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The Role of Superconductors in Gravity Research

The Role of Superconductors in Gravity Research

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Introduction

This paper is a historical survey of the role superconductors have played in the recent search for laboratory-scale manipulation of gravity. The invention of superconductors and, in particular, the recent development of high-temperature ceramic superconductors have provided the impetus for pursuing a connection between gravity, electromagnetism, and, in particular, magnetism and matter in the solid state. The discovery of yttrium-barium-copper oxide (YBCO) $YBa_2Cu_3O_7$ ceramics able to superconduct at liquid nitrogen temperatures allowed many laboratories around the world to fabricate these superconductors in various experimentally useful sizes. True Meissner repulsion was obtained by cooling them using relatively cheap liquid nitrogen rather than liquid helium. For the theoretician, the possibility of considering the superconductor being a macroscopic quantum object as a reality rather than a fantasy suggested several avenues for developing theories connecting gravity and gravity-like forces to engineerable matter. For the experimentalist, extrapolations from these theories suggested there might actually be gravitational disturbances in the laboratory that would be amenable to measurement, assuming all necessary precautions were taken to exclude artifact.

Gravity Waves

A distinction should be made between gravitational waves, the gravitational "force," and anomalous forces. Currently, work on gravitational waves is divided into two more or less distinct realms: low frequency (less than a few hundred Hz) and high frequency (greater than ~ several tens of kHz). The existence of gravitational waves of any frequency is a natural outcome of Einstein's theory of general relativity (GR). The search for low-frequency gravitational waves currently utilizes large, heavy, and long metal bars as detectors together with interferometers, strain gauges, and accelerometers in an attempt to detect quadrupolar gravitational waves from cosmological sources, such as binary stars. The general idea is that if a large mass of precisely known dimensions is effectively isolated from the surrounding environment (such as Earth) by means of special vibration and other isolators, the masses will interact with the small-amplitude gravity waves emitted by large masses in the cosmos and their lengths will change, but by extremely small amounts. LIGO, LISA, VIRGO, DECIGO (Japan), and CEGO (China) are some of the acronyms given to these experiments. They are primarily attempts to verify the existence of these waves to further solidify the understanding that GR gives us about the nature of space and matter. Several researchers consider that high-frequency gravitational waves (HFGW) will be produced in the laboratory under certain conditions in the near future (Reference 1). These researchers have a considerably more ambitious view of the future than the low-frequency gravitational wave researchers, including the use of HFGW for communications, telescopy, microscopy, and possibly propulsion. Some consider that the production and detection of these waves will be mediated, or at least assisted, by superconductors (References 2, 3). Current research on the link between HFGW and the manipulation of gravity for propulsion is at present only theoretical. If gravitational waves can interact with and be converted into forces in laboratory-scale matter, it is hoped that those forces would be manifest not as gravitational forces per se, as these gravitational forces would be exceedingly small and difficult to unequivocally detect in the laboratory, but rather as electromagnetic or ponderable nongravitational forces, thus making them more amenable to detection by electromagnetic means.

Gravitoelectromagnetism

The gravitational "force" arises from the tendency of one body to accelerate toward another. (Force is in quotation marks here merely for simplicity and ease of use when comparing gravity with other forces, as many other gravity-like forces can be easily confused in the laboratory with actual gravitational attraction.) The physical explanation for gravitational attraction has been elusive at best. Several notable attempts at novel explanations have recently been published. Puthoff (Reference 4) developed an idea originally put forward by Sakharov (Reference 5) that posits gravity as a Casimir-like attraction arising within the universal sea of fluctuating electromagnetic interactions, sometimes called zero-point fluctuations. Alzofon (Reference 6) presented an engineering approach to interacting with gravity by means of altering nuclear entropy using a technique associated with electron paramagnetic resonance called dynamic nuclear orientation—that is, enhanced polarization of the magnetic moments of nucleons by interaction with pulsed polarized electron spins. Hughes (Reference 7) analyzed the Kopernicky Conjecture, which holds that gravity is nothing other than the slight difference between forces of coulomb attraction and repulsion. However, none of these researchers appealed to the special form of matter constituting superconductors.

