Experimental Gravitation in India: Progress, Challenges and Prospects

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ABSTRACT

Experimental gravitation is a relatively young field in India. The decade old activity started with torsion balance experiments to study the Equivalence Principle and fundamental aspects of gravity and took a significant diversion to search for new composition dependent feeble forces. After obtaining important constraints on the strength of these forces the effort now is to test the equivalence principle with improved sensitivity. Complementary to this experimental activity, there is also a group active in studying various practical aspects related to the detection of gravitational waves like data analysis, detector configurations etc. In this talk I review the experimental aspects.

1. Introduction

It is significant to be able to talk about progress in experimental gravitation in India in front of an expert audience in which four or more teacher-student generations of theoretical relativists are present. In contrast to this long and rich tradition, experimental gravitation in India is a very young field.

Efforts towards performing gravitation experiments in India starts with the document "Challenges in experimental gravitation"[1] in which it was proposed to take up the fabrication of novel torsion balances to study various fundamental aspects of gravity. This was in 1981 and within two or three years a major experimental program was started with the support of DST. By 1987 we had a torsion balance which could measure differential accelerations of 10^{-12} cm/sec^2 operating in the specially constructed underground laboratory in Gauribidanur near Bangalore. During the next five years the balance was operated to search for new composition dependent forces feebler than gravity - a fifth force. This diversion was an important step since these experiments provided important constraints on the strength of new Yukawa forces coupling to isospin and lepton number for all ranges above 30 cm or so. Subsequently some new designs for torsion balances were tested to improve the sensitivity and now we are preparing to perform a sensitive test of the equivalence principle with a sensitivity approaching 10^{-14}, 100 to 1000 times better than earlier laboratory experiments. There are also smaller experiments planned with new torsion balances.

There are two equally significant views of the importance of experiments which test the universality of free fall (UFF). The principle which states that the gravitational acceleration of test bodies with same initial conditions is independent of their composition or structure is termed the Weak Equivalence Principle (WEP). The Einstein Equivalence Principle (EEP) states that the UFF is an exact principle applicable to all matter and interactions, including gravity. The generalization of the Galilean UFF to a fundamental principle which uniquely implied the General theory of relativity is a giant leap. At the same time, it was a recognition of the power of accurate empirical observations in which the UFF was found valid for various bodies good to 20 parts in a million[2]. (Though UFF was established to 10 parts in a billion by baron von Eötvös[3] before Einstein's 1907 paper on the equivalence principle and applicability of special relativity to accelerated frames, Einstein was not aware of these unpublished results. A noticeable publication happened only in 1922, three years after Eötvös's death and Eddington's demonstration of gravitational light deflection during solar eclipse.) It is clear that even a small violation of the universality of free fall for any kind of matter or energy has serious implications for the correct theory of gravity. (Schiff had conjectured that WEP with local Lorentz invariance implies EEP.) Equally importantly there could be other long range forces in nature coupling to conserved or nearly conserved charges which act along with gravity mimicking a violation of the equivalence principle. This is the second aspect of tests of equivalence principle I was mentioning and this paradigm was pioneered by Lee and Yang when they used null results from the Eötvös experiment to constrain the strength of a long range force coupling to baryon number[4]. Many particle physics theories which attempt to go beyond the unsatisfactory aspects of the Standard model in fact predict new macroscopic range force coupling to combination of baryon number and lepton number. Any experiment which test the equivalence principle by measuring the differential acceleration of two test bodies towards a larger source body is also sensitive to the existence of new composition dependent forces and therefore these experiments are a direct probe to physics beyond the standard model. In this context these very low energy experiments acquire a new significance as one of the small number of non-accelerator probes presently available to foundations of particle physics.

