Quantitative FORC Analysis: Mean Field Theory and Local Cluster Corrections

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Outline

1. Developed mean field theory of FORC for interacting single phase nanoparticle arrays
2. Tested/verified theory experimentally on nanoparticle arrays
3. Incorporated local field/exchange corrections
4. Expanded work for soft-hard composites

Experiments

Polycrystalline Co ellipses

E-beam lithography

Liftoff technique

Major/minor axis: 220/110nm

Created 50x50 micron array

Measure middle of the array to avoid edge effects

Created

- magnetizing arrays
- demagnetizing arrays

Varied coupling strength by varying separation: 150/200/250 nm

Simulations

100x100 dipole array

Each dipole has its own anisotropy H_k^i

Distribution $D(H_k^i)$: experimental, peaked, rectangle, Gaussian

Interaction: $H_{int}^i = \alpha M(H) + H_{nn}^i$

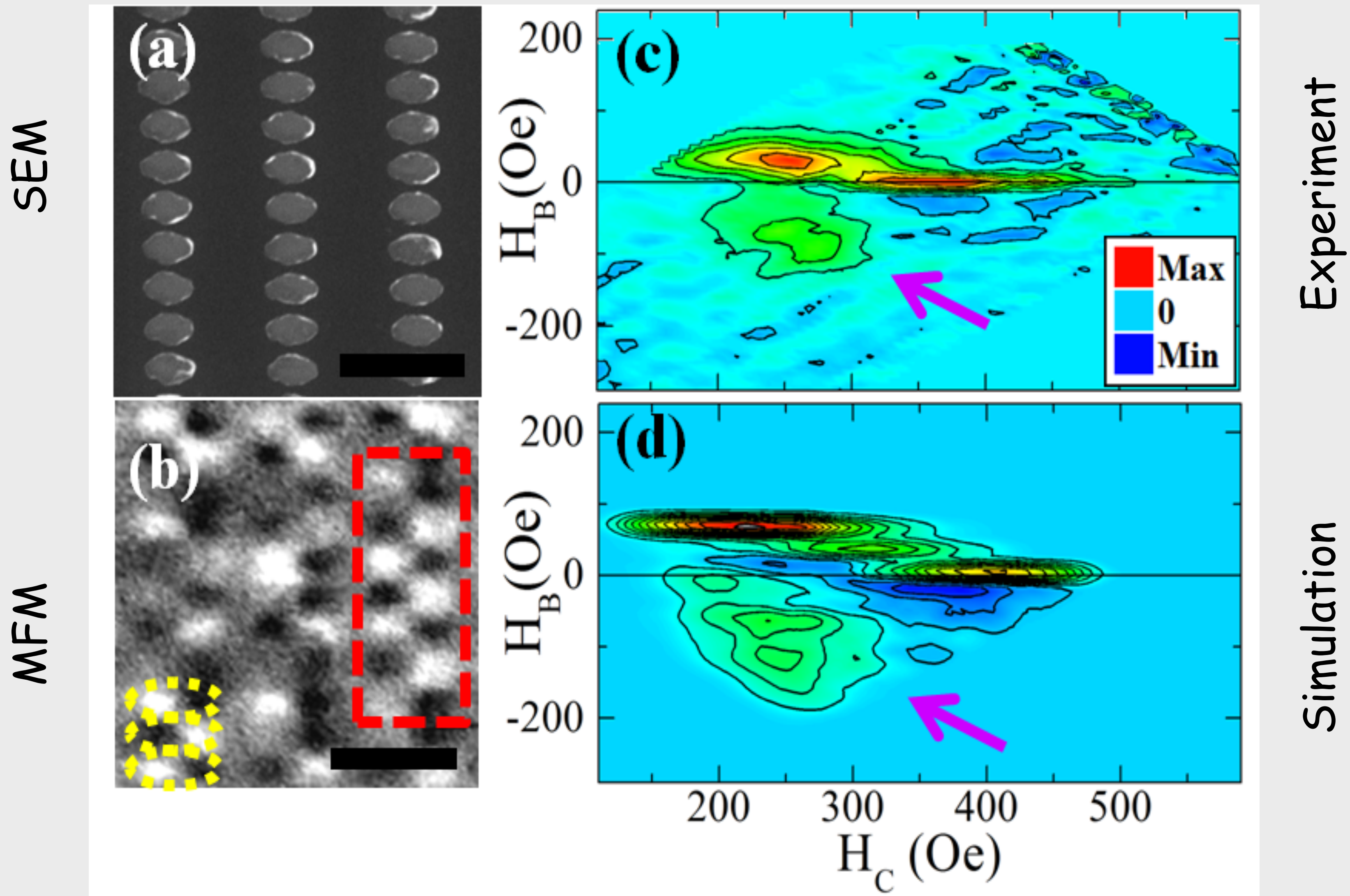
- no interaction
- mean field level $\alpha M(H)$, α calibrated at saturation
- added nearest neighbor exchange/coupling

