Advanced Applications of Quantum Mechanics

Potential Research Opportunities for Supporting the Defense Threat Reduction Agency Mission

Edward Toton
TOTON Incorporated

George Ullrich
Science Applications International Corporation

February 2008
Report Number: ASCO 2008 012
The mission of the Defense Threat Reduction Agency (DTRA) is to safeguard America and its allies from weapons of mass destruction (chemical, biological, radiological, nuclear, and high explosives) by providing capabilities to reduce, eliminate, and counter the threat, and mitigate its effects.

The Advanced Systems and Concepts Office (ASCO) supports this mission by providing long-term rolling horizon perspectives to help DTRA leadership identify, plan, and persuasively communicate what is needed in the near term to achieve the longer-term goals inherent in the agency’s mission. ASCO also emphasizes the identification, integration, and further development of leading strategic thinking and analysis on the most intractable problems related to combating weapons of mass destruction.

For further information on this project, or on ASCO’s broader research program, please contact:

Defense Threat Reduction Agency
Advanced Systems and Concepts Office
8725 John J. Kingman Road
Ft. Belvoir, VA 22060-6201
ASCOinfo@dtra.mil
ADVANCED APPLICATIONS OF QUANTUM MECHANICS
Potential Research Opportunities for Supporting the Defense Threat Reduction Agency Mission

Edward Toton
TOTON Incorporated

George Ullrich
Science Applications International Corporation

February 2008

The views expressed herein are those of the authors and do not necessarily reflect the official policy or position of the Defense Threat Reduction Agency, the Department of Defense, or the United States Government.

This report is approved for public release; distribution is unlimited.

Defense Threat Reduction Agency
Advanced Systems and Concepts Office
Report Number ASCO 2008-012
ACKNOWLEDGEMENTS

This work was performed under contract DTRA01-00-D-003, Delivery Order 0020, Technical Instruction 18-07-4, in support of the Defense Threat Reduction Agency’s Advanced Systems and Concepts Office.

The authors wish to express their appreciation to Dr. James Scouras and Mr. David Algert for their steadfast support and insightful guidance throughout the course of the study. We would also like to thank Drs. Monte Chawla, Calvin Shipbaugh, and Michael Frankel for their participation on a peer review panel and their constructive critiques of the final report.
# TABLE OF CONTENTS

Preface ........................................................................................................................................................... ix

Executive Summary ........................................................................................................................................ xi

Historical Perspective .................................................................................................................................... 1

Basic Research and the DTRA Mission ........................................................................................................ 5

The Scope of Quantum Mechanics Research and Development .......................................................... 9
  Controlling the Quantum World ............................................................................................................... 12
  Quantum Physics and Energetic Materials ............................................................................................... 24

Assessment ................................................................................................................................................... 29

Recommendations ....................................................................................................................................... 33

Enclosure 1 .................................................................................................................................................. 35
The attacks of September 11, 2001 propelled the United States into a new understanding of national security. Transnational organizations and rogue states, often provided resources through the influx of petrodollars, can represent an existential threat to the United States and its allies. Implacable enemies can draw on technologies developed before and during the Cold War to acquire and use weapons of mass destruction (WMD) against U.S. citizens and allies.

DTRA’s unique mission to counter WMD presents difficult challenges. Tools needed to detect and identify WMD materials and devices are not in hand, let alone reliable methods to neutralize or otherwise counter WMD weapons and their effects. But DTRA has aggressive programs in place for the development of ways to achieve these capabilities and is receptive to new ideas, as well. The urgency of meeting the DTRA mission leads to examination of the DTRA investment model. In particular, the promise of breakthroughs in quantum mechanics within the foreseeable future suggests that there may be opportunities for capabilities that only a few years ago would have been regarded as indistinguishable from science fiction.

The question before DTRA is whether it should regard basic quantum mechanics research as a pool of work conducted without potential mission application but from which exploratory development could draw relevant results as they develop, or whether DTRA should take a more proactive role in encouraging basic research in directions that more immediately address its own mission. The purpose of this report is to explore the feasibility of the latter – to survey the state of physics based on quantum mechanics principles, to consider the DTRA mission, to suggest possible relationships of research products and DTRA mission need, and to recommend possible DTRA participation in the related research.

The findings and recommendations presented here are quite preliminary – this survey measured by a six week level of effort. There are promising new technologies that can emerge within the next decade, there are research areas that have particular relevance to the DTRA mission, and there is good justification for developing a capability within DTRA that embraces the understanding of the fundamental physics of quantum mechanics and that maintains a current and active participation in this research community.

David Algert
Senior Scientist
Advanced Systems and Concepts Office
Defense Threat Reduction Agency
EXECUTIVE SUMMARY

The study summarized in this report answers the questions: Are there advanced applications of quantum mechanics consistent with, and supportive of, the DTRA mission and ASCO science & concepts operational objectives? and What mechanisms might be put in place to monitor research community progress, identify milestones/progress that may have unique relevance to DTRA, and facilitate development of quantum-based capabilities unique to the DTRA mission? The unique mission of the Defense Threat Reduction Agency (DTRA) to counter weapons of mass destruction (WMD) presents difficult challenges: tools needed to detect and identify WMD materials and devices are not in hand, let alone reliable methods to neutralize or otherwise counter WMD weapons and their effects. DTRA has aggressive programs in place for the development of ways to achieve these capabilities and it is receptive to new ideas, as well. The urgency of meeting the DTRA mission and the promise of breakthroughs in quantum mechanics prompted this preliminary study: there may be opportunities for capabilities within the foreseeable future that only a few years ago would have been regarded as indistinguishable from science fiction.

