Condensed Matter Surfaces of Neutron Stars:

Applications ~~and Tangents~~

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Overview

- Condensed matter surfaces
  - Atomic physics/chemistry in strong B fields
  - QM calculation of properties
- Applications of condensed matter surfaces
  - Thermal radiation from a “bare” NS surface
  - Vacuum gap pulsar emission models

NS Condensed Matter Surfaces

- Condensed matter surface: atmosphere “negligibly” thin
- Cohesive energy is the key parameter

$$|E_S| - |E_A|$$

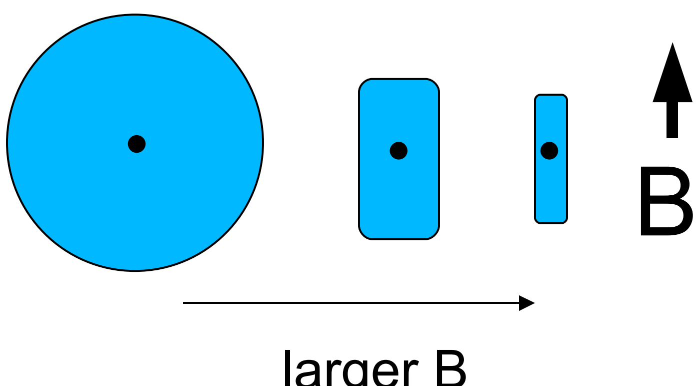
  - Depends on B field and composition
  - Much larger than at B=0
- Work function and density important, too

Bound States in Strong Magnetic Fields: Atoms

- Critical field:

$$\hbar\omega_{ce} = \left(\frac{e^2}{a_0}\right) \Rightarrow B_0 = 2.35\times 10^9\,G$$

