# THE EXCHANGE BIAS MANIFESTO
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There is a time in the life of scientists when it is important to consider:

What is the Grand Purpose of it all?.

In this case, we started wondering, why all papers in Exchange Bias start by stating something like:

*"Although exchange bias was discovered more than 40 years ago, the origin of this phenomenon is still not clear".*

This brief document attempts to put some order into this issue and raise some relevant questions. We would appreciate any corrections, comments and additions. However we must insist on one requirement: Be brief!.

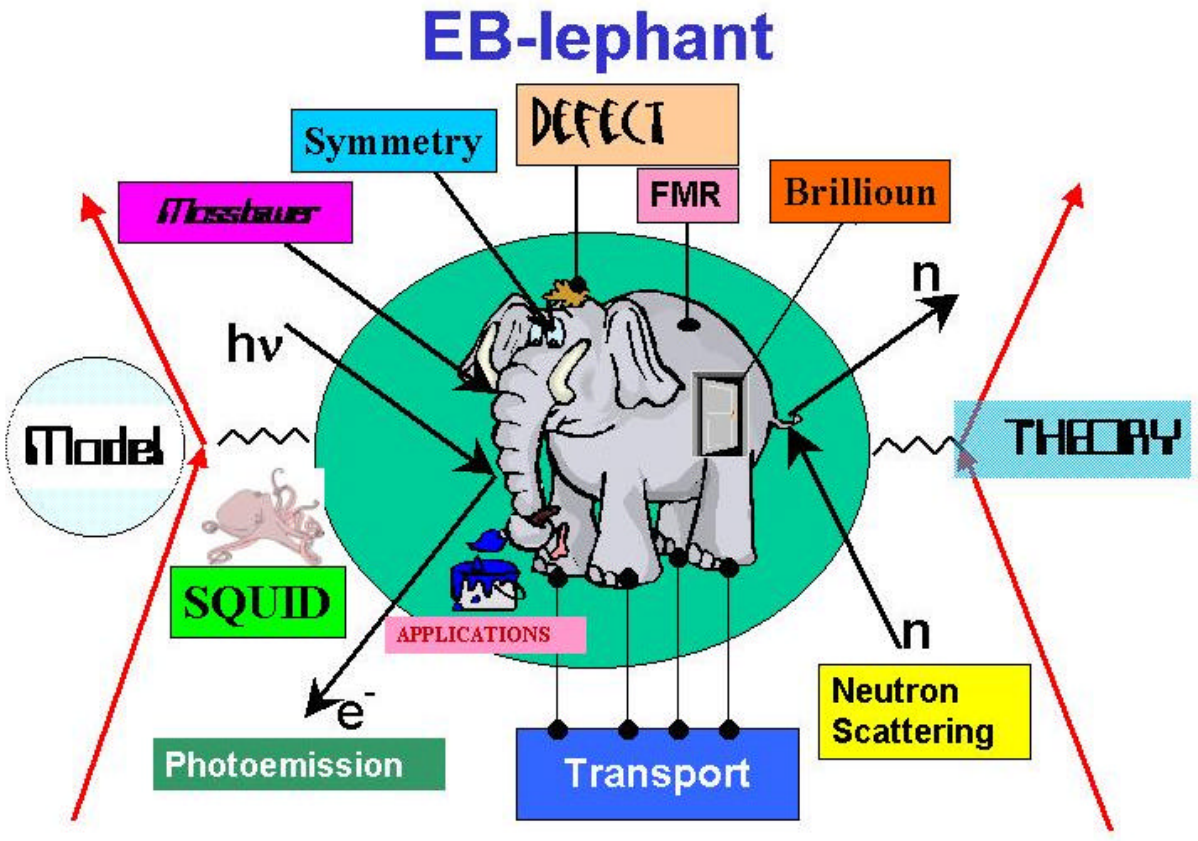



**Figure 1** Status of the Exchange Bias field, based on the introduction of literally hundreds of papers.

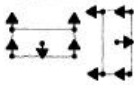
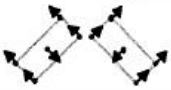
| Sample | $\uparrow H_{FC}$ Orientation (arrows show directions of Fe spins) | $H_E$ [Oe] | $\sum_{domains} \lvert\overline{S_F} \bullet \overline{S_{AF}}\rvert$ | F anisotropy axes (arrow length qualitatively indicates size of anisotropy) | Asymmetric reversal | Magnetization reversal mechanism |
|---|---|---|---|---|---|---|
| u-AF |  | -32±2 | 1 |  | no | Rotation |
| u-AF |  | -2±2 | 0 |  | no | Domain nucleation and wall motion |
| p-AF |  | -30±2 | $\frac{2^a}{\pi}$ |  | no | Domain nucleation and wall motion |
| t-AF |  | -76±2 | $\frac{1}{2}$ |  | no | Rotation |
| t-AF |  | -325±2 | $\sqrt{2}$ |  | yes | Rotation (L.H.S.) Domain nucleation and wall motion (R.H.S) |

Figure 2 One possible good (i.e.brief) way to summarize the status of research for a particular system. In this case for FeF2 (110)-Fe (policrystalline). From M. Fitzsimmons et al, Phys Rev. B 65, 134436(2002)

## "Philosophical" Considerations

- There are many apparently confusing, contradictory (?) facts. See figure 1.
- There are very diverse systems, with various degrees of control on the structure.

