NASA/TM–20220016371

Survey of Quantum Technologies in Aerospace

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Introduction

The 20th century produced major theories in physics beyond Newtonian – Relativity for the large and Quantum Mechanics for the small [ref. 1]. There has been a recent and rapid development of quantum technologies greatly aided by the Nano technology revolution [refs. 2 – 5], termed the second quantum revolution. The first quantum revolution involved stable quantum states and resulted in nuclear power, semi-conductors, GPS, lasers, Bose-Einstein condensates, super-fluidity, super-conductivity, Magnetic Resonance Imaging, advanced communications, and imaging devices. Quantum technology is the next big little thing beyond Nano. Quantum physics has been responsible for the successful computation of many phenomena that Newtonian physics could not address, is accurate to many decimal places, yet has some serious issues such as the 120 orders of magnitude over prediction of the cosmological constant. Quantum technology addresses control of quantum systems, the systems under development include quantum communications, metrology, computing, optics/imaging, sensing, navigation, materials, artificial intelligence (AI), biology, electronics, chemistry, information systems, cryptography, thermodynamics/energetics, and medicine. The developing importance of quantum technology is attested to by, in many government projects and programs [e.g., refs. 6-9]. This increases marketplace applications and the emergence of quantum technology instruction in educational institutions. The prime example for quantum technology is quantum computing, proffering many orders of magnitude computing capability increases. As an example, in aerospace and other application areas involving fluids there are hopes-to-predictions for the ability to directly compute turbulence at the speed required for design optimization, thereby producing both greatly improved designs and obviating many to most experimental/wind tunnel studies, along with their substantial costs and time. As another example, quantum interferometers in space offer many orders of magnitude increase in signal to noise ratio. There are two basic keys to quantum technology developments going forward. The first is understanding the physics and applications of quantum entanglement, a cornerstone of what has been termed “The Second Quantum Revolution.” The second is success in the search for the “stable Qbit.” The latter is especially critical for quantum computing. Efforts include increasing the life of quantum states, aimed at usual operational conditions such as room temperature lifetimes much greater tham microseconds to milliseconds.. There have long been quantum technologies, devices, or effects such as lasers, Bose-Einstein condensates, super fluidity, fermionic condensates, photovoltaics, semiconductors, quantum gravimeters and magnetometers, and quantum magnetic deflagration which operate in the macroscopic, classical world. Current quantum technologies under development are targeted at many-body quantum entanglement. Entanglement has been measured at occurring more than 10,000 times the speed of light and, although predicted by quantum physics, there is essentially no fundamental understanding of how this occurs. It is one of the many “unsolved problems in Physics.” This report of quantum technologies in aerospace will address some current issues in quantum physics, indicate the richness of the search for the stable Qbit, provide summaries of the various quantum technology efforts, and then consider applications in aero and space for both space science and space faring.

Issues in Quantum Physics

Perhaps the most global issue with quantum physics is physical interpretation. This is unresolved to the extent that even after a century when students query this they are told to be quiet and compute. The approaches and sizable numbers of constants and mathematics that together constitute quantum theory work well, except when they do not. An example of this is with the cosmological constant, where the discrepancy is huge. Also, when quantum physics first originated the concept of quantum entanglement, it had no cogent physical explication as to how this can occur, especially at a measured speed faster than10,000 times light speed, obviously highly “non-local.” References 10 and 11 summarize “common” extant “interpretations” of quantum physics. Most focus on the “physics” responsible for the shift from a quantum state that is general, to a specific realization. Some say the general state is realized in detail in a multiplicity of parallel worlds. Others state that making a “measurement” of the state makes the decision, or that the extant boundary conditions, environmental disturbances, termed decoherence, decides the issue (of which making a measurement could be one such). The fact that removing environment disturbances and experiments near absolute zero temperature stabilizes quantum states suggests the decoherence interpretation may be more right than wrong. The bottom line appears to be that quantum is a recipe that works well to make numbers at small scales and for many phenomena not addressed successfully by Newtonian physics. It is also responsible for much of modern technology, but there is no agreement regarding quantum gravity, and it disagrees with relativity. There have been many efforts to create a theory of everything, one that subsumes quantum and relativity as special cases, thus far without success.

