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Physics in Perspective

The Roles of Experiment*

Allan Franklin**

In this paper I examine some of the roles that experiment plays in science. One of its important roles is to test theories, but it can also call for a new theory, either by showing that the accepted theory is incorrect, or by exhibiting a new phenomenon that needs explanation. Experiment can also provide hints toward the structure or mathematical form of a theory. It can also provide evidence for the existence of the entities involved in our theories. Finally, it may also have a life of its own, independent of theory. I will illustrate these roles using episodes from the history of contemporary physics including: 1) the discovery of parity nonconservation; 2) the discovery of Bose–Einstein condensation; 3) the demonstration that the "Fifth Force," a proposed modification of Newton's Law of Gravitation, did not exist; and 4) the discovery of the electron by J. J. Thomson. I will also discuss an epistemology of experiment, a set of strategies that provides grounds for reasonable belief in experimental results.

Key words: Physics; experiment; confirmation; refutation.

Introduction

The late Richard Feynman, one of the leading theoretical physicists of the twentieth century, wrote, "The principle of science, the definition, almost, is the following: *The test of all knowledge is experiment*. Experiment is the *sole judge* of scientific 'truth.'[1] Although an activity as varied and successful as science cannot be summed up in any simple method, Feynman got its essence.

The interaction between theory and experiment is complex. One cannot answer the question, "Which comes first, experiment or theory?" simply. Experiment plays many roles in science. One of its important roles is to test theories, but it can also call for a new theory, either by showing that the accepted theory is incorrect, or by exhibiting a new phenomenon that needs explanation. Experiment can also provide hints toward the structure or mathematical form of a theory. It can also provide evidence for the existence of the entities involved in our theories. Finally, it may also have a life of its own, independent of theory. Scientists may investigate a phenomenon just because it looks interesting. This will also provide evidence for a

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** Allan Franklin works on the history and philosophy of science, particularly on the roles of experiment in physics.

future theory to explain. As we shall see, a single experiment may play several of these roles at once.

In all of this activity, however, we must remember that science is fallible. Theoretical calculations, experimental results, or the comparison between experiment and theory may all be wrong. Science is more complex than "The scientist proposes, Nature disposes." It may not always be clear what the scientist is proposing. Theories often need to be articulated and clarified. It also may not be clear how Nature is disposing. Experiments may not always give clear-cut results, and may even disagree for a time.

If experiment is to play these important roles in science then we must have good reasons to believe experimental results. Perhaps even more importantly, we make decisions both as individuals and as a society based on scientific knowledge, and we must have confidence that such knowledge is reliable and trustworthy. I will briefly discuss below an epistemology of experiment, a set of strategies that provides reasonable belief in experimental results. Scientific knowledge can then be reasonably based on experimental results.

In this paper I will discuss some of the roles that experiment plays in physics. I will examine the discovery of nonconservation of parity in the weak interactions, an episode in which experiments confirmed one theory and refuted another at the same time. This was a crucial experiment. I will also discuss the discovery of Bose–Einstein condensation, a case in which a theoretical prediction was confirmed seventy years after it was first made. "The Fall of the Fifth Force" will illustrate not only the refutation of a speculative hypothesis, but also examine how the physics community deals with discordant experimental results. Finally, I will show how J. J. Thomson's experiments on cathode rays provided evidence for the existence of the electron, yet another role for experiment.

The Discovery of Parity Nonconservation: A Crucial Experiment

We learn about the methodology of science not by *a priori* thought, but rather by looking at illustrative episodes from the history of physics. In the practice of science we can see its methods. Let us consider first an episode in which science worked clearly and simply. This was a "crucial" experiment, one that decided unequivocally between two competing theories, or classes of theory. The episode was that of the discovery that parity, mirror-reflection symmetry or left-right symmetry, is not conserved in the weak interactions. Parity conservation was a well-established and strongly-believed principle of physics. It states that physical laws are symmetric with respect to left and right, or to space reflection. In particular, parity conservation requires that the laws of nature do not distinguish between left and right, and that we cannot distinguish between an experiment and its mirror image.* A

* For example, if we wish to determine the magnetic force between two currents we first determine the direction of the magnetic field due to the first current, and then determine the force exerted on the second current by that field. We use two Right-Hand Rules. We get exactly the same answer, however, if we use two Left-Hand Rules. This is left-right symmetry, or parity conservation, in electromagnetism.

violation of parity conservation, or mirror symmetry, is shown in Figure 1. Suppose that a radioactive nucleus decays so that the decay electron is emitted in a direction opposite to the spin direction of the nucleus. The mirror reflection of the decay differs from the real experiment. In the mirror experiment the electron is emitted in the same direction as the spin, as shown.

In the early 1950s physicists were faced with a problem known as the "$\tau-\theta$" puzzle. Based on one set of criteria, that of mass and lifetime, two particles (the τ and the θ) appeared to be the same, whereas on another set of criteria, that of spin and intrinsic parity, they appeared to be different. T. D. Lee and C. N. Yang realized in 1956 that the problem would be solved, and that the two particles would be different decay modes of the same particle, if parity were not conserved in the decay of the particles, a weak interaction.[2] They examined the evidence for parity conservation and found, to their surprise, that although there was strong evidence that parity was conserved in the strong (nuclear) and electromagnetic interactions, there was no supporting evidence that it was conserved in the weak interaction. This had never been tested.