Theoretical significance of experiments

Various extensions of the standard model with a view to correct some of its fundamental problems result in the prediction of new long range forces[5]. Supersymmetric solution to the hierarchy puzzle also brings in new fundamental particles and in some models there are new forces mediated by spin-1 particles. For example there could be a force coupling to the charge B-L (baryon number minus lepton number) with an arbitrary range and strength a few percent relative to gravity for ranges around a meter or more. There are models which attempt to solve the problem of the cosmological constant by invoking a new field which helps dynamically tune the cosmological constant to near zero value and this model predicts a composition dependent force. This force couples to a linear combination of mass and smaller contributions of baryon number and lepton number and hence violates UFF. There are also predictions of new forces from the axion solution to the strong CP puzzle (spin dependent force), Kaluza-Klein type quantum gravity models and supergravity models. Supergravity models pioneered by Scherk predicts a UFF violating force coupling approximately to B-0.17L with a strength of 0.03 % of gravity. Another important charge which could be a source of a new field is B-2L (or the nuclear isospin). A new force mediated by the dilaton arising from broken scale invariance was extensively discussed by Fujii[6] and was an important factor in generating renewed interest in new macroscopic range forces.

The experimental program

The recent interest in experimental study of new forces was inspired by indications in the old Eötvös data and in the data from some mine experiments to measure the value of the Newtonian gravitational constant of the existence of a new force coupling to baryon number with a strength of about 1% of gravity and a range between 100 m and 1 km[7]. Probably Eötvös himself was aware of and was disturbed about the fact that his data showed a scatter more than his estimate of the errors in the experiment. But in the early part of the century nuclear quantum numbers were not known and there was no possibility to analyze the residuals in the measurements of differential accelerations and relate them to the fundamental charges mentioned earlier. A reanalysis of the data by Fischbach et al showed a very suggestive indication of the existence of a new force. This observation was supported strongly by the observations by Stacey et al that the value of the gravitational constant measured in deep mines in Australia was consistently higher than the laboratory value and value measured at the surface indicating the existence of a repulsive force with a range smaller than the depth of 1000 m at which the higher value was measured[8]. There were also some less convincing indication from new measurements on the neutral K-meson system.

A finite range fifth force coupling to charge Q is conventionally described by the Yukawa potential

$$V_5 = \frac{f^2}{4\pi}\frac{Q}{r}\exp(-r/\lambda)$$

where f^2 is the coupling strength and λ is the range of the force. If Q is proportional to mass then the force is composition independent and manifests macroscopically as a violation of the inverse square law of Newtonian gravity in experiments measuring gravitational acceleration. When Q is not strictly proportional to mass, the force is composition dependent. A direct method of searching for such a force when λ is macroscopically large involves measuring the difference in acceleration of two compositionally different objects in the field of another massive object. Therefore it is useful to write the total interaction potential including that of gravity as

$$V_{tot} = \frac{-Gm_1m_2}{r}[1 - \alpha q_1 q_2 \exp(-r/\lambda)]$$

between two bodies of mass m_1 and m_2. In this expression, α is the coupling strength in units of gravity ($\alpha = f^2/4\pi G m_H^2$ where m_H is the mass of the hydrogen atom) and

q is the charge per unit mass, the *specific charge*. We assume that gravity itself is composition independent, a fact tested to an accuracy of 10^{-12} in modern Eötvös type torsion balance experiments by Dicke and Braginsky[9]. The important charges under consideration are the Baryon number (B), Lepton number (L) and linear combinations of these charges like the nuclear isospin ($I \equiv N - Z \doteq B - 2L$ for normal nuclei) since these have considerable theoretical significance.

All the experiments performed so far have failed to see any evidence for the existence of a new force coupling to any of the important charges for ranges above 10 cm and strength as low as 10^{-4} to 10^{-5} of gravity[10]. The most sensitive Galilean free fall experiments where two test masses are dropped in vacuum chamber and their differential displacement is monitored have obtained an upper limit of about a meter for the product of the range and strength, i.e., $\alpha\lambda \leq 1$m. For ranges less than 10 km or so, torsion balance experiments have better sensitivity and I will mainly describe the TIFR torsion balance experiment to bring out the main aspects.

