PERSPECTIVE • OPEN ACCESS

A big measurement of a small moment

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

OPEN ACCESS

PUBLISHED
20 July 2017

PERSPECTIVE

A big measurement of a small moment

B E Sauer, J A Devlin and I M Rabey
Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, United Kingdom

Keywords: electron dipole moment, time reversal violation, thorium monoxide

Abstract

A beam of ThO molecules has been used to make the most precise measurement of the electron's electric dipole moment (EDM) to date. In their recent paper, the ACME collaboration set out in detail their experimental and data analysis techniques. In a tour-de-force, they explain the many ways in which their apparatus can produce a signal which mimics the EDM and show how these systematic effects are measured and controlled.

It is well known that the electron has a magnetic dipole moment. This property has been measured with exquisite precision and provides one of the most successful comparisons between experiment and theory. However, no one has ever been able to detect the analogous *electric* dipole moment (EDM), d_e. In principle, there is no reason why an electron should not have an EDM, but a non-zero value of d_e will violate time reversal symmetry T. The Standard Model of particle physics does contain some T-violation, but the value of d_e it predicts is almost vanishingly small—the displacement of the electron's charge from its centre of mass is predicted to be less than a Planck length. This is many orders of magnitude smaller than current experiments could ever measure. However, theories that extend the Standard Model, such as supersymmetry, will typically include additional sources of T-violation. The inclusion of more T-violation can help to explain matter–antimatter imbalance that is seen in the Universe today, something which is currently unexplained by the Standard Model. Measuring a non-zero value of d_e would provide direct evidence for the existence of new T-violating physics and would help to shed light on this enduring mystery. Until then, null results constrain the T-violation new theories can permit.

Figure 1 shows a range of theoretical predictions for the electron EDM from several different models. To date, experimental measurements of d_e have tightly constrained, or even ruled out, many of these theories. The most stringent upper limit on the magnitude of d_e was set in 2014 by the ACME collaboration [1], placing an upper limit of $|d_e| < 9.3 \times 10^{-29}$ e cm with 90% confidence, ruling out many models. Now, the intricate details of this experiment are described thoroughly for the first time [2], highlighting the painstaking effort required to make this precise measurement.

The first step in measuring an EDM is choosing a suitable atom or molecule to probe. Very early on in the search for EDMs, it was realized [3] that certain atoms could strongly amplify the dipole moment of their constituent particles. For the electron, d_e is amplified through relativistic effects, so heavy, high-Z, atoms are preferred for experiments. It was also quickly realized that polar molecules, with their large internal fields, could also act as amplifiers for dipole moments [4]. One way to describe the advantage of molecules over atoms is to note that an EDM experiment requires an external electric field to mix states of opposite parity. In an atom these are typically electronic states, which are far apart in energy and thus require a very large field to achieve significant mixing. However, in a molecule there can be very closely spaced levels of opposite parity (for instance, neighbouring rotational states, or even Λ-doublets), which are much easier to fully mix.

It is remarkable that the dipole moment of the molecule can be orders of magnitude larger than the dipole moment of the electron [5][1]. However, the formidable technical difficulty of precision measurement with molecules led to a 30 year delay before these theoretical predictions were taken up experimentally. One major difficulty was developing techniques to produce and detect appropriate molecules. A molecule which is sensitive

[1] The use of a polar molecule to search for d_e is implicit in this paper. The first explicit statement of the idea appears to be in [5].

