Inquiry-based learning worksheet

Target audience: High-school students

Duration: 1:30 up to 2 hours

Pre-requisites: *No prerequisite*
(However, I expect high-school students to know about the constitution of atoms (= a nucleus + electrons), if not I can still adapt.)

Learning goals:
A glimpse into the quantum world:

- *The existence of energy quantisation and spins;*
- *Zeeman interaction;*

A more general statement:

- *Observing a perturbed system can allow you to measure this perturbation.*

Driving question:

How can we use quantum systems to detect magnetic fields?

Note: Here Envy, my little NV spin which helps me in everyday work :)

The activity begins from here and has 3 parts: predictions, observations and reasoning.

Part 1. Predictions

In this section, list some hypotheses that you can propose to the students to get them thinking or speculate about the correct answer to the driving question. You can also think about the possible predictions students may come up with that could be discussed.

Prediction 1	Prediction 2	Prediction 3
We can deconstruct the question into two parts. What is a quantum system and how to detect magnetic fields? Quantum systems are very small systems we cannot see under the microscope! They probably have a special property which enables them to detect magnetic fields.	When you want to measure a parameter, you need to look at a system which is affected by this parameter. For some thermometers, it's the level of mercury which is changing. For magnetic fields, there is probably something as well… Like the needle of a compass which rotates following the magnetic pole of the Earth! There are maybe quantum compasses.	We can use a big magnet to find smaller ones! By moving a very big magnet in a given space, it will attract all the small magnets around and this way, we can find them all! So maybe if we do the opposite and move a lot of small magnets, “quantum magnets” then... we can find the big magnet?

Questions to ask the students:

Q.1: Discuss the different predictions in groups, decide which one you agree with (if any) and note your reasoning here:

……

In the discussion, which one do you agree with?

- *a. Prediction 1*
- *b. Prediction 2*

c. *Prediction 3*
d. *None of them*

Instructor notes:
Facilitation of discussion:
As an instructor, mention here how you will facilitate the discussion based on which prediction the student agrees with.

For all: there is a difficulty to express how quantum systems can be related to magnetic fields detection, which is normal as they don't know much about quantum physics. So first I want them to really understand things they can relate to (*i.e.* detecting magnetic fields classically) and then we would explore quantum properties in the second part of the activities.

For prediction 1:	**For prediction 2:**	**For prediction 3:**
That's a very good start! Now, it would be nice to elaborate a bit more about this special property which would enable quantum objects to sense magnetic fields. First, how can we determine if a material is magnetic or not? [Expected answer: something like: you need to try if the material sticks to another magnetic material or not (like a magnetic board), so I want the student to talk about **interactions**.]	It's a very good way of reasoning. Before developing the "quantum compasses", we need to understand why the needle of a compass rotates depending on a magnetic pole and what are our degrees of freedom (*i.e.* the needle will rotate faster towards a strong magnetic pole, but also if it is closer etc.).	There are two very interesting points addressed here. First, the existence of "quantum magnets" with the idea of using magnets to sense/detect other ones. The second point is about using a lot of them. It is a very good remark but we should discuss it only in the end because it goes beyond the scope of the subject today. So, let's focus on the existence of "quantum magnets" for the moment. [Note: In sensing, bigger the number of probes, better the sensitivity, but I don't think it's good to mention too many notions here. In the case students start developing about it, I would say something like: more

		“quantum magnets” you use, better your chances to detect the magnet you are looking for.]

Part 2: Observations

In this section, write the questions that engage students with a simulation or real experiment, games or video, etc. to acquire evidentiary support that helps them to decide which of the predictions are true or to develop new or modified predictions. For each question, add instructor notes and the goal of the question.

This section will be divided into two parts:

- ***Hands-on experience part***

First part is about playing with standard magnets (and compasses), more or less big, more or less strong, so they can explore how the interactions change depending on material, whether you stack some magnets together or not.

Q1: *Take two magnets and approach them to each other. Try with several magnets as well, what do you observe?*
Goal: To show the concept of a dipole

- *Answer: Sometimes they attract each other but sometimes they repel each other. It actually depends on how you rotate the magnet. → Notion of dipole (eventually used later to talk about spins up and down).*

[Instructor Note: I am convinced they already know about magnets having "north" and "south" poles and opposite poles attract each other but I want to start with a question I am sure they are able to answer. I believe the students will feel confident because they were able to answer the first question without difficulty. This way, they will more easily dare to answer tricky questions.]

***Q2:** Now approach a magnet to a compass: what do you observe?*
Goal: To show we can use magnets to detect other… magnets!