Indian (TIFR) experiment

In the original proposal for starting gravitation experiments in India, some novel designs for the main detector element - the torsion balance- were described. One important concept was that of a gravitational monopole and a compositional dipole. Such a mass element will not couple to gradients in the gravitational field while responding to composition dependent forces. In experiments searching for composition dependent forces, this is what is ideally needed since the major source of systematic noise in such experiments is the coupling of the multipole moments of the torsion balance to gradients in the gravitational field of the source masses. A ring made of two semi rings of two different materials satisfy this criteria if the balance and the source masses are constrained to be in a plane. This design was employed in the TIFR experiments. The TIFR fifth force experiments have been performed in three phases, with the first phase starting in 1987 and the last phase completing in 1992 (See ref.11 for details on design and implementation). These were resonance experiments in which the source masses are moved around the ring shaped mass element of the torsion balance at the natural period of the pendulum, and the changes in the amplitude of the torsional oscillations are monitored to see the influence of a composition dependent interaction. Fig. 1 schematically shows the structure of the pendulum mass element and the modulation scheme in which the angular deflection of the dipole balance is periodic if the force exists. When the modulation frequency matches the natural frequency the angular amplitude increases linearly in time for observation times smaller than the damping time of the balance which in this case is around 10 days.

The mass element of the torsion pendulum is in the form of a ring formed by sandwiching two semicircular rings, one made of copper and the other of lead, between thin annular rings of aluminium. Azimuthal grooves cut in the lead half equalizes its mass and the first two mass moments of the ring about the suspension axis, with that of the copper half. The ring weighing 1500 gms and an optical quality mirror attached to it by copper wires are suspended with the plane of the ring horizontal from a $105\mu m$ diameter tungsten fibre, inside a UHV chamber in which the pressure is less than 10^{-8} torr.

The natural period of this balance was 795.6 seconds. The apparatus was operated in an underground laboratory, about 23 m deep, specially constructed for performing such sensitive experiments. The laboratory is situated in a remote village (Kashapura) near Gauribidanur, 80 km north of Bangalore, in the seismically quiet region of Deccan Plateau. The temperature fluctuations are less than a millidegree and gradients in temperature are less than 10 microdegree inside the pit, in the relevant bandwidth around the frequency of the pendulum. Two layers of μ-metal shield around the chamber provided magnetic shielding to the required level.

Periodic movement of the source masses, kept at a radial distance of about a meter from the torsion balance, between two diametrically opposite positions at the natural frequency causes resonant modulation of the torsional oscillations if there is a composition dependent force. This manifests as a linear increase or decrease of the amplitude of the oscillations, depending on the relative phase of the driving signal and that of torsional oscillations.

Various gravitational couplings between the gradients of gravitational field from the source masses and the small residual quadrupole moments of the torsion balance were suppressed to a large degree by choosing a source mass configuration which is highly symmetrical as far as the mass distribution is concerned, maintaining a large asymmetry in charges like isospin and lepton number which can generate composition dependent fields. The strategy was to limit all such spurious couplings to second order effects in unavoidable small asymmetries. The source mass configuration in relation to the torsion balance is an elaborate version of the simple source mass indicated in fig. 1b and this consists of several piles of lead masses and brass masses arranged on the four arms of a rotating truss such that there is a large azimuthal asymmetry in the distribution of relevant charges (of new forces) while maintaining a high degree of (fourfold) symmetry in gravitational couplings. Two of the arms, 90^o apart, are loaded with lead masses arranged in two piles on each arm symmetrically in the vertical direction with respect to the pendulum plane. The other two arms are loaded similarly with brass masses. Since lead has considerably higher isospin and lepton number per unit mass compared to brass (copper) large azimuthal asymmetry in these charges is generated in this configuration. The brass masses serve as balancing masses and more importantly as symmetrizing masses as far as gravitational gradients are concerned. The improvement in sensitivity from phase I to phase III of the experiments is due to the identification and elimination of many systematic effects, mainly of gravitational origin.

The result from the phase I experiment was crucial in ruling out the existence of a new force coupling to isospin[12]. The first few experiments from various groups had conflicting results with a possibility of reconciliation if there was a force coupling approximately to the charge B-2L. But this possibility was found untenable since our experiment (and simultaneously another experiment from the Eöt-Wash group in Seattle[13]) did not see any evidence for such a force down to a sensitivity of 10^{-3} for α.

In phase II, the overall sensitivity of the experiment increased tenfold and provided the most significant constraints on the strength of a new force coupling to isospin[14]. Further improvement in sensitivity was achieved in phase III and till recently we had the most stringent constraints on the strength of a fifth force coupling to isospin or lepton number. The acceleration sensitivity of the torsion pendulum employed is among the highest in the world and it is about 10^{-12} cm/sec^{-2}.

