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**Altermagnetism: Emerging Opportunities in a New Magnetic Phase**

# Magnetic octupoles as the order parameter for unconventional antiferromagnetism

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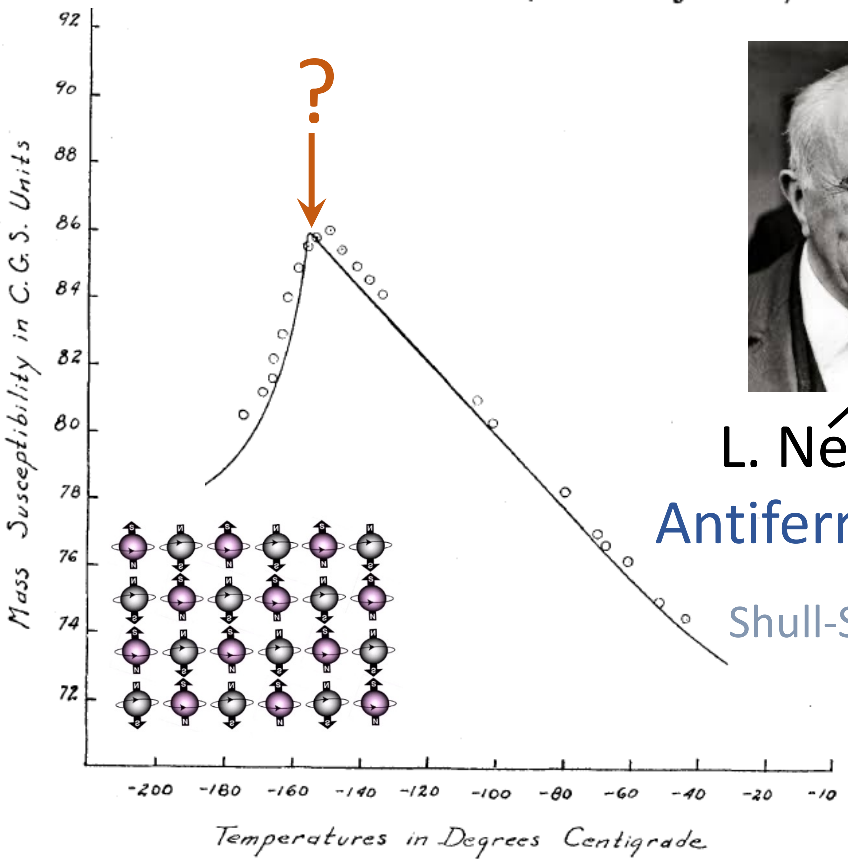
Wednesday, May 10th

# Antiferromagnetism: an early example of “hidden” magnetic order

**The Magnetic Susceptibility of MnO as a Function of the Temperature**

RAYEN WELCH TYLER, *University of Illinois*
(Received June 10, 1933)




L. Néel (1934)

Antiferromagnetism

Shull-Smart, PRB **76**, 1256 (1949)

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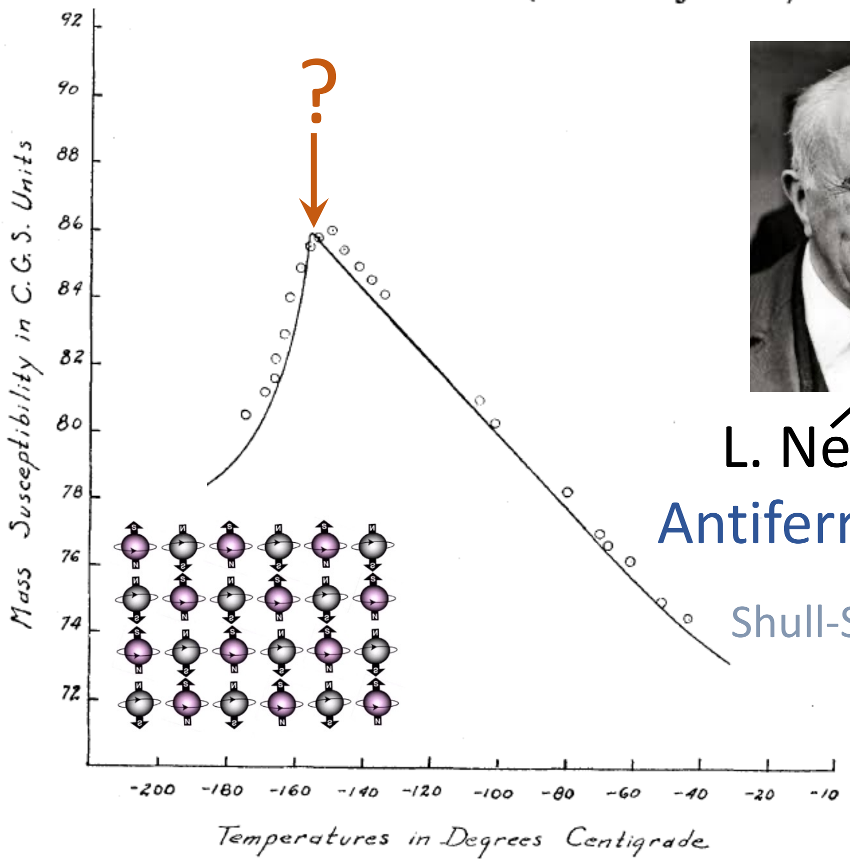


L. Néel (1934)

Antiferromagnetism

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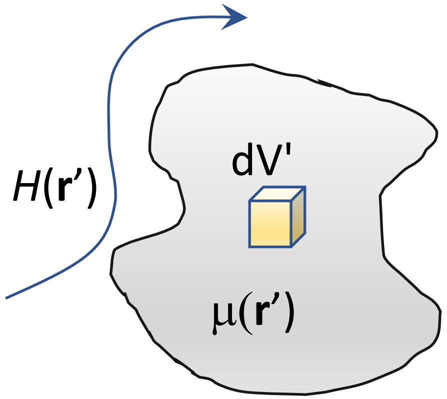
Inconvenience of staggered magnetization $\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$

- Absence of any ferroic ordering
- No information on conjugate field to select magnetic domain
- Can not distinct AFMs with & w/o broken time-reversal symmetries

# Magnetic multipoles : Recent example of "hidden" magnetic order




$$\mathcal{E}_{\mathrm{int}} = -\int \vec{\mu}(\vec{r'}) \cdot \vec{H}(\vec{r'}) dV'$$