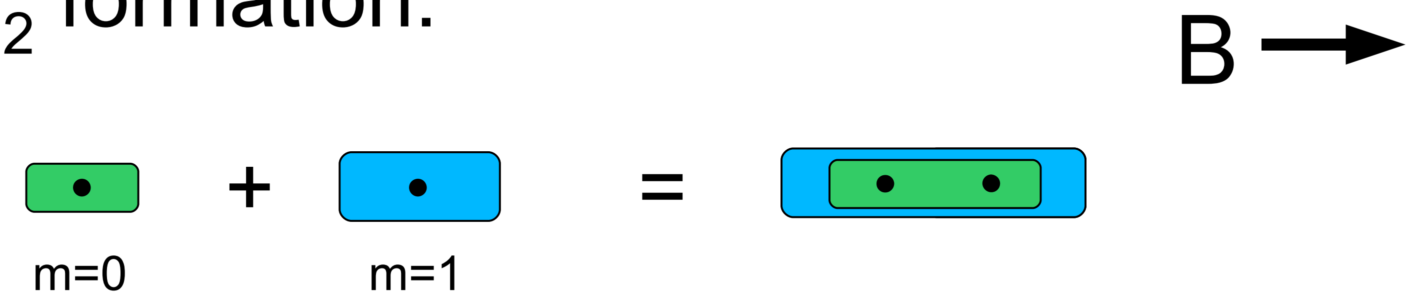
- Binding energy grows with B



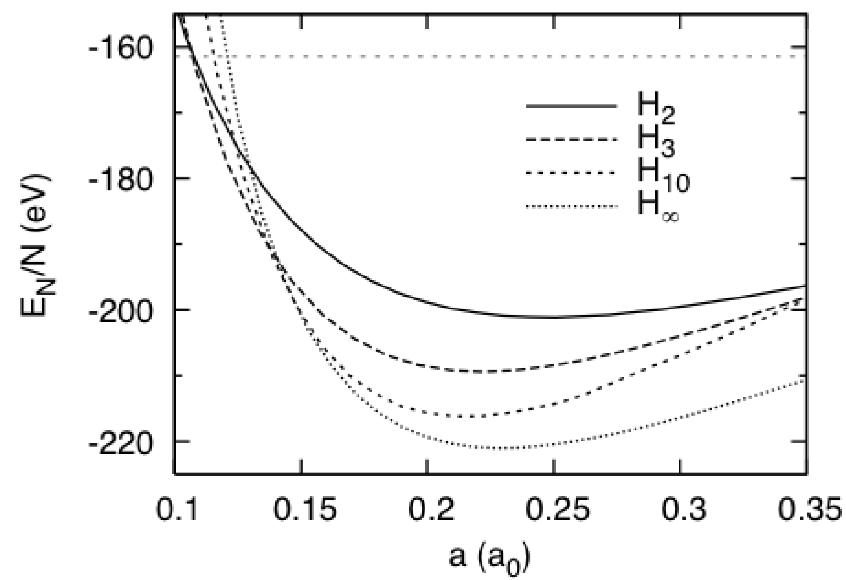
$$|E_{\mathrm{H}}| = 13.6\,\mathrm{eV}, \quad 0\ \mathrm{G}$$
$$160\,\mathrm{eV}, \quad 10^{12}\ \mathrm{G}$$
$$540\,\mathrm{eV}, \quad 10^{14}\ \mathrm{G}$$

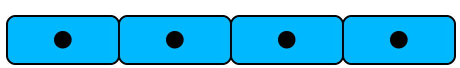
Bound States in Strong Magnetic Fields: Molecules

- H_2 formation:



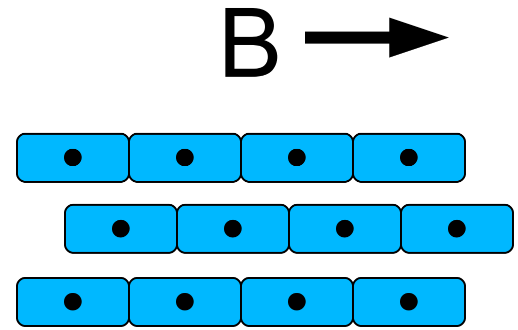
- Can form H_2, H_3, ..., H_N but also He_N, C_N, Fe_N, etc.





Bound States in Strong Magnetic Fields: Condensed Matter

- Formation of 3D condensed matter: interactions among molecular chains



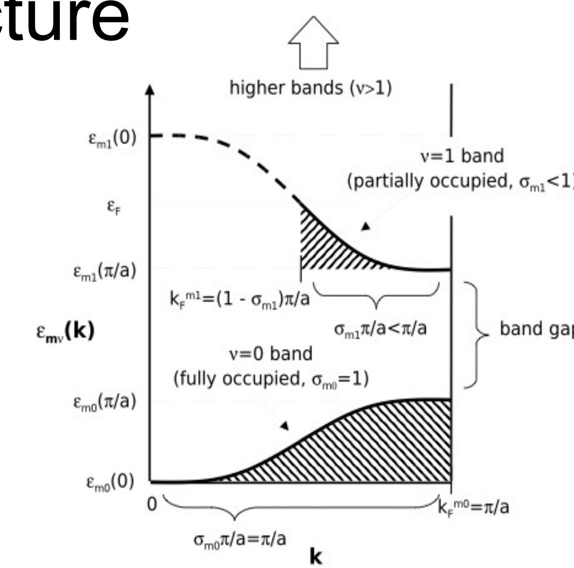
- Cohesive energy grows w/ B
  - Binding energy per cell: $|E_S| \propto Z^{9/5} B^{2/5}$
  - Atomic binding energy: $|E_A| \propto Z^2 (\ln B)^2$

Calculation of NS Surface Properties

- Self-consistent QM calculation
- Simplifications:
  - Zero-pressure condensed matter
  - No impurities
  - Transverse (to B) wave functions predetermined
- Calculations done in the 1980s (Jones, Neuhauser et al.): condensed matter weakly bound or unbound at 10^{12} G

New Calculations (Medin & Lai 2006)