Another important aspect which was built into the later experiments was that the signature of the force was a difference signal from two experiments with one serving as a control experiment. This eliminated to large extent some of the larger gravitational couplings and the confidence in the result was greatly enhanced. The mass suspension scheme was designed to ensure that the radial positions of the centre of masses were stable to within 0.3 mm or so even after rotations, unloading, reloading etc. This repeatability of radial position ensures that the gravitational couplings, if any, remain unchanged from run to run and the *difference experiment* is possible. One set of experiments (fifth force experiments) were done in which there is maximal asymmetry of composition dependent charges, and another set of control (null) experiments were done for the same duration in which this asymmetry is nulled by mixing brass and lead source masses isotropically with respect to the pendulum. So we have data with the composition dependent fields switched on and off, *with the gravitational coupling remaining more or less same.* Subtracting the average extracted growth rate in the control experiments from that of the fifth force experiments gives the true fifth force signal.

A high sensitivity optical lever with a resolution of 3×10^{-9} rad/$\sqrt{\text{Hz}}$ measured the angular position of the pendulum and the data was digitally processed to yield the average rate of change of amplitude during the resonant drives. This translates into values for various coupling constants.

The 2σ limit on the strength of the Isospin coupling is given by the expression

$$-5.9 \times 10^{-5} \leq \alpha_I \leq 3.44 \times 10^{-5}$$

This represents the *best upper limits on* α_I from all the experiments till recently[10,15].(The Eöt-Wash group at the University of Washington, Seattle has now improved this constraint by another factor of 12 in the same range[16]). As an absolute upper limit on the strength of forces coupling to Isospin we write

$$|\alpha_I| \leq 5.9 \times 10^{-5}$$

This limit is applicable beyond a range of 2 m or so and below this range the numbers are to be scaled appropriately by taking into account of the Yukawa character of the potential, with a source to detector distance of 1.2 meters. At 1 m, the limits are higher by a factor of 1.5 and for $\lambda = 20$ cm, the upper limit on α is less than 0.4% of gravity.

We can also derive upper limits on the strength of a new force coupling to other important charges like L and B-L. We get these limits by scaling the limits on α_I by the ratio of relevant specific charge to the specific isospin charge. The relevant multiplication factor here is 3.93. These limits are approximately equal (and opposite in sign) and are given by

$$|\alpha_{B-L}| \approx |\alpha_L| \leq 2.32 \times 10^{-4}$$

There had been attempts to explain the Eötvös correlations using new, but arbitrary, charges conceived entirely on a phenomenelogical spirit. One such charge which was advocated by Fischbach himself was a spin dependent charge Q_s defined as

$$Q_s = M\delta; \quad \delta = \begin{cases} 1 & \text{for } J > 0 \text{ ;} \\ 0 & \text{for } J = 0. \end{cases}$$

where M is the mass of the nucleus, and J is its nuclear spin The fundamental importance of this charge is not very clear, but our interest in such a charge is due to an observation by Hall et al[17] that with Q_s the correlations seen in the Eötvös data are still significant and that this is the only charge other than the baryon number which has this property. Since most of the experiments used sources or test mass elements which have negligible fraction of the charge under consideration, it was not feasible to rule out such a possibility convincingly. The charge Q_s for lead is 0.2258 and for brass it is 1.0. In our isospin experiments lead was the *source* and brass was the *counter mass.* But we can also consider ***brass as the source*** and lead as the counter masses. With this interpretation, the same isospin experiment can be used to yield a very stringent limit on α_{Q_s}. We get

$$-1.44 \times 10^{-6} \leq \alpha_{Q_s} \leq 8.41 \times 10^{-7}$$

$$\text{or} \quad |\alpha_{Q_s}| \leq 1.44 \times 10^{-6}$$

This limit is about two orders better than that could be derived from any other experiment.

Improvements and new ideas

In the last two years some effort was directed towards improving the intrinsic sensitivity of the torsion balance. One of the strategy was to replace the cylindrical section suspension fibre by a rectangular section tungsten ribbon. The ratio of the torsion constants for the two cross sections of same area scales approximately as $1 : \frac{2t}{w}$ where t is the thickness and w is the width of the ribbon. The 105 μ diameter fiber when replaced by a ribbon which is 30μ x 300μ increases the period by about a factor of two with a resulting improvement in sensitivity by a factor of 4, slightly less than expected, but very significant for the future experiments. This torsion balance has also shown improved drift characteristics enabling continuous monitoring for longer durations. Coupled with an improved optical lever with a sensitivity of 3×10^{-10} rad. for angular deflections for one second averaging, the same fifth force search could now be done with a sensitivity approaching 5 parts in a million for α_I and 5×10^{-4} for α_B. This requires suppression of any residual systematic effects that would be visible at the improved sensitivity.