Lee and Yang suggested several experiments that would test their hypothesis that parity was not conserved in the weak interactions. One was the beta decay of oriented nuclei (Figure 1). Consider a collection of radioactive nuclei, all of whose spins point in the same direction. Suppose also that the electron given off in the radioactive decay of the nucleus is always emitted in a direction opposite to the spin of the nucleus. In the mirror image the electron is emitted in the same direction as the spin. The mirror image of the decay is different from the real decay. This would violate parity conservation, or mirror symmetry. Parity would be conserved only if, in the decay of a collection of nuclei, equal numbers of electrons were emitted in both directions. This was the experimental test performed by C. S. Wu and her collaborators in 1957.[3] They aligned ^{60}Co nuclei and counted the number of decay electrons in the two directions, along the nuclear spin and opposite to the spin. Their results are shown in Figure 2 and indicate clearly that more electrons are emitted in a direction opposite to the spin than along the spin direction. Parity is not conserved in the weak interactions.

Two other experiments, reported at the same time, on the sequential decay $\pi \rightarrow \mu \rightarrow e$ also showed parity nonconservation.[4] These three experiments decided between

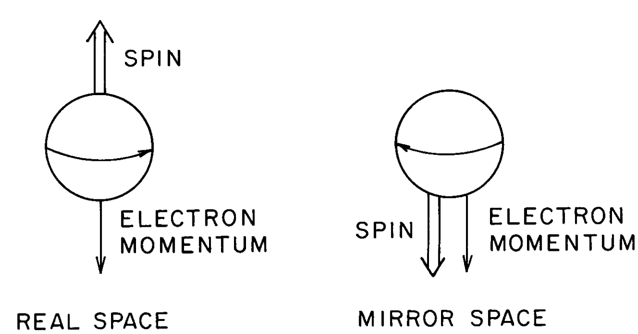

Fig. 1. Nuclear spin and momentum of the decay electron in both real space and in mirror space.

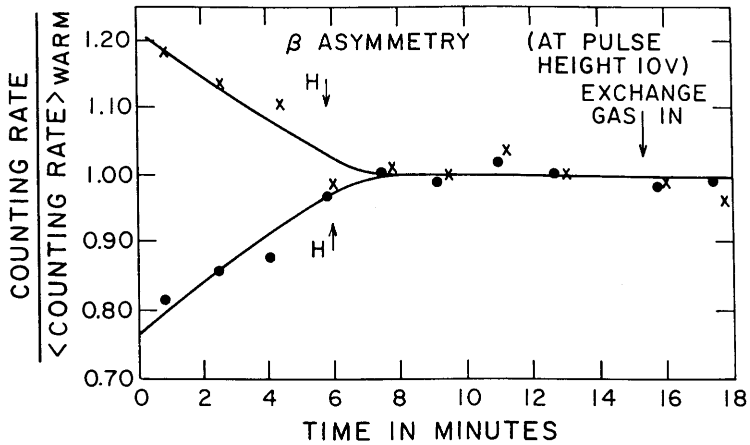

Fig. 2. Relative counting rates for β particles from the decay of oriented ^{60}Co nuclei for different nuclear orientations (field directions). There is a clear asymmetry with more β particles being emitted opposite to the spin direction. *Source*: C. S. Wu, et al., "Experimental Test for Parity Nonconservation in Beta Decay" (ref. 3), p. 1414.

two classes of theories – that is, between those theories that conserve parity and those that do not. They refuted the theories in which parity was conserved and supported those in which it was not. These experiments also called for a new theory of β decay and the weak interactions because the then-accepted theory conserved parity.

The Discovery of Bose–Einstein Condensation: Confirmation After Seventy Years

In the previous episode we saw a decision between two competing classes of theories. There was, however, no explicit theoretical prediction to compare to an experimental result. In this next episode, the discovery of Bose–Einstein condensation, we will see the confirmation of a theoretical prediction seventy years after it was first made. A noteworthy aspect of this episode is that the phenomenon in question had never been observed previously. This raises an epistemological problem. How do you know you have observed something when it has never been seen before?

Elementary particles can be divided into two classes: bosons with integral spin (0, 1, 2, . . .), and fermions with half-integral spin (1/2, 3/2, 5/2, . . .). On the one hand, fermions, such as electrons, obey the Pauli exclusion principle. Two fermions cannot be in the same quantum-mechanical state. This explains the shell structure of electrons in atoms and the periodic table. On the other hand, any number of bosons can occupy the same state. At sufficiently low temperatures, when thermal motions are very small, there is a strong tendency for a group of bosons to all go into the same state. S. N. Bose in 1924 and Albert Einstein in 1924–1925 predicted that a gas of noninteracting bosonic atoms will, below a certain temperature, suddenly develop a macroscopic population in the lowest energy quantum state.*[5]

The experiment that first demonstrated the existence of Bose–Einstein condensation was done by Carl Wieman, Eric Cornell, and their collaborators.[6] The experimental apparatus is shown in Figure 3. In outline the experiment was as follows. A sample of ^{87}Rb atoms was cooled in a magneto-optical trap. It was then loaded into a magnetic trap and further cooled by evaporation. The condensate was formed and the trap removed, allowing the condensate to expand. The expanded condensate was illuminated with laser light and the resulting shadow of the cloud was imaged, digitized, and stored.**

