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Low-energy Tests of Fundamental Physics

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This article presents a personal perspective on why it is interesting and important to test all kinds of fundamental laws and search for as-yet-undiscovered particles and interactions using laboratory-based non-accelerator techniques. Such room-scale experiments are already spearheading discovery, and can be expected to become even more important as accelerators reach seemingly inevitable limits.

Law-abiding Natural World?

The scientific view of the world is based on the belief that there are fundamental rules, laws of nature, that underlie all natural phenomena. While this view has been supported by the vast body of experiments, scientists have had many 'surprises' along the way, where what had been believed to be a firm law was eventually found to be completely broken once the experimental reach was extended to a previously unexplored range of parameters or to a new type of interaction. The famous twentieth-century examples include replacing the laws of classical physics (e.g. Newton's laws) with quantum mechanics in the microscopic world, special relativity in the realm of fast particles, and general relativity on astronomical scales. Another striking example is the rise and fall of the law of parity – the invariance with respect to spatial inversion (colloquially known as left–right or mirror symmetry), which, as far as we know, is strictly obeyed by electromagnetic and strong interactions, but was found to be violated by weak interactions at a $\approx$100% level. Discovered in a series of striking and beautiful experiments in the late 1950s, parity violation came as a shock and a 'wake-up call' to many theorists, who initially had difficulties believing that there is actually an intrinsic difference between 'left and right'. Shortly after, L.D. Landau and others found brief comfort in the idea that the symmetry can be restored by combining the operation of spatial inversion (P) with charge conjugation (C), resulting in the so-called CP symmetry. The logic is that P by itself is somehow not a 'proper' operation, and should always come together with C. This is a really nice idea, except that when experimentalists set out to test it, CP violation (albeit only at a small level) was discovered in 1964. What a lesson in humility!

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Beyond 'Beyond Standard Model (BSM)' Physics

While CP is violated, adding a third operation – that of time reversal (T) – seems to, once again, restore the symmetry. In fact, the corresponding CPT Theorem is just that: a statement that is mathematically proven within the framework of Quantum Field Theory (QFT), the formalism behind essentially all of the modern physics that is connected to experiments (which is the only kind of physics of interest to us here). Taught by the discoveries of P and CP violation, many researchers are keen on mounting sensitive tests of CPT invariance, and, in fact, various experiments are ongoing and becoming more and more sensitive and intricate. It should be understood, however, that a discovery of CPT violation would be a paradigm-shifting discovery on a scale much more serious than the discovery of P and even CP violation. Indeed, these latter violations can be easily incorporated into QFT, while CPT would necessitate the introduction of some altogether new theoretical framework that we can call 'beyond beyond the Standard Model' (BBSM) physics. As we discuss searches for new physics below, we will draw distinction between BSM and BBSM.

Problems, Big Problems, and even Bigger Problems

The physics of particles and interactions has, arguably, been very successful. Particle multiplets are well understood and all essential particles predicted by the Standard Model (SM) have, indeed, been found. The SM also predicts things such as magnetic moments of the electron and the muon, and these predictions are, in some cases, verified at a level of $\approx 10^{-13}$. Despite such impressive achievements, it would be wrong to say that our understanding of the physical world is anywhere close to being complete.

An example of an open question is the so-called 'strong-CP' problem. Indeed, CP violation has been observed in quark–antiquark bound states (mesons), but not yet in other systems. In particular, once CP symmetry is off the table, one may expect to see a non-zero permanent electric dipole moment (EDM) of particles such as the neutron. It turns out that the theory of strong interactions (quantum chromodynamics, QCD) can easily accommodate CP violation. In fact, no EDM has been detected so far despite more than a half-century of intense searches, leading to a peculiar problem (given the fact that CP violation was unanticipated to start with): we need to explain why CP violation in strong interactions is so *small*. A certain QCD phase that can, a priori, be between 0 and 2π is forced to be less than 10^{-10} by the non-observation of neutron EDM. An easy explanation is that it is 'accidental' that the phase is so small, but many physicists are unhappy with such 'fine tuning'. In the 1970s, elegant theories were developed to solve the strong-CP problem by pulling the phase towards zero, but they predict the existence of a new scalar particle, the axion, that itself has not been observed as yet – and, again, not for the lack of trying.