- Extended to ~10^{15} G
- Atoms, molecules, infinite chains, 3D matter
- Improved treatment of band structure
- Density functional theory
  - Exchange-correlation function appropriate for large B

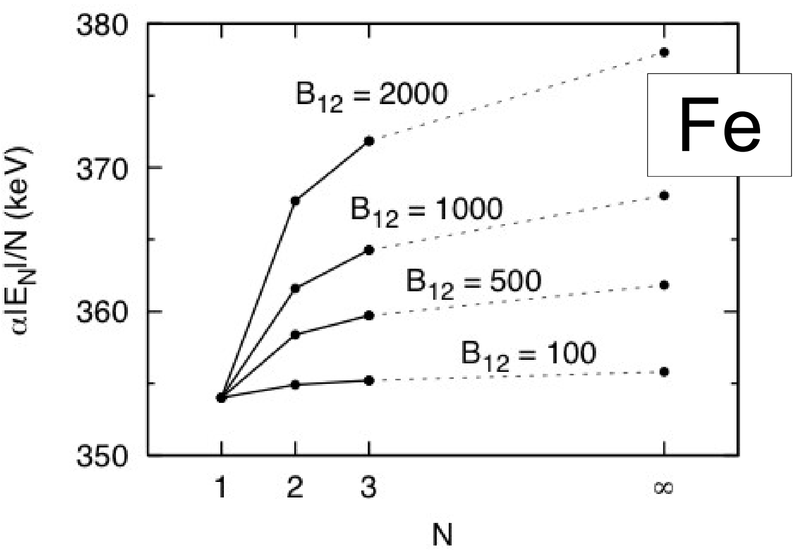


$$\text{DFT}: \int dr\, n(r)\, \varepsilon_{exc}[n(r)]$$

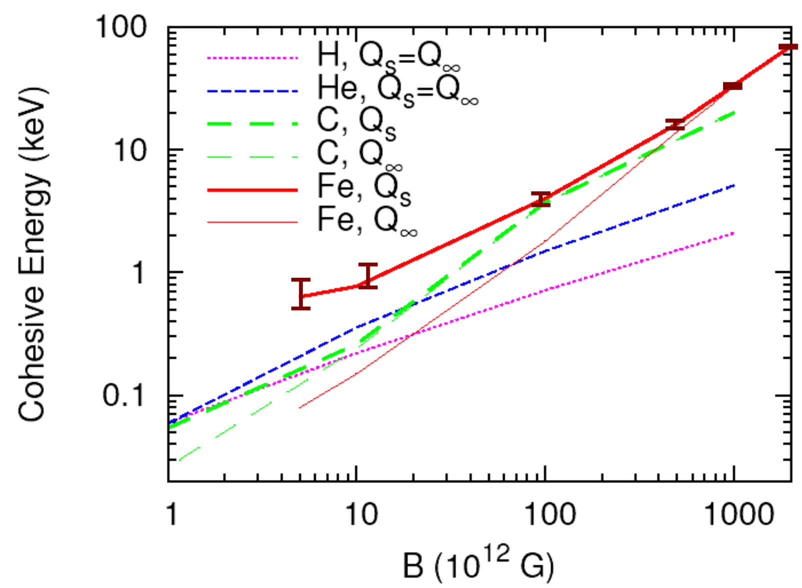
$$\text{HF}: \sum_{1,2} \int dr\, dr'\, \Psi_1^*(r)\Psi_2^*(r')\Psi_1(r')\Psi_2(r)$$

Cohesive Energy Results

- Binding energy of molecules approaches infinite chain limit
- 3D matter weakly bound at $B{\sim}10^{12}$ G but increasingly bound for larger fields