In 2007 the National Research Council issued a report (NRC, Controlling the Quantum World, National Academies Press (2007)) that outlined six research areas with the promise of dramatic utility to the problems of society, homeland defense, and military capability within the next ten years. These areas encompass the use of new instrumentation and tools that allow unprecedented control of quantum phenomena. Of these, this preliminary study identified three areas – quantum computing, quantum optimization, and nano-structure fabrication – that have compelling relevance to the DTRA mission, as shown in the figure. In addition, this study concurred with current DTRA interest in energetic sources the successes of which will depend on physics development at the quantum level; for example, the observations of transmutation in laboratory settings has prompted theoretical speculation that non-local, coherent neutron wave functions with multi-nucleus overlap may facilitate nuclear transformation without invoking the strong nuclear force operative in stellar and thermonuclear fusion reactions.

The conclusions of this study are that quantum mechanics is central towards understanding and advancing technologies governed by “physics in the small,” quantum research intersects numerous DTRA missions and may spawn dramatic enhancements in key capabilities, and quantum research should be considered as a major potential thrust in DTRA’s new Basic and Applied Sciences initiative. Key enhancements include: improved (GPS-independent) weapon accuracy through revolutionary space-time measurements, more robust penetrators through nano-scale manufacturing of new materials, and more energetic payloads through quantum control and manipulation in the formulation process of these materials. The nature of basic quantum research summarized in this Report, now the subject of active participation by both national and international university research centers, U.S. laboratories, and by the new China $40M initiative for establishment of ten quantum research institutes, argues well for a further DTRA investigation into what pathways should be pursued to leverage existing research organizations and to fund focused research activities not specifically addressed elsewhere.
HISTORICAL PERSPECTIVE

The seminal discovery that led to the quantum mechanical formulation of the physical world was the necessity of quantization of frequencies in the black body spectrum, first advanced by Max Planck in 1900. The view of the microphysical world that evolved from the work of Bohr, Heisenberg, Planck, Schrödinger, and others during the early part of the last century was wholly unfamiliar to the classical physics community. Often, objections were formulated through careful argumentation that would seem to imply contradiction with reality. But instead, objections based on the philosophical foundations of physical description furthered the developing understanding of the quantum world. Successful descriptions and mathematical predictions continued to accumulate, with the achievement of understanding of such phenomena as the stability of matter, the emission and absorption spectra of gas-phase elements, the photoelectric effect, the structure of atoms and nuclei, and, with Einstein’s establishment of the equivalence of energy and matter, nuclear reaction characterization that could explain the longevity of stars.

One of the foremost national-security research programs was the Manhattan Project, dedicated to the development of the atomic bomb. The success of the atomic bomb was due to the understanding of the chain reaction process of nuclear fission and neutron capture by nuclear isotopes of uranium and plutonium – processes that could be described operationally without quantum mechanical insight; the success of the thermonuclear bomb (now referred to as the hydrogen bomb) depended critically on the concept of quantum tunneling: the approach of hydrogen nuclei through the Coulomb barrier – the electromagnetic force between two positively charged protons – in a region that is classically prohibited.

The conceptual framework for the conduct of war near the end of the first half of the twentieth century could have led to other mission-oriented basic research; in terms of military need, one could have imagined ways to improve communications, navigation, and weapons, but it is unlikely that this approach could have led to the quantum-based technologies of the second half of the twentieth century: semi-conductors, photodiodes, integrated circuitry, e-beam lithography, computers, charge coupled devices, packet radio, Internet, masers and lasers, fiber optics, superconductivity, communications satellites, global positioning satellites, and others. Rather, it took an adoption of “possibility thinking”, i.e., new paradigm thinking, to look for new kinds of technologies that might have military utility. DARPA was created (as ARPA in 1958) to avoid the kind of technological surprise that the Soviets achieved with Sputnik; the Air Force Office of Scientific Research in the latter half of the last century provided basic research support that contributed to the invention of the maser, integrated circuit, computer mouse, global positioning system, superconductivity, and chemical laser.