Another 'big problem' is, in a sense, a happy one. When we measure the properties of antiparticles in the laboratory, they appear to be rather similar (or symmetric, as in the case of electric charge) to those of particles. Yet, we see essentially no antimatter in the universe. This is good for us as we do not have to worry about annihilating

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and turning into light. But what is the reason for the asymmetry? A.D. Sakharov formulated a set of necessary criteria for matter–antimatter asymmetry that include baryon number non-conservation (enabling, for example, decay of protons into electrons and photons) that has not been observed yet, leaving this an open problem.

Problems like these, which include the lack of understanding of hierarchy – the vast difference in the masses of all known particles that could 'naturally' be expected to be comparable to either the grand-unification-theory (GUT) energy scale of 10^{16} GeV or the Plank scale of 10^{19} GeV – are serious ones, but, in my opinion, they pale compared with the problem of understanding the origin of the so-called 'dark sector' consisting of dark matter (DM) and dark energy (DE).

Dark Matter and Dark Energy

Simply put, a major problem in modern physics is that we do not know what constitutes most of the mass–energy content of the universe. The first inkling that 'something was amiss' came in the 1930s in a study of galactic velocities in a galactic cluster – the measured velocities indicated the presence of a much larger mass in the cluster than could be accounted for by the observed objects, which led Fritz Zwicky to coin the term '*dunkle Materie*' (German for dark matter). Over the years, it was found that the 'missing mass' problem persists on a variety of spatial scales, from galaxies in which, almost universally, the velocities of stars do not follow what is expected from Kepler's laws given the amount of galactic visible matter, to the necessity for extra mass in models of formation of the large-scale structure of the universe, to additional evidence coming from the analysis of the cosmic microwave background.

A variety of explanations for what DM could be were put forward, but no uncontested detection has occurred so far. Since there is plenty of evidence of the gravitational effects of DM, 'detection' refers to some sort of a non-gravitational interaction, for instance, a collision of a DM particle that could be registered with a high-energy-physics-style detector. In fact, for a number of years, the most 'popular' DM candidates have been weakly interacting massive particles (WIMPs) with a mass in the GeV range that are searched for in just this way.

Another possible explanation for DM is that it consists of some ultralight particles (with a mass somewhere between 10^{-22} and 10 eV) claimed to 'naturally' emerge in string theories. It turns out that, even without knowing much about what these particles are, we can say a whole lot about them just from the fact that they are confined in galaxies and appear to be interacting only weakly with normal matter and among themselves. First of all, since DM is confined in the galaxy and the galactic escape velocity is $\sim 10^{-3}\,c$, where c is the speed of light, DM particles should be deeply non-relativistic (this applies also to WIMPs). Second, the observed DM density in the galaxy is $\approx 0.4\,\mathrm{GeV/cm^3}$ or roughly one proton mass equivalent per three cubic centimetres. The number density of the DM particles assuming that they are all of the same kind is obtained by dividing this mass–energy density by the particle's mass, which results in high number densities for light particles. 'High' in this case means that the DM gas is quantum-degenerate. Interestingly, this tells us that ultralight DM

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has to be bosonic. This is because the Fermi velocity of a fermionic DM gas would exceed the galactic escape velocity, breaking the galactic confinement. Prime candidates for DM are axions and, more generally, axion-like particles (ALPs). A particular appeal of these scalar particles is that they can potentially solve many of our outstanding problems while simultaneously explaining the nature of DM. This includes the strong-CP problem (solved by axions), the matter–antimatter asymmetry problem (through shedding light on the origin of CP violation), and even the hierarchy problem, as has been actively discussed by theoreticians in the last year or so.

