Quantum Origins of Anomalous Hall: Berry Phase & Atomic Ordering in Heusler Alloys

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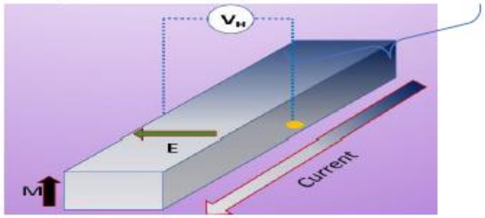
QIT, IIIT Allahabaad

27.07.2025

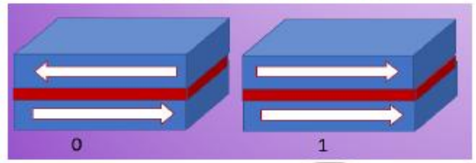
In our lab we work on…………..

Anomalous Hall



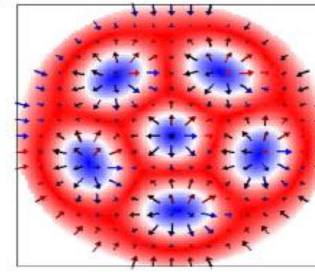
Magneto-transport

Magnetoresistance

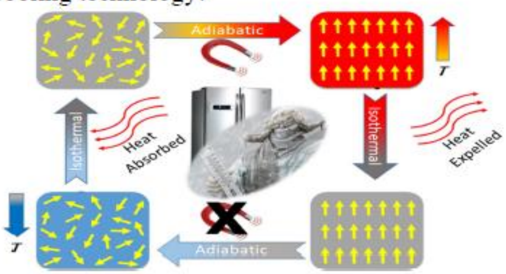


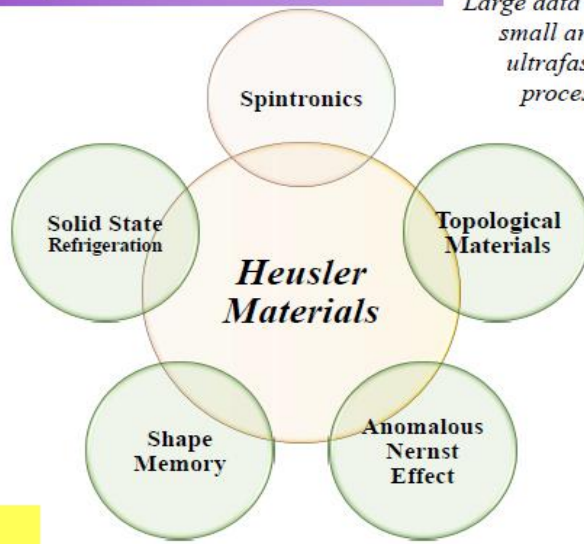
Skyrmions

A topological object
Revolution in the computing technology
Large data storage in small area and ultrafast data processing

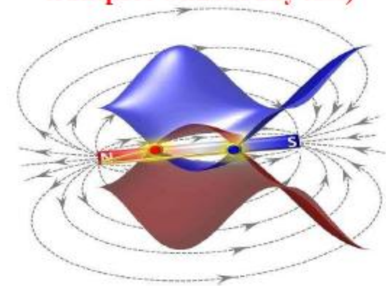


Solid State Refrigeration
Environment Friendly--New Developing cooling technology!

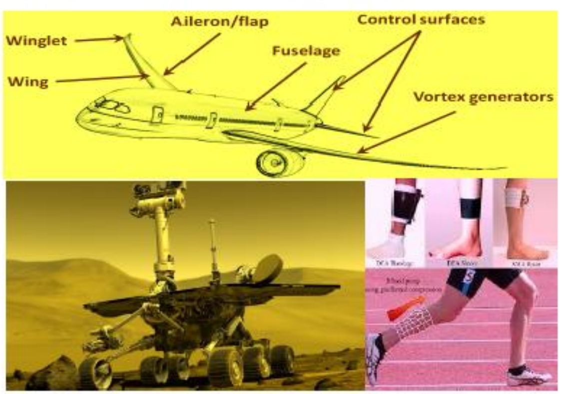


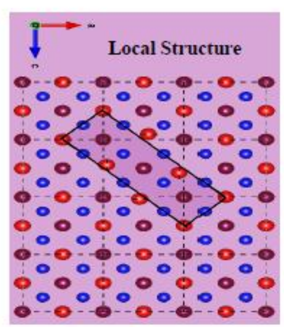


Weyl semimetal: Quantum Transport
(think the world where charge transport without any loss)



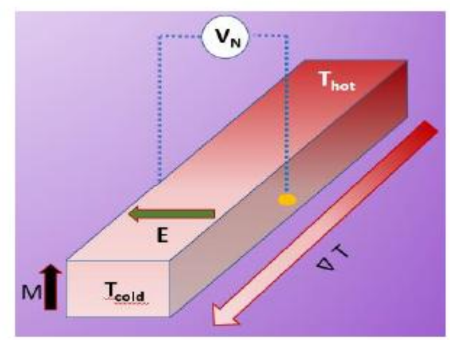
Shape Memory: Memorise their previous form in thermomechanical and magnetic variations.





Anomalous Nernst Effect

A result of charge current driven by temperature gradient



On going Research work in Functional Materials Laboratory

Research @ Anomalous Hall

Scopus

Analyze search results

< Back to results

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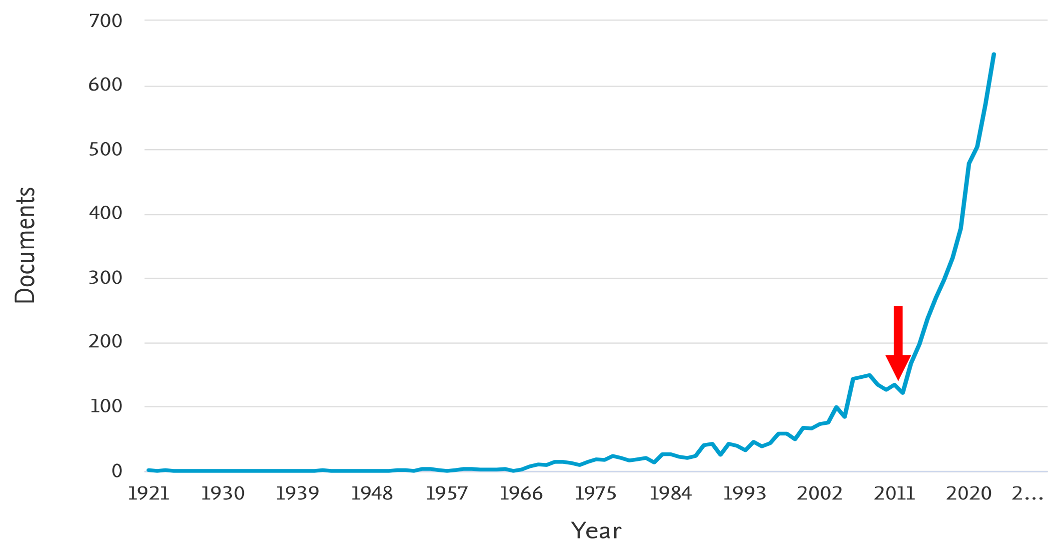
TITLE-ABS-KEY (anomalous AND hall AND effect)

6,384 document results

Select year range to analyze: 1921 to 2023 Analyze

Year	Documents
2023	648
2022	570
2021	504
2020	478
2019	377
2018	331
2017	297
2016	269
2015	237
2014	197

Documents by year



Applications of anomalous Hall effect

- *AHE depend on the electronic and magnetic structure of material has become a useful experimental tool for solid state physicist . For e.g. study of extremely thin magnetic layers and to observe the propagation of conduction electrons in a metal.*

- *The ability of the anomalous Hall effect to trace the magnetic impurities in metal can.*

- *We could study the spin-dependent properties e.g. spin-orbit coupling with the help of AHE.*

Samsung Galaxy S4 s-view cover (Sensor)

Non-volatile memory device

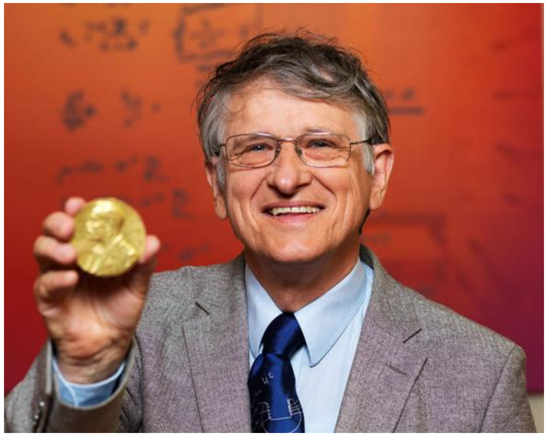
- *High sensitivity ($s = \frac{\partial R}{\partial H} = \frac{\mu R_{AH}\chi}{t}$, χ=magnetic susceptibility, t=thickness of the sample) far beyond the semiconductor typically 1000 ohm/T.*

- *Widely used in sensors and memory devices due to their linear field response, thermal stability, high-frequency operation (can operate at GHz frequency), sub-micron dimensions of samples etc.*

Rev. Mod. Phys. ***82****, 1539 (2010), J. Appl. Phys. 122, 033901 (2017)*

Nobel Prize in the area of Hall Effect

Nobel Prize in Physics (1985)
For the discovery of integer quantum Hall effect



Klaus von Klitzing

Nobel Prize in Physics (1998)
Discovery of new form of quantum fluid with fractionally charged excitations
(Associated with Fractional quantum Hall effect)

Photo from the Nobel Foundation archive.
Robert B. Laughlin

Photo from the Nobel Foundation archive.
Horst L. Störmer

Photo from the Nobel Foundation archive.
Daniel C. Tsui

➢ Outline

- Basics: Anomalous Hall effect

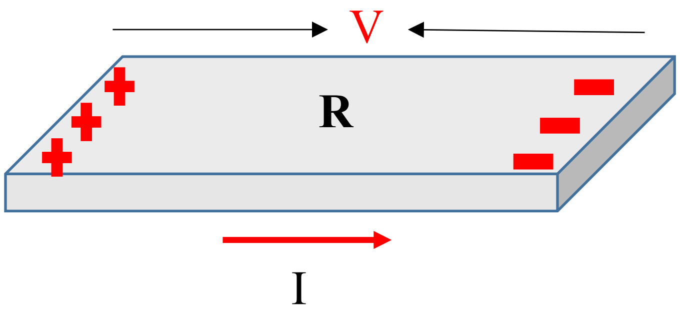
- Results:
- Atomic disorder and Anomalous Hall in Heulser Compounds
- Tunning with chemical disorder

- Conclusion

Electrical transport

When an electric current flows through a conductor a longitudinal voltage develops across the conductor.

R = Resistance of the conductor

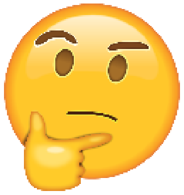


Follow ***ohms law***

$V = I*R$

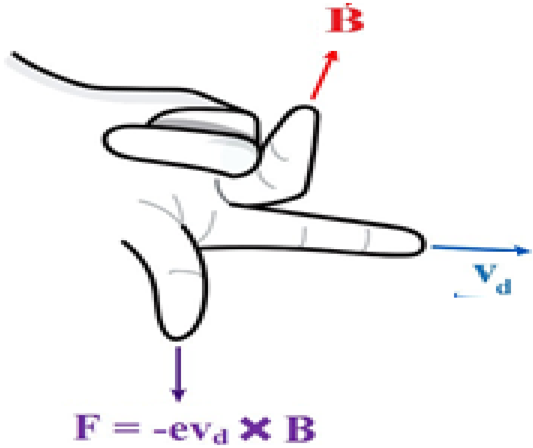
George Ohm

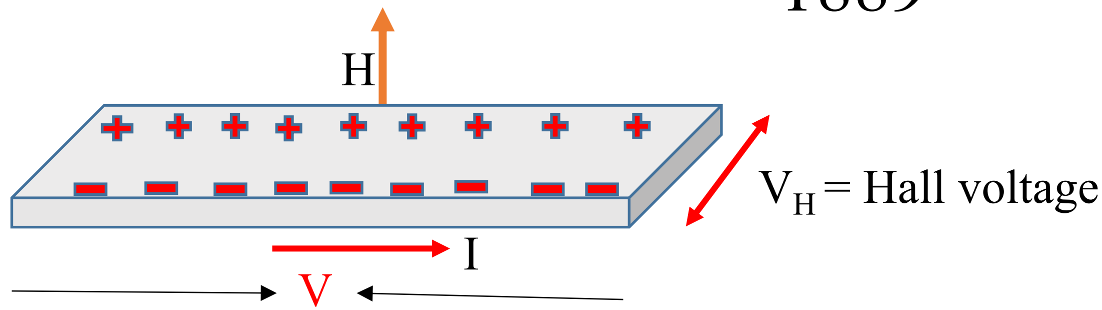
What will happen if we place the current carrying conductor in external magnetic field



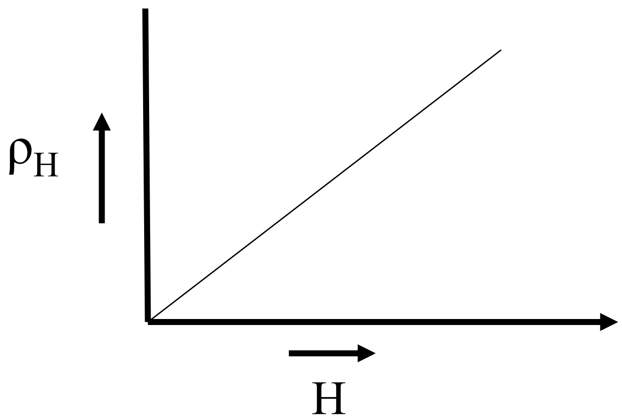
Hall effect

1889





Appearance of transverse voltage and hence resistivity in current carrying conductor placed in orthogonal magnetic field.



$$\rho_H = R_0 H$$

R_0 → Hall coefficient

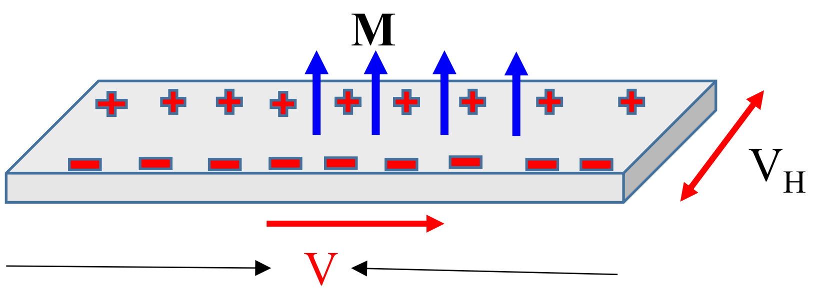
$$R_0 = 1/ne$$

Edwin Hall

'n' is the carrier concentration **(Revolutionized the semiconductor physics & industry)**

Anomalous Hall effect (AHE)

In ferromagnets the Hall resistivity enhances many times in comparison to the normal metal

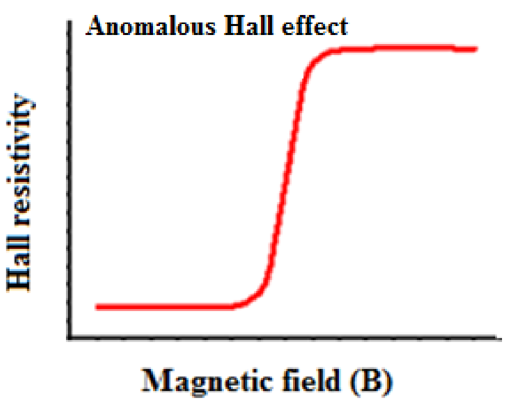


$$\rho_H = R_0 H + R_s M$$

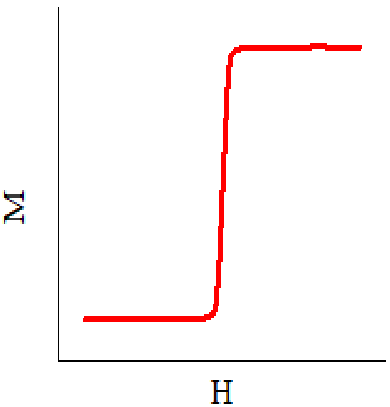
Anomalous Hall resistivity

$$\rho_H = \rho_O + \rho_{AH}$$

AHE somehow looks related to the magnetization, fairly indicates that the AHE is spin dependent phenomenon.