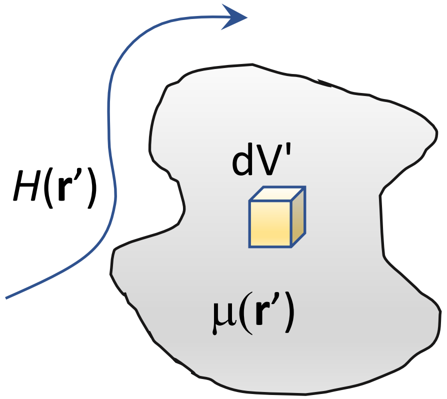
$$= -\vec{H}(0) \cdot \int \vec{\mu}(\vec{r'}) dV' - \partial_i H_j(0) \int r'_i \mu_j(\vec{r'}) dV' - \partial_i \partial_j H_k(0) \int r'_i r'_j \mu_k(\vec{r'}) dV' ..$$

Magnetic dipole    Magnetoelectric multipole    Magnetic octupole

$$= -\vec{m} \cdot \vec{H}(0) - \mathcal{M}_{ij} \partial_i H_j(0) - \mathcal{O}_{ijk} \partial_i \partial_j H_k(0) ..$$

Ederer *et. al*., PRB **76**, 214404 (2007); Spaldin *et.al.,* PRB **88**, 094429 (2013)

# Magnetic multipoles : Recent example of “hidden” magnetic order

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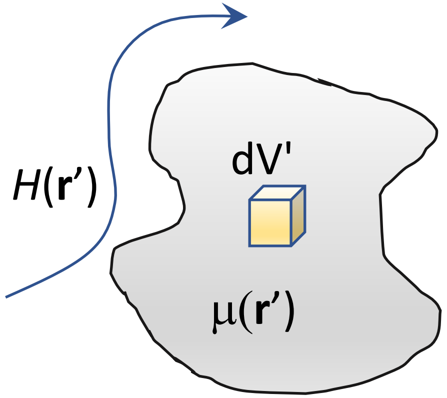


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*ON THE MAGNETO-ELECTRICAL EFFECT IN ANTIFERROMAGNETS*

I. E. DZYALOSHINSKIĬ

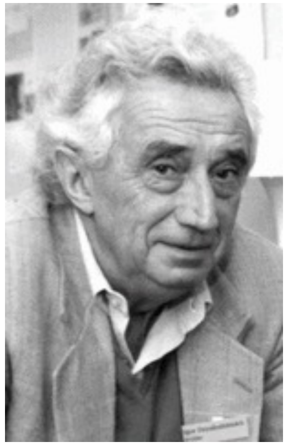
Institute for Physical Problems, Academy of Sciences, U.S.S.R.

Submitted to JETP editor June 17, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 881-882 (September, 1959)

$P_i = \alpha^{ME}_{ij} H_j$

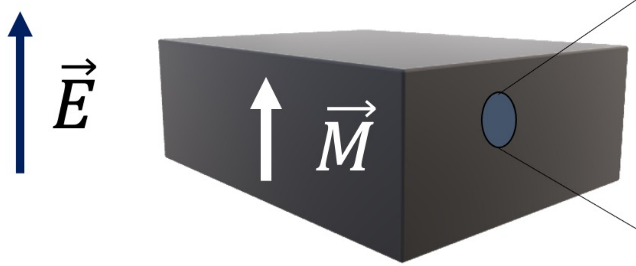
$M_i = \alpha^{ME}_{ji} E_j$

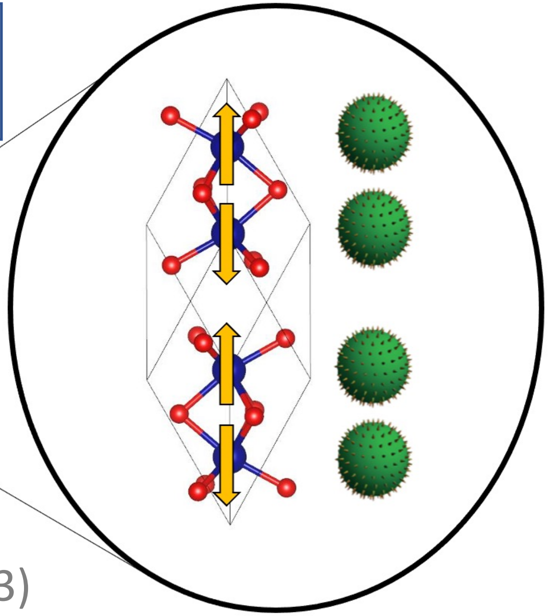


I. Dzyaloshinskii

Astrov, Sov. Phys. JETP 11, 708 (1960)

AFMs with ferroic ordering of magnetoelectric multipoles ➔ Magnetoelectric effect

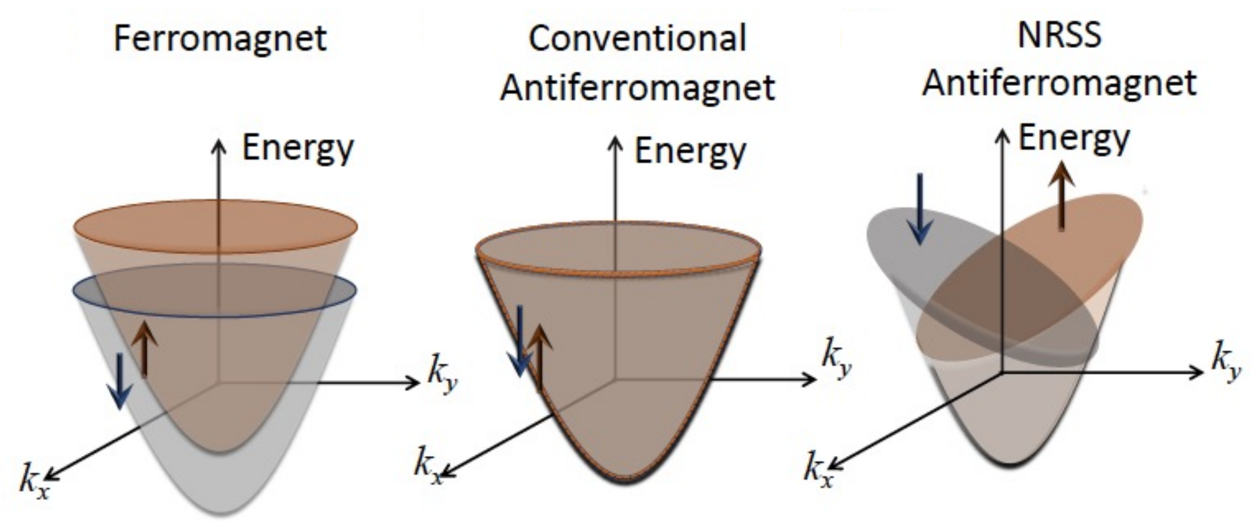


Spaldin *et. al.*, Phys. Rev. B **88**, 094429 (2013)
Verbeek *et. al.*, arXiv:2303.00513 (2023)