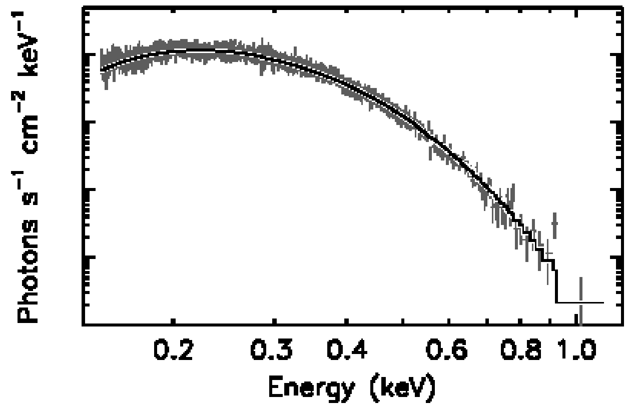


$$\alpha = 1, \frac{354.0}{637.8}, \frac{354.0}{810.6}, \frac{354.0}{1021.5}$$

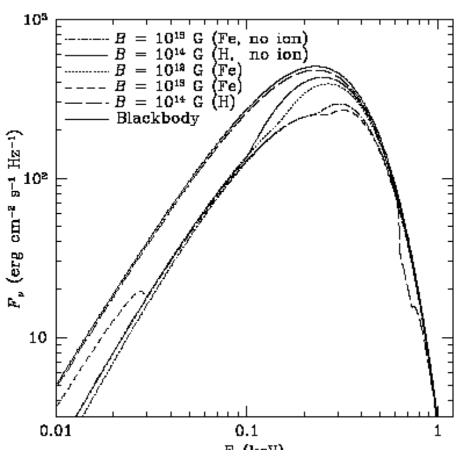


Application: Thermal Emission from a Condensed Matter Surface

- Some NS spectra best fit by blackbody
  - e.g., RX J1856.5-3754 (Burwitz et al. 2003, Trumper et al. 2004)
  - Could be explained by thermal emission directly from condensed surface (van Adelsberg et al. 2005, Ho et al. 2007)



Spectrum of RX J1856.5-3754 (Burwitz et al. 2003)

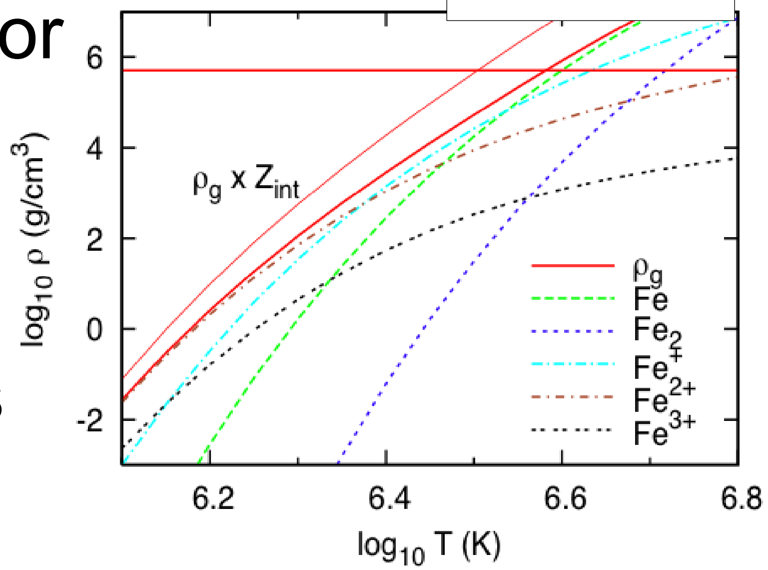


Emission models for condensed NS surfaces (van Adelsberg et al. 2005)

