PHYSICS

Chiral anomaly without relativity

A condensed matter system exhibits an effect usually associated with particle physics

By **Anton Burkov**

The Dirac equation, which describes relativistic fermions (like electrons moving at nearly the speed of light), has a mathematically inevitable but puzzling feature: negative-energy solutions. The physical reality of these solutions is unquestionable, as one of their direct consequences—the existence of antimatter—is confirmed by experiment. However, the interpretation of the solutions has always been somewhat controversial. Dirac's own idea was to view the vacuum as a state in which all the negative energy levels are physically filled. This "Dirac sea" idea seems to contradict a common-sense view of the vacuum as a state in which matter is absent. On the other hand, the Dirac sea is a very natural concept from the point of view of condensed matter physics, as there is a direct and simple analogy: filled valence bands of an insulating crystal. There exists, however, a phenomenon within the context of relativistic quantum field theory, whose satisfactory understanding seems to be hard to achieve without assigning physical reality to the Dirac sea. This phenomenon, the chiral anomaly, presents a quantum mechanical violation of chiral symmetry; it was first observed experimentally in particle physics as a decay of a neutral pion into two photons. On page 413 of this issue, Xiong *et al.* (*1*) report the observation of this phenomenon in a condensed matter system—a crystal of Na_3Bi—manifesting as an unusual negative longitudinal magnetoresistance; the vacuum/insulating crystal analogy is now all the more tangible.

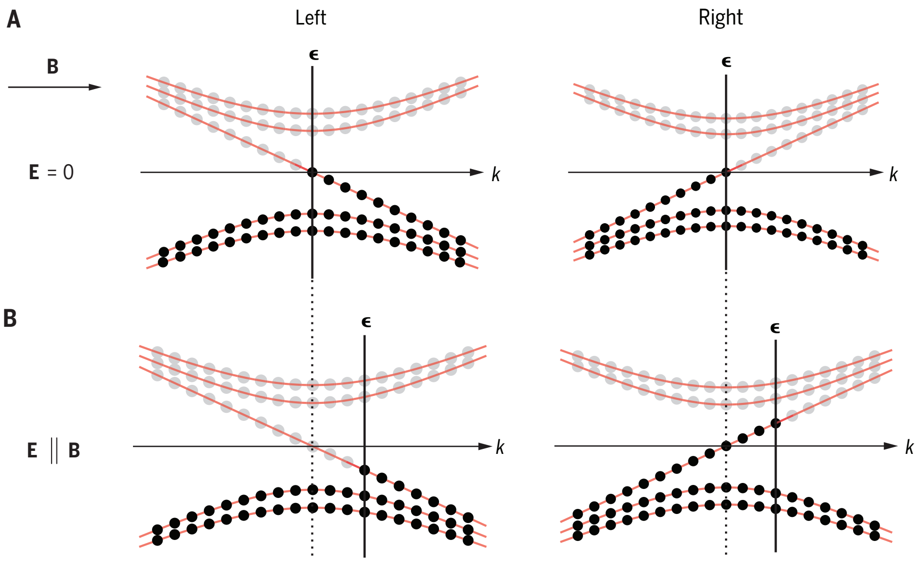
The chiral anomaly is an unexpected feature of relativistic quantum field theory. If the Dirac equation is applied to a hypothetical massless fermion, then the particle is expected to possess a strictly conserved physical quantity called chirality, which refers to the handedness (left or right) of its internal angular momentum (i.e., spin) relative to the direction of its linear momentum. This conservation of chirality may be viewed as a consequence of chiral symmetry of the Dirac equation for massless particles: It has no preference for either chirality and does not mix the two chiralities.

However, when one passes from the Dirac equation to the corresponding relativistic field theory (which is made unavoidable by the negative-energy solutions of the Dirac equation), the chiral symmetry disappears once another fundamental physical principle, that of gauge invariance, is taken into account. Chirality is no longer conserved when the fermions are placed in an electromagnetic field with collinear electric and magnetic components. This property was discovered by Adler and by Bell and Jackiw (*2*, *3*), who were trying to explain the observed decay of a neutral pion into two photons, which seemed to be prohibited by the chiral symmetry.

The chiral anomaly is readily understood when the Dirac sea is considered real (*4*). In this case, the chiral anomaly follows from the form of the energy eigenvalues of the Dirac equation for a massless left- or right-handed charged fermion in the presence of a constant magnetic field (see the figure). These solutions have the form of Landau levels, discrete energy levels that disperse continuously as a function of the component of the linear momentum along the direction of the field. The handedness of the particles is reflected in the existence in each case of a special Landau level whose dispersion is chiral; that is, it has a slope of a specific sign, positive or negative. Whereas all other Landau levels have either strictly positive or strictly negative energy, the chiral Landau levels necessarily contain both negative and positive energy states. The chiral anomaly arises as a direct consequence of the existence of these chiral Landau levels.

Invoking the Dirac sea picture, all the negative energy states are filled by fermions while all the positive energy states are empty. Now suppose that in addition to the magnetic field, an electric field is applied in the same direction. The electric field will accelerate the particles, which means their momentum will change with time. This implies (see the figure) the simultaneous production of particles of one chirality and antiparticles of the opposite one. The total charge is conserved but the chirality is not.

