Innovative Idea for the Clean Energy Sources

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In our daily life, you might use a car or bus to commute, or you probably use an airplane to trip abroad. These vehicles are, of cause, mainly working with fossil fuel. These days, an electric motor car is developed, however, most of the electricity itself is generated by fossil fuel, especially in Japan. In terms of that, your smartphone and a textile mill where your clothes are made, even an agricultural machine for growing vegetables are all powered by fossil fuel.

Fossil fuel is one of the biggest environmental problems because it produces tons of thousands of greenhouse gas which is deeply connected to global warming. Though that problem is a well-known and long-term problem, the critical solutions are unknown yet and we always need to try to find it very much. In this essay, I want to share with you a new way of saving fossil fuels. It is a "thermoelectric effect".

The thermoelectric effect itself is a well-known phenomenon for long years as the 'Nernst effect' or 'Seebeck effect'. When one side of the material having a thermoelectric effect is heated and the opposite side is cooled, the electricity is generated. In other words, we can transform thermal energy into electricity, called thermoelectric transformation. By using this effect, we can utilize the dumped thermal energy from a muffler of a car or a place where garbage is burned. Thermoelectric transformation using that effect must become the powerful solution for the problem of fossil fuel. However, any practical thermoelectric transformation device is not developed until today. One of the biggest reasons is the size of the thermoelectric effect. One of the most powerful materials is Bi_2Te_3 (Bi: Bismuth, Se: selenium) at room temperature [1], though the efficiency of thermoelectricity is only 10% of that of the Carnot cycle, a mechanical method for thermal transportation. The figure of merit of thermoelectricity is evaluated by Zeeman coefficient times temperature, $ZT = S^2\sigma T/\kappa$, where S is the Seebeck coefficient, σ is electrical conductivity and κ is thermal conductivity. Having a bigger ZT index indicates a better thermoelectrical effect. The reason for the small ZT index is quite simple; the ZT index is proportional to the electric conductivity σ and inversely proportional to the thermal conductivity κ, but these two are the same trend against any parameter. In other words, if you want to find a material having good electric conductivity to get a bigger ZT index, the thermal conductivity also become better. Therefore, the *ZT* index does not change very much. Moreover, there are other difficulties to realize a thermoelectrical transformation; the Nernst effect needs an external magnetic field and the Seebeck effect is the longitudinal thermoelectric effect so that the electricity occurs in the same direction as the thermal current. Then, even if you want to make a nice device using the Seebeck effect, the device must be one-dimensional and less flexible.

The 'Anomalous Nernst effect (ANE)' has been attracting attention in recent years as an effect that solves the short points I mentioned above. Firstly, ANE is the transverse thermoelectric effect. That means that the electricity emerges perpendicular to the thermal current, and we can make a compact and flexible device by making the most of it. Second, ANE does not need any external magnetic field because the origin of ANE is topological property, which is one of the inherent properties of a material. In 2020, a wonderful material having a giant ANE was found [2]. Surprisingly, it is only made of iron and gallium both of which are abundantly existed in nature and easy to be made a large bulk sample written as Fe_3Ga. The origin of the giant ANE of Fe_3Ga is also considered to be a topological property. In contrast to the Nernst and Seebeck effect, therefore, this kind of effect could be large as increasing the topological property.

By the way, what is topology? I would like you to introduce a little about it here. The topological property is recently recognized as a new kind of aspect for describing phases of material. Topological classification is often explained as the relationship between a donut and a ball or a real and schematical route map of trains. A donut has a hall at the center, but the ball has no hall. So, a donut cannot be a ball unless changing its number of halls. The route map of trains in Tokyo, for another example of topology, is so complicated that we cannot draw a precise picture of it. So, we need to make a schematic one without changing the important feature. That is exactly the topology. The schematic one is made by contentiously changing the real one but does not change the number of halls, or topology. In these two examples, the number of halls is called "topological number". In solid-state physics, the topological number is called the "Chern number" which is like a magnetic monopole, but it is defined in the momentum space, not the real space. Please remind that ANE does not need an external magnetic field, though the Nernst effect itself needs one. In ANE, the Chern number replaces a part of a magnetic field. Therefore, the size of ANE is roughly determined by the Chern number. Surprisingly, they found Fe_3Ga by calculating the topological properties of over 1000 magnetic materials.

Even Fe_3Ga, the size of ANE is still too small to use in the industrial situation, however, further inclement is greatly expected by controlling the topological property. If we get a practical thermoelectric device, we will be able to efficiently reuse energy that we have been throwing away, and that will connect to the wonderful world in the future.

[1] S K Mishra, *et al.,* J. Phys.: Condens. Matter 461, **9** (1997).

[2] A. Sakai, *et al.,* Nature 581, **53** (2020).