Colloquium Report 1

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How round is the electron and why does it matter?

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Historically, there was no generally accepted model of the atom at the end of the 19th century. Most physicists believed that the atom was the most basic building block and was indivisible. To find an explanation for the connection between electricity and matter few scientists argued about the existence of a fundamental charge, which was introduced as the term "electron". Dr Tarbutt began with stating the well-known measured properties of the electron.

The mass of an electron, which was given as 9.109 382 15±0.00000045x10^{-31}kg, can be obtained using following formula:

$$m_e = \frac{2\,R\,h}{\alpha^2\,c}$$

R= Rydberg constant h= Planck constant
$\boldsymbol{\alpha}$= fine structure constant c= speed of light in vacuum

The charge of the electron was stated as –1.602 176487±0.000000040x10^{-19}C. It can be calculated with the formula:

$$e^2 = \frac{2\,h\,\alpha}{\mu_0\,c}$$

μ_0= permeability of free space

Dr. Tarbutt also discussed the values for the magnetic dipole moment and the spin of an electron. He supplied the value –9.284 76377±0.00000023x$10^{-24}\frac{J}{T}$ and 5.272 858 14±0.00000026x10^{-35}Js respectively. To compute these values following formulas were used.

$$\mu_e = g_e\,{\lambda_c}^2\,f_q\,\frac{e}{8\,\pi}$$

μ_e = electron magnetic moment g_e = dimensionless magnetic moment

λ_c = Compton wavelength f_q = quantum frequency

$$S = \frac{\hbar}{2}$$

S= Spin $\hbar$= reduced Planck Constant

These values originate from the Committee on Data for Science and Technology (CODATA) 2006, at the National Institute of Standards and Technology (NIST) [1]. The not so well known and measured property of the electron is its roundness or the exact term, the electric dipole moment. The question asked in this presentation was, "What is the roundness of the electron and why does it actually matter?"

Because the electron is a fundamental particle, it is important to find out as much as we can about its physical properties. Besides that fact, there is a deeper connection between the roundness of the electron and symmetry. Symmetry is probably one of the most important ideas in physics. Having a spherical shape and therefore possessing a high degree of symmetry plays an important part in the symmetries of physical systems. The shape of the electron, roundness or non-roundness, is profoundly connected to the Time – reversal symmetry, the Matter – antimatter symmetry, and the possibility to discover new physics or new symmetries in nature.

The basic idea of Time reversal – symmetry is that, given that one recorded a film with a storyline, the film is first watched forward and secondly, it will be watched in reverse. If there is no difference in playing the film forward or backward, it is called Time - reversal symmetric, because you cannot tell the difference if the film was played forward or backward. On the other hand, if you can tell the difference, then it is not time reversal symmetric. This leads to two questions which are interconnected with each other. Do basic physical laws make distinction in time flowing forward or backward? And, "Where does the concept of the arrow of time come from? To visualise the problem the following scenarios were probed.

Scenario 1 encompasses the sequence of a dropping egg. First it is an unbroken egg in the hand. After letting it go and a short flight time it will disintegrate on impact. Watching this sequence forward and then in reverse, it becomes immediately clear which of the sequence is played forward or backward. Scenario 2 incorporates a pendulum swing. After letting the pendulum go it will swing forward and backward. Watching this sequence forward and then in reverse, it will be difficult to tell the difference. Of course after a while it will become apparent because of the changing amplitude of the swing. In one sequence the amplitude becomes larger and in the other the amplitude gets smaller. As a result we can distinguish which is the forward played sequence and the backward played sequence. Scenario 3 involves a free floating electron. Assuming an egg-shape form of an electron with a round end and a pointy end and knowing that electrons have a spin in a certain direction, visualised by the right hand rule, where the fingers follow the direction of the spin and the thumb points either upwards or downwards. If the sequence is going forward the electron is spinning with the pointy end up and the spin pointing up as well. In the case of watching the movie in reverse the spin has to go in reverse as well. In this illustration the spin will point down while the pointy end still points up. Therefore it is quite easy to recognise which sequence is played forward and which is played backward. This example shows beautifully that even the most fundamental laws of physics, that the fabrics of nature itself make a distinction between time flowing forward and backward. But Scenario 3 is flawed. The whole argument is breaking down instantly, if we assume electrons with perfectly spherical shapes. In that case it is no longer evident which way the sequence is played. This dilemma offers a beautiful opportunity to find out the answers to the questions above. Measuring the shape of the electron can tell us if physical laws distinguish between time flowing forward or backward. If it would be found egg-shaped, then we know for sure that such a distinction occurs, right at the most fundamental level of nature and an egg-shaped electron breaks the Time- reversal symmetry.

Matter-antimatter symmetry incorporates the idea that for every particle there is an antiparticle in existence. Particle and antiparticle are exactly identical except for their charges, which are opposite. An electron looks exactly like a positron, except that the electron has a negative charge and the positron has a positive charge. This is true for all other particles and antiparticles. So we say there is symmetry between matter and antimatter. At the beginning of the universe, according to the Big Bang Theory, matter and antimatter were created in exactly equal amounts. However, our observable universe contains 80 billion Galaxies and all are made of matter. To explain this observation something has to break the symmetry between matter and antimatter, so that all the antimatter vanishes and only matter prevails to create a universe in the state we can observe today. It turns out that a non-spherical electron does exactly that.

