Hello readers! This post is about antiferromagnets. I talk about the general concepts in antiferromagnetism and then later I dive into some interesting complex antiferromagnetic states. I hope you have a good read! Please feel free to reach me out at my email for any further questions! (*vsaxena@physnet.uni-hamburg.de*)

ANTIFERROMAGNETISM

The most popular class of magnetic materials is a ferromagnet. In ferromagnets there are many regions where the magnetic moments of neighbouring atoms are aligned parallel to each other. These regions are called as domains. Each domain has all the magnetic moments aligned in the same direction. And when an external magnetic field is applied, all the domains align their magnetisation direction with the applied field's direction - a characteristic exhibited by ferromagnets.

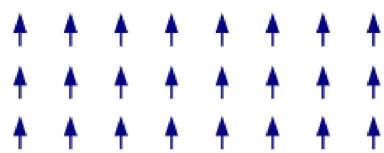

Figure 1 An ideal schematic of a ferromagnet, where all the spins are aligned in the same direction (Wikipedia)

Governing equation: Heisenberg exchange, **J > 0**

$$H = J_{i,j} \sum_{i \neq j} \vec{S_i} . \vec{S_j}$$

Amongst many applications, ferromagnets have been heavily used in devices for memory storage[1]. But one problem that ferromagnetic based devices cannot avoid is the effect of external unwanted magnetic fields. If the device comes in a region with a sufficiently high magnetic field, it's magnetisation can easily get affected by it and the device can stop working!

To overcome this problem, antiferromagnetic materials came into the limelight. A lot of research began on antiferromagnets and is still a very hot topic of research at the fundamental and applied level[2].

Fun fact: Iron (Fe) is widely known for being ferromagnetic. But at ultra-thin layer thickness, Fe is an antiferromagnet! *Kubetzka A. et al., "Revealing antiferromagnetic order of the Fe monolayer on W001: Spin-polarized scanning tunnelling microscopy and first-principles calculations," Phys. Rev. Lett. 94, 087204, 20051*

So what does an antiferromagnet look like?

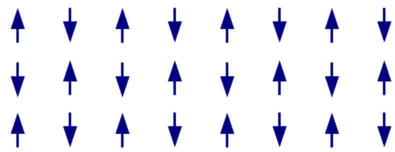

Figure 2 An ideal antiferromagnet - can be viewed as two interpenetrating ferromagnetic sublattices (Wikipedia)

This is an ideal picture of an antiferromagnet where the net magnetisation is zero. It can also be viewed as two interpenetrating ferromagnetic sublattices with opposite magnetisation.

Governing equation: Heisenberg exchange, **J < 0**

$$\boldsymbol{H} = \boldsymbol{J_{i,j}} \sum_{i \neq j} \overrightarrow{\boldsymbol{S_i}} . \overrightarrow{\boldsymbol{S_j}}$$

To see the beauty of antiferromagnetism and the interesting physics that it provides us with, we would have to go to the **atomic level**. Considering a simple triangular lattice geometry, we will try to see how can we place spins on each site with an antiferromagnetic coupling.

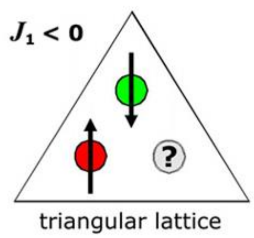

Figure 3 Antiferromagnetic coupling on a hexagonal lattice[5] Reprinted with permission from Ref. [5], Copyright 2014, IOP Publishing.

It turns out that the third spin is not parallel or anti-parallel to the other two spins due to geometric frustration. And as a result what happens is that the spins cant and are now at an angle of 120^0 with each other. This is the lowest energy spin configuration in this geometry in an ideal case, when we consider only the interaction between nearest neighbour spins. This is called as the **Néel state**.

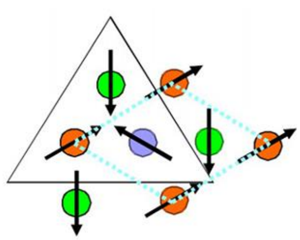

Figure 4 Néel state - the spins are at an angle of 120^0 to each other[5] Reprinted with permission from Ref. [5], Copyright 2014, IOP Publishing.

A very simple yet interesting thought that can come to the reader would be how to determine the spin state of a magnetic moment in an antiferromagnet. With respect to this, a very interesting experimental study performed by scientists at IBM was where they studied a chain of 8 Fe atoms on a Cu_2N overlayer on Cu(100) using a spin-polarized STM!