Courtesy: X. Verbeek

# A new type of magnetism: "Altermagnetism"




Smejkal *et. al*., Sci. Adv. **6**, eaaz8809 (2020)
Naka *et. al*., Nat. Commun. **10**, 4305 (2019)
Ahn *et. al*., Phys. Rev. B **99**, 184432 (2019)
Hayami *et. al*., J. Phys. Soc. Jpn. **88**, 123702 (2019)
Yuan *et. al*., Phys. Rev. B **102**, 014422 (2020); Phys. Rev. Materials **5**, 014409 (2021)
Smejkal *et. al*., Phys. Rev. X **12**, 031042 (2022); Phys. Rev. X **12**, 011028 (2022)
Mazin, Editorial: Phys. Rev. X **12**, 040002 (2022)
Mazin et.al., PNAS **118**, e2108924118 (2021)
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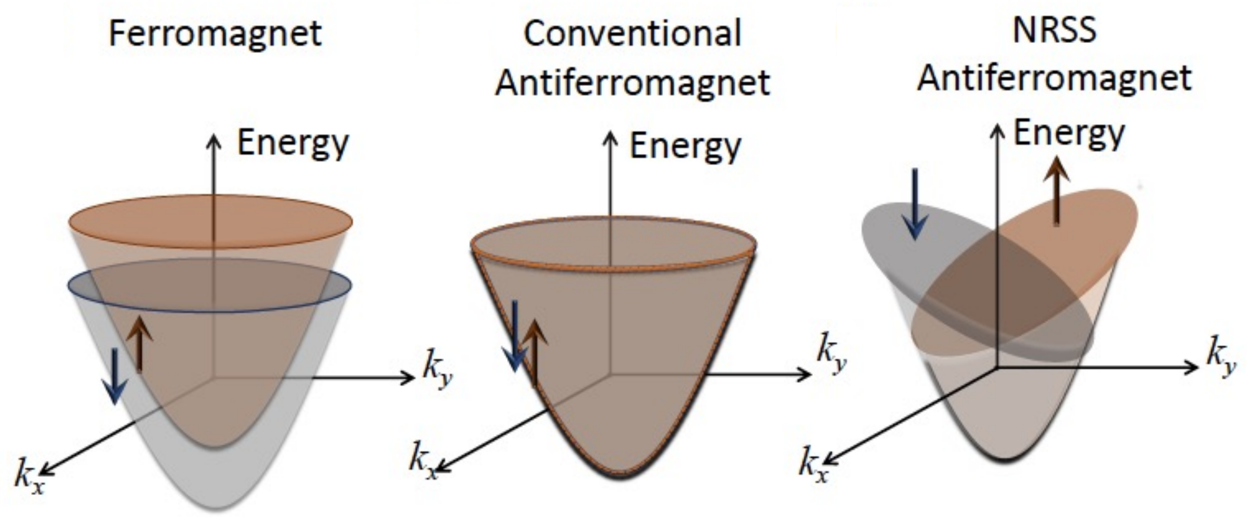
Emerging properties: Spontaneous Hall effect, Giant magnetoresistance, spin current generations, etc..

# A new type of magnetism: “Altermagnetism”





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Emerging properties: Spontaneous Hall effect, Giant magnetoresistance, spin current generations, etc..

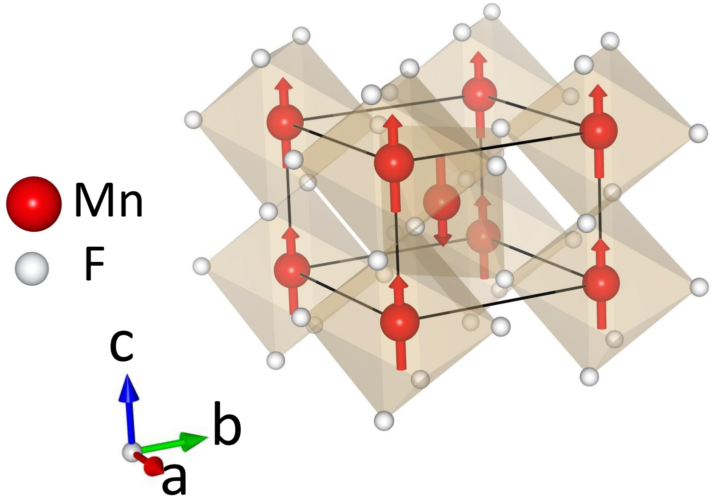
Centrosymmetric “altermagnets” with non-relativistic spin splitting

$$\mathcal{E}_{\rm int} = -\cancel{\vec{m}\cdot}\vec{H}(0) - \cancel{\mathcal{M}_{ij}}\partial_i H_j(0) - \boxed{\mathcal{O}_{ijk}}\partial_i\partial_j H_k(0)..$$

Magnetic octupole

# Plan of talk : A classic example of “antiferromagnet”

$MnF_2$




PHYSICAL REVIEW VOLUME 90, NUMBER 5 JUNE 1, 1953

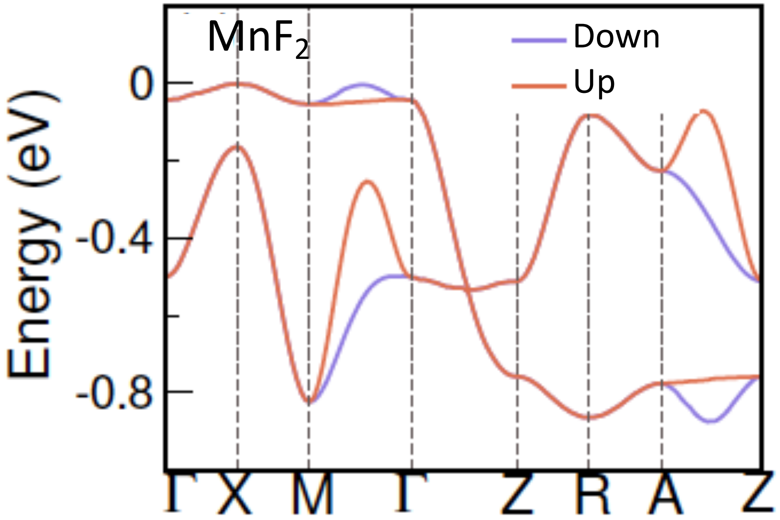
**Neutron Diffraction Studies of Antiferromagnetism in Manganous Fluoride and Some Isomorphous Compounds***

R. A. Erickson†,‡
*Laboratory, Oak Ridge, Tennessee and Agricultural and Mechanical College of Texas, College Station, Texas*

(Received Februrary 24, 1953)

