Fe-based superconductors (FBS) at high magnetic fields

Alex Gurevich

Old Dominion University, Norfolk, VA

Dept. Physics, University of Virginia, Sept. 26, 2011
Outline

- Fe-based superconductors: unconventional multiband superconductivity mediated by magnetic fluctuations
- High $T_c$ and huge upper critical magnetic fields. Interplay of orbital and paramagnetic pairbreaking in multiband SCs and their effect on $H_{c2}(T)$
- Manifestations of the $s^\pm$ pairing symmetry in the temperature dependence of $H_{c2}(T)$.
- Strong Pauli pairbreaking in FBS can lead to FFLO. Does the $s^\pm$ pairing facilitate or inhibit the FFLO instability?
- FFLO in multiband FBS: what happens if one band is FFLO unstable but another one is not?
- Tuning $H_{c2}(T)$ by doping: FFLO triggered by the Lifshitz transition
Diverse family of Fe-based superconductors (FBS)
Phenomenology of pnictides

H. Luetkens et al, Nature Mat. 8, 305 (2009)

C. Lester et al, PRB 79, 144523 (2009)
Multiband superconductivity in oxypnictides

Five d-orbitals of Fe hybridized with p-orbitals of As

Several disconnected pieces of FS

Multiple superconducting gaps

**Haule and Kotliar, NJP 025021 (2009)**

**ARPES and tunneling:**  
$$\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$$

**Ding et al, EL 83, 47001 (2008)**
The Matthias rules are violated:

\[ T_c = \Omega e^{-1/NV} \]

- High symmetry is good, cubic symmetry is best
- High density of electronic states is good
- Stay away from oxygen
- Stay away from magnetism
- Stay away from insulators
- Stay away from theorists
Huge $H_{c2}$ in pnictides

- High slopes $H_{c2}' = 2-100$ T/K at $T_c$
- $H_{c2}(0)$ for 1111 and 122 FBS, extrapolate to $> 100$T
- Short GL coherence lengths

$$\xi_0 = \left[ \frac{\phi_0}{2\pi T_c H_{c2}'} \right]^{1/2} = 1 - 2 \text{ nm}$$

result from high $T_c$ and low carrier density in semi-metallic FBS

$$\xi_0 = \frac{\hbar v_F}{2\pi T_c}$$

Dirty limit can hardly be reached

AG, Nature Mat. 10, 255 (2011)
High-field measurements at NHMFL

45T Hybrid Magnet  
*Highest DC Magnetic Field*

“world’s highest steady-field resistive (35 T) and hybrid (45 T) magnets”

NHMFL/LANL
Cooper pairs at high magnetic fields

- Larmor orbital motion of Cooper pairs: Vortex structure and orbital pairbreaking in vortex cores

- Paramagnetic pairbreaking

- Critical orbital velocity $v_c$ to destroy superconductivity $\rightarrow$ upper critical field: $H_{c2}$

- Zeeman energy = binding energy of the Cooper pair $\rightarrow$ paramagnetic limit: $\mu_B H_p = \Delta$
Type-II superconductors

- Hexagonal lattice of vortex lines, each carrying the flux quantum $\phi_0$
- Vortex density $n(B) = \phi_0 / B$
- Spacing between vortices: $a = (\phi_0 / B)^{1/2}$
Paibreaking velocity, vortex core, and coherence length

Doppler shift of the electron spectrum in the superflow:

\[ E(p) = \pm \sqrt{\Delta^2 + (\epsilon_p - E_F)^2} \pm p_F \vec{v}_s(t) \]

Gap reduction: \( \Delta(v_s) = \Delta - p_F |v_s| \)

the critical velocity \( v_c = \Delta / p_F \)

Superfluid velocity around the vortex and the coherence length \( \xi \):

\[ v = \frac{\hbar}{m^* R}, \quad \frac{\hbar}{m^* \xi} = v_c \quad \Rightarrow \quad \xi = \frac{\hbar v_F}{\Delta} \]
Upper critical field:

At $H = H_{c2}$ normal vortex cores overlap:

$$\left(\frac{\phi_0}{H}\right)^{1/2} < \xi \quad \Rightarrow \quad H_{c2} = \frac{\phi_0}{2\pi \xi^2}$$

Effect of anisotropy:

$$H_{c2}(\theta) = \frac{H_{c2}}{\sqrt{\cos^2 \theta + \epsilon \sin^2 \theta}}, \quad \epsilon = \frac{m_{ab}}{m_c} < 1$$

Enhancement of parallel $H_{c2}$:

$$H_{c2}^\parallel = H_{c2} \sqrt{\frac{m_c}{m_{ab}}} \sqrt{\frac{\pi^2 c \sqrt{m_{ab} m_c}}{2e\hbar}} \frac{\Delta^2}{E_F}$$

Mass anisotropy, high $T_c$ and low $E_F$ greatly enhance $H_{c2}$.
Does increasing $H_{c2}$ by disorder work in FBS?