Plato had cast necessity as the mother of invention. The ancient Egyptians found a way to move five-ton blocks of stone (a monolithic lintel, resting on two stelae at the temple of Osiris weighs about 300 tons), invented the rope and turning pole to redirect pulling forces, but did not discover the tack-and-pulley leveraging system. While necessity may be the mother of invention, there are many kinds of inventions possible and of these some can be dramatically superior to others. In the last century consumer desire for a tape-based music system led Lear to invent the eight-track tape – a solution for the problem of relatively low fidelity tape systems of the time. The eight-track system used a high rate of tape transport that led to acceptable signal-to-noise ratios. Soon thereafter, Dolby invented a system of amplified signal recording at

---

1 “Little Boy” – gun concept used to assemble a critical mass of U-235 that was detonated over Hiroshima, Japan, August 6, 1945 without prior test.
2 Concept first demonstrated on “Event Mike” – the first successful test of the “super” Teller-Ulam design, conducted on the island of Elugelab on Eniwetok Atoll in the Marshall Islands on November 1, 1952.
the high and low frequency ends of the spectrum and a corresponding recalibration in the playback system that also overcame the signal-to-noise problem. This allowed the use of small cassettes and slow tape transport and the Lear system was quickly relegated to history. In the 1960s the IBM Selectric typewriter allowed the switching of typing balls to change fonts. Today much of the population is familiar with typewriters only through pictures, font changing is done with a few clicks of a mouse, and printing is executed only after the document is completed on screen.

There are different kinds of necessities. The traditional necessities that Plato refers to are those things that are needed within a given problem-solving context such as providing combat vehicles more robust to IED detonations, or better grease seals to keep out micron-sized sand particles. Other kinds of necessities are products of imagination – new solutions to old problems or entirely new capabilities. Ideas that are free creations of the mind in science fiction sometimes breed necessity thinking. The personal communicator used in the 1960s' Star Trek series was thought of as a highly prized, yet unobtainable, tool. Then, wired telephones were ubiquitous and public telephones could be found easily at gas stations, on street corners, and wherever public transportation was available. Today, the cell phone continues to see explosive commercial growth and continued evolution in capability beyond anything imagined in the 1960s and public telephones have virtually vanished from society.

As another example of the prescience of science fiction, consider the film The Day the Earth Stood Still (1951, 20th Century Fox) in which Gort, the robotic companion of Klaatu (the alien visitor to Earth), emitted a collimated beam of energy from his visor to destroy military equipment. The laser, invented at Bell Labs by Schawlow and Townes in 1958, depends critically on the quantum mechanical nature of atoms and radiation. The mid-infrared advanced chemical laser (MIRACL) became operational at the high energy laser system test facility (HELSTF) at White Sands Missile Range, New Mexico on September 6, 1985, was the first continuous wave laser to operate at mega-watt beam power, and appears to be a good realization of the fictional weapon concept.

When contemplating new ideas for military capabilities that fall outside traditional necessity, it is important to maintain awareness of the difference between what is possible and what is impossible. In 1956 the president of the Royal Astronomical Society proclaimed that humans would never put a man on the moon. To do so (he said) would require a rocket standing four hundred feet high with the ability to produce seven million pounds of thrust. The Apollo rocket launched for a moon landing in 1969 was three hundred sixty feet high and it produced seven and a half million pounds of thrust. His calculations were consistent with physics principles, i.e., the posed problem did not violate the tenets of physics, but his faith in engineering ingenuity was not sufficient to accept the consequence of his calculations. When entertaining new concepts, engineering may often find a solution, but it is essential that the physics principles be satisfied.

Quantum mechanics experienced a considerable number of philosophical challenges in the last century during its formative years, even by Einstein himself. But quantum mechanics survived, was stronger for the challenges, and has enjoyed unqualified success in explaining phenomena at variance with intuition with unprecedented predictive accuracy. The quantum mechanics of the last century was utilized in a semi-classical sense in terms of invention – lasers depended on stimulated emission by individual atoms, semiconductors depended on the control of tunneling, and charge coupled devices stored charges produced by the photoelectric effect in capacitor arrays leading to electronic digital representations of images. As we enter the twenty-first century the features of quantum mechanics that are ripe for exploitation deal with non-local phenomena and with the very essence of quantum mechanics – superposition of states. Here, the physical principles are sound and widely accepted by the scientific community but the engineering paths to implementation are not completely understood. Some novel energetic materials concepts are also discussed here and these fall into the category of quasi-classical behavior. But some of these raise basic physics issues and some have engineering issues as barriers to implementation. That is to say, some of these may not be possible in principle and some may be realized only after aggressive engineering development.
The DTRA mission is to develop the capabilities and tools to counter weapons of mass destruction (WMD). This is a broad charter that allows not only effort to develop better capabilities for existing tools but effort in developing completely new approaches to the problem of countering WMD. The bulk of quantum physics discussed in this report is at a very early stage of development with little actual product accomplishment, yet it promises successes wholly different than cautious extrapolations of conventional technologies allow. For example, quantum computing promises unprecedented communication, sensor, and computational capabilities compared to the “Lear” hardware expansion and von Neumann programming strategy underlying all computational schemes in existence today. The defense and homeland security applications that are talked about in quantum physics are conventional; they address known technology needs with the hope of new techniques to meet these needs. What is exciting is that dramatically new ideas that have not yet been imagined will emerge from quantum mechanics research.