Magnetic octupole

- Correlation to structure and spin : octupolar domains
- Relevance to non-relativistic spin splitting



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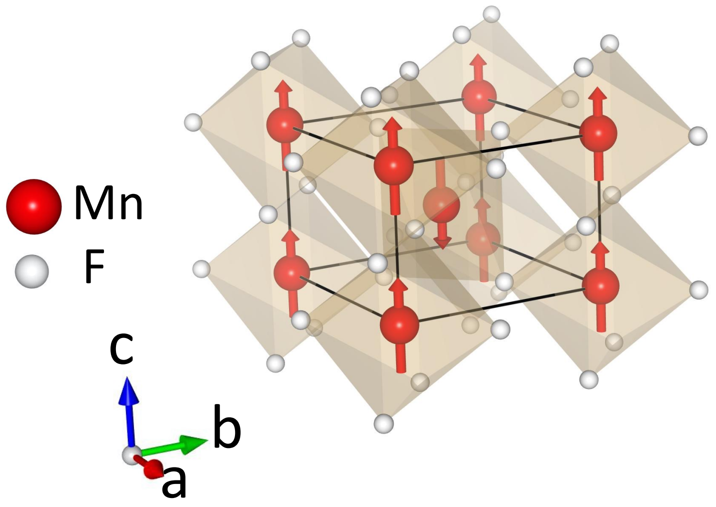


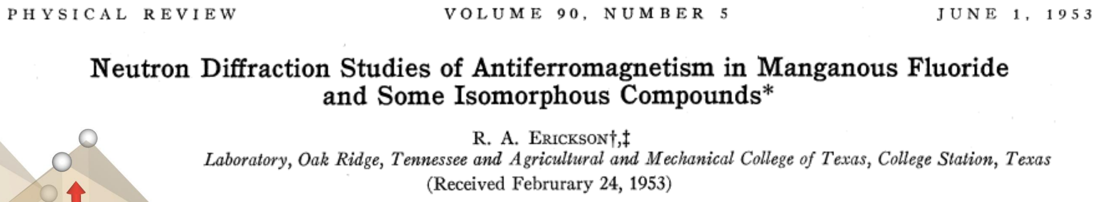
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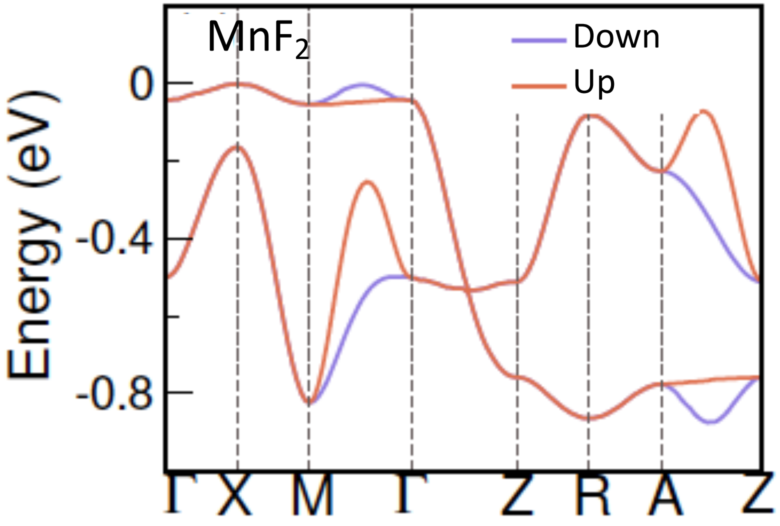



Magnetic octupole

- Correlation to structure and spin : octupolar domains
- Relevance to non-relativistic spin splitting

