Precision, Precession, and the Anomalous Anomaly of the Muon

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Editors’ note

Hi everyone,

Welcome to the first issue of the new physics Departmental newsletter, The Nucleus!

Our aim for this newsletter is to provide topical information to our current staff and students, as well as motivating future physicists to learn more about the subject. We are all passionate about physics and want to share some of the most interesting and cutting-edge news. In each issue we will showcase features on international and local research, fact files and interviews with current staff and students as well as brainteasers to provide an insight into the skills required to succeed in physics. Information about events and opportunities in physics for all ages will be provided, along with contact details for those interested in pursuing a career in the field or simply wanting to attend a public talk from the experts. We hope you enjoy this newsletter and that you will want to find out more about the topics we feature!

The Nucleus Team

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Undergrad advice

This issue we asked Professor Tara Shears for her one piece of advice to undergraduates considering a career in research.

“You've got to love your subject. Most time in research is spent not getting very far and making mistakes and devising cross-checks to make sure you understand what you're seeing - it takes a long time. If you can step back from the minutiae of coding or cabling to recapture what it was that led you into this in the first place, what you're still in awe of, what you are still amazed by, then you will go back to your problems refreshed and determined, and you will do well. So don't ever do it because you can. Do it because you really want to.”

Want to get involved in creating the next issue of The Nucleus? Have any feedback or want more details on any of our stories?
Email us at LiverpoolNucleus@gmail.com
Muons are one of the building blocks of nature, hundreds of them passing through the human body every second from cosmic radiation. Their properties are among the most precisely predicted and measured in science. But for the last ten years, particle physicists have known that there is a tantalising discrepancy between theory and experiment: the muon is not spinning on its axis exactly as predicted and the difference may be the result of new particles and new physics beyond the so-called ‘Standard Model’. Now an experiment to make ultra-precise measurements of muon spin properties is being constructed at Fermilab with the collaboration of Liverpool particle physicists. It should establish or otherwise explain the existence of the discrepancy and point the way to new ground-breaking physics.

What could possibly possess a bunch of one hundred or so allegedly sane physicists to dismantle a highly successful experiment based in Brookhaven on the east coast of America and send it lock, stock and barrel on a 3200 mile journey by road, sea and canal to end up amongst the bison at Fermi National Laboratory in the mid-west?

“the difference between the real value and Dirac’s prediction, ‘g-2′, became known as the anomalous magnetic moment.”

Classical electromagnetism tells us that when charged objects spin, the circulating currents generate a magnetic moment and the angular momentum axis will tend to align with magnetic fields. There is a general relationship between the angular momentum and the magnetic moment in which the gyromagnetic ratio, $g$, depends on the details of the circulating currents. What is not so obvious is that even structureless, point-like particles like electrons and muons can have spin and magnetic and electric dipole moments. As Dirac discovered, spin arises naturally when relativity and quantum mechanics are combined and Dirac’s description of this led to a prediction that, for particles like electrons and muons with spin ½ħ, $g$ should be 2. And it very nearly is. Dirac’s prediction remains one of his greatest achievements. Nearly but not exactly: The measured value of $g$ for the electron was about 2.0023 and the difference between the real value and Dirac’s prediction, “g-2”, became known as the anomalous magnetic moment. Over the following decades, the task of measuring and explaining this anomaly became a touchstone for the development of both experimental and theoretical particle physics.

Understanding of the anomaly began with the development of Quantum Electrodynamics, our theory of electromagnetic interactions. The spinning particles drag ephemeral virtual particles in and out of the surrounding vacuum in such a way that the magnetic moment increases a little. Later it was realised that as well as these electromagnetic effects, other interactions: the strong and weak interactions would all contribute to the anomaly. Calculating g-2 became a tour de force for particle theory. The whole panoply of the Standard Model of particle physics is needed to get the prediction right. Intricate perturbation theory calculations involving tens of thousands of weird and exotic Feynman diagrams (see the below image for some examples) were needed as well as the input from dozens of experiments. The most recent experimental measurements and theoretical calculations of the electron anomaly agree at the parts per trillion level – a fantastic success for the standard model.

“interestingly, in the muon case, the agreement between experiment and theory isn’t quite so good; a difference of the order of $x10^{-13}$."