This report discusses the DTRA/ASCO mission and the state of quantum mechanics research. A general discussion is given of the more mysterious features of quantum mechanics – superposition and entanglement – both of which can be used in computational schemes. Several topics are discussed with specific applications of interest to DTRA, followed by conclusions and recommendations for DTRA action with respect to quantum physics research.
Basic research is generally understood to be scientific investigation that is primarily curiosity driven rather than motivated by a particular application. In the latter part of the twentieth century following the unprecedented scientific achievement of both the atomic and thermonuclear weapons, governmental agencies, including the services and the Central Intelligence Agency, became engaged in support of basic research at universities, laboratories, and non-profit institutions. Universities met this enthusiasm for basic research with expansion of departments and growth in the production of PhD students.

In the latter half of the last century the United States struggled with the costly Vietnam War and the huge outflow of entitlement funds authorized by the passage of Lyndon Johnson’s Great Society legislation. Senator Mike Mansfield (D, Montana), who served as Senate Majority Leader from 1961 to 1977, proposed a bill in the late 1960s that defense appropriations for basic research be limited to those efforts for which the principal investigator could demonstrate a military objective. A chill ran through university departments, contracts were not renewed, and a flood of newly minted PhD scientists spread through the streets of America with passage of the Mansfield Act in 1968. The Mansfield Amendment of 1973 limited defense appropriations through ARPA to those showing direct military utility. The business model for DoD acquisition was restructured so that basic research became a field from which engineering development could glean concepts and proofs of principle for fashioning militarily useful products, and the funding of basic research by the DoD was eschewed.

There is a well-worn joke describing a drunken man staggering around a lamppost at night searching for his car keys (because that is where the light is), although he had lost them somewhere else in the dark. This is sometimes used to decry research approaches that use that which is known but which is, in fact, inappropriate for the problem (lamppost physics). In contrast, the DoD mission need is the illumination for promoting mission oriented basic research. If a funding agency identifies a mission need and promulgates this in its search for relevant basic research, this is a spotlight illuminating an area of the basic research landscape that is otherwise only dimly lit. Unlike the futile search of the drunken man, this illumination provides the attraction for researchers to explore the landscape of need within an entire landscape supported by basic research, without modifying the premises of performing basic research.


Systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind. It includes all scientific study and experimentation directed toward increasing fundamental knowledge and understanding in those fields of the physical, engineering, environmental, and life sciences related to long-term national security needs. It is farsighted high payoff research that provides the basis for technological progress.

And it states that

3 Department of Defense Instruction - DoDI3210.1, September 16, 2005
It is DoD policy that:

- Basic research is essential to the Department of Defense’s ability to carry out its missions because it is:
  - A source of new knowledge and understanding that supports DoD acquisition and leads to superior technological capabilities for the military; and
  - An integral part of the education and training of scientists and engineers critical to meeting future needs of the Nation’s defense workforce.

- The Department of Defense shall:
  - Conduct a vigorous program of high quality basic research in the DoD Component laboratories; and
  - Support high quality basic research done by institutions of higher education, other nonprofit research institutions, laboratories of other Federal agencies, and industrial research laboratories.
  - The DoD Components’ conduct and support of basic research shall be consistent with the principles stated in Enclosure 1 (Principles for the Conduct and Support of Basic Research).

It is clear, then, that the business model for defense acquisition has broken the constraints of the last century to return to a view of the importance of greater knowledge and understanding as the foundation for technological progress leading to superior technological military capability.

Where does DTRA stand in relation to DoD Instruction 3210.1? The mission statement of DTRA⁴ is as follows:

The Defense Threat Reduction Agency safeguards America and its allies from Weapons of Mass Destruction (chemical, biological, radiological, nuclear, and high explosives) by providing capabilities to reduce, eliminate, and counter the threat, and mitigate its effects.

This is the spotlight shining on the landscape of basic research. It is broad and it can embrace a large spectrum of basic research and technologies. DoD Instruction 3210.1 says that the sound business model for acquisition authorizes DTRA to conduct high quality basic research. Therefore, the question of whether DTRA should support basic research in quantum mechanics must be decided by whether any of this research lies within the illumination defined by the DTRA mission. Without doubt, the research of the twenty-first century is so fundamental to the physics underpinning our current technologies that it directly underpins the DTRA mission. Investment decisions must then be made on individual concepts based on their specific credibility and engineering challenges, rather than on obsolete business models.

ASCO’s role in DTRA is as follows:⁵

The Advanced Systems and Concepts Office, or ASCO, identifies, encourages, and executes high-impact projects to encourage new thinking, address technology gaps and improve the operational capabilities of DTRA, DOD and other government agencies in response to weapons of mass destruction (WMD) threats. Composed of a small cadre of military and civilian personnel, augmented by temporary detailees from other government agencies, industry and academia, ASCO asks the tough questions about current and over-the-horizon WMD threats.

---

⁴ http://www.dtra.mil/about/mission/index.cfm
⁵ op. cit.
Consistent with this, ASCO has posed the following questions:

- What is the current scope of quantum mechanics R&D?
- Are there advanced applications of quantum mechanics consistent with, and supportive of, the DTRA mission and ASCO science & concepts operational objectives?
- What mechanisms might be put in place to:
  - Monitor research community progress,
  - Identify milestones/progress that may have unique relevance to DTRA,
  - Facilitate development of quantum-based capabilities unique to the DTRA mission?