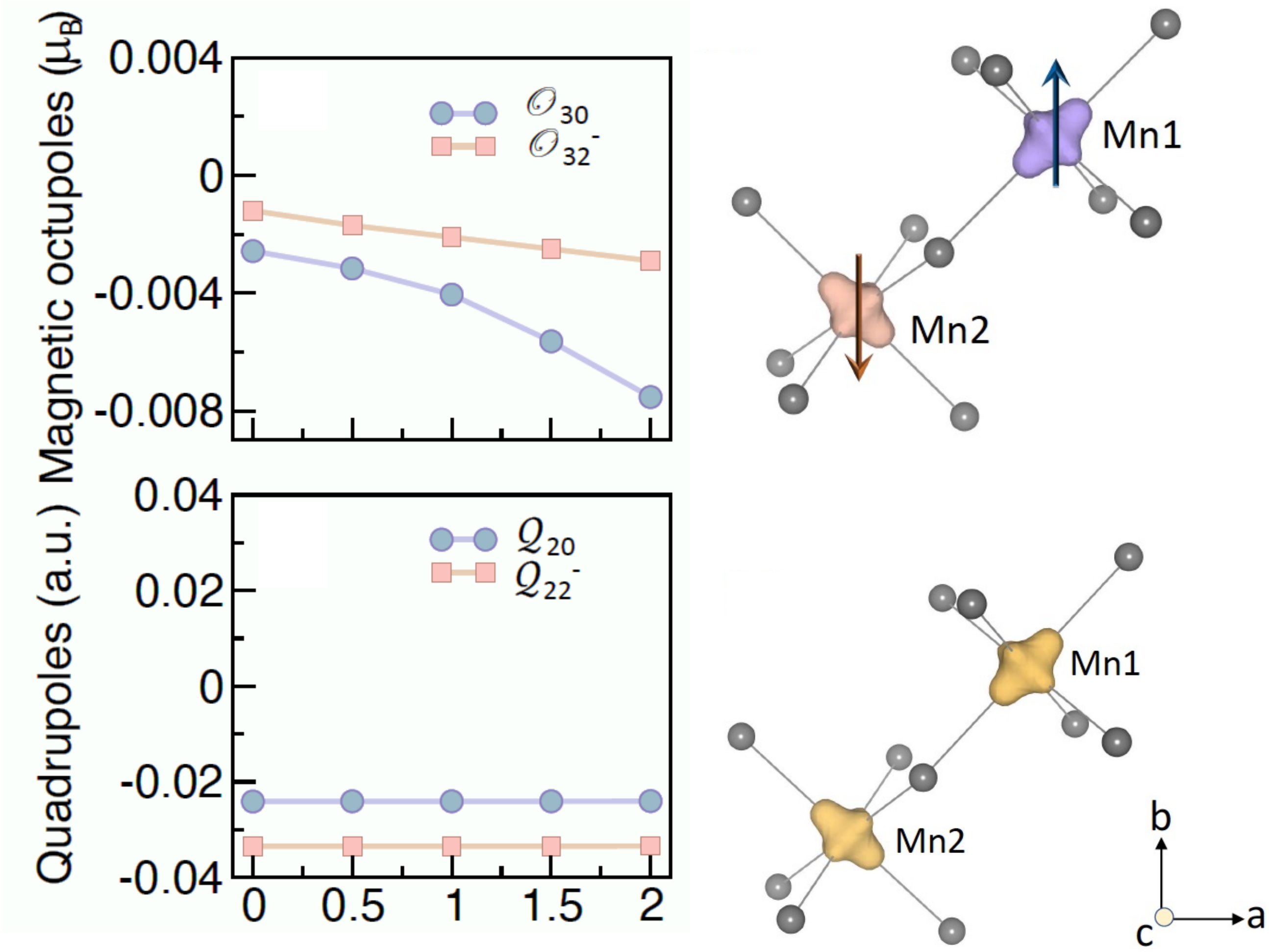
Implication of magnetic octupoles

- Piezo & antipiezo-magnetic effects
- Magnetic Compton profile

# Magnetic octupoles

Magnetic octupoles: Ferro-type ordering : $\mathcal{O}_{32-}$ (xym$_z$), $\mathcal{Q}^{(\tau)}_{x^2-y^2}$ ; Anti-ferro-type ordering : $\mathcal{O}_{30}$ [(3z$^2$-r$^2$)m$_z$], $t_z^{(\tau)}$

Charge quadrupoles: $\mathcal{Q}_{20}$ (Ferro), $\mathcal{Q}_{22}^-$ (AF)




Relative SOC strength

# Magnetic octupoles

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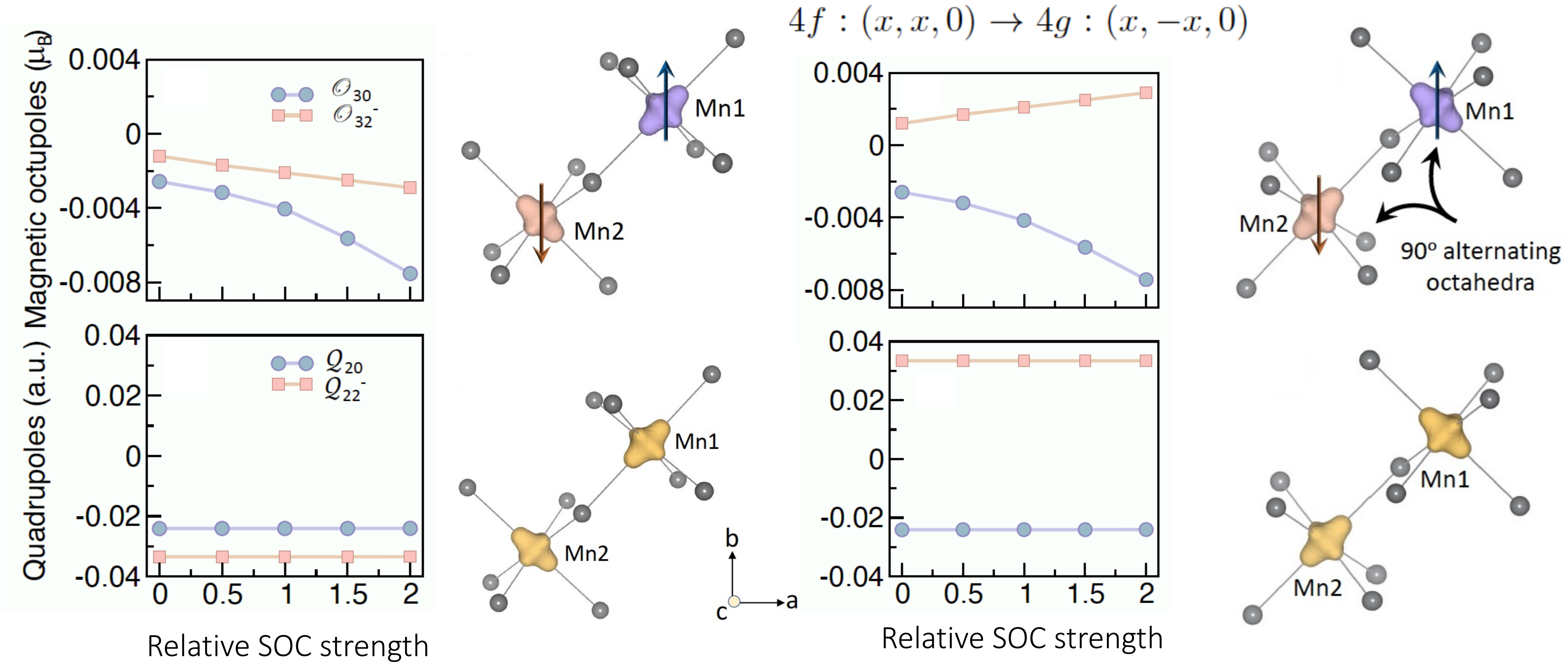
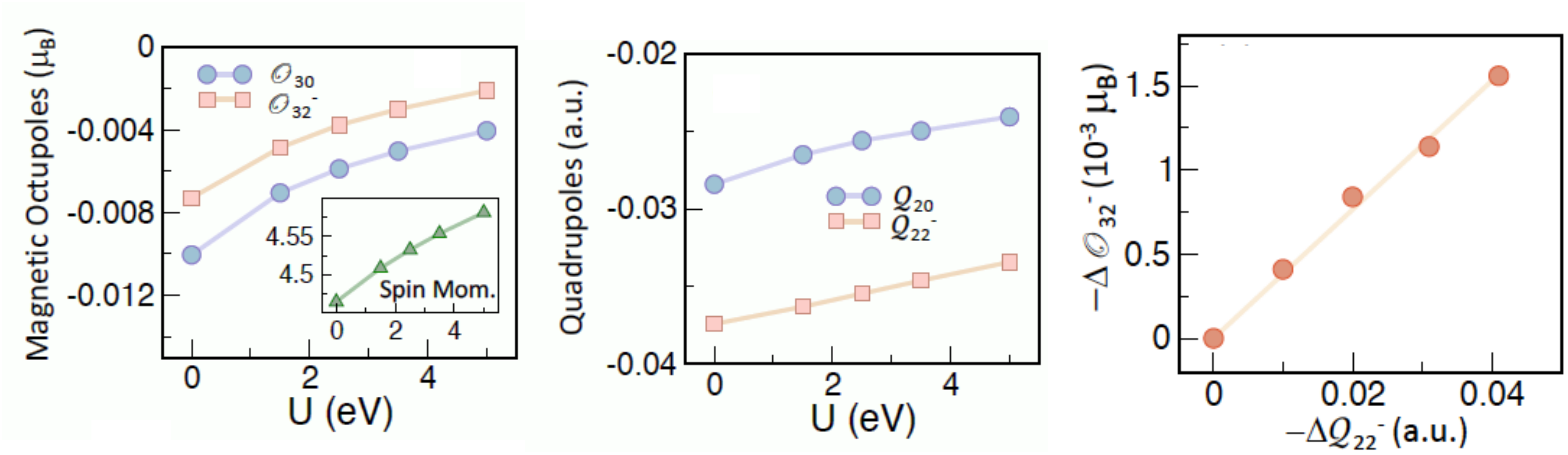