The "attraction" of modifying gravity—whether your own, your spacecraft's, or that of a nearby large mass—for propulsive purposes lies in two general categories of effect:

- The modifying, neutralizing, or negating of the gravitational attraction of a nearby body, typically Earth.
- The provision of propulsive force or impulse to a spacecraft based on manipulation of the same underlying physical phenomenon that forms the basis of gravity.

The theoretical and experimental attempts outlined in this paper deal with both these possibilities.

In experiments designed to produce a gravity-like force or to interact directly with a local gravity field, the researcher has to be looking for extremely small deviations from a null result. Observations to date demonstrate that interactions between gravity and electromagnetic fields, given the field densities and strengths available to even the most well-equipped laboratory, are many orders of magnitude smaller than those required to begin to see such forces. Braginski et al. (Reference 8) showed that ordinary matter cannot be used to generate measurable gravitational fields in the laboratory. The standard edict against such things as gravity shields can be summed up by noting the absence of negative gravitational mass, at least in this sector of the universe, resulting in the relative "gravitational permittivity/permeability" being unity in normal matter. Therefore, demonstrating that a new force, whether gravitational or not, has been discovered in the laboratory will require an intense effort to provide proof. This implies being able to distinguish between true gravity-like forces and gravity interactions and a host of prosaic effects masquerading as these forces. A list of potential artifacts attendant on such experiments can be found in Reference 9.

General relativity introduces a metric tensor theory of gravity, and while it does not explain the fundamental physical basis of the gravitational attraction between two bodies, it does allow the prediction of a large range of interactions between bodies. Similarly, Maxwell's vector equations do not explain the fundamental basis for electromagnetic interactions but do allow us to predict the outcomes of such interactions. It is possible to reformulate the tensor format of GR into a simple vector format that is valid only for a subset of GR conditions, namely in the weak field approximation and for nonrelativistic velocities. Using perturbation theory, for example, to compute the equations of motion in the simplified GR equations results in terms that have direct analogs in Maxwell equations where electrical current flow is replaced by mass flow, for example. Forward (Reference 10, 11) was among the first to investigate this analog. One term is analogous to the Biot-Savart-like magnetic field and is generally referred to as the "gravitomagnetic field" (and also sometimes as "gravitational frame dragging" or the "Lense-Thirring Effect") and has the dimensions of s^{-1}. Another term is analogous to the electrostatic coulomb field and is referred to as the "gravitoelectric field." Essentially, the gravitomagnetic field produces a force between currents of flowing matter, while the gravitoelectric field produces a force between masses themselves (the Newtonian gravitational field). Sometimes the term "gravitoelectromagnetic field" is used to refer to both the gravitoelectric and gravitomagnetic fields.

Gravity is thus composed of a (Newtonian) velocity-independent field and a (gravitomagnetic) velocity-dependent field analogous to the electric and magnetic fields in electromagnetic theory. The simplified GR/Maxwell equations show that there is also a Faraday-like law of induction that can generate Newtonian gravitational fields from time-varying gravitomagnetic fields.

Modern attempts to confirm the existence of the gravitomagnetic field include highly accurate laser ranging of the Earth-Moon distance (Reference 12), as well as the launch of the Gravity Probe B satellite (Reference 13).

Historical Timeline

In order to aid future researchers, it is instructive to follow the general historical development of the modern search for a link between electromagnetism, matter, and gravity. This outline will include both theoretical and experimental aspects, expanding and emphasizing experimental issues where appropriate. Because of space limitations, not all of the many contributions to the field can be highlighted. The reader is encouraged to consult the source references cited in this paper to obtain a fuller appreciation of the amount of effort that has been expended in this area of physics.

Podkletnov and Nieminen (Reference 15) published what is considered the first possible evidence for an experimental link between high-temperature liquid nitrogen (LN2) superconductor effects and gravity, allegedly in the form of a gravity shield. Many scientists since then have cast considerable doubt on their findings. Notwithstanding these severe criticisms, since the publication of this paper, many other researchers have considered that the experimental search for gravity-related forces could be taken out of the realm of pure speculation and onto the laboratory bench. Podkletnov's apparent experimental success has in turn prompted some theoreticians to consider fresh approaches to investigating superconductors as a special form of condensed matter capable of modifying and/or producing such forces.