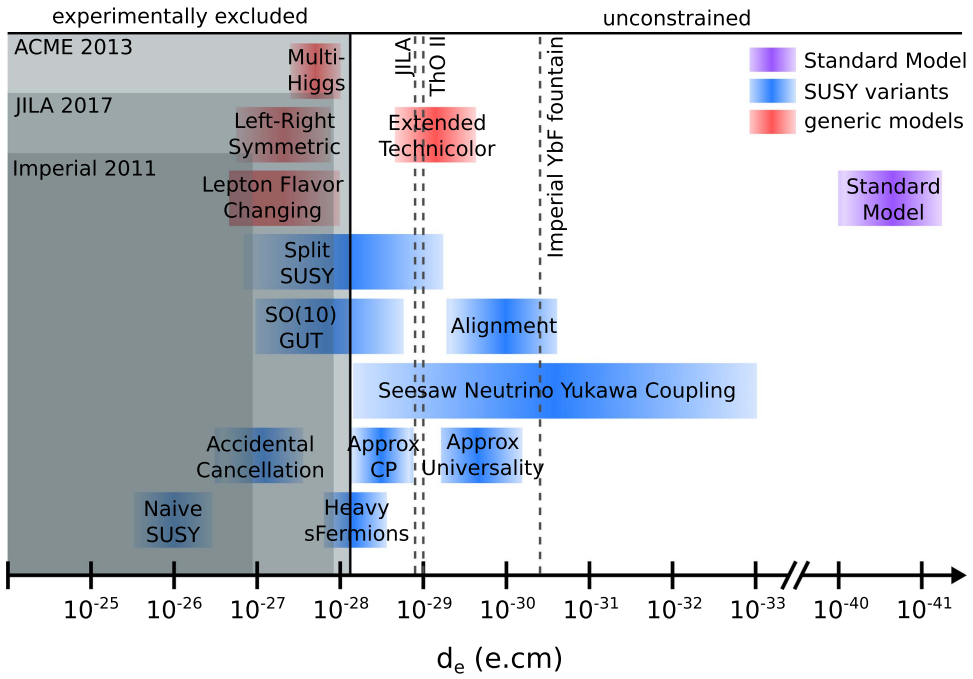

Figure 1. Limits on the electron EDM from molecular experiments: ACME [1], Imperial [6], JILA [7]. The colored bars show the predicted size of the electron EDM from various extensions to the Standard Model. The dashed bars show limits that may be achieved from an upgrades to the ACME and JILA experiments and a fountain experiment under construction using laser-cooled YbF [8]. (Figure adapted from [3].)

to d_e must have an unpaired electron spin; this unpaired spin makes the molecule chemically reactive and so even producing the molecule in the gas phase can be difficult. The first molecular experiment which overcame these difficulties to measure d_e used YbF [6], which has a single unpaired electron in its ground state. The ACME collaboration was able to considerably improve on the limits of d_e by using the molecule ThO. In its ground state ThO has no electron spin, but it has a long-lived excited state in which two electrons have their spins parallel. The state has five times greater amplification of d_e than YbF, and the interaction energy is a billion times larger than that of a free electron in the same electric field.

To measure d_e the ACME collaboration recorded the precession rate of the ThO spin in an electric field. To make this measurement, ThO molecules are produced in a cryogenic source, then travel down a beamline into a region where two conductively coated glass plates apply a small electric field ($\sim$100 V cm^{-1}) which fully mixes the states of opposite parity. There, a linearly polarised laser beam carefully prepares their spin in a plane perpendicular to the electric field. Continuing through the electric field, the ThO spin begins to rotate due to the interaction of the electric dipole with the electric field. After around a millisecond, a second laser beam interrogates the ThO molecules to see how far the spin has precessed.

The size of this rotation caused by d_e is extremely small—a molecule travelling at the average velocity will rotate less than 12 μrads. For a precession this tiny, the basic experiment outlined above is only the smallest step towards a measurement of d_e. The real challenge comes from distinguishing the true effect from the many ways the apparatus can mimic the signature of the EDM. In this regard, the researchers of the ACME collaboration were greatly aided by some favourable properties of the long-lived exited state of ThO. In the electric field, the two orientations of the ThO internuclear axis—either parallel to or anti-parallel to the the applied field—have slightly different energies. By changing the state preparation laser frequency, the researchers were able to choose the direction of the electric field experienced by the ThO spin. The orientation of the ThO molecule could also be more straightforwardly reversed by keeping the state preparation laser frequency the same but changing the sign of the voltages applied to the electric field plates. Since flipping the direction of the internal molecular field also flips the sign of the spin precession angle caused by a true EDM, the researchers were able to separate the signature of an EDM from many other spurious effects.

