

MAGNETIC ORDERING AND SPIN WAVE DYNAMICS IN TRANSITION METAL
ARSENIDES

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BY

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DISSERTATION

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Abstract

Metallic antiferromagnets have gained interest in recent times due to the possibility of being useful as a memory device. Arsenic forms a large pool of magnetic metals in combination with other transition metals that have largely been ignored so far. In this report, we discover a new ternary metallic arsenide in the Cu-Mn-As phase space, identify its chemical and magnetic structure, and characterize its electrical and magnetic properties. We also carry out the magnetic structure refinement of Mn_3As_2 from neutron powder diffraction data at different temperatures to understand the magnetic ordering in Mn-As compounds. Using inelastic neutron scattering measurements, we determine exchange interactions in Fe_2As , which has the same structure as CuMnAs, showing a highly 2D magnon character although the phonons are 3D. Finally, we report a magnetic-structural coupled transition across 300 K in tetragonal CuMnAs and determine the correct magnetic structure of the compound.

Acknowledgments

This project would not be possible without many people. Firstly, thanks to my advisor, Prof. Daniel P. Shoemaker.

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Chapter 1

Introduction

1.1 Magnetic information storage

2 In computer architecture, there is typically a trade-off between the optimum speed or re-
3 sponse time and the complexity and size of memory storage. Volatile memory refers to
4 temporary memory storage where the data is lost when the power is removed. Volatile
5 memory such as SRAM (static random access memory) and DRAM (dynamic random access
6 memory) are used as CPU caches and main memory respectively. SRAM, although has much
7 faster access times and does not require periodic refreshing, requires four to six transistors
8 per bit as compared to one transistor and capacitor in DRAM devices. Non-volatile memory
9 (NVM) storage devices, on the other hand, retain their data for a long period of time until
10 disturbed. Modern computers mostly use flash memory based solid state drives (SSD) and
11 magnetic hard disk drives (HDD) for storing large amounts of data permanently. The first
12 HDD was invented in 1956 by IBM and since then, HDD have seen more than 8 orders of
13 magnitude improvement in the storage density. However, the trilemma in magnetic recording
14 between poor thermal stability, coercive fields and signal-to-noise ratio has resulted in the
15 HDDs reaching a saturation limit in their device performance. Flash memory uses floating
16 gate MOSFETs (metal oxide semiconductor field effect transistors) to store memory and does
17 not contain any moving parts unlike HDDs. Although SSD have dominated the NVM market-
18 share, there is an increasing need for alternative NVM technologies that are fast, low power
19 consuming and have high storage density.

20 One such emerging NVM is MRAM (magnetoresistive random access memory). Unlike
21 flash memory which uses electronic charge as a medium of memory storage, MRAM uses
22 the electronic spin degree of freedom to store memory. MRAM devices consist of cells with
23 magnetic tunnel junctions (MTJ) that have two ferromagnet (FM) layers separated by an
24 insulating layer. One of the layer is pinned where the magnetization orientation is fixed
25 and acts as a reference layer. Depending on the orientation of the free layer, the tunneling
26 magnetoresistance (TMR) is high or low and hence, memory can be read using electrical
27 currents. Early MRAMs were written by induced fields from heavy currents passed on the
28 adjacent layer. With recent developments in spin transfer torque in ferromagnets, it has
29 become possible to write using electrical currents. This has reduced the power consumption

30 significantly and made commercialization of MRAM devices possible.

31 **1.2 Antiferromagnets for potential applications as a memory unit**

32 Historically, antiferromagnets (AFM) have been used as inactive components in MTJ, pri-
33 marily in exchange biasing the pinned FM layer. However in 2010, Gomonay *et al.* proposed
34 electrical switching of AFMs using STT by passing a spin polarized current injected from
35 a fixed FM layer through the AFM layer. The electrical current gets spin polarized in the
36 FM layer and transfers its angular momentum to the AFM moments to switch it from one
37 orientation to another. There are advantages to using AFM over FM in MRAM devices. AFM
38 are not easily affected by external magnetic fields and do not produce stray fields of their
39 own. They have smaller domains which would allow for higher storage densities. Since
40 the precession frequency of AFM moments is the geometric mean of exchange interaction
41 and magnetocrystalline anisotropy, the dynamics in AFM materials occur in GHz timescales
42 which is useful for fast precessional switching. Although the AFM can be switched using
43 electrical currents from parallel to perpendicular orientation with respect to the FM magne-
44 tization direction, the reverse process cannot be obtained electrically. High magnetic fields
45 above the spin flop transition of the AFM needs to be applied in order to switch back the
46 AFM to its original state.

47 Spin orbit torque based electrical switching in FM does not require the presence of a pinned
48 FM layer at all. Since the fieldlike torque experienced by the moments are quadratic to the
49 magnetization of the FM, the concept is also equally applicable to AFM. In 2016, Wadley *et*
50 *al.* showed that in AFM with certain symmetries, the current induced spin polarization of
51 charge carriers is staggered across the two magnetic sublattices resulting in a fieldlike torque
52 that is in the same direction for the two sublattices. This is possible in materials which are
53 globally centrosymmetric but locally non-centrosymmetric and the two sublattices are related
54 to each other by a center of inversion.

55 **1.3 Exploration of Cu-Mn-As phase space**

56 **1.4 Exchange interactions in Cu₂Sb type materials**

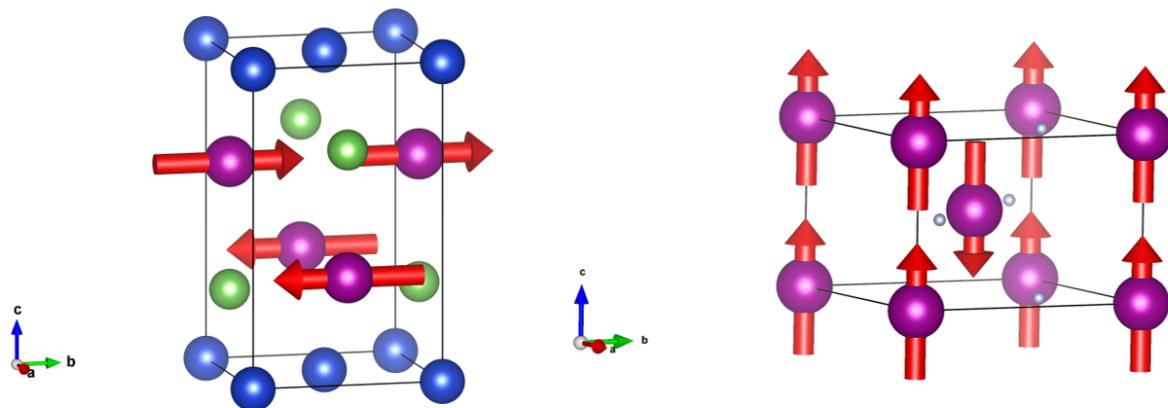


Figure 1.1: Electronic band structure

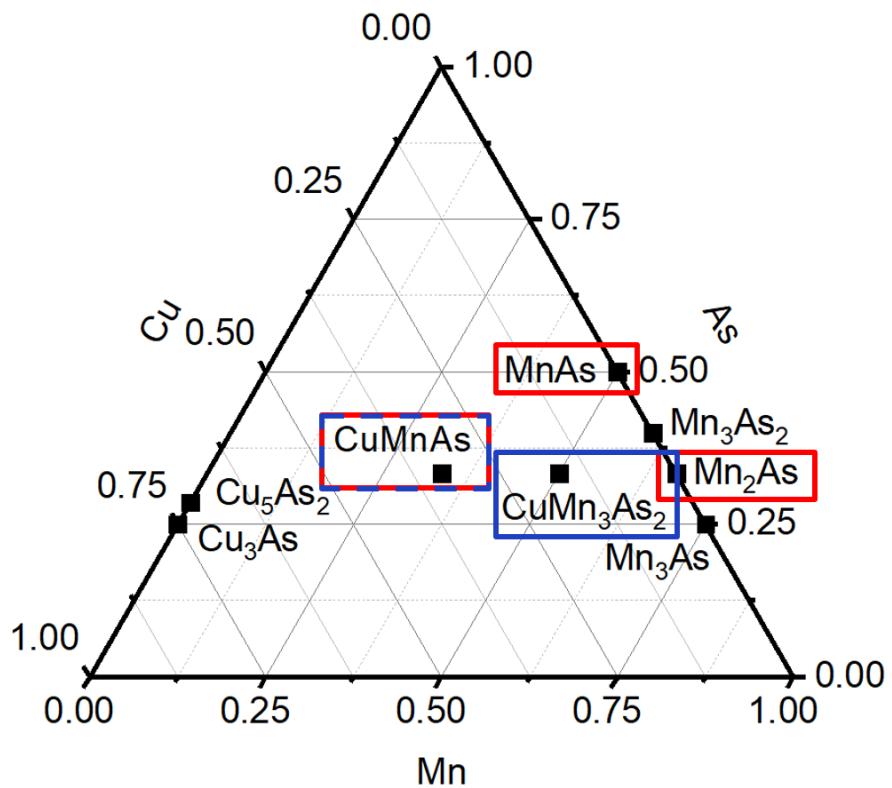


Figure 1.2: Electronic band structure

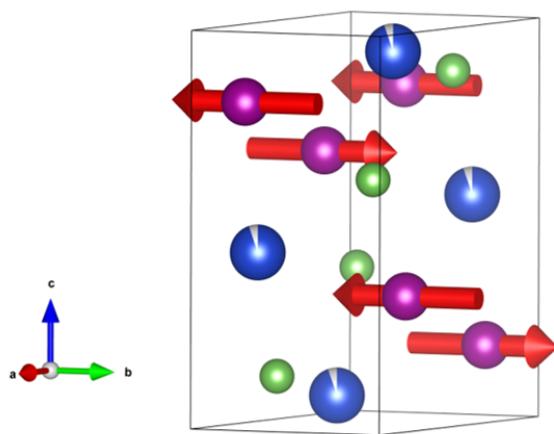


Figure 1.3: Electronic band structure

Chapter 2

Theory of electrical switching in metallic antiferromagnets

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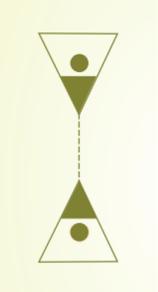
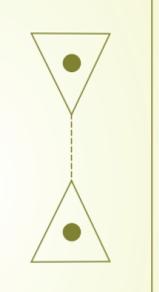
Bulk symmetry: Site symmetry: Symmetry schematic: Effect/consequence: Name:	a Centrosymmetric Inversion symmetry 	b Non-centrosymmetric (bulk inversion asymmetry) Dipole field  Inversion asymmetry 	c Centrosymmetric Dipole field  Inversion asymmetry 	
	R-1	D-1	R-2	D-2

Figure 2.1: Electronic band structure

Table 1 | Classification of spin polarization in nonmagnetic bulk materials on the basis of bulk space group and site point group.

Site point group \\ Bulk space group	Non-centrosymmetric (at least one site)			Centrosymmetric (all sites) ($C_1, C_2, C_3, C_4, C_6, C_{1v}, C_{2v}, C_{3v}, C_{4v}, C_{6v}$, $D_{4h}, S_6, D_{3d}, D_{6h}, T_h, O_h$)	
	Non-polar (all sites) ($D_{2h}, D_{3h}, D_{4h}, D_{6h}, S_{4h}, D_{2d}, C_{3h}, D_{3h}, T, T_d, O$)	Polar (at least one site) ($C_1, C_2, C_3, C_4, C_6, C_{1v}, C_{2v}, C_{3v}, C_{4v}, C_{6v}$)	Dipoles add up to zero	Dipoles add up to non-zero	
Non-centrosymmetric (for example, $F\bar{4}3m$)	a D-1 Example: GaAs, ZrCoBi	b D-1 Example: γ -LiAlO ₂	c R-1 & D-1 Example: BiTel, α -SnTe	<i>Not possible (Site point group cannot be centrosymmetric if space group is non-centrosymmetric)</i>	
Centrosymmetric (for example, $R\bar{3}m$)	d D-2 Example: Si, NaCaBi	e R-2 & D-2 Example: MoS ₂ , Bi ₂ Se ₃ , LaOBiS ₂		f Absence of spin polarization Example: β -SnTe	