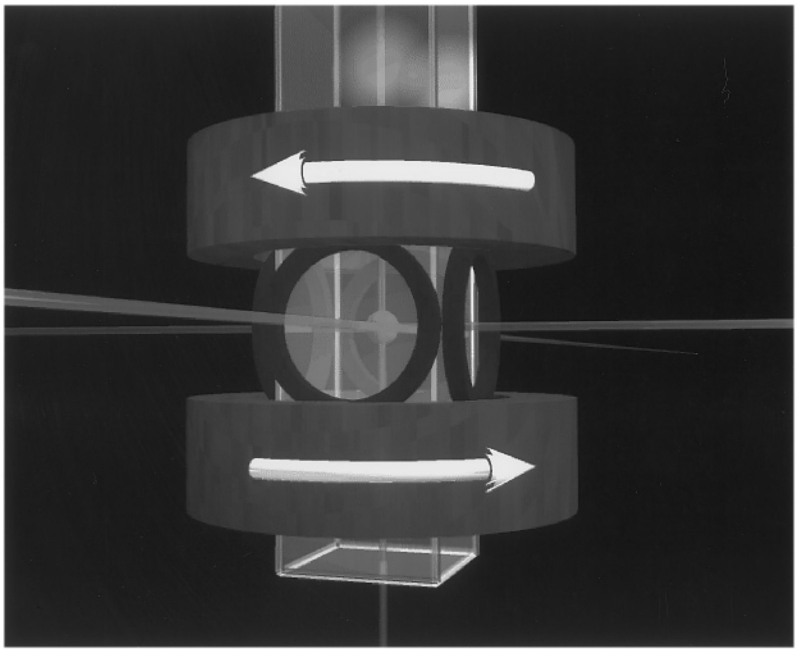

Fig. 3. Schematic of the Bose–Einstein condensation apparatus. *Source*: M. H. Anderson, et al., (ref. 6), p. 199.

* Bose's paper had originally been rejected by the *Philosophical Magazine*. He then sent it, in English, to Einstein with a request that if Einstein thought the paper merited publication that he would arrange for publication in the *Zeitschrift für Physik*. Einstein personally translated the paper and submitted it to the *Zeitschrift für Physik*, adding a translator's note, "In my opinion, Bose's derivation of the Planck formula constitutes an important advance. The method used here also yields the quantum theory of the ideal gas, as I shall discuss elsewhere in more detail." This discussion appeared in Einstein's own papers of 1924 and 1925.

** One difficulty with using rubidium is that at very low temperatures rubidium should be a solid. (In fact, rubidium is a solid at room temperature.) Wieman, Cornell and their collaborators avoided this difficulty by creating a system that does not reach a true equilibrium. The vapor sample created equilibrates to a thermal distribution as a spin polarized gas, but takes a very long time to reach its true equilibrium state as a solid. At the low temperatures and density of the experiment the rubidium remains as a metastable super-saturated vapor for a long time.

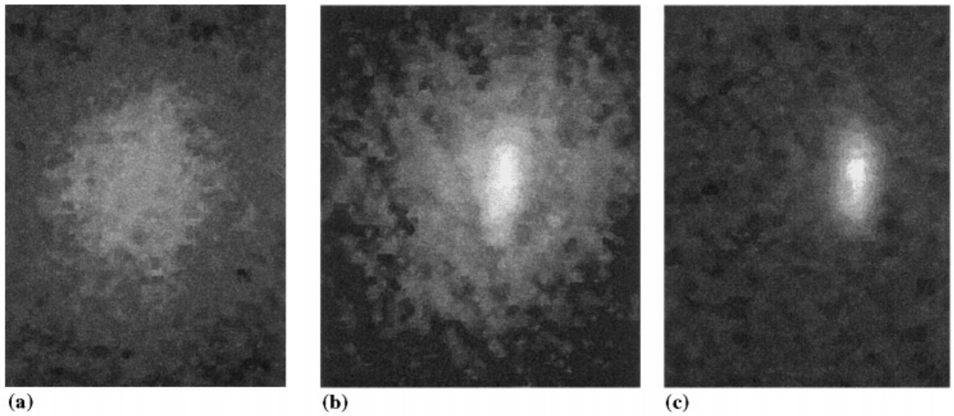

Fig. 4. False color images of the velocity distribution of the rubidium Bose–Einstein condensation cloud: (a) just before the appearance of the condensate, (b) just after the appearance of the condensate, and (c) after further evaporation has left a sample of nearly pure condensate. *Source*: M. H. Anderson, et al. (ref. 6), p. 199.

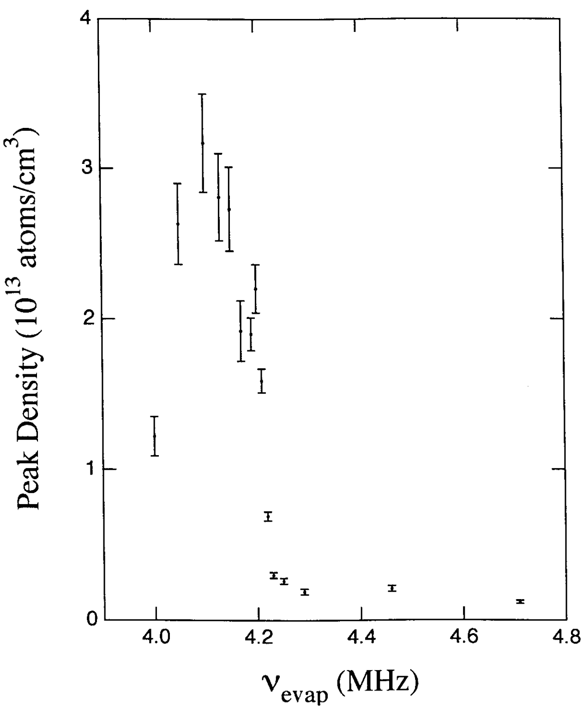

Fig. 5. Peak density at the center of the sample as a function of the final depth of the evaporative cut, ν_{evap}. As evaporation progresses to smaller values of ν_{evap}, the cloud shrinks and cools, causing a modest increase in peak density until ν_{evap} reaches 4.23 MHz. The sudden discontinuity at 4.23 MHz indicates the first appearance of the high-density condensate as the cloud undergoes a phase transition. *Source*: M. H. Anderson, et al. (ref. 6), p. 200.