The singular characteristic of quantum physics and the major focus of the second quantum revolution and developments in quantum technology is quantum entanglement [ref. 12 and 13]. This is wholly non-local wherein if two or more quantum materials are entangled/related and then moved apart or if one part is changed, then the other part is also altered instantaneously no matter how far apart they are. As stated, using the available sensors, the measurements of the speed of action of this spatially separated alteration process are greater than 10,000 times the speed of light [ref. 14]. This very well verified feature of quantum physics was identified early on and in the latter part of the 20th century experimentally. Recent measurements successfully provided maximum assurance of its presence and validity [refs. 15 and 16]. However, the physical "understanding" that enables instantaneous notification over an arbitrarily vast spatial distance (i.e., wholly non-local behavior), is unknown. There are theoretical speculations-to-theories, some involving retrocausation [ref. 17], but no validated explanatory physical mechanisms or constructs. This is one of the many unsolved problems in physics. This lack of physical understanding has not impeded the now rapid development of quantum technology whose major benefits are mainly due to the operationalization of entanglement. While physics has long maintained that entanglement cannot be used to transmit information, ref. 18 suggests that entanglement can be used as a generator of morse code.

The stabilization of quantum states and the material(s) of quantum technology and entanglement are the keys to seriously increasing their technical capabilities and usefulness. References 19 - 21 discuss the occurrence of quantum phenomena in the classical warm, wet world, citing their observation in biological applications in nature. Macroscopic quantum entanglement has also been demonstrated in the laboratory (e.g., refs. 20 and 21) at room temperature, and quantum repeaters (e.g., ref. 22) are under development to restore entangled states disrupted by environmental decoherance.

The Search for Stable Qbits, The Key to Improved Quantum Technology

The application of quantum physics for technological purposes usually requires long-lived quantum states. Given the extreme sensitivity of quantum states to environmental effects (e.g., decoherance), the historical approach to increase their lifetime has been to drastically reduce the environmental disturbance levels the quantum states are exposed to via employing ultra-low temperatures and a vacuum, or to impose serious magnetic control to mitigate them. The energy of quantum fluctuations is smaller than the Boltzmann thermal energy. There is a plethora of quantum states in terms of materials and behaviors. There are also many possible quantum arrangements or systems and there is an increasing number of ways to control quantum behavior. We are currently in the midst of these types of studies including combinatorially, in the ongoing hunt for the stable Qbit [ref. 23]. In the midst of this hunt, there are ongoing studies to understand what appear to be several applications of relatively long-lived quantum systems applications in biology, living systems, wet, warm, large molecule, noisy, non-equilibrium open living systems [refs. 24, 25]. The large number of quantum technology application areas and their sizable-to-tremendous technological payoffs have instigated this stable Qbit hunt, and per this section of the report there are several approaches which are providing up to orders of magnitude more quantum lifetime at "room temperature" conditions. We are making progress. Once a suitable Qbit is discovered, ideated and developed, proven quantum technology developments are expected to be rapid. Candidate Qbits include photons, electrons, ions, neutral atoms and molecules, superconducting devices and quasi-particles, and others. Qbit performance issues include stability/decoherence, fault tolerance, cost, and scalability.

Quantum Biology – The following instances of quantum effects in biological systems have been identified [refs. 24, 26]:

- Energy transfer in photosynthesis
- Hydrogen tunneling in enzyme reactions
- Olfaction, inelastic QM tunneling for vibration sensing, entanglement in supra molecules

- Vision, eyes sensing single photons, rapid (< 200 fsec) photoisomerization reaction rate
- DNA mutation, nearest neighbor entanglement
- Brain cells, microtubules
- Avian magnetic compass, quantum superposition and entanglement, spin coherence

The evidence for quantum coherence in photosynthesis "is direct and overwhelming" [ref. 27]. Light harvesting processes in photosynthetic organisms exhibit remarkable quantum efficiency, usually > 95% [ref. 28]. "Electron tunneling identified as a wide spectrum process in photosynthesis, cellular respiration and electron transport in DNA" [ref. 29].