Figure 2.2: Electronic band structure

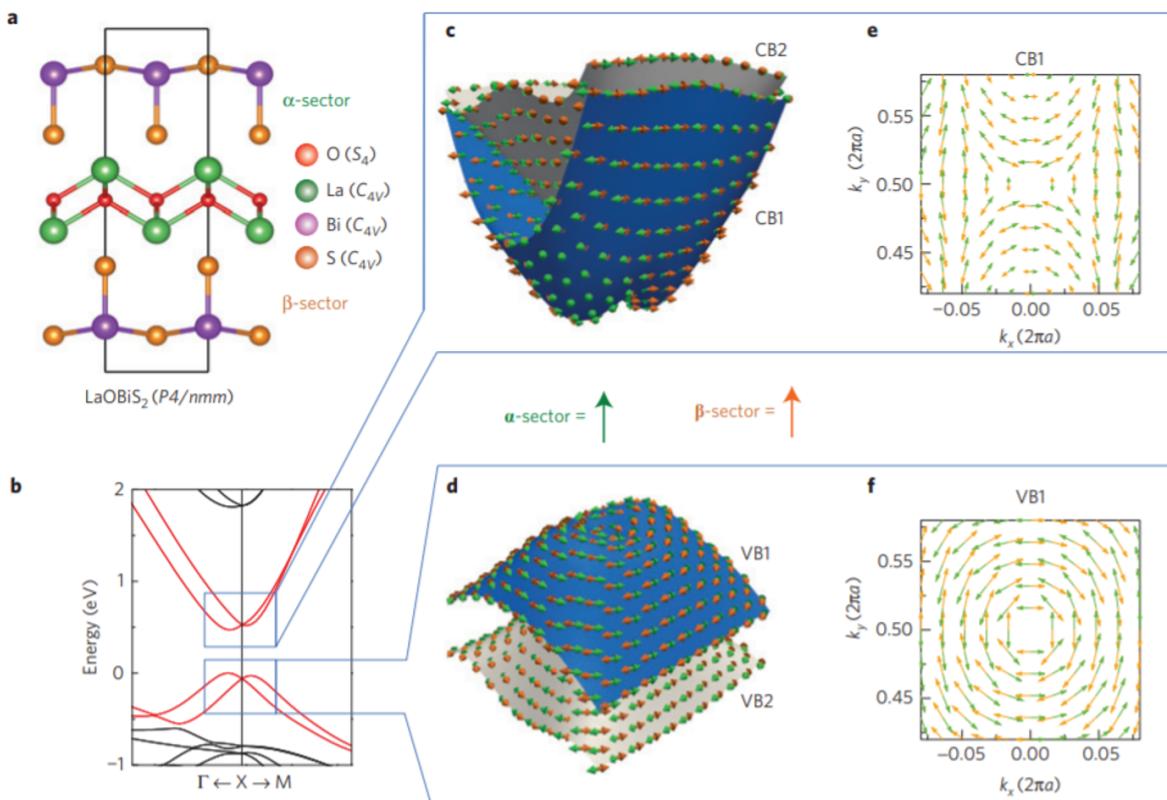


Figure 2.3: Electronic band structure

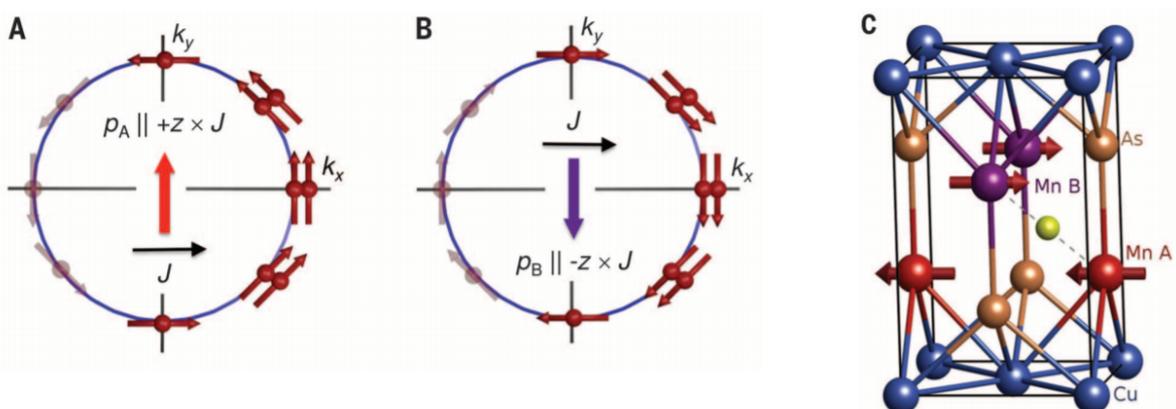


Figure 2.4: Electronic band structure

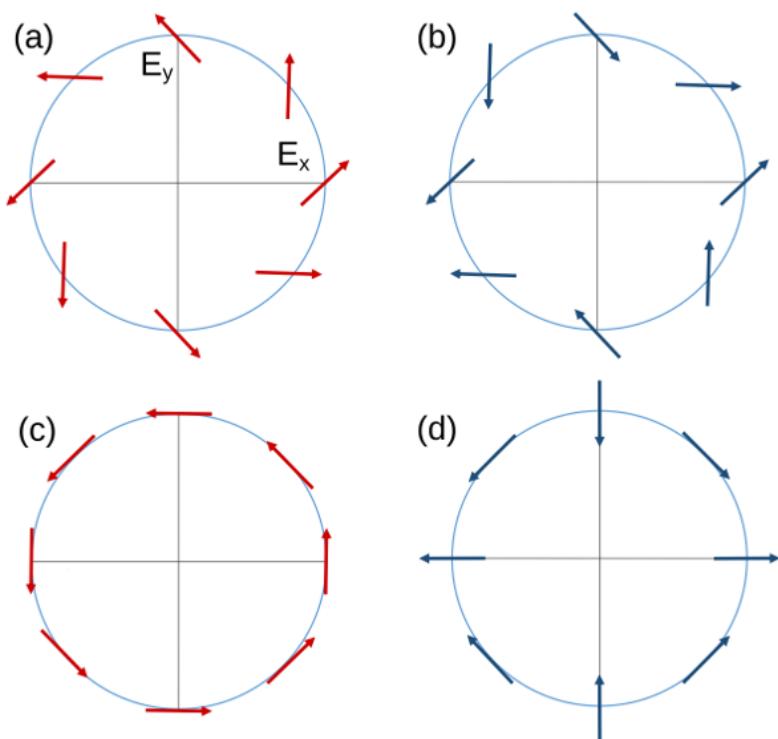


Figure 2.5: Electronic band structure

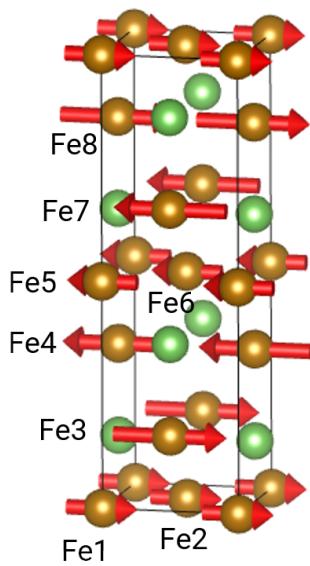


Figure 2.6: Electronic band structure

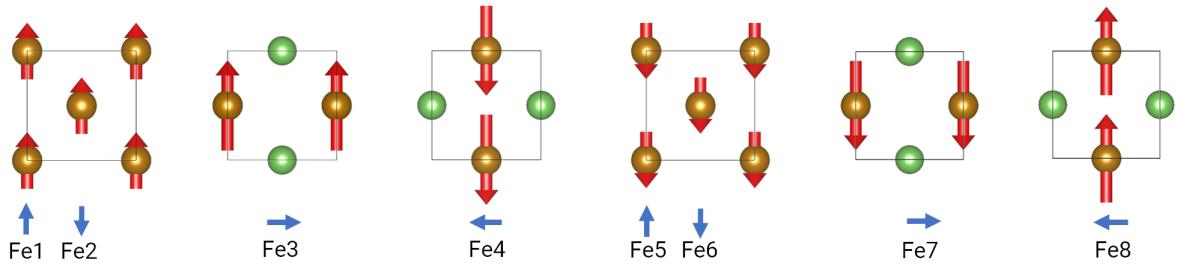


Figure 2.7: Electronic band structure

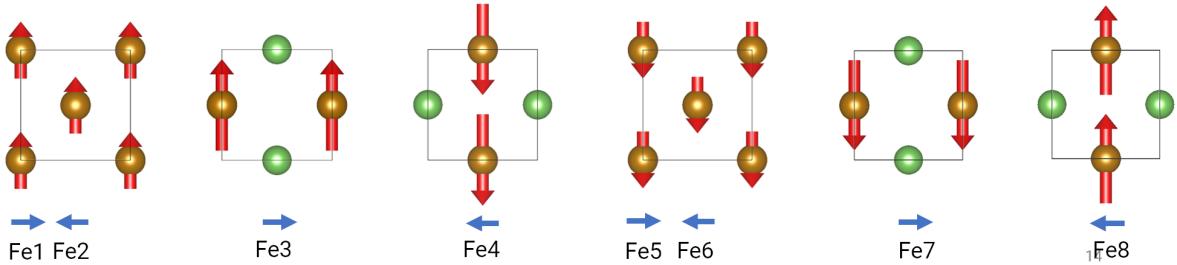


Figure 2.8: Electronic band structure

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Chapter 3

Magnetic structure refinement from neutron diffraction measurements

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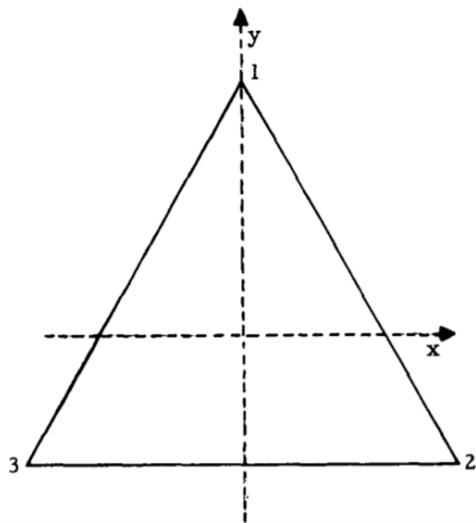


Figure 3.1: Electronic band structure

	E	C_3	C_3^2	σ_1	σ_2	σ_3
E	E	C_3	C_3^2	σ_1	σ_2	σ_3
C_3	C_3	C_3^2	E	σ_3	σ_1	σ_2
C_3^2	C_3^2	E	C_3	σ_2	σ_3	σ_1
σ_1	σ_1	σ_2	σ_3	E	C_3	C_3^2
σ_2	σ_2	σ_3	σ_1	C_3^2	E	C_3
σ_3	σ_3	σ_1	σ_2	C_3	C_3^2	E