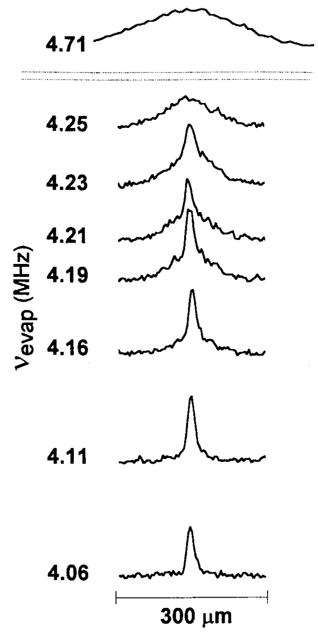

Fig. 6. Horizontal sections taken through the velocity distribution at progressively lower values of ν_{evap} shows the appearance of the condensate fraction. *Source*: M. H. Anderson, et al. (ref. 6), p. 200.

The experimental results are shown in Figures 4–6. Figure 4 shows the velocity distribution of the rubidium gas cloud (a) just before the appearance of the condensate, (b) just after, and (c) after further evaporation of the cloud has left a sample of nearly pure condensate. This figure also shows the spatial distribution of the gas.* Although the measurement process destroyed the condensate sample, the entire process can be repeated so that one can measure the cloud at different stages. Figure 5 shows the peak density of the gas as a function of ν_{evap}, the RF frequency used to excite the atoms into a non–confined state and to assist the cooling by evaporation. There is a sharp increase in density at $\nu_{evap} = 4.23$ MHz (megahertz). This indicates the appearance of Bose–Einstein condensation. As the sample is further cooled one expects to observe a two-component cloud with a dense central condensate surrounded by a diffuse non-condensate. This is seen clearly in both Figures 4 and 6. Figure 6 shows horizontal sections of the rubidium cloud. At 4.71 MHz, above the transition temperature, one sees only a broad thermal distribution. Beginning at 4.23 MHz one sees the appearance of a sharp central peak, the Bose–Einstein condensate, above the thermal distribution. At 4.11 MHz the cloud is almost a pure condensate.

There are three clear indications of the presence of Bose–Einstein condensation: (1) the velocity distribution of the gas shows two distinct components, (2) the

* The spatial distribution is identical to the velocity distribution for all harmonic potentials if each axis is linearly scaled by the harmonic oscillator frequency for that dimension.

sudden increase in density as the temperature decreases, and (3) the elliptical shape of the velocity distribution (Figure 4). The velocity distribution should be elliptical, because for the harmonic trap used the force in the z direction was eight times larger than in the x and y directions. No phenomenon other than Bose–Einstein condensation could plausibly explain these results.

This result was sufficiently credible that Keith Burnett, an atomic physicist at Oxford University, remarked in the same issue of *Science* in which Wieman and Cornell reported their result, "In short, they have observed the phenomenon called Bose–Einstein condensation (BEC) in a gas of atoms for the first time. The term Holy Grail seems quite appropriate given the singular importance of this discovery."[7] Burnett's view was shared by the physics community.*

A theoretical prediction had been confirmed after seventy years.

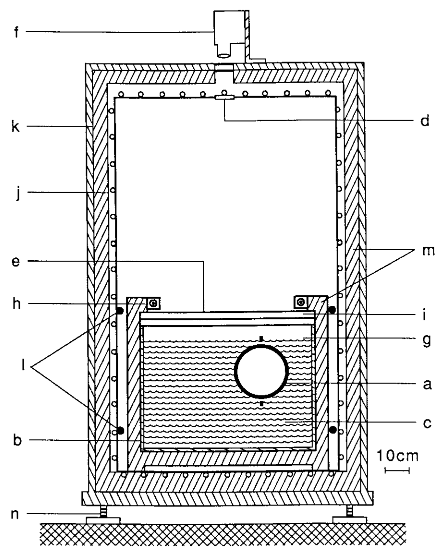

Fig. 7. Schematic diagram of the differential accelerometer used in Thieberger's experiment. A precisely balanced hollow copper sphere (a) floats in a copper-lined tank (b) filled with distilled water (c). The sphere can be viewed through windows (d) and (e) by means of a television camera (f). The multiple-pane window (e) is provided with a transparent x-y coordinate grid for position determination on top with a fine copper mesh (g) on the bottom. The sphere is illuminated for one second per hour by four lamps (h) provided with infrared filters (i). Constant temperature is maintained by means of a thermostatically controlled copper shield (j) surrounded by a wooden box lined with Styrofoam insulation (m). The Mumetal shield (k) reduces possible effects due to magnetic field gradients and four circular coils (l) are used for positioning the sphere through forces due to ac-produced eddy currents, and for dc tests. *Source*: P. Thieberger, "Search for a Substance-Dependent Force with a New Differential Accelerometer" (ref. 10), p. 1067.

* Wieman and Cornell were awarded the London Prize, the most important award for work in low-temperature physics.

The Fall of the Fifth Force

The "Fifth Force" was a proposed modification of Newton's Law of Universal Gravitation. Based on a reanalysis of the original Eötvös experiment,* Ephraim-Fischbach and collaborators in 1986 suggested modifying the gravitational potential between two masses from $V = -Gm_1m_2/r$ to $V = -Gm_1m_2/r\ [1 + \alpha\, e^{-r/\lambda}]$, where the second term gives the Fifth Force with strength α and range λ.[8] The reanalysis also suggested that α was approximately 0.01 and λ was approximately 100 m. In addition, in contrast to the ordinary gravitational force, the Fifth Force was composition dependent. The Fifth Force between a copper mass and an aluminum mass would differ from that between a copper mass and a lead mass.[9]

In this episode, we also have a hitherto unobserved phenomenon along with discordant experimental results. The first two experiments on the Fifth Force gave contradictory answers. One experiment supported the existence of the Fifth Force, whereas the other found no evidence for it. The first experiment, that of Peter Thieberger in 1987, looked for a composition-dependent force using a new type of experimental apparatus, which measured the differential acceleration between copper and water.[10] The experiment was conducted near the edge of the Palisades cliff in New Jersey to enhance the effect of an intermediate-range force. The experimen-