Down-flip: $H + H_{int}^i < -H_K^i$

Up-flip: $H + H_{int}^i > H_K^i$

Re-evaluate M(H), keep flipping until all dipoles stable

Demagnetizing Arrays

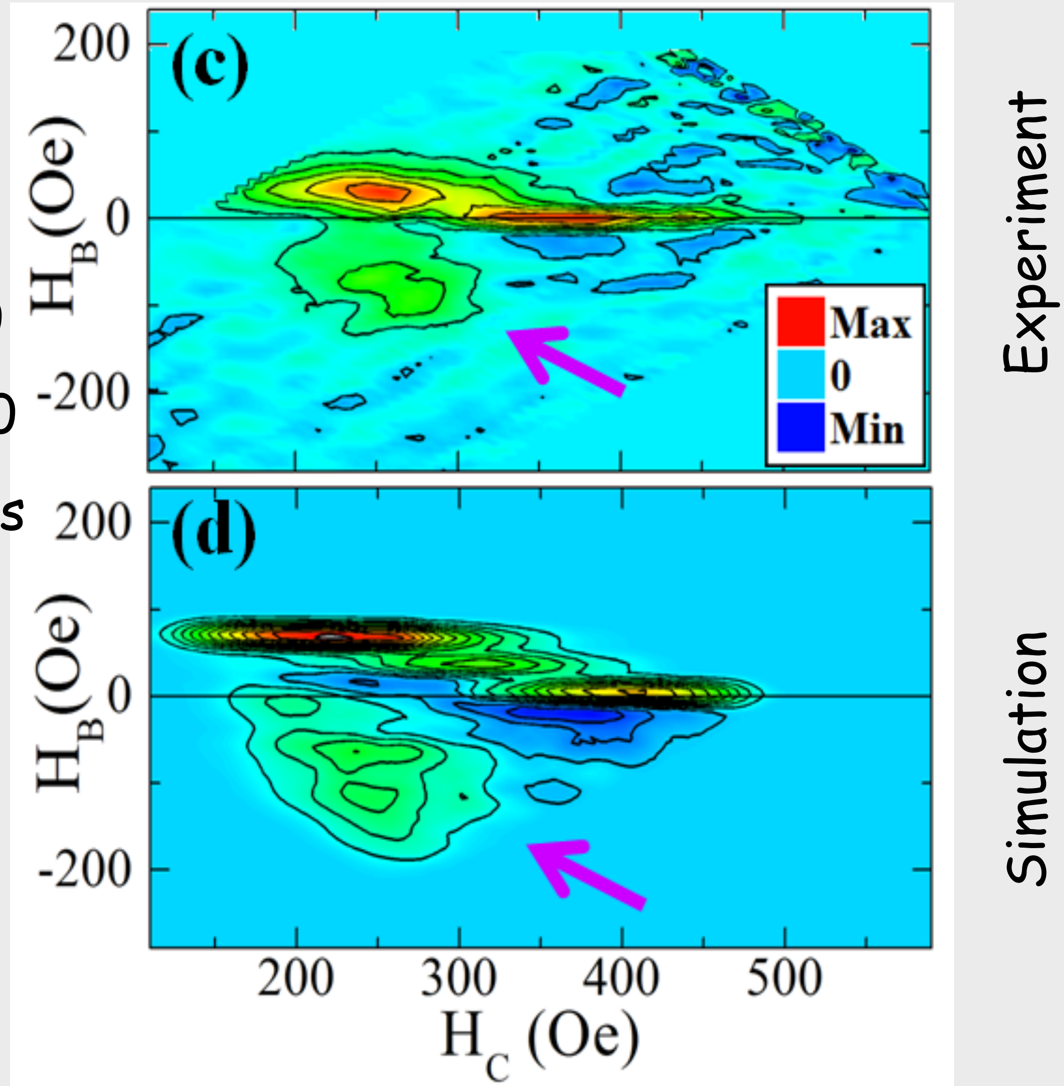


Demagnetizing Arrays

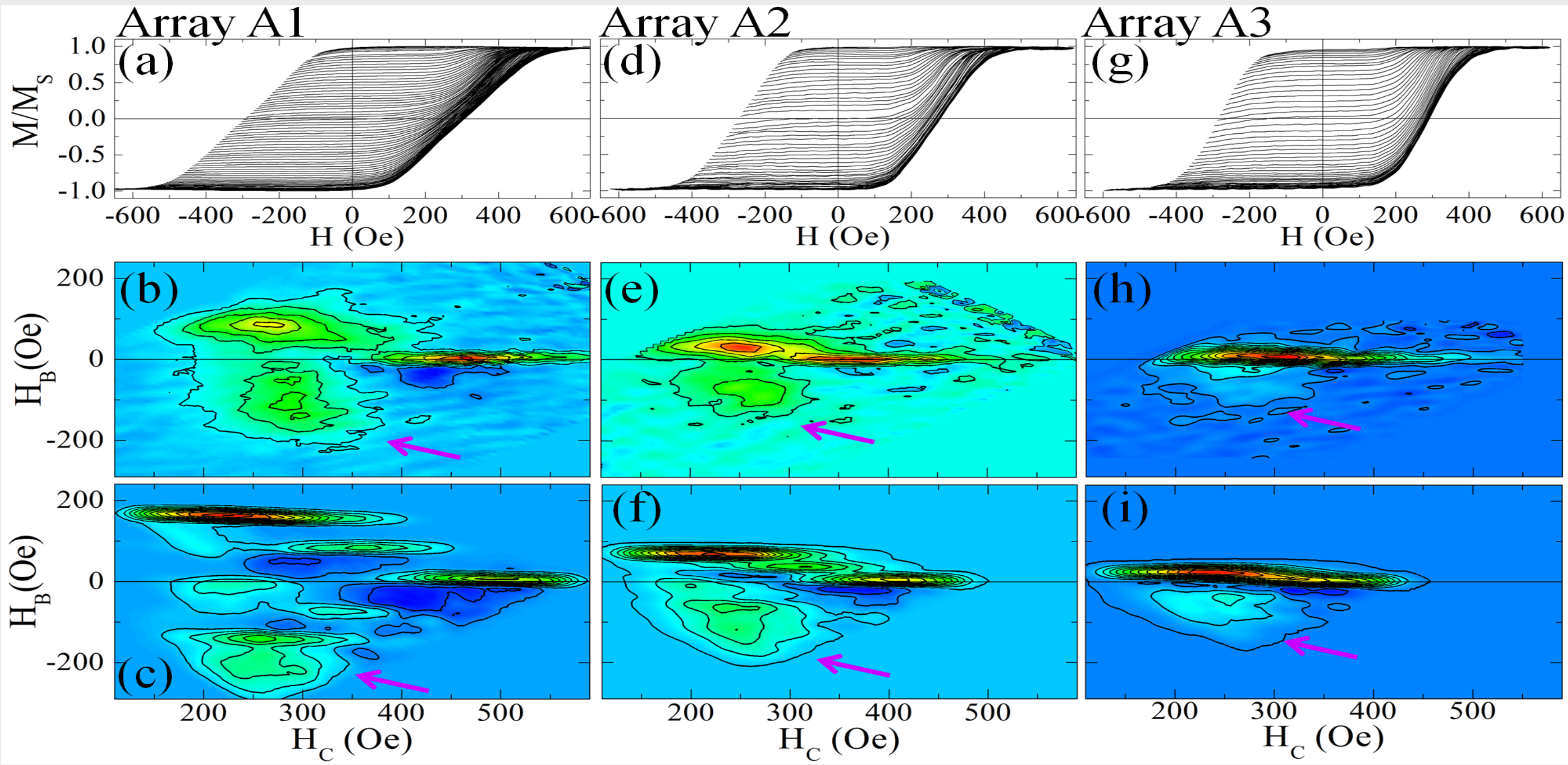
No interaction: Ridge

Interaction: Ridge:

1. Min H_K end shift $H_B>0$
2. Max H_K end stay $H_B=0$
3. Ridge length increases
4. Edge develops down (boomerang/wishbone)
5. Negative feature (high H_K region)



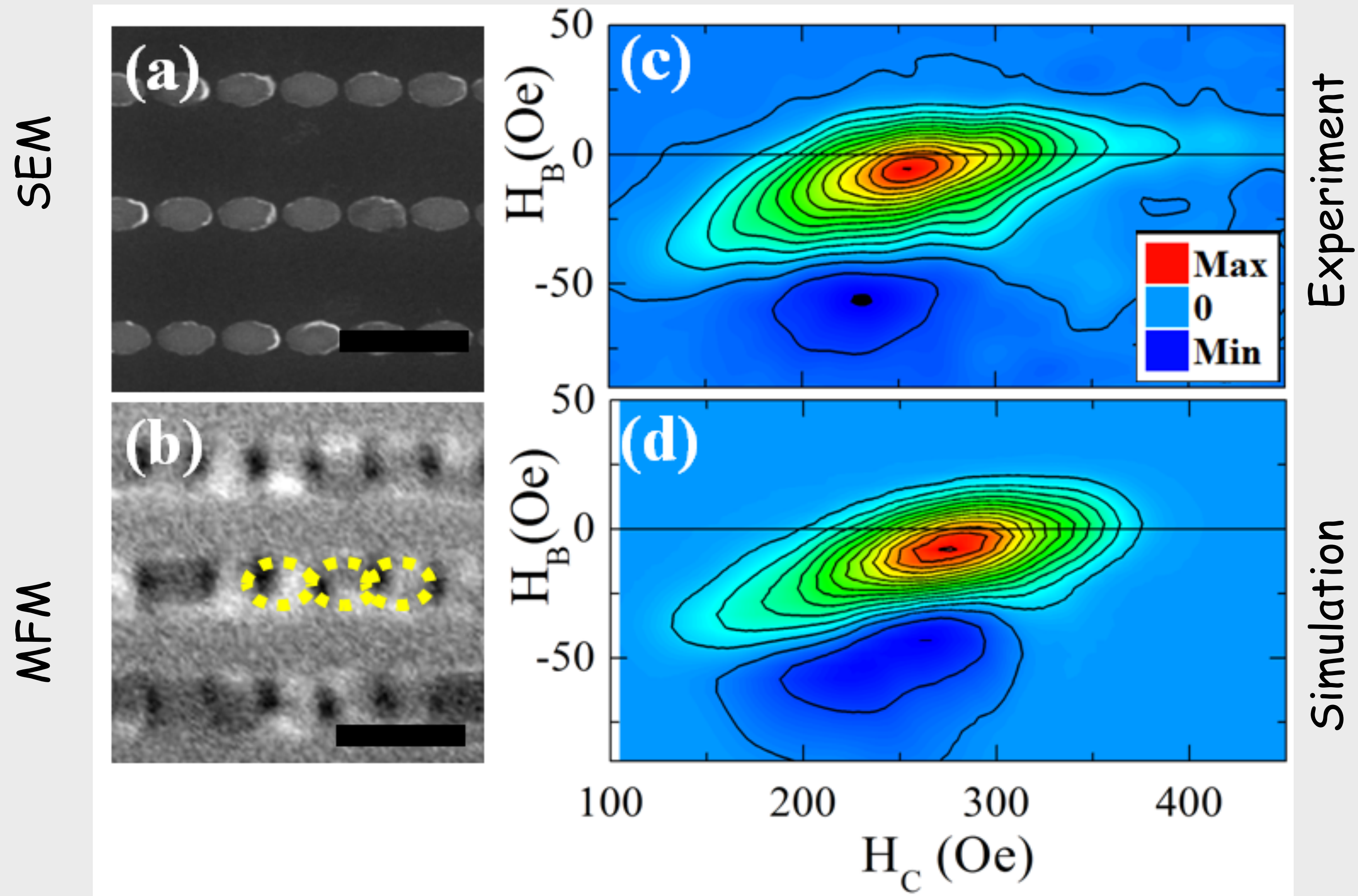
Demagnetizing Arrays – Experimental Trends



Increasing interaction (right to left):