Figure 3.2: Electronic band structure

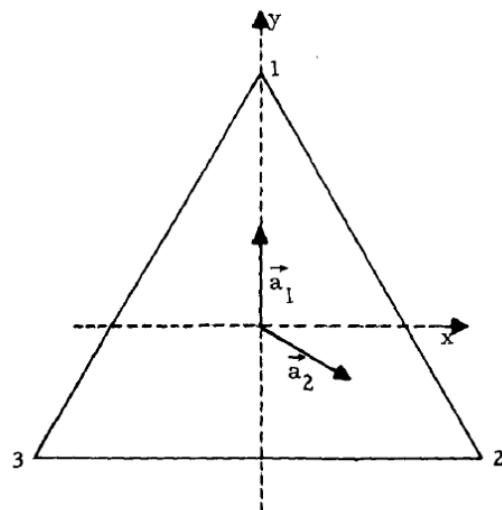


Figure 3.3: Electronic band structure

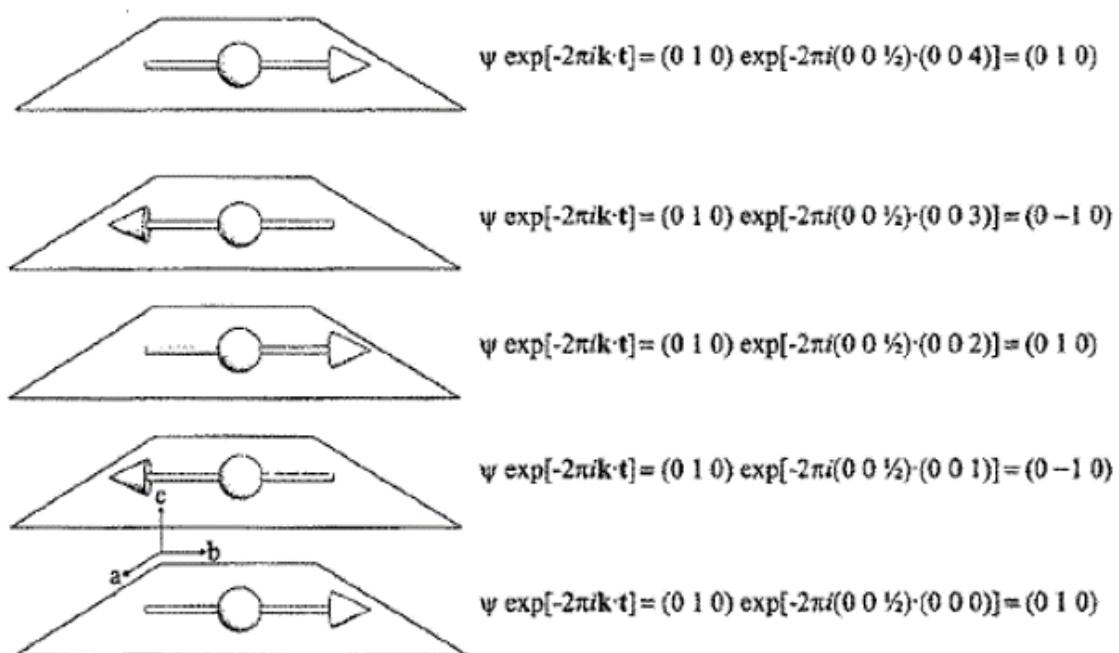


Figure 3.4: Electronic band structure

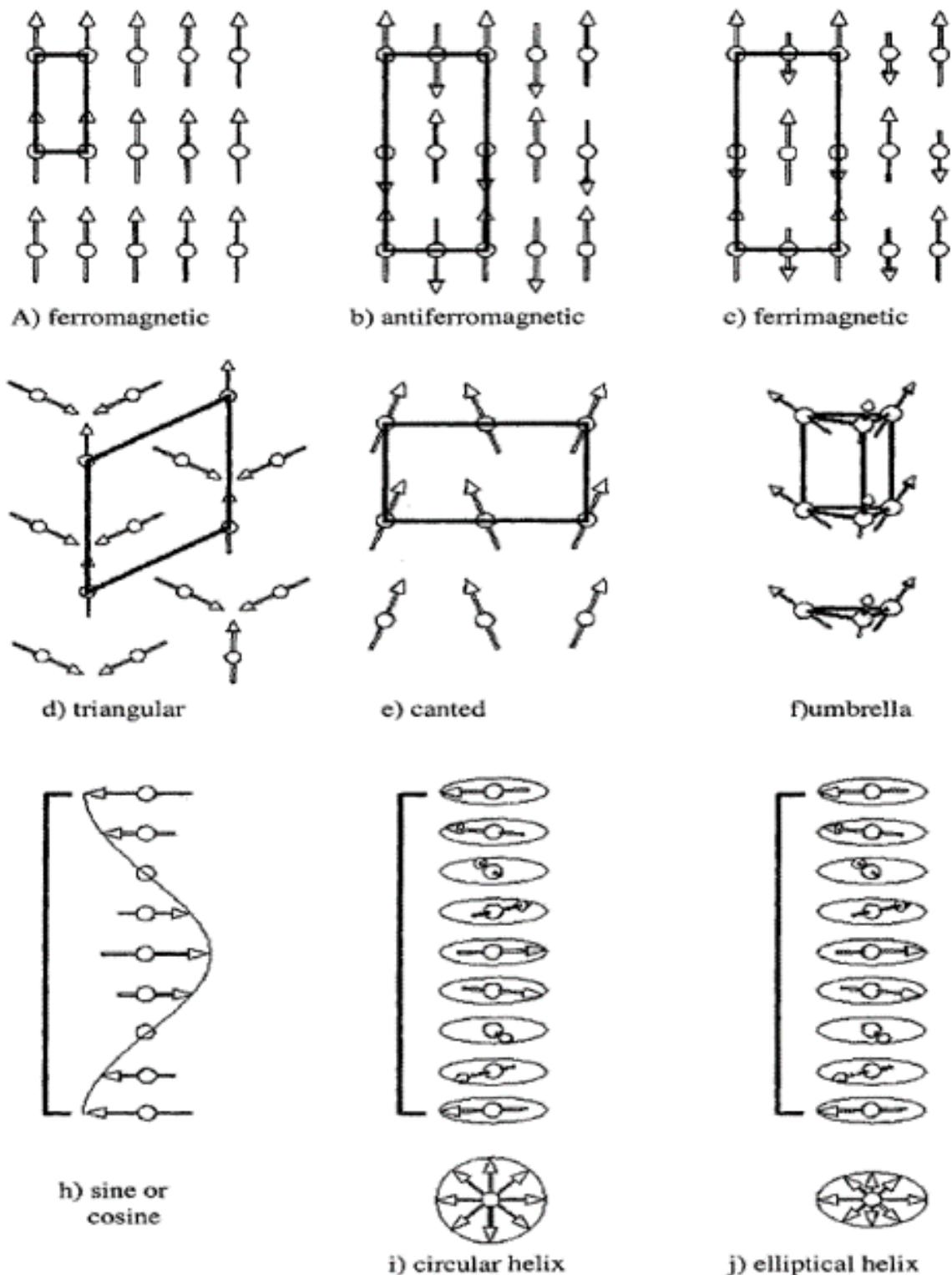


Figure 3.5: Electronic band structure

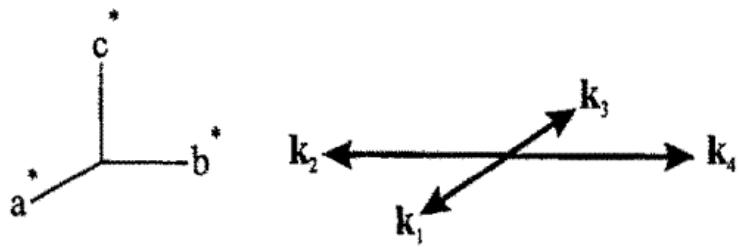


Figure 3.6: Electronic band structure

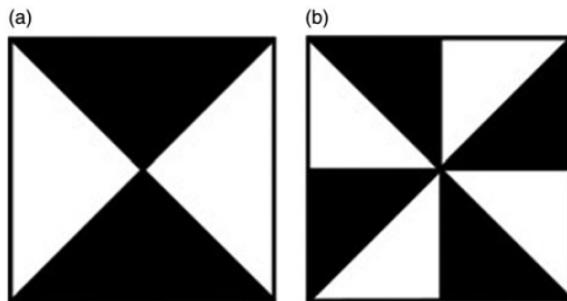


Figure 3.7: Electronic band structure

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Chapter 4

Materials synthesis and characterization

165 This is a citation to [1] and [2].

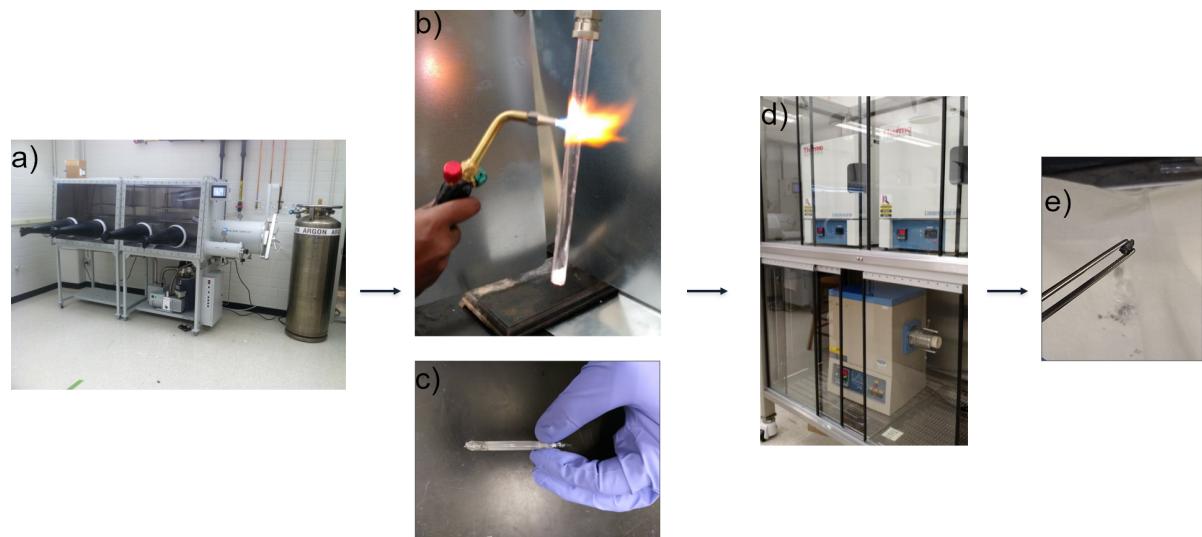


Figure 4.1: Electronic band structure

Chapter 5

Discovery and magnetic frustration of hexagonal Cu_{0.82}Mn_{1.18}As

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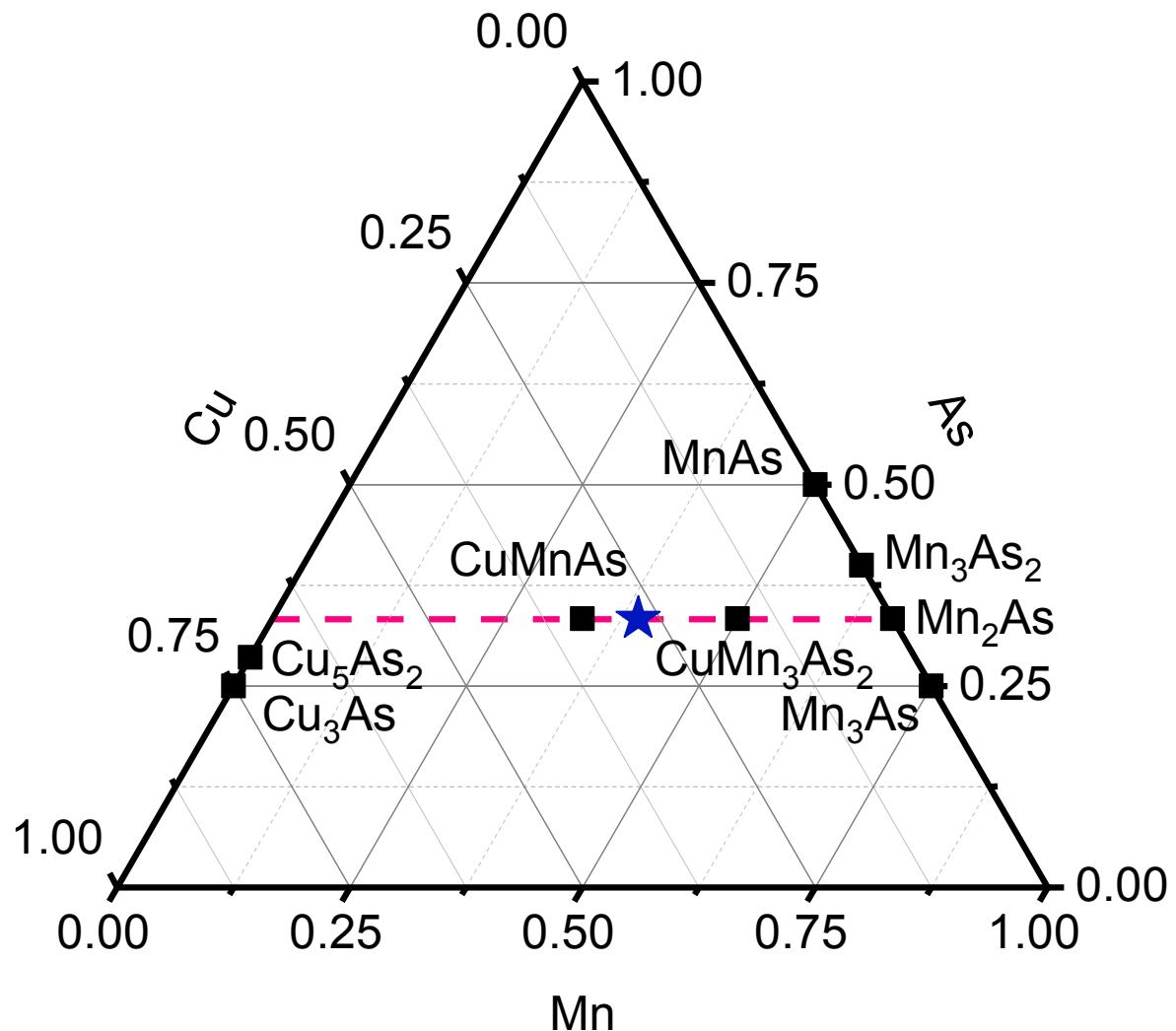


Figure 5.1: Electronic band structure

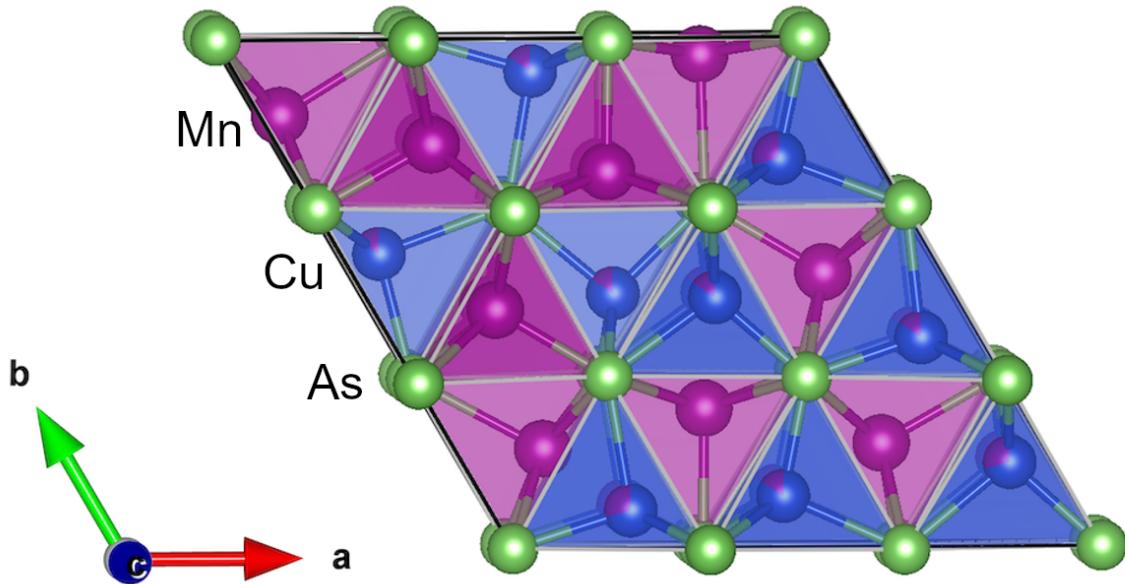


Figure 5.2: Electronic band structure

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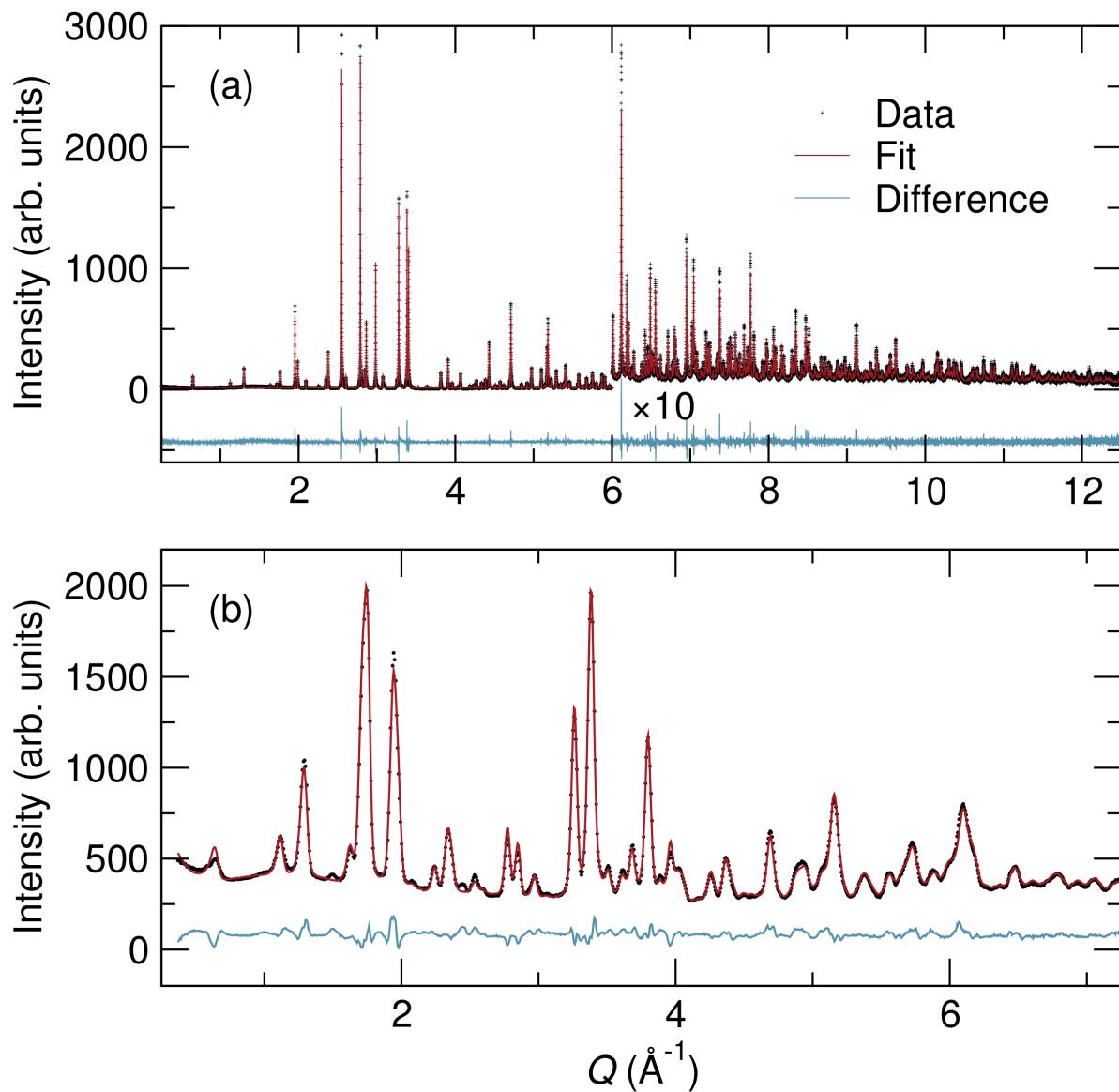