A more recent and even bigger problem than DM is dark energy (DE). In the 1990s, measurements, using supernovae explosions as 'standard candles', of the recession speeds of galaxies as a function of their distance from us have shown that the universe is expanding with an accelerating rate, apparently due to the effect of DE. I remember a great deal of scepticism among physicist and astronomers when these reports first emerged; however, within a few years, under the weight of experimental evidence, the 'pendulum has swung', and the reality of DE is presently accepted nearly universally. As in the case of DM, this is reinforced by evidence from different directions, in this case, once again, from the analysis of the cosmic microwave background.

Accelerators and Table-top Experiments

The fact that modern physics, despite all its overwhelming successes, is facing many challenging problems raises the question of what are the best ways toward solving these mysteries. Certainly, accelerator-based experiments have been a powerful way to study elementary particles and fundamental interactions. However, it appears that this way of doing physics is approaching its limits. Already, accelerators are tens of kilometres in size and consume as much power as a medium-sized city (so it is typical for large accelerators to actually not run during winter when electricity is more expensive). While researchers are restlessly looking for ingenious ways to make more efficient, compact, higher-energy and higher-intensity accelerators, in my subjective opinion it is hard to imagine accelerator-based science surviving more than perhaps one generation of machines and experiments. (I should add here that predictions about technology frequently turn out to be wrong, and I sincerely hope that this will be the case with future accelerators.) If so, small-scale low-energy experiments as well as astrophysical observations are bound to play a more significant role in fundamental physics in the future.

In fact, small-scale experiments and astronomical observations were the main drivers of fundamental physics before the advent of accelerators. As accelerator-based experiments gained prominence, they have provided a new and unique window into fundamental physics but have by no means replaced small-scale experiments and astronomy; on the contrary, all three basic approaches have wonderfully complemented each other over the years. Indeed, parity violation was discovered in a room-scale beta-decay experiment and confirmed in experiments with atoms; $W^{\pm}$ and Z bosons were discovered and meticulously studied in collider experiments (this is impossible in non-accelerator experiments), while the accelerated expansion of the universe was discovered via astronomical observations (I cannot fathom another way to do this). Sometimes,

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enthusiasts of table-top fundamental-physics experiments state that such experiments provide as much information as accelerator-based experiments at orders-of-magnitude smaller costs. While it is hard to argue with the latter, I disagree with the idea that such experiments replace accelerators. It seems to me that there is no real competition here; there is, however, a wonderful complementarity of different approaches.

From Challenges to Opportunities

There is a lot to do for small-scale laboratory experiments. First of all, there will be significant progress in SM and BSM physics. Parity violation will be precisely measured in a variety of atoms, including isotopic chains. This approach is promising to make such experiments a tool to study things such as the spatial distribution of neutrons in atomic nuclei, as well as to probe neutral- and charged-current weak interactions within the nucleus. Parity violation will be measured in molecules (a challenge that has not been met so far), including chiral molecules, where parity violation was speculated to play a role in the origin of a particular handedness of biological molecules. In my opinion, it is unlikely parity violation has anything to do with it, but measuring the effect is an extremely well-motivated goal nevertheless. Searches for the EDMs of atoms, molecules and the neutron have all seen impressive recent progress and these will continue to improve. Even if no EDM is seen, the upper limits on their magnitude have proven to be highly effective in constraining various BSM theories, many of them predicting EDMs larger than is already excluded by experiments.

The second class of experiments comprises searches for possible violations of things such as Lorentz invariance, searches for a possible temporal variation of fundamental 'constants' (these searches are catalysed by spectacular developments in table-top atomic clocks that have reached long-term stability at the 10^{-18} level), etc. While these effects are clearly BSM, they can be accommodated by relatively straightforward modifications, typically involving the presence of some kind of background fields. A modern theoretical framework called Standard Model Extension (SME) has been useful in parametrizing broad classes of such effects, which is useful for comparing different experiment with each other. Certain CPT-violating effects, including hypothetical differences in the properties of particles and antiparticles, are also incorporated in the SME. There has been impressive experimental progress in recent years in matter–antimatter comparisons, including production, trapping and, most recently, precision spectroscopy of antihydrogen atoms, as well as comparisons of the masses and magnetic moments of protons and antiprotons.