A typical curve of Hall resistivity in ferromagnets



A typical M-H curve For ferromagnets

Beyond the Lorentz force ……..

Origin of the anomalous Hall effect

Controversial over a long decades

Several experimental studies have done
to understand the origin of anomalous Hall

Theories of J. Smit, R. karplus and J.M. luttinger successfully explain the origin of AHE

$$\rho_{\mathrm{H}} = \rho_O + \rho_{A\mathrm{H}}$$

$$\rho_{AH} = a\,\rho_{xx} + b\,\rho^2_{xx}$$

$a\,\rho_{xx}$ → Skew Scattering (extrinsic)

$b\,\rho^2_{xx}$ → Intrinsic mechanism + Side jump (extrinsic)

R. Karplus et.al Phys. Rev. 95, 1154 (1954)

J.M. luttinger Phys. Rev. 112, 739 (1958)

J. Smit Phys. Rev. 92, 1576 (1953)

Rev. Mod. Phys. 82, 1539 (2010)

Intrinsic (Quantum) Origin of anomalous Hall effect

Intrinsic mechanism: Purely arises from the band structure of the material

(AHC)

$$\sigma_{\alpha\beta} = -\frac{e^2}{\hbar}\sum_n \int \frac{d^3k}{(2\pi)^3}\Omega^n_{\alpha\beta}(k) f_n(k),$$

Berry curvature $\Omega^n(R) = \nabla_R \times A_n(R).$

Phase picked by the wave function in an infinite small loop around the (k_x,K_y) point of an energy band in reciprocal space

Equivalent to the magnetic field in k space and result into the anomalous Hall conductivity (AHC).

Rev. Mod. Phys. 82, 1959 (2010)

Berry Phase: A Quantum Mechanical Phenomenon

Classical Boltzmann Transport

Classical transport theory describes how **electrons move** in a solid under external forces (like electric or magnetic fields) **without quantum effects** like spin, Berry phase, or wave interference.

Group velocity of electron:

$$\frac{d\langle \mathbf{r} \rangle}{dt} = \frac{1}{\hbar}\frac{\partial E}{\partial \mathbf{k}} .$$

Force on electron in the presence of both E and F:

$$\hbar \frac{d\mathbf{k}}{dt} = -e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

explains ordinary Hall effect

as Lorentz force:

$$\mathbf{F} = -e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

In Steady state, electric force balances the magnetic force:

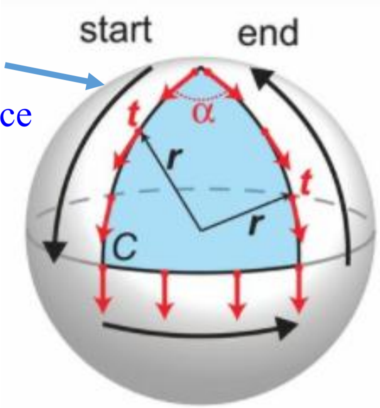
$$-e\mathbf{E}_{\text{Hall}} = -e(\mathbf{v} \times \mathbf{B})$$

$$\Rightarrow \mathbf{E}_{\text{Hall}} = \mathbf{v} \times \mathbf{B}$$

Fails to explain anomalous Hall effect due to quantum geometric phase (Berry phase).

If a quantum mechanical system is perturbed by a weak perturbation, then after a time t' (say), the system does not find a new quantum state but return to its original state with a phase factor.

classical example is the parallel transport of a vector around a path on a curved surface



Science 356, 845-849 (2017)

$$\gamma_n(t) = \int d\mathbf{R} \cdot \mathbf{A}_n(\mathbf{R}),$$

Berry Phase

Berry vector potential

Rev. Mod. Phys. 82, 1959 (2010)

Quantum corrections: Including Quantum Berry phase

Modified group velocity:

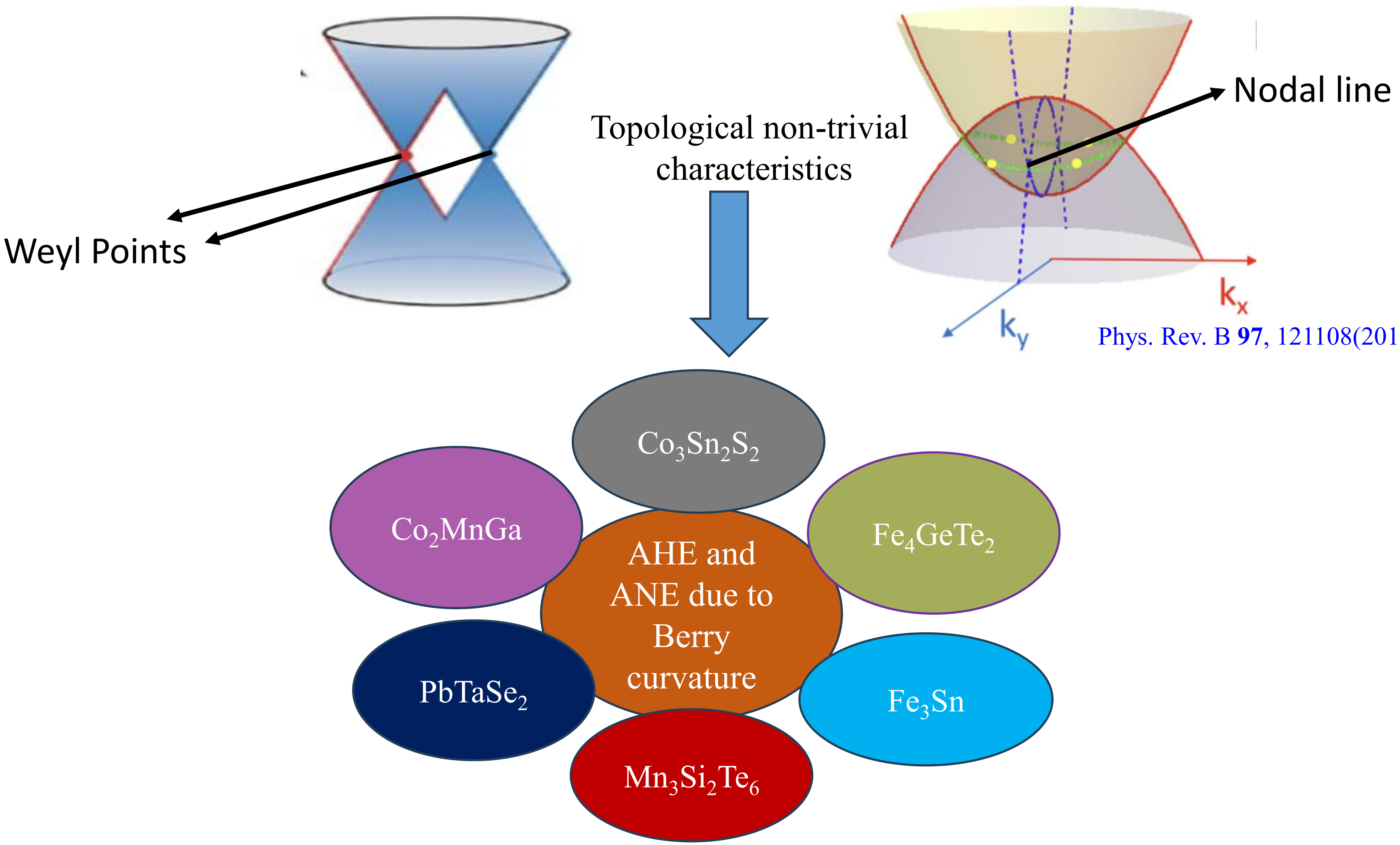
$$\frac{d\langle \mathbf{r} \rangle}{dt} = \frac{1}{\hbar}\frac{\partial E}{\partial \mathbf{k}} + \dot{\mathbf{k}} \times \boldsymbol{\Omega}_n(\mathbf{k})$$

Berry curvature

The curvature of Berry phase is equivalent to the magnetic field in k space and result into the additional contribution to the anomalous velocity of electrons.

- **Classical transport also uses momentum space – but considers only energy not wavefunctions.**
- **Berry phase comes from wavefunction geometry- not energy but how the state itself evolves as k changes.**

Sources of Berry curvature



Phys. Rev. B **97**, 121108(2018)

Therefore, tuning of Fermi level close to these topological non-trivial characteristics can significantly enhance AHE and ANE

Materials Selection

Research @ Heusler alloys

Scopus

Analyze search results

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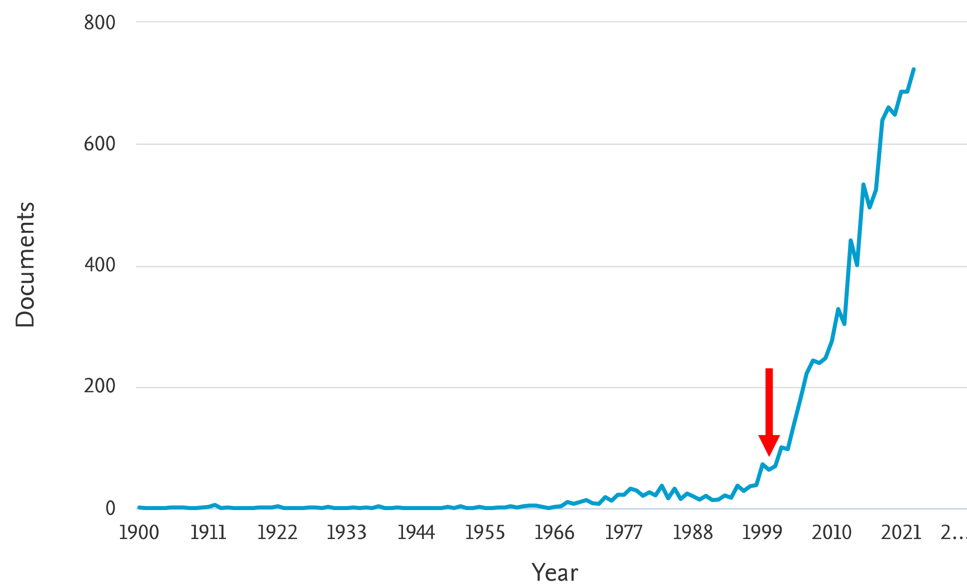
TITLE-ABS-KEY (heusler)

9,710 document results

Select year range to analyze: 1900 to 2023 Analyze

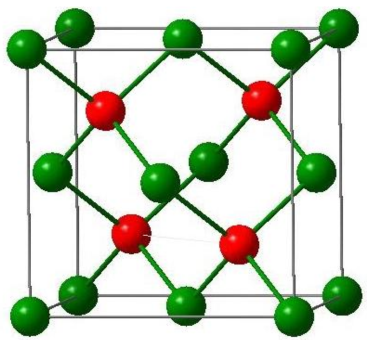
Year ↓	Documents ↑
2023	723
2022	686
2021	686
2020	648
2019	660
2018	639
2017	524
2016	495