It would be a breakthrough of the first order to discover a repeatable, laboratory-scale, heretofore hidden connection between gravity, special forms of matter that can be created in the laboratory, and electromagnetism that would possibly unlock the door to new transportation systems, new energy sources, and a host of other earthly benefits, not to mention professional accolades and untold wealth for the technology developers. However, the rush to be the first to successfully find a repeatable and verifiable link between superconductors and gravity has produced many casualties. Theoreticians have made assumptions to force their theories to explain the putative experimental results. Most experiments have been literally thrown together with little thought paid to the myriad traps and pitfalls that litter the minefield of experimental physics in this uncharted territory. This is primarily due to the expectation that the sought-after forces will be extremely tiny and hard to distinguish from prosaic influences.

The most prominent, albeit controversial theoretical work on creating laboratory-detectable gravitomagnetic fields via high-temperature superconductors was initiated by Li and Torr (Reference 16-18). Their work expanded on earlier work by DeWitt (Reference 19) and Ross (Reference 20), who considered modifications to the London equations, which relate supercurrent (that is, Cooper pair) flow to electric and magnetic fields in and around a superconductor, to include gravitomagnetic fields. Dewitt showed that a time-varying gravitomagnetic field must arise owing to the presence of magnetic flux quantization in superconductors. Dewitt's work was expanded on by Ross, who produced a modified set of London equations. These papers laid the theoretical foundations for the later work of Li, Torr, and Tajmar, for example.

In the late 1980s while at the University of Alabama, Douglas Torr was examining neglected areas of physics, including aether theories and experiments, as well as gravitational wave antennas, the subject of a paper awarded the Gravity Research Foundation's "First Award" in 1989. In 1991, Torr and Ning Li published a paper on the effects of a gravitomagnetic field on superconducting matter (Reference 16). Ordinarily, all magnetic fields are excluded from the interior of a superconductor because of Meissner expulsion. However, by solving the coupled Maxwell, GR, and London equations for the internal magnetic and gravitomagnetic fields of superconductors exposed to external gravitomagnetic and magnetic fields, they predicted a small residual internal magnetic field. This in turn produces an internal gravitomagnetic field. The fields are related to one another by the Cooper pair mass-to-charge ratio. The gravitomagnetic field penetration depth is larger than the normal magnetic field depth.

A year later the same authors presented papers at a meeting of the American Physical Society (Reference 17). Buoyed by the apparent success of their previous analyses, part of the title of one presentation was "A Theoretical Basis for a Principle of Electrically Induced Gravitation." In this paper, they used coupled Ginzburg-Landau equations to calculate the relative strengths of the electric and gravitational fields in superconductors in the presence of magnetic and gravitomagnetic fields. They concluded that under certain circumstances, a secondary gravitational field could be induced inside a superconductor and "provide a basis for the electrical generation of gravitational fields in the laboratory."

Then came the bombshell. A Russian materials scientist on staff at the Institute of Materials Science at the Tampere University of Technology in Finland published a paper in 1992 on an apparent gravity shielding experiment using a spinning superconductor disk (Reference 15). In the mid-1980s, the lead author, Evgueny E. Podkletnov, had published several papers on ceramics while at the Institute for High Temperatures in Moscow. He later moved to Finland, where he completed his doctorate under then-Director of the Institute of Materials Science Pentti Kettunen. Podkletnov's thesis was on preparation of pure YBCD whiskers by magnetron sputtering, and he was producing this material for powder-in-tube high-temperature superconducting wire for a local business concern. According to Kettunen (Reference 21), the spinning disk experiment was not actually performed at the institute but rather was conducted by Podkletnov and others "after hours." Kettunen also confided that although he was aware of the existence of the gravity shielding experiment through "so many others" telling him about it, he never witnessed it himself. He did confirm the story Podkletnov later told about discovering the shielding effect by watching the smoke from a coworker's pipe float up exactly in the "shadow" of the spinning disk. The disk was apparently made in Russia for sputtering purposes and brought to Finland.