Another idea which was pursued and some preliminary experiments were done was on the possibility of fabricating very long period pendulums using the concept of gravitational negative restoring[1,18]. In fact one of the torsion balance designs discussed in the original proposal was based on this idea. Though torsion balances remain the best transducers for measuring differential accelerations in gravitation experiments, there are several problems in increasing their intrinsic sensitivity within current design strategies. One of the major problems to be solved is the difficulty in realizing a pendulum of large mass, and also of very long period and hence low thermal noise and better sensitivity; the requirements of high load-bearing capacity *and* of a low torsion constant of the suspension fiber are contradictory. We have done a preliminary experiment with a torsion balance set up in which gravitational torques are configured to act against the restoring torque from the suspension fibre. This set up makes use of the horizontal gradients in the horizontal gravitation field generated by fixed masses juxtaposed with the mass elements of a Cavendish torsion balance, with all the masses lying more or less in a single plane (Fig. 2).

A deflection of the balance from its equilibrium position causes unbalanced gravitational gradient force, which is linear in the small deflection, acting on the pendulum with the sign of the resulting torque opposite to that from the fibre - a negative restoring force. The effective torsion constant is given by the expression

$$\tau_{eff} = \tau_{fibre} - \tau_{grav}, \qquad \tau_{grav} = 8\frac{GM}{R^3}ml^2$$

for the configuration in Fig.2a , where M is the mass of the passive elements, $2m$, that of the pendulum, $2l$ its length and R, the distance between the masses. With the torsion constant of the fibre thus effectively reduced, it is possible to attain *arbitrarily large periods* provided the natural period of the pendulum without the negative restoring scheme is large compared to the quantity $1/\sqrt{G\rho}$, the same parameter which determines the onset of gravitational instability in astrophysical systems, where ρ is the effective density of the distributed masses in the system. Experiments with a 300 g dumb-bell balance with a suspension which was rather stiff (to avoid the difficulties associated with enormous sensitivity to very small torques, since the first measurements were done in an enclosure which was not evacuated) gave a 5% increase in period for a 1000 sec pendulum. A torsion balance with a period of several hours is well within the possibility of this scheme and this will be tested soon.

With increased sensitivity the balance is susceptible to various systematic effects and the advantage of higher sensitivity is useful only if these systematic effects are suppressed. Passive shielding of various disturbances is one possibility. Another scheme which is proposed is to employ a differential design. Normally torsion balance experiments are performed with a single torsion balance. If there are uncontrollable systematic effects larger than the signal averaging over a long observation period is not going to reduce the noise. Minimally two pendulums with almost the same characteristics are required, configured with their compositional axes 180° out of phase. Then the two composition dependent signals will be out of phase whereas the systematic effects from temperature variations etc. are expected to be more or less similar enabling a noise subtraction throughout the time of observation. This idea is being pursued to the design level at present (see fig. 3 for a schematic description.)

New challenges

It is clear from the description so far that many challenges were taken up head-on to build up a visible group in experimental gravitation and the exercise has helped in preparing to face new challenges. Also, the progress has brought in new challenges. A sensitive test of the equivalence principle is one of the major experimental programs for the future and also there are smaller significant experiments where torsion balances will be the main detector element.