1. Min H_K end shift $H_B>0$, Max H_K end stays $H_B=0$
2. Edge and negative region develops

Magnetizing Arrays



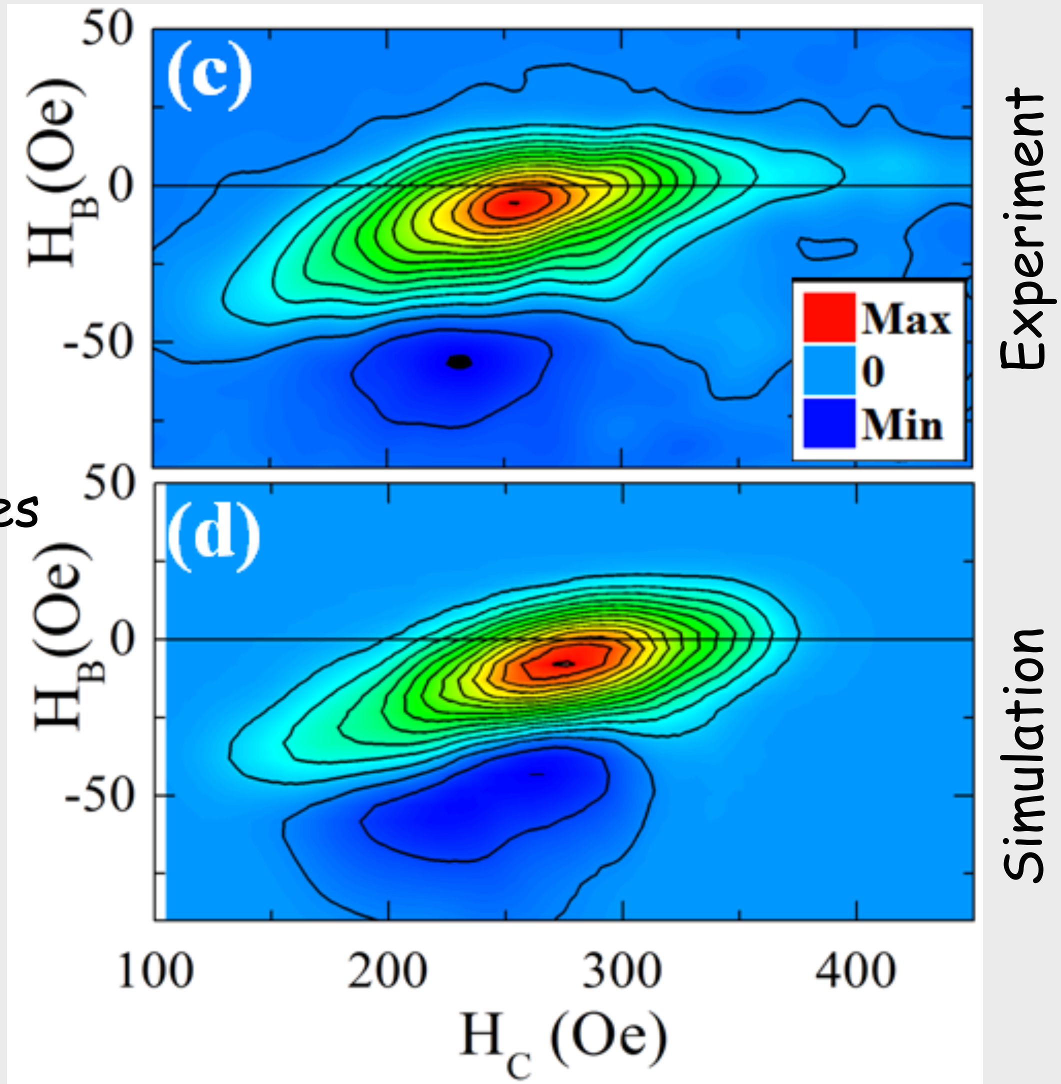
Magnetizing Arrays

No interaction: Ridge

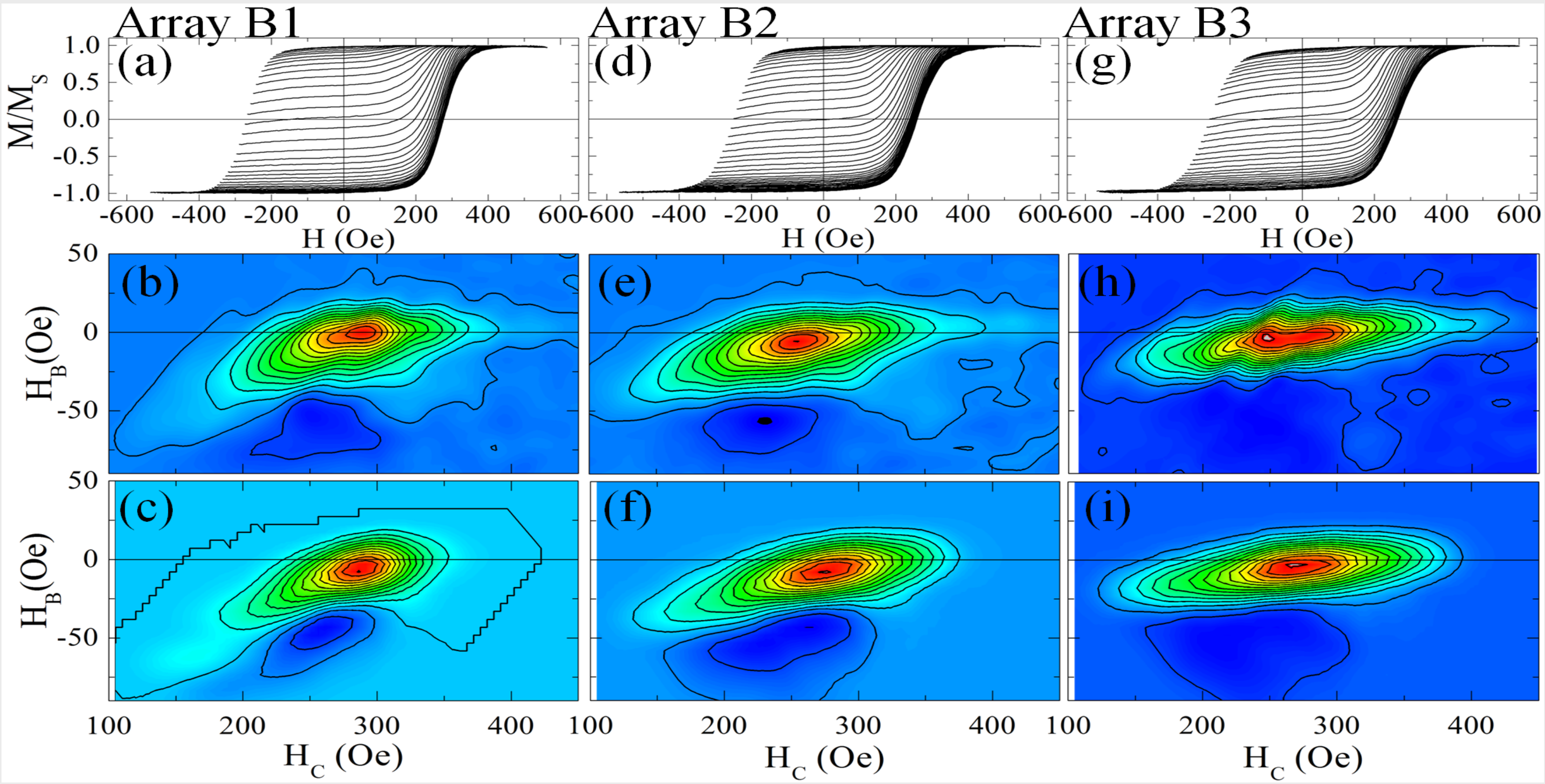
Interaction: Ridge:

1. Low H_K end pushed dn
2. High H_K end stays
3. Ridge length decreases
4. No visible edge
5. Negative feature

   (low H_K region)



Magnetizing Arrays – Experimental Trends

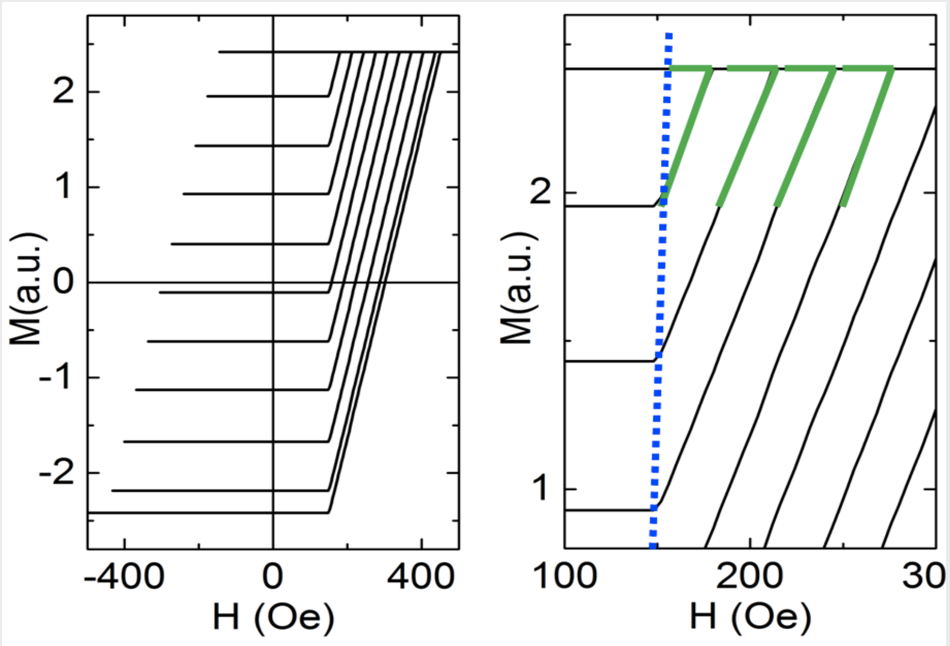


Increasing interaction (right to left):

1. Min H_K end shift H_B<0 , Max H_K end stays H_B=0
2. No edge, negative region develops

Non-Interacting Arrays - Ridge

$\rho(Hb=0,Hc)=D(H_K)$



$P_i(H_K^i)$ down-flips at $H_{dn}^i=-H_K^i$ and up-flips at $H_{up}^i=H_K^i$

$H_R>-H_K^i$, P_i no contribution

$H_R=-H_K^i$, P_i is the last to down-flip, last to up-flip:

upflip dM/dH jump unmatched by previous H_R: $-d(dM/dH)/dH_R>0$

Demagnetizing Arrays - Ridge

$H_{tot}=H+\alpha M(H) \quad \alpha<0$

$P(H_k^{min})$ unmatched (min)