The coauthor of the gravity shielding experiment, Risto Nieminen (this Risto Nieminen is emphatically not the more famous professor of computational physics currently at Helsinki University of Technology), was a technician working at the Institute of Materials Science during Podkletnov's time there. He was not involved in Podkletnov's experiments but noted (Reference 22) that they were likely conducted at either the Tampere Institute of Technology's Department of Electrical Engineering or the Institute of Physics. To this day, he is still not sure why he was asked to coauthor the paper, except possibly for his proofreading skills. Strangely, the only persons who contacted Podkletnov in the mid-1990s about the paper were the Italian theoretical physicist G. Modanese and this author. Podkletnov claimed he had never heard of the work of Li and Torr prior to publishing the paper.

According to the 1992 paper, the essence of his experiment was the high-speed rotation of a relatively large (14.5-cm diameter x 6-mm thick) YBCO sintered ceramic superconducting disk in the vapors of liquid helium (LHe). The disk was levitated by Meissner repulsion over a large support electromagnet immersed in LHe that was powered by a variable-frequency supply from 50 Hz to 10^6 Hz. At the diametrical periphery of the disk were positioned two additional but smaller electromagnets also powered by variable frequency supplies. These two "rotational" electromagnets were used to spin the disk in some unspecified manner. A small nonconducting, nonmagnetic test mass was suspended from an analytical balance about 15 mm from the top of the disk. Subsequent information from Podkletnov indicated that to obtain the maximum stable test sample weight loss of about 0.3 percent, the optimum conditions required operation of these two electromagnets at frequencies of 10^5 Hz and disk rotational speeds of several thousand rpm.

Apart from the difficulty believing, on purely theoretical grounds, that such an enormous weight loss was possible, there was considerable doubt about the validity of the observations based on experimental issues. Among many other concerns, a few comments regarding the cryostat are in order. The only information on the physical configuration of the experiment is given in the sketch provided in Reference **15**. Referring to that figure, it is difficult to believe the only thing separating the vapors of LHe in the cryostat from the laboratory atmosphere was a thin plastic film. Ordinarily, so much water vapor and other gases would have condensed on the outer surface of the film as to render it completely opaque, thus making the observation of the disk extremely unlikely. If the cryostat was actually designed roughly per the sketch in the article, the LHe would be boiling so vigorously that it would rupture any film unless adequate He gas escape was provided. As pointed out by dePodesta (Reference 23), thermal currents and buoyancy changes above such a cryostat would be so severe as to render the determination of the weight of a test mass suspended only 1.5 cm above the disk (and therefore only a few mm above a separating film covered with ice) virtually impossible. This was an entirely unsatisfactory cryogenic design for the purpose.

Important issues such as how the disk was balanced, how it was prevented from rupturing at high speeds, how much power was used to operate the coils, and what means were employed to prevent the balance from being affected by the magnetic fields from the coils were not addressed in the article. Nevertheless, the article caused experimentalists around the world to try to duplicate the essence of the experiment, generally in an overly simplified manner. All started out using the less costly LN2 approach with either fixed or rotating permanent magnets and small (~ 2- to 3-cm diameter) disks purchased commercially. Several researchers, including Gonnelli at Turin Politecnico (Reference 24), Woods at the University of Sheffield (Reference 25), and this author witnessed very slight apparent weight changes while the disk was passing through its critical temperature, Tc. However, in most cases, the effect was so close to the noise that further experimentation was not considered. At a private unpublished meeting (see below) hosted by Professor R. Gonnelli at the Turin Politecnico in April 1999, however, Podkletnov made it clear that unless the exact disk formulation was followed, high-frequency magnetic fields were employed (not permanent magnets), and a larger disk was spun at lower temperatures, the shielding effect would be extremely small.

The experiment has remained controversial since its publication. Very few scientists put any stock into it at all. Most damning to Podkletnov's case was the complete lack of any supporting evidence that the experiment had ever actually taken place.