The laboratory experiments test the weaker form of the equivalence principle which is a statement of the UFF for all interactions except gravity. The gravitational binding energy of typical laboratory test masses are only 10^{-27} of their rest mass and therefore in experiments which measure differential accelerations at the level of 10^{-12} no significant statement on the free fall of gravitational binding energy can be made. It is possible to test the strong form of the equivalence principle which includes the UFF for gravity by looking for an anomalous differential acceleration between the Earth and the Moon towards the Sun in laser ranging experiments. The accuracies obtained translate to a sensitivity for differential acceleration at the level of about 10^{-13}. Since the difference in gravitational binding energies is around 10^{-10}, Lunar laser ranging test the Strong Equivalence principle with a sensitivity of 0.1%. It is essential that the laboratory experiments have matching sensitivity so that this limit can be interpreted as unambiguous statement on the free fall of gravitational binding energy. At present the constraints on the UFF for the binding energy contributions from weak interactions also are not better than 1% - 10% and an improved test of the WEP is important. The general feeling is that achieving sensitivities beyond 10^{-14} or so in a terrestrial experiment would be hard and this has prompted a joint proposal to NASA and the European Space Agency for a Satellite Test of the Equivalence Principle (STEP). But the launch of this high technology mission is not expected before 2005 and a laboratory experiment which can reach a sensitivity of 10^{-14} in the next two or three years is of high significance in this context.

At present the torsion balance has sensitivity exceeding 10^{-12} for measurement of differential accelerations and the calculated intrinsic thermal noise is two orders lower than this. But there are other sources of random noise from seismic microvibrations and other environmental factors which limit the effective sensitivity. The effort is perform a long term experiment lasting a year or more where some of the random noise is averaged out. For this the systematic effects need to be suppressed by a factor of 100 or so compared to what is observed during the fifth force experiments and we are planning to house the torsion balance in a dual vacuum chamber - the present UHV chamber inside another vacuum chamber- to achieve better thermal shielding and isolation from pressure changes in the atmosphere. Also there is an additional air tight sealing possible for the experimental well. We will have to replace the present balance with another one which is fabricated with materials of better magnetic characteristics and better machining tolerances to achieve an effective sensitivity of 10^{-14}.

The initial ambitions in starting gravitation experiments in India included the detection of galactic dark matter, possibly in the form of massive neutrinos, using a suitably prepared high sensitivity torsion balance. The sensitivity needed for such a task is a million times more than what is presently achieved, but the ideas involved are still very attractive. There have been alternatives to the dark matter hypothesis, and one such important class of suggestions is called Modified Newtonian Dynamics (MOND)[19]. The idea is that either the law of inertia or the law of Newtonian gravity is modified below a critical acceleration a_o, typically of the order of 10^{-8} cm/sec^2. The suggested modification is non linear; $F = m(aa_o)^{1/2}$ where 'a' is the normal Newtonian acceleration. This, for small accelerations typical of galactic halo regions gives flat rotation curves. The phenomenelogical ideas have been subsequently elevated to the status of a field theory by Milgrom and Bekenstein[20]. It is tempting to think of a direct test of this theory since the maximum intrinsic accelerations during the free torsional oscillations of our pendulum is one order less than a_o! Also the pendulum can measure accelerations about three to four orders smaller than a_o. But a conceptual difficulty arises because the MOND does not obey the Strong Equivalence Principle. Since the torsion pendulum is already in the field of local masses, sun and the galaxy and so on which are all larger than a_o, it is argued that MOND can never be tested in the laboratory, since the addition law for accelerations is nonlinear in the theory spoiling the possibility of a null experiment. It would be very significant if some way of getting around this difficulty could be envisaged.

Modern experiments have provided very stringent constraints on the strength of new feeble forces for ranges beyond a centimeter or so. But, it is important to note that there are no serious constraints on the coupling strengths of new forces for ranges below 1 mm and in the micrometer region forces with strength a billion times that of gravity cannot be ruled out! It is a challenging area for the experimental physicists, to conceive and execute precision experiments to probe this region. Our group is planning a new series of experiments with neutral atomic beams propagated between parallel plates with very small gap, and normally the transmission of the beam will be affected by short range forces like the Vander Waals force and the Casimir force. Modulation of the gap between the mirrors would enable a phase sensitive detection scheme of the forces acting on the propagating beam. One might be able to extract some information on the strength of short range composition dependent forces by choosing suitable elements for the atomic beams when all the known contributions are subtracted out.

A discussion of experimental gravitation in India is incomplete without mentioning the involvement of groups from IUCAA, Pune and CAT, Indore in projects for the detection gravitational waves. Though there are no actual experiments done here in this field, considerable amount of work has been done on aspects related to gravity wave data analysis and on configurations for deployment of detectors. Significant results on matched filter waveform analysis was obtained by the IUCAA group and these results were presented here by other speakers. The CAT group is involved in designing and fabricating UHV systems for gravity wave experiments. The reason that experimental effort is lacking is because the technology infrastructure is far too inadequate for a dedicated effort and the financial commitment required is far too high to justify in the present context. In fact the present collaborations are in a way the most ideal and practical way for Indian scientists to participate in the important world wide efforts to detect gravitational waves.