Third, there are experiments such as the searches for possible small violations of the Bose–Einstein and Fermi–Dirac quantum statistics for identical particles, the spin–statistics connection, etc. These experiments are in a (BBSM) class of their own because they cannot be accommodated within conventional QFT. While it is of great importance to check the fundamental cornerstones of modern physics, experiments in this class have their particular peculiar features. For example, how, in the absence of theory, may it be possible to compare the results for experiments in different systems? I am glad that such challenges have not stopped experimentalists from performing beautiful

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searches, which include currently ongoing exquisitely sensitive tests of the Pauli Exclusion Principle by looking for electron transitions to already occupied atomic states.

To conclude this section, I would like to share with the reader an anecdote dating back to the late 1990s. One of the pioneers of the SM, Sheldon Glashow, was visiting the Lawrence Berkeley Laboratory and gave a full-length colloquium on the topic of Lorentz symmetry violation. As my colleagues and I were developing an experiment to search for possible small violations of Bose–Einstein statistics by photons, I came up to Professor Glashow after the talk and asked him what his opinion was of a possibility of such an effect. His answer was (to the best of my recollection): 'Have shame, young man, you cannot violate everything!'

Does Gravity Respect Parity?

As mentioned above, our current understanding is that parity is conserved by strong and electromagnetic interactions but is violated by weak interactions. What about gravity? The mainstream theories of gravity do not seem to be able to accommodate parity violation; however, experimental evidence for the absence of parity violation in gravitational interactions is all but absent. But how would one go about setting up a gravitational parity test? For example, in atoms, parity violation leads to a term in the Hamiltonian proportional to $\vec{\sigma} \cdot \vec{p}$, i.e. there is *correlation* between the spin of the electron $\vec{\sigma}$ and its momentum $\vec{p}$. Testing some such correlation, for instance, with planets rotating around a star does not seem realistic, if only because of the individuality of all such systems (in contrast to atoms, which are all exactly identical for a given atomic species). I have pondered this question for a while (during off hours) and likely annoyed more than one colleague by dragging them into a discussion of this topic. In one such discussion, my former quantum mechanics professor I.B. Khriplovich suggested that, if one is to retain the equivalence principle while giving up P symmetry (you cannot violate everything!), experiments should probably be more easily carried out not with conventional gravity, but rather with 'artificial gravity' produced by a centrifuge, where accelerations can be much larger than the acceleration of Earth's gravity, and could be better controlled by the experimentalist. Now, presumably, one would want to use a spin-polarized sample and look for some P-odd correlation. The variables we have available to construct such a correlation are the spin-polarization of the sample $\vec{\sigma}$, the radius vector of the sample $\vec{r}$, and its angular velocity $\vec{\Omega}$. But the only T-even, P-odd (pseudoscalar) correlation that can be constructed out of these quantities is

$$\vec{\sigma} \cdot \vec{\Omega} \times \vec{r} = \vec{\sigma} \cdot \vec{v} \propto \vec{\sigma} \cdot \vec{p} \tag{1}$$

i.e. exactly the same correlation as in atomic parity-violation. (Here, $\vec{v} = \vec{p}/m$ is the linear velocity of the sample.) The next logical step is to ask oneself: but why do we need a centrifuge at all? May we not be able to say something about parity violation in gravity from atomic parity violation experiments themselves (in fact, intra-atomic accelerations are much larger than what can be achieved with a centrifuge)? This appears to be an open question, although thinking in this direction has led to an unexpected research direction briefly mentioned below.

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It is worth mentioning here that experiments with spin-polarized atoms have put stringent limits on the P-odd and T-odd correlation $\vec{\sigma} \cdot \vec{g}$, where $\vec{g}$ is the acceleration due to gravity. But since the corresponding 'gravitational dipole moment' (GDM) violates time reversal invariance as well as the equivalence principle, such experiments cannot be regarded as a test of P-invariance in gravitational interactions per se.

