Hall sign reversal in certain metamaterials

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this momentum whole," and therefore should outrun, and not hit, the target. He illustrates the ball passing to the right of the target. A rotating Earth should produce detectable effects.

Thus Riccioli was not an anomaly. What we now call the Coriolis effect was being described and illustrated by different authors a century before Coriolis was born. The twist to the story is that the effect was first described by Riccioli, and then by Dechales, as part of an anti-Copernican argument. Nonetheless, if we grant honor to firsts in science, it seems the "Coriolis" effect might be due for a renaming.

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The proliferation of electronic sensing and computer control has increased the importance of Hall-effect devices. Among their many applications are magnetometers, contactless position sensors, and magnetic-field-activated switches for ignition timing.

Hall-effect measurements in the simply connected (no voids), flat-plate Hall-bar geometry are widely used in the laboratory to characterize the carrier type—electrons or holes—in metals and semiconductors. In a typical measurement, a device-normal magnetic field, the applied current, and the Hall electric field lie in mutually orthogonal directions. Because negatively charged electrons and positively charged holes are deflected to the same side of the device by the magnetic field for a given orientation of the magnetic field and the current, sign-inverted Hall effects for electrons and holes are usually taken as direct evidence for sign-inverted Hall coefficients for the two types of carriers, and the sign uniquely determines carrier type in the material.

The cover story of the February 2017 issue of PHYSICS TODAY (page 21) highlights a paper that claims to report a novel sign reversal of the Hall coefficient in chain-mail-like three-dimensional metamaterials.[1] The experimental validation of a "mind-boggling prediction"[1] was cited as another example of "metamaterials with electromagnetic, acoustic, or mechanical properties that are qualitatively different from those of their constituents."

The reported sign inversion of the Hall effect in the metamaterial specimen should be attributed to a change in effective geometry rather than to a change in sign of the Hall coefficient. That's because the metamaterial specimen was not simply connected; its tori included voids. I and my colleague, in 1994, reported sign inversion of the Hall effect in specimens with voids or physical holes.[2] We were studying "anti-Hall bars," in which the current and voltage contacts are on the interior boundary of a void in a semiconducting plate. Such a configuration exhibits a sign-reversed Hall effect with respect to the standard Hall-bar geometry.

Because a change in geometry can change the sign of the Hall coefficient, geometry needs to be explicitly taken into account when determining the sign in multiply connected specimens. Whereas a simply connected voidless specimen can serve to realize only a single Hall effect on the bar's exterior boundary, many voids with interior boundary contacts, or anti-Hall bars, can be placed within a multiply connected specimen. By injecting a current through the interior boundary of each anti-Hall bar, we showed that it is possible to obtain multiple simultaneous Hall effects in a single specimen, one from each anti-Hall bar. Thus the sign of the Hall effect in the multiply connected specimen is not a direct indicator of the sign of the Hall coefficient, as is the case in the simply connected Hall-bar geometry.

The relation between Hall-effect measurements made on a standard Hall bar and on an anti-Hall bar can be understood as follows. Imagine that a standard Hall bar, with contacts on the exterior boundary, has a single void in the interior. The sample can be transformed into a single anti-Hall bar via an inversion transformation—that is, by turning the sample inside out. The transformation shifts the exterior boundary and contacts to the sample's interior while moving the boundary of the hole to the exterior.

Suppose the direction of the magnetic field is fixed. If the exterior Hall voltage is positive for positive current in the Hall bar with a void, turning the sample inside out to obtain the anti-Hall bar produces a negative Hall voltage on the interior boundary. That's because the sample's orientation becomes flipped with respect to the magnetic field. A characteristic of the Hall effect is that the sign of the Hall voltage reverses when the direction of the magnetic field reverses. Consequently, the inversion transformation reverses the sign of the Hall effect on the interior (anti-Hall bar) boundary with respect to the Hall effect on the exterior (Hall bar) boundary.

The repeating unit in the metamaterial shown on the February cover is a torus with contacts either on the inner or outer boundaries. The reported sign reversal is therefore the effect that I and my colleague discovered more than 23 years ago.

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Sulfur hydride and superconductivity theory

In his comments in "Unmasking the record-setting sulfur hydride superconductor" (PHYSICS TODAY, July 2016, page 21) Sung Chang quotes Mari Einaga, who explains that the Bardeen-Cooper-Schrieffer (BCS) theory "was largely abandoned because of the discovery of cuprates and other unconventional superconductors." We believe that is true, and it has curtailed development of the BCS theory. Indeed, Jorge Hirsch, in a dramatic review,[1] has called the whole theory into question.

Hirsch listed metallic hydrogen and metal hydrides as examples of the failure of the BCS theory's predictive power: The predicted high transition temperature, T_c, in those two cases has not materialized.[1] However, in an ironic twist, Mikhail Eremets and colleagues have recently found T_c = 203 K in sulfur hydride.[2] Their finding appears to vindicate the BCS theory because Tian Cui and his team had used the theory[3] to predict the record-breaking high T_c before the experiment by Eremets and colleagues, and Ion Errea and coworkers later verified Cui and coworkers' results theoretically.[4] Both groups used the McMillan formula (derived from a generalized version of BCS theory), which relates T_c to the electron–phonon coupling strength and the Coulomb pseudopotential, a measure of the Coulomb repulsion between electrons.

Despite that twist, Hirsch does have other points that need serious consideration. He argues that in the BCS theory, the Coulomb pseudopotential acts as a wild card that can be freely adjusted to fit the theory with any experimental result.[1] The Coulomb pseudopotential, 0.16 from a private communication with Errea, is unusually large compared with its typical value of approximately 0.12. The discrepancy needs to be explained.

We note, too, that the electrical resistivity of sulfur hydride under pressure in the normal state is experimentally measured in reference 2 but is not theoretically evaluated in references 3 and 4. The theoretical evaluation should be consistent with the experimental measurement because, according to BCS theory, both resistivity and superconductivity arise from the same electron–phonon interaction. Historically, a considerable number of researchers attempted but were unable to find consistent resistivity and superconductivity theoretically, even in simple metals.[5] The significance of those failures should not be underestimated. A similar evaluation should be made on sulfur hydride, and an understanding sought of the unusually large Coulomb pseudopotential there.

In his article, Chang states that "the BCS theory has a deceptively simple recipe for achieving high T_c: Create a high density of conduction-electron states and couple the conduction electrons to high-frequency phonons." But he voices caution. Perhaps understanding normal-state electrical resistivity and Coulomb pseudopotential in sulfur hydride can be of some help in getting to the bottom of the problem.

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