Documents by year

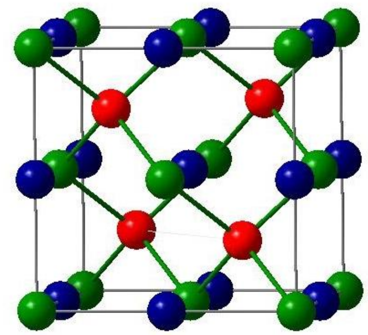


Heusler alloys

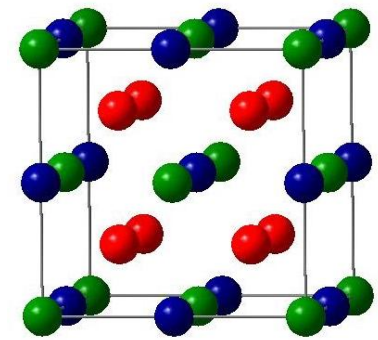
ZnS

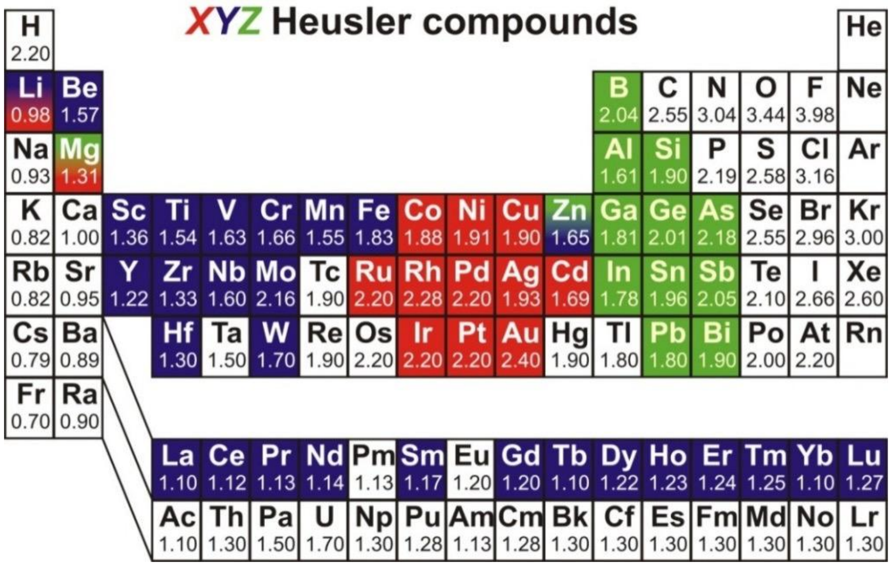


Heusler XYZ



X_2YZ $L2_1$

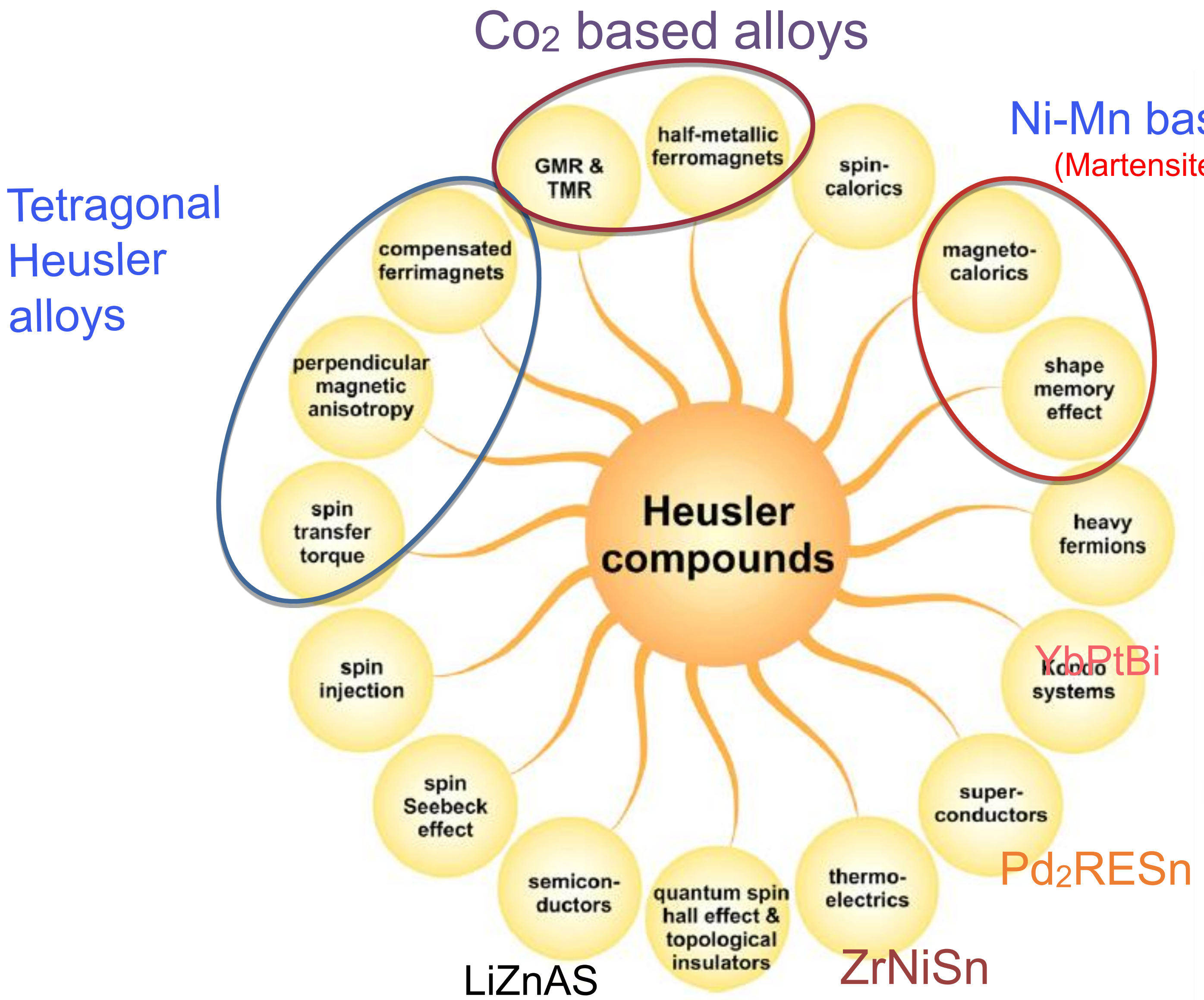


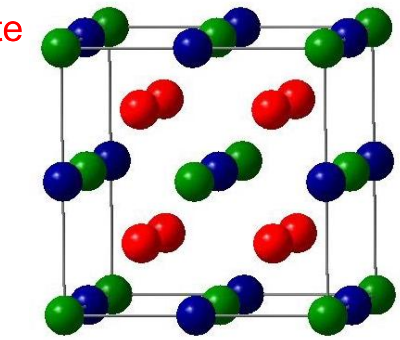


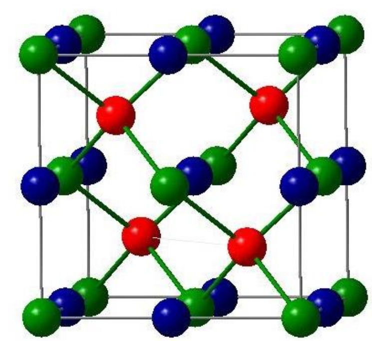
Heusler compound is an inter-metallic alloy based on a Heusler phase

Friedrich Heusler: Cu_2MnAl (1903)

Why Heusler alloys ??







Most recently: Quantum effect (Weyl, Anomalous Hall, Skyrmion)

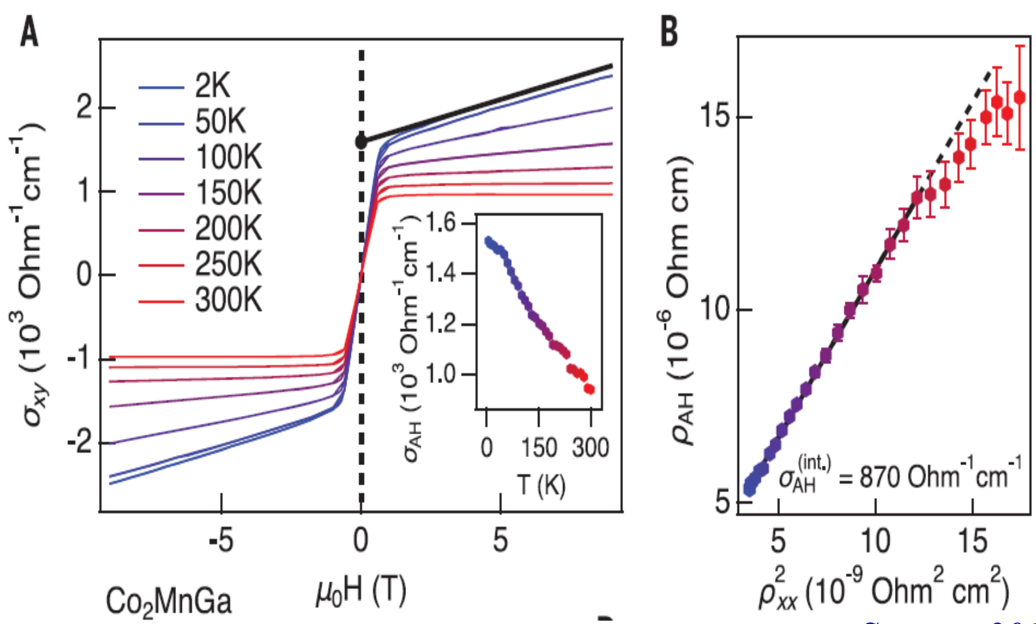
EXCITING

Co-based Heusler alloys

Co- based Heusler alloy →
- Large spin polarization
- High curie temperature
- Large intrinsic AHC

→ Useful for spintronics and other memory based applications

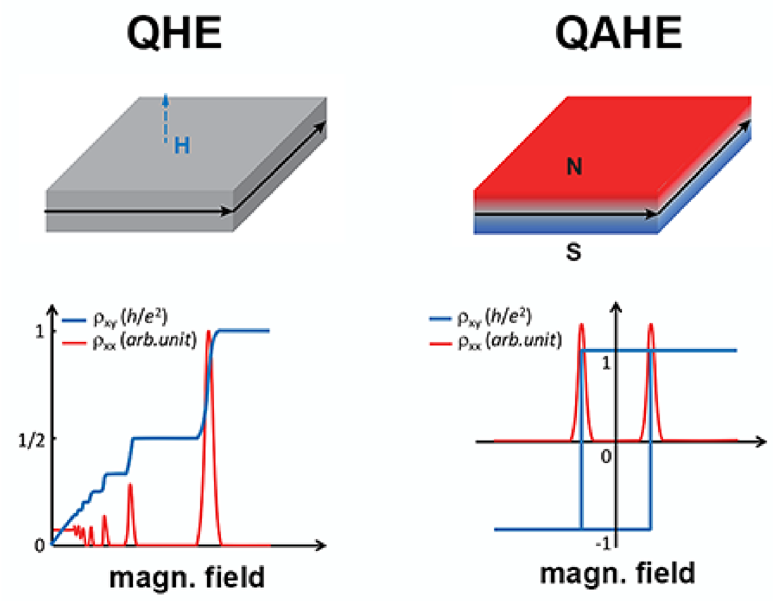
- Time-Reversal-Breaking Weyl Fermions in Magnetic Heusler Alloys
  Physical Rev. Letters 117, 236401 (2016).
- Anomalous Hall effect and the role of Berry curvature…..*Phys. Rev. B 100, 054445 (2019)*
- Discovery of topological Weyl fermion lines and…. *Science-2019 DOI: 10.1126/science.aav2327*



Science-2019 DOI: 10.1126/science.aav2327

Fundamental Physics and Materials Engineering

- Theory suggest possibility of the quantized AHC, that is, a 3D quantum AHE (QAHE).
- How can be reached to the 3D QAHE or giant AHE?
- What is the recipe to find such materials?



Answers to these questions are not only of fundamental importance, but also likely leads to technological applications.

Co based Heusler : A promising class for anomalous transport

nature COMMUNICATIONS

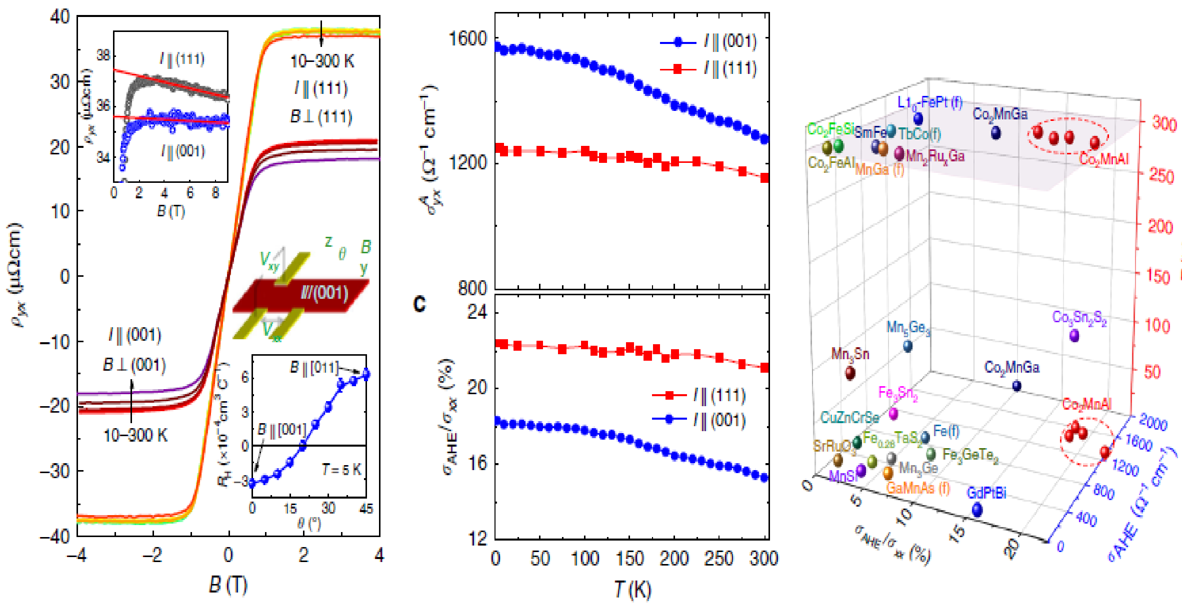
ARTICLE

Check for updates

https://doi.org/10.1038/s41467-020-17174-9 OPEN

Giant room temperature anomalous Hall effect and tunable topology in a ferromagnetic topological semimetal Co_2MnAl

Peigang Li[1,6], Jahyun Koo[2,6], Wei Ning[3✉], Jinguo Li[4], Leixin Miao[5], Lujin Min[3,5], Yanglin Zhu[1,3], Yu Wang[1,3], Nasim Alem[5], Chao-Xing Liu[3], Zhiqiang Mao[1,3✉] & Binghai Yan[2✉]



All previous studies disorder B2 phase.

This study ordered $L2_1$ phase

Very large AHC, up to 1300 $\Omega^{-1}cm^{-1}$ at room temperature.

Atomic ordering effect

Nat Commun **11**, 3476 (2020)

Atomic ordering & AHC in Co_2-based Heusler alloys

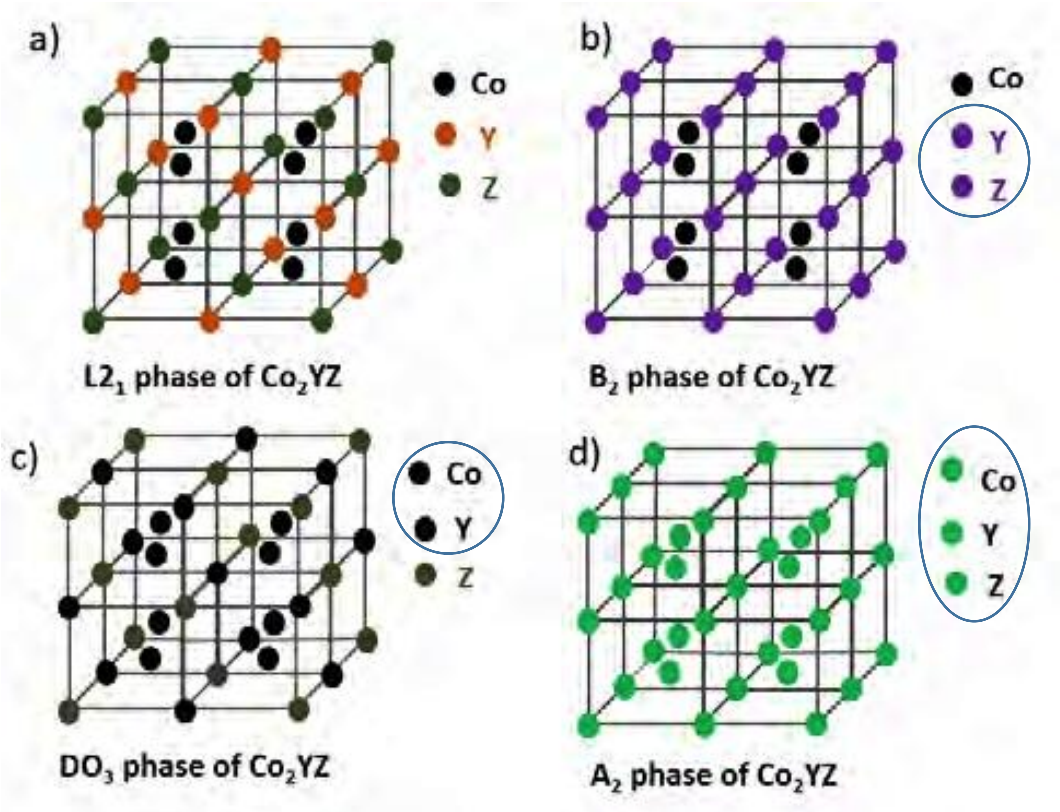
Co_2YZ : *All atoms at their own positions:* ***$L2_1$ ordered***
Mixing of Y and Z atoms: ***B2 disorder***
Mixing of Co and Z atoms: ***DO_3 disorder***
Mixing of all atoms: ***A2 disorder***

Disorder: A common phenomenon in the Co_2-based Heusler alloys

Exp.: Co_2FeSi, Co_2FeAl, Co_2MnAl (thin film) etc. show the different types of disorder

- Co_2MnGa 1300 S/cm
- Co_2FeGe 78 S/cm
- Co_2MnAl 1600 S/cm
- Co_2TiSn 100 S/cm
- Co_2FeAl 39 S/cm
- Co_2FeSi 189 S/cm
- Co_2FeGa 181 S/cm
- Co_2MnSi 100 S/cm
- Co_2MnSn 82 S/cm
- Co_2CrAl 438 S/cm
- Co_2VSn 1400 S/cm
- Co_2VGa 66 S/cm

Value of AHC in different Co_2-based Heusler alloys

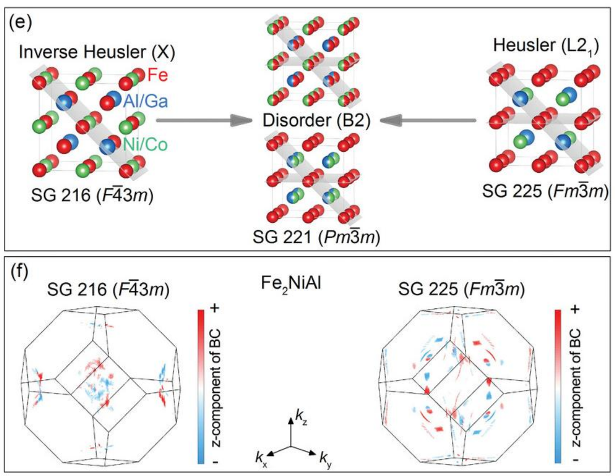


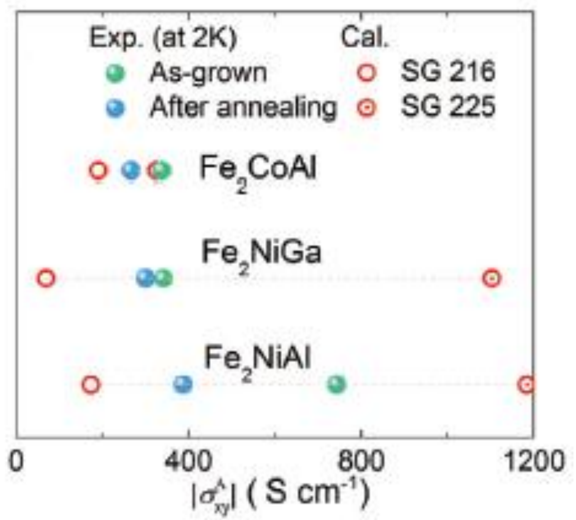
*PRB 91, 134409 (2015);Phys. Rev. B **85**, 012405;Phys. Rev. B **83**, 174410 (2011);Phys. Rev. B **101**, 134407 (2020); J. Magn. Magn. Mater. **448**, 371 (2018)*

Effect of disorder on AHC

- Recently Fe_2-based Heusler alloys are reported to have lower AHC values with B2 type disorder in comparison to ordered structure.