Effect of the elastic mean free path $\ell$ on the orbitally-limited

(Werhamer-Helfand-Hohenberg, 1966)

$$H_{c2} = \frac{\phi_0}{2\pi \xi^2}$$

Clean limit: $\ell \gg \xi_0 \implies \xi = \xi_0$ and

$$H_{c2} \equiv \frac{\pi \phi_0 \Delta^2}{2\hbar^2 v_F^2} \propto T_c^2$$

Dirty limit: $\ell \ll \xi_0 \implies \xi = (\ell \xi_0)^{1/2}$

$$H_{c2} = \frac{\phi_0 \Delta}{2\hbar v_F \ell} \propto T_c \rho_n$$

Works in conventional superconductors: 10–fold increase of $H_{c2}$ in MgB$_2$

Does not work in FBS because $\ell < \xi_0 \sim 1$-2 nm implies the Joffe-Regel limit and $\ell k_F < 1$ for which the conventional transport theories fail

$H_{c2}$ in semi-metallic FBS can be effectively tuned by doping
Orbital or Pauli-limited $H_{c2}$?

- Orbitally limited
  - Werthamer-Helfand-Hohenberg
  - 1963-1965

- Mostly Pauli limited
  - Sarma, Maki 1963-1964
  - Gruenberg and Gunther, 1966

**Graphs:**
- Left graph: $H_{c2}/H_{c2}(0)$ vs. $T/T_c$ showing an orbitally limited behavior.
- Right graph: $\mu H/\Delta_0$ vs. $T/T_c$ showing a mostly Pauli limited behavior with a FFLO indication.
Pauli pairbreaking

**Chandrasekhar – Klogston limit**

\[
\frac{\chi_n}{2} H_p^2 = N(0) \frac{\Delta^2}{2} , \quad \chi_n = 2\mu_B^2 N(0)
\]

- \(\chi_n\): magnetic energy
- \(H_p\): condensation energy

First order phase transition

\[
\mu_B H_p = \Delta / \sqrt{2}
\]

Using BCS

\[
\Delta = 1.78 k_B T_c
\]

yields a useful relation

\[
H_p [\text{Tesla}] = 1.84 T_c [\text{Kelvin}]
\]
Relation between orbital and Pauli pairbreaking

- Maki parameter $\alpha_M = 2^{1/2}H_{c2}^{\text{orb}}/H_p$:

\[
\alpha_M = \frac{\pi^2 \Delta}{4 E_F} \frac{m_{ab}}{m_0}, \quad H \perp ab
\]

\[
\alpha_M = \frac{\pi^2 \Delta}{4 E_F} \sqrt{\frac{m_{ab} m_c}{m_0}}, \quad H \parallel ab
\]

- In ordinary metallic BCS superconductors with $m_{ab} \sim m_0$ and $\Delta \ll E_F$, paramagnetic pairbreaking is negligible, $\alpha_M \ll 1$

**Pauli-limited superconductors with $\alpha_M > 1$**

- Heavy fermions with $m_{ab}/m_0 \sim 10^3$
- Highly anisotropic materials with $m_c/m_0 \sim 10^6$: layered organic SC, high-$T_c$ cuprates (BSCCO), etc for $H \parallel ab$
- Semi-metallic, strongly correlated FBS with $E_F < 0.01-0.1$ eV, and $m_{ab}/m_0 \sim 10$
Orbital and Pauli coupling: FFLO state

Cooper pairing with nonzero momentum $Q = 2q$: modulation of the order parameter along $H$

$\Delta(z) = \Delta_0 \cos(Qz)$ (Larkin-Ovchinnikov)
$\Delta(z) = \Delta_0 \exp(iQz)$ (Fulde-Ferrel)