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Figure Captions

1. **Fig.1)** A. The mass element of the torsion balance which is a gravitational monopole and compositional dipole consists of Copper and Lead semirings sandwiched between Aluminium annular plates. B. The position of the source mass (S) is switched between positions 1 and 2 periodically at the natural frequency of the balance.

2. **Fig.2)** A. The gravitational negative restoring force balance. The suspension fibre is perpendicular to the plane of the diagram. The arrows at the top represent the gravitational force between the mass elements of the balance and the passive, negative restoring masses. B. A symmetrized design which is less sensitive to gradients in external gravitational field.

3. **Fig.3)** A. Schematic design of the differential torsion balance. TB1 and TB2 are the two balances with their compositional axis 180^o out of phase. B. The source mass positions with respect to the differential balance. The deflections due to composition dependent effects will be in opposite directions in this case.

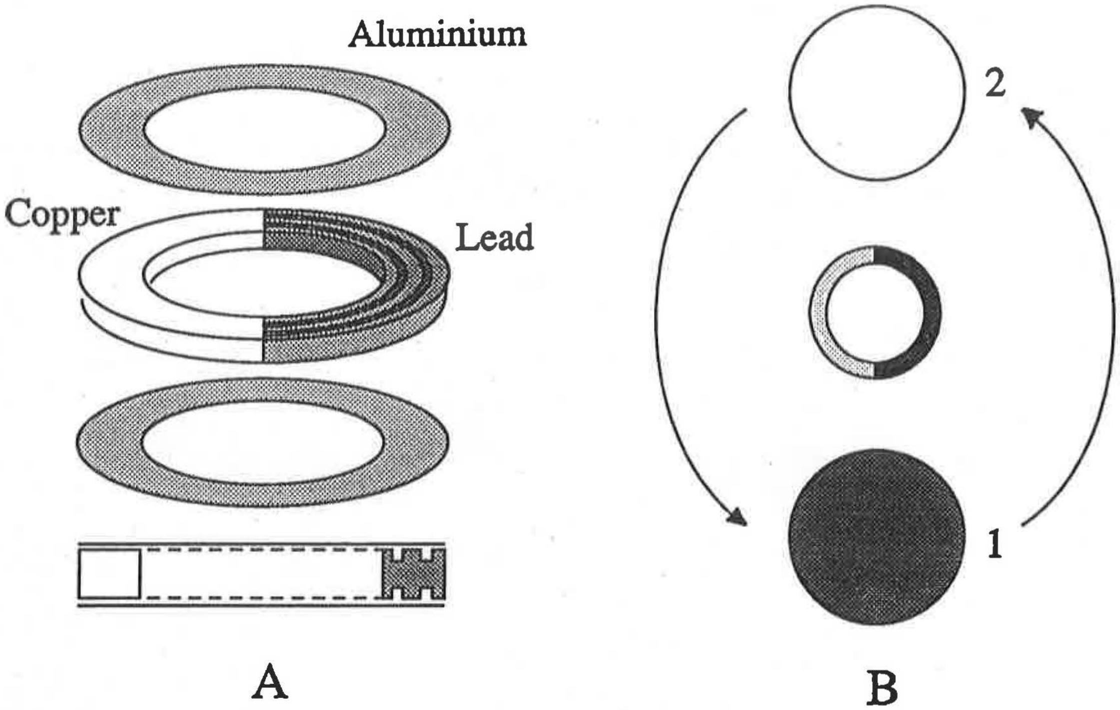

Fig.1) A. The mass element of the torsion balance which is a gravitational monopole and compositional dipole consists of Copper and Lead semirings sandwiched between Aluminium annular plates. B. The position of the source mass (S) is switched between positions 1 and 2 periodically at the natural frequency of the balance.