Figure 5.3: Electronic band structure

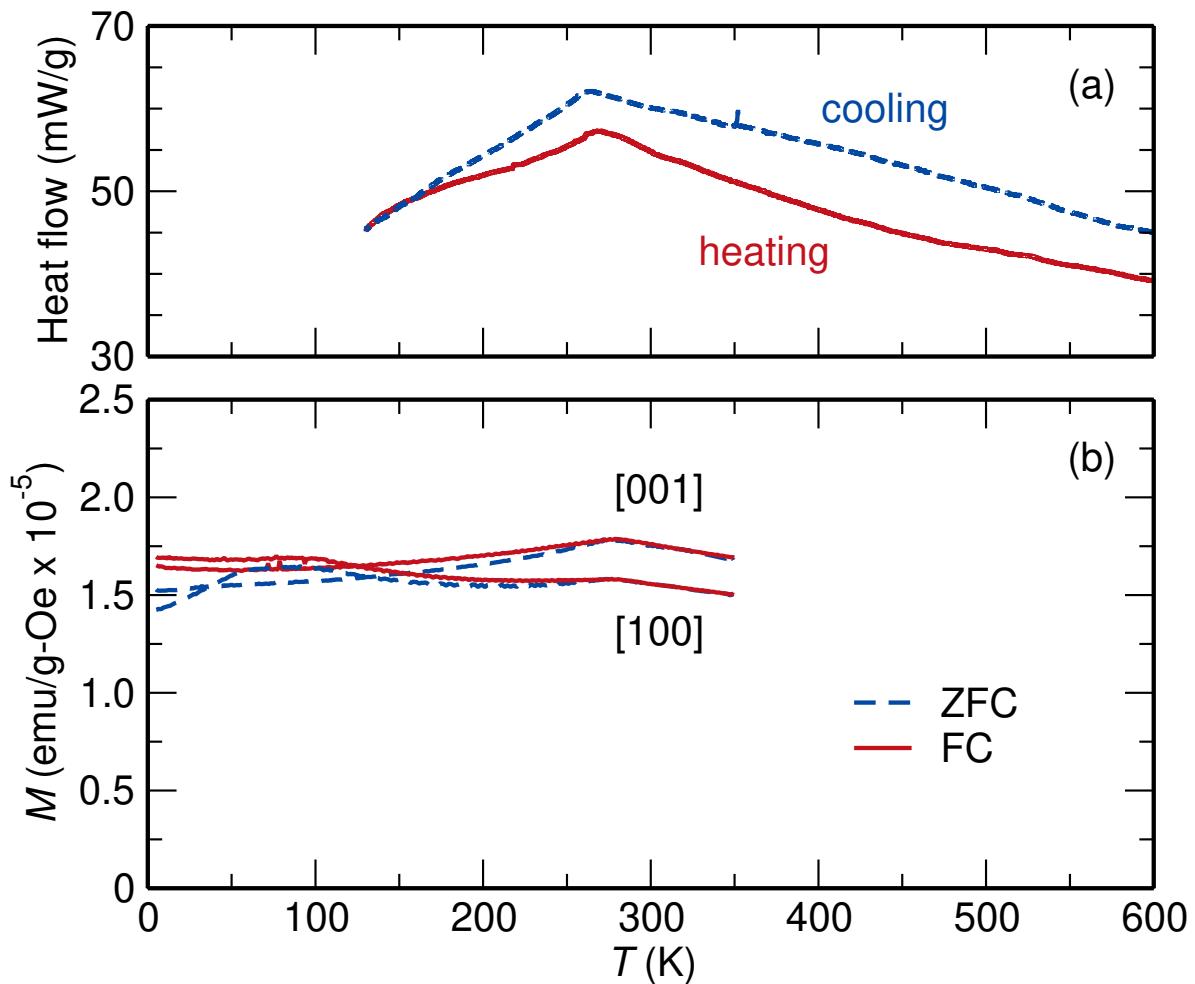


Figure 5.4: Electronic band structure

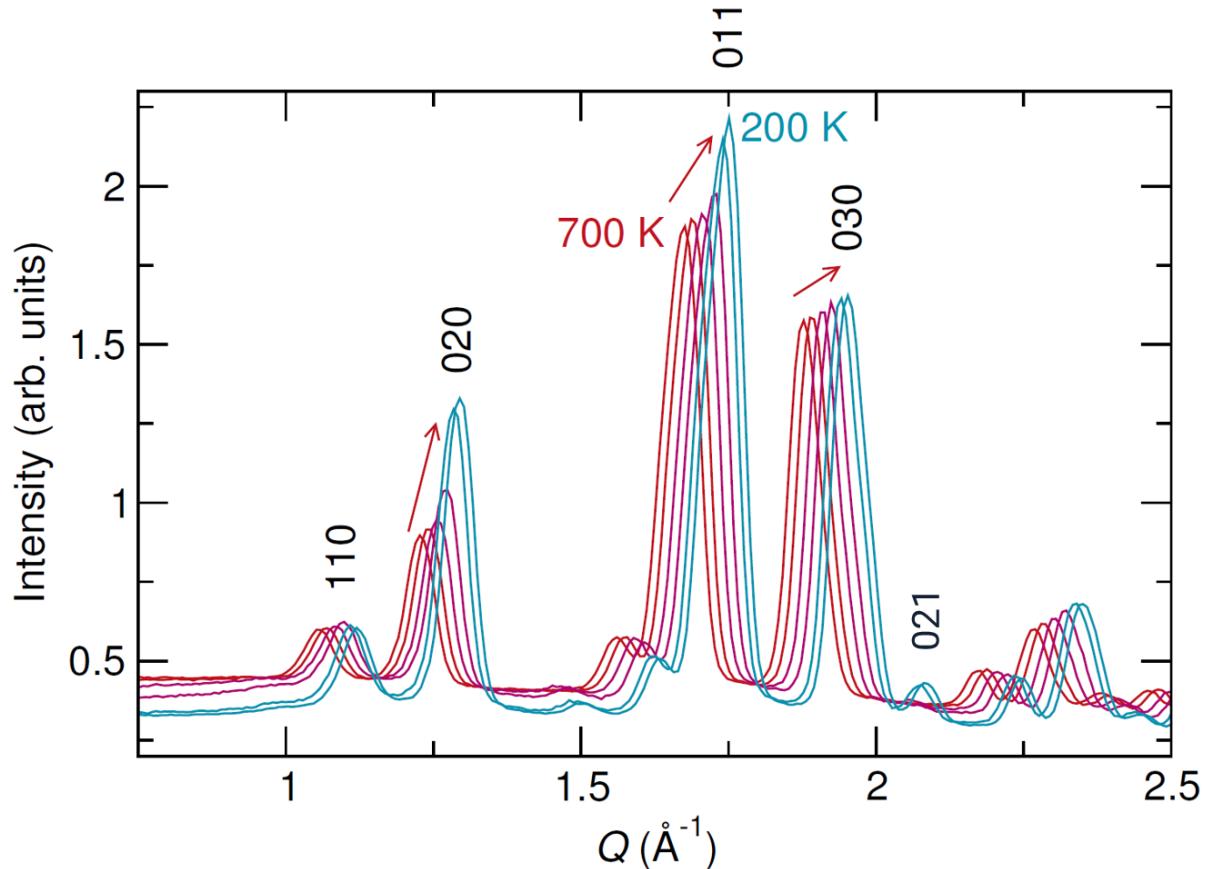


Figure 5.5: Electronic band structure

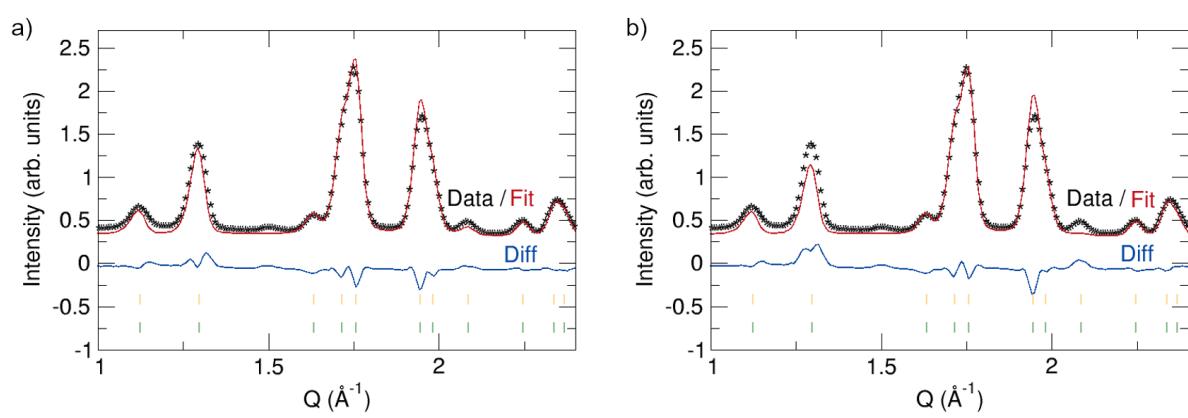


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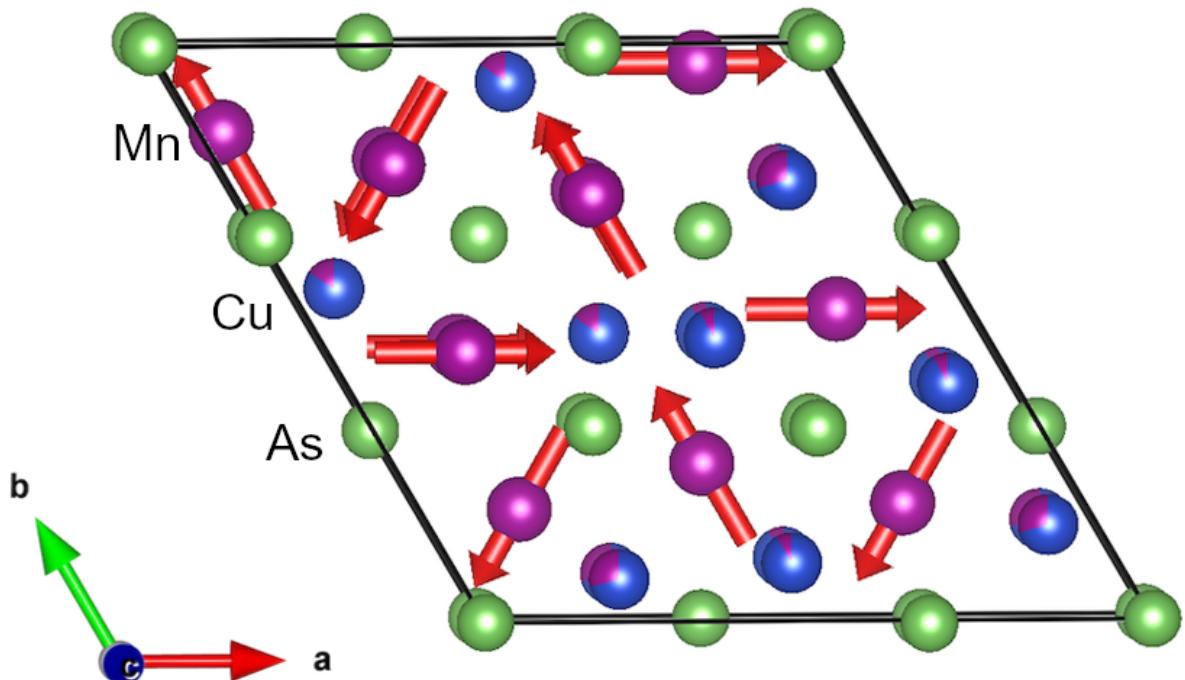


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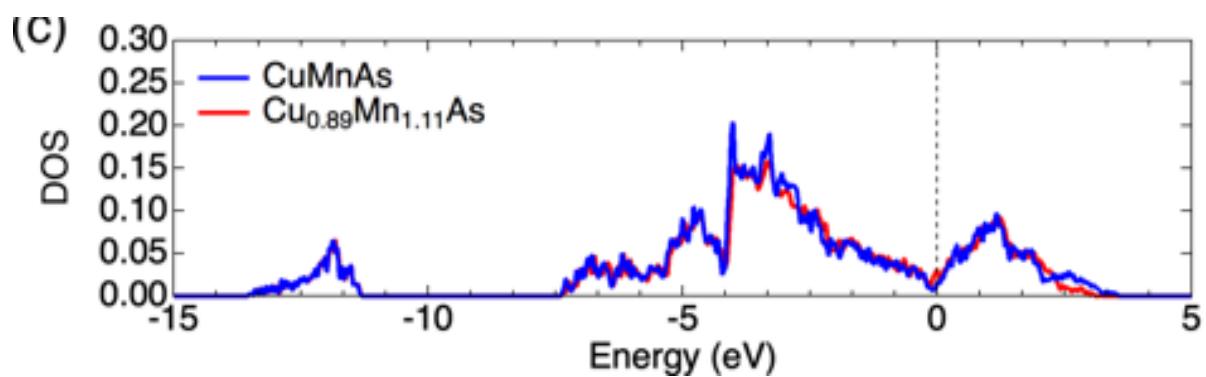