The observation of the phenomenon reported by Xiong *et al.* was made possible by the recent discovery of Weyl and Dirac semimetals, which are crystalline materials whose electronic structure mimics the energy-momentum relation of relativistic fermions (*5*–*9*). The specific material studied by Xiong *et al.*, Na_3Bi, is a Dirac semimetal, which means that the left- and right-chirality electrons coexist at the same point in the



Illustrating the chiral anomaly. (**A**) Energy spectrum of the left- and right-handed fermions in the presence of a magnetic field **B**. Filled states with negative energy are shown as black dots, empty states with positive energy as gray dots. (**B**) Same spectrum, but in the additional presence of an electric field **E** parallel to the magnetic field **B**. Right-handed particles and left-handed antiparticles have been produced. ε, energy; *k*, wavevector.

Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada, and National Research University ITMO, St. Petersburg 197101, Russia. E-mail: aburkov@waterloo.edu

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crystal momentum space. This, however, is not important, as a similar effect should be observed in Weyl semimetals, where opposite-chirality fermions exist at distinct points in momentum space. The way that the chiral anomaly manifests in Na_3Bi is through magnetoresistance (a dependence of the electrical resistance of the material on an applied magnetic field). The physical picture of the chiral anomaly, when applied to a Dirac or Weyl semimetal, implies a magnetic field–dependent contribution to the resistance, which is negative (the resistance is reduced and the material becomes a better conductor when the magnetic field is applied) and quadratic in the field (*10*, *11*). The effect also exists only when the current is aligned with the direction of the field (the magnetoresistance is longitudinal), survives up to a temperature of about 90 K, and is large (quickly rising to more than 100% as the temperature decreases below 90 K). These features are unusual and cannot be explained by any other known mechanism but the chiral anomaly.

What makes the observed effect important, apart from the analogy to particle physics, is that the chiral anomaly is a purely quantum mechanical phenomenon without any classical analogs. Yet the observed longitudinal magnetoresistance is a macroscopic effect, seen in a large sample. Such macroscopic quantum phenomena are typically observed only at very low temperatures. The fact that the chiral anomaly manifestation in Na_3Bi is observed at temperatures as high as 90 K makes it especially interesting and potentially useful technologically. ■

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NEUROSCIENCE

The unknowns of cognitive enhancement

Can science and policy catch up with practice?

By **Martha J. Farah**

"Man is not going to wait passively for millions of years before evolution offers him a better brain." These words are attributed to the 20th century Romanian psychopharmacologist Corneliu Giurgea, an early advocate of cognitive enhancement—that is, the use of medications or other brain treatments for improving normal healthy cognition. Contemporary attempts at cognitive enhancement involve an array of drugs and devices for modifying brain function, such as pills taken by students to help them study, or electrical stimulators focused on prefrontal cortex by electronic game players ("e-gamers") to sharpen their skills. What is known about current methods of cognitive enhancement? What specifically do they enhance, for whom, and with what risks? We know surprisingly little.

In the United States, stimulants such as amphetamine and methylphenidate (sold under trade names such as Adderall and Ritalin, respectively) are widely used for nonmedical reasons (*1*). However, it is not known how many of these users are seeking cognitive enhancement, as opposed to getting "high," losing weight, or some other effect—there is simply a lack of epidemiological data. Student surveys suggest that cognitive enhancement with stimulants is commonplace on college campuses, where students with prescriptions sell pills to other students, who use them to help study and finish papers and projects (*2*). Similar use by college faculty and other professionals to enhance workplace productivity has been documented, but prevalence is unknown (*3*, *4*).

These practices have been interpreted as paradigm cases of cognitive enhancement (which is distinct from treatment for a cognitive disorder) generally aimed at improving executive function—the ability to marshal cognitive resources for flexible multitasking or focusing, as needed. Because these drugs are widely used to treat attention deficit hyperactivity disorder (ADHD), in which executive function is impaired, they are assumed to enhance executive function in healthy individuals as well. However, the current evidence suggests a more complex state of affairs. The published literature includes substantially different estimates of the effectiveness of prescription stimulants as cognitive enhancers. A recent meta-analysis suggests that the effect is most likely real but small for executive function tests stressing inhibitory control, and probably nonexistent for executive function tests stressing working memory (*5*).

Why, then, do these drugs continue to be used for enhancement? One possibility is that there are important individual differences in people's response to them, with some people benefiting (*2*). In addition, stimulants have other effects for which they may be used. In a report entitled "Just How Cognitive Is 'Cognitive Enhancement'?," sociologist Scott Vrecko interviewed students who used Adderall and found that they emphasized motivational and mood effects as reasons for using the drugs for schoolwork (*6*). Subsequent research confirmed the role of these noncognitive factors for students enhancing with Adderall; although they differed minimally from nonusers on attention task performance, they exhibited substantially greater differences in motivation and worse study habits, along with more depressed mood (*7*).

There is, of course, a close relation between cognitive performance, on the one hand, and motivation, on the other. Even if one's laboratory-measured executive function is not appreciably increased, one is likely to get more done, and of better quality, if one is feeling cheerful and "into" the tasks at hand. Unfortunately, the mood- and motivation-boosting abilities of stimulants are related to their well-known dependence potential, and that potential is a major concern. How likely is it that cognitive enhancement use of stimulants will lead to dependence? The prevalence of drug dependence among enhancement users is not currently known.

Another drug used for cognitive enhancement is modafinil (trade name Provigil). Best known for its ability to preserve alertness and cognitive function under

Department of Psychology, University of Pennsylvania, Philadelphia, PA 19104, USA. E-mail: mfarah@psych.upenn.edu

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