However, it doesn’t end there. Roughly speaking, the contribution of virtual particles to the anomaly is proportional to $\left( m_e / M_{\mu\text{anom}} \right)$. Because the electron mass is tiny, any effect of new physics not included in the Standard Model which would typically involve new heavy particles is strongly suppressed. If instead we look at the muon anomalous magnetic moment, the contributions are proportional to $\left( m_\mu / M_{\mu\text{anom}} \right)$. The muon is 200 times more massive than the electron and so the muon anomaly is about 40,000 times more sensitive to new physics. And interestingly, in the muon case, the agreement between experiment and theory isn’t quite so good; a difference of the order of $x10^{-13}$.

Some examples of the 12,500 Feynman diagrams that need to be evaluated to compute the muon anomaly

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There is an anomaly in the anomaly! The discrepancy of a few parts per million is intriguing; it may be the result of contributions to the anomaly not contained in the Standard Model. Something new like supersymmetry or extra space-time dimensions perhaps: a chink in the otherwise apparently rock-solid Standard Model...

...or it could just be a statistical fluctuation. The statistical significance of the discrepancy is about 3.5σ. That’s enough to capture physicist attention (the experimental paper announcing the results remains one of the most highly cited in particle physics) but not quite the canonical 5σ needed to declare a ‘discovery’. There’s only one thing to do in these circumstances: repeat the experiment with increased precision.

The Brookhaven experiment (E821), which produced the number above, used a technique originally developed at CERN to extract the anomaly from a measurement of the rate at which the muon spin precesses in a magnetic field. Every few milliseconds, a pulse of around 10000 muons is injected into a storage ring: a circular vacuum tube about 15m in diameter. The muons are constrained to circulate in the ring by a very uniform vertical magnetic field produced by superconducting coils embedded in a continuous circular steel yolk surrounding the vacuum pipe.

Muons are unstable and will decay: their mean lifetime is about 2 microseconds, but because they are moving rapidly – they have an energy of 3.1 GeV - relativity tells us that this lifetime is dilated and the muons manage to circulate a few 100 times on average before they expire. This limits the time over which we can measure the precession frequency but on the other hand we rely on the decays to determine which way the spin axis is pointing and hence give us a handle on the precession frequency. Here’s how it works: The muons enter the ring in a polarised state. That is their spins are aligned along their direction of motion. As the muons circulate in the ring, the spin direction rotates and would remain always parallel to the direction of motion if $g$ were exactly 2. Because it’s not, the spin direction rotates with a different frequency to the muon’s momentum vector (see diagram, top right). If you imagine sitting at a fixed point in the ring, you would see the muon spin axis rotate with a frequency equal to the difference between the circulation frequency and the precession frequency, $\omega$.

This frequency difference is directly proportional to the anomaly. To measure it we rely on a fortuitous property of muon decays.

Muons decay into electrons and neutrinos:

$$\mu \rightarrow e + \nu_{\mu} + \bar{\nu}_{e}$$

The muon’s energy is shared out between the three decay products and the emerging electron can have any energy up to the maximum 3.1 GeV but it turns out that the highest energy electrons emerge in directions closest to the muon spin axis.

The electrons can be detected in a system of calorimeters and particle tracking detectors spread around the inside of the ring. The detectors measure the electrons’ energy and determine where the decay took place. As the muon spin direction wobbles around with the frequency $\omega$, the energy of the decay electrons entering the detectors goes up and down in sympathy. What we do is count the number of electrons which have energy above a fixed threshold as a function of time. This number also goes up and down with frequency $\omega$. Because it’s a frequency it can be determined extremely precisely.

To get the anomaly itself, we also need to know the magnetic field equally precisely. Here ‘precisely’ means better than a few tens of parts per billion! To get this level of precision, extraordinary care needs to be taken. The magnet is constructed to micron precision and a lengthy process of ‘shimming’ (that is fine-tuning the 1.4 T field by adjusting small steel wedges and small current carrying coils) to get the field as uniform as possible. Temperature variations, changing currents in the electronics, even passing vehicles, can affect the field at the sub parts per million level. Any apparatus that gets in or near the ring has to pass strict field impact criteria. Deviations in the field uniformity are measured using numerous NMR probes at fixed locations around the ring. These continuously monitor the field to track the small changes that occur over time. Every two or three days, a small laser-tracked trolley loaded with NMR probes is pulled around the inside of the vacuum tube measuring the field as it goes. The whole system of field measuring probes is cross calibrated with a single standard probe. The NMR probes measure the field by relating it to the precession frequency of protons in water contained in small glass spheres in the probes. This sounds disastrously circular! Doesn’t it imply that we need to know the magnetic moment of a more complicated object, the proton, with at least the same precision we’re aiming at for the muon? Fortunately, that’s not the case. What actually enters the equations is the ratio of the proton magnetic moment to that of the muon and that has been measured extremely precisely (to 120 parts per billion) by measuring yet another frequency associated with the hyperfine structure of muonium (a bound state of a muon and an electron like hydrogen but with the proton replaced by a muon).