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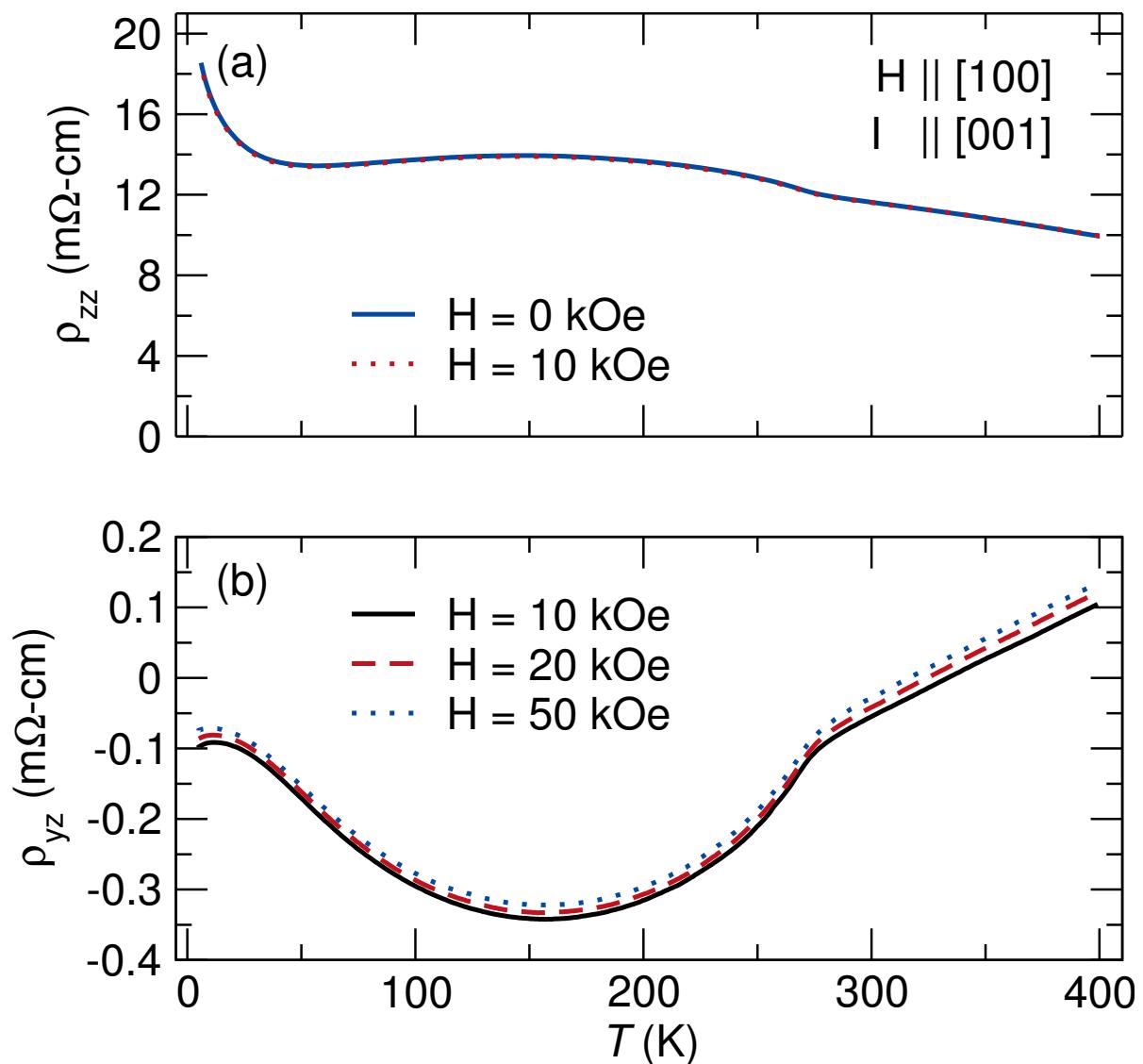


Figure 5.9: Electronic band structure

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Chapter 6

Two step magnetic ordering in monoclinic Mn₃As₂

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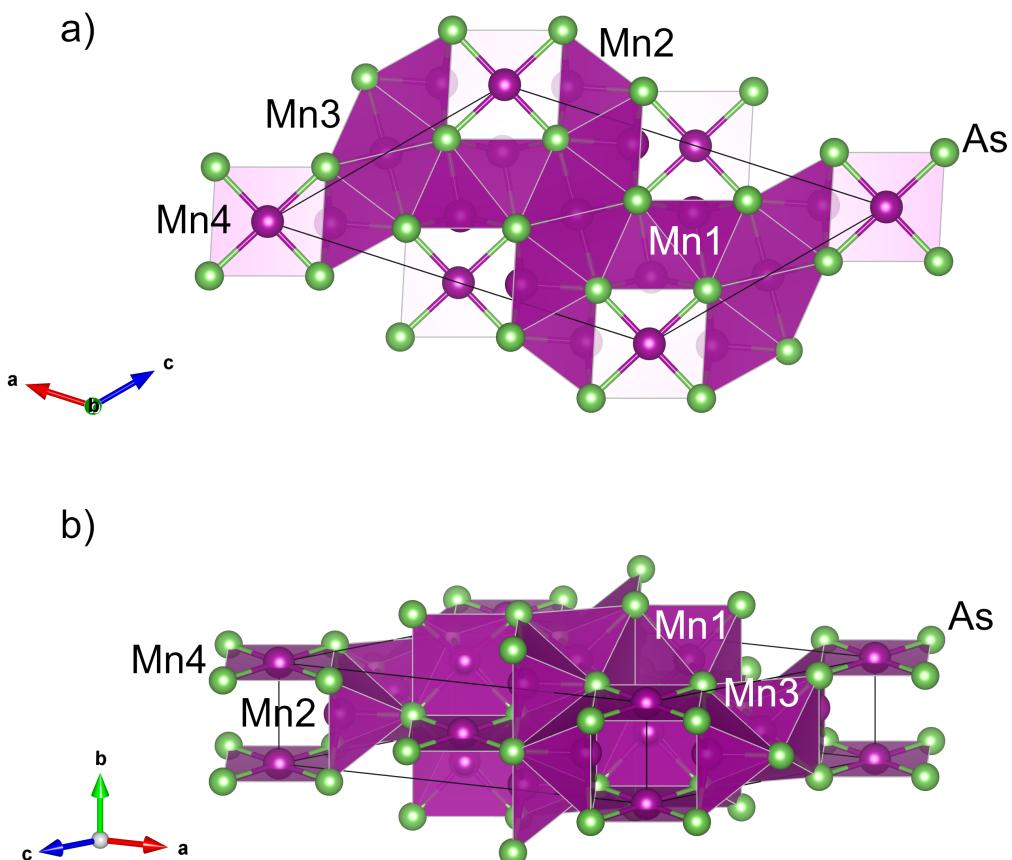


Figure 6.1: Electronic band structure

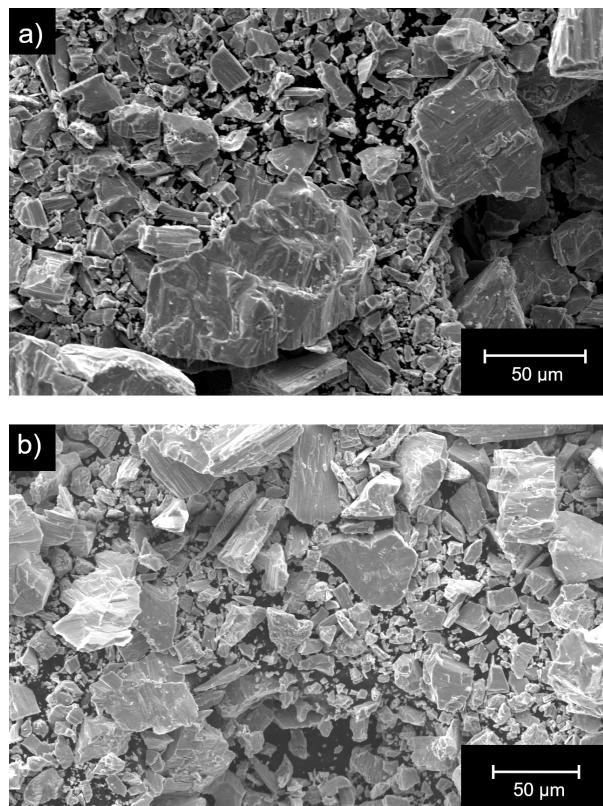


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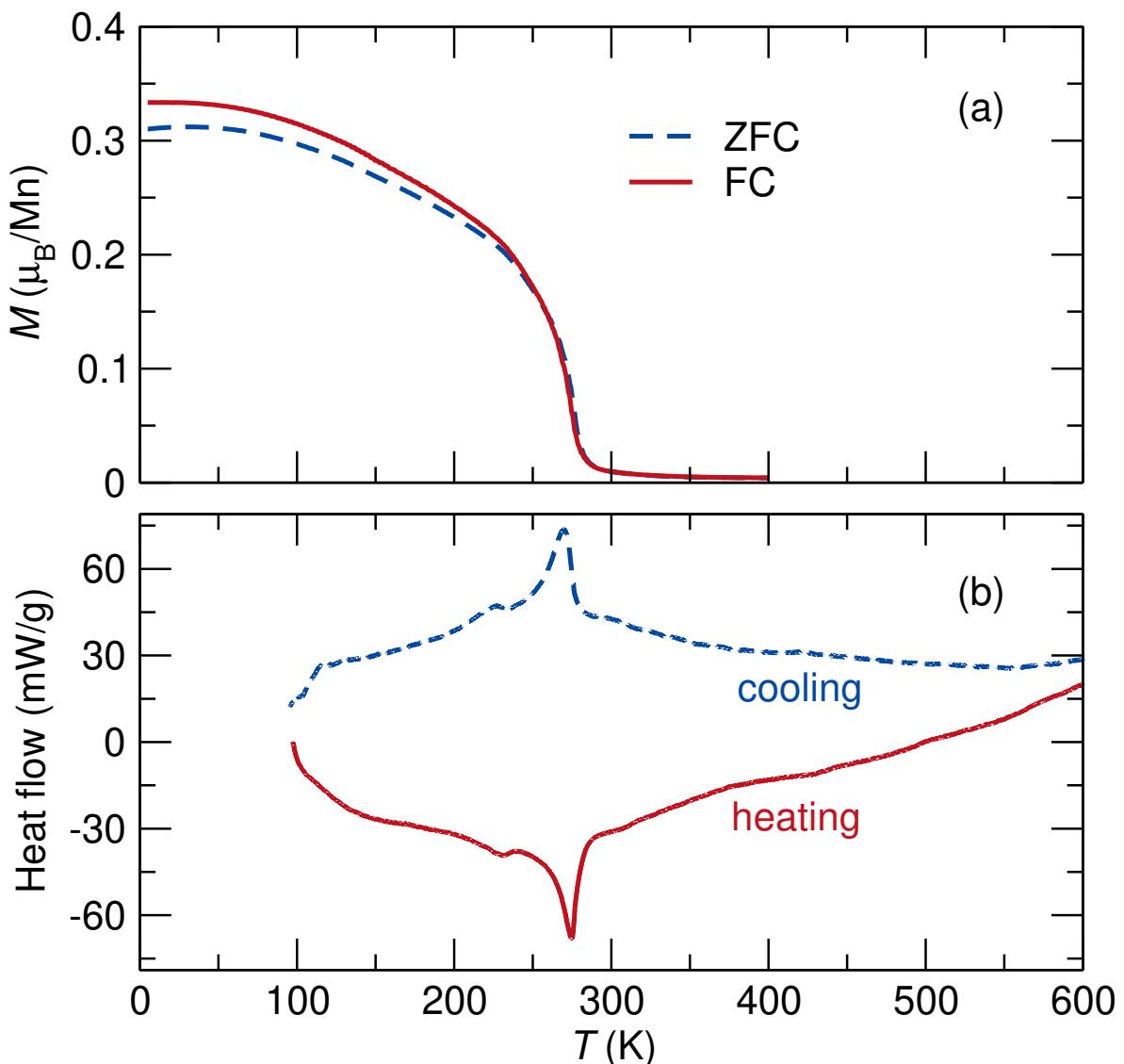


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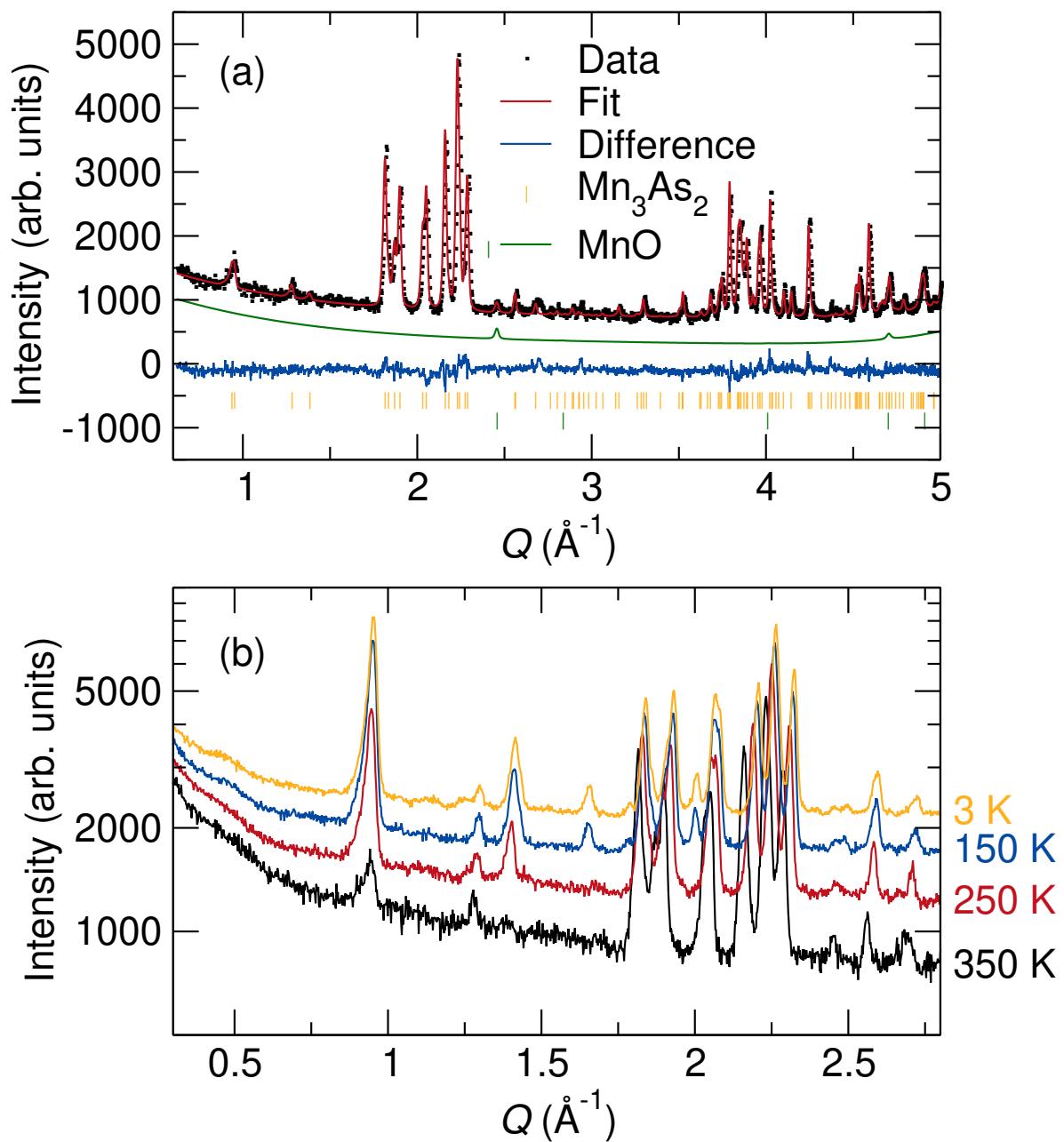