As the Podkletnov article began to slowly circulate, Li and Torr published another article (Reference 18) expanding on their earlier investigations in an attempt to outline the physical mechanism underlying the production of a gravitomagnetic field inside a superconductor. Basic to their consideration was an assumption of near-zero magnetic permeability in the superconductor and the requirement of coherent alignment of lattice ion spins in conjunction with a time-varying applied magnetic vector potential field. With this understanding, they determined values for laboratory-scale induced internal gravitomagnetic fields and external gravitoelectric fields and how these fields could be maximized. However, in 1994 Kowitt (Reference 26) claimed that their 1992 and 1993 results were not credible owing to their assumption of near-zero permeability inside a superconductor. However, Li and Torr rather effectively countered shortly thereafter, and Woods (Reference 3) also called that criticism into question. Later, however, Harris (Reference 27) argued in a more effective critique that Li and Torr's previous results were erroneous because they assumed arbitrary (and extremely small) distances from the lattice ion to the observer, thus producing unreasonably large effects. In fact, Harris pointed out that the correct estimation of the induced gravitoelectric field outside a superconductor is some 20 orders of magnitude smaller! No evident rebuttal has been forthcoming from Li or Torr.

At about this time, Torr and Li parted company, although both continued to work in the area. In 1995, Li was sufficiently convinced that she now had the answer to producing an artificial gravity field that could be measured outside a superconductor that she approached R. Koczor at NASA to fund further development of her version of the theory. By this time the Podkletnov paper had been "discovered," and a few forward-thinking NASA scientists determined that perhaps it was time to initiate some research in the area. After all, now there was a peer-reviewed theoretical basis for a peer-reviewed experiment. Also at this time, this author and colleagues began preliminary experiments in Toronto after contacting Podkletnov. Our approach was to attempt to reproduce the 1992 Physica C spinning disk experiment with additional data from Podkletnov but using a better cryogenic design with the possibility of mechanically spinning the disk. This author and colleagues started manufacturing our own large YBCO disks in house.

The following year, while still at the Tampere University of Technology's Institute for Materials Science, Podkletnov and Vuorinen attempted to publish updated spinning disk experiments in the British Journal of Physics D Applied Phys Vol. 29 (1996), but the paper was withdrawn in a cloud of controversy. It was later published on the Internet (Reference 28) under the authorship of Podkletnov and Levit and then Podkletnov alone. Vuorinen and Levit had coauthored papers on ceramic processing with Podkletnov previously. This new experiment involved a large AC levitated 27-cm-diameter bi-layer sintered YBCO disk spun to 5,000 rpm using two-phase high-frequency radiofrequency (RF) "rotation" fields and allegedly showed gravitational shielding in the few percent range. The cryostat design was somewhat better in that there was considerably more shielding of the test mass from buoyancy and thermal current effects. There was no independent confirmation that this experiment actually took place. Vuorinen and Levit had disappeared from the scene when this author asked Podkletnov whether they were available to discuss the experiment. Nevertheless, this author arranged for Podkletnov to visit the Toronto laboratory for preliminary consultation on the experimental design to replicate his 1992 Physica C results.

Meanwhile, a 1997 University of South Carolina press announcement declared that investors were being sought for a "Gravity Generator" technology based on confirmatory experiments apparently underway at the university involving nonrotating high-temperature superconductors and RF coils. This machine would "replace the wheels of a car…lift and propel aircraft, drive generators more efficiently and produce gravity-free environments on Earth." Evidently, the work of Douglas Torr, who had recently taken up a post there, was the basis for the announcement. Unfortunately, the excitement was short-lived, as a subsequent announcement was issued stating that the previous announcement was "premature."

In preliminary experiments at NASA, Koczor, Li, et al. failed to see expected shielding effect in a Podkletnov-like experiment (Reference 29). However, they were using a small, commercially available disk levitated above permanent magnets at LN2 temperatures. Undeterred, they pressed on, buoyed by the Internet publication of Podkletnov's previously rejected paper and discussions with Podkletnov himself. The following year, Noever and Koczor (Reference 30) published the results of their investigations into nonrotating superconductor disks irradiated by radiofrequencies from 1 to 15 MHz and detected a very weak gravity increase. This finding was later shown by the same authors to be the likely result of an instrumentation artifact (Reference 31).