Adv. Sci. ***8****, 2100782 (2021)*





Is it always true ???

Co_2FeAl, an ideal candidate to investigate (B2 is stable structure) ….

Anomalous Hall effect in Co_2FeAl Heusler compound:
Literature

- The stable structure of Co_2FeAl is B2 type.
  *J. Magn. Magn. Mater. **442**, 288 (2017)*

- The AHC in Co_2FeAl thin films shows controversial results in terms of origin and the magnitude of AHC.
  [*J. Magn.Magn. Mater.442, 288 (2017), J. Magn. Magn. Mater.362, 52 (2014)*]

- The Berry curvature calculation gives AHC ~ 39 S/cm.
  PRB 91, 134409 (2015)

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Experimental AHC ~ 100 S/cm

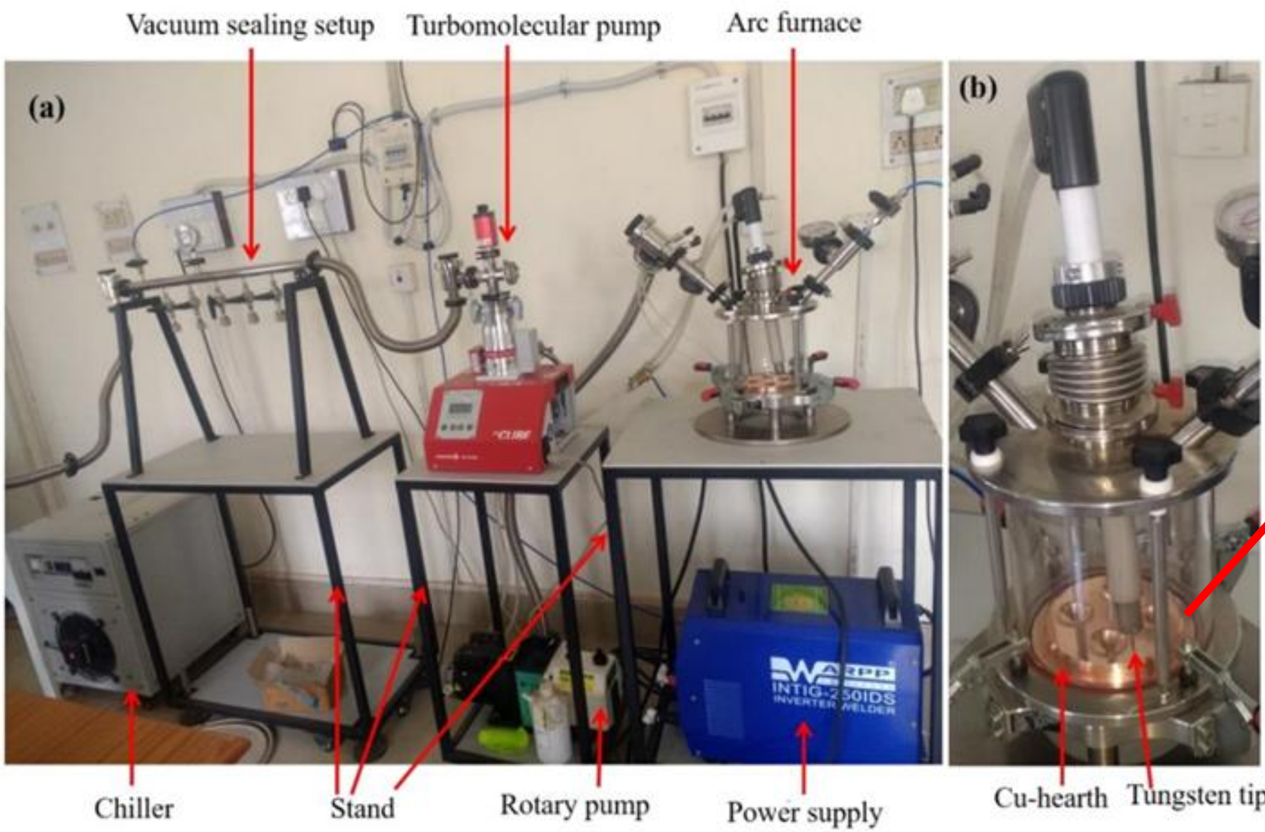
Theoretical AHC (ordered) ~39 S/cm

J. Magn.Magn. Mater.442, 288 (2017),
J. Magn. Magn. Mater.362, 52 (2014)
PRB 91, 134409 (2015)

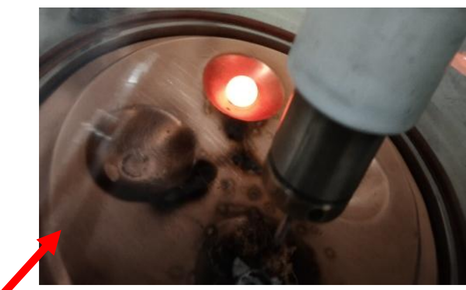
Origin of large Anomalous Hall???

Synthesizing the material

Arc Melting Technique



Synthesis of intermetallic systems under the argon atmosphere



Sealed quartz tube

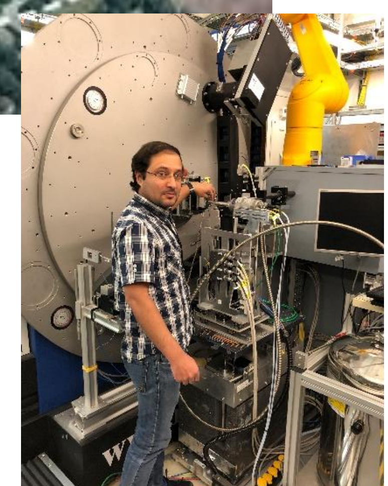
Co_2FeAl Heusler compound: Sample and Structure

Gaurav Shukla

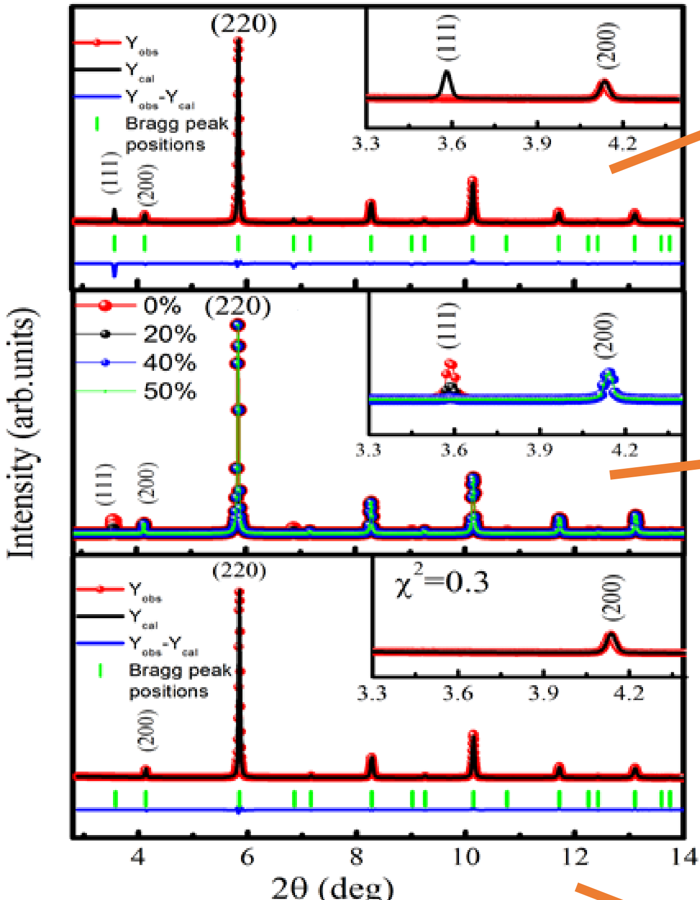
- Sample preparation: Arc Melting (High Vacuum)
- Structure: Synchrotron x-ray diffraction (DESY: GERMANY)

Capillary: Rotating: uniform distribution of intensities

High flux: Low intensity peaks



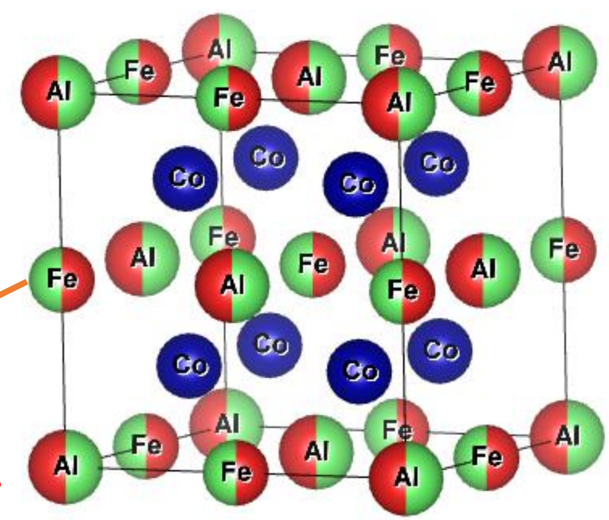
Co_2FeAl Heusler compound: Crystal Structure



If consider completely ordered structure

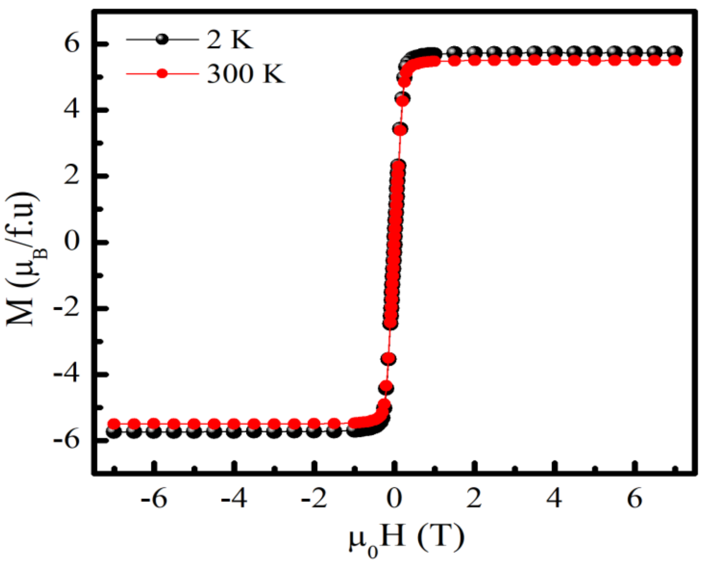
Simulations with anti-site disorder

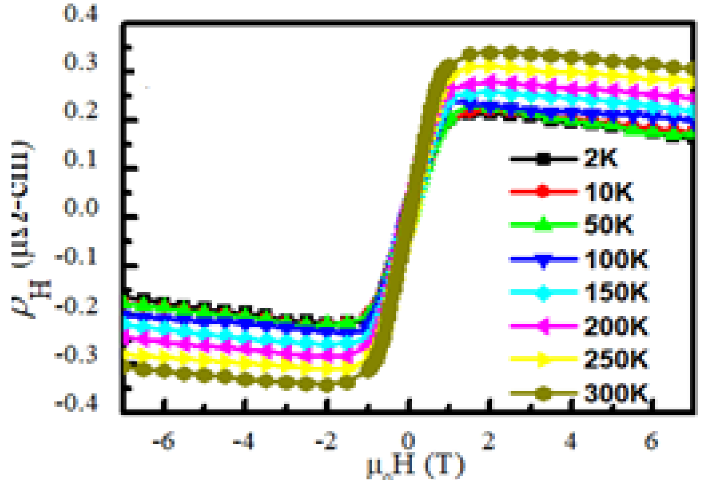
50 % Fe-Al anti-site disorder

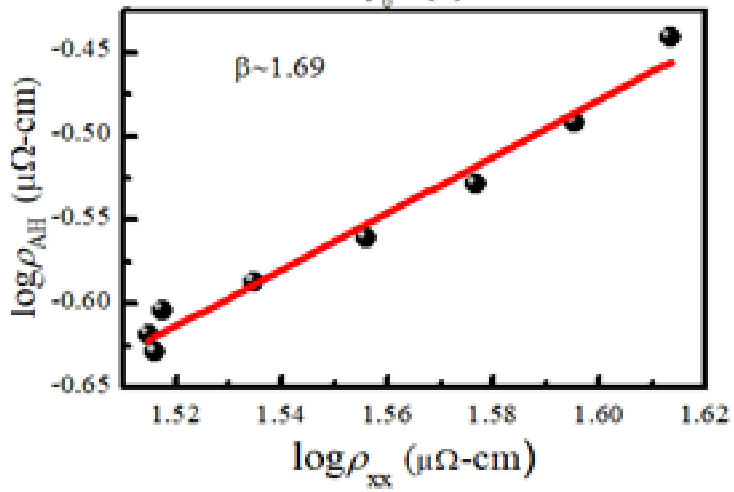


G. Shukla….and Sanjay Singh, Phys. Rev. B **105**, 035124 (2022)*

Magnetization and Hall results







Linear Fitting is employed using relation $\rho_{AH} \propto \rho_{xx}^{\beta}$. β was (taking log both side in $\rho_{AH} \propto \rho_{xx}^{\beta}$) found 1.69 which indicates intrinsic contribution. [$\beta = 1$ for skew scattering and $\beta = 2$ for the intrinsic origin]

G. Shukla….and Sanjay Singh, Phys. Rev. B **105**, 035124 (2022)*

Hall analysis

Intrinsic origin

$$\rho_{AH} = a^{skew}\rho_{xx} + \sigma^{int}\rho^2_{xx}$$

skew scattering parameter

Intrinsic AHC

$a^{skew} = 0.002$

$\sigma^{int} = 155$ S/cm

*** *We ignore the saturation magnetization in fitting because the change of M with T is very small.*
If M changes significantly with T :

$$\rho_{AH} = (a^{skew}\rho_{xx} + \sigma^{int}\rho^2_{xx})M_s$$

or

$$\rho_{AH}/M_s\rho_{xx} = a^{skew} + \sigma^{int}\rho_{xx} \quad \textit{(Linear equation)}$$