Figure 6.4: Electronic band structure

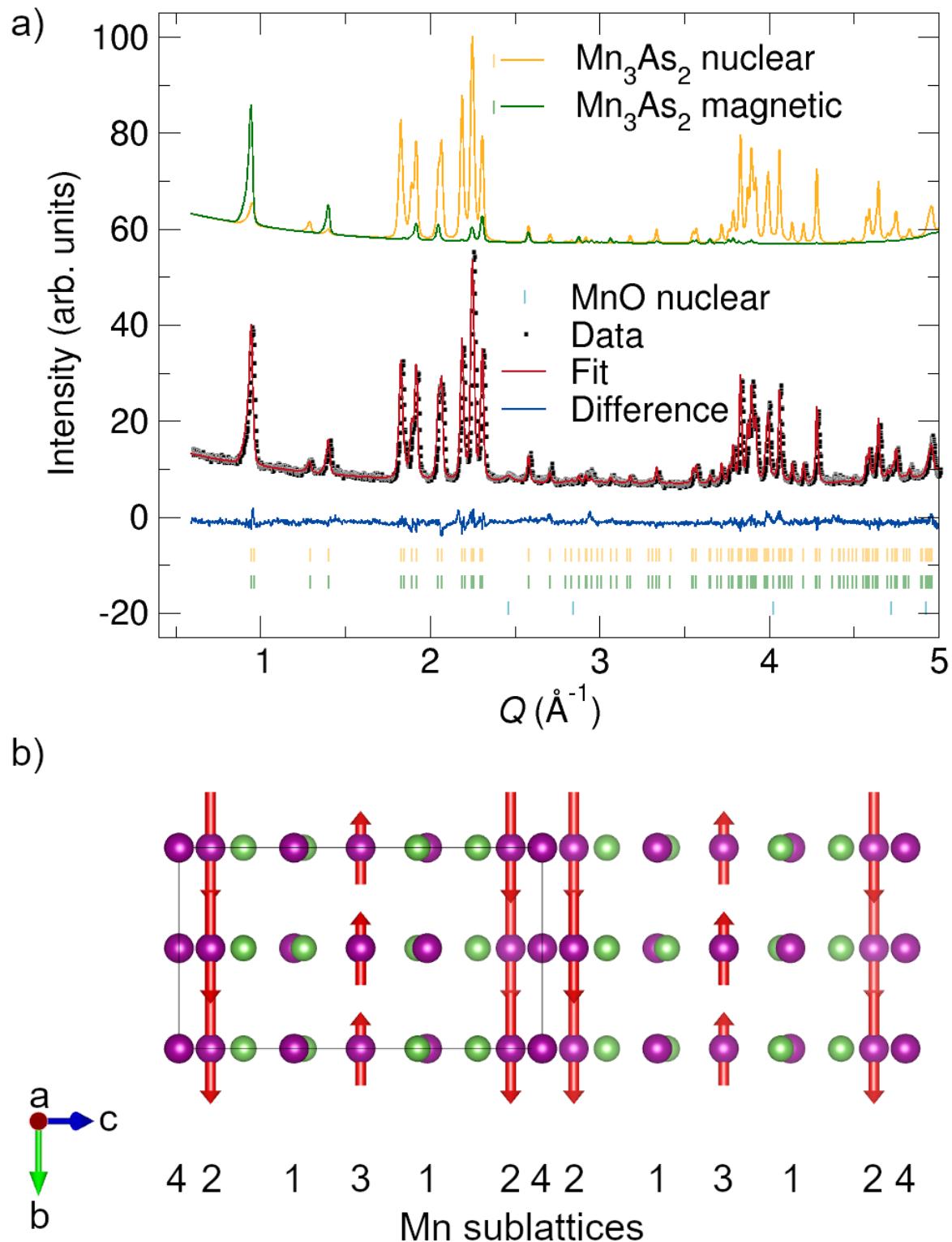


Figure 6.5: Electronic band structure

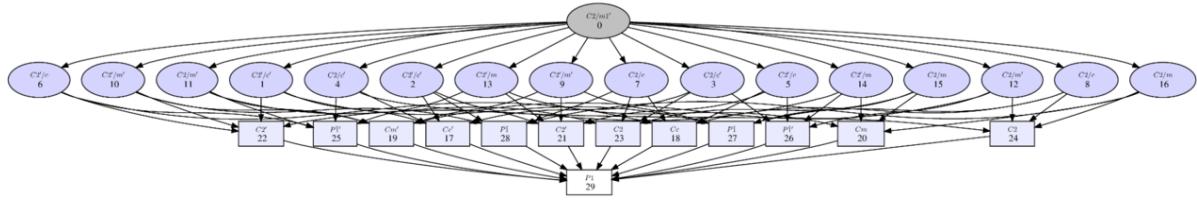


Figure 6.6: Electronic band structure

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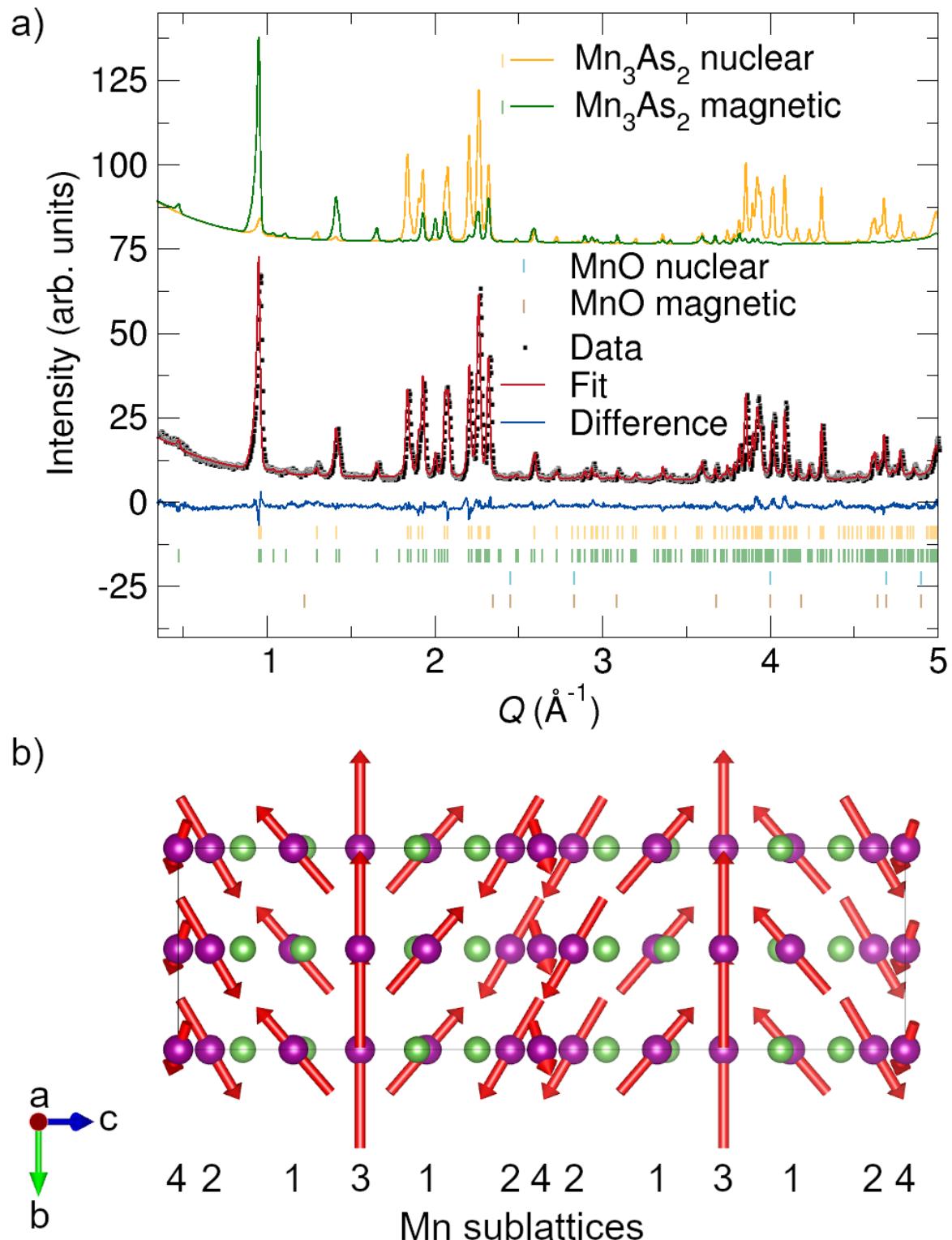