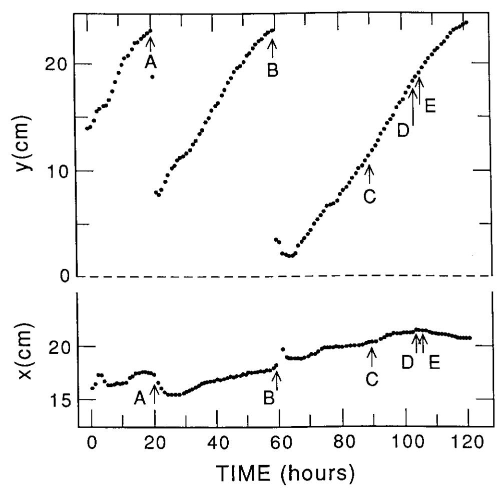

Fig. 8. Position of the center of the sphere as a function of time. The *y* axis points away from the cliff. The position of the sphere was reset at points A and B engaging the coils shown in Figure 7. *Source*: P. Thieberger, "Search for a Substance-Dependent Force with a New Differential Accelerometer" (ref. 10), p. 1067.

* The original Eötvös experiment was designed to measure the ratio of the gravitational mass to the inertial mass of different substances. Roland Eötvös found that these two masses were equal to approximately one part in a million.

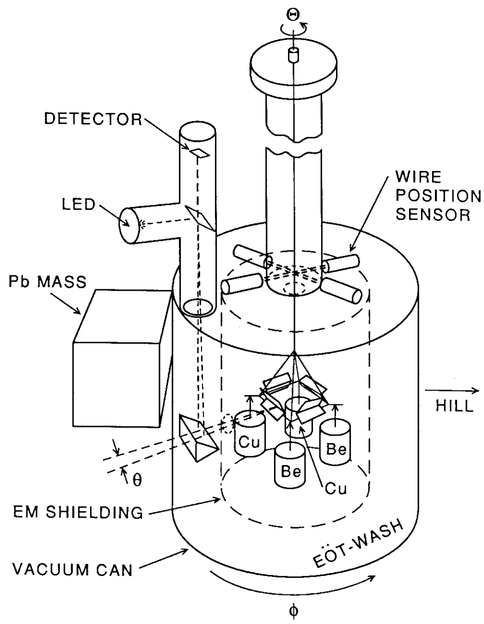

Fig. 9. Schematic view of the University of Washington torsion pendulum experiment. The Helmholtz coils are not shown. *Source*: C. W. Stubbs, et al., "Search for an Intermediate-Range Interaction" (ref. 12), p. 1070.

tal apparatus is shown in Figure 7. The horizontal acceleration of the copper sphere relative to the water can be determined by measuring the steady-state velocity of the sphere and applying Stokes's law for motion in a resistive medium. Thieberger's results are shown in Figure 8. The sphere clearly has a velocity, indicating the presence of a force. He found a velocity 4.7 ± 0.2 mm/h in the y-direction (perpendicular to the cliff, as predicted) and 0.6 ± 0.2 mm/h in the x-direction. Thieberger concluded, "The present results are compatible with the existence of a medium-range, substance-dependent force."[11]

The second experiment, by the whimsically named Eöt–Wash group, was also designed to look for a substance-dependent, intermediate-range force.[12] The apparatus was located on a hillside on the University of Washington campus, in Seattle (Figure 9). If the hill attracted the copper and beryllium bodies differently, then the torsion pendulum would experience a net torque. This torque could be observed by measuring shifts in the equilibrium angle of the torsion pendulum as the pendulum was moved relative to a fixed geophysical point. Their experimental results are shown in Figure 10. The theoretical curves were calculated with the assumed values of 0.01 and 100m, for the Fifth Force parameters α and λ, respectively. These were the best values for the parameters at the time. There is no evidence for a Fifth Force.

The problem was, however, that both experiments appeared to be carefully done, with no apparent mistakes in either experiment. Ultimately, the discord between

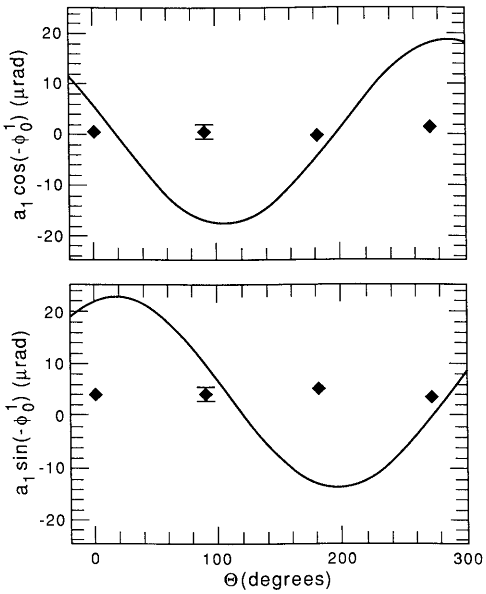

Fig. 10. Deflection signal as a function of θ. The theoretical curves correspond to the signal expected for $\alpha = 0.01$ and $\lambda = 100$ m. *Source*: F. J. Raab, "Search for an Intermediate-Range Interaction: Results of the Eöt–Wash I Experiment" (ref. 12), p. 574.

Thieberger's result and that of the Eöt–Wash group was resolved by an overwhelming preponderance of evidence in favor of the Eöt–Wash result.[13] The subsequent history is an illustration of one way in which the scientific community deals with conflicting experimental evidence. Rather than making an immediate decision as to which were the valid results, which seemed extremely difficult to do on methodological or epistemological grounds, the community chose to await further measurements and analysis before coming to any conclusion about the evidence. The torsion-balance experiments of the Eöt–Wash group were repeated by others.[14] These repetitions, in different locations and using different substances, gave consistently negative results. In addition, P. G. Bizzeti and collaborators, using a float apparatus similar to that of Thieberger, also obtained results showing no evidence of a Fifth Force.[15] There is, in fact, no explanation of Thieberger's original, presumably incorrect, results. The scientific community chose, I believe quite reasonably, to regard the preponderance of negative results as conclusive.* Experiment had shown that there is no Fifth Force.