Answers to these questions will emerge from discussion of the scope of quantum mechanics research and development that exists today.
THE SCOPE OF QUANTUM MECHANICS RESEARCH AND DEVELOPMENT

The principles of quantum mechanics underlie much of the current technology in communications, sensors, and computer technology. Technologies dependent on quantum principles continue to be explored to find ways to meet new requirements such as providing remote detection and identification of biological threat clouds that could be deployed against U.S. or allied troops. For example, sensors have been proposed that utilize quantum dots, nanostructures that bind a small number of electrons. They are manufactured, so that the energy spectra can be engineered for special applications. They are analogous to atoms in that they bind electrons, but the potential wells designed to bind the electrons but do not have the symmetry of the Coulomb potential produced by atomic nuclei. Quantum wells are variants of the quantum dot; quantum wells bind electrons in one spatial dimension and allow free electron motion in the remaining two directions. Figure 1 is a depiction of an efficient generator of light using quantum well fabrication. The frequency of the emitted light is tunable by design of quantum well size. Potential applications range from electronic displays to electrically-pumped nanoscale lasers.

The scope of quantum mechanics research that promises new technology is wide and it is predominantly found as basic research. Products such as the light generating nano-device are still in the laboratory phase of development; a finer comb would be needed than used in this preliminary assessment to reveal concepts that have reached sufficient maturation for handover to exploratory development. Because the principles of quantum mechanics are so fundamental and often counter-intuitive, and the laboratory fabrication process complex, new concepts take time to mature. The physics may be sound, but the engineering is often challenging.

The Committee on AMO Sciences 2010 was commissioned by the Department of Energy and the National Science Foundation to assess research opportunities in atomic, molecular, and optical sciences (AMO) over the next ten years. Its subsequent report, Controlling the Quantum World, is part of the ongoing Physics 2010 survey undertaken by the National Academy Board on Physics and Astronomy under the National Research Council. The purpose of the NRC report is to present the most promising opportunities for research in atomic, molecular, and optical sciences based on what is currently known. The assessments of the committee are based on sound physics principles, sound technical approaches, and on experience in anticipating obstacles and in engineering solutions for difficult problems. The committee outlined six research areas with the promise of dramatic utility to the problems of society, homeland defense, and military capability within the next ten years. These areas encompass the use of new instrumentation and tools that allow unprecedented control of quantum phenomena. A summary of the committee’s findings and recommendations is provided subsequently.

---

6 That is, the identification process is mediated with objects transported to a threat cloud, the identification is performed locally within the cloud, and interrogation is performed remotely by laser scan.
In addition to the recommendations of the NRC Committee on AMO research, we provide a brief discussion of a few concepts that address the gap in energetic materials, i.e., the wide range of specific energy bounded on the low end by the energetics of chemical explosives and on the high end by the energetics of nuclear fission and fusion. These concepts are problematic with respect to basic physics, engineering realizations, or both in various ways, but they depend fundamentally on the quantum mechanical properties of matter.

### History of Quantum Mechanics

**Quantization of Radiation and Energy**

Max Planck – 1901
- Resolved contradiction (classical calculation yields infinite energy) in black body radiation spectrum with assumption of quantized packets of energy:
  \[ E = h\nu (=\hbar/2\pi)[2\pi\nu] = h\omega, \]
  \[ h, \text{ a fundamental physical constant } \cong 6.6\times10^{-27}\text{erg}\cdot\text{sec} (\cong 1\times10^{-27}\text{erg}\cdot\text{sec}) \]

Einstein – 1906
- Proposed that light is comprised of quanta of energy (photons) to explain photoelectric effect – near-instantaneous electron emission from metals for which classical predictions much longer than observed, frequency threshold below which no emission, no matter how intense the light.

Bohr – 1913
- Discovered laws of hydrogen spectra
  \[ hv = \frac{2\pi^2me^4}{\hbar^2} \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right) = 13.6 \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \text{eV} \]

**Wave Mechanics**

Schrödinger –1926
- Wave function contains all that can be known about a system
- Defined equation for probability amplitude for quantum systems
- Associated operators with each observable such as energy, momentum, position, etc.
- Observations reveal instances of values that can only be probabilistically predicted

**Uncertainty Principle**

Heisenberg – 1927
- Defined fundamental uncertainty in any measurement of complementary variables, e.g.,
  \[ \Delta x \Delta p > \hbar \]
- Increased accuracy of measurement of one variable induces increased uncertainty in knowledge of the complementary variable

*continued*
Principles & Features of Quantum Mechanics

**Superposition**

State of a system in general is the sum of all possible states
E.g., an electron’s spin is always measured as \( \frac{1}{2} \hbar \)
\[ |Ψ⟩ = a|+\rangle + b|−\rangle, \quad |a|^2 + |b|^2 = 1, \quad a, b \text{ complex numbers} \]
Probability of measuring spin up is \(|a|^2\); probability of measuring spin down is \(|b|^2\); probability of measuring *either* up or down is 1

**Wave-Particle Duality**

In quantum mechanics a particle is described by a wave function \( Ψ(x,t) \) representing the probability amplitude for observing the particle near \( x \) at time \( t \): \( p(x,t)dx = |Ψ|^2 dx \). The wave function describes the wave properties of matter historically thought of as particulate and non-wavelike.