Figure 6.7: Electronic band structure

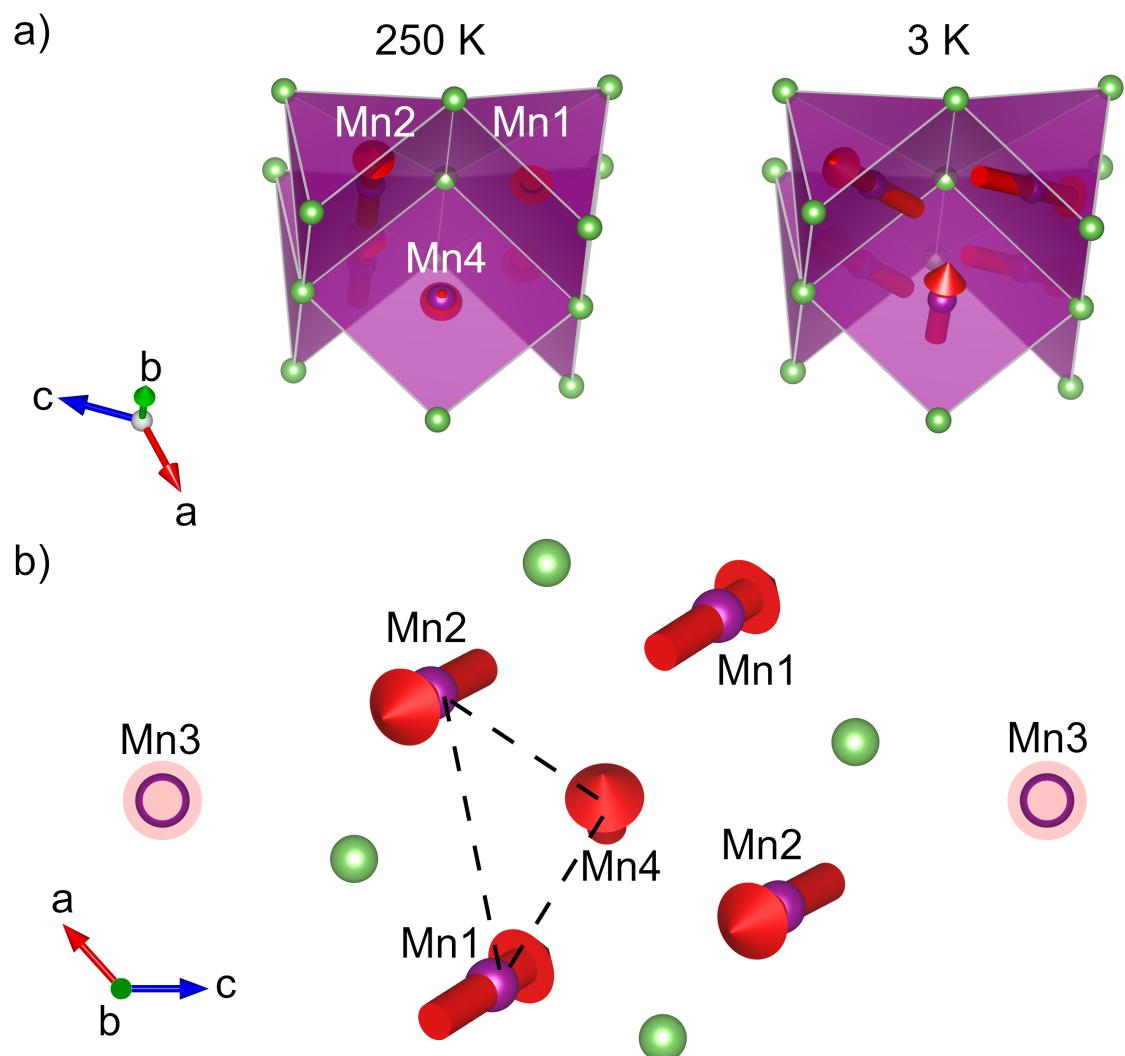


Figure 6.8: Electronic band structure

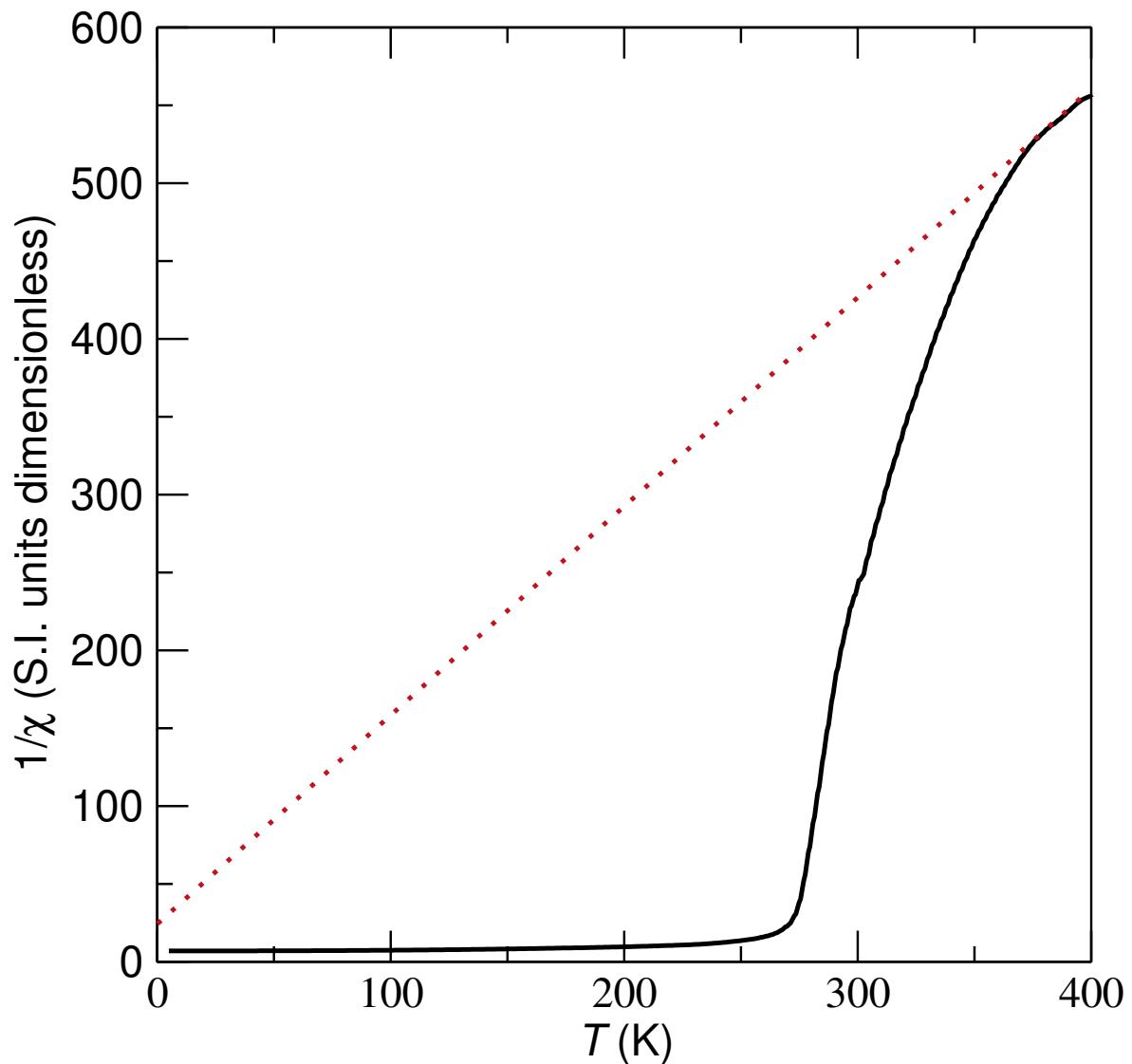


Figure 6.9: Electronic band structure

Chapter 7

Spin canting in tetragonal CuMnAs

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Chapter 8

Exchange interactions in Fe₂As probed by inelastic neutron scattering

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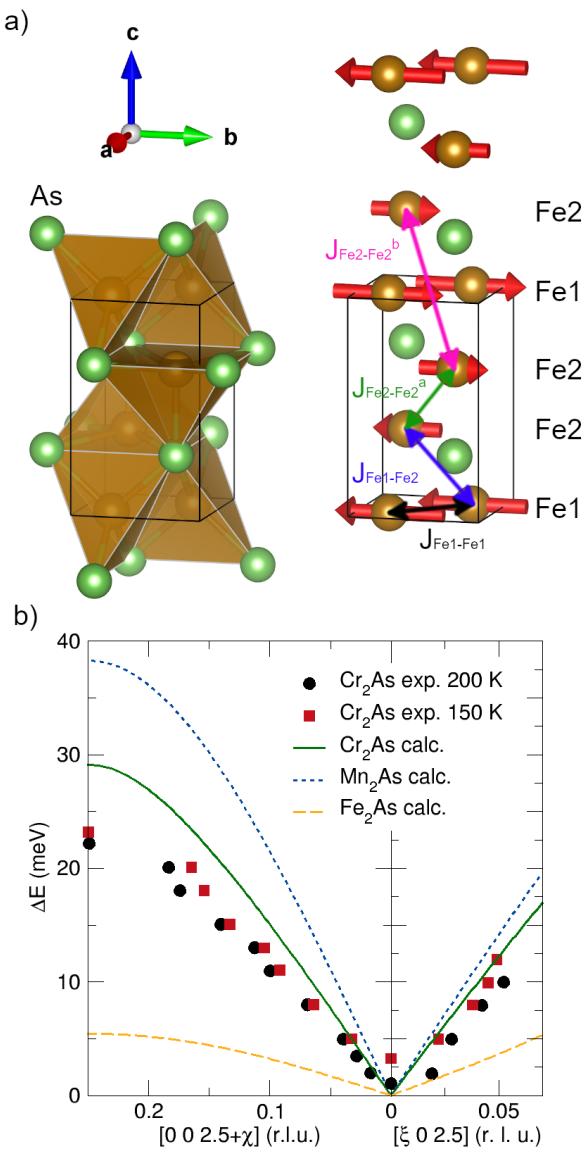


Figure 8.1: Electronic band structure



Figure 8.2: Electronic band structure

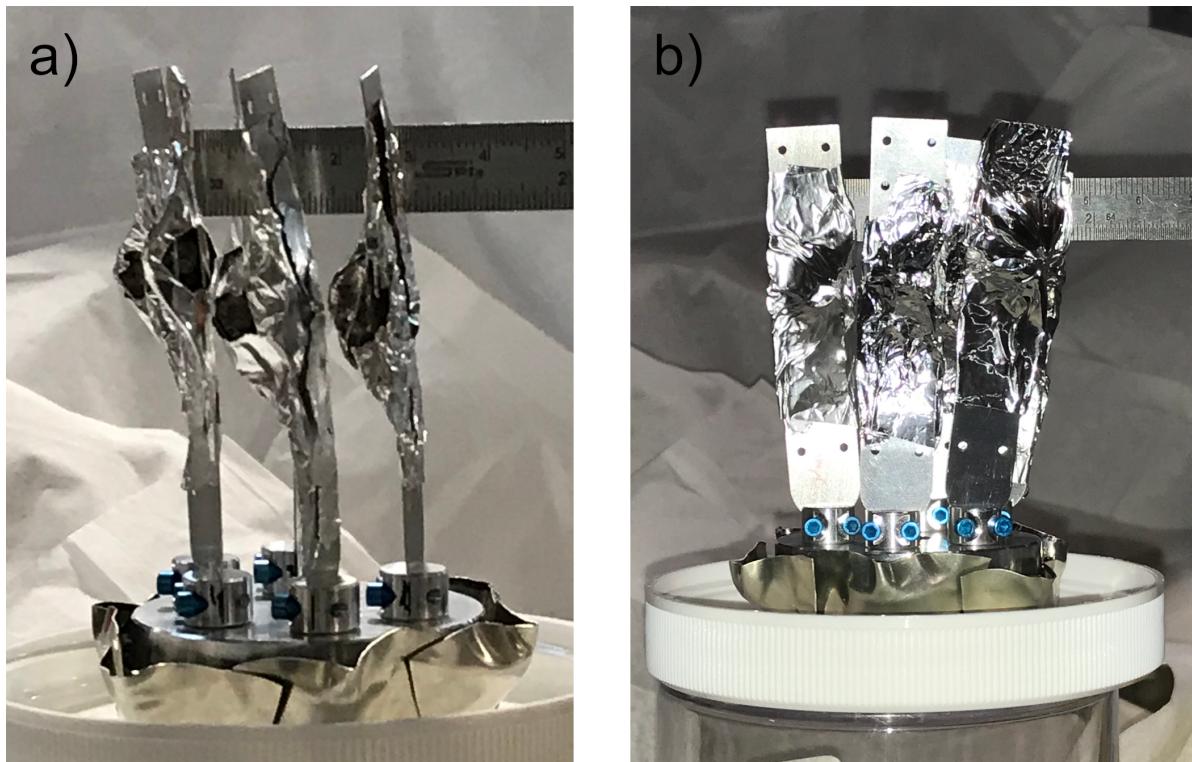


Figure 8.3: Electronic band structure

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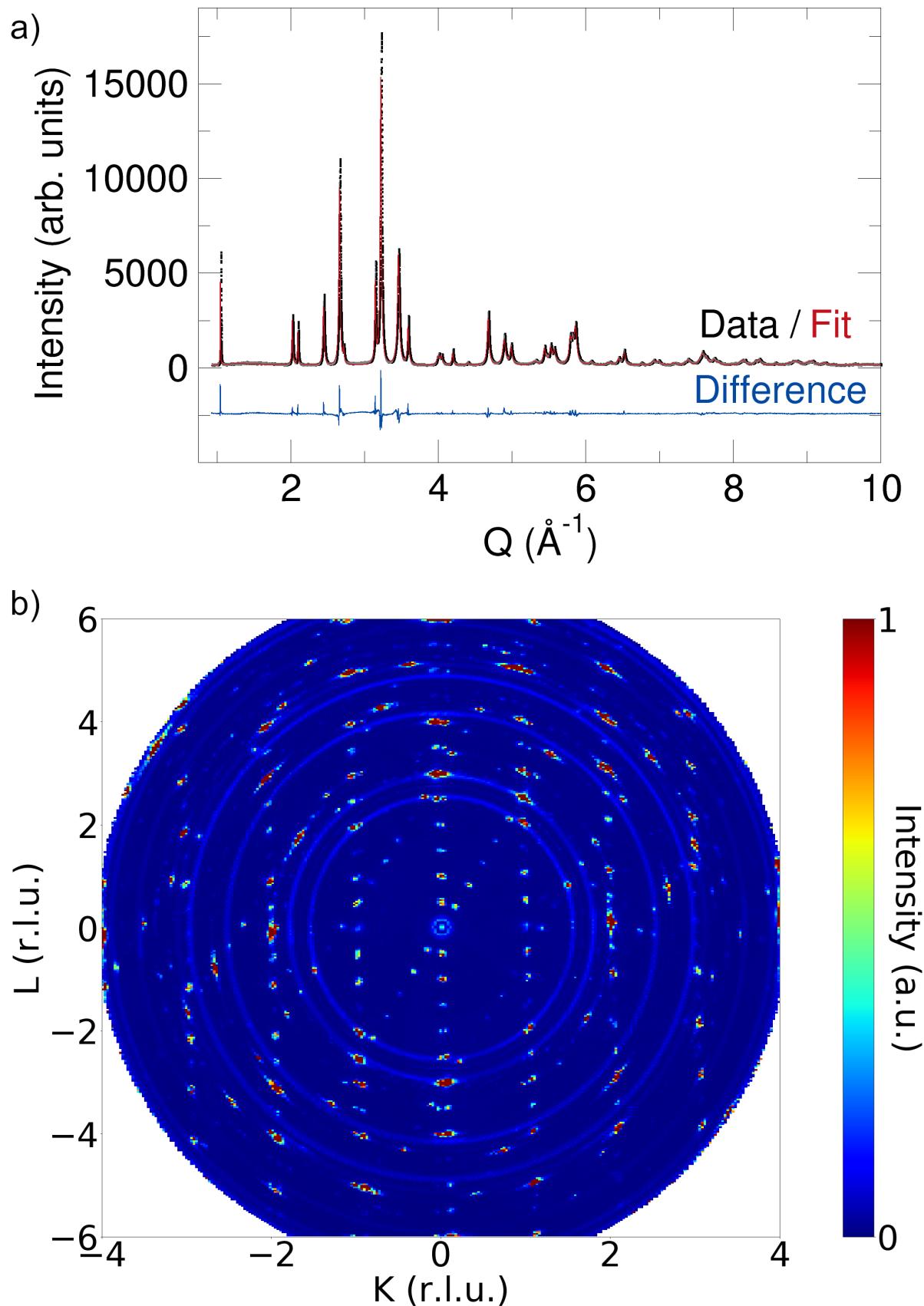