In 1999, this author was asked to present the state of the Toronto experimental replication to the assembled physicists and engineers at the April 1999 Turin Politecnico meeting. Gonnelli and others presented their initial findings of a tiny possible weight change in test samples suspended above a disk as it passed through Tc. Also presenting was G. Modanese, who had been formulating his own theoretical explanations for the Podkletnov results. Podkletnov described how the "gravity shielding" effect was discovered. Apparently his group had made large sputtering target disks of YBCO for the aforementioned single-crystal processing, and to ensure the correct uniformity and porosity, the disk was set into rotation (presumably mechanically) while being levitated over a "supporting solenoid." This allowed quick and complete scanning of the target's surface by means of a small, movable test magnet suspended above the rotating disk and connected to an analytical chemical balance. When the smoke from a technician's pipe inexplicably appeared to rise above the apparatus, they considered the possibility of gravitational shielding and substituted a nonmagnetic, nonconducting test mass for the small suspended magnet. Note that the normal rotational speeds for magnetron sputtering are in the tens, not thousands, of rpm.

Podkletnov went on to describe his first experiments with the so-called high-voltage "gravity beam" apparatus. An array of single-crystal whiskers of YBCO was grown on a small (few cm^2 in area) substrate using a technique later commercialized by materials scientists (Professors Kettunen and Tiainen) at the Tampere University of Technology. This plate was placed upright in a small LN2 dewar and electrically attached to a small (~200-kilovolt) van de Graaff machine. A grounded metal annular disk was placed a few centimeters laterally away. The whole assembly was placed in a large bell jar that was evacuated and back-filled with argon to prevent YBCO degradation by water vapor. When the static machine was operated, a light blue planar "discharge" was seen to pass from the superconductor array to the annulus. At this instant, a pencil standing upright on a table in an adjoining room and separated from the experiment by a thick concrete wall fell over.

Around this time, Koczor had raised some NASA funding to commission the commercial fabrication of a 27-cm bi-layer disk conforming to Podkletnov and Levit's 1997 specifications. Podkletnov visited the Toronto laboratory for a second time to assess the experimental progress, in particular the fabrication of the special bi-layer sintered ceramic YBCO disks. Upon persistent questioning about the methods he used to power the various coils (without sustaining high-voltage arcs), keep them in phase at high frequencies, and maintain stability during rotation, it was learned that Podkletnov was not involved in the electrical design but only in the ceramic side of the experiment. Nevertheless, he claimed that with our apparatus and "home-made" disks, one should see the shielding effect, but at a somewhat smaller magnitude than his original results owing to our expected lower rotational speeds.

For several years prior to 1999, Professor Harald Reiss had been working on tests of gravity's influence on high-temperature superconductors and vice versa as a researcher at Asea Brown Boveri and later the University of Wuerzburg in Germany, where he taught courses in superconductivity. In that year he published (Reference 32) the results of precise measurements of the weights of superconducting and non-superconducting samples cooled below Tc and found anomalies not easily explained away. He weighed small, disk-shaped samples held in a specially made capsule while dipping it into LN2 and found a slight (~0.5 percent) weight increase of a high-temperature superconductor for which he was not able to offer a prosaic explanation. We supplied some YBCO disks for his experiments. His analysis of possible artifacts is thorough and very useful to other researchers investigating this area. In 2003, he published (Reference 33) an update of his ongoing LN2 experiments with increased precision and artifact reduction. He was still observing weight changes during Tc transition to a repeatable degree not achieved elsewhere.

1999 saw the wind-up of the NASA small-diameter nonrotating disk experiments with no unequivocal results. As the budget for such experimentation had been exhausted by the costly fabrication of the 27-cm bi-layer disk, Koczor tried to interest others, including our laboratory, to take on the task of levitating and RF-spinning this monster disk at LHe temperatures; we respectfully declined. Around 2002, Koczor gave up trying, as the experiment was deemed too difficult without considerable effort, and no spare disks were available in case the only YBCO disk that was made broke!