Phase Transitions on the Surface of a NS

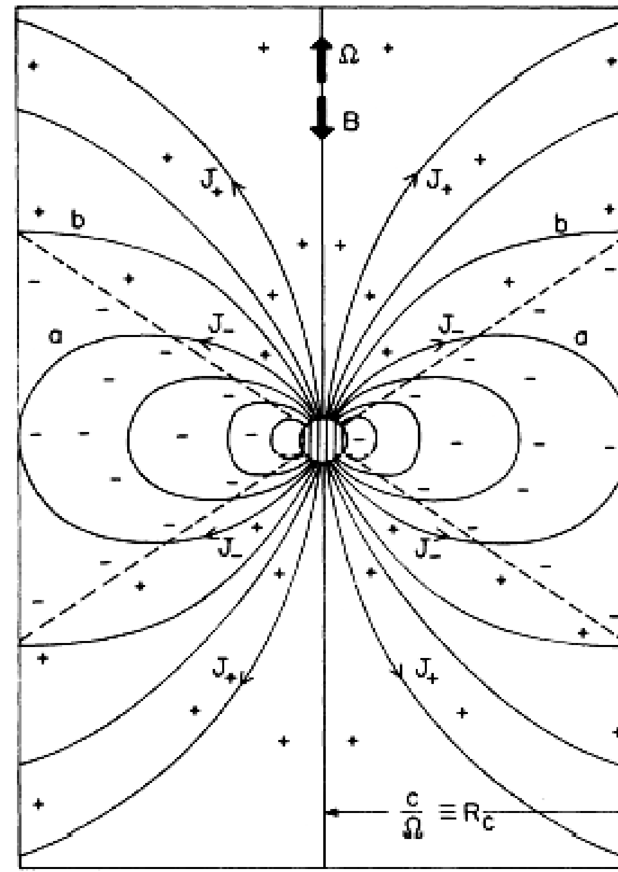
- Estimate the phase transition temp. T_{crit}
  - Various species in chemical equilibrium
  - Phase transition occurs when $\rho_g \sim \rho_s$
  - Assume zero-pressure vapor until T very close to T_{crit}
- We find that $kT_{crit} \sim 0.1\ E_S$

Fe, 10^{14} G



Application: Vacuum Gap Pulsar Emission Models

- NS magnetosphere requires $\rho_{GJ} \simeq \frac{\Omega \cdot B}{2\pi c}$ to screen $E_{||}$
- If $\rho < \rho_{GJ}$ in some region, an acceleration zone forms there
  - Vacuum gap model: $\rho < \rho_{GJ}$ due to large cohesive energy (Ruderman-Sutherland 1975)
  - Space-charge limited flow: due to inertial effects (Arons-Scharleman 1979, Muslimov-Tsygan 1992)



NS magnetosphere
(Ruderman-Sutherland 1975)