Laboratory Searches for the Dark Sector: Dark Matter and Others

As mentioned above, ultralight bosons have emerged as viable and attractive candidates for DM, particularly because they might solve not one but perhaps several problems in modern physics. It appears that the same also holds for DE. However, traditional particle-physics techniques based on the observation of particle collisions are completely inadequate for detecting such bosonic fields, for which a classical-field description is more convenient than the particle picture. A colleague has drawn an analogy with trying to detect a gentle breeze – one would be better off with some kind of a sail for this that would sense collective behaviour of many particles rather than with a molecular-level detector registering collisions of individual air molecules. The experiments attempting to detect DM axions and axion-like particles that I am currently involved with are based on sensing the effect of the bosonic fields on nuclear spins. These are the Cosmic-Axion Spin-Precession Experiment (CASPEr) and the Global Network of Optical Magnetometers for Exotic physics searches (GNOME). The former is based on various nuclear magnetic resonance (NMR) techniques 'customized' for DM detection, while the latter is a collection of time-synchronized atomic magnetometers distributed around the Earth that are shielded from environmental magnetic fields but should be sensitive to a quasi-magnetic field originating from DM. Networking multiple sensors has been a general trend in recent years and not only for DM detection (where, in addition to networks of magnetometers, there are now also atomic-clock networks and mixed-sensor networks), but also gravimeter networks for testing Lorentz invariance and networks of optical interferometers, such as the gravitational-wave observatories LIGO and Virgo, whose years of development have been rewarded by stunning observations of multiple gravitational-wave events originating from mergers of black holes in binary systems.

Returning to DM and DE, in the past several years it was realized that different 'dark-sector' candidates can produce detectable steady, time-dependent and, particularly, oscillating or transient signals in magnetometers, atomic clocks, as well as optical and atom interferometers. It was even realized (actually, while considering whether parity is respected by gravity as discussed above) that certain ultralight DM candidates may produce atomic parity violation effects mimicking those due to weak interactions. Thus, it was possible to reanalyse the data from completed atomic parity-violation experiments and constrain these DM scenarios.

Optimistic Outlook, Healthy Scepticism and Diversity of Ideas

These examples illustrate an exciting and perhaps unexpected development of just the past few years: two mature and advanced fields of DM searches and low-energy fundamental-physics tests are coming together into one common field, which can be

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thought of as a new branch of observational astronomy, bubbling with ideas and standing – as I strongly suspect and hope – on the verge of major discoveries.

As a final remark, I would like to advocate for scientific scepticism and acceptance of the diversity of scientific ideas. This is not something that is taken for granted by many scientists. I have encountered negative attitudes towards BSM searches, let alone BBSM work. Yet, in my opinion, questioning and testing the foundations is very important, particularly in view of all the gaping problems in modern physics. Each individual test is, obviously, a high-risk proposition. But the realm of small-scale low-energy experiments is exactly where such tests can be carried out by relatively small teams at low cost. I hope that a broad spectrum of such work will continue to enjoy the acceptance and support of the scientific community. I also think that when we do not really know what, say, DM is, a variety of scenarios should be pursued in parallel. In the case of the DM puzzle, WIMPS, ultralight bosons, modified theories of gravity, and alternative forces should all be critically examined.

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Further Reading

D. DeMille, J.M. Doyle and A.O. Sushkov (2017) Probing the frontiers of particle physics with tabletop-scale experiments. *Science*, **357**(6355), pp. 990–994. doi: 10.1126/science.aal3003.

About the Author

Dmitry Budker was born in the USSR and graduated with honours from the Novosibirsk State University in 1985. After working as Junior Researcher at the Novosibirsk Institute of Nuclear Physics he moved to the USA, where he obtained his PhD in physics from the University of California, Berkeley in 1993. He stayed at Berkeley, joining the faculty in Physics in 1995. In 2014, he became a Professor at the Johannes Gutenberg University and the Leader of the Matter-Antimatter-Asymmetry Section at the Helmholtz Institute Mainz in Germany. He remains on the Berkeley faculty in the role of Professor of Graduate School. Professor Budker's research interests span a broad range of topics, including sensitive magnetometry, experimental tests of fundamental symmetries, experimental searches for dark matter, magnetic resonance, and spectroscopy of complex systems. He is a Fellow of the American Physical Society (APS), and a former Chair of the APS Group on Precision Measurements and Fundamental Constants.

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