FS nesting facilitates the FFLO state
FFLO in heavy fermions and organics

Layered organic SC


Heavy fermions

CeCoIn$_5$
Theory of anisotropic FFLO (single band)

Linearized Gor'kov equation in a uniaxial SC with ellipsoidal FS:

\[ \Psi(\vec{r}) = \int d^3r \Psi(\vec{r}') \int D(\vec{k}) \exp \left[ i \vec{k} \cdot (\vec{r} - \vec{r}') + \frac{i \pi}{\phi_0} \vec{H} \cdot (\vec{r} \times \vec{r}') \right] \frac{d^3k}{(2\pi)^3} \]

\[ D(\vec{k}) = \text{Re} \sum_{\omega > 0} \frac{4\pi \lambda T}{\nu \sqrt{k_{\perp}^2 + \epsilon k_z^2}} \tan^{-1} \frac{\nu \sqrt{k_{\perp}^2 + \epsilon k_z^2}}{2(\omega + i\mu_B H)} \]

H\(_{c2}\) is an eigenvalue of the Schroedinger equation for a particle with q = 2e

Werthamer and Helfand, (1964)

Tilted first Landau level eigenfunction:

\[ \Psi(x, y) = \Delta \exp \left[ -\frac{\pi H}{2\phi_0} (c_x x^2 + c_y y^2) \right] \exp[iQ \vec{r}] \]

\(c_x\), \(c_y\) and the FFLO vector \(Q\) are determined by the condition that \(H_{c2}\) is maximum
**Exact solution**

- FFLO wave vector $\mathbf{Q}$ is not parallel to $\mathbf{H}$ unless $\mathbf{H}$ is along the symmetry axis. The angle $\gamma$ between $\mathbf{Q}$ and $\mathbf{H}$:

  $$\tan \gamma = -\frac{(1-\varepsilon) \sin 2\theta}{2(\cos^2 \theta + \varepsilon \sin^2 \theta)}$$

- Competition between the FFLO kinetic energy $\varepsilon Q_z^2$ and the Zeeman energy

- GL angular scaling works for all $T$
  (Brison et al, Physica C 250, 198 (1995))

- $H_{c2}$ is maximum provided that:
  \[ AG, PRB 82, 184504 (2010) \]

\[
c_x = \varepsilon^{1/2}_\theta, \quad c_y = \varepsilon^{-1/2}_\theta
\]

\[
\varepsilon_\theta = \cos^2 \theta + \varepsilon \sin^2 \theta
\]

\[
H_{c2}(\theta) = \frac{H_{c2}(0)}{(\cos^2 \theta + \varepsilon \sin^2 \theta)^{1/2}}
\]
Equation for $H_{c2}$ and $Q$

$$\ln t + U(t, b, q) = 0$$

$$U = 2e^q^2 \Re \sum_{n=0}^{\infty} \int_{0}^{\infty} du e^{-u^2} \left\{ \frac{u}{n+1/2} - \frac{t}{\sqrt{b}} \tan^{-1}\left( \frac{u\sqrt{b}}{(n+1/2)t+i\alpha b} \right) \right\},$$

$$b = \frac{\hbar^2 \nu^2 \varepsilon_{\theta}^{1/2} H}{8\pi \phi_0 T_c^2}, \quad \alpha = \frac{4\mu_B \phi_0 T_c^2}{\hbar^2 \nu^2 \varepsilon_{\theta}^{1/2}}, \quad q^2 = \frac{Q^2 \varepsilon_{\phi}^0}{2\pi H \varepsilon_{\theta}^{3/2}}$$

- FFLO transition for $\alpha > 1$
- Spontaneous FFLO vector $Q(T)$ appears at low $T$
- The FFLO period $\ell(T) = 2\pi / Q(T)$ diverges at the spinodal: $T = T_{FFLO}$
- At zero $T$: $\ell(0) \sim \xi_0$. First order transition line between two spinodals.
Electron spectrum from ab-initio calculations and ARPES

- multiple bands crossing the Fermi level
- two hole pockets at \( \Gamma \) and two electron pockets at \( M \)

LaFeP(O,F)

FeSe\(_{0.42}\)Te\(_{0.58}\)
New features of FBS revealed by ARPES

- Small Fermi energies: \( E_F \sim 0.02\text{-}0.5 \text{ eV} \)