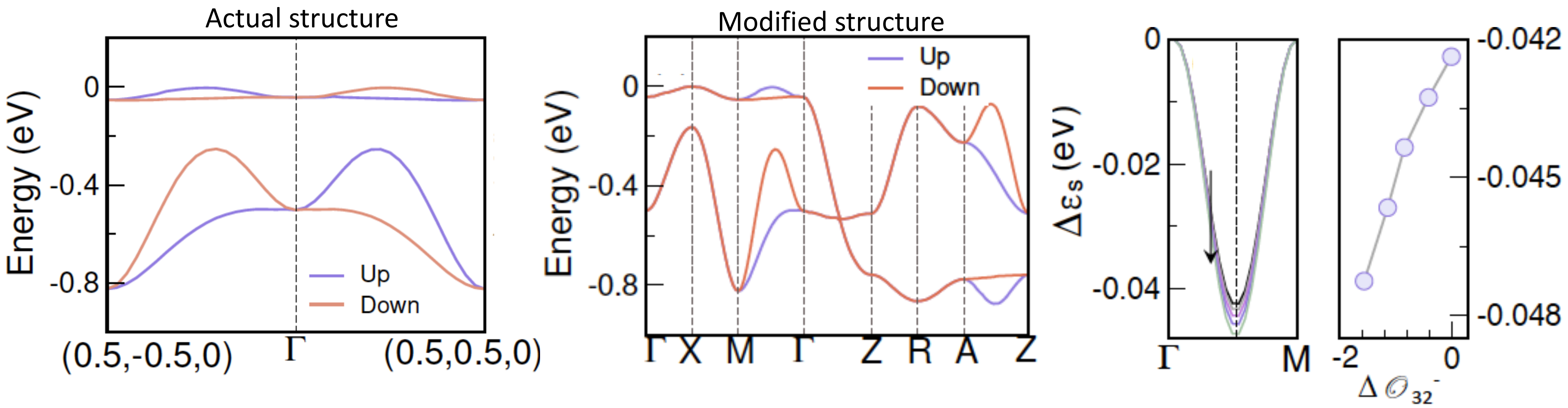
# Quantify the effect of neighboring nonmagnetic ions




- Variation with Hubbard U : similar behavior for quadrupoles and octupoles
- Quantify the effect of neighboring nonmagnetic F environment  via electric quadrupoles
- Systematic increase in the octupoles as the quadrupole moment increases

L. Schaufelberger, M. E. Merkel, A. M. Tehrani, N. A. Spaldin, and C. Ederer (to be published)
https://github.com/materialstheory/multipyles

# Spin splitting and its tuning




$xym_z \rightarrow k_xk_ym_z$

Watanabe-Yanase, PRB **98**, 245129 (2018)

- Reversal of spin splitting with ***90º rotation***
- ***Reversal of spin splitting*** for the opposite sign of magnetic octupoles
- ***Controlling spin splitting*** via tuning the strength of the magnetic octupole
- Crucial insight into ***conjugate fields*** for the formation of magnetic domain

↓

Product of stress (rank-2, even under inversion) and magnetic field (odd under TR)

Baruchel *et. al.*, J. Phys. Colloques **49**, C8 (1988)

# Plan of talk : A classic example of “antiferromagnet”

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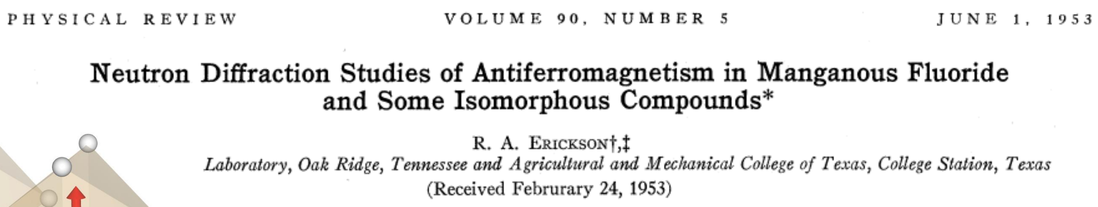
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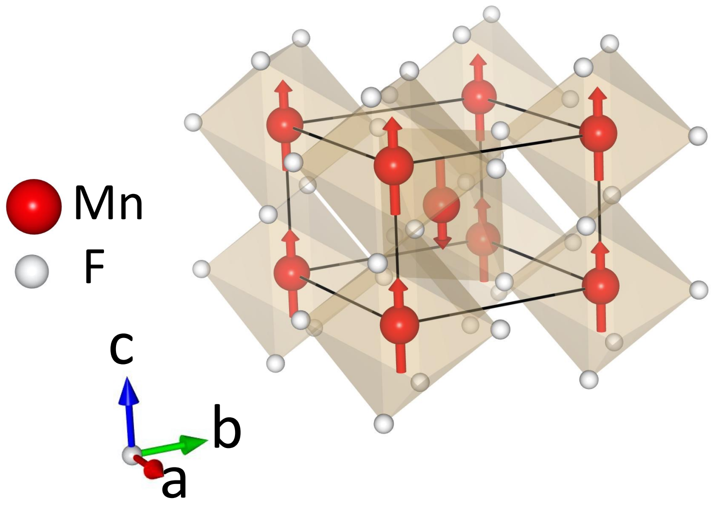


Magnetic octupole

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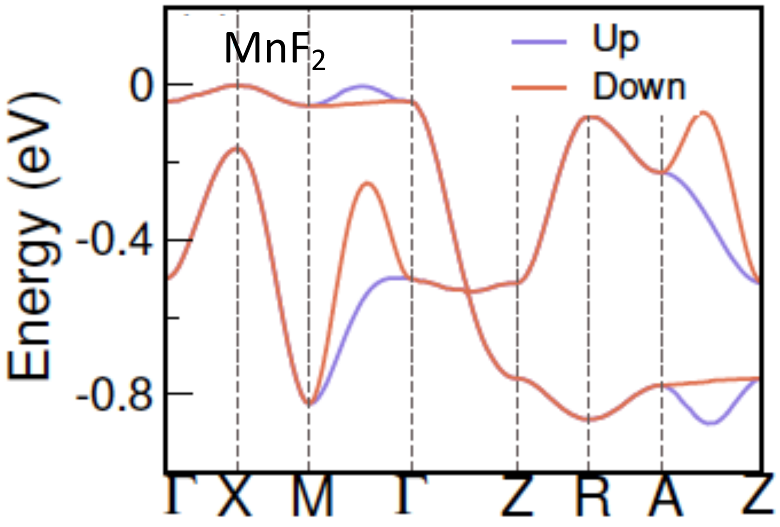
- Relevance to non-relativistic spin splitting