Two years later, Podkletnov and his collaborator on theory, Modanese, published a paper on the web concerning an enhanced version of the gravity beam, or "Impulse Gravity" experiment (Reference 34). This was the first general publication of the high-voltage impulse force experiment. Enough technical description was available to allow an assessment of the validity of experimental setup. Unfortunately, many unresolved technical questions cast considerable doubt on whether the experiment actually had been undertaken. Neither Podkletnov nor Modanese provided by a shred of confirmatory evidence. However, the paper presented a general summary of the theoretical work by Modanese and included an extensive bibliography.

Our own version of the Podkletnov spinning disk experiment was completed in late 2001 and published in 2003 (Reference 35) showing a null result. It represented—and still represents—the closest published replication of the original Podkletnov experiment. It contains a discussion of the experimental difficulties arising from the nature of the experiment itself and highlights the inability of the experimentalist (Podkletnov) to supply critical data on his alleged prior experiments. Such a lack would have seriously hampered our replication had not Podkletnov been actively involved in the experimental setup, at least from the standpoint of the construction of the ceramic disk. In fact, we sent to Podkletnov in Finland one of our bi-layered disks that he pronounced acceptable for experimentation. Unfortunately, neither Podkletnov's 1992 publication nor subsequent discussions with Podkletnov allowed a complete understanding of how the original experiment was carried out.

In 2001, Tajmar and De Matos began publishing a set of theoretical and experimental papers (Reference 36) that essentially carried on and incorporated Li and Torr's earlier work while also providing additional insights. Martin Tajmar was a newly minted post-doc working at the European Space Research & Technology Centre, Holland. The paper condensed the previous work, including that of Li and Torr, to show that every electromagnetic field is coupled to a gravitoelectric and gravitomagnetic field and that the coupling "is generally valid and does not require special properties like superconductivity." The authors acknowledged the criticisms of Li and Torr by Kowitt and Harris and noted that the simple coupling coefficient they derive is exceedingly small. However, it can be increased by using massive ion currents (for example, moving/rotating mass or dense plasmas) and by aligning electron and nuclear spins. In a roughly concurrent publication (Reference 37), De Matos and Tajmar, now at the Austrian Research Centres, extended their previous ideas and used a Barnett Effect analog to show that "any substance set into rotation becomes the seat of a uniform intrinsic gravitomagnetic field."

Some experimentalists were still not willing to give up on superconductor-mediated gravity effects, in spite of the failure of our replication and the null results of NASA and others. In 2002, a few researchers at Boeing Phantom Works in California attempted to interest their management in replicating the Podkletnov high-voltage impulse gravity beam experiment but were turned down in part because of the publicity resulting from a leaked copy of the internal proposal getting to the media. That same year, Chiao in California proposed (Reference 38) using superconductors as gravitational wave transducers into RF radiation and vice versa and attempted an experiment that apparently failed. Harris (Reference 39) later rebutted Chiao by stating that neither gravitoelectric nor gravitomagnetic fields accompany gravitational waves.

In his 1950 book on superfluids, London (Reference 40) derived an expression for the magnetic field produced by a rotating superconductor or superfluid that was proportional to the Cooper pair mass-to-charge ratio and the angular velocity. This is also called the London moment, and its value had been measured in the laboratory by Tate et al. (Reference 41). A general expression of the London moment can be used to determine the Cooper pair mass. In a 2003 paper, Tajmar et al. (Reference 42) noted that the Tate experiments showed that the Cooper pair mass, which had been predicted to be slightly smaller than twice that of the electron, was actually slightly larger. Intrigued that there had been no published solution to this disagreement, Tajmar asked if a gravitational effect might be at work. By applying his previous work to this "Cooper Pair Mass Anomaly," he found that a relatively huge internal gravitomagnetic field would be required to explain the mass anomaly, a field that may be investigated in the laboratory. In fact, he proposed an experiment "measuring the torque on a spinning gyroscope produced by the gravitomagnetic field possibly generated by rotating superconductors." His subsequent publications showed that he was convinced that the "anomalous gravitomagnetic London moment" can actually be detected in the lab and noted that an experiment was already underway under his direction.