- Large effective mass renormalization: \( m^* \sim (2\text{-}16)m_e \)

- Several shadow bands near the FS: Lifshitz transition upon doping

- Strongly correlated semimetals

- Good candidates for the FFLO state: \( \alpha > 1 \)

- Example of a Pauli-limited SC: \( \text{FeSe}_{0.5}\text{Te}_{0.5} \):
  \( T_c = 16\text{K}, \ E_F = 25 \text{ meV}, \ m_{ab} = 10m_e \)

\[ \alpha = \frac{\pi k_B T_c m_{ab}}{E_F m_e} \]

\( \alpha = 1.5 \) even for \( H || c \)

- In-plane coherence lengths \( \xi \approx 1\text{-}2 \text{ nm} \)
Multiband pairing gap symmetries

- \( s^\pm \) pairing: gaps with opposite signs
  - Mazin, Singh, Johannes, Du, PRL 101, 057003 (2008);

- Combined \( s \) and \( d \)-wave gaps
  - Kuroki et al, PRL 101, 087004 (2008);
  - Graser, Maier, Hirshfeld, Scalapino, NJP 11, 025016 (2009)

Strong interband repulsion: \( \lambda_{12}\lambda_{21} > \lambda_{11}\lambda_{22} \)

Phonons are not sufficient to explain high Tc

**Pairing coupling constants**

\[
\Lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{pmatrix}
\]

**Impurity scattering rates**

\[
\Gamma = \begin{pmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{pmatrix}
\]
Critical temperature

Suhl, Mattias, Walker PRL 3, 552 (1959); Moskalenko, FMM 8, 25 (1959):

\[
T_{c0} = 1.14 \omega_d \exp\left[-(\lambda_+ - \lambda_-) / 2w\right],
\]

\[
\lambda_\pm = \lambda_{11} \pm \lambda_{22}, \quad \lambda_0 = \sqrt{\lambda_-^2 + 4 \lambda_{12} \lambda_{21}},
\]

\[
w = \lambda_{11} \lambda_{22} - \lambda_{12} \lambda_{21},
\]

Interband coupling increases \( T_c \)

\[
T_c \approx T_{c0} - \frac{\pi \gamma_{12}}{8} \left(1 \mp \sqrt{\frac{N_1}{N_2}}\right)^2
\]

Golubov, Mazin, PRB 55, 15146 (1997);

- **Weak interband pairing** in MgB\(_2\), \( \lambda_{12} \lambda_{21} < \lambda_{11} \lambda_{22} \)
- **Strong interband pairing** in pnictides, \( \lambda_{12} \lambda_{21} > \lambda_{11} \lambda_{22} \)

\( T_c \) suppression by impurities is much weaker for the two-gap s\(^{++}\)(-) than for s\(^\pm\) (+)
Two-gap superconductivity in MgB$_2$

- Big gap, $\Delta_\sigma \approx 7$ meV
- Small gap, $\Delta_\pi = 2.3$ meV

- 2D big gap for in-plane $\sigma$-orbitals s and 3D small gap for out-of-plane $\pi$-orbitals

- Weak interband coupling due to orthogonal $p_z$ and $p_{xy}$ orbitals of B

Liu, Mazin and Kortus (2002); Choi et al, (2002)

Band structure calculations:
$\lambda_{11} \approx 0.81$, $\lambda_{22} \approx 0.3$, $\lambda_{12} \approx 0.12$, $\lambda_{21} \approx 0.09$

$w = \lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21} > 0$
Multiband superconductivity on repulsion

- BCS gap equations for two bands:

\[ \Delta_1 = \lambda_{11} \Delta_1 \int \frac{d\varepsilon}{E_1} \tanh \left( \frac{E_1}{2T} \right) + \lambda_{12} \Delta_2 \int \frac{d\varepsilon}{E_2} \tanh \left( \frac{E_2}{2T} \right) \]

\[ \Delta_2 = \lambda_{22} \Delta_2 \int \frac{d\varepsilon}{E_2} \tanh \left( \frac{E_2}{2T} \right) + \lambda_{21} \Delta_1 \int \frac{d\varepsilon}{E_1} \tanh \left( \frac{E_1}{2T} \right) \]

where \( E = (\varepsilon^2 + \Delta^2)^{1/2} \)