Example: Double slit experiment

A single electron emitted by the source arrives at a recording screen after passage through a double-slit screen and always produces a localized excitation, a measured location of the electron. This demonstrates the particle nature of electrons. The accumulation of many such independent excitations reveals a distribution of spots on the screen consistent with an interference pattern. This means that interference must occur for each photon between part of its wave function passing through the upper slit with part of its wave function passing through the lower slit. This is proof of the wave nature of particles and the superposition of states — each electron must pass through both slits simultaneously.

**Tunneling**

In classical physics an electron in a potential well formed by a finite barrier, with insufficient energy to surmount the well, is permanently confined to the well. In quantum mechanics the electron can exist in the unphysical region within the barrier and has a probability of escaping the well. The process of escape is quantum tunneling and occurs in spontaneous nuclear decay and in the fusion of protons by means of tunneling through the Coulomb repulsive barrier, a completely quantum phenomenon.

**Entanglement**

Einstein, Podolsky, and Rosen (Phys Rev 47, 1935, p.777) first introduced the concept of entanglement to challenge the completeness of quantum mechanics in describing reality. It is now recognized that quantum systems that are brought into interaction remain in an entangled quantum state after separation sufficient to eliminate physical interactive effects. If a measurement is made on one system then the wave function for the second system is forced into only those quantum states compatible with the prior entanglement. This occurs *instantly* upon measurement of a property of one of the systems no matter how far apart the two systems might be at observation.
Controlling the Quantum World

The NRC Committee on AMO Sciences identified six broad challenges for the next decade:

- Revolutionary new methods to measure space and time,
- Ultra-cold AMO physics,
- High-intensity and short-wavelength sources,
- Ultra-fast quantum control,
- Quantum engineering on the nanoscale, and
- Quantum information.

As a result of federal agencies’ investments in research programs that support AMO sciences, progress has been made that make credible the expectation that these challenges can be met in the next decade. New tools and new capabilities have been developed to achieve unprecedented control of quantum phenomena that underlie the scientific basis for each of the six challenges.

The products and capabilities that can be expected to result from rising to meet these challenges are wide ranging, have potential application to the breadth of society, while some have clear relation to meeting the DTRA mission needs, some could have DTRA mission utility, and some resulting products and capabilities could be in the form of technological surprise. It is consistent with the purpose of this report that we consider each of these challenges and draw from them those that are most immediately of relevance to the DTRA mission.

Revolutionary New Methods to Measure Space and Time

A.A. Michelson once said, "The important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…. Our future discoveries must be looked for in the sixth place of decimals.” The historical breakthroughs of relativity and quantum mechanics of the last century have been a clear lesson that a declaration of completeness of understanding of the physical world can be reckless and even haughty. Quantum mechanics gave us a view of the microphysical world unlike anything suggested by early scientists and philosophers and Einstein's general theory of relativity gave us a world view in which matter influences the very fabric of space and time itself.

Research scientists in general relativity routinely discuss dimensions as large as the diameter of the universe (about 14 billion light-years) but also entertain distances down to the Planck length \( l_p = \sqrt{\hbar G/c^3} \approx 1.6 \times 10^{-35} \text{ m} \) (where \( G \) is the gravitational constant) and at which strong quantum mechanical effects are thought to arise in the gravitational field itself. These scientists cast the assumption of the permanence of physical laws across this great expanse of space and time, not with careless abandon, but with cautiousness and even trepidation, remaining vigilant for discrepancy in observations and theory. Nonetheless, the discovery of the emission spectra of hydrogen in the light from stars in distant galaxies gives us cautious assurance of the permanence of quantum mechanical behavior over great distances and times.

The near-term advances promised in atomic, molecular, and optical sciences show hope of probing into these fundamental assumptions of the laws of physics themselves. That the universe seems to be comprised predominantly of matter as opposed to anti-matter suggests that there must be a violation of the CPT symmetry law (symmetry under combined changes in charge, parity, and time-reversal) that is an essential component of the Standard Model of physics. High energy physicists have been studying the possibility of

---

9 op. cit., p.2
10 Albert A. Michelson, speech given in 1894 at the dedication of Ryerson Physics Laboratory, University of Chicago
existence of a new force of nature that breaks this symmetry and advances in AMO capabilities in the measurement of time may give conclusive evidence of this.

The measurement of time is fundamentally connected to the structure of the atom. The Bohr model of an atom postulated the existence of non-radiating (and therefore stable) electron orbits governed by fundamental quantization rules. A hierarchy of electron states gives rise to a spectrum of discrete energy levels in an atom. If an electron were to transition from a higher energy state to a lower state, the change in energy of the system would result in the emission of a photon whose energy would be the difference of energy levels. This can be written as $\Delta E = h \nu$ where $h$ is Planck’s constant and $\nu$ is the frequency of the radiation given off by the change of the electron’s energy level. Since the frequency is the reciprocal of the period of oscillation of the radiation, this provides a direct basis for the period of a clock (through atomic state transitions). Atomic clocks are systems that use isolated atoms to maintain highly stable clock frequencies. The technology of atomic clocks has improved greatly, approaching an accuracy of one second in sixty million years.

