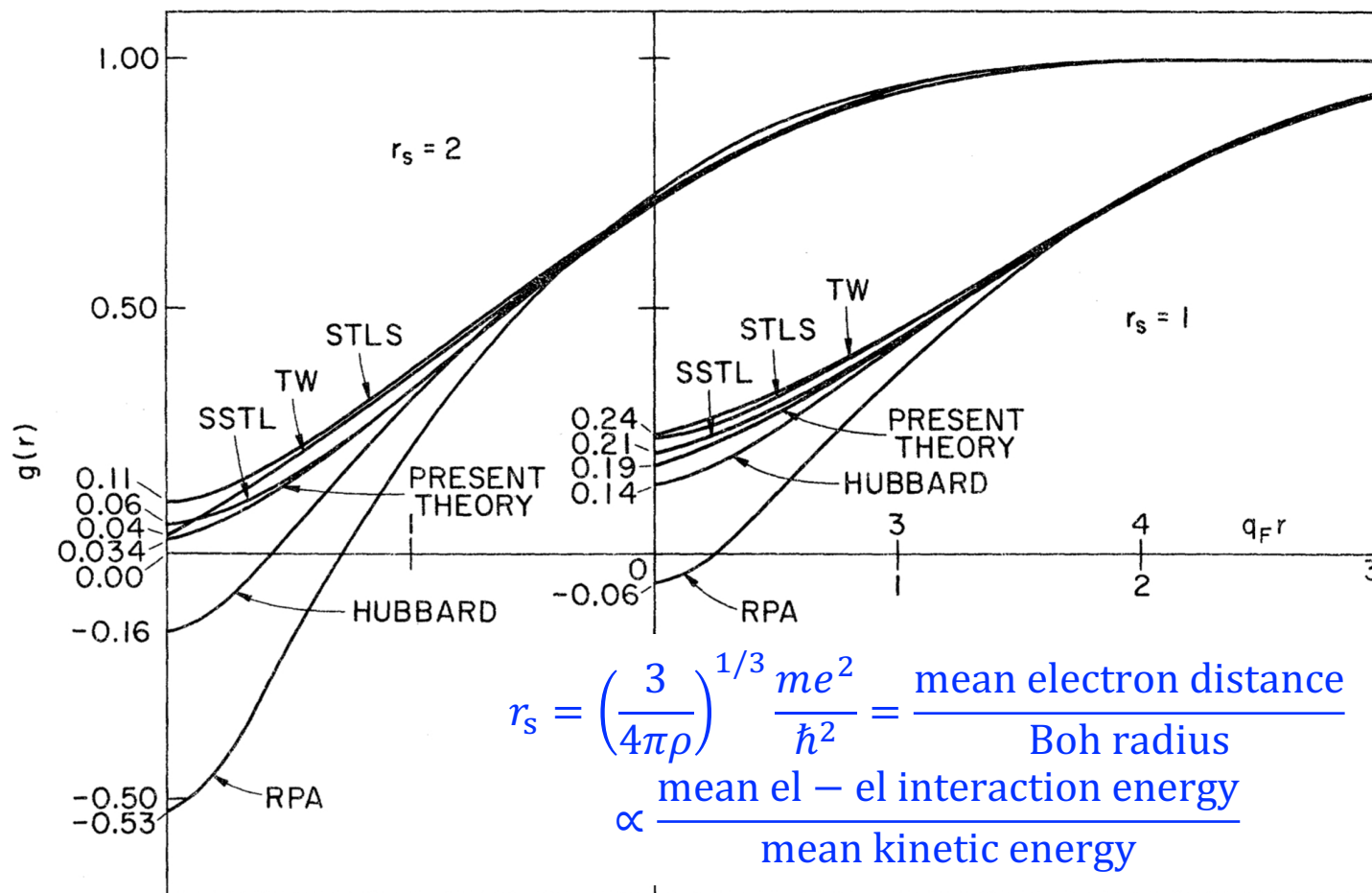


- $g_{\text{HF}}(r)$ represents Pauli exclusion principle between same-spin electrons embodied in the antisymmetric Slater determinant

- See note on Hartree-Fock approximation

Exchange & Coulomb Holes

- $g(r)$ of homogeneous electron liquid with various approximations for incorporating the correlation effect, which represents additional Coulomb (or correlation) hole



P. Vashishta & K. S. Singwi, "Electron correlation at metallic densities. V," *Phys. Rev. B* **6**, 875 ('72)

Exchange-Correlation Functional

- **Universal functional (of density) that describes many-body effects beyond the mean-field approximation**

$$v_{\text{Hxc}}(\mathbf{r}) = \int d\mathbf{r}' \frac{e^2 \rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + v_{\text{xc}}(\mathbf{r}) \quad v_{\text{xc}}(\mathbf{r}) = \frac{\delta E_{\text{xc}}}{\delta \rho(\mathbf{r})}$$

potential energy due to electron-electron interaction Hartree (mean-field) potential exchange-correlation potential

- **Some commonly used exchange-correlation functionals**

> **LDA (local density approximation):** $E_{\text{xc}} = \int d\mathbf{r} \rho(\mathbf{r}) \epsilon_{\text{xc}}(\rho(\mathbf{r}))$

