“The Glass of Magnets and Beyond”

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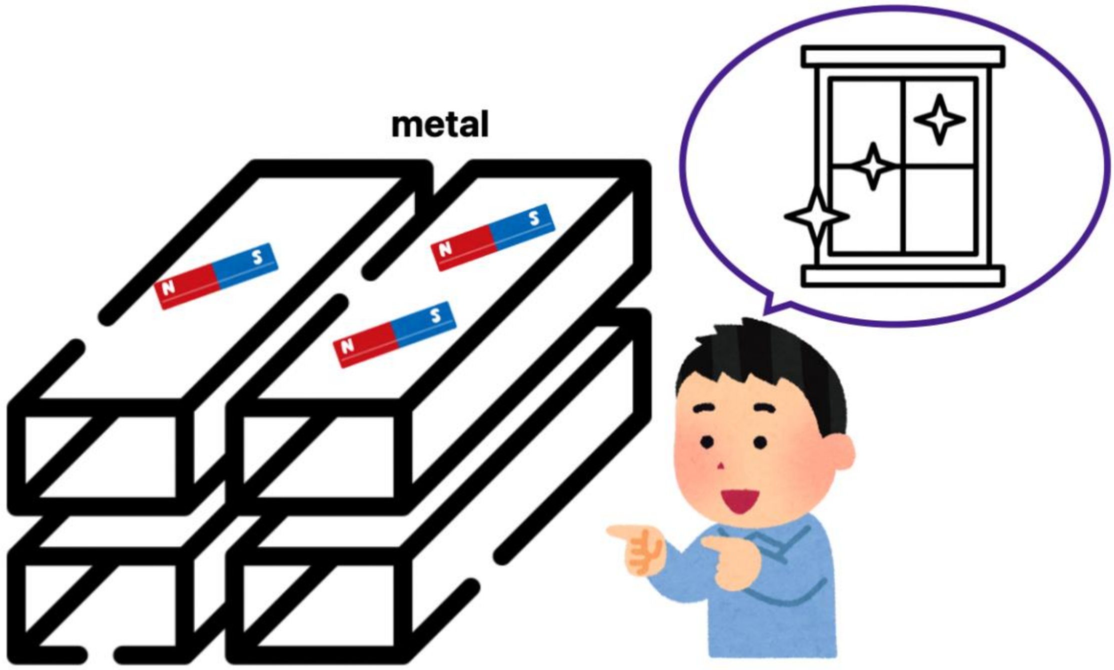

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I’m sure you have known about window glass before. It’s a hard and transparent material. What would you answer if you were asked whether it is a solid or a liquid? Well, it’s hard to answer even for scientists. Generally, glass is said to be an amorphous solid that exhibits properties of both. Its hardness exhibits solid-like properties. On the other hand, the random arrangement of small particles constituting glass (say, molecule) shows liquid-like (or jelly-like) properties. There are debates about whether glass is a jelly-like substance that extremely slowly changes shape. Though we are familiar with window glass, studying glass remains an active frontier in physics.

Setting aside window glass, we shift our attention to another form of “glass” known as spin glass. It was discovered in cooled metals and consisted of “tiny magnets”. Before we continue, we first clarify some basic concepts - spin, phase and phase transition.

Let’s start by discussing “phase.” For instance, while books and wood cannot stick to refrigerators, neodymium magnets can. “Phase” refers to such different states and the origin of phases are the collective behavior of “spins.” For simplicity, imagine a spin as a tiny magnet. Within materials, there is an enormous number of spins, and they interact each other. If we observe the spins in books or wood, they are randomly changing north-pole directions. This continuous reorientation of spins causes them to cancel out each other’s magnetic effects. Conversely, if we observe magnets, we see that the north-poles of spins are somewhat aligned. Differences in spin-spin interaction and spin-environment interaction can lead to such different phases. The important point is that the same materials could change to different phases if we tune the environment of materials such as temperature. This change is called “phase transition.” The most familiar case of phase transition is water transitioning from a liquid phase to an ice phase through cooling. Similarly, certain magnetic materials like iron, can undergo a transition where non-magnetic material becomes magnet by cooling.

Now that we have grasped the fundamental concepts, let’s delve a bit deeper into the discovery of the spin glass phase and the research surrounding it. Since the 1960s, scientists extensively investigated the electric properties of “dilute magnetic alloys” at low temperatures. These alloys consist mainly of non-magnetic materials with a small proportion of magnetic substances. While many are intrigued with unique electric phenomena induced by spins in magnetic substances, scientists made a surprising discovery by studying their magnetic properties in 1972. They observed a previously unknown phase transition. The new phase was called "spin glass." Scientists are motivated to deepen their understanding of the spin glass phase through experimental and theoretical investigations, partly because it is closely associated with unresolved physics problems, such as the nature of window glass.

Then, what happens in the spin glass phase? In this phase, the spins' orientation is like those in books or wood, where they are oriented in random directions. However, there is one key difference: in the spin glass phase, each spin appears to be frozen (reminiscent of window glass). It is shown that the interaction between spin has a high level of complexity, making the spin glass' behavior genuinely unique.

About experimentalists, they use specialized equipment to study unique phenomena in the spin glass phase. This includes a cooling apparatus capable of reaching very low temperatures and a device to measure the material's magnetization, indicating its magnetic strength.

Here we will explore one of the fascinating phenomenon in spin glass: the "memory effect." In this experiment[1], we'll use $CdCr_{1.7}In_{0.3}S_4$ as material that emerges spin glass phase. Except for some temperatures, we'll lower the temperature of materials at a constant rate, recording magnetization data. At 12 K, we pause briefly before continuing to cool to 5 K. We can observe a reduction of magnetization at 12 K compared to the surrounding temperatures. Then, the truly perplexing part comes next. When we increase the temperature without stops, the magnetization data shows a similar decrease at 12 K as during the temperature decrease. If we do not pause at 12 K when lowering the temperature, such magnetization's reduction does not occur when cooling and heating. These results suggest that a bunch of tiny magnets can somehow remember their thermal history and the phenomenon is called memory effect. Isn't it fascinating? Various similar experiments and theoretical considerations have been added regarding this phenomenon.

So far, we have seen the experimental aspects of spin glass but how about the theoretical side of spin glass? Through studying these experimental results, scientists aim to understand the underlying rules behind these observations and explain them using mathematical tools. This process is called "building models." As they encountered phenomena that the existing model could not account for, they devised various new models and developed new mathematical techniques. One notable achievement in this field was made by G. Parisi, who proposed a compelling theory for spin glass and was awarded the Nobel Prize in 2021 for his contributions.

The study of spin glass involves a synergy between experimental and theoretical approaches around physics, with each stimulating the other's progress. Furthermore, scientists have found that the techniques and concepts of spin glass exhibit a wide range of applicability that extends beyond the discipline of physics. They are now used in information science, social sciences, and biology. For example, by treating people's opinions (such as agreement or disagreement on specific topics) as spin orientations (north or south), the research suggests that spin glass concepts can be applied to the study of group formation in society. Other research shows that the spin glass theory can help to optimize the collection of medical data, thus reduce the burden on patients. The scope of spin glass theory extends far and wide. However, there are still many unexplained phenomena including the memory effect. Their underlying mechanisms continue to be the subject of ongoing research. To tackle this challenge, the young readers like you, who possess the power to think flexibly and creatively, are needed.

[1] K. Jonason *et al.*, Phys. Rev. Lett. **81**, 3243 (1998)