Along with the increased insight and understanding of biological processes and capabilities, the central issue with quantum biology of extreme interest to the development of quantum technologies is how is this done, how can many-body quantum states survive for operational times in these warm/wet/open, etc. biological conditions? Some insights on how thus far include the finding that for green fluorescent protein generated photons with successful polarization entangled between photon pairs, barrel shaped structures surrounding the protein protected the entanglement state [ref. 30]. Other possibilities not specific to biological conditions include decoherence delay by operating in the critical transition region between coherent and decoherent/chaotic behavior, controlled sequences to regularize the environmental states, and replacing environmental chaos with ordered inputs and stored quantum state information to resurrect/restore the state. Reference 31 provides a theory as to how quantum systems operating at the right level between chaos and regularity can increase coherence time by orders of magnitude. Overall, given the critical impacts of successful decoherence control upon the development of quantum technology, it is important to determine the perhaps several reasons how quantum behavior can persist long enough in biological systems to provide significant capabilities for utilization in quantum technology.

Approaches to Maximize Quantum, QBIT Coherence – The traditional, conventional approach to quantum state stabilization with environmental disturbances is to minimize these disturbances via ultra-low temperatures, including via laser cooling and vacuum (e.g., ref. 32). This approach has coherence time of one second, which is much greater than usual times in the microsecond range. An alternative or sometimes coincident approach is to apply magnetic controls, which can sometimes be effective even at room temperatures. There are a plethora of Qbit control approaches which are often a function of the particular Qbit of interest. Perhaps the most successful general control approach with more disparate instantiations thus far is to "vibrate" or dynamically cycle/alter the environment in various ways to delay equilibration. Such an approach was suggested in connection with explications of quantum biology. The apparent record for coherence maintenance time for ions may be an observed three hours for a temperature pulse stabilized cryo system and 39 minutes for a room temperature system (ref. 33). Self-induced oscillations from "Quantum many body scars" which delayed thermalization, were effective in increasing coherence time in ref. 34 and for many systems in the summary in ref. 35. This was also the case in refs. 36, 37, 38 (factor of 10x increase in coherence time), 39, 40, 41 (10 seconds), 42, and 43 (60x coherence time). Some dynamic stabilizing perturbations in these studies were self-induced and some were applied. Overall, considering that many efforts to develop quantum technology devices are dealing with micro to millisecond coherence times, it would appear that utilizing dynamic perturbations for many Qbit candidates might be efficacious, perhaps seriously so. In addition to those mentioned thus far, there is a large number of alternative approaches to increase coherence time. These include ions [ref. 44, 45], materials [refs. 46 – 52], and geometry [refs. 53 - 55]. Also, there are schemes or approaches to re-establish the quantum state [refs. 56 – 58] and the related error correction approaches [refs. 59 – 62]. There are studies of extremely deeply cooled molecules [ref. 63] and massively entangled crystals [ref. 64]. Overall, the multiplicity, diversity, and major improvements in coherence times obtained in ongoing research bodes well for serious improvements, greatly enhanced capabilities, and impacts of quantum technology going forward.

Applications of Quantum Technology

There is a long list of active and potentially revolutionary applications of quantum technology. As indicated, most of these applications make use of many-body quantum entanglement. Perhaps foremost of these in terms of technological and societal impacts is quantum computing. This application is especially important with Moore's Law winding down as we create computers whose features approach atomic dimensions. A shift is needed to a very different machine architecture and enabling physics and quantum computing conceptually could supply those. Related to quantum computing are quantum information systems and quantum communications with the latter positing a different encryption approach and the former non-E-M communications that potentially cannot be detected or intercepted, at high band width. Quantum computing would enable the ab initio design of materials at quantum scales with revolutionary properties. Quantum sensing provides miniaturization and much improved sensitivity and resolution as well as imaging better than the Rayleigh limit, atom optics/orders of magnitude improvements in inertial navigation, gravimeters and magnetometers, and biological/health breakthrough capabilities. Other expected quantum technology enablements include increased PV efficiency and catalysis, higher temperature superconduction, designer chemistry, unique electronics, molecular manufacturing and, via computing, artificial general intelligence.