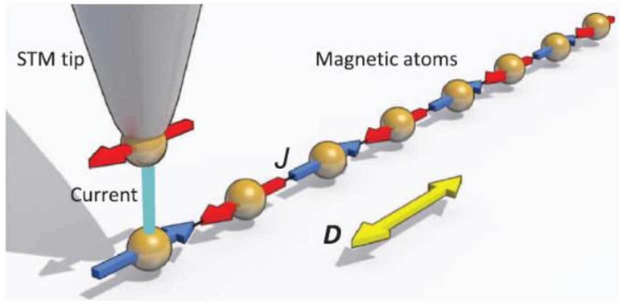

Figure 5 Schematic showing the spin dependent tunnelling of a spin-polarized STM tip. The spin-polarized tip is used to probe the magnetic state of the chain of 8 Fe atoms. Reprinted with permission from Ref. [3],Copyright © 2012, American Association for the Advancement of Science..

Let me briefly explain how does spin-polarized scanning tunnelling microscopy (SP-STM) work. A normal STM tip is coated with a few monolayers of a magnetic material such as Iron. And then this tip has a certain magnetization at the apex (*Figure 5)*. This magnetization can be controlled by applying an external magnetic field. So the researchers arranged 8 atoms of Fe on an overlayer

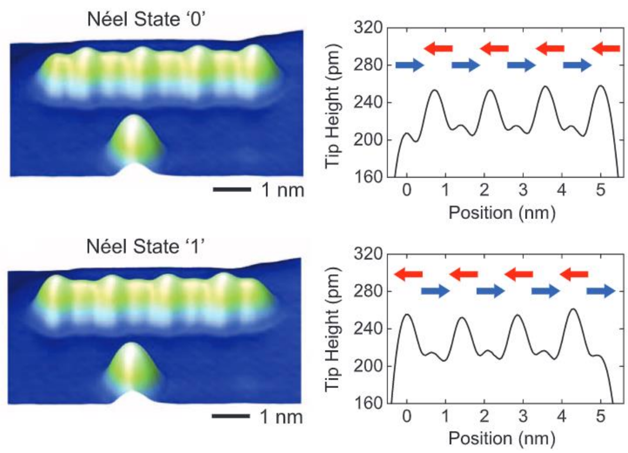

Figure 6 linear chain of eight Fe atoms assembled on a Cu2N overlayer on Cu(100). Top row - showing the Néel state '0' and the corresponding SP-STM line profile. Bottom row – showing the Néel state '1' and the corresponding SP-STM line profile. Reprinted with permission from Ref. [3], Copyright © 2012, American Association for the Advancement of Science.

of Cu_2N on Cu(100) surface[3]. And then they did a scan (took an image) and saw bright and dark lines corresponding to alternating spins of the Fe atoms. In the next step, they took the STM tip and placed it on top of one of the Fe atoms and applied a small voltage pulse of 7mV. And again, then they did a scan (took an image).

Now, the magnetic contrast was opposite to that observed in the first case, i.e. prior to applying the voltage pulse. This tells us that there is an energy barrier between the 2 spin states which can be switched by giving it the required energy (*Figure 6*). But it should be kept in mind that it is not easy to do it for any AFM material as there are other factors too[3].

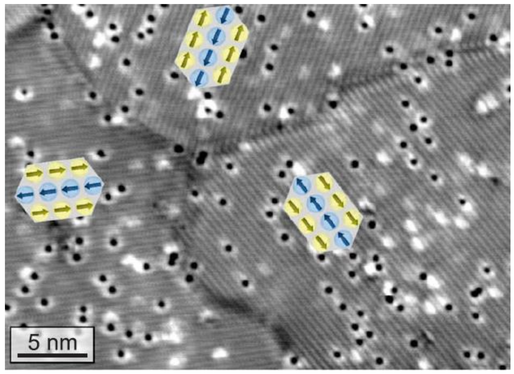

Figure 7 SP-STM image showing the three rotational domains of the RW-AFM state observed for a monolayer of Mn or Re(0001). The schematic of the RW-AFM is placed over the corresponding domains.[4]

Now, if we go beyond the nearest neighbour interaction, i.e. we also consider the $\boldsymbol{J_2}$, we can have a different antiferromagnetic ground state. What we mean by this is that we are now also studying the exchange interaction of $\boldsymbol{S_1}$ with $\boldsymbol{S_3}$. In the previous case, only the exchange interactions between $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$, i.e. nearest neighbours was important in terms of energy. In some materials, the effect of $\boldsymbol{J_2}$ is significant and it results in providing a different magnetic ground state other than the Néel state. For example, for the system of a single monolayer of Mn on Re(0001), row wise antiferromagnetic state is observed! This is a very interesting state where the spins in one row are aligned ferromagnetically, but are coupled antiferromagnetically to the spins in the neighbouring row[4].

References

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There is a lot more interesting physics that antiferromagnets offer. Researchers are pushing the limits to realise devices based on AFMs!Stay tuned for my next post! I will come back some more interesting magnetism!