* It is a fact of experimental life that experiments rarely work when they are initially turned on and that experimental results can be wrong, even if there is no apparent error. It is not necessary to know the exact source of an error in order to discount or to distrust a particular experimental result. Its disagreement with numerous other results can, I believe, be sufficient.

Evidence for a New Entity: J. J. Thomson and the Electron

Experiment can also provide evidence for the existence of entities involved in our theories. In this section I will discuss the grounds for belief in the existence of the electron by examining J. J. Thomson's experiments on cathode rays. His 1897 experiment on cathode rays is generally regarded as the "discovery" of the electron.

The purpose of J. J. Thomson's experiments was clearly stated in the introduction to his 1897 paper:

> The experiments discussed in this paper were undertaken in the hope of gaining some information as to the nature of Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the aether to which – inasmuch as in a uniform magnetic field their course is circular and not rectilinear – no phenomenon hitherto observed is analogous: another view of these rays is that, so far from being wholly aetherial, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity.[16]

Thomson's first order of business was to show that the cathode rays carried negative charge. This had presumably been shown previously by Jean Perrin. Perrin placed two coaxial metal cylinders, insulated from one another, in front of a plane cathode. The cylinders each had a small hole through which the cathode rays could pass onto the inner cylinder. The outer cylinder was grounded. When cathode rays passed into the inner cylinder, an electroscope attached to it showed the presence of a negative electrical charge. When the cathode rays were magnetically deflected so that they did not pass through the holes, no charge was detected. "Now the supporters of the aetherial theory do not deny that electrified particles are shot off from the cathode; they deny, however, that these charged particles have any more to do with the cathode rays than a rifle-ball has with the flash when a rifle is fired."[17]

Thomson repeated the experiment, but in a form that was not open to that objection. His apparatus is shown in Figure 11. The two coaxial cylinders with holes are shown. The outer cylinder was grounded and the inner one attached to an electrometer to detect any charge. The cathode rays from A pass into the bulb, but would not enter the holes in the cylinders unless deflected by a magnetic field.

> When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer when the induction coil producing the rays was set in action was small and irregular; when, however, the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer.... If the rays were so much bent by the magnet that they overshot the slits in the cylinder, the charge passing into the cylinder fell again to a very small fraction of its value when the aim was true. *Thus this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays.*[18]

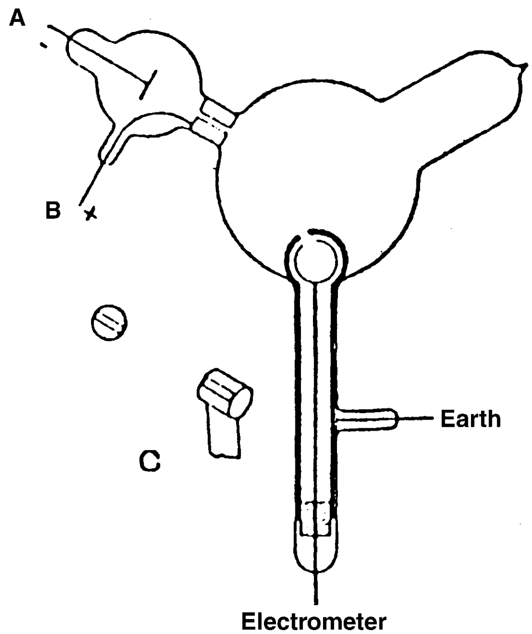

Fig. 11. Thomson's apparatus for demonstrating that cathode rays have negative charge. The slits in the cylinders are shown. *Source*: J. J. Thomson, "Cathode Rays" (ref. 16), p. 295.

This experiment also demonstrated that cathode rays were deflected by a magnetic field in exactly the way one would expect if they were negatively charged material particles.

There was, however, a problem for the view that cathode rays were negatively charged particles. Several experiments, in particular those of Heinrich Hertz, had failed to observe the deflection of cathode rays by an electrostatic field. Thomson proceeded to answer this objection. His apparatus is shown in Figure 12. Cathode rays from C pass through a slit in the anode A, and through another slit at B. They then pass between plates D and E and produce a narrow well-defined phosphorescent patch at the end of the tube, which also had a scale attached to measure any deflection. When Hertz had performed the experiment he had found no deflection

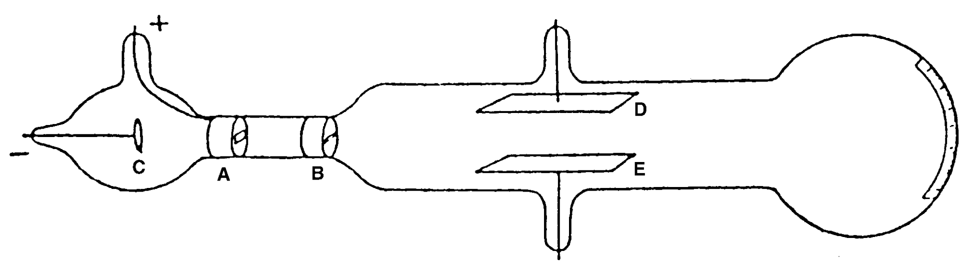

Fig. 12. Thomson's apparatus for demonstrating that cathode rays are deflected by an electric field. It was also used to measure m/e. *Source*: J. J. Thomson, "Cathode Rays" (ref. 16), p. 296.