All this information provides us with a precise time-dependent field-map of the inside of the ring. What actually matters is the field that the circulating muons experience on average. This depends not only on the field map but also the details of the trajectories taken by the muons as they move around the ring. They don’t follow exactly circular paths at the dead centre of the beam-pipe, instead they weave intricate paths that oscillate in and out, up and down, around the ‘ideal trajectory’. That behaviour in turn depends on the intricacies of the beam dynamics of the muon beam going right back to the accelerator systems that feed muons into the ring. It’s the business of ‘accelerator physicists’ like those just down the road at the Cockcroft institute to understand the deep physics needed
to calculate this. Furthermore, to achieve the precision we’re after we need to measure some properties of the particle trajectories (as functions of time) and feed this into the models to improve the average field determinations.

This finally brings us to the reasons for moving the experiment! The aim is to reduce the measurement errors by a factor of four. If the E821 discrepancy turned out to be real, the 3.5σ significance they achieved would become something more like 7.5σ - enough to spark a revolution in particle physics. To get that improvement, everything needs to improve, starting with the number of muons measured and the quality of the muon beam. There was no way to do this at Brookhaven so the decision was made to uproot the entire experiment and move it to Fermi National Laboratory (FNAL) in Batavia near Chicago. The superior accelerator complex at FNAL can supply a much cleaner muon beam and deliver around twenty times the number of muons into the ring. Much of the storage ring could be dismantled and trucked overland but the superconducting coils are in a single piece. The contract to move the coil was tendered out and eventually won by Emert International whose company motto: “Yeah, we can move that” proved to be the case. I recommend googling their web site. The boss keeps a video record of all their contracts including this one.

Many lessons were learnt during the E821 experiment and it’s now understood how to improve the measurement. The errors that need to be reduced are the combined effect of dozens of systematic and statistical errors. Every one of these has to be tackled – a single bad systematic error would dominate and render any other improvements useless. At the top of the E821 ‘wish list’ was a set of detectors that could accurately track the decay electrons back to the decay point and relate this information to the signals in the energy-measuring calorimeters and the beam dynamics. The additional information they give can be used to reduce a whole raft of systematic errors. The Particle Physics Group at Liverpool is designing and building just such a set of detectors for the new experiment at Fermilab.

The detectors consist of thousands of ‘straws’ – small straw-like tubes coated with aluminium and gold each strung with a thin gold-plated tungsten wire along its axis. The tubes are filled with a mixture of argon and carbon dioxide gases and the wire is held at high voltage. When electrons from the muon decays pass through the straws, they leave a trail of ionisation in the gas and the liberated secondary electrons drift towards the central wire producing a signal which is electronically processed to give an accurate time-of-arrival at the wire. Knowing the speed that the ionisation drifts through the gas lets us determine precisely when and where the decay electron passed through the straw. The combined information from all the straws it crossed enables us to reconstruct the full trajectory. Straw trackers have been built before, but the detailed requirements of the g-2 straw trackers present a number of interesting challenges. They are small: the straws are only about 10 cm long and 0.5 cm in diameter. The trackers are located inside the vacuum pipe and the gas in the straws is at atmospheric pressure which presents some interesting mechanical problems. Because it’s going in a vacuum, everything has to be kept clean; the assembly will take place entirely within the clean-room facilities in the Oliver Lodge Building (good that we have them!). The materials used must be non-magnetic: the support structures are made from a carefully chosen grade of aluminium and carbon fibre. The machining of the structures is tricky and we are fortunate to have top class in-house expertise and a brand new 5-axis milling machine that is capable of doing it...and we have to complete the design and construction of three trackers by the end of 2015! As well as providing the trackers, Liverpool has other contributions to make. I already mentioned the need to understand some intricate beam dynamics. Understanding of the beam properties has to be improved over that achieved at Brookhaven. Colleagues from the Cockcroft Institute just happen to be world experts in ‘coherent betatron oscillations’ which are the most important aspect of the beam behaviour to be understood and modelled.