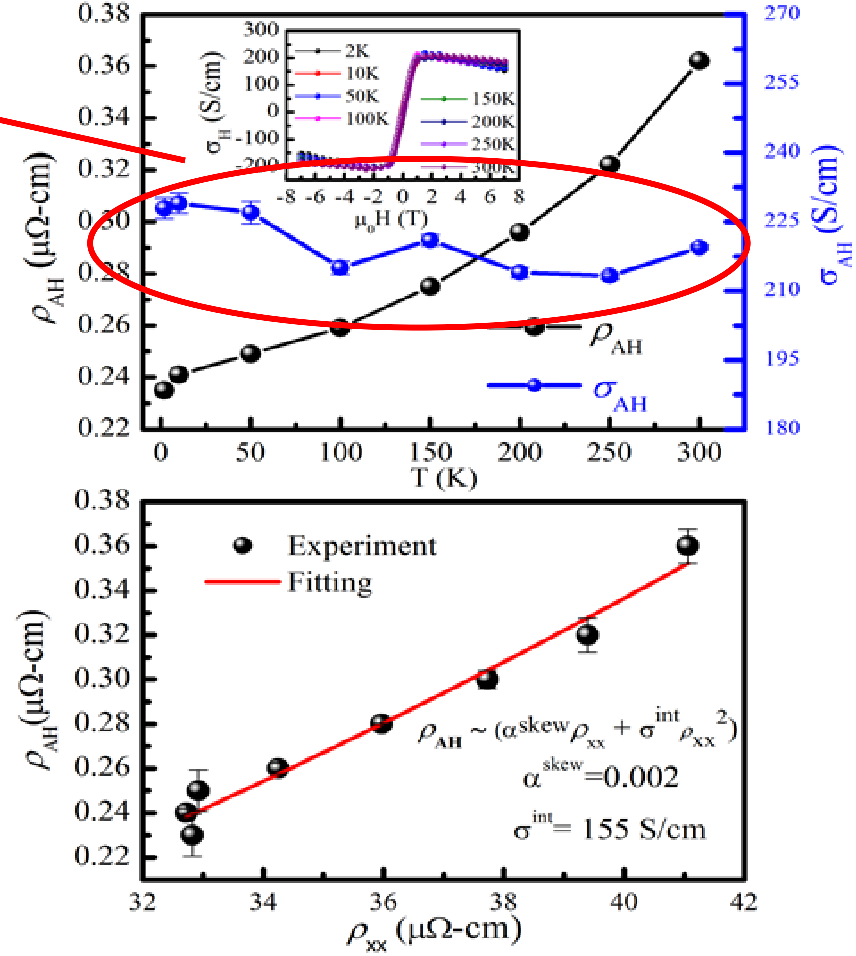
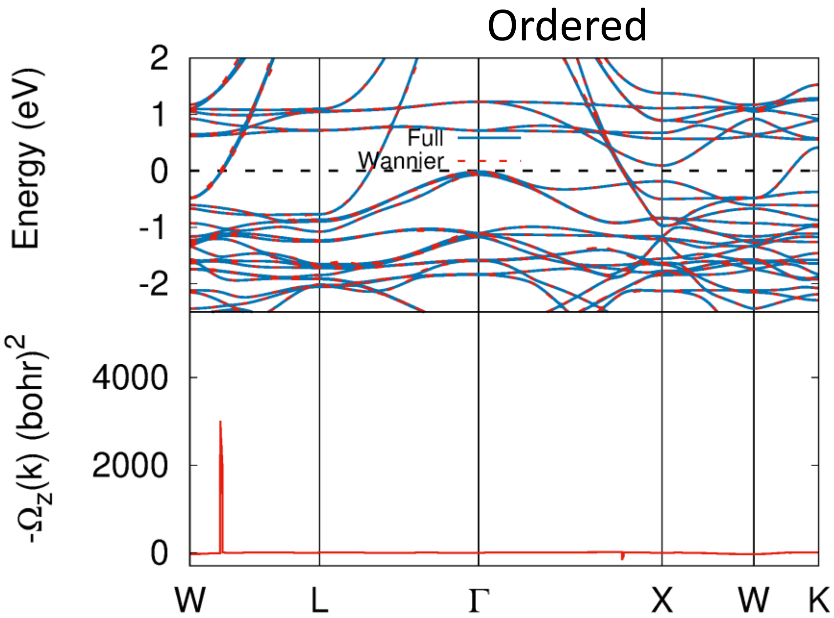


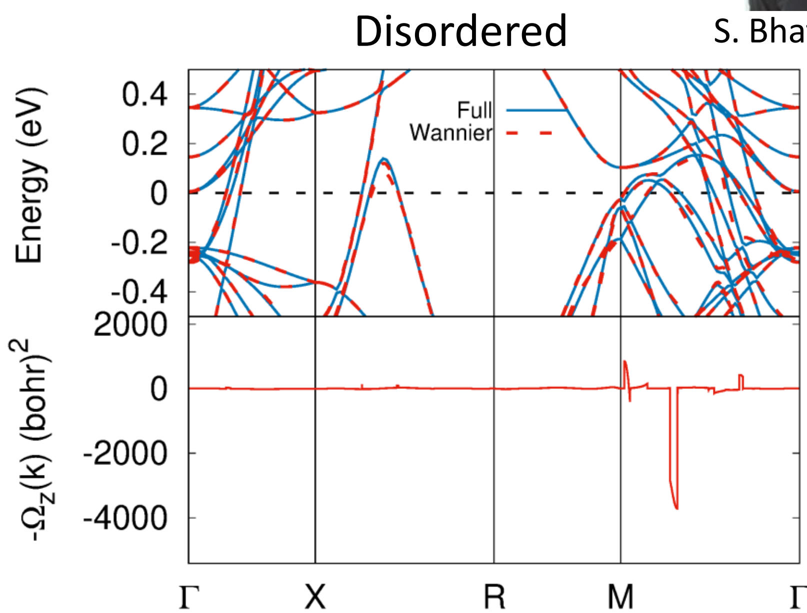
Fig. Temperature variation of AHC and the scaling analysis

G. Shukla….and Sanjay Singh, Phys. Rev. B **105**, 035124 (2022)*

First principles calculation

S. Bhattacharjee





The calculated AHC value = **42 S/cm**

Lower than the Experimental intrinsic AHC = 155 S/cm

The AHC value for the 50 % Fe/Al disorder came out = **63 S/cm**

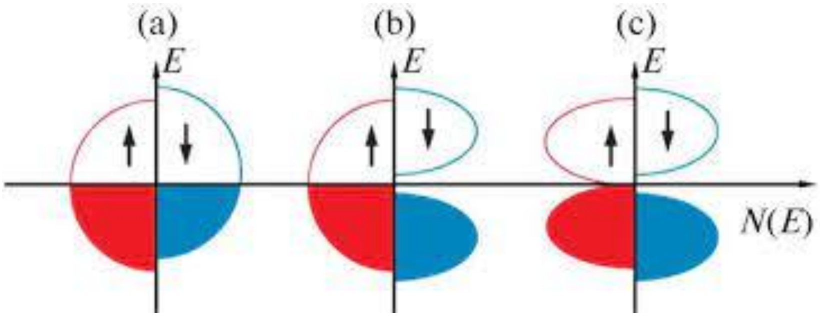
Conclusion:* disorder in the system can enhance the Berry curvature-induced intrinsic AHC. *It depends upon the disorder-induced change in the electronic band structure.

G. Shukla….and Sanjay Singh, Phys. Rev. B **105**, 035124 (2022)*

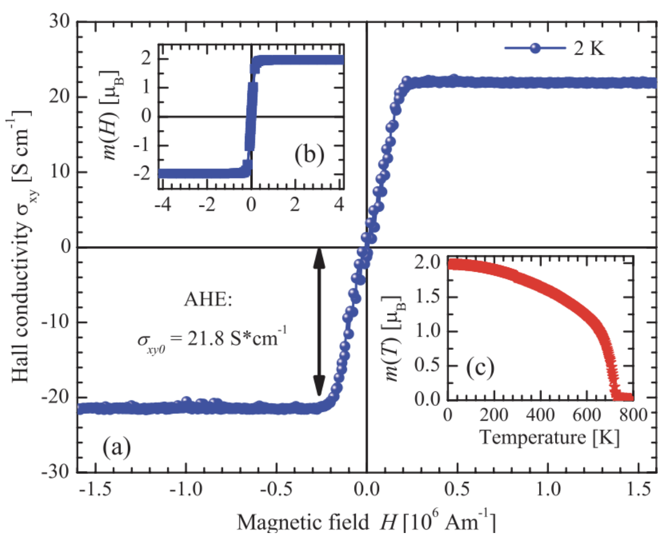
Is increasing AHC in Co_2FeAl due to
antisite disorder
just an incident ???

Spin-gapless semiconducting Heusler compound: Mn_2CoAl

- Spingapless semiconductors exhibit a band gap for one spin channel and a zero band gap for another spin channel.
- The first experimental evidence of spin-gapless semiconductor behavior was observed in the Mn_2CoAl compound.

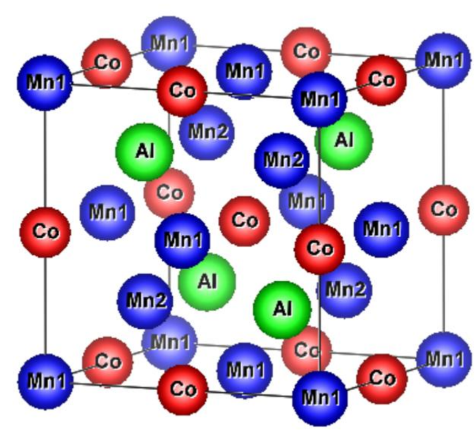


Unresolved issue ???



The experimental anomalous Hall conductivity (AHC) ~22 S/cm

Theory ~ 3 S/cm.



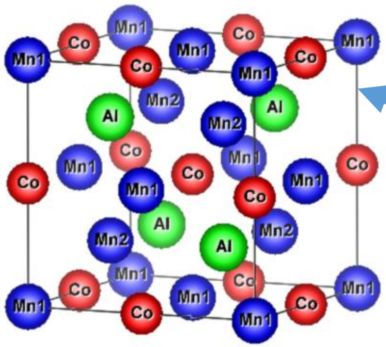
Inverse Heusler (F-43m)

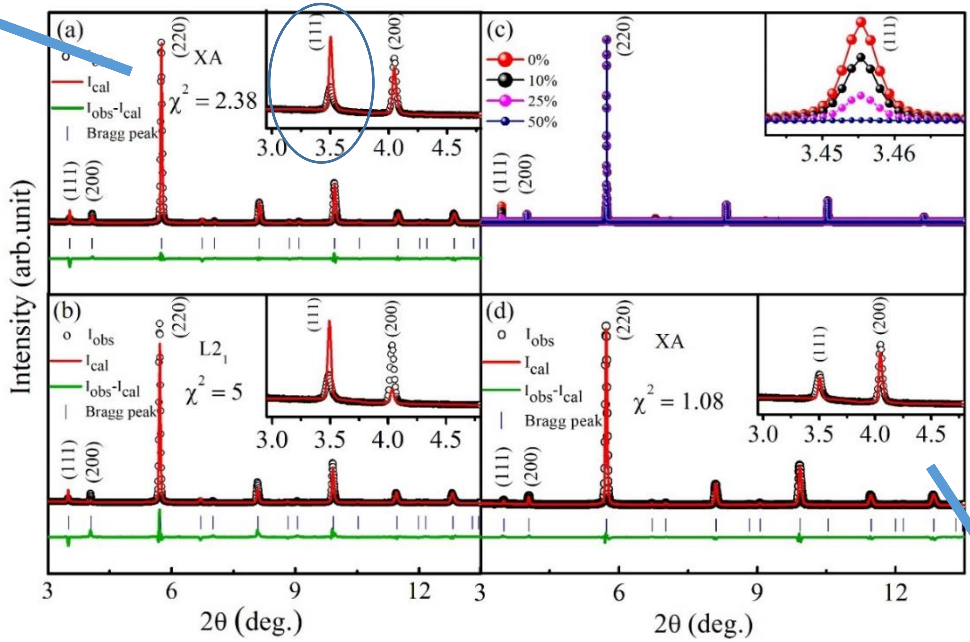
S. Ouardi et.al. PRL 110, 100401 (2013)

Crystal structure (our result): Synchrotron XRD

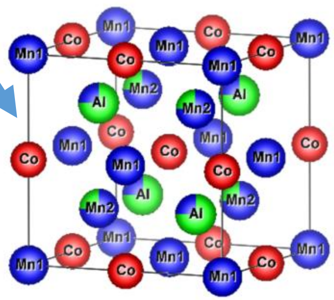
Nisha

Ordered structure





Disordered structure



XRD analysis: 25% anti-site disorder between Mn and Al atoms.

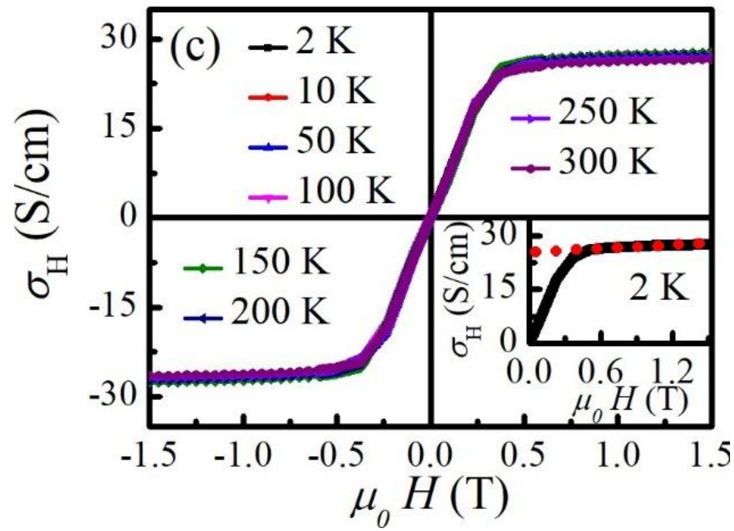
Nisha Shahi,…Sanjay Singh, Phys. Rev. B* ***106****, 245137 (2022)*

Anomalous Hall

Experiment:

$$\sigma_H = \frac{\rho_H}{(\rho_H^2+\rho_{xx}^2)}$$

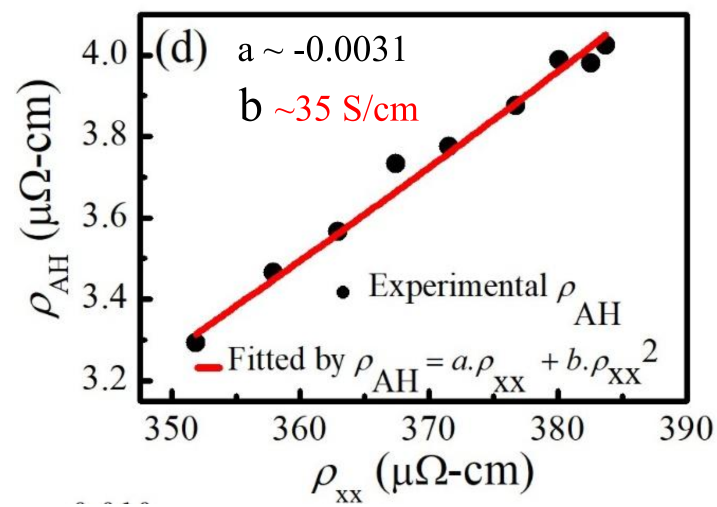
- Total Hall conductivity ~27 S/cm



- By using the scaling relation-

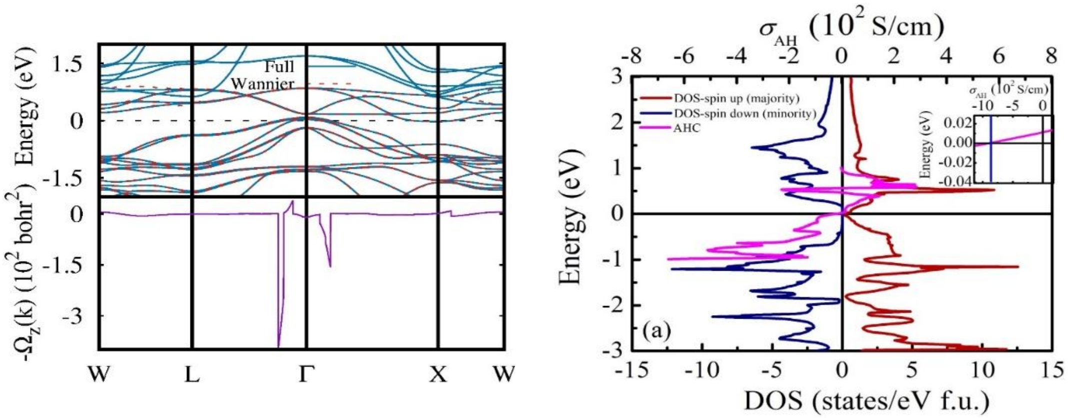
$$\rho_{AH} = a\rho_{xx} + b\rho_{xx}^2$$