- *Answer: the needle follows the magnet. We can conclude we need a magnetised material to detect magnetic fields.*

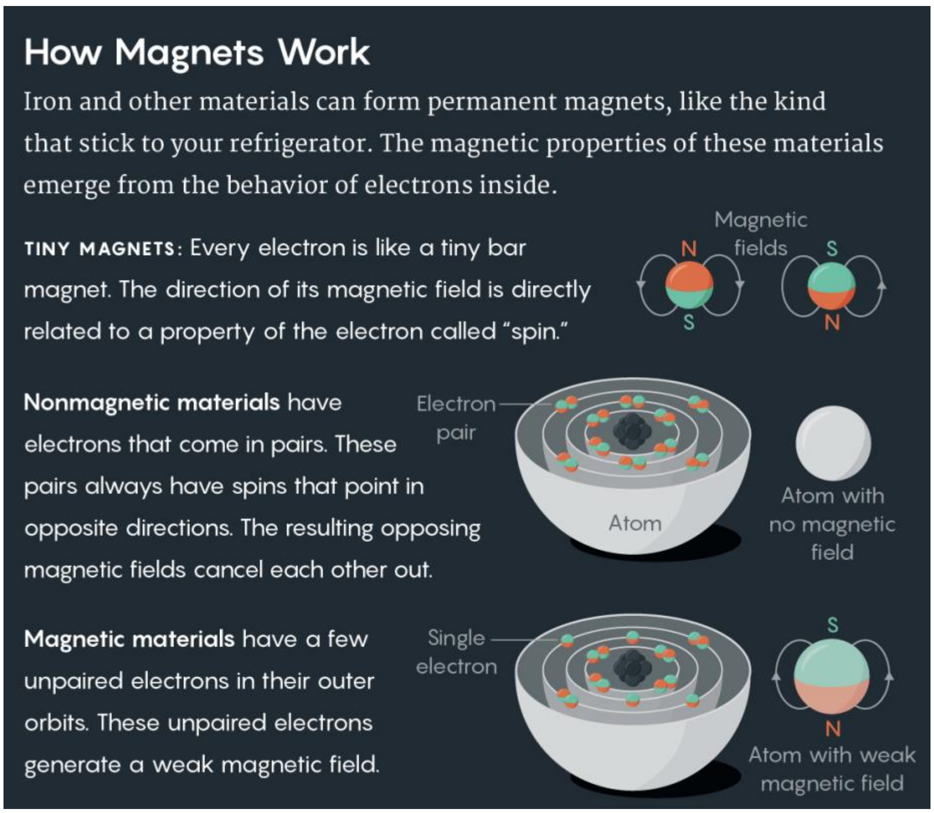
Instructor Note: The other aspect to explore is also the fact you can modify a system by giving it some energy: for this I'll be giving a stress ball they can deform by pressing on it. [The nice thing with it is it will relax to its initial state over time, but that's a bonus! ;)]

***Q3:** Now take the stress ball and squeeze it, what do you observe?*
Goal: To show you can modify the state of an object if you give it some energy + the amount of given energy matters.

- *Answer:* The stronger you squeeze it, the more you deform the ball, *i.e., the* more energy you give to an object, the more you can modify its state from the initial one.

Transition: *→ How can this be interpreted in the quantum world? As they've already mentioned the idea that the quantum world = very small world, I will introduce some atomic notions as shown below.*

- ***Reasoning part → Quantum aspect***



[Source: *https://www.quantamagazine.org/a-childs-puzzle-has-helped-unlock-the-secrets-of-magnetism-20190124/]*

In this part, we can now start discussing spins and discretisation of states in quantum systems. For this we will watch this video about Stern and Gerlach experiment and comment it afterwards: https://www.youtube.com/watch?v=rg4Fnag4V-E

Q3: *What did you learn in this video?*
Goal: To learn that using a magnet, you can bring electrons only to two states (contrary to the classical case).

- *Answer: If we approach a small magnet A to another big magnet B, the direction of A deviates following B's direction. Now if we approach a quantum magnet A' to the magnet B, there are only two directions possible: up and down.*

Instructor Note: I will comment on it to add that here, these positions represent the energy states of the electron which can only have these two states possible (while with the stress ball, we could deform it in many ways).

Q4: Now… What would happen if I place a stronger magnet? What can possibly change there?
Goal: To learn that the splitting of the spins' energy levels depends on the magnetic field strength.

- *Answer: The stronger the magnetic field, the larger the splitting.*

Instructor Note: Of course, I don't expect them to give the answer right away**.** To lead them to the answer, I will play the video again and stop at the classical part in a first time. "Remember the stress ball now, if I press stronger, what will happen?" [If the analogy with the stress ball does not lead them to the answer, then I'll take a plastic bottle filled with water and show them: the stronger you squeeze the bottle on its sides, the more you'll split water. With that, it should be good.]
Once they have the answer, I press on play again, let them watch the quantum case again and ask the question once more: they should have the answer now.

Part 3: Making sense/Reasoning

In this section, ask questions on what evidence from the simulation or experiment supports their prediction.

In the end I would like them to come up with the idea we can change the state of the spins using magnetic fields. Besides, if we look at the separation between the two states, we can quantify the strength of the magnetic field.

Revisit the key question:

After the activity, students revisit the question now using ideas that are supported by evidence from this activity.

Now they have almost all the notions in hands to answer the initial question:

How can we use quantum systems to detect magnetic fields?

I want them to conclude that magnetic fields modify the energy state of the electron (or quantum system): as with the stress ball, the stronger we press on it, the more flatten/deformed it becomes. Here it is the same, the stronger the magnetic field, the bigger the splitting between the two energy states. In the end, we can measure this splitting to infer the magnetic field strength. With that, we have answered the initial question!

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