Finally, improving the experimental measurement is of course important in its own right, but the error on the experimental value is about the same as the error on the theoretical prediction. If we are to settle the anomalous anomaly question, it’s no good shrinking the experiment error if the theory error stays as it is. So in parallel with the experimental effort, theorists are working to reduce the error on the prediction. We are again fortunate in that we have a colleague in the theory group, Thomas Teubner, who just happens to be a world expert in doing the necessary calculations.

This confluence of highly relevant expertise has made us very welcome in the new g-2 collaboration and convinced our own funding agencies to cough up. The measurement is challenging and fascinating. It provides a beautifully way to search for new physics, complementary to the more well-known method of smashing things together at the highest possible energy. All we’ve got to do is make it work!

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For images and videos of the g-2 move see http://muon-g-2.fnal.gov/bigmove/
Liverpool Telescope 2
The Next Generation of Robotic Telescope

The Liverpool Telescope is a 2 metre aperture robotic telescope located at the Observatorio del Roque de Los Muchachos on the Canary island of La Palma, one of the world’s premier observing sites. It is owned and operated by Liverpool John Moores University. The reason LJMU is unique amongst UK universities in owning a facility of this class is due to the founders of the telescope foreseeing the potential of robotic observing. Robotic telescopes like the Liverpool Telescope are completely autonomous throughout the night; the robotic control software is entirely responsible for safe operation of the telescope and chooses itself what and when to observe from a list of potential targets sent to the telescope via the internet from astronomers around the world.

The net result is that the telescope can be administered by a small staff of 10 based at the Astrophysics Research Institute in Liverpool, and the operational costs are within the means of a university. LJMU has been a trailblazer in this regard: robotic telescopes are now much more commonplace at observatories across the globe, but the Liverpool Telescope, in its tenth year of operation, is still the largest robotic telescope dedicated to scientific observing in the world. From a scientific perspective, a robotic telescope is the ideal tool for ‘time domain astronomy’. We live in a universe that is highly variable, on timescales from a fraction of a second to many multiples of a human lifetime. With no need for an astronomer to be present at the telescope, monitoring variable objects over long periods of time is made much simpler with a robotic telescope.

However, a robotic telescope really comes into its own for the study of unpredictable events: so called ‘targets of opportunity’. Transient explosive phenomena are commonplace in the universe, and some of the most active areas of astronomical research today are the study of phenomena such as supernovae and gamma-ray bursts: the latter of which temporarily outshine the rest of the universe in gamma rays. These cosmic explosions are studied with the aim of understanding the properties of their progenitors and it is therefore crucial to observe them as close in time to the original explosion as possible. Robotic telescopes are a powerful tool for this kind of work: by removing the human observer from the equation the reaction time of these facilities is significantly faster than classical telescopes. Based on the brightness of the optical emission the robotic control system chooses which instrument to use, attempting to mimic the choice that a human would make in the same situation. This flexible capability has been extremely productive; the findings are beyond the capabilities of much larger telescopes since they cannot match the rapid reaction capability of the Liverpool Telescope.

“the scientific potential for such a facility in the new era of time domain astronomy is huge.”

Interest in the time domain is set to escalate in the coming decades with the construction of a number of major new facilities such as the Large Synoptic Survey Telescope (LSST), which will image the entire Southern sky every few nights and is expected to detect up to 100,000 explosive transients per night. This new era of time domain astronomy calls for a new generation of robotic telescope for scientific exploitation.

Currently, a typical task for the Liverpool Telescope following an interesting supernova detection would be monitoring the light from the source on timescales of hours, days and weeks: the rise, peak and decay which characterises the explosion. Soon, much of this monitoring will be provided ‘for free’ by the survey telescopes, since they will be repeatedly covering the entire sky on timescales of days. What will be missing, and is sorely needed for scientific exploitation, is follow-up spectroscopy, to characterise the abundances and velocities of the components in the ejecta.

Liverpool Telescope 2 will therefore have a diameter of 4 metres. We also want the telescope to be very fast slewing, to catch fast fading targets like gamma-ray bursts as soon as possible. Our target is that with Liverpool Telescope 2 we will be on target and taking data within 30 seconds of receiving a ‘trigger’ from some other detection facility.