Quantum Computing – Quantum computing (QC) [refs. 65 and 66] utilizing superposition, interference, entanglement, logic gates, and measurements can, conceptually, solve any problem that classical computing can. The estimated future market covers many uses [ref. 66], with applications at the trillion-dollar level. There have, over the years, been a wide range of speculations as to the potential speedup that quantum can provide over classical computing, including many large-to-revolutionary values. These drive much of the world-wide efforts in quantum computing, which is very much a work in progress. The major realization issue for QC is as stated long coherence times for Qbits. Many different QC approaches are being studied [ref. 65], including superconducting, trapped ion, quantum dot, quantum wells, nuclear spin, electron spin, cavity trapping, fullerenes, linear and non-linear optics, diamond-based, bose-einstein doped optical fibers and carbon nanospheres, etc. Projected revolutionary applications include encryption and decryption of classical encryption, search, optimization, system simulation including turbulence, chemistry, nanotechnology, AI, and biology including drug discovery. Challenges in addition to long coherence time for Qbits include increases in numbers of qbits or gates. The current leading hardware contenders [ref. 66] are superconductors, ion traps, photonics, quantum dots, and cold atoms. References 67-76 provide a cross section of the state-of-the-art of quantum computing architectures, references 77-82 for materials for quantum computing, and references 83 to 87 on quantum computing algorithms. Per reference 88, the imposed fluctuation approach for increased coherence time discussed previously is being applied. There is much development needed yet on turning Qbits operations into a viable "computer", including network/communications related issues and much else [e.g., ref. 89].

Quantum Communications – There are three major applications of quantum technology to communications – cryptology, decryption and a communications approach that is not E-M via the quantum vector and scalar potentials. Quantum computing capabilities envisaged can conceptually decrypt the bulk of current encryption approaches, which has generated significant concern, especially in the financial and national security sectors, and augmented efforts to develop quantum computers [refs. 90 – 92]. Also, quantum crypto keys can be used to protect from decryption [refs. 93– 95]. Quantum computing is still a work in progress, therefore quantum encryption has developed first, with demonstrations of Earth to space and ever longer terrestrial distances as well as counterfactual quantum communication, where no particles travel between the recipients [e.g., refs. 96, 97]. The issue is the usual need to ensure quantum coherence, and there is progress with quantum repeaters [refs. 98, 99]. Also, there are potential security concerns [e.g., ref. 100].

The unique to quantum technology non-EM communication approach is described in ref. 101, "Communication and Apparatus With Signals Comprising Scalar and Vector Potentials Without Electromagnetic Fields", a U.S. Patent. There were related earlier patents. This approach is under development and includes scalar waves only, E-M waves were suppressed. Very penetrating and non-shieldable, (far field decays as 1/r not one over r squared, requires quantum detectors/Josephson junctions), and non-detectable by usual E-M devices, enables high bandwidth communications including through the water column. This is an answer to several of the IT/cyber concerns with the current E-M based IT.

Quantum Sensing – Quantum sensing in many cases or situations enables more precise measurements (e.g., operations below 'shot noise") than the usual limits on macroscopic sensor approaches [ref. 102] through use of such as quantum state "squeezing" and quantum entanglement [ref. 103]. Major functionalities for quantum sensing include motion, e-m fields, and imaging. There is widespread application of quantum entanglement and again, long coherence time is critical. The greatest impacts of quantum sensing thus far include gravimeters and magnitometers, which are sensitive enough to provide navigation utilizing the spatial variability of the Earth's magnetic and gravity fields and mapping of underground variations for mining applications, volcano alertments, and construction activities [refs. 104, 105]. Quantum interferometers proffer very significant improvements, orders of magnitude sensitivity improvement, and some eight orders of magnitude improved signal to noise ratio [refs. 106, 107]. Atom optics, involving a Boise-Einstein condensate, which contain atoms at the same quantum state interacted with lasers can provide orders of magnitude improvements in inertial navigation, a replacement for GPS that does not have the serious jamming and interference issues that GPS has [ref. 108]. Quantum radar is a quantum sensor that is a work in progress. There have been huge investments in a wide variety of radar systems over many decades. There are several ways to employ quantum technology to improve radar performance, varying from factors of two to much more [refs. 109 – 111]. Quantum sensing will improve the capabilities of "smart dust", millimeter to nano wireless arrays/networks of dust motes with onboard sensors, communications, energy harvesting, and computing having a plethora of applications including climate/environmental, planetary, agriculture, industrial, military and health monitoring, and serving as a global climate grid and a "central nervous system for the planet" [ref. 112.]. Ref. 113 provides a cogent summary of quantum sensing for energetics.

