

Einstein and the Gravity Probe B Experiment

In this world year of physics, it is appropriate to appreciate the interplay of theory and experiments in physics. The first exposure to experiments one gets typically involve experiments that determine various properties of materials such as their densities, boiling/freezing temperatures, refractive indices. Further on, one meets more sophisticated ones determining masses, charges etc of more elementary particles such as protons, electrons etc. Then there are experiments involving huge particle accelerators that *create*, new types of matter and infer laws governing their behaviour. There are also experiments that are designed to test particular predictions of particular theories very, very precisely. One such experiment which has been recently completed is the Gravity Probe B Experiment.

Gravity Probe B is a joint experiment of Stanford University and NASA. It is a space based experiment, originally proposed by Leonard Schiff of Stanford University in 1960, and involves flying the experimental assembly, the ‘probe B’, in a low orbit around the earth for over a year. It was launched on April 20, 2004 and has completed data collection last month. The data analysis is expected to take another year after which the results of the tests will be known. Incidentally, Gravity Probe A was another experiment NASA carried out in the mid seventies which tested and confirmed the prediction of gravitational red-shift or change in the color of light propagating in a gravitational field.

Gravity Probe B is a highly sophisticated experiment designed specifically to test one particular prediction of one particular theory. The theory is Einstein’s theory of gravity, also known as the General Theory of Relativity or GTR for short. According to this theory, a large spinning body, earth for example, modifies the space-time geometry in its vicinity. Another, small spinning body, in an orbit around the large body, precesses or changes its axis of rotation in response to the space-time geometry. The theory predicts the amount of precession and the test consists of measuring the precession and checking it against the theoretical prediction.

Several questions arise immediately: why this theory is being tested? why this particular test involving spinning bodies? what is so special about the experiment itself? In the following, we will try to understand answers to these questions.

The Theory: Eleven years after the miraculous year of 1905, Einstein presented his General Theory of Relativity and drastically revised our conception of space-time and the phenomenon of gravity. What was the earlier conception and what is the revision?

Intuitively, we are all familiar with the *three dimensional space* in which we conduct our activities at various *times*. Since Newton and prior to 1905, everyone assumed that while location labels of an event (eg a light being turned on some where at certain time) depend on where an observer is (and vary if the observer is moving relative to the event), the same does not apply to the time label. Two observers with identical, synchronized clocks will assign the

same time label to an event irrespective of their (uniform) motion relative to the event. This assumes that the information that the event has taken place is received by all such observers *instantaneously* or with infinite speed.

In 1905, presenting his Special Theory of Relativity, Einstein correctly questioned this assumption and replaced it with a new and factually correct postulate that the speed of light in vacuum is a constant of nature *independent of the state of motion of an observer*. This implies that just as the length of a rod in space remains the same even if we look at it with any orientation, so also the (“length”)² of the *space-time interval between two events* remains the same for all observers in uniform relative motion. This invariant quantity is given by $(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 - c^2(t_2 - t_1)^2$ where c is the speed of light in vacuum which is approximately 3,00,000 kilometers per second and $x_i, y_i, z_i, t_i, i = 1, 2$ denote the coordinate labels of any two events. (Recall that an event has four labels, three for its spatial location and one for its time of occurrence.) It is the invariance property of this length links the space and time together and requires us to think of space and time as a single entity now called the *Space-Time*. The four dimensional space-time of special relativity is known as the *Minkowski* space-time while the three dimensional space is the familiar Euclidean space. Some consequences of this changed affairs regarding notions of space and time are that uniformly moving objects contract along the direction of motion but are unchanged in dimensions along perpendicular directions and moving clocks slow down.

During 1905 and 1916, Einstein went further. He considered a rotating platform and sought to measure its circumference and radius. Our observer relative to whom the platform is rotating, is an inertial observer and can use special theory of relativity to do the measurements. Accordingly, the measuring rods along the circumference would contract since they are laid along the direction of motion while those along the radial directions, being perpendicular to the direction of motion, will have no change in the length. Consequently, the circumference would be larger and the ratio of circumference to radius would be larger than the usual Euclidean geometry value, 2π . Therefore, an observer who co-rotates with the platform, must infer a *non-Euclidean* geometry. Thus an observer who is accelerated with respect to an inertial observer could infer his/her non-inertial status by determining the geometry.