Implication of magnetic octupoles

- Piezo & antipiezo-magnetic effects
- Magnetic Compton profile

# Implications of magnetic octupoles: Piezo and anti-piezomagnetic effects

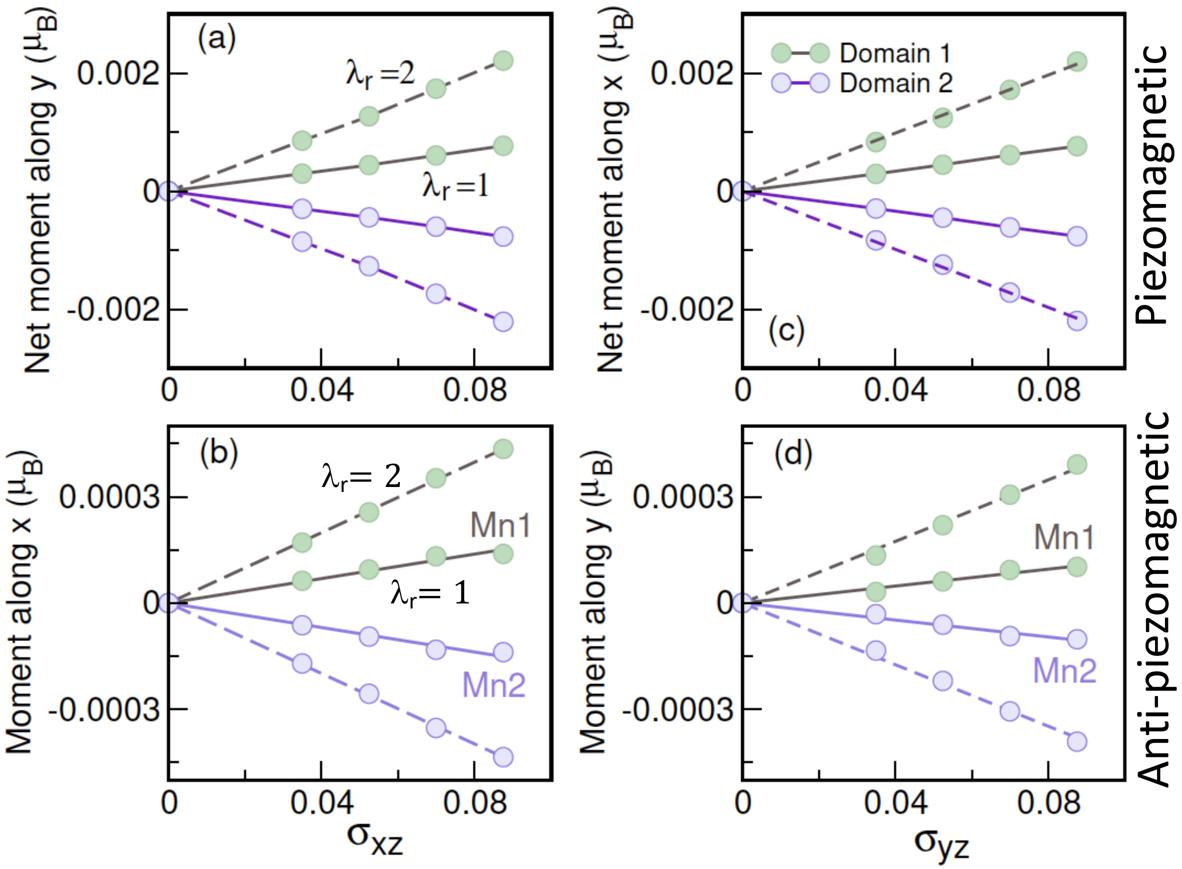
Piezomagnetic effect: Application of stress generates a change in net magnetization

Allowed components in $MnF_2$:

$$\mathcal{M}_x = \Lambda_{xyz}\sigma_{yz}, \mathcal{M}_y = \Lambda_{yxz}\sigma_{xz}, \mathcal{M}_z = \Lambda_{zxy}\sigma_{xy}$$

Baruchel *et. al.* , JMMM 15-18, 1510 (1980); Borovik-Romanov J. Exptl. Theoret. Phys. **38**, 1088 (1960)

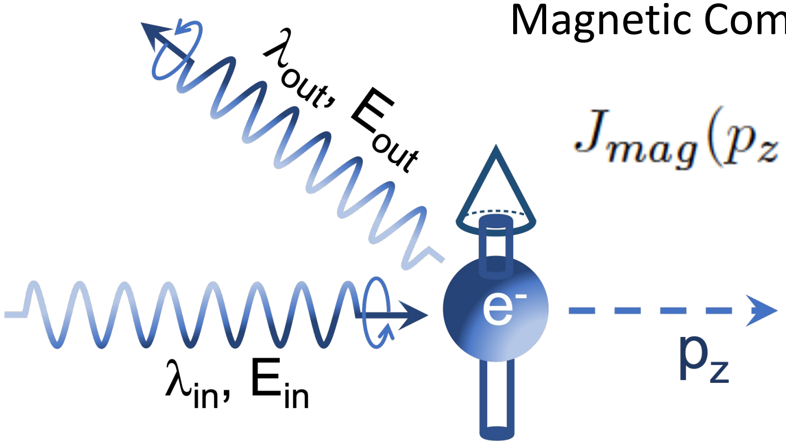
Magnetic Octupole tensor $\mathcal{O}_{ijk}$ → Piezomagnetic response $\Lambda_{ijk}$




Urru-Spaldin, Ann. Phys. **447**, 168964 (2022)

- ***Universal*** to all materials with non-zero magnetic octupoles
- ***Reversal*** for opposite magnetic domains
- Depends on ***SOC*** effect
- Prediction of ***anti-piezomagnetic effect***
- Same dependence on spin-orbit coupling strength and magnetic domain