Quantum Simulation, Computation – As computers have improved by orders of magnitude over many decades, we are now doing exoflop computing, modsim including optimization is replacing experiment and performing design in many arenas. Quantum computing is projected-to-expected to provide major computing capability increases that would produce massive benefits for science, engineering, and society. These benefits include ab initio design of materials at the quantum level, direct computation of turbulent and transitional flows, future projections and optimization as a whole, sense making for the evolving global sensor grid, chemical processing, drug development, climate projections, physics/cosmology, and artificial general intelligence. Overall, application to ongoing seriously rapid and massive widespread and societal changing technology acceleration(s) which are clearly disruptive in a favorable manner.

Quantum Energetics – Quantum sensing and computing can enable further optimization of energy production, transmission, utilization, conservation, and load balancing [ref. 113]. Quantum physics has enabled a vastly improved radiologic nuclear battery based upon utilization of high energy gamma, via several processes, to free up inner band electrons. This battery proffers up to some 20 Kws/Kg of isotope, alpha, Kgs/Kw of order one and is some factor of 30 plus lighter than a reactor [ref. 114]. Refs. 115 – 117 indicate that quantum technology can enable the production of two electrons per photon for photovoltaics, essentially doubling the efficiency of PV. This should have massive impacts upon the shift to renewable energy for climate change amelioration. Research indicates that quantum technology can increase the efficiency of thermal electrics, enabling increased utilization of energy regeneration from waste heat [refs. 118, 119]. Ref. 120 indicates that quantum technology can provide improved catalysis for the operation of fuel cells. Quantum technology can vastly reduce the time required to charge batteries [refs. 121 – 122].

Quantum Technology and AI – AI essentially languished as expert systems until circa 2012 when the computers acquired sufficient capability to seriously apply neural nets or "Big Data Deep Learning." Since then, this version of AI along with associated computing, has increased the capability and breadth of application of AI to the point where it can now ideate, create, and increasingly make decisions by informed algorithms. The AI benefits to society are increasingly important with some downsides in privacy and employment erosion as AI empowered machines or robotics have subsumed some employment. The AI approach to ideation resembles that of the human subconscious, where information is loaded and the machines craft quasi-random combinatorials which are then evaluated for system level efficacy. Quantum computing will, in a projected major manner, greatly increase the information loaded and the number of quasi-random combinatorials evaluated with improved system evaluation. With quantum computing it may be potentially possible to load data from the evolving global sensor grid and the contents of the web, so the machine learns what humans consider common sense and at quantum machine speed, producing artificial general intelligence (AGI). Ref. 123 describes the recent status of quantum AI. The immature status and development of quantum computers drives progress in quantum AI. Refs. 124 and 125 provide useful background.

Quantum Technology Optics – Termed photonics, it concerns generation, control, and detection of photons and their interactions with matter. This is a well-developed technology arena. Several books are available (e.g., refs. 126, 127) and there are dedicated journals, AMO (atomic, molecular, optical) physics and a strong literature. Photons exhibit quantum characteristics at room temperature, and photonics is a traditional quantum physics area which transitioned early on into very useful technology, especially with lasers, sensing, and communication. Refs. 128 and 129 are useful summaries of the subject. Of considerable interest with a large number of applications is using quantum technology to exceed the Rayleigh Diffraction limit for imaging. There are approaches aimed at this under study including multiphoton entangled states [ref. 130]. As stated previously, quantum entanglement interferometers proffer orders of magnitude sensitivity improvement, with many orders of magnitude increases in signal to noise ratio. A recent version utilizes parametric amplifiers [ref. 131]. Photonics as a whole is a key approach/option in quantum computing and quantum communications and is having an increasing role in manipulating matter [ref. 132].