Einstein also noted the curious fact that a body’s inertial mass equals its gravitational mass. Recall that inertia is body’s resistance to applied force and inertial mass is its quantification as the ratio of applied force to the acceleration acquired. Newton’s law of gravity on the other hand says that the gravitational force between two bodies is proportional to their masses and inversely proportional to the square of the distance between them. These masses are the gravitational masses. There is no a priori reason for these two masses to be equal, but they are observed to be so (within experimental errors). Einstein makes the postulate that this observed equality is actually an exact property of nature. It follows immediately, from the Newton’s law of motion that uniform gravitational field is indistinguishable from uniform acceleration. An observer in a freely falling lift will not detect the force of gravity at all.

Inertial observers of special relativity are precisely such observers who do not detect force of gravity. Equivalently, observers who *do* detect gravity are necessarily accelerated with respect to the inertial ones.

But now one must conclude that gravity changes the Euclidean geometry since accelerated observers infer so! Furthermore, since matter produces gravity (eg Earth's gravity) and gravity affects geometry, matter must also affect geometry!! This in essence is the main message of GTR: The space-time has a geometry which is *determined* by the distribution of matter (energy included). Small test bodies, respond to the changed geometry and those free of any other force simply follow a geodesic of the space-time geometry. (Geodesics are the 'straightest lines' of the non-Euclidean geometries, an example being the longitudes or great circles on a globe.) A popular, intuitive metaphor is to imagine the space-time as being like a malleable rubber sheet which is distorted by bodies moving on it and the force of gravity is a manifestation of the curved nature of the space-time.

This sounds beautifully imaginative, but does this picture of space-time and gravity predict any new observable effects which can be verified? Indeed, it does! Among the novel predictions of GTR are: (1) light bends while traveling near massive bodies, first confirmed during the solar eclipse of 1919 during which apparent positions of stars behind the solar disc were observed to be shifted, quantitatively in agreement with GTR. This effectively makes massive bodies such as galaxies to act like 'gravitational lenses' producing multiple images of sources behind them. Many such lenses have been seen. (2) Orbits of planets around the Sun which are elliptical, precess. That is the angular position of the planet changes a bit every time the planet returns to its closest distance from Sun. This 'precession of perihelion' has been quantitatively confirmed, notably for the planet Mercury ('Budha'). (3) Massive stars can collapse to form 'black holes' – objects so dense and strongly gravitating that even light cannot escape from their 'interiors'. Galaxies are believed to have super-massive black holes, with mass in excess of million solar masses, at their centers and there are also excellent candidates for lighter black holes. (4) Accelerated masses would produce 'gravitational waves' much like accelerated charges produce electromagnetic waves. There is already indirect evidence inferred from the in-spiraling of the Hulse -Taylor binary pulsar (pulsar is a rotating neutron star) for which a Nobel prize was awarded in 1993. Experiments for direct detection are being done and planned, but there is no confirmation yet. (5) The "Big Bang" model of cosmology according to which our universe began about 13.7 billion years ago from an extremely hot and dense state (a space-time "singularity"). This is very widely believed as well.

A theory making successful predictions from planetary scales of million kilometers (light minutes) to cosmological scales of billion light years deserves to be tested as rigorously and diversely as possible. The one peculiar, and qualitatively new prediction of GTR which has not been tested so far concerns small spinning bodies. GTR predicts that a small spinning body would precess (its axis of rotation would change direction) due to curvature, near a massive body and an additional precession if the massive body is also spinning. This in fact

is the object of the Gravity Probe B experiment. Note that in the pre-GTR conception, a small spinning body will *not* precess during a free fall. Indeed such spinning bodies, called gyroscopes, are used in the so called inertial guidance system of aeroplanes.

That GTR contains such an effect within itself has a bearing on another conceptual issue concerning the *relativity of acceleration*. This issue has a long history and is well highlighted by Newton's bucket experiment. Newton considered a simple experiment: Hang a half filled bucket by a rope and set it spinning by twisting the rope. After a while the water stars spinning with the bucket and its surface becomes concave. Still later, when the rope is fully untwisted, the bucket stops spinning and the water is still spinning with its surface curved. The rope then starts twisting in the opposite sense setting the bucket to spin in the opposite direction, which makes the water stop spinning with its surface becoming flat again. The intriguing question is: *what is the rotation of the water (and the consequent curved surface) relative to?*

It cannot be relative to the bucket because the curved surface is seen both when the bucket and water are rotating together as well as when the bucket is not rotating and water is rotating. Thus the curving of the surface is not dependent on the relative rotation of water and the bucket. Newton advanced this observation to suggest that the surface curves when the water is rotating relative to the 'absolute space', a notion that survived for centuries ('absolute' here means that it exist even if nothing else exist). Towards the end of the 19th century, Ernst Mach suggested otherwise. Absolute space is perhaps only a theoretical idea and may not be real at all. He suggested that the curving of the surface of the water would be determined by rotation relative to the distant stars. He then asked: what happens if one views the water to be 'non-rotating' and the distant stars to be 'rotating' (about the same axis as the bucket but in the opposite sense, thus still maintaining the relative rotation of the two). Would the surface be curved? Of course one could not determine the outcome of such a thought experiment. Instead he proposed that our notions and formulations of inertia and dynamics be such that in either view, the surface should be curved. Such a revised formulation will banish absolute space and absolute acceleration. He did not give any specific formulations though.