- \( s^\pm \) pairing for repulsive interaction \( \lambda_{12} < 0 \) and opposite signs of \( \Delta_1 \) and \( \Delta_2 \)

- Pairing glue due to AF spin fluctuations, \( w = \lambda_{11} \lambda_{22} - \lambda_{12} \lambda_{21} < 0 \)

\[ \lambda_{nm} = \frac{JN_n \chi(Q)}{1 - JN_n \chi(Q)} \]
Convex $H_{c2}(T)$ in two-band models

- Bilayer toy model of two-band SC
- Interaction of two bands with conventional $H_{c2}(T)$ can produce unconventional $H_{c2}(T)$ with upward curvature
- Model independent mechanism
\( H_{c2} \) for two coupled bands (clean limit) \( H_{\parallel\parallel c} \)

\[
a_1 (\ln t + U_1) + a_2 (\ln t + U_2) + (\ln t + U_1)(\ln t + U_2) = 0,
\]

\[
U_1 = 2e^{q^2} \text{Re} \sum_{n=0}^{\infty} \int_{q}^{\infty} du e^{-u^2} \left\{ \frac{u}{n + 1/2} - \frac{t}{\sqrt{b}} \tan^{-1} \left[ \frac{u\sqrt{b}}{(n + 1/2)t + i\alpha b} \right] \right\},
\]

\[
U_2 = 2e^{sq^2} \text{Re} \sum_{n=0}^{\infty} \int_{qs}^{\infty} du e^{-u^2} \left\{ \frac{u}{n + 1/2} - \frac{t}{\sqrt{b}\eta} \tan^{-1} \left[ \frac{u\sqrt{b}\eta}{(n + 1/2)t + i\alpha b} \right] \right\}
\]

Band coupling parameters:

\[
a_1 = (\lambda_0 + \lambda_\nu) / 2w, \quad a_2 = (\lambda_0 - \lambda_\nu) / 2w, \quad \lambda_\nu = \lambda_{11} - \lambda_{22}, \quad \lambda_0 = (\lambda_\nu^2 + 4\lambda_{12}\lambda_{21})^{1/2}, \quad w = \lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}
\]

Band asymmetry parameters:

\[
\eta = \left( \frac{v_2}{v_1} \right)^2, \quad s = \frac{\varepsilon_2}{\varepsilon_1}
\]
Limiting cases for $\alpha << 1$

$$H_{c2}(T) = \frac{24\pi\phi_0 T_c (T_c - T)}{7\zeta(3) \hbar^2 (c_+ v_1^2 + c_- v_2^2)}$$

$T \approx T_c$

- In the GL region, $H_{c2}$ is limited by the FS pocket with the largest Fermi velocity. The $s^{++}$ and $s^\pm$ scenarios behave similarly

$$H_{c2}(0) = \frac{\pi e^2 \phi_0 T_c^2}{2\gamma \hbar^2 v_1 v_2} \exp(g)$$

$$g = \left[ \frac{\lambda_0^2}{w^2} + \frac{\lambda_-}{w} \ln(\eta) + \frac{ln^2\eta}{4} \right]^{1/2} \text{sgn}(w) - \frac{\lambda_0}{w}$$

- $H_{c2}(0)$ is limited by the largest Fermi velocity for the $s^\pm$ pairing but the smallest Fermi velocity for the $s^{++}$ pairing
Can $s^{\pm}$ be distinguished from $s^{++}$?

No paramagnetic effects, $\alpha \ll 1$:

Strong band asymmetry causes upward curvature in $H_{c2}(T)$

Conventional $s^{++}$ for MgB$_2$: $w > 0$: convex $H_{c2}(T)$ at low $T$

Unconventional $s^{\pm}$ for pnictides: $w < 0$: convex $H_{c2}(T)$ at intermediate $T$

$s^{\pm}$ increases orbitally-limited $H_{c2}$
Mass anisotropy facilitates FFLO

If the passive band with $\alpha < 1$ has large mass anisotropy, the active band with $\alpha > 1$ can enforce the global FFLO state.

- Reduction of the FFLO kinetic energy $\varepsilon_2 Q_z^2$ in the passive band 2 with $\alpha_2 < 1$.

\[
\eta = \left(\frac{v_2}{v_1}\right)^2, \quad s = \frac{\varepsilon_2}{\varepsilon_1}
\]
Band competition: hidden FFLO

\[ \alpha_1 = \frac{2\pi k_B T_c}{v_1^2 m_e}, \quad \alpha_2 = \frac{2\pi k_B T_c}{v_2^2 m_e} \]

- Due to the significant differences in the band parameters, one band can be FFLO unstable \((\alpha_1 > \alpha_c)\) but another one is not \((\alpha_2 < \alpha_c)\).