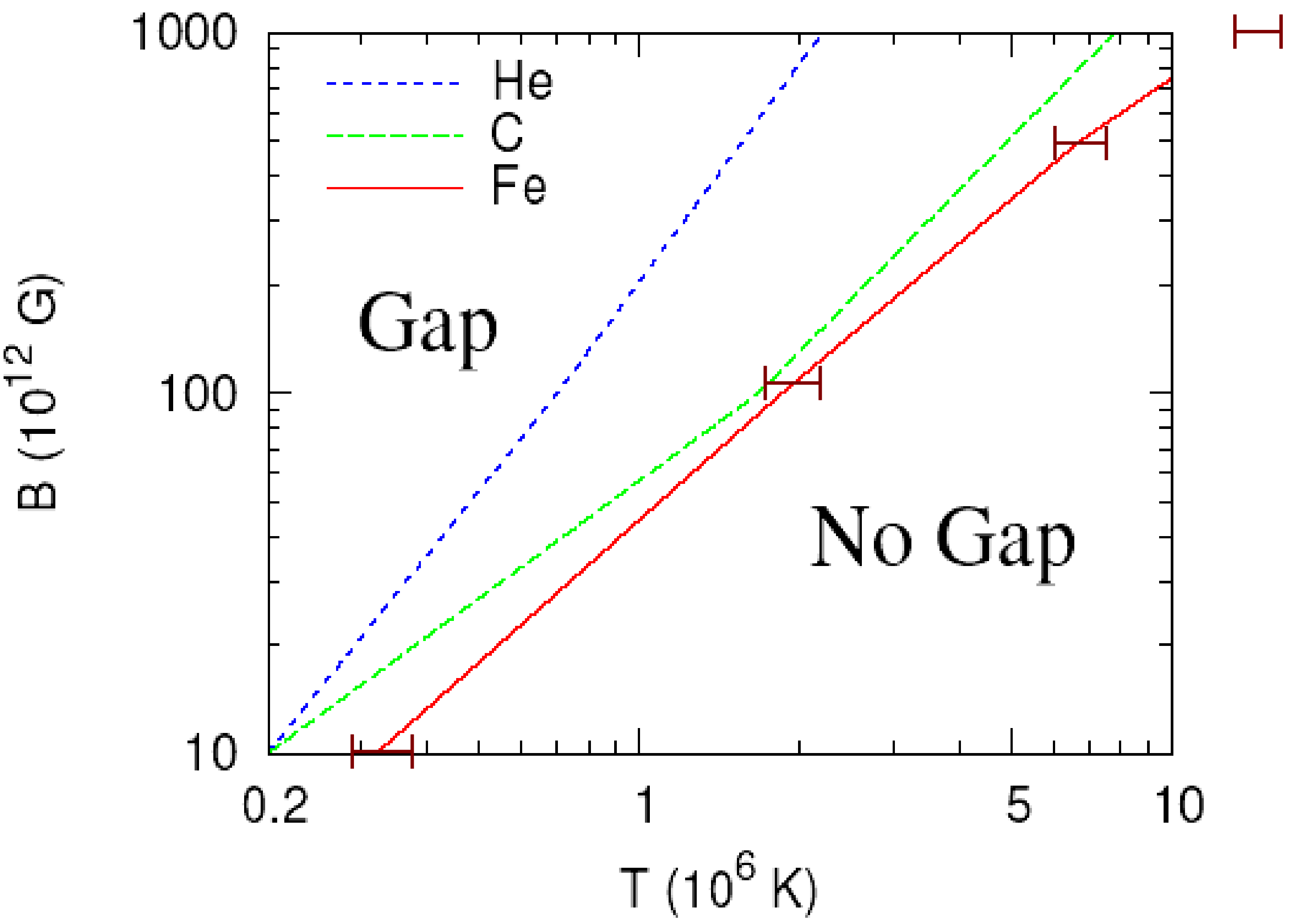
Electron/Ion Thermal Emission

- Vacuum gap forms if $(Z_i) e \mathcal{F} < \rho_{GJ} c$
- Energy barrier:

$$E_B = W, \quad \text{electrons}$$
$$E_B = E_S + I - Z_i W, \quad \text{ions}$$

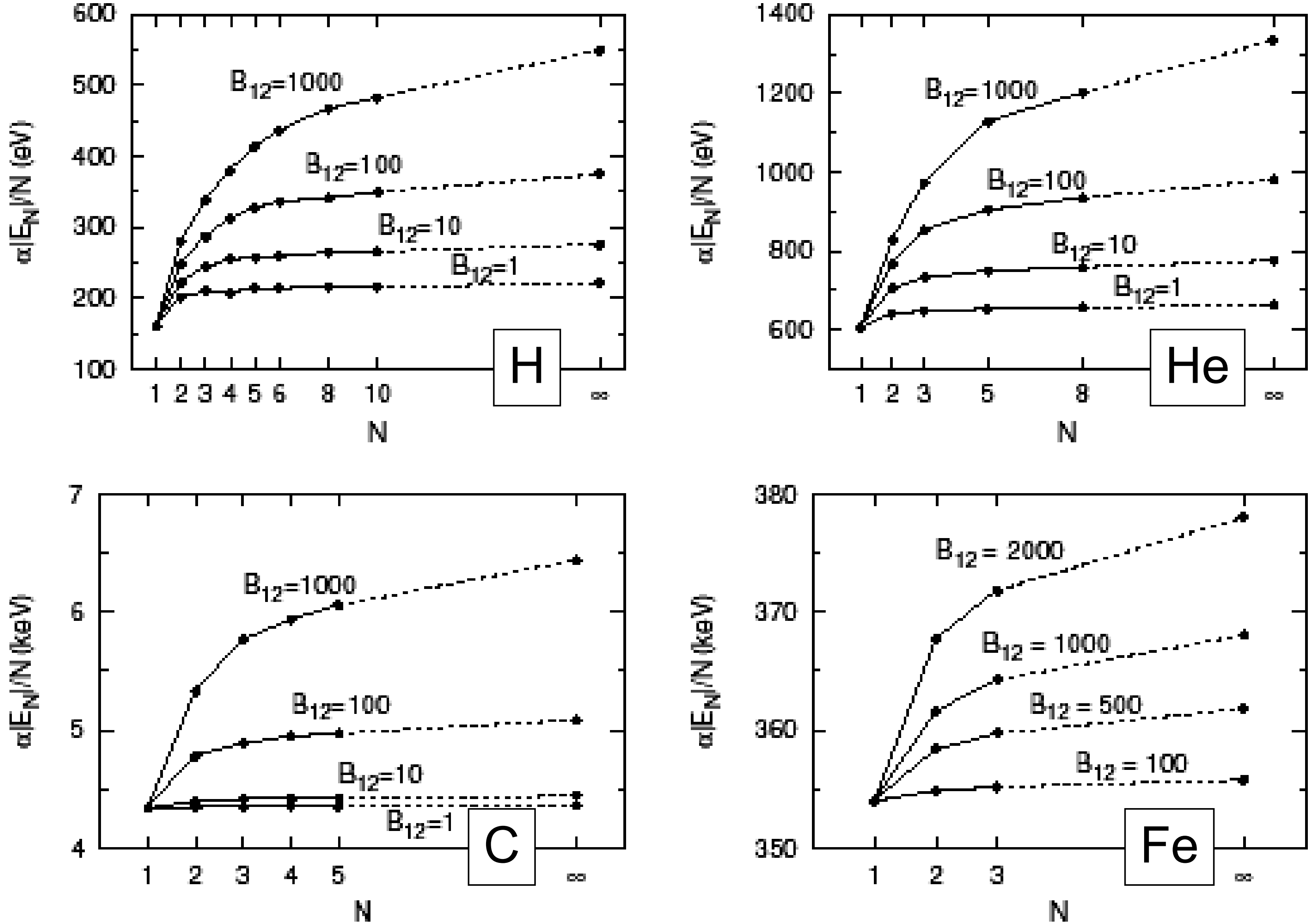
- Emission rate $\mathcal{F} \propto \exp(-E_B / kT)$
  - Prefactor depends on T (electrons) or the surface density and ν_i (ions)
- We find that $kT_{crit} \sim 0.03\ E_B$