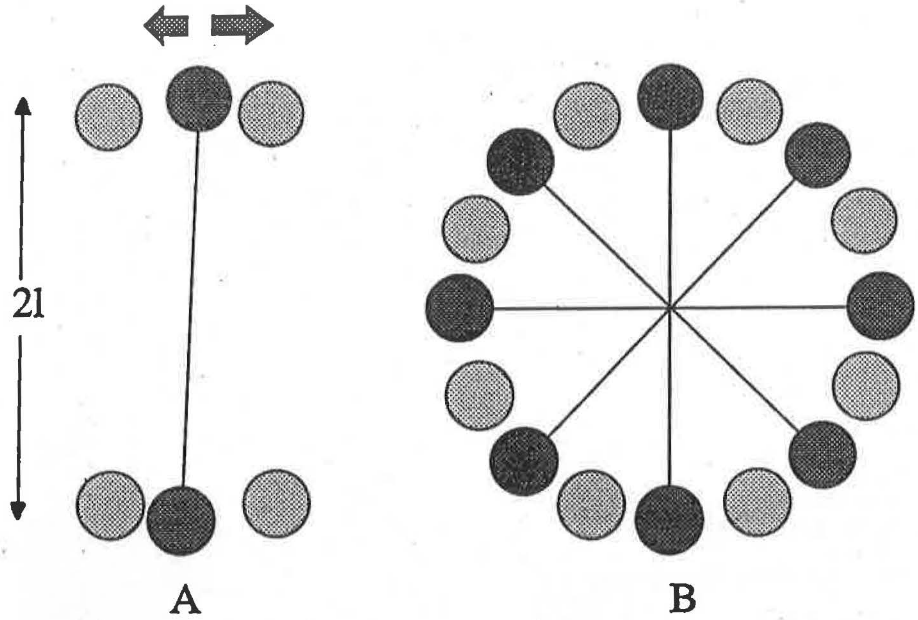

Fig.2) A. The gravitational negative restoring force balance. The suspension fibre is perpendicular to the plane of the diagram. The arrows at the top represent the gravitational force between the mass elements of the balance and the passive, negative restoring masses. B. A symmetrized design which is less sensitive to gradients in external gravitational field.

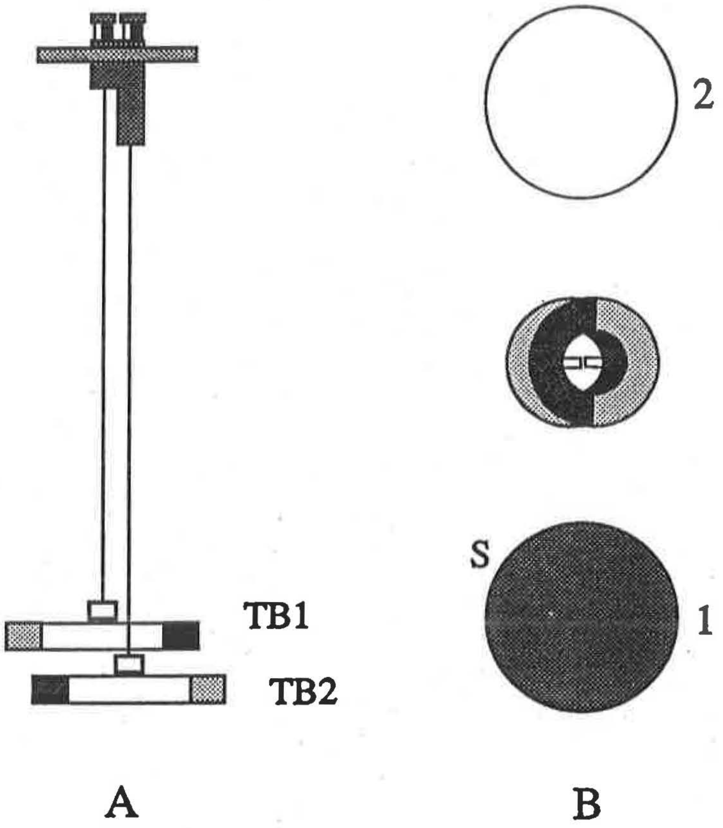

Fig.3) A. Schematic design of the differential torsion balance. TB1 and TB2 are the two balances with their compositional axis 180° out of phase. B. The source mass positions with respect to the differential balance. The deflections due to composition dependent effects will be in opposite directions in this case.