Intrinsic ~35 S/cm



Nisha Shahi, …Sanjay Singh, Phys. Rev. B* ***106****, 245137 (2022)*

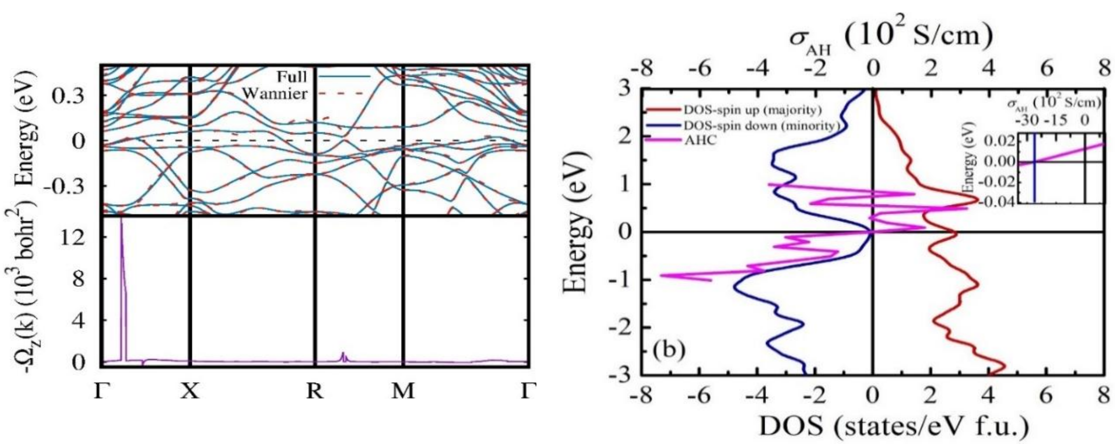
Anomalous Hall effect: Theoretical study



Ordered

Intrinsic AHC

~8 S/cm



Disordered

Intrinsic AHC

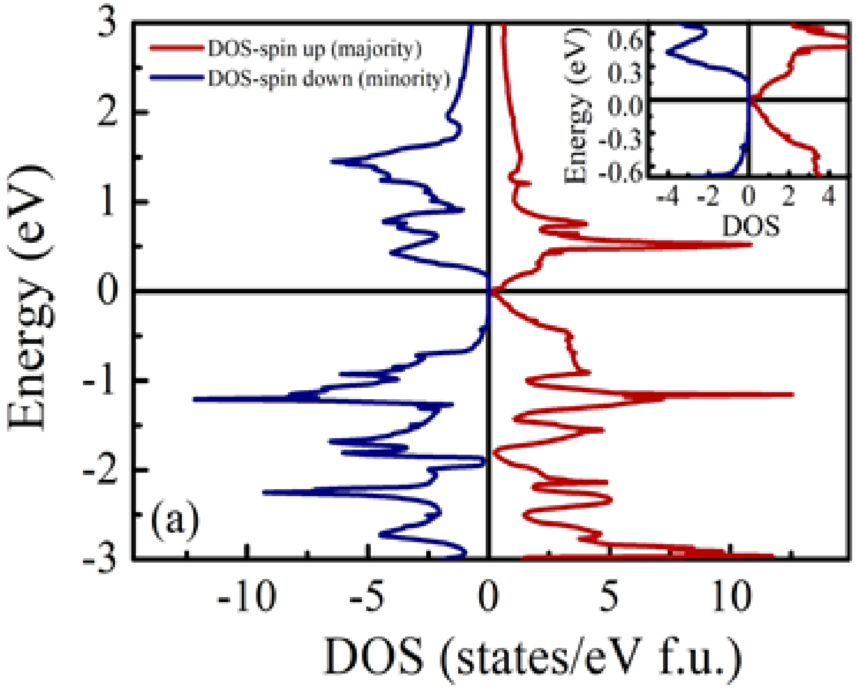
~26 S/cm

Nisha Shahi,…Sanjay Singh, Phys. Rev. B **106**, 245137 (2022)*

What does disorder actually do here??

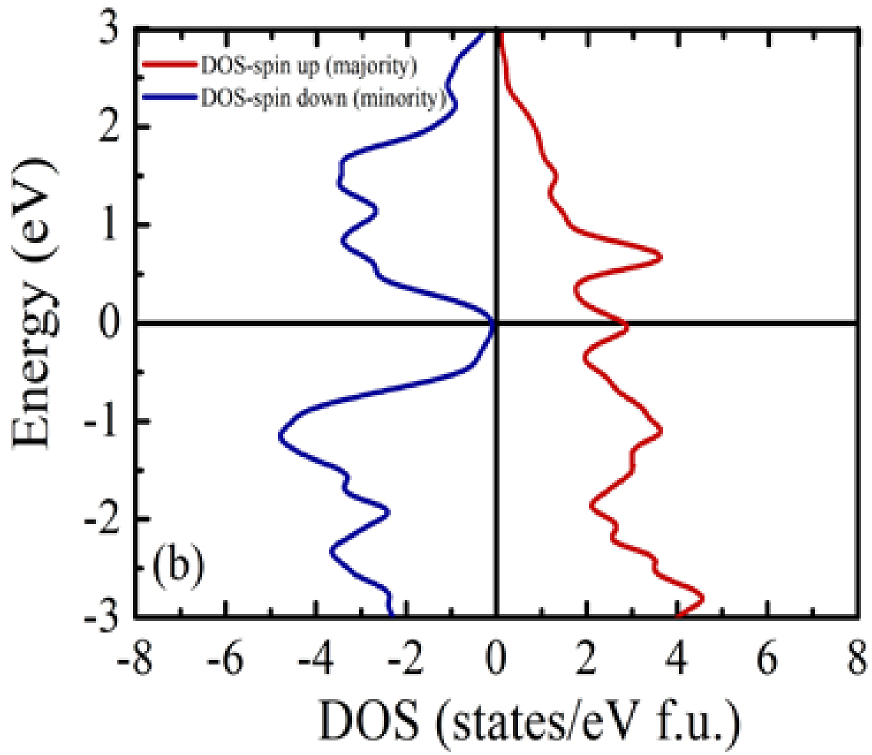
Ordered

~7 S/cm



Disordered

~30 S/cm



Disordered enhances half metallic behavior and AHC

Nisha Shahi,…Sanjay Singh, Phys. Rev. B **106**, 245137 (2022)*

Controlling anti-site disorder is not easy…..What is an alternative way to enhance AHC?

Chemical disorder is in our hands….

Payal

PHYSICAL REVIEW MATERIALS **5**, 124201 (2021)

Role of chemical disorder in tuning the Weyl points in vanadium doped Co_2TiSn

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Surasree Sadhukhan and Sudipta Kanungo

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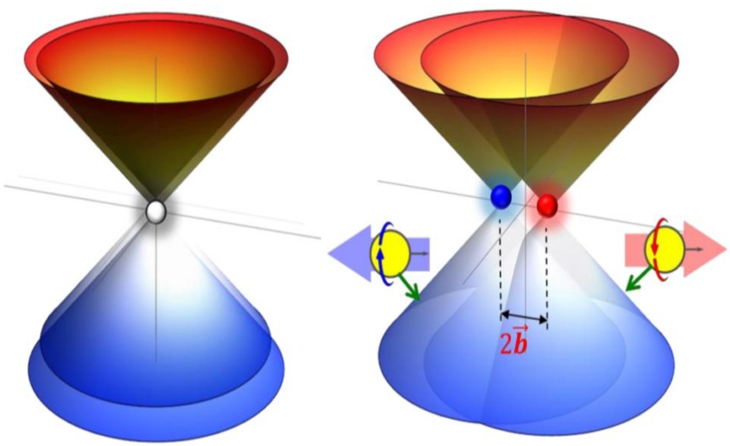
(Received 23 December 2020; revised 12 October 2021; accepted 8 November 2021; published 3 December 2021)

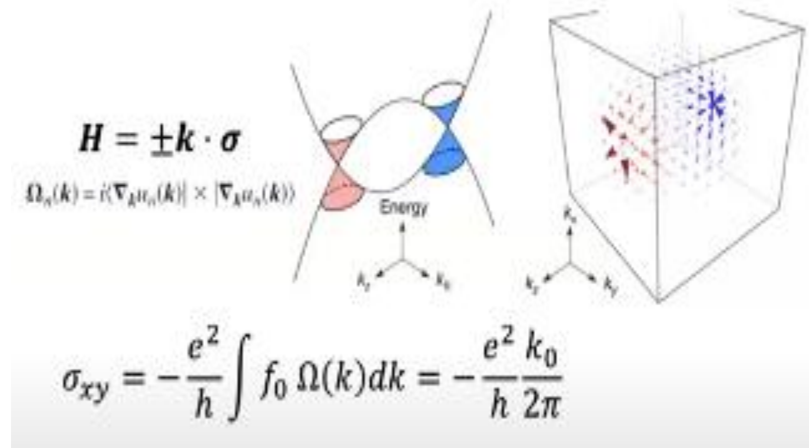
Weyl point and Anomalous Hall conductivity (AHC)

Broken time-reversal
and/or
Inversion symmetry

- A Weyl semimetal is a solid-state crystal whose low energy excitations are Weyl fermions
- Weyl points of opposite chirality act either as source or sink of Berry curvature.
- **Berry curvature**: Equivalent to fictitious magnetic field in momentum space

Dirac semimetal *Weyl semimetal*

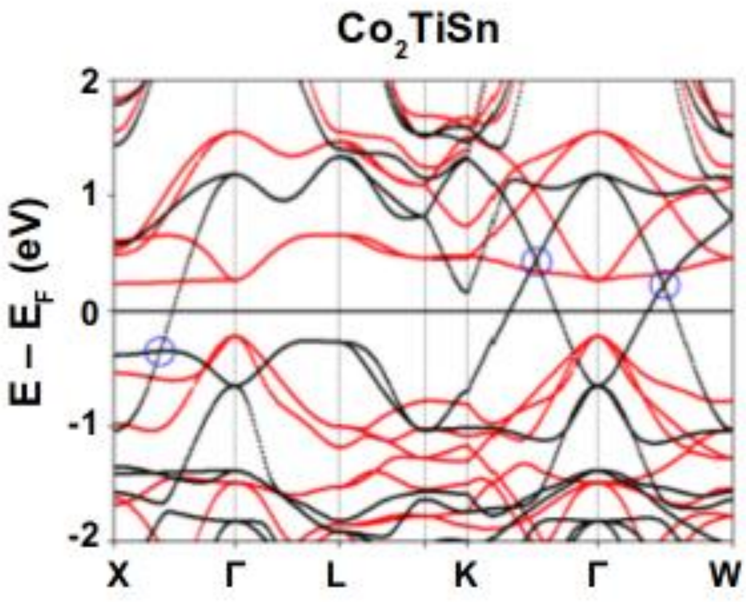


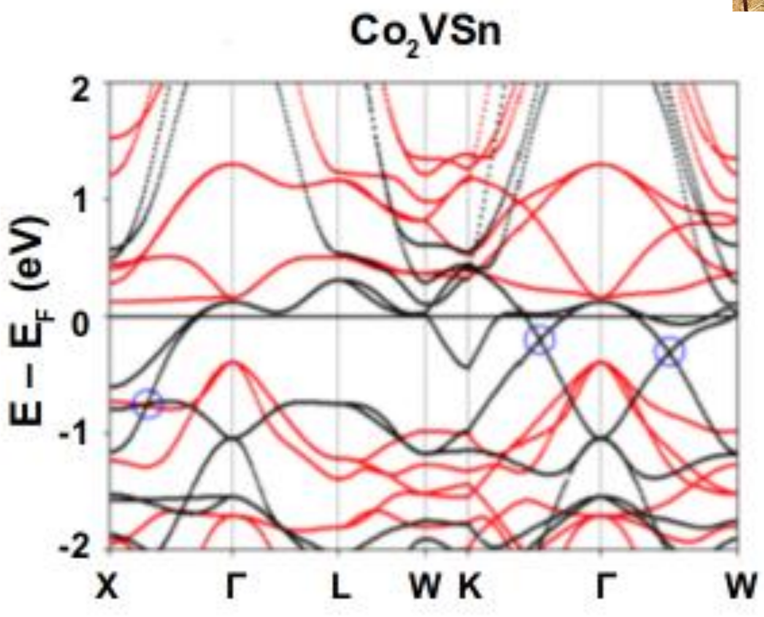


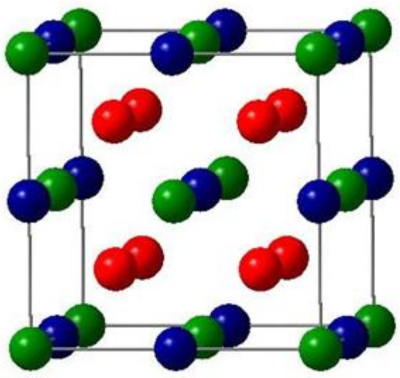
Weyl points → Large Berry curvature → Large AHC

The problem

Payal







Co_2 (Ti/V)Sn :
Fm-3m (cubic)

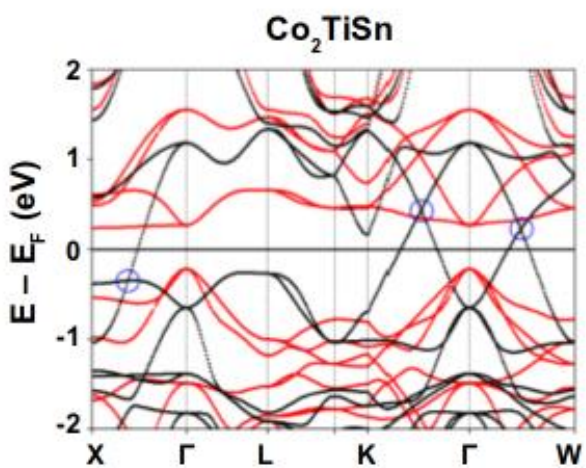
P. Chaudhary…..Sanjay Singh Phys. Rev. Mater.* ***5****, 124201 (2021).*

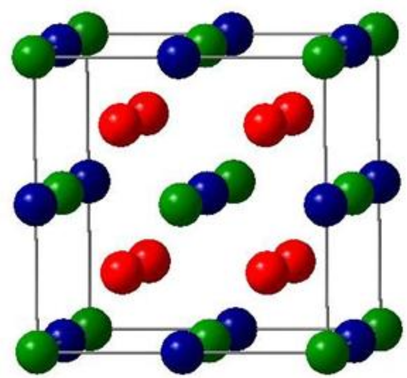
The solution

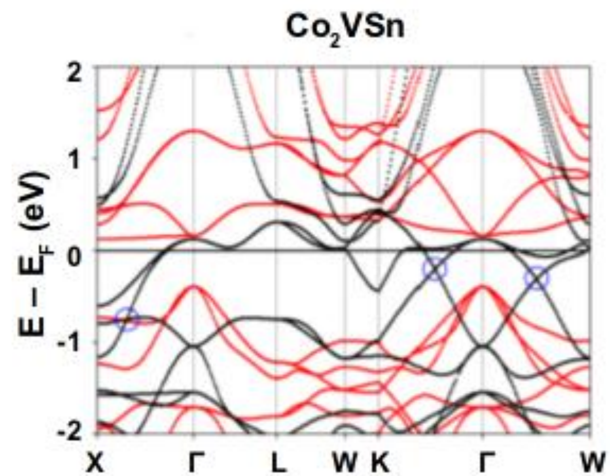
Payal

Valence electron

Substituting V (5) in place of Ti (4 VE)??