Vacuum Gap Formation Conditions

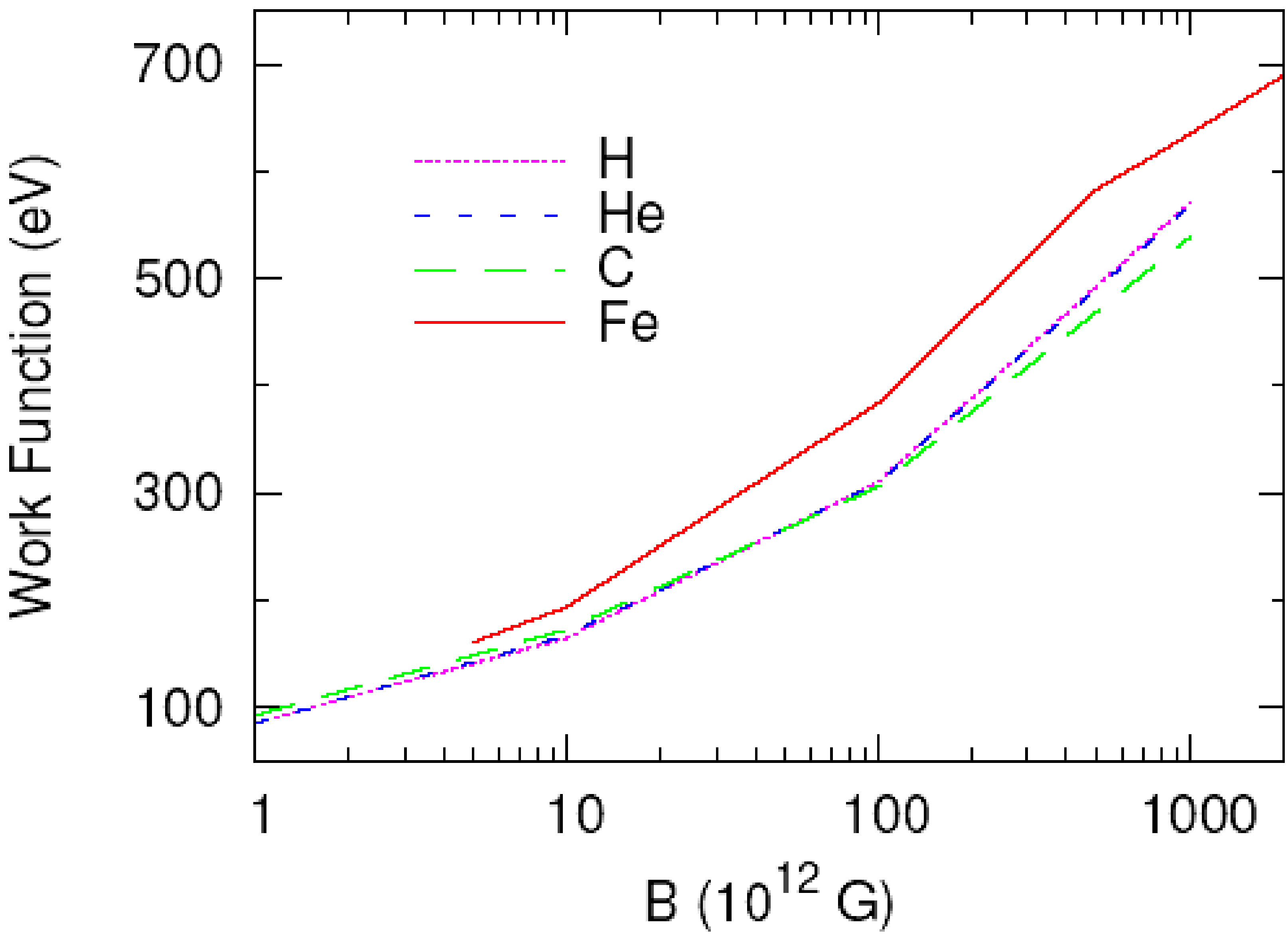


Summary

- In strong magnetic fields ($B > 10^{13}$ G) H, He, C, and Fe have large cohesive energies
- Depending on the NS surface temperature, the cohesive energy can be large enough for condensed matter surfaces to form
- This has important consequences for "bare neutron star" and "vacuum gap" emission models



H
He
C
Fe
B12=1000
B12=100
B12=10
B12=1
B12= 2000
B12 = 1000
B12 = 500
B12 = 100
α|EN|/N (eV)
α|EN|/N (keV)
N



700
500
300
100
Work Function (eV)
H
He
C
Fe
1
10
100
1000
B (10^12 G)

Unresolved Issue: High-B Radio Pulsars vs. Magnetars

- Recent observations found several radio pulsars with fields comparable to those of magnetars (e.g., McLaughlin-Kaspi 2003)
  - Overlap of magnetars and radio pulsars in the P- $\dot{p}$ diagram
- No "pulsar-like" radio emission (but see Camilo et al. 2006)

Unresolved Issue: High-B Radio Pulsars vs. Magnetars (continued)

Why is there no radio emission from quiescent magnetars?

- One possibility: particle emission due to twisted magnetic fields overwhelms acceleration region
- Another possibility: vacuum gap forms for high-B pulsars (T < a few x 10^6 K), but not for magnetars because of the high temperature (T > 4 x 10^6 K)