The design process is well underway, and we aim to have Liverpool Telescope 2 in operation at the beginning of the next decade, which coincides nicely with the other big projects that the worldwide astronomical community have planned. We aim to build the telescope on La Palma, at the same observatory as the existing Liverpool Telescope. The future of the existing Liverpool Telescope is yet to be decided, but one option we are considering is to run the two telescopes in parallel as a combined facility for simultaneous spectroscopy and photometry. The scientific potential for such a facility in the new era of time domain astronomy is huge. As we have opened new observational windows on the universe we have always discovered entirely new classes of objects. With Liverpool Telescope 2, when those new phenomena are found, Liverpool astronomers will be there first.

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Gravitational Waves
Evidence for Cosmic Inflation?

Measurements of the cosmic microwave background (CMB) are a key part of modern observational cosmology. This light shows us a snapshot of the universe when it was 380000 years old. The universe cools as it expands, and at this time, the temperature becomes low enough for electrons to readily combine with protons and helium nuclei, and the mean free path of photons increases dramatically. This black-body radiation has since cooled to 2.725 Kelvin. The CMB varies in temperature by less than one part in ten thousand between different directions on the sky (once the dipole and Galactic emission have been accounted for).

Most cosmologists regard cosmic inflation as the best explanation, put forward so far, of why the universe appears nearly homogeneous on large scales. Inflation refers to an epoch at around $10^{-35}$ seconds after the big bang when the universe went through a period of exponential expansion. This means that the entire observable universe was in effect causally connected prior to inflation. As well as explaining the near homogeneity, inflation predicts how the amplitude of the temperature fluctuations in the CMB depends on the angular scale as seen on the sky. This is because quantum fluctuations, prior to and during inflation, get blown up to a macroscopic scale. The measurement of the power spectrum of fluctuations, the angular variation in the CMB, is a test of cosmic inflation predictions. Measurements of this are in agreement with inflation, however, subject to some parameter adjustments that describe the inflation potential. In detail the CMB, in this model, arises from initial fluctuations set by a black-body radiation field, and damping in the primordial plasma over the period of inflation.

So far so good but what next? It turns out that primordial gravitational waves are predicted to be generated during inflation. These gravitational waves flowing through the universe, at the time the CMB formed, affect the polarisation of the light as viewed by us. The amplitude of this polarisation signal depends on the energy scale of inflation. Measurement of this signal is regarded as the key test of cosmic inflation. This is a hard measurement to make; the polarisation signal is significantly smaller than the temperature fluctuations, and needs to be disentangled from other sources that cause polarisation in the CMB.

That realisation is compelling. Wanting to understand what went on in the very deepest, smallest scales, and study particle physics, was just an extension of that, and then when I went to CERN during my PhD and was able to work in a very small way with everyone else towards understanding more, I just didn’t want to stop. And I haven’t, ever since.

I was surprised to hear that you are the first female physics professor at the university. Why do you think it’s taken so long for the Department to have a female professor?

Yes, that’s right, and it does seem quite shocking to me too. This is a feature of physics in the UK by the way, not just Liverpool, so I think the underlying reasons are universal. About 20% of an undergraduate cohort are female, and this fraction drops as you go higher up the academic scale. It’s easy to see why; an academic job can only be secured after you’ve proven your research worth on a series of (very) short term contracts, and historically the academic hierarchy was organised a little differently with very few professorships.

What’s changed is that now the researcher stage is more flexible, and offers greater support to men and women if you need it for having a family or finding a job in the same place as your partner, and also that the number of professorships have increased in institutions. In other words, you are less likely to be lost if you want stability and there are more chances to progress up the scale. I think now we’re seeing the situation start to redress itself and I’m confident that I won’t be the only female physics professor for long.

The BICEP2 team have claimed to detect the effect of primordial gravitational waves on the CMB. They observed the polarisation of the CMB at 150 GHz from a telescope based at the South Pole. The instrument had an angular resolution of 0.5 degrees, observed 380 square degrees of sky looking out of the Galactic plane, and extracted a polarisation signature called a B-mode. On angular scales between 1 and 10 degrees, the B-mode signature is expected to be dominated by the gravitational wave signal. What is remarkable about this detection is that the amplitude of the signal is at the high end of predictions, and implies an inflation energy scale of about $10^{16}$ GeV. If this detection is real, the B-mode amplitude and further measurements will test theoretical physics at an energy scale far beyond that produced in particle accelerators or high-energy cosmic rays. Of course, the result needs confirming, of most significance is whether the signal could be the result of some previously unknown dust or gas component in our own galaxy. Polarisation measurements of different parts of the sky and at different frequencies within a year or two should confirm or deny the BICEP2 claim.

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