Now, GTR does provide a formulation which does not use absolute space ideas and does make the geometry dependent on the matter distribution. Treating the distant stars as stationary and the water rotating one has the usual explanation of the curved surface. If however one views the universe as rotating, then the geometry near the bucket is different and the surface could be again curved. This was indeed demonstrated theoretically in the mid-eighties by computing the geometry inside a rotating shell. The GTR answer to the question posed by Newton is that the water surface is curved whenever the water rotates *relative to the local gravitational field*. Since a rotating body has a rotating gravitational field, it follows that space-time geometry is "dragged" by a rotating body, much like a viscous fluid is dragged by an immersed spinning object. This dragging of geometry is referred to as "frame-dragging".

It is obviously hard to rotate the whole universe or go very close to a rotating black hole where frame-dragging is strong, but we just can watch a small spinning body, freely falling in an orbit near our spinning earth. Realization of this simple idea is the basic design premise of the Gravity Probe B experiment.

The Experiment: It turns out that an optimal orbit for such a gyroscope is a polar orbit about 400 miles from earth. The spinning gyroscope is then expected to precess about an axis perpendicular to the orbit due to the curvature effect independent of the spin of earth. This precession is known as ‘geodetic precession’ and the theory gives its rate to be about 6.6 arc second per year (one arc second is $1/3600$ of a degree). There is an additional precession about the axis parallel to the earth’s spin axis. It is known as the ‘frame-dragging precession’ (Lense-Thirring Effect) and is estimated to be about 40.9 milli-arc seconds per year which is about a 100 times smaller. These are very tiny amounts especially since a spinning gyroscope could also precess due to several other causes such as irregularities in its shape, frictional drag, electro-magnetic drag etc. These would cause precessions much larger than the precessions due to GTR, and hence these have to be controlled very, very carefully. Herein lies all the sophistication required to conduct the experiment successfully and is the main reason why the experiment has taken over 40 years to realize. This story by itself is quite fascinating and is an illustration of how a precision experiment is designed. Let us consider the basic requirements, the challenges they pose and how they are met.

There are four basic requirements: (1) gyroscope should spin in a stable manner; (2) one should be able to determine its axis of rotation, ideally with no disturbance; (3) one should be able to compare the spin direction with ‘distant stars’; (4) gyroscope should be in a free fall. The last requirement is important because the theoretical estimate of the precession rates is computed for a freely falling gyroscope and the experiment is to be designed to realize the theoretical conditions as precisely as possible. Let us go through these one by one.

(1) *The Gyroscope:* On an extended body, forces acting at different locations on the body generically produce a torque make the body “rotate”. The main forces producing torque could be tidal forces due to gravity, stray electric fields if the gyroscope has any asymmetrical distribution of stray electric charges, earth’s magnetic field if there are tiny induced currents due to the spinning and ordinary frictional drag due to atmosphere. The last one is minimized by spinning the gyroscope in a vacuum with pressure less than ten billion times smaller than the atmospheric pressure. The gravitational instabilities are minimized by making the gyroscope small (3.8 cm diameter) and nearly perfectly spherical. Even on a ping-pong ball, under a microscope one would see ‘valleys and hills’ which are deviations from sphericity. The gyroscope however is made so spherical that its hills and valleys are no more than 40 atomic layers tall (or deep). If earth were to be as spherical, then the tallest mountain would be only 8 feet tall. The gyroscope is also made to be of uniform density (or homogeneous) to a very high degree so that deviations are less than one part in a million. It is made up of pure quartz crystal which can retain its properties even at very low temperatures at which the experiment

is to be operated. It is ensured that any stray electric charge distribution is also spherical to one part in 10 million. Finally the magnetic field due to earth is shielded out by enclosing the ‘probe’ in lead bags.

The gyroscope is set spinning in a suspended state in a small en-casing. Its clearance from its housing is only a thousandth of an inch and it remains centered to within a millionth of an inch even as it spins at a maximum rate of 10000 RPM. It is coated with a thin layer of Niobium metal which is a super-conductor at 1.8 degrees Kelvin (271.2 degrees Celsius below zero). The suspension of the gyroscope is done by tiny electric fields applied symmetrically. In all there are five such gyroscopes in the gravity probe B.