- Passive band reduces manifestations of the FFLO in the WHH-like shape of \(H_{c2}(T)\), but FFLO is still there.

- “Hidden” FFLO: no apparent signs in \(H_{c2}(T)\) but can be revealed as the first order PT by magnetic torque and specific heat or NMR.
Experiment-I: LiFeAs

- Undoped composition corresponds to the maximum $T_c$
- No suppression of FFLO by doping-induced disorder
- Good candidate to search for FFLO, mean free path $>> \xi$


- Small jump in magnetic torque develops below 8K

Experiment-II: FeSe$_{0.5}$Te$_{0.5}$ films

- 100-400 nm thick FeSeTe films, $T_c = 16.2$K. Huge slopes $H_{c2}' > 100$ T/K for $H || ab$

C. Tarantini et al. cond-mat. arXiv: 1108.5194
FFLO triggered by the Lifshitz transition

- \( H_{c2} \) equation in effective 2-band form:

\[
\lambda (\ln t + \tilde{U}_1)(\ln t + U_2) = 2 \ln t + \tilde{U}_1 + U_2,
\]

\[
\tilde{U}_1 = \frac{U_1 + gU_3}{1+g}, \quad g = \frac{\lambda_{23}\lambda_{32}}{\lambda_{12}\lambda_{21}} = \frac{m_3^2V_{23}^2}{m_1^2V_{12}^2} \sqrt{\eta},
\]

\[
\lambda = (\lambda_{12}\lambda_{21} + \lambda_{23}\lambda_{32})^{1/2}
\]

- reduction of the FFLO instability threshold
Enhancement factors

\[ g = \frac{\lambda_{23} \lambda_{32}}{\lambda_{12} \lambda_{21}} = \frac{m_3^2 V_{23}^2}{m_1^2 V_{12}^2} \sqrt{\eta} \]

Small Fermi energies in FeSeTe
Tamai et al, PRL 104, 097002 (2010)

Mass enhancement of a shrinking FS Pocket BaFe$_2$(As$_x$P$_{1-x}$)$_2$ revealed by dHvA oscillations
Shishido et al, PRL 104, 057008 (2010)
Quantum oscillations in $H_{c2}(T)$

- First LL quasiclassic solution works for $\alpha < 7$.
- For higher $\alpha$ (small $E_F$ of the emerging FS pocket), quantum oscillations due to higher LLs become important

\[
T_c(H) = T_{c0}(H) \left[ 1 - \frac{2\omega_c}{E_F} \exp \left( -\frac{2\pi^2 T_{c0}}{\omega_c} \right) \sin \left( \frac{2\pi E_F}{\omega_c} + \frac{\pi}{4} \right) \right]
\]

Rajagopal and Vasudevan, Phys. Lett. 23, 539 (1966)

For $E_F = 3$ meV, the field range $H \sim 30T$ is accessible at low temperatures
Magnetic defects caused by $\alpha$ particle irradiation

- A “clean” way of introducing disorder without doping and segregation of impurity phases
- $\alpha$ particles mostly interact with Nd, As and Fe.
- Displacement of Fe produces the Frenkel radiation defects
- Partial restoration of magnetic moment of Fe$^{2+}$ ion
- Irradiation defects cause both nonmagnetic and magnetic scattering

$2 \text{ MeV } ^4\text{He}^{2+}$ ion beam

Ion range in NdFeAsO$_{0.7}$F$_{0.3} \sim 4.2 \ \mu$m
Uniform damage across the 1 $\mu$m thick crystal

Lee, Prado and Pickett, PRB 78, 174502 (2008)
Kemper et al, PRB 80, 104511 (2009)
Effect of irradiation on $\rho(T)$ of a Nd-1111 single crystal

- $T_c$ gradually decreases and the resistivity increases after each irradiation dose with a significant upturn developing at low $T$.

- $T_c$ vanishes at a rather high dose = $5.25 \times 10^{16} \text{ cm}^2$.