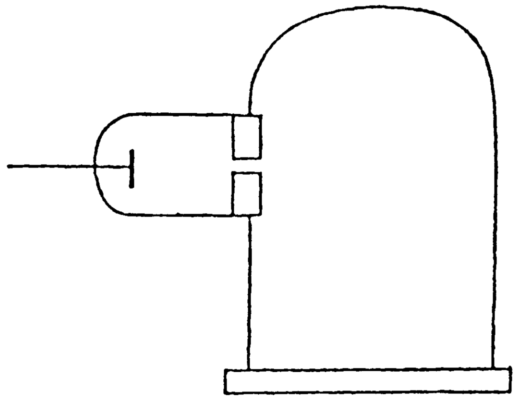

Fig. 13. Thomson's apparatus for demonstrating the magnetic deflection of cathode rays. *Source*: J. J. Thomson, "Cathode Rays" (ref. 16), p. 301.

when a potential difference was applied across D and E. He concluded that the electrostatic properties of the cathode ray are either nil or very feeble. Thomson admitted that when he first performed the experiment he also saw no effect. "[On] repeating this experiment I at first got the same result [no deflection], but subsequent experiments showed that the absence of deflexion is due to the conductivity conferred on the rarefied gas by the cathode rays.* On measuring this conductivity it was found that it diminished very rapidly as the exhaustion increased; it seemed that on trying Hertz's experiment at very high exhaustion there might be a chance of detecting the deflexion of the cathode rays by an electrostatic force."[19] Thomson performed the experiment at lower pressure [higher exhaustion] and observed the deflection.

Thomson also demonstrated that the cathode rays were deflected by a magnetic field. His apparatus for demonstrating the magnetic deflection of cathode rays is shown in Figure 13. The rays from the cathode in the side tube passed through the slit into a bell jar and were bent by a magnetic field provided by two Helmholtz coils (not shown). The cathode rays passed in front of a vertical glass plate ruled into small squares. The path of the rays was photographed as they passed through the bell jar.

Thomson concluded:

> As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.**[20]

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* Thomson actually investigated the conductivity of the gas in the tube under varying pressure conditions.

** Thomson's argument is the "duck argument." If it looks like a duck, quacks like a duck, and waddles like a duck, then we have good reason to believe that it is a duck. One need only reconstitute the argument using "it" as cathode rays and negatively charged particles as ducks.

Having established that cathode rays were negatively charged material particles, Thomson went on to discuss what the particles were. "What are these particles? are they atoms, or molecules, or matter in a still finer state of subdivision." To investigate this question Thomson made measurements on the mass-to-charge ratio of cathode rays. He used two different methods. The first used the total charge carried by the beam of cathode rays in a fixed period of time, the total energy carried by the beam in the same time, and the radius of curvature of the particles in a known magnetic field.* Thomson used three different types of tube. The first and the third were similar to Figure 12, but with plates D and E removed and replaced by two coaxial cylinders attached to the end of the tube. The difference between these two was that the openings in the first cylinders were much larger than in the third type of tube. The second type of tube was similar to that used for photographing the paths of the particles in a magnetic field (Figure 13), with two cylinders again placed in the tube. Thomson obtained the following average values (my calculation) for m/e: $(0.41 \pm 0.07) \times 10^{-7}$, $(0.53 \pm 0.05) \times 10^{-7}$, and $(0.87 \pm 0.15) \times 10^{-7}$ g/absolute electromagnetic unit, respectively.** Thomson believed that the last value, that obtained with tube 3, was the most reliable because of charge leakage from the inner to the outer cylinder caused by the conductivity of the residual gas induced by the cathode rays in the other types of tube.

Thomson's second method eliminated the problem of leakage, and used both the electrostatic and magnetic deflection of the cathode rays.*** His apparatus is shown in Figure 12. It also included a magnetic field that could be created perpendicular to both the electric field and the trajectory of the cathode rays. Thomson considered this method both less laborious and also more accurate than the magnetic-deflection and heating methods.

Let us consider a beam of particles of mass m, charge e, and velocity v. Suppose the beam passes through an electric field F in the region between plates D and E, which has a length L. The time for a particle to pass through this region is $t = L/v$. The electric force on the particle is Fe and its acceleration is $a = Fe/m$. The deflection d at the end of the region is given by

$$d = \tfrac{1}{2}at^2 = \tfrac{1}{2}(eF/m)L^2/v^2.$$

Now consider a situation in which the beam of cathode rays simultaneously pass through both F and a magnetic field B in the same region. Thomson adjusted B so

* Let e be the charge of an individual particle and m be its mass. Let N be the number of particles passing through a crossection of the beam in a given time. $Q = Ne$ is the total charge carried by these particles. The total energy W carried by the particles is $W = \frac{1}{2}Nmv^2$, where v is the velocity of the particles. Thomson measured Q with an electrometer and W by measuring the temperature rise of a body of known thermal capacity. He also measured the radius of curvature when the particle passed through a known magnetic field: $mv^2/\rho = evB$, where ρ is the radius of curvature and B is the magnetic field. Thus $mv/e = B\rho$. Combining these equations one finds that $m/e = B^2\rho^2Q/2W$. If B, ρ, Q, and W are measured then one knows m/e.

** One absolute unit of electricity in the electromagnetic system was defined as the amount of electricity that would deposit 0.01118 g of silver in electrolysis.

*** This is the method shown in most modern physics textbooks.

that the beam was undeflected. Thus the magnetic force was equal to the electrostatic force:

$evB = eF$ or $v = F/B$.

This determined the velocity of the beam. Thus,

$m/e = B^2L^2/2\,dF$.

Each of the quantities in the above expression was measured, so e/m or m/e could be determined.

Using this method Thomson found a value of m/e of $(1.29 \pm 0.17) \times 10^{-7}$ g/absolute electromagnetic unit. This value was independent of both the gas in the tube and of the metal used in the cathode, suggesting that the particles were constituents of the atoms of all substances. It was also far smaller, by a factor of 1000, than the smallest value previously obtained, 10^{-4}, for the hydrogen ion in electrolysis.