Materials and Quantum Technology – There are several quantum technology materials functionalities with goals including: materials to produce and increase coherence of quantum states, the use of quantum technology to design and ideate improved materials for classical and quantum properties, a part of atomic and molecular engineering, and material production and utilization involving quantum technology. Classical materials development was via chemistry, essentially dealing with electron band interactions, etc. With quantum computing and starting with atomic and subatomic states, new optimized materials with unique, tailored functionalities and capabilities (including optical and electronic or magnetic capabilities beyond semi-conductors and for a spectrum of applications), new forms of matter with tailored properties, are emerging (e.g., ref. 133). An exciting development, but actual operational use of such materials, requires care in materials processing. Conventional materials processing approaches produce grain boundary problems and dislocations in the microstructure which alters, usually in a negative manner, the designed in properties. There are four degrees of freedom in quantum materials – lattice, charge, orbital, and spin [ref. 132]. Refs. 134 and especially 135 provide summaries of the exceeding richness and multiplicity of the spectrum of new quantum materials. Ref. 135 includes a section on Qbit developments for quantum computing. Ref. 136 addresses quantum tunneling in chemistry, including at room temperature.

Military Applications of Quantum Technology - Quantum encryption and decryption, quantum communications, along with quantum sensing and computation, given the increasing dominance of information on the battlefield, are critical to national security going forward, as is the sensemaking and autonomous operations superiority of quantum AI. Refs. 137 and 138 provide up-to-date extensive reviews of quantum technologies and their applications to national defense including TRL levels and world capabilities. The quantum vector/scalar potential non-EM communications mentioned previously are especially important, as is quantum crypto for E-M communication. Going forward, superb sensing/sense making/imaging, navigation, autonomous operations/fires, and associated communications will be absolutely essential for a viable deterrent. Quantum technology is required to prevail. Then there is utilization of quantum computing to design equipage and optimized materials for various metrics.

Quantum Technologies In Aerospace

Quantum technologies will revolutionize aerospace in terms of capabilities across the application spectrum - climate sensing, communications, planetary science/cosmology, power and energy, safety, regulatory, operations, commercial deep space, exploration, and colonization [refs. 139 – 146]. Quantum technology enables possibilities for operating at quantum vice classical limits, enhancing sensitivity, accuracy, stability, security, and capabilities. Some specific quantum aerospace applications include optical communications, cryptology, non-E-M communications, sensors, GCR radiation protection, timing, navigation, powering/energizing everything space, lasers, imaging, via quantum computing AI/AGI/trusted autonomy, interferometers, superconductors, atom optics/cold atoms, gravity gradiometers and magnetometers, and materials. Space in particular provides a more salubrious environment for maintenance of coherent quantum states due to vacuum, low temperatures, micro-g, and low disturbances overall, if disturbance fields from vehicles and human operations can be reduced in quantum operational spaces. Otherwise, the emerging approach of applied disturbance fields can be employed to delay decoherence.

Space quantum science includes climate related measurements, red shift, vacuum energy, the foundations of quantum mechanics, gravitational waves, the search for dark matter and energy, etc. employing such as atom interferometry, atomic clocks, cold atoms, and lasers [ref. 139]. NASA quantum-based instruments include quantum well multiplier infrared photodetectors, ultrasensitive near infrared optical receiver using avalanche photodiodes, quantum cascade laser oscillator for infrared spectrometer, optical interference gravity gradiometers for 3-D subsurface mapping, quantum well modulating retroreflector, quantum interferometers, atomic clocks, and a variety of lasers/ lidars. The references and discussion thus far herein address the major space initial quantum technology utilizations, including quantum crypto, optical communications, timing, initial sensor applications, navigation, lasers, imaging, superconducting, atom optics/cold atoms, gravity gradiometers and magnetometers, quantum materials, and photonics. There are five nascent quantum applications in space that could literally revolutionize space faring: Non-E-M vector/scalar potential comms, curved silicon crystals to provide ultra-low weight galactic cosmic radiation (GCR) shielding, a nuclear battery order to orders of magnitude lighter that a reactor and previous nuclear batteries, quantum computing and resulting AGI to enable “sensemaking and trusted autonomy in space and the fifth, explications of the too many serious unsolved problems in physics with the possible upside of expanded opportunities for interstellar transportation.