C. Tarantini, M. Putti, AG et al. PRL 104, 087002 (2010)
Logarithmic resistivity

\[ \Phi = 7.5 \times 10^{15} / \text{cm}^2 \]

\[ \rho_2(T) = \rho_0 + a_1 T + a_2 T^2 \]

\[ \Delta \rho(T) = \rho(T) - \rho_2(T) \]

- Logarithmic temperature dependence
  
  \[ \Delta \rho(T) = A_K \ln(T_0 / T) \]

- \( A_K \) increases with fluence
- \( T_0 \approx 110\text{-}120 \text{ K} \) is independent of fluence

- Kondo scattering induced by irradiation?
- No sign of saturation at low \( T \).
  Kondo temperature \( T_K < 2 \text{K} \).
Dependence of fluence

\[ \rho_0, \rho_{50K}, A_K \] quantify non-magnetic and magnetic scattering.

Both \( \Delta \rho (T) \) and \( \rho_0 \) have the same dependence on the concentration of the irradiation defects.
Suppression of $T_c$ by irradiation defects

Non-magnetic scattering rate $\Gamma$

$$\Gamma = \Delta \rho_0 / \mu_0 \lambda_0^2$$

Pairbreaking interband scattering rate $g$

$$g = \frac{\Gamma h}{4\pi k_B T_c 0}$$

- Nd-1111 looks more like the s-wave MgB$_2$ and $V_3$Si rather than the d-wave cuprates

- High density of irradiation defects: mean free path $l = v_F / \Gamma \sim 2.4$nm
Effect of scattering on $T_c$

Equal gaps: $\Delta_1 = - \Delta_2$:

**Pairbreaking:**
- Nonmagnetic inter-band scattering
- Magnetic intra-band scattering

**Non-pairbreaking:**
- Intra-band nonmagnetic scattering
- Inter-band magnetic scattering

Reduction of nonmagnetic inter-band scattering for strong impurity potentials

$$\frac{1}{2\tau} \rightarrow \frac{\pi c N V^2}{1 + (\pi N V)^2}$$

$Irradiation$ 
experiment gives $g_c \approx 1.7$

$g_c = 1/4\pi T_c \tau \approx 0.15$

G. Priosti and P. Muzikar, PRB 54, 3489 (1996);
M. Kulic and O. Dolgov, PRB 60, 13062 (1999).
Magnetic Kondo scattering

- Strong intra-band Abrikosov-Gorkov magnetic pairbreaking

\[ \ln \frac{T_{c0}}{T_c} = \psi\left(\frac{1}{2} + \frac{1}{4\pi T_s T_c}\right) - \psi\left(\frac{1}{2}\right) \]

- Effect of Kondo scattering on BCS superconductivity:
  E. Muller-Hartmann, J. Zittartz, PRL 26, 428 (1970); P. Schlottmann, SSC 21, 663 (1973);
  T. Matsuura, S. Ichinose, Y. Nagaoka, Prog. Theor. Phys. 57, 713 (1977);

- \( T_K > T_{c0} \): Kondo screening reduces pairbreaking as compared to the AG theory

- \( T_K < T_{c0} \): Kondo scattering enhances pairbreaking as compared to the AG theory. Multi-valued dependence of \( T_c \) on the impurity concentration

For Nd-1111 crystals, \( T_K < 2K \) and \( T_c = 46K \): any multiband BCS superconductivity would be suppressed irrespective of pairing symmetry
Conclusions

- Anomalous temperature dependencies of $H_{c2}(T)$ reflect the effects of multiband pairing and strong Pauli limiting in FBS
  - $s^\pm$ pairing, low carrier density and high $T_c$ enhance the orbitally-limited $H_{c2}(T)$
  - Strong Pauli pairbreaking in FBS can lead to FFLO.
  - Hidden FFLO in multiband FBS: The WHH shape of $H_{c2}(T)$ does not mean the absence of FFLO. Torque, NMR and specific heat experiments at high fields are needed.
  - Possibility of tuning $H_{c2}(T)$ by doping but not disorder: FFLO triggered by the Lifshitz transition
  - Unusual behavior of Kondo impurities in pnictides: strong enhancement of resistivity but weak suppression of $T_c$ even for the mfp $\approx \xi$
  - Magnetic impurity scattering is to be intertwined with pairing AF interaction
  - Grossly enhanced paramagnetic limit: evidence for the AF enhancement of $H_p$