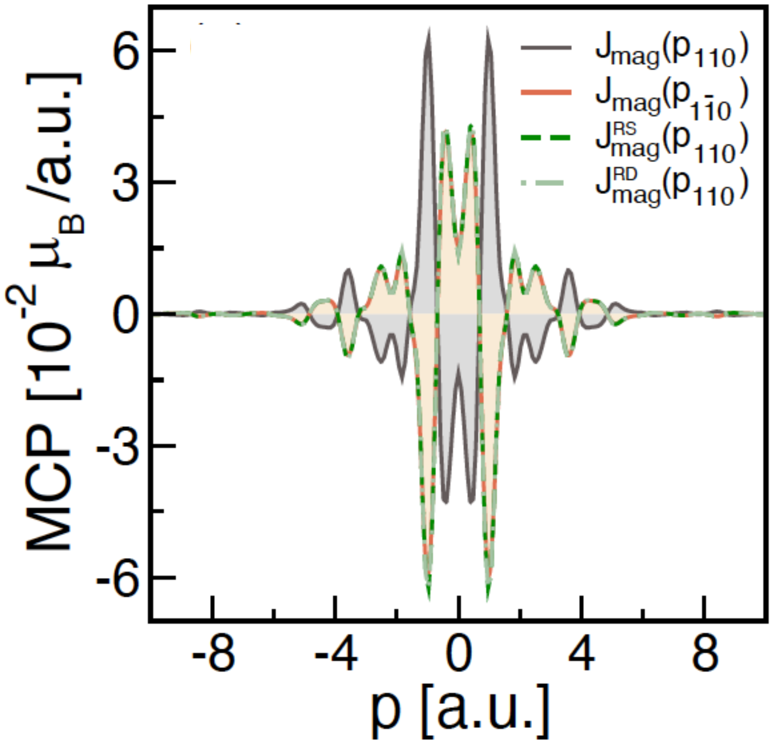
# Direct detection of magnetic octupole via magnetic Compton scattering




Magnetic Compton profile (MCP)

$$J_{mag}(p_z) = \int\int [\rho^{\uparrow}(\vec{p}) - \rho^{\downarrow}(\vec{p})] dp_x dp_y$$

Platzman-Tzoar, PRB **2**, 3556 (1970)

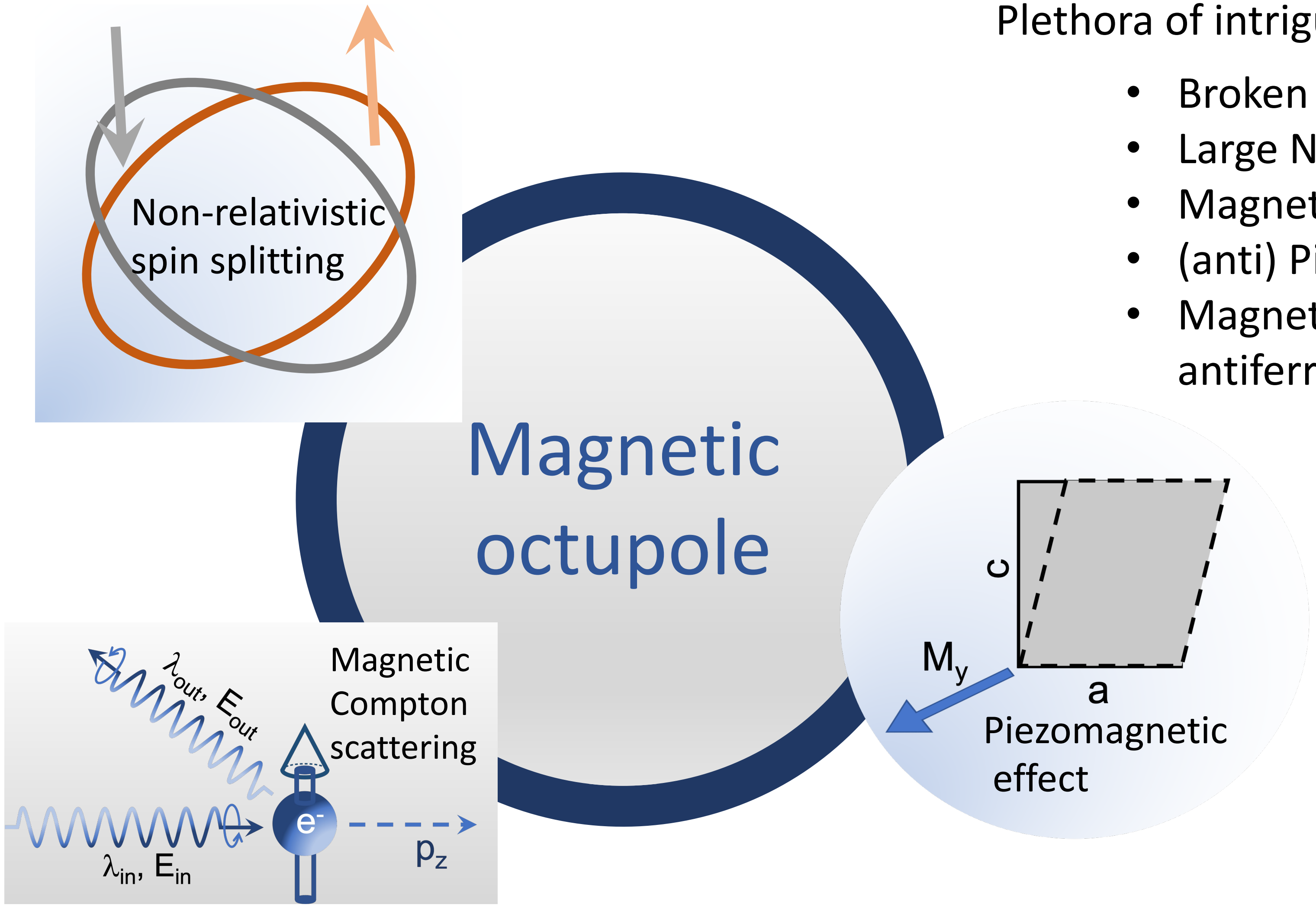



- Non-zero MCP, unusual for conventional antiferromagnets
- MCP is symmetric in *p*
- Occurs w/o SOC
- Much larger magnitude than ferroelectrics

Bhowal-Collins-Spaldin, PRL 128, 116402 (2022)

- The integral of the MCP is zero → zero net moment
- MCPs along (110) and (1-10) have opposite signs
- Experiments require single magnetic domain (piezomagnetic annealing)

# Summary and outlook




Plethora of intriguing physical properties and insights:

- Broken time-reversal symmetry
- Large NRSS
- Magnetic domains & conjugate field
- (anti) Piezomagnetic effect
- Magnetic Compton profile in antiferromagnets

Bhowal-Spaldin, arXiv:2212.03756 (2022)

- Second-order magnetoelectric effect
- Surface magnetism
- Spin-phonon interactions

Connection between sub-fields of physics → New avenues for future exploration

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Sophie Weber

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Prof. Steve Collins

diamond

Dr. Jon Duffy

THE UNIVERSITY OF WARWICK

Dr. Urs Staub

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