Non-E-M Vector/Scalar Potential Quantum Communications – As mentioned in the quantum technology communications section, there are patents and efforts utilizing quantum technology as the communication approach, in addition to quantum crypto functionality. This communication approach is based upon use of the vector and scalar quantum potentials with the E-M fields suppressed. The issues associated with E-M communications (our current communications mode) are many, including interception, alteration, cyber attacks, environmental interference, etc. This quantum communications approach, documented in six patents in the 1980s and the Puthoff patents in 1998 [ref. 101] and 2019 [ref. 147], is penetrating, non-shieldable, has a far field signal that drops off as one over R vice one over R squared for E-M, is not detectable by E-M devices, has high band width and utilizes Josephson junctions. The fundamental enabling physics is the Aharonov-Bohm effect [refs. 148, 149]. The approach is under serious development and if successful, will be far more capable in space than even optical communications. Some have asserted that this will go through planets. This is TBD. The technology has obvious and hugely important national security implications.

Curved Silicon Crystals for lightweight GCR Radiation Protection for Humans – For this opportunity, both the issue and the putative solution space involve quantum physics. GCR protection is of major importance for enablement of human operations in deep space. The major human health hazards in space faring are operability, radiation, and micro-g. Ref. 150 explicates the many and major, not just carcinogenesis, health impacts of GRC, which is particle radiation, fully ionized iron at GEV levels, which is far more worrisome than gamma. In terms of protection using mass, three plus meters of thickness is required, and the mass offering protection must be composed of significant hydrogen, low Z materials to minimize secondaries. Cheap space access can enable such protection, employing a reusable overcoat left in space between trips. Also enabled by cheap space access is cheap fuel in space. This enables fast transits (e.g., to Mars) which greatly reduce the exposure duration. There is also a breakthrough nuclear battery which could power VASIMR (Variable Specific Impulse Magnetoplasma Rocket): the high thrust electric propulsion with 6,000 seconds of Isp for fast transits. There is, in addition, the possibility that mm long curved silicon crystals could deflect the particle radiation, reducing much the additional weight for radiation protection.

Some 40 years ago, the accelerator community started using small, curved silicon crystals to redirect particles into measurement locations. There is a substantial literature documenting the practice [e.g., refs. 151 – 161]. John Norbury of NASA Langley Research Center is working on using the crystals as GCR protection for humans in space. When impacted, the small, curved silicon crystals produce large electric fields which redirect incident ions. This is a very different radiation protection approach from the usual use of large amounts of low Z, hydrogen containing materials, with a mass on the order of the spacecraft mass. Studies are beginning to determine whether the crystals could provide GCR shielding for space suits, if necessary, using an exoskeleton to handle the crystal mass and inertia. The accelerator related tests of these crystals indicate they are effective into TEV energy levels in excess of the GCR GEV levels. A major difference in the accelerator application of the crystals and spacecraft GCR protection from GCR is the nearly isotropic nature of the impinging particle incidence in space. As on moons, asteroids, or planets there is blockage by the body, in this case spacecraft, so less than full steradian incidence. The acceptance angle of the particle incidence angle to the silicon crystal is small, inhibiting use for protection in space. However, there is another interaction mode termed volume reflections which has a much wider acceptance/redirection angle capability. Some 80% of the incident particle radiation could conceivably be redirected. The major forward work is the design of a nearly omni-directional incident particle silicon crystal shield for humans, including utilization of multiple layers and determining the possible need for, and design of, a shield for gamma production if it occurs. There is some information that germanium crystals may provide greater particle turning, deflection.