Making this technique work in practice required exquisite control of the polarisation, intensity, beam pointing and frequency of the state preparation and readout lasers, as well as the ability to precisely tune the magnetic and electric fields experienced by the molecules. Imperfections in these properties could combine together to produce subtle effects which could potentially sneak through and give a precession angle which mimics d_e. The ACME researchers devoted the lion's share of their efforts towards discovering, understanding

and modelling these subtle effects, reducing their experimental imperfections and carefully measuring how those that remained could influence their measurement of d_e.

The ACME result represents an order of magnitude reduction in the possible size of the dipole moment, strongly restricting the form of a swathe of new T-violating physics. In the future, we can expect to hear again from ACME as they continue to improve their experiment. Using a new molecular source, new optical state preparation techniques and a host a small improvements they expect a substantial increase in sensitivity. Elsewhere in the field, the YbF experiment is undertaking a similar revamping. New techniques are also being applied to the problem. An experiment using trapped molecular ions, HfF^+ [7], trades molecule numbers for interrogation time. Their radiofrequency trap provides nearly three orders of magnitude longer spin precession time compared to current beam experiments. Their recent result provides independent confirmation of the limit set by ACME and the authors predict that the next generation of their experiment will further reduce the uncertainty of their method by an order of magnitude. Looking further to the future, we can expect the largest sensitivity increase to come from applying newly developed direct laser cooling techniques to molecular EDM experiments [8]. YbF and BaF have electronic structures similar to SrF and CaF, both of which have been successfully cooled to milli-kelvin temperatures. Researchers in the UK and the Netherlands are actively pursuing this approach, with the ultimate goal of producing a laser cooled fountain of molecules sensitive to the EDM. As figure 1 shows, these enhanced experiments will be sensitive enough to definitively confirm or disprove the predictions of various extensions of the Standard Model. Thanks to the careful work of the ACME collaboration, there is now an even smaller space in which an EDM could be hiding.

ORCID

B E Sauer https://orcid.org/0000-0002-3286-4853
J A Devlin https://orcid.org/0000-0002-4448-5471
I M Rabey https://orcid.org/0000-0001-7997-5246

References

[1] The ACME Collaboration 2014 *Science* **343** 269
[2] The ACME Collaboration 2017 *New J. Phys.* at press (https://doi.org/10.1088/1367-2630/aa708e)
[3] Spaun B N 2014 A ten-fold improvement to the limit of electron electric dipole moment *PhD Thesis* Harvard University (http://gabrielse.physics.harvard.edu/gabrielse/papers/2014/2014 Spaun Benjamin.pdf)
[4] Sandars P G H 1965 *Phys. Lett.* **14** 194
[5] Sandars P G H 1967 *Phys. Rev. Lett.* **19** 1396
Sushkov O P and Flambaum V V 1978 *Zh. Eksp. Theor. Fiz.* **75** 1208
Sandars P G H and Phys Sov 1978 *Sov. Phys.-JETP* **48** 608
[6] Hudson J J, Kara D M, Smallman I J, Sauer B E, Tarbutt M R and Hinds E A 2011 *Nature* **473** 493–6
Kara D M, Smallman I J, Hudson J J, Sauer B E, Tarbutt M R and Hinds E A 2012 *New J. Phys.* **14** 103051
[7] Cairncross W B, Gresh D N, Grau M, Cossel K C, Roussy T S, Ni Y, Zhou Y, Ye J and Cornell E A 2017 arXiv:1704.07928 [physics.atom-ph]
[8] Tarbutt M R, Sauer B E, Hudson J J and Hinds E A 2013 *New J. Phys.* **15** 053034