To get closer to our answer about how round the electron is, different theories predict different answers to that question. The Standard Model of particle physics is an immense successful theory relating the electromagnetic, weak and strong nuclear interactions which controls the dynamics of the known subatomic particles. However, the Standard model has shortcomings especially in regards to the above mentioned problem of matter and antimatter symmetry. This leads to some extension theories to incorporate things the Standard model cannot explain.

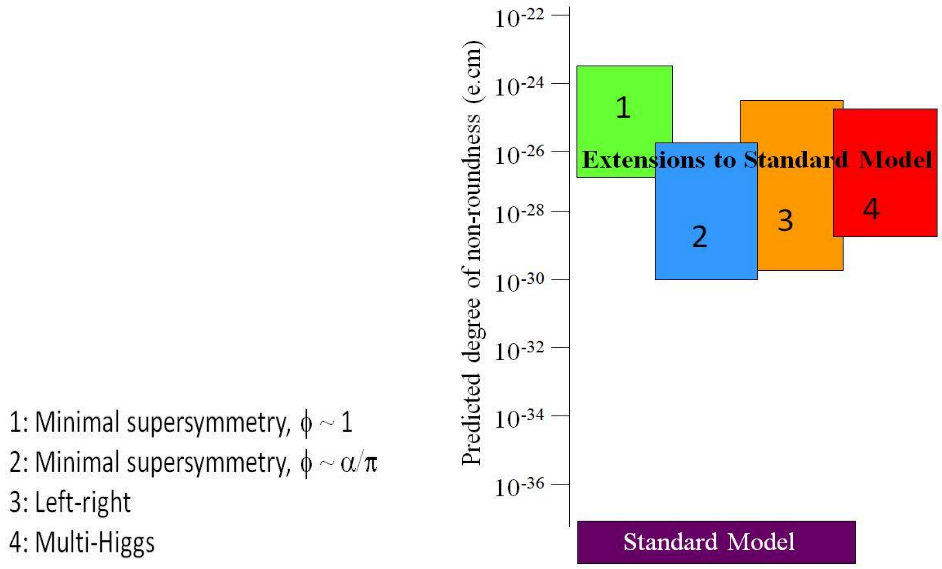
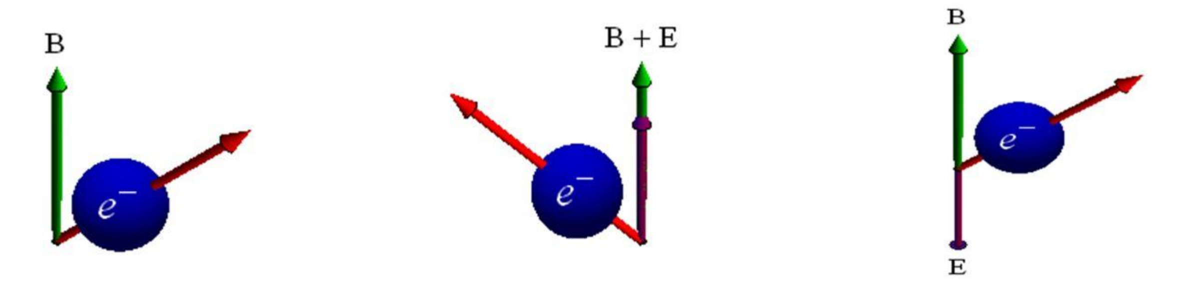


Figure 1: Predicted degree of non-roundness of electron from the Standard model and extensions

In Figure 1 the prediction on how round the electron is, are shown in regards to the standard model as well as the theorised extensions to it. The Standard model predicts the non-roundness of the electron in the region of 10^{-37} e.cm. The Unit of this measurement is composed of the electric charge e, multiplied by the measurement of length in centimetre. This actually means that the electron deviates by 10^{-37} cm from a perfect sphere. In contrast to the standard model all the theoretical Extension models predict a very much different number. All these models predict a number around a billion times larger than the one by the standard model.

As mentioned before, electrons are spinning particles and measuring their spin precession can tell us the shape of the electron.



a.) Electron precessing in magnetic field

b.) Electron precessing in parallel magnetic and electric field

c.) Electron precessing in anti-parallel magnetic and electric field

Figure 2: Electron spin precession due to magnetic and electric fields

As seen in Figure 2a, Electrons exhibit a precessing spin when exposed to a magnetic field. If in addition to the magnetic field an electric field is added to the setup which is parallel to the magnetic field, the electrons precessing spin rate will speed up as symbolised in Figure 2b. In contrast, if the electric field applied to the electron is anti-parallel to the magnetic field the precessing spin rate will slow down as seen in Figure 2c. In the case of a perfectly spherical electron the reversal of the electric field would not have any impact. To measure the non-roundness of the electron, the change of the precessing spin rate with the reversal of the electric field can be gauged.