Advanced Nuclear Batteries - Recent invention of nuclear batteries with up to orders of magnitude greater energy density and much reduced overall weight (alpha down to order one, up to 22 KWs/kg of isotope vice usual 20 Watts/kg) which lasts for years, opens an entirely different in-space transportation and surface mobility trade space [e.g., ref. 114]. The NASA version is the quantum energetic process based Nuclear Thermionic Avalanche Cell (NTAC), which releases a large number of intra-band or inner shell electrons via utilizing high energy photons or beta radiation of 100 keV to MeV. The battery design scales from powering phones to tens of megawatts, with the far longer-term operability expected of nuclear vs. chemical batteries. Other potential utilization includes powering satellites, terrestrial and deep space mining, ships, manufacturing, and utilize nuclear fission waste as fuel to generate electricity, reducing the radioactivity in the process. For on-surface transportation, there are three obvious possibilities to utilize this new nuclear capability: lower speed, nuclear ramjets, and nuclear rockets. On Mars, such a nuclear battery could supply propulsive lift for long haul, as well as short haul via intaking CO_2 from the atmosphere and pressurizing it via electric motors turning axial flow compressors exhausted downwards using ejector nozzles to provide lift and thrust. For higher speeds up to high supersonics, the new nuclear batteries could either power heating and additional compression for an atmospheric ramjet or heating for a conventional rocket, with or without addition of chemical energy using on-planet ISRU derived propellant or propulsive mass. There are a multitude of ISRU applications for such nuclear batteries, especially for autonomous and lunar night operations. Electrolysis of ice into hydrogen propellant and oxidizer to enable a lunar economy or for return fuel from Mars requires far more power than current technologies can deliver (except much larger and more expensive nuclear reactors). Projections of full-scale performance suggest that the new nuclear batteries can provide essentially all on body/planet energy requirements, including those that require portability.

Aerospace Impacts, Enablements of Projected Quantum Computing Capabilities – As noted herein, quantum computing projections include large-to-huge speedup and some indications that a general-purpose quantum computing machine may be possible [ref. 162]. There are a bevy of barrier enablements in aerospace that such computing capability could satisfy having major impacts:

- Capability to compute turbulence via direct numerical simulation at flight Reynolds Numbers fast enough for design optimization. This capability would largely obviate the need for wind tunnels.
- Capability to develop AI approaching AGI enabling autonomy, with applications including robotic in situ resource utilization on bodies in space, an air traffic management (ATM) system capable of handling tens of millions of air vehicles, sense-making for the increasing swarms of nano and quantum sensors including the emerging global sensor grid and the emerging global climate grid. Such AI would also enable high end robotic autonomy for in space body use and space faring in general. Nominally, humans in space cost orders of magnitude more than robots, so huge cost savings along with increased in space robotic, greater than human, capabilities.
- Aerospace design and scheduling as a whole.

Addressing the Large Number of Unsolved Problems in Physics – There is a Wikipedia regarding unsolved problems in physics which has a large number of entries, shortfalls, that continues on for several pages [ref. 163]. These include: major cosmological and other issues including the 120 orders of magnitude QED over prediction of the cosmological constant, the fact that we cannot find dark matter/energy that are supposed to be approximately 94% of cosmological matter-energy has no explication, physics in regards to the measured greater than 10,000 times light speed of the action of quantum entanglement, and many more questions. There are some theories, including many worlds, retro causation, non-commutative quantum space-time, etc. All of this and much more needs superb quantum aerospace-based sensors to sort out. The sorting out could conceivably inform the development of the long sought "Theory of Everything" that includes quantum and relativity as special cases, as well as non-locality. It should also inform the quest for viable interstellar transportation.

Concluding Remarks

The development of Nano technology has enabled and led to the development of quantum technology which includes the application of quantum entanglement and quantum many body physics, to an increasing spectrum of technological, often barrier, problems, issues, and shortfalls. There is a relatively long-standing segment of quantum technology that involves stable quantum states that has and is proving to be extremely valuable including semiconductors, quantum optics, sensors, timing, lasers, materials, superconducting, etc. The major new applications involving quantum states subject to decoherence are quantum crypto, quantum vector/scalar potential non-EM comms, advanced sensors, computing, interferometers, and others. Many of these quantum technologies, old and newer, have massive technological and econometric implications, notably with respect to semiconductors, lasers, non-EM quantum comms, quantum crypto, timing, advanced nuclear batteries, computing/AI/AGI, and materials. For aerospace the impacts of advanced nuclear batteries, non-EM quantum comms, and computing/AI/AGI/Autonomy, are "game-changing." The combined impacts of quantum technology, including sensors in space, considering their impacts upon the many major unsolved problems in cosmological physics, could be the key to the theory of everything and interstellar transportation. The shift to the "quantum age" now that we have ways to seriously delay decoherence, should be at least as momentous as that from the industrial to the IT age. It's the early days yet for some technologies and applications, but the engineering schools are now teaching quantum technology [ref. 164] which will hasten applications.

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