(2) *Spin axis read-out:* On such a highly spherical gyroscope with no markings on it, how can one determine its axis of rotation? Here comes the need for super-conductivity. Many materials, when cooled to very low temperatures, lose all resistance to electrical currents and become ‘super-conductors’. If one applies a magnetic field to a super conductor, currents are induced within the super-conductor in such a manner that magnetic field is expelled from within the super-conductor. This is known as the Meissner effect. However, rotating super-conductors generate their own magnetic moment (like a small bar magnets) known as the ‘London moment’ (named after the physicist Fritz London). Its direction is precisely aligned with the axis of rotation. This magnetic moment can be delicately measured by a SQUID (Super-conducting Quantum Interference Device) with a sensitivity of 10^{-14} gauss of magnetic field and this is how the axis of the gyroscope is determined. The need for Niobium, the low temperature and shielding of external magnetic fields is now clear. The low temperatures are achieved by super-fluid Helium and its controlled evaporation is used to pass the vapour through the casing of the gyroscope and spin it up.

(3) *Guide Star:* To detect a change in the direction of the spin axis, one needs to refer it to some other direction which presumably does not change itself! Ideally such a direction would be defined by some very distant but strong astronomical source such as a quasar (quasars are star like sources which are however million to billion light years away, well beyond our galaxy. Usual stars however are members of our own galaxy). These are however very faint. One can choose some relatively closer bright star whose motion relative to the distant quasars is sufficiently precisely known by other astronomical observations. This is precisely what is done. A star known as IM Pegasi (in the constellation Pegasus or ‘Maha Ashwa’) is chosen as a guide star which is kept in focus by a telescope attached to the probe which contains the spinning gyroscope and read-out instruments. This star is about 300 light years away and is also a radio source which can be tracked by radio telescopes on earth. Its motion relative a distant quasar is known very precisely. Thus, the change of the gyroscope spin axis is measured relative to the direction of the guide star and since its change relative to a distant quasar is known precisely enough, one obtains the rate of precession of the gyroscope relative to the distant quasar.

The tracking of the guide star is done by a telescope made from a single quartz block with parts put together by ‘optical contact’ (so that there are no mechanical screws etc which could generate instabilities). It has an aperture of 5.6 inch, length of 4 inches and is able to remain focused on the center of the star’s image to within 10^{-4} arc seconds.

(4) *Drag free motion*: The idealization of free fall used in the theoretical estimate is achieved by having a ‘proof mass’ (another small gyroscope) fall freely and tiny sensors and boosters are used to adjust the space craft’s motion and orientation so as to follow it without touching. Since the space craft is much larger (a scale of 10 feet) than the gyroscope, its motion will have small deviations from free fall. Since the gyroscope is contained within the space craft, this could exert force on the gyroscope thereby disturbing its free fall. The arrangement of ensuring that the space craft ‘follows’ the proof mass ensures that the space craft and consequently other gyroscopes continue to be in free fall.

There are many more technical details with the exact assembly of the basic gyroscope, read-out instruments, shielding systems, cooling systems, telescope assembly, data acquisition and transmission, navigational control systems etc, all delicate components being enclosed within a space craft which is put in orbit by a roaring and thundering rocket. Just ensuring that the experiment is capable of detecting the tiny precession rates predicted by GTR, has required creative use of a whole range of scientific facts (eg super-conductivity, London moment, super-fluidity etc) and technological art (drag free control, spin-up by evaporating helium gas flow, SQUID, splitting star’s image for precise focusing etc). Some of the technologies did not even exist when the experiment was first proposed in 1960 (even NASA did not exist then).

What is remarkable is that the push for such an experiment was sustained for over forty years with patient progress towards needed technologies. It highlights that even a 90 year old and successful theory, GTR, still has some untested aspects and that 90 year success is no justification for complacency (more conventional tests of GTR also continue to be carried out at greater precession). To look for tiny precessions of small gyroscope because some fancy theory predicts it, may appear to be rather extravagant indulgence. but it is not without rewards. It is only the greater challenges that drive the limits of our scientific understanding as well as technological mastery.

This is a written version of the lecture given at the Mylapur Children Club on Oct 30, 2005 and a talk at the monthly meetings of the Science Club on Sept 3, 2005. A very readable and detailed account of the Gravity Probe B experiment can be found at <http://einstein.stanford.edu>.

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Nov 10, 2005