> **LSDA (local spin density approximation):** $\epsilon_{\text{xc}}(\rho_{\uparrow}(\mathbf{r}), \rho_{\downarrow}(\mathbf{r}))$

> **GGA (generalized gradient approximation):** $\epsilon_{\text{xc}}(\rho(\mathbf{r}), |\nabla \rho(\mathbf{r})|)$
PBE: Perdew, Burke & Ernzerhof, *Phys. Rev. Lett.* **77**, 3865 ('96)

> **MetaGGA: functional of kinetic-energy density**

$$\tau_{\sigma}(\mathbf{r}) = \frac{1}{2} \sum_{n \in \{\text{occupied}\}} |\nabla \psi_{n\sigma}(\mathbf{r})|^2$$

SCAN: Sun, Ruzsinszky & Perdew, *Phys. Rev. Lett.* **115**, 036402 ('15)

HK vs. PBE

Generalized gradient approximation made simple

JP Perdew, K Burke, M Ernzerhof - Physical review letters, 1996 - APS

Abstract Generalized gradient approximations (GGA's) for the exchange-correlation energy improve upon the local spin density (LSD) description of atoms, molecules, and solids. We present a simple derivation of a simple GGA, in which all parameters (other than those in

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Inhomogeneous electron gas

P Hohenberg, W Kohn - Physical review, 1964 - APS

Abstract This paper deals with the ground state of an interacting electron gas in an external potential $v(r)$. It is proved that there exists a universal functional of the density, $F[n(r)]$, independent of $v(r)$, such that the expression $E \equiv \int v(r) n(r) d r + F[n(r)]$ has as its minimum

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Lesson: Publish something simple that others can use

Other Exchange-Correlation Functionals

- Select an appropriate functional for the purpose & target system of the QMD simulation

> LDA+U method for transition metals

$$\delta E_{\text{LDA+U}} / \delta n_i = \epsilon_{\text{LDA}} + U \left(\frac{1}{2} - n_i \right)$$

Occupation of i -th orbital

Anisimov *et al.*, *Phys. Rev. B* **44**, 943 ('91)

> DFT-D: van der Waals (vdW) functional for molecular crystals & layered materials

$$E_{\text{disp}} = -s_6 \sum_{i < j} \frac{C_{ij}}{R_{ij}^6} f_{\text{damp}}(R_{ij})$$

Grimme, *J. Comput. Chem.* **25**, 1463 ('04); *J. Chem. Phys.* **132**, 154104 ('10)

> Nonlocal correlation functional

$$E_c^{\text{nl}} = \frac{1}{2} \int d\mathbf{r} \int d\mathbf{r}' \rho(\mathbf{r}) \phi(\mathbf{r}, \mathbf{r}') \rho(\mathbf{r}')$$

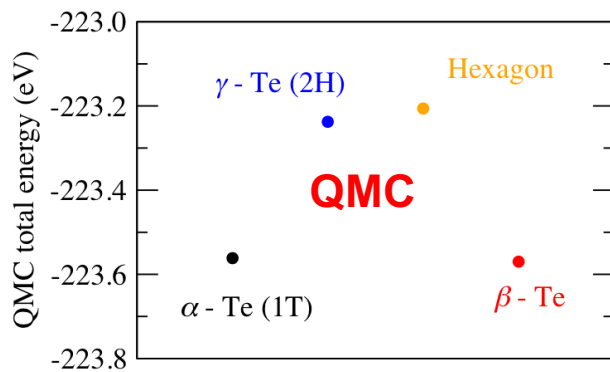
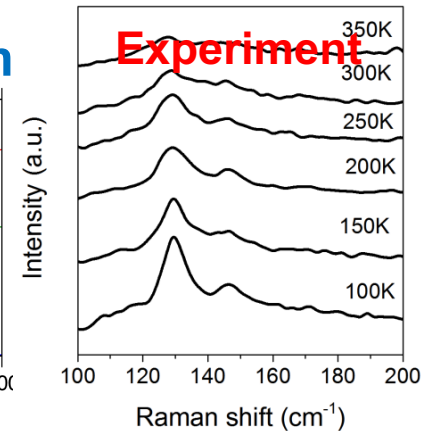
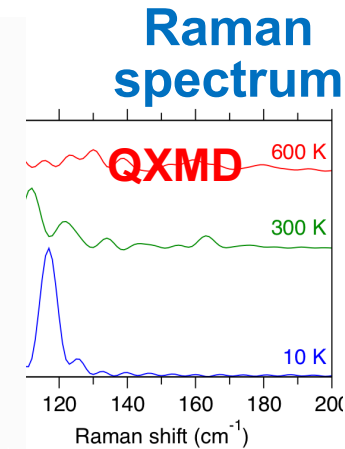
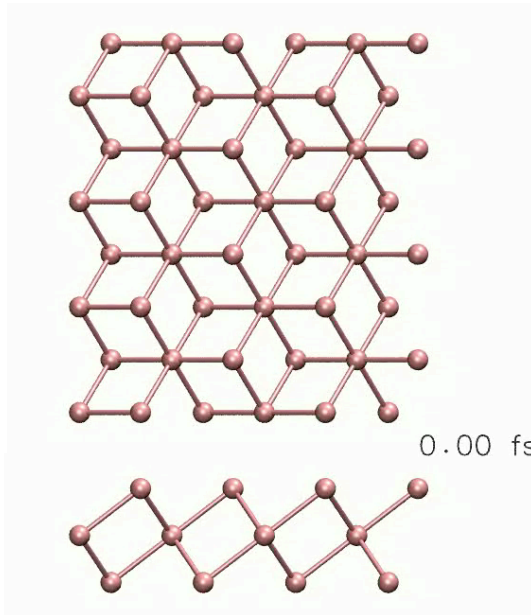
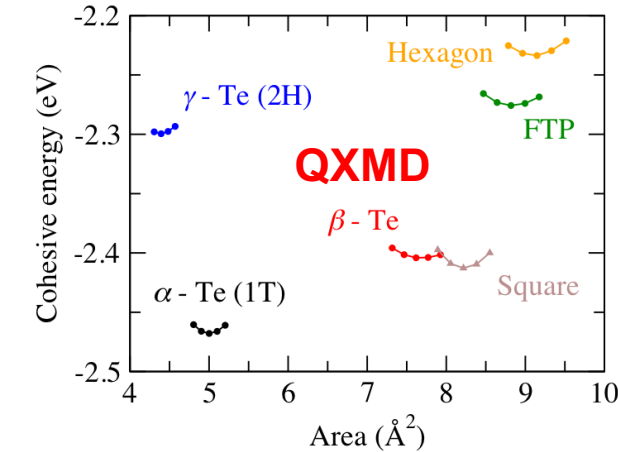
Dion *et al.*, *Phys. Rev. Lett.* **92**, 246401 ('04)