In order to extract information from a small number of isolated atoms it is necessary to average the weak signals from these few atoms over long periods of time. A limitation of the accuracy of measurement is known as the shot-noise limit. If $N$ atoms are used in the averaging, then the precision in the measurement is limited to $1/\sqrt{N}$. This expression is a classical estimate treating the $N$ atoms as independent entities. On the other hand, it is possible to consider the $N$ atoms as part of a larger quantum mechanical system. When the atoms are allowed to interact, they become an entangled quantum system and the $N$-atom system becomes a complex, entangled system that allows measurements, the precision of which depends on $N$ as $1/N$ rather than as $1/\sqrt{N}$ allowing considerable precision improvement.

The global positioning system (GPS) depends critically on the accuracy of clocks to perform its function. The global positioning system, depicted in Figure 2, is composed of 24 operational GPS satellites that orbit above the earth in twelve-hour orbits. Each satellite has on-board atomic clocks. Each satellite transmits data that indicates its location and the current time. An earth-based receiver (ground, airborne, low orbit) obtains information from several satellites and measures the slightly different times of arrival of signals from the satellites. The distances to the satellites from the receiver can be computed by estimating the time it takes for the signals to reach the receiver. Receivers do not have atomic clocks, so that the time estimations have errors. When a receiver estimates its distance from a satellite, it estimates the radius of a sphere that it is on, with the satellite at the center of a sphere. When it uses three satellites, the receiver should lie at a point at the intersection of the three spheres. Because of timing errors in the receiver, it adjusts the radii of the three spheres by the same amount to produce an intersection as its best estimate of its position. The positions of the three satellites form a plane. Since displacements of the receiver along a line perpendicular to this plane produces small changes in the radii of the three spheres, the computation of position with three spheres provides accuracy only in the plane of the three satellites. When at least four satellites are used, the receiver can then compute its position in three dimensions.

---

11 National Air and Space Museum http://www.nasm.si.edu/gps/work.html
Clearly, atomic clocks play an essential role in the GPS system. Recently, micro-fabrication techniques have created micro-clocks with dramatically enhanced receiver clock performance. Figure 3 shows a miniature clock with “chip-scale” dimensions.

Since the performance of the GPS system depends on the accurate timing of the satellites, any improvement in time measurement can be used to improve the location estimation process for earth-borne receivers. Whereas GPS can be used for guidance of military airborne weapons platforms, the improvement of GPS capability can yield dramatic improvements in targeting and hit-point accuracy. Furthermore, the advance of engineering planning in the areas of autonomous vehicles and weapons can be further facilitated by enhanced GPS navigation. We see then that new advances in quantum control of atomic systems such as quantum entanglement and new designs with micro-scale components can have significant impact in DoD systems performance.

Interferometric techniques are used to measure distance and velocity with very great accuracy. The wavelengths of visible light fall in the micron range. When a beam of laser light (which has a very sharply defined wavelength by the nature of laser formation) is split into two halves and these halves are made to travel along two distinct paths, the halves can then be superimposed at some point distant from the origin of the laser light. If the maxima of the waves add together at the assembly point, this is called constructive interference; if the waves arrive out of phase so that the maximum of one half is added to the minimum of the other, this is called destructive interference and no net wave strength is observed. Even small dephasings of the two halves of the laser beam can be observed and measured with great accuracy. This means that small differences in the path lengths of the two halves of the laser beam can be measured with great accuracy that extend well below the wavelength of the laser radiation.

Ring laser gyroscopes (RLGs) are in widespread use in commercial and military navigational systems. An RLG is a device that sends two halves of a laser beam around a (polygonal) ring in opposing directions that are then compared by means of an interferometric output leg. If the ring is at rest in an inertial frame of reference, the degree of interference is constant in time. If the ring is rotated with respect to the inertial frame, the velocities of the mirrors used to deflect the paths of the beams into the ring configuration will produce Doppler shifts in the frequencies of the reflected beams. The beam that travels in, say, a clockwise direction when the rotation is counterclockwise will experience a net Doppler redshift and the counterclockwise traveling beam will experience a net Doppler blueshift. This change in frequencies results in changes of wavelengths and this appears as a change of degree of interference in the interferometric leg. Measurement of the shift of interference then gives a direct observation of the rotation rate of the RLG in the plane of the ring.

Fiber optic gyroscopes (FOGs) use optical fibers to carry the laser beams. New developments in band gap fibers that use microstructure cores allow the internal beams to travel mostly in air but are nonetheless controlled by the fiber itself. These advances in photonic band gap fibers promises to greatly advance inertial navigation technology.