$H_{dn}^{min}=-H_K^{min}-\alpha M_S$

$H_{up}^{min}=H_K^{min}-\alpha M_S$

Low H_C end shifted by

$\Delta H_B=\alpha M_S \quad \Delta H_C=0$

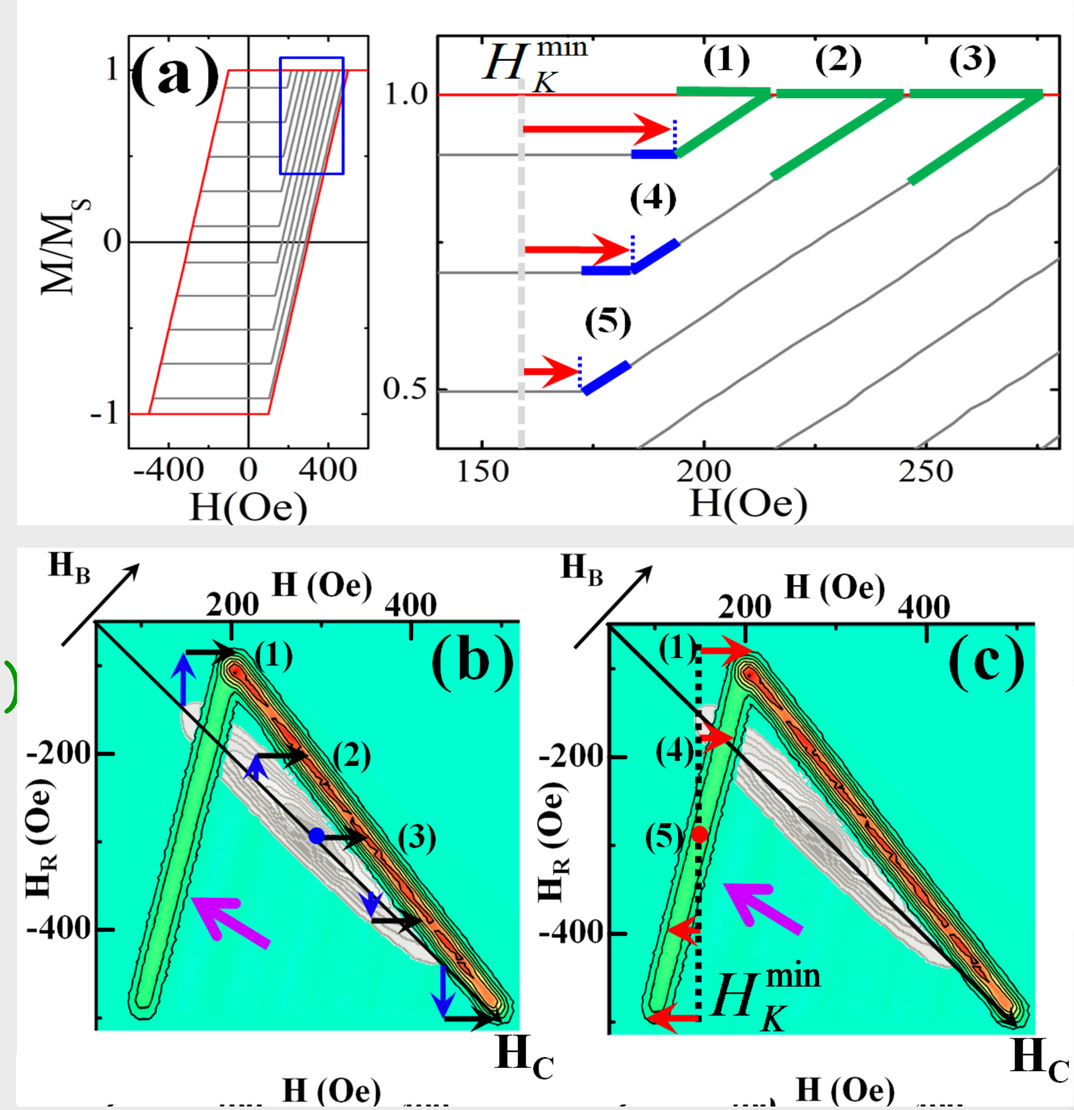
$P(H_k^{max})$ unmatched (max)