The result of these measurements taken is the discovery that the electron is round within the measurement uncertainty of 10^{-27}e.cm. So the outcome of that study is that the electron may not be round but the deviation from being a perfect sphere has to be less than the measured 10^{-27} e.cm. Figure 3 shows the measurement in context of the previous graph from Figure 1. Interestingly the measured roundness of the electron already rules out extension models to the standard model. Every model which lies above the dashed line in Figure 3 has to be wrong, because of the observed measurement. Until more precise measuring instruments are developed in the future, the precise answer to how round the electron actually is will elude us.

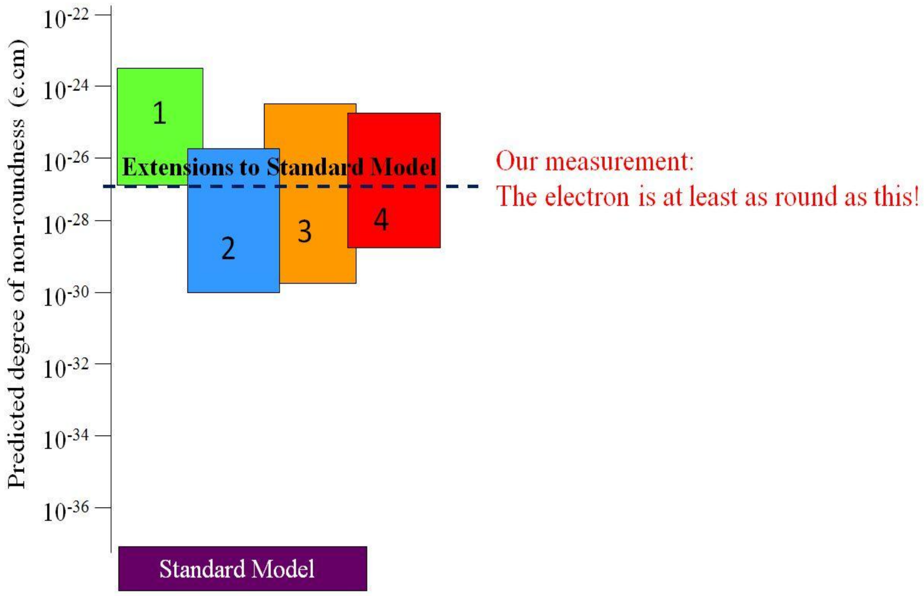


Figure 3: Measured non-roundness in regards to the standard model and its extensions [2]

Referees Report

I attended several colloquia and lectures over the past few months and years for this module and my course study. They include:

Prof Sir Arnold Wolfendale	Durham University	The Search for Intelligent Life
Dr Gbenga Oduntan	University of Kent	Where does Space Begin?
Dr Michael Tarbutt	Imperial College London	How round is the electron and why does it matter?
Prof Ofer Lahav	University College London	Testing The Dark Energy Paradigm and Beyond
Dr John Richer	University of Cambridge	Astrophysics with the Atacama Large Millimetre Array (ALMA)

This and other Kent Physics Centre lectures provided me with a wide spectrum of speakers to compare. Dr Tarbutts talk was an informative way to lead the audience through the reasoning why it is important to measure the roundness of an electron and towards the final goal of measuring the roundness.

The talk lasted for about 50 minutes and described the well-known measured properties of the electron as well as the importance of the electron to the symmetry of physical systems and the process of measuring the non-roundness of the electron. The length was appropriate and the talk was not overwhelmingly scientific, since the audience for these Kent Physics Centre lectures are mostly of mixed science and none-science background. The speaker spoke clearly, in good English, did not appear nervous and did not lose his string of thoughts by the disruptions of several late arrivals.

Dr Tarbutt kept the audience occupied with a variety of demonstrations to visualise physical processes for example the rotating gyroscope and the rotating bicycle wheel, which I really liked. For that he also kept the audience that was further away in mind and connected a webcam to his laptop computer to relay the signal on to the large screens. A PowerPoint presentation was used and the slides were not overloaded with information like some of Prof Lahav slides.

As the talk incorporated a vast amount of theoretical physics ideas not all could be explained in detail and in the time for the talk provided. One example is the reason why the electron breaks the matter-antimatter symmetry. These missing links were picked up by the audience later at the question and answer round. Researching into the well-known properties of the electron, it appeared that Dr Tarbutt used the data sets from the 2006 publication of CODATA. To give this presentation an even more up to date character, the speaker could have used the published data of 2010.

This talk was very interesting especially for me, since my real interests lie more in the field of Space Science and Astrophysics and not in particle physics.

References

[1] National Institute of Standards and Technology. 2011. CODATA Internationally recommended values of the Fundamental Physical Constants [internet]. Available at: <http://physics.nist.gov/cuu/Document/all_2006.pdf> [accessed 05 December 2011]

[2] Hudson, J.J. et al., 2011. Improved measurement of the shape of the electron. *Nature* , 26 May, 473, pp.493-496