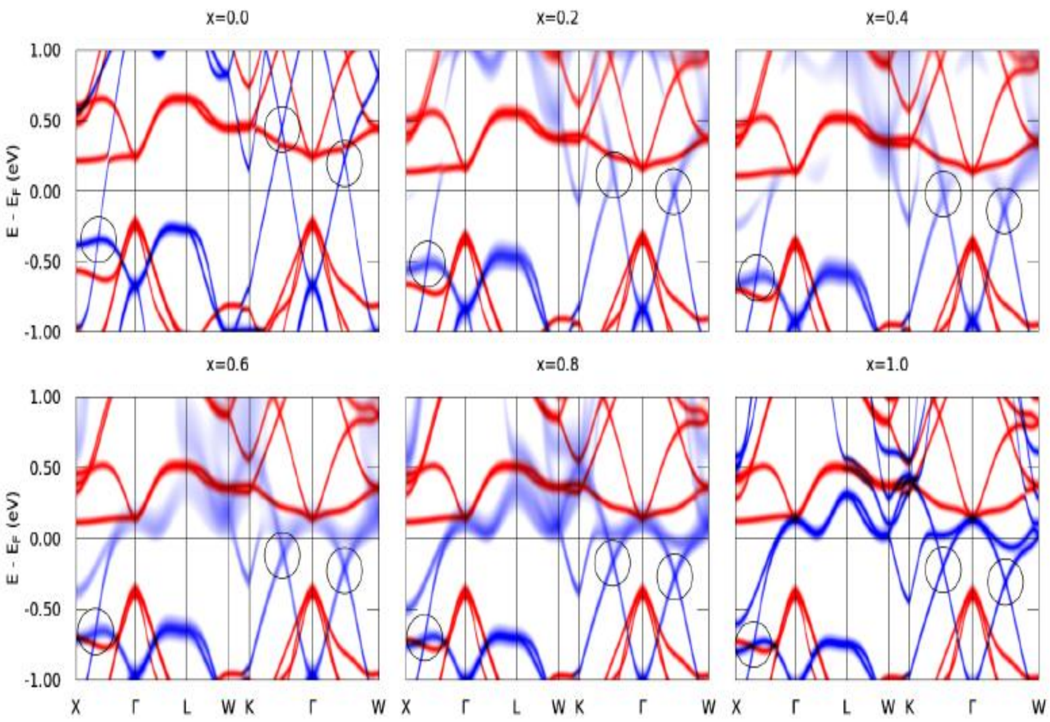




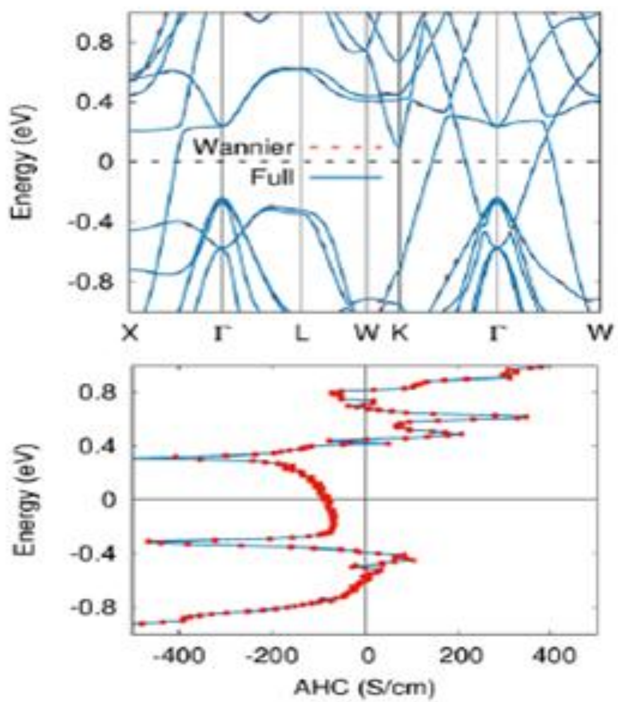
Co_2 (Ti/V)Sn :
Fm-3m (cubic)

P. Chaudhary…..Sanjay Singh Phys. Rev. Mater.* ***5****, 124201 (2021).*

Material engineering: Tuning of AHE by Chemical disorder



Band structure of $Co_2Ti_{(1-x)}V_xSn$.



Band structure (electronic + Wannier) plots and energy dependence AHC in Co_2TiSn.

AHC for x = 0.5 is 196.84 S/cm two times of x= 0 (~ 99 S/cm)

Controlling AHC….. Chemical disorder

PHYSICAL REVIEW MATERIALS **8**, 034203 (2024)

Ujjawal

Theoretical Investigation

Tuning of nodal line states via chemical alloying in Co_2CrX (X = Ga, Ge) Heusler compounds for a large anomalous Hall effect

Ujjawal Modanwal,[1] Gaurav K. Shukla,[1] Ajit K. Jena,[2] Satadeep Bhattacharjee,[2] Sunil Wilfred D'Souza,[3] Jan Minár,[3] and Sanjay Singh[1,*]

[1]*School of Materials Science and Technology, Indian Institute of Technology (Banaras Hindu University), Varanasi 221005, India*
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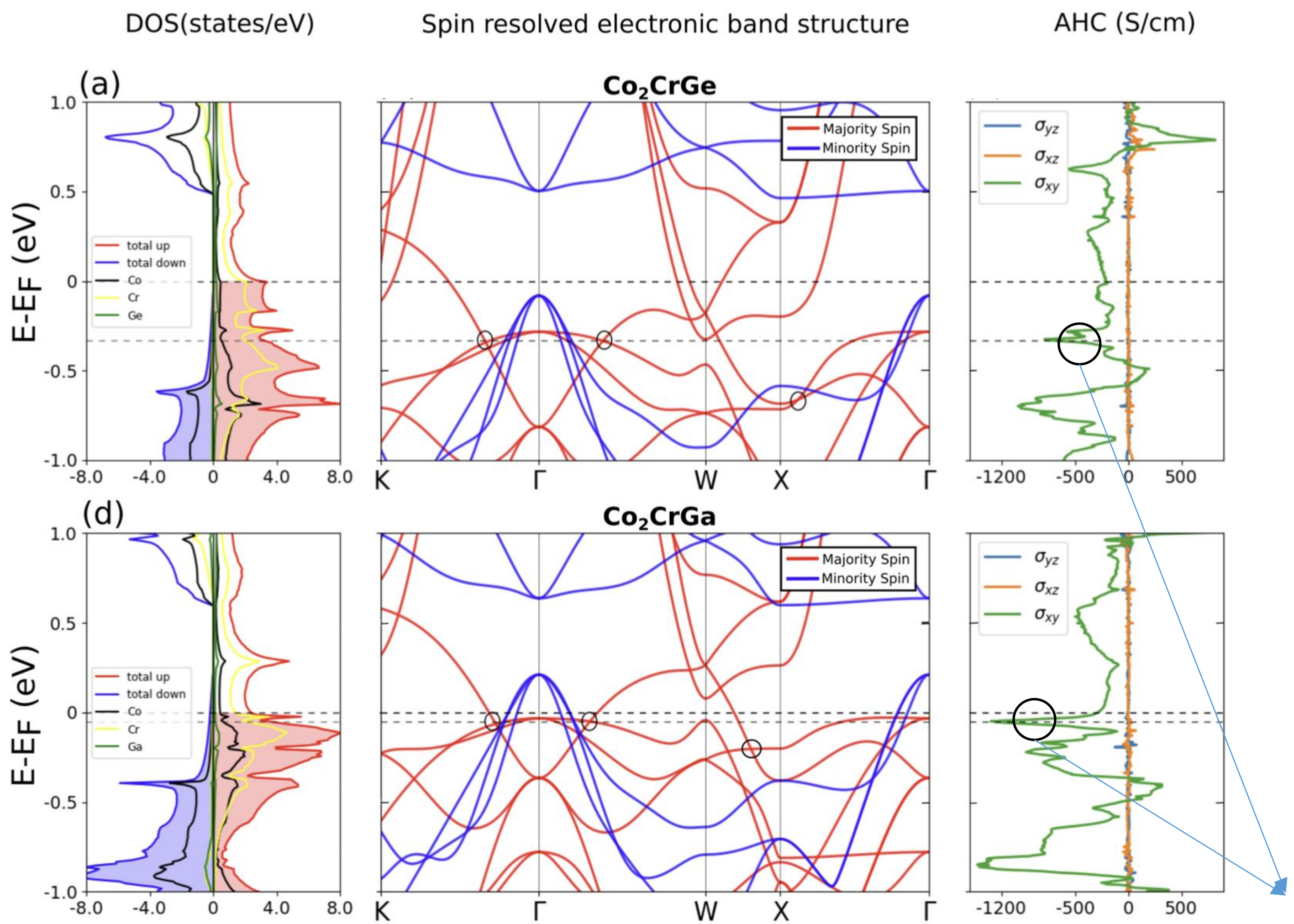
(Received 27 June 2023; revised 23 January 2024; accepted 28 February 2024; published 22 March 2024)

Topological materials have attracted significant interest in condensed matter physics for their unique topological properties leading to potential technological applications. Topological nodal line semimetals, a subclass of topological materials, exhibit symmetry-protected nodal lines, where band crossings occur along closed curves in the three-dimensional Brillouin zone. When the nodal lines are gapped out due to perturbation in the Hamiltonian, a large Berry curvature (BC) arises in the surrounding area of the gapped nodal line, leading to exotic anomalous transport responses. In this paper, we studied the Co_2CrX (X=Ga, Ge) Heusler compounds that exhibit mirror symmetry-protected nodal line states below the Fermi level. The BC calculation yields anomalous Hall conductivity (AHC) of about 292 and 217 S/cm for Co_2CrX (X=Ga, Ge), respectively, at the Fermi level, which increases by up to 400% at the nodal line energy level. We theoretically analyzed that 20% and 60% zinc (Zn) alloying in Co_2CrX (X=Ga, Ge) effectively lowers the Fermi level by 50 meV and 330 meV, respectively, aligning with the protected crossings. Consequently, we identified $Co_2CrGe_{0.4}Zn_{0.6}$ and $Co_2CrGa_{0.8}Zn_{0.2}$ as compositions to achieve the significant AHC of 800 and 1300 S/cm, respectively. The explicit AHC calculation for these alloyed compositions is in good agreement with our predictions. Our findings highlight that chemical alloying is an efficient way to enhance AHC in nodal line hosting materials.

DOI: 10.1103/PhysRevMaterials.8.034203

Very large:
1300 S/cm



DOI: 10.1103/PhysRevMaterials.8.034203

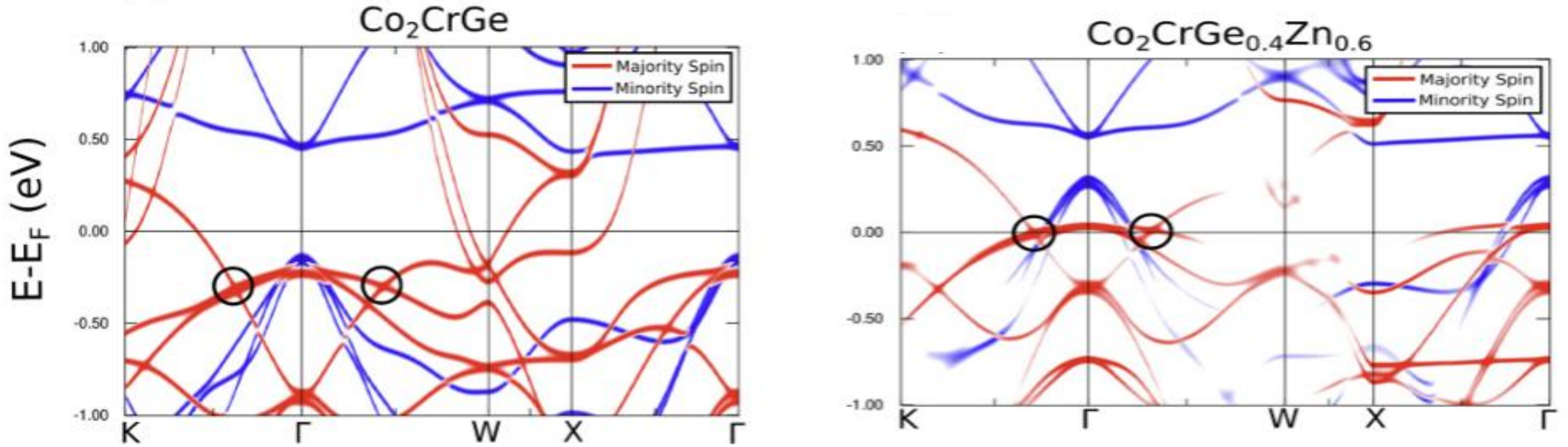
Sharp increment in AHC due to large BC if we may shift Fermi level

AHC

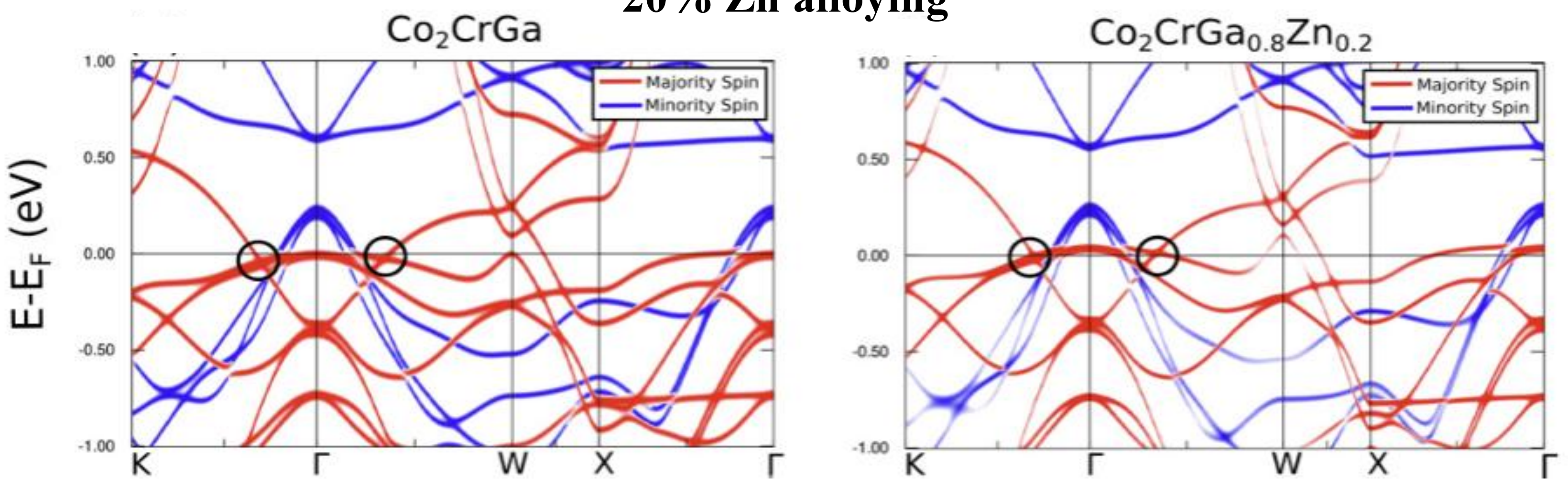
Co_2CrGa ($E\text{-}E_F$ = 0 eV) ~292 S/cm	Co_2CrGe ($E\text{-}E_F$ = 0 eV) ~217 S/cm
Co_2CrGa ($E\text{-}E_F$ = 50 meV) ~1300 S/cm	Co_2CrGe ($E\text{-}E_F$ = 330 meV) ~800 S/cm