$H_{dn}^{max}=-H_k^{max}+\alpha M_S$

$H_{up}^{max}=H_K^{max}-\alpha M_S$

High H_C end shifted by

$\Delta H_B=0 \quad \Delta H_C=\alpha M_S$

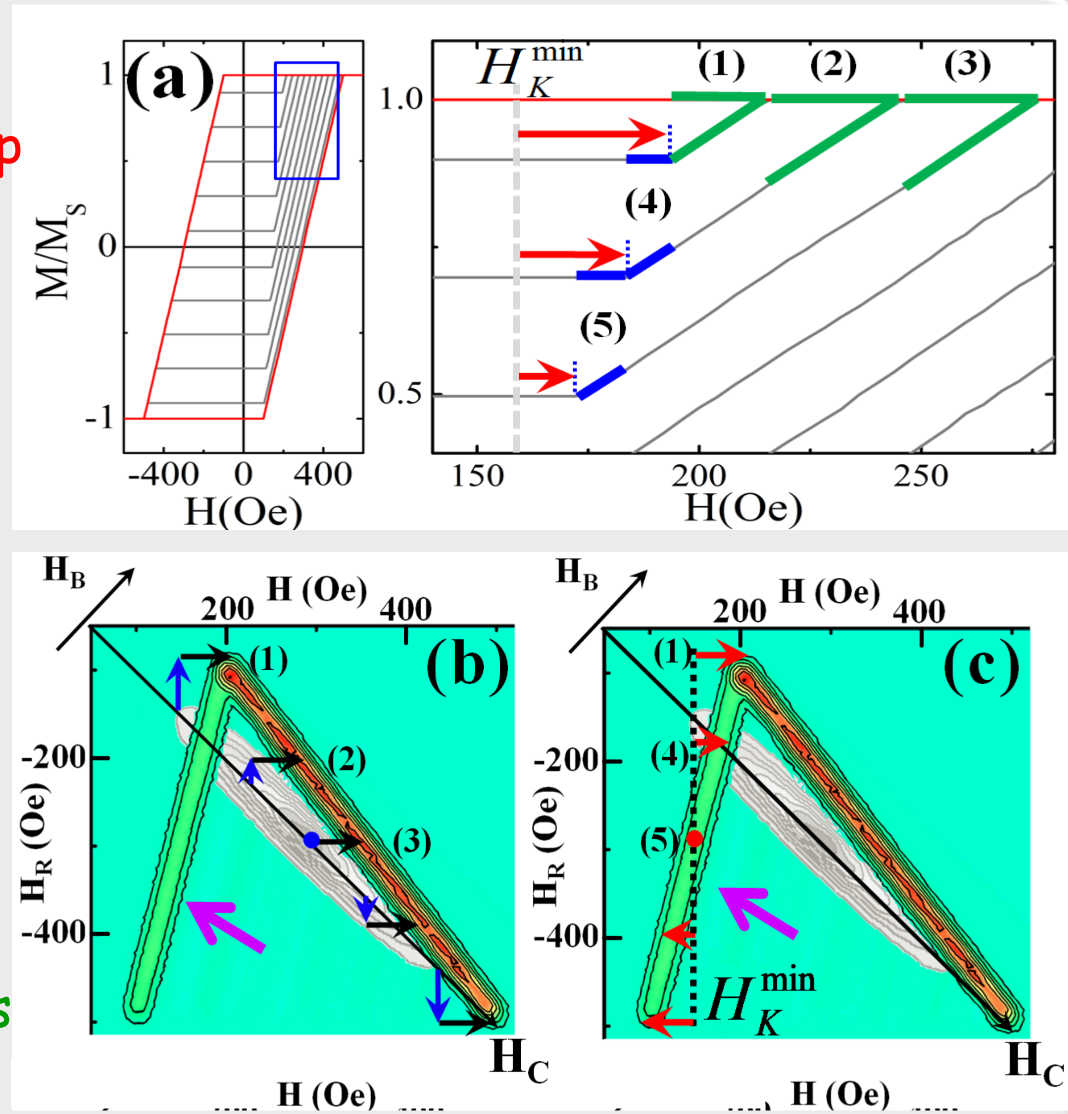


Demagnetizing Arrays - Ridge

Ridge: unmatched last flip

1. Min H_K end shift H_B>0
2. Max H_K end stay H_B=0
3. Ridge length increases
4. Edge develops down (boomerang/wishbone)
5. Negative feature

Shift at both min H_K and max H_K can be used to quantitatively extract Ms



Demagnetizing Arrays - Edge

$H_{tot}=H+\alpha M(H)$ $\alpha<0$

$P(H_k^{min})$ up unmatched (4-5)

top:

$H=H_K^{min}-\alpha M_S$, $H_R=-H_K^{min}-\alpha M_S$

bottom

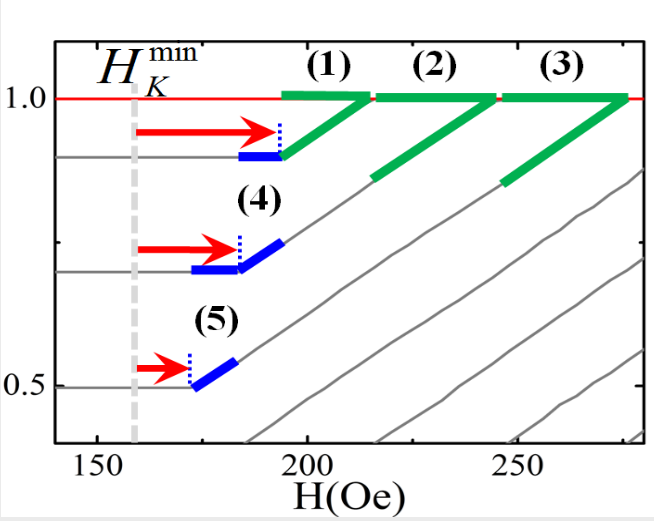
$H=H_K^{min}+\alpha M_S$, $H_R=-H_K^{max}+\alpha M_S$

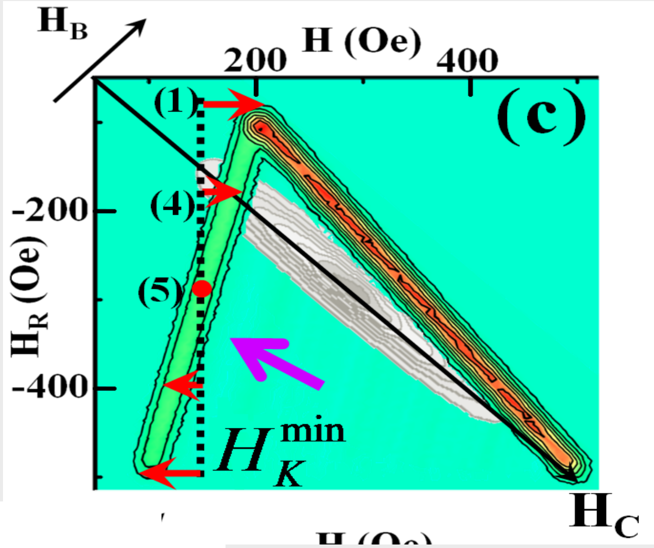
top:

$H_C=H_K^{min}$, $H_B=-\alpha M_S$

bottom:

$H_C=(H_K^{min}+H_K^{max})/2$, $H_B=\alpha M_S+(H_K^{min}-H_K^{max})/2)$



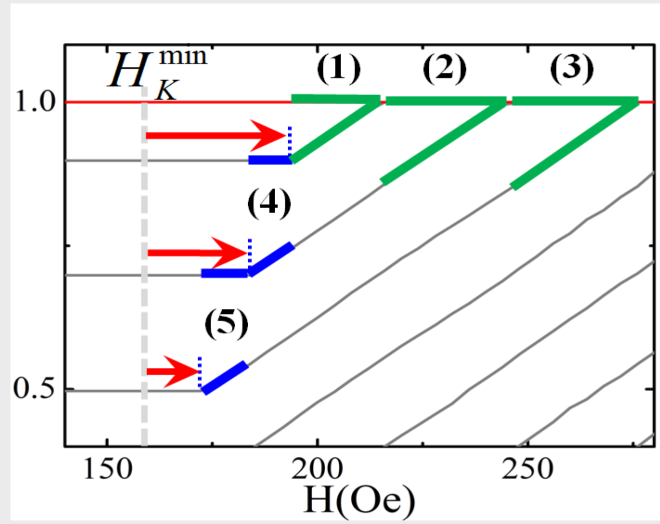


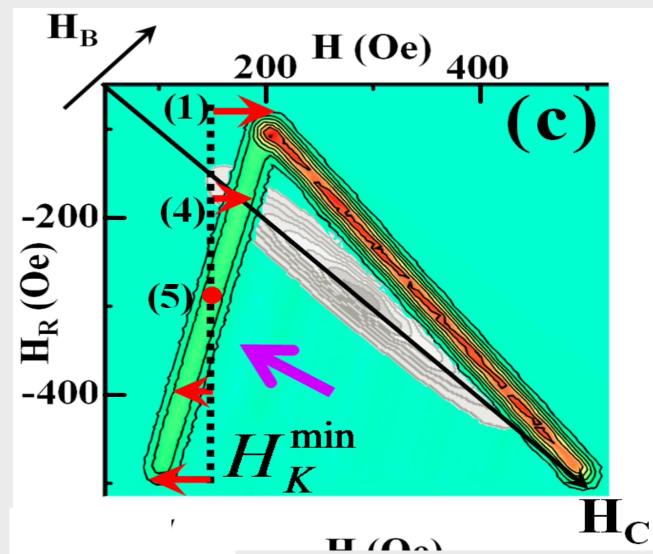
Demagnetizing Arrays - Edge

Edge: unmatched first flip

1. Min H_K end shift H_B>0
2. Max H_K end stay H_B=0
3. Ridge length increases
4. Edge develops down (boomerang/wishbone)
5. Negative feature

Tilt and length of edge can be used to quantitatively extract mean and width of $D(H_K)$





Demagnetizing Arrays – Negative Region

Change rectangular $D(H_K)$ to Gaussian

Consider FORC of $P(H_K^{Cent})$: $H_R=-H_K^{Cent}$

dM/dH of next FORC ($H_R<H_R^{Cent}$) would

match dM/dH^{cent} for flat $D(H_K)$,

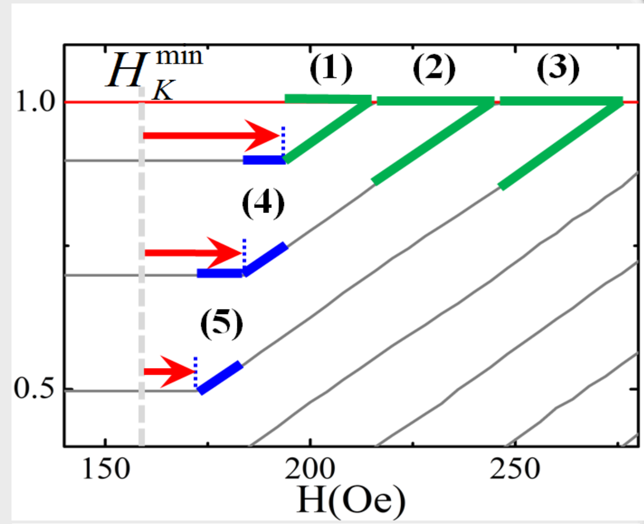
no change in dM/dH, zero FORC

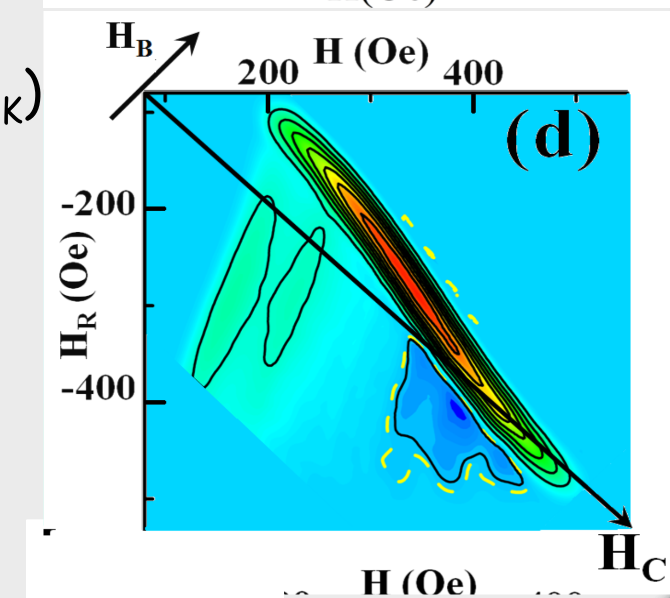
But, for decreasing half of Gaussian $D(H_K)$

the number of dipoles aligned with

$FORC^{Cent}$ is less than on $FORC^{Cent}$:

dM/dH decreases, **negative FORC in the high H_K region**





Demagnetizing Arrays – Mean Field Theory

Explains all experimental features:

1. Min H_K end shift $H_B>0$

2. Max H_K end stay $H_B=0$

3. Ridge length increases

4. Edge develops down (boomerang/wishbone)

5. Negative feature - high H_K region

\+ Tilt and length of ridge and edge can be used to quantitatively extract Ms and mean/width of $D(H_K)$