Thomson remarked that this might be due to the smallness of m or to the largeness of e. He argued that m was small, citing Phillip Lenard's work on the range of cathode rays in air. The range, which is related to the mean free path for collisions, and which depends on the size of the object, was 0.5 cm. The mean free path for molecules in air was approximately 10^{-5} cm. If the cathode ray traveled so much farther than a molecule before colliding with an air molecule, then it must be much smaller than a molecule.*

Thomson had shown that cathode rays behave as one would expect negatively charged material particles to behave. They deposited negative charge on an electrometer, and were deflected by both electric and magnetic fields in the appropriate direction for a negative charge. In addition, the value for the mass-to-charge ratio was far smaller than the smallest value previously obtained, that for the hydrogen ion. If the charge were the same as that on the hydrogen ion, the mass would be far less. In addition, the cathode rays traveled farther in air than did molecules, also implying that they were smaller than an atom or molecule. Thomson concluded that these negatively charged particles were constituents of atoms. In other words, Thomson's experiments had given us good reasons to believe in the existence of electrons.

The Epistemology of Experiment

If experiment is to play all of these important roles, and others, in science, then we must have good reasons for believing in the correctness of experimental results. In the following discussion I present an epistemology of experiment, a set of strategies that physicists can, and do, use to argue for the correctness of their results. These strategies can, in fact, be independently justified.[21]

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* Not everything Thomson concluded is in agreement with modern views. Although he believed that the electron was a constituent of atoms, he thought that it was the primordial atom from which all atoms were constructed, similar to Prout's view that all atoms were constructed from hydrogen atoms. He also suggested that the charge on the electron might be larger than that of the hydrogen ion.

Perhaps the most important and widely used strategy is that of experimental checks. The experimenter checks that the apparatus can reproduce known results. For example, if we wished to argue that the spectrum of a substance obtained with a new type of spectrometer is correct, we might check that this new spectrometer could reproduce the known Balmer Series in hydrogen. If we correctly observe the Balmer Series, then we strengthen our belief that the spectrometer is working properly. This also strengthens our belief in the results obtained with that spectrometer.

Another widely used strategy is that of independent confirmation, observing the same result with two different experimental apparatuses. If we observe the same astronomical object with both an ordinary telescope and with a radio telescope, then we have good reason to believe the observation. It would be extremely unlikely that two such different experimental apparatuses would produce the same incorrect result. If we can eliminate all plausible sources of experimental error and eliminate all alternative explanations of the result, then we also have good reason to believe the result. When scientists claimed to have observed electric discharges in the rings of Saturn, they argued for their result by showing that it could not have been caused by defects in the telemetry, by interaction with the environment of Saturn, by lightning, or by dust. The only explanation left for their result was that it was due to electric discharges in the rings. (The same strategy was applied in the discovery of Bose–Einstein condensation. There was no other plausible explanation of the experimental results.) In addition, the same result was observed by both Voyager 1 and Voyager 2. This provided independent confirmation.

Sometimes scientists may argue for a result by intervening in their experiment. One reason we might believe that the image of a cell observed with a microscope is correct is because we have injected fluid or stain into the cell. We expect to observe that the cell changes size or color. When we do, we believe our microscope is working properly, and we trust the images we see.

These strategies provide us with good reasons to believe experimental results. The results are then legitimately used in the various ways we have already discussed.

In the episode of parity nonconservation, the experimenters gave arguments to support their claim that their result was, in fact, due to the asymmetric β decay of polarized ^{60}Co nuclei. They calibrated their electron counter by observing the electrons of known energy from the already known ^{137}Cs conversion line. They also established that the nuclei were polarized by observing the known γ-ray asymmetry between the equatorial and polar directions. In the case of Bose–Einstein condensation the experimenters argued that no plausible malfunction of their apparatus or other alternative explanation could explain the three indications of the presence of Bose–Einstein condensation: (1) the velocity distribution of the gas showing two distinct components, (2) the sudden increase in density as the temperature decreases, and (3) the elliptical shape of the velocity distribution (Figure 4). In both of the discordant experiments on the Fifth Force, the experimenters argued that not only was their apparatus sensitive to such a force, but that all plausible sources of error that might mimic or mask the effect of such a force had been eliminated. Ultimately it was decided, on the basis of an overwhelming preponderance of evidence, that Thieberger must have overlooked such an effect. Thomson's experimental results were credible because his apparatus was based on the already well-supported theories of electricity and magnetism.

Conclusion

In this paper I have illustrated several, but certainly not all, of the important roles that experiment plays in science. We have seen experiment deciding between two competing theories, calling for a new theory, confirming a theory, refuting a theory, and providing evidence for the existence of an elementary particle. I have also outlined an epistemology of experiment, a set of strategies that provides us with reasonable grounds for belief in experimental results. We have also seen that these strategies were, in fact, used in the experiments discussed earlier. Thus, experiment can legitimately play these important roles and provide the basis for scientific knowledge.

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Department of Physics
Campus Box 390
University of Colorado
Boulder, CO 80309-0390, USA
e-mail: Allan.Franklin@Colorado.edu

Fickle Fame

The fourth Lord Rayleigh, J. J. Thomson's biographer, recalled a story illustrating Thomson's lack of fame late in life in certain circles:

> An incident which caused a good deal of amusement was as follows. A paragraph had appeared in the *Manchester Guardian*, representing someone of prominence in local government there as depreciating the value of book learning.
>
>> There was (he said) a clever boy at school with me, little Joey Thomson, who took all the prizes. But what good has all his book learning done him? Who ever hears of little Joey Thomson now?

Quoted in Lord Rayleigh [Robert John Strutt], *The Life of Sir J. J. Thomson, O. M*. (Cambridge: Cambridge University Press,1942), p. 269.