For comparison of DFT-D & nonlocal correlation functionals, see
Shimojo *et al.*, *J. Chem. Phys.* **132**, 094106 ('10)

Validation of XC Functional

- Comparison with high accuracy methods, such as quantum Monte Carlo (QMC), & experimental data
- Sensitivity analysis among different exchange-correlation (xc) functionals
- Consistency of the obtained result with the level of approximation

Example: Atomically thin tellurium (tellurene)



	a (\AA)	B (N/m)
GGA	4.26	23.2138
GGA-D	4.17	28.6845
Spin GGA	4.26	22.1372
Hybrid HSE	-	23.8448
Hybrid HSE with GGA-D	-	29.7649

a : Lattice constant
 B : Bulk modulus

Band-Gap Problem

- **Janak's theorem equates the ionization potential (IP) & electron affinity (EA) with the Kohn-Sham (KS) eigenenergies of the highest occupied molecular orbital (HOMO) & lowest unoccupied molecular orbital (LUMO), respectively**
Janak, *Phys. Rev. B* **18**, 7165 ('78)
- **Band gap, $E_{\text{gap}} = \text{IP} - \text{EA}$, is usually underestimated with GGA-type exchange-correlation (xc) functional**
- **This is partly due to self interaction: Note the Hartree potential $v_{\text{H}}(\mathbf{r}) = \int d\mathbf{r}' e^2 \rho(\mathbf{r}') / |\mathbf{r} - \mathbf{r}'|$ includes repulsive interaction of an occupied electron with itself (artifact), but not for an unoccupied electron**
- **Self-interaction correction (SIC): A quick fix subtracts the self-interaction of each KS orbital, $v_{\text{H},n\sigma}(\mathbf{r}) = \int d\mathbf{r}' e^2 [\rho(\mathbf{r}') - |\psi_{n\sigma}|^2] / |\mathbf{r} - \mathbf{r}'|$, which introduces an orbital-dependent KS potential (expensive & deviates from the DFT principle)**
Perdew & Zunger, *Phys. Rev. B* **23**, 5048 ('81)
- **Thorough analysis of the band-gap problem focuses on the discreteness of an electron**
Cohen *et al.*, *Science* **321**, 792 ('08)
Mori-Sanchez *et al.*, *Phys. Rev. Lett.* **100**, 146401 ('08)

Hybrid Exact Exchange Functional

- **Hartree-Fock (HF) approximation, with the underlying antisymmetric Slater determinant, is free from self interaction**
- **Hybrid exact-exchange functional incorporates part of the exact exchange using HF approximation & the rest with other xc functional (it is not strictly DFT)**

B3LYP: e.g., Stephens *et al.*, *J. Phys. Chem.* **98**, 11623 ('94)

PBE0: Perdew *et al.*, *J. Chem. Phys.* **105**, 9982 ('96)

- **Range-separated hybrid exact-exchange mixes HF & other xc functional at different distance**

HSE: Heyd, Scuseria & Ernzerhof, *J. Chem. Phys.* **118**, 8207 ('03)

For comparison of LSDA, SIC & HF for a 2-electron problem, see Nakano *et al.*, *Phys. Rev. B* **44**, 8121 ('91)

- **See note on** Hartree-Fock approximation