- Thus, AHE can be increased by coinciding these band crossings with Fermi level

60% Zn alloying



20% Zn alloying



DOI: 10.1103/PhysRevMaterials.8.034203

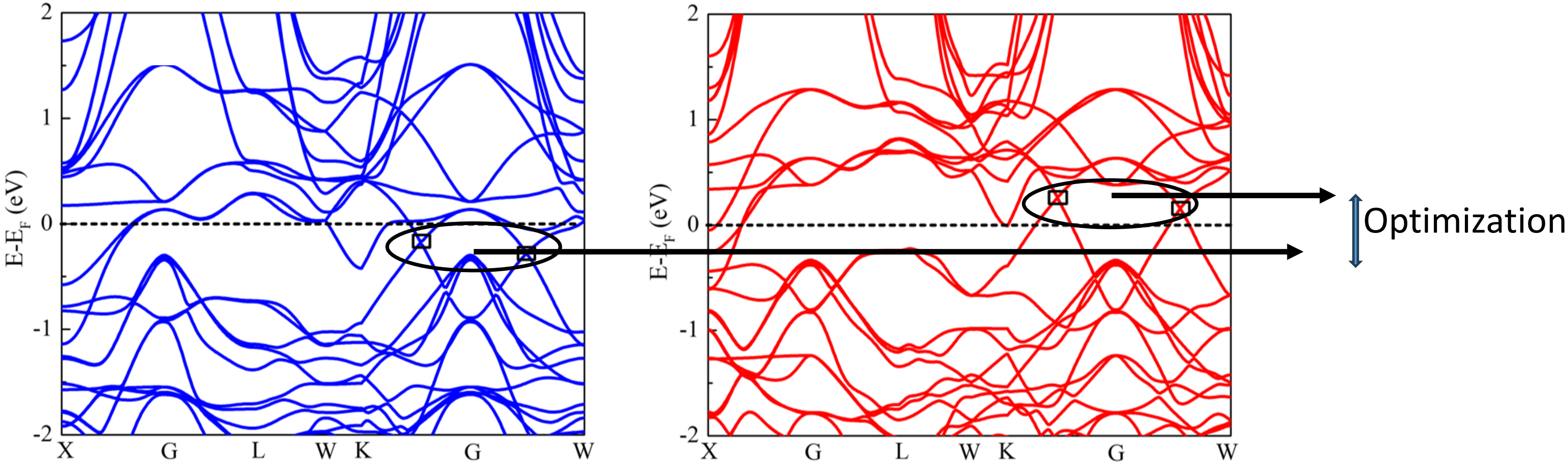
AHC calculated for close compositions $Co_2CrGa_{0.75}Zn_{0.25}$ and $Co_2CrGe_{0.5}Zn_{0.5}$ aligned with the previously predicated value at nodal line positions

Experimental proof?????

Controlling AHC….. Chemical disorder

Experimental Investigation

$Co_2VSn_{1-x}Al_x$ Weyl semimetal

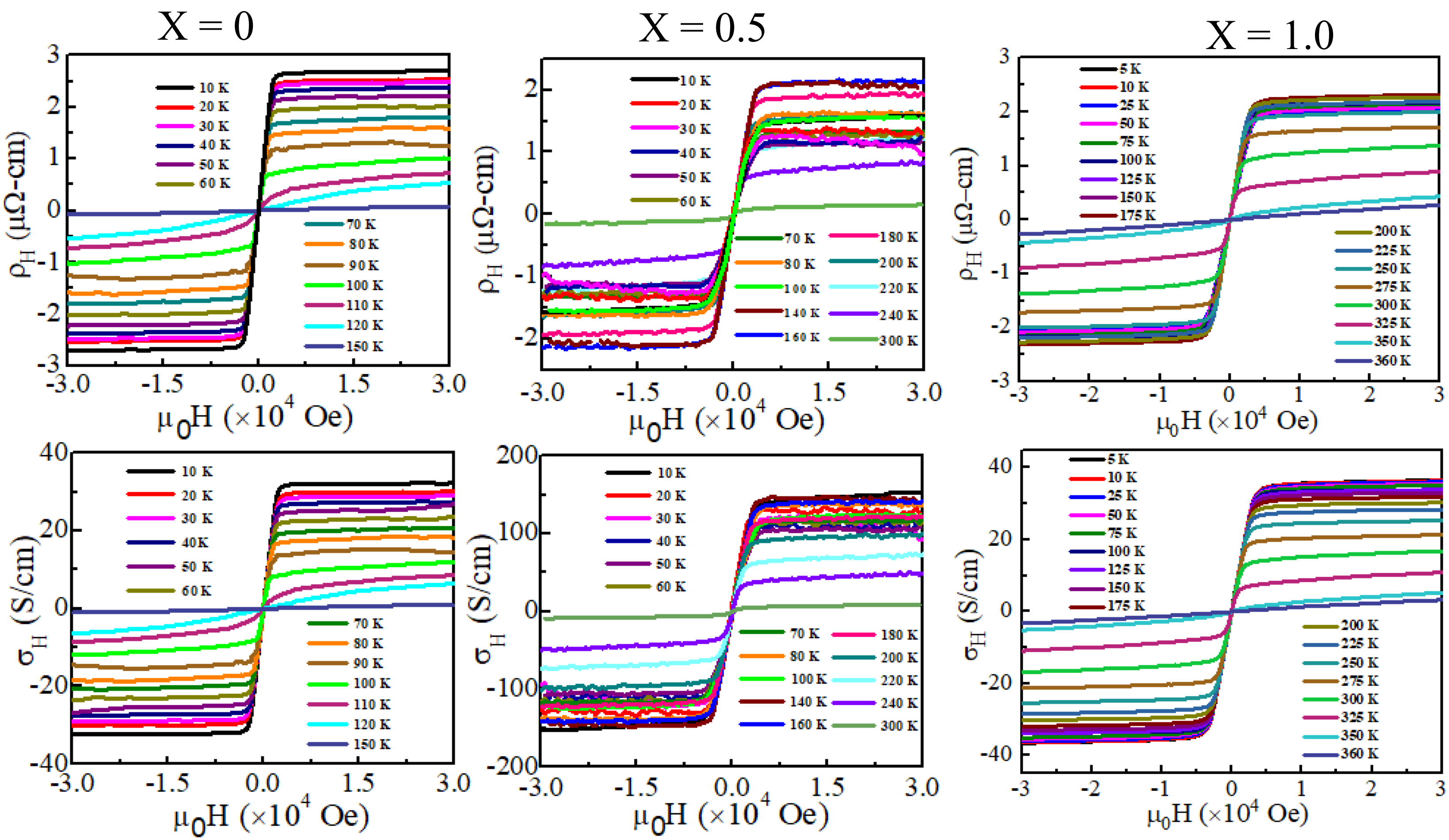


Valence electron: Substituting Al (3 VE) in place of Sn (4 VE) VE)??

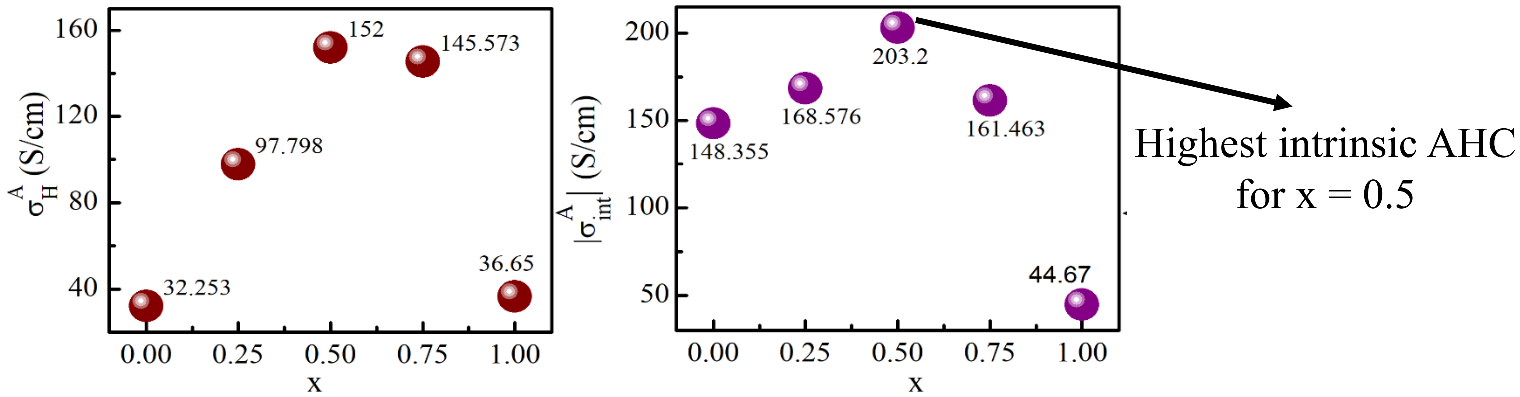
Controlling AHC….. Chemical disorder

Experimental Investigation

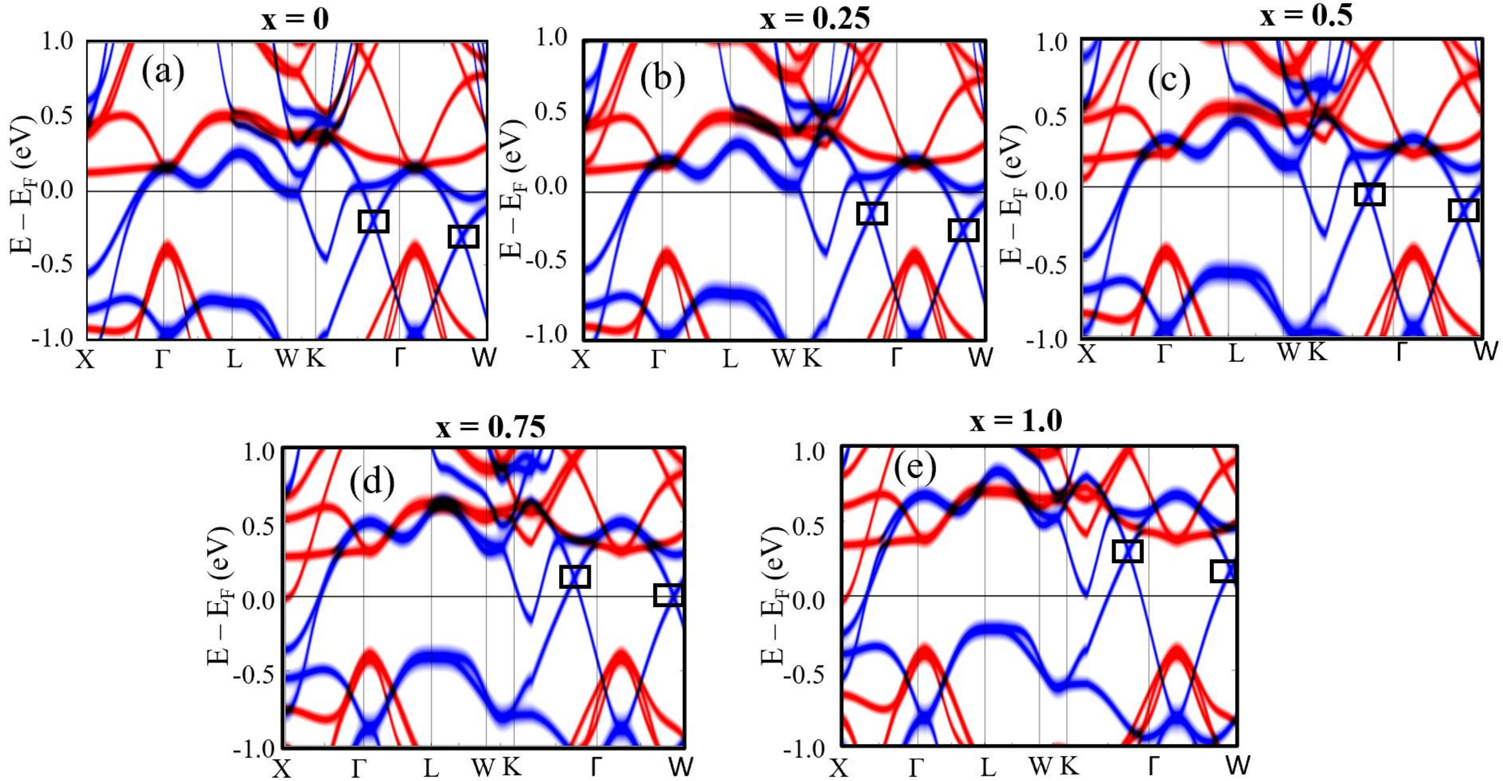
Hall Resistivity and Conductivity of $Co_2VSn_{1-x}Al_x$



Summary of Experimental AHC



Theoretical Calculation: Bloch Spectral Function Plots



Shifting of nodal line upwards with Al doping. Nodal line nearly coincides with E_F for x = 0.5

Conclusions

- Resolved the controversy about Anomalous Hall effect in Co_2FeAl and Mn_2CoAl Heusler compound and established it quantum origin
- Our work provides a basic understanding that, how the atomic ordering influence the Berry curvature and give a path to create large AHC due to modification of the Berry curvature induced by atomic/chemical ordering
- Large (quantum) Anomalous Hall effect may put forward for zero loss and clean energy devices.

Thank you!

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सत्यमेव जयते

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GUC ADE

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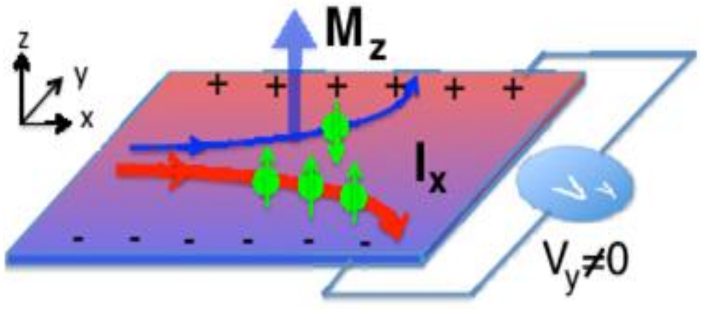
Anomalous transverse transport phenomena for clean energy

A thermoelectric counterpart

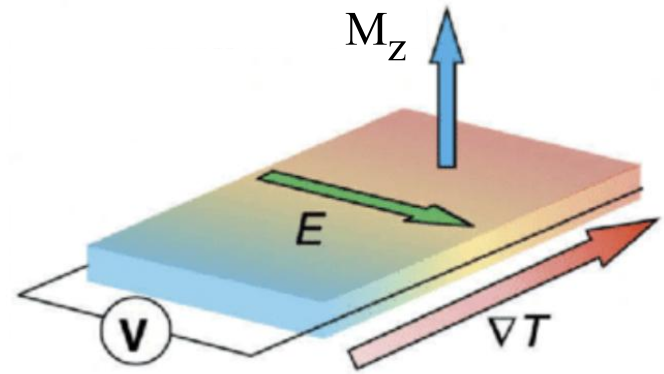
Anomalous Hall effect (AHE)



Rev. Mod. Phys. 82, 1539

Generation of transverse voltage perpendicular to current and applied magnetic field

Anomalous Nernst effect (ANE)



Sci. technol. adv. Material, *20*(1), pp.262-275.

Generation of transverse voltage perpendicular to Temp. gradient and magnetic field

Recycling waste heat into electricity

Both governed by

$$\rho_H = R_0 H + RsM$$

$$\vec{E}_{ANE} = S_{ANE} \nabla T \times M$$

Berry curvature

AHE is governed by sum of Berry curvature over all occupied states and ANE is determined by the Berry curvature at Fermi level.