In an attempt to bring some order to the discussion about correct laboratory practices in experiments designed to detect gravity-like forces, Reiss and Hathaway (Reference 43) collaborated on a paper published in 2005. They tried to remind experimentalists about the perils and pitfalls in the kind of research documented in the present paper. This author meanwhile presented an extensive list of experimental issues that is available and is still being added to on the Internet (Reference 9). These issues range from spurious mechanical effects to electromagnetic and electrostatic effects together with a discussion of signal analysis and instrumentation issues.

The following year, Tajmar et al. (Reference 44) described the results of an experiment they had performed to try to validate their conclusions about the anomalous London moment, which they termed the "gravitomagnetic London moment." The experiment involved spinning niobium and high-temperature ceramic superconductor rings at LHe temperatures. No external magnetic fields were applied. They claimed to have found the expected large gravitomagnetic field as detected by nearby accelerometers that matched to within a factor of 1.5 of their theoretical results. Eric Davis at the Institute for Advances Studies in Austin has raised concerns about the theoretical basis for the claim. Davis contends (Reference 45) that the basis for calculating the Cooper pair mass is still so fraught with uncertainties as to leave Tajmar's mass anomaly unfounded. This leaves the theoretical basis of Tajmar's experiment in some doubt. There were also several concerns about the experimental design and protocol.

By 2007, Tajmar (Reference 46) recognized that new data from improved experiments did not match their prior predictions. Nevertheless, an unexplained residual signal persisted that exhibited several unexpected features, including a relatively large coupling constant of 10^{-8} between the observed acceleration effect and the applied angular velocity. The effect appears to be proportional to angular momentum and inversely proportional to temperature after passing a critical temperature (which is dependent on the material of the spinning ring and is not coincident with the superconducting critical temperature). In addition, the effect is more pronounced in the clockwise rotation direction (as viewed from above), and it does not decay as a dipole field would. While Tajmar et al. endeavor to address all possible systematic errors or prosaic explanations, they conclude that the "measurements rule out our previous theoretical model that predicted a coupling proportional to the material's Cooper pair and lattice mass density." The residual signal observed in the most recent experiments remains unexplained.

After Tajmar et al. considered improvements to the apparatus suggested by other researchers, Tajmar's effect continued to approach the noise floor. Unfortunately, the explanations Tajmar provided in 2008 (Reference 47) for the residual effects became more difficult to understand and believe. It is not known whether Tajmar is continuing the experimentation at present.

As of this writing, there have been no further pronouncements from Podkletnov. No one has published a replication of his "gravity beam" experiment, and as time passes, more and more scientists are coming to the conclusion that the experiment was never actually performed. Concerns about experimental procedures are not confined to the fringe, either. Final analysis of the Gravity Probe B satellite data is also apparently in serious difficulty (Reference 48), adding weight to the conclusion that experimentation in this area is fraught with difficulty even for the most experienced researchers.

Conclusion

Although the payoff of the discovery of a superconductor-mediated interaction between matter and gravity would be tremendous, only a few researchers are pursuing this goal. The main reason for this is the adherence to dogma concerning the impossibility of increasing the matter/electromagnetic coupling coefficients. This adherence is reinforced by reputable physicists pointing out that the theoretical constructs presented so far are based on questionable foundations. As with any forays into the unknown, one has to accept a few bumps along the way, including sometimes going back to the starting point in order to start again. The likelihood of scientific ridicule is extremely high in the search for laboratory-scale gravitational interactions.

Increased understanding of the nature of high-temperature superconductivity will be advantageous in setting the firm basis from which to proceed. True scientists will continue to speculate about the ideas considered above, whether outlandish or not. Experiments will continue until either funding runs out or theory proves unequivocally that the expected effects will be far too small to see; however, experimentalists must ensure that other researchers have complete information so they can replicate experiments. Theory will continue regardless, but theoreticians must ensure that the scientific foundations are correct, and experimentalists must remain wary of potential traps.

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