Figure 8.4: Electronic band structure

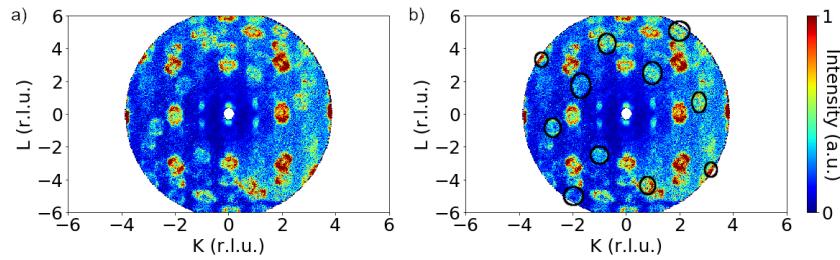


Figure 8.5: Electronic band structure

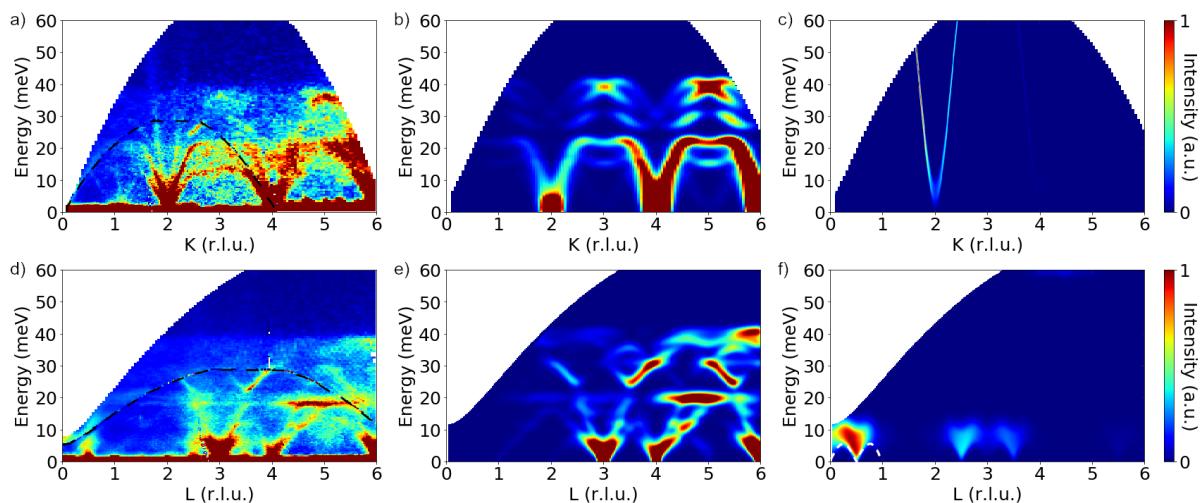


Figure 8.6: Electronic band structure

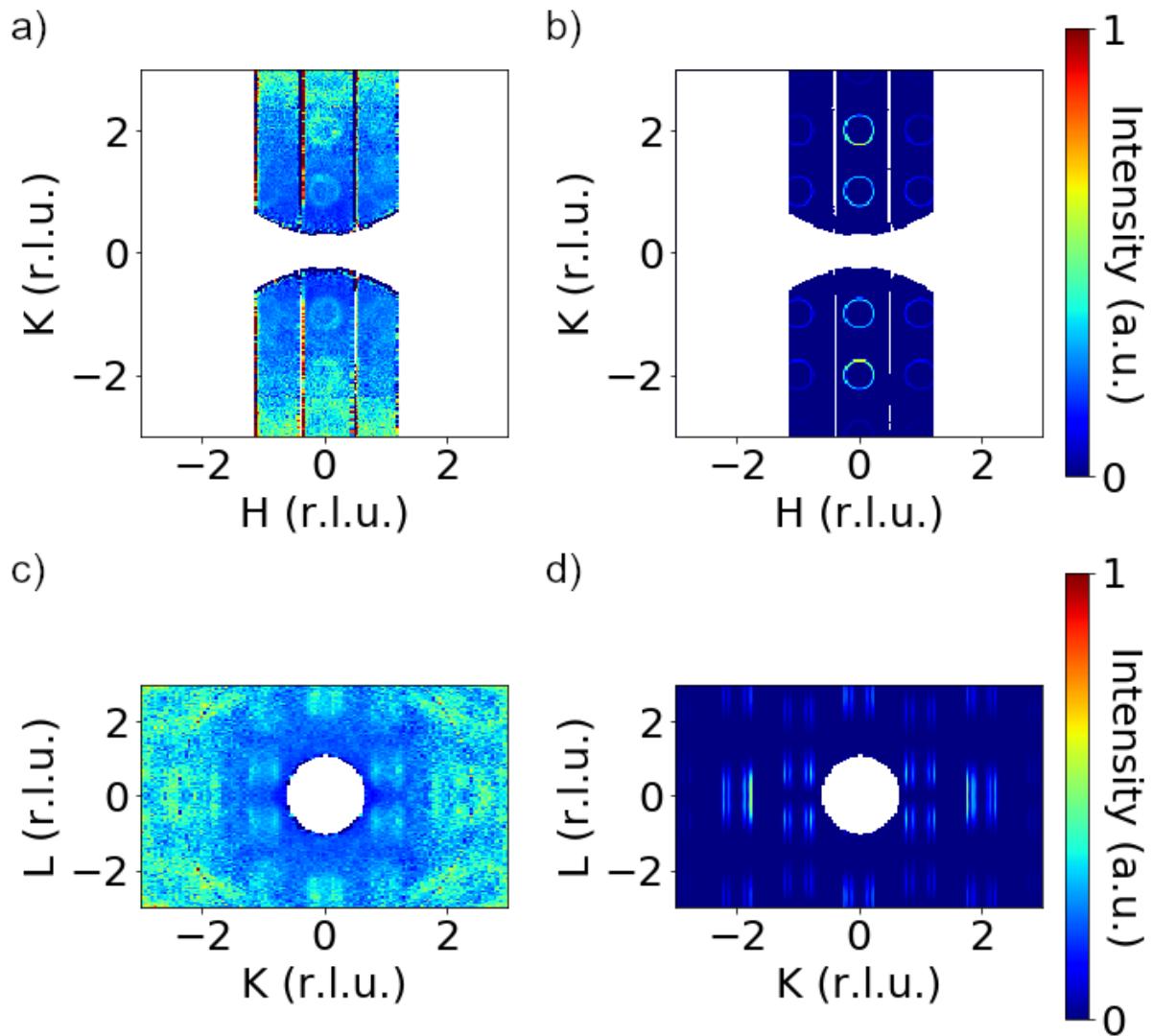


Figure 8.7: Electronic band structure

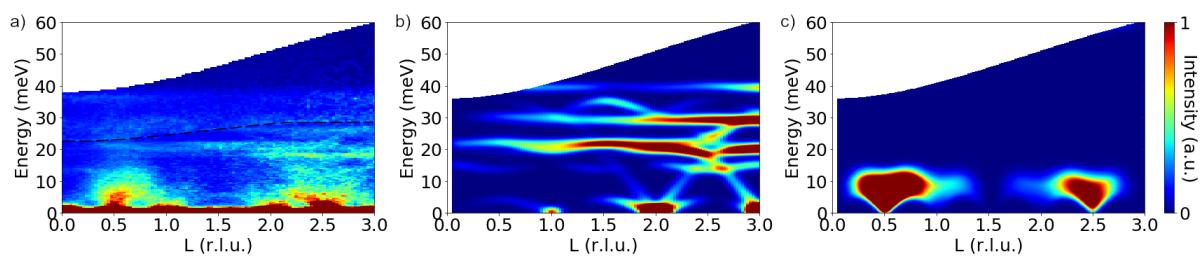


Figure 8.8: Electronic band structure

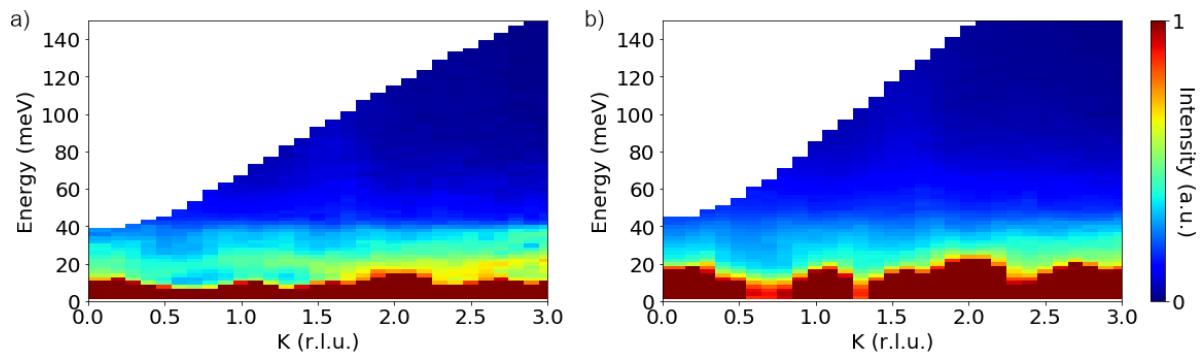


Figure 8.9: Electronic band structure

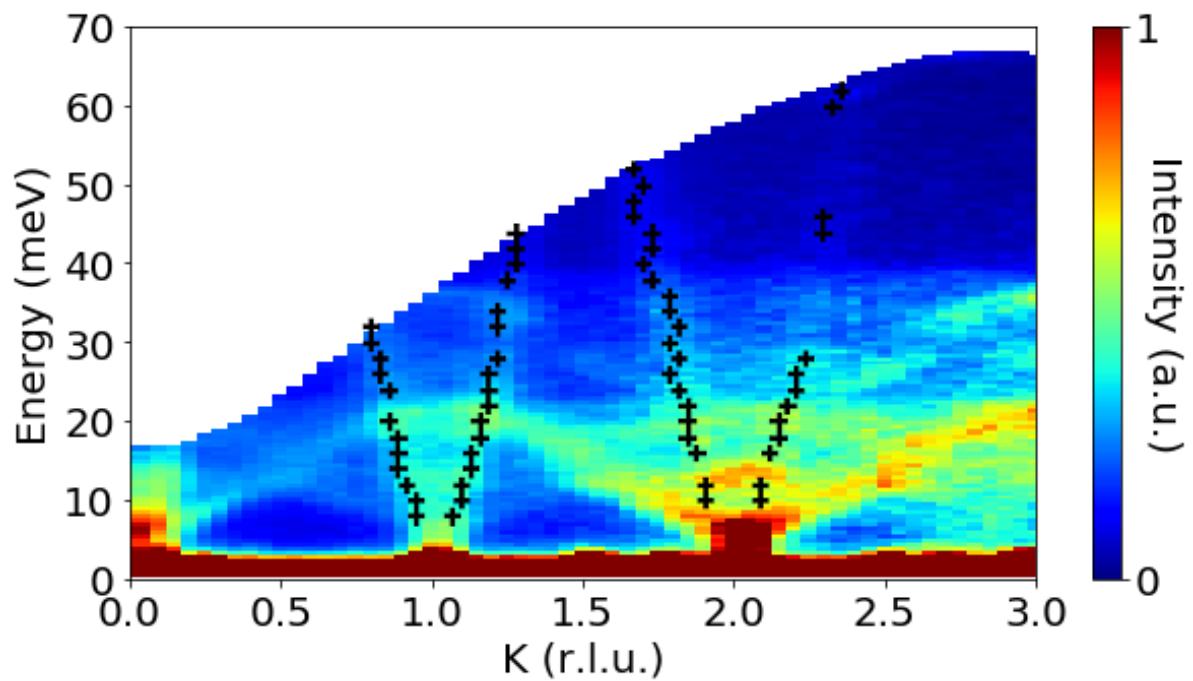


Figure 8.10: Electronic band structure

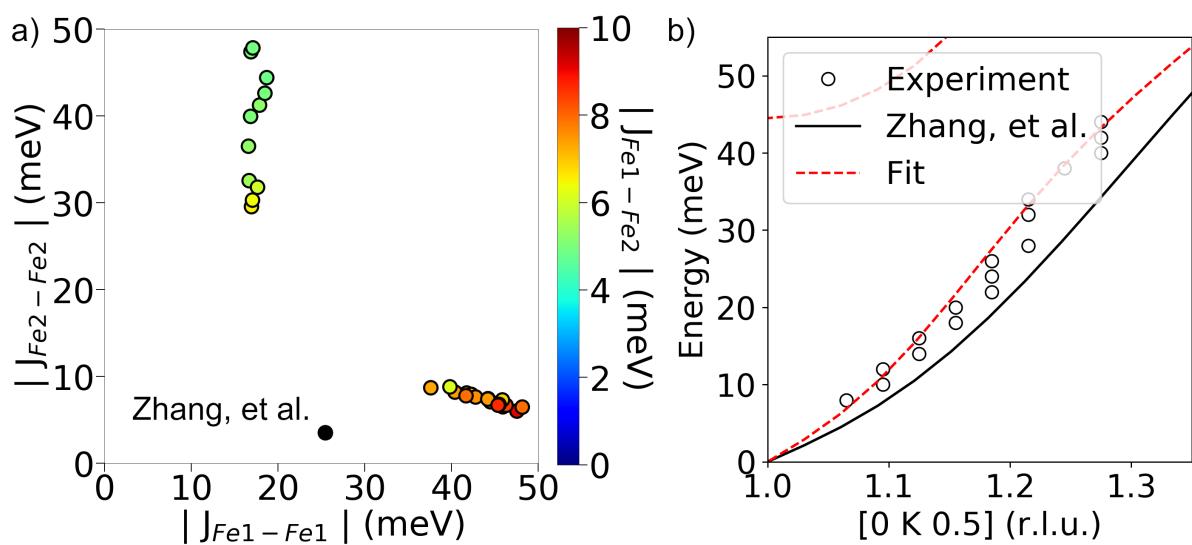


Figure 8.11: Electronic band structure

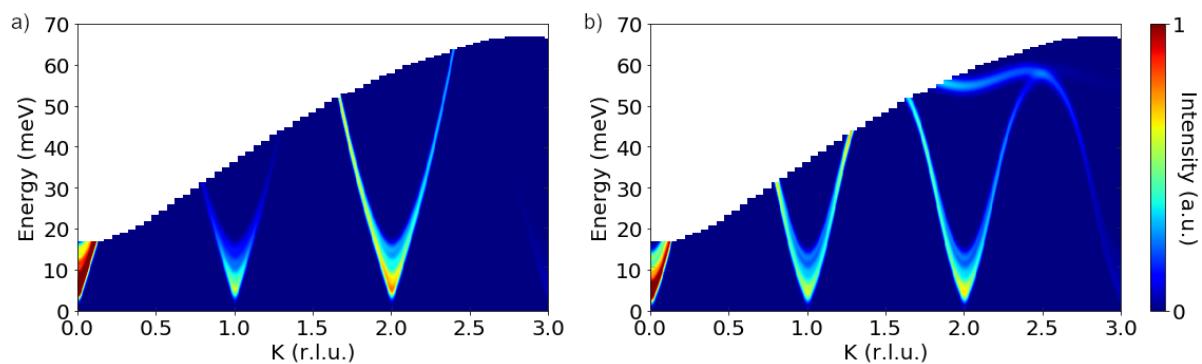


Figure 8.12: Electronic band structure

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Chapter 9

Conclusions

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References

- [1] S. W. Walker, *The Shape of Things: A Practical Guide to Differential Geometry and the Shape Derivative*. SIAM, 2015.
- [2] W. W. Hager and H. Zhang, “Algorithm 851: CG DESCENT, a conjugate gradient method with guaranteed descent,” *ACM Transactions on Mathematical Software*, vol. 32, pp. 113–137, 2006.