  Because of this it is important to have some brief concise way of classifying the main results, as indicated in figure 2 above. This should be amplified and other similar tables be constructed.
- The purpose is to find out which facts are essential, which are just side issues
- It is probably useful (?) to categorize the systems:

  **1.** Crystalline AF – Interface - Crystalline F

  **2.** Complex AF- Interface – Complex F

  **3.** Disordered Magnet – Interface – F

  **4.** Hard F – Interface – Soft F (Spring Magnet)
- The various parameters needed to characterize an exchange biased system are:

  1. Growth method (thin film, natural oxidation, …)
  2. Characterization tools (quantitative, qualitative?)
  3. AF crystal structure
  4. F crystal structure
  5. Interfacial roughness
  6. Neel temperature
  7. Curie Temperature
  8. Thin film crystal structures
  9. Bulk and thin film anisotropies
  10. Bulk and thin film spin structure
  11. Blocking temperature
  12. Cooling field
  13. Cooling procedure

14. Exchange Bias

15. Coercivity

16. Left and Right hand dependence of M-H as a function of T

17. Reversal Mode

18. Training?

## Definitions

1.- "Parallel", "perpendicular" to the interface.

2.- "90°", "collinear" with respect to the AF spins.

## ESTABLISHED(?) EXPERIMENTAL FACTS TO BE EXPLAINED (More or less ordered systems)

| | Experiment | | System |
|---|---|---|---|
| 1) | Spin orientation<br>Parallel (F-AF) Spins Favored | | $FeF_2$-Fe, Co/Pt-CoO (?), $FeF_2$-Co/Pt |
| 2) | Compensated vs uncompensated | | depends on system? maximized<br>Compensated ($FeF_2$, $MnF_2$, FeMn)<br>Uncompensated (CoO) |
| 3) | Positive He | | $FeF_2$-, $MnF_2$-Fe, Co-CoO |
| 4) | Coupling: | A) 90° | $FeF_2$-Fe, Co-CoO |
| | | B) Collinear | $LaFeO_3$- Co, FeMn- Co |
| 5) | Roughness non-monotonic | | $MnF_2$-Fe |
| 6) | Ion irradiation initial increase | | NiFe/FeMn |

7) AF dilution increase — $CoO$-Co, $FeF_2$-Fe

Metallic (Py-IrMn+Rh,Pt..)

8) Loose spins ??? — Py-CoO

9) Crystallinity

| | | |
|---|---|---|
| Single Xtals | small | CoO, NiO, $FeF_2$ ??? |
| Epitaxial | varied | |
| Twin | large | $FeF_2$ |
| Poly | intermediate | $FeF_2$, CoO |

10) He maximized (w/r AF anisotropy)

| | |
|---|---|
| Along ? | $FeF_2$-Co?, $MnF_2$-Fe |
| Close | CoO-FeNi |

11) AF anisotropy — $MnF_2$<<<<$FeF_2$<<CoO

12) 3rd order anisotropy — $MnF_2$-Fe, NiFe-CoO

13) Asymmetric loop — $FeF_2$-, $MnF_2$-Fe, CoO-Co,

NiMn-NiFe, PtMn-NiFe

14) Asymmetric Reversal — $FeF_2$ (twinned), CoO

15) Training — Fe, Co, Ni, $Ni_{50}Fe_{50}$, $Ni_{81}Fe_{19}$ - FeMn

$La_{(2/3)}Ca_{(1/3)}MnO$,$La_{(1/3)}Ca_{(2/3)}MnO_3$Co, -

CoO,Ni, NiFe - NiO, NiFe - $\alpha Fe_2O_3$, Co -

$LaFeO_3$,Co – IrMn

No — $FeF_2$-, $MnF_2$- Fe

16) Rotation in F, some — $FeF_2$-, $MnF_2$-Fe, CoO-Co

17) Vertical shift — $MnF_2$-,$FeF_2$-Fe, CoO-Co

18) Coercivity enhancement — $FeF_2$-,$MnF_2$-Fe,CoO-Co, NiFe-FeMn

$La_{(2/3)}Ca_{(1/3)}MnO_3$ –

$La_{(1/3)}Ca_{(2/3)}MnO_3$ -, all(?)

19) Reversible measurements bigger — Co-CoO (AMR, BLS)

20) Thickness dependence

i) AF (up+1/d) — $FeF_2$-Fe, CoO-Co, FeMn-FeNi

AF (up+flat) — CoO-Co, FeMn-FeNi

ii) F (1/d) — $FeF_2$-Fe

21) Cooling field — $FeF_2$-, $MnF_2$-Fe, CoO-Co

22) Magnetic history, cooling from T

## RANDOM QUESTIONS

1) Is more than one theory possible? This is the case after all for the resistivity.
2) Is it possible that different structural parameters are responsible for $H_e$ and $H_c$? The angular symmetries are different apparently?
3) Is there a correlation between He and asymmetry in reversal? Does large asymmetry imply large $H_{eb}$?
4) Is the correlation between asymmetry and 3$^{rd}$ order anisotropy important?
5) What about the crystalline orientation?
6) Are domain walls important for $H_e$, $H_c$, both or one of them?
7) Is crystallinity (rocking curve width) important?
8) Are uncompensated spins needed, do they exist, ...?
9) Is the phenomenology of Exchange Bias the same independent of system: bilayer, multilayer, disordered AF, spring magnet,…?
10) Will we ever solve this or we will get tired before and die?. This is more relevant to me than some of you young lads.

# Other Considerations

1. Numerical simulations show anisotropic reversal in M either from:
    a) Third order anisotropy.
    b) Stoner-Wohlfart + Domains.
2. Most CoO on Co is done by oxidizing Co in air.