Ultra-Cold AMO Physics

Absolute zero is the theoretical temperature corresponding to the absence of all thermal energy from a system. It is defined as zero degrees on the Kelvin scale and it corresponds to −273.15 degrees on the Celsius scale, and −459.67 degrees on the Fahrenheit scale. For quantum systems absolute zero corresponds to minimum state energy. In 2003, MIT scientists were able to cool a sodium gas to a half a billionth of a degree. As the temperature of a gas is lowered the de Broglie wavelength of an atom can begin to overlap that of its nearest neighbor; if the atoms are bosons the result of the overlap is a Bose-Einstein condensate. For sufficiently low temperatures a Bose-Einstein condensate has a large number of its atoms will form a superfluid condensate in which these atoms move as a wave within the structure confining the condensate. The superfluid can be macroscopically observed and it moves without friction and without the need for any motive force to overcome friction.

The cold gas experiments that use simple cavity traps are being supplanted by experiments in which the atoms are confined in periodic potentials similar to crystals by creating optical lattices. These lattices are formed by means of periodic standing waves produced by counter-propagating laser beams (Figure 4). Such lattices can be controlled with great precision and they can be constructed as one- to three-dimensional lattices. The confining well depths are controlled by the amplitudes of the laser beams and it is possible to allow trapped neutral atoms to migrate through the lattices quite like electrons in conductors.

Understanding and controlling cold neutral atoms in lattices may have great potential in the realization of quantum computers. There it will be necessary to provide interactions of bits without interaction of these with the surrounding structures. Should structural interactions occur, decoherence sets in and meaningful solutions cannot be extracted from the wave functions. Ions have interactions over significant ranges so that structural interactions are a problem while neutral atoms have no interactions with their environment. On the other hand, it is difficult to induce interactions among neutral atoms. The cold lattice approach may offer ways to overcome these difficulties and produce relatively long coherence intervals sufficient for quantum computing.

---

13 *Science* 12 September 2003:Vol. 301. no. 5639, pp. 1513 - 1515

14 The de Broglie wavelength is the wavelength associated with a particle in the wave-particle duality picture in quantum mechanics. It is defined through the expression $p = h/\lambda$, where $p$ is the momentum and $\lambda$ is the wavelength. The kinetic energy of a particle is related to the temperature under thermal conditions by $KE = p^2/2m = f kT/2$, where $f$ is the number of degrees of freedom of the particle, $m$ is its mass, and $k$ is the Boltzmann constant. This means that $\lambda = h/fkT$; as $T$ decreases, $\lambda$ increases.

15 It is known that all quantum matter can be categorized by a fundamental symmetry behavior. For n identical particles, say photons, protons, or atoms, the wave function for these n particles must be either symmetric in the interchange of any two of the particles or anti-symmetric under the interchange of any two of the identical particles. Those particles that have symmetric collective wave functions are bosons, and those that are anti-symmetric are fermions. This means that many bosons can share the same state and that no two fermions can share the same state. The stability of matter – the fact that matter does not collapse – is due to the fact that electrons are fermions and that they must occupy different orbital states in atoms.

High-Intensity and Short-Wavelength Sources

Since the invention of the laser, research has continued to explore the behavior of matter at ever increasing laser intensities. When laser light is focused on a target surface, increased intensities of light can be achieved by reducing the focus area. But the principles of optics show that the focal area cannot be reduced below a circular area whose diameter is about the wavelength of the incident light. Enhancing the intensity of the light further requires the use of more powerful lasers at the selected frequency and by reducing the wavelength of the laser radiation.

At the quantum level fundamental particles of matter interact with quanta of light. At the quantum level, as in the photoelectric effect, the intensity of light radiation for a fixed wavelength of the light is proportional to the number of photons that are within the radiation. This means that the enlargement of a source laser that holds the frequency fixed increases the number of photons that reach the target area per unit of time. But it is also true that a quantum of light is inversely proportional to its wavelength ($E = h\nu = hc/\lambda$). It is therefore possible to increase the intensity of the source by decreasing its wavelength or increasing its frequency.

The Heisenberg uncertainty principle states that there is an inverse relationship between the uncertainties in two complementary variables. In the case of the measurement of the position of an electron in an atom, a short wavelength laser pulse must be used so that the wavelength of the incident radiation is smaller than the diameter of the atom. The consequence of this is that a high momentum is imparted to the electron so that its subsequent position becomes much less certain. (In fact, the localization of the electron to within a hydrogen atom requires a photon of more than 14eV – more than enough to ionize the atom.) That is to say, one can construct high-intensity lasers through a combination of choices of bulk power and frequency, but with different fundamental physics behavior when interacting with matter. Figure 5 shows the dramatic increase in laser power since its invention and indicates some of the physical effects produced at different intensity regimes.

Advances in atomic and optical physics are yielding intense bursts of radiation in the x-ray spectrum of radiation. These bursts can often be treated as laser emissions and their very short wavelengths deliver very energetic photons to their targets. Even though the target material is dissociated by the interactions of atomic and molecular matter, the high degree of localization of its components that is brought about by the short wavelength of the radiation yields very high stroboscopic views of the structure of this matter. What x-ray diffraction technology has yielded in understanding the DNA structure of living organisms will now penetrate the workings of extremely small objects – from atoms to viruses and nanostructures. This will be accomplished by advances in sources such as the x-ray free-electron laser (XFEL) at the Stanford Linear Accelerator Center (SLAC).¹⁸

As described previously, optical frequency lasers can be made to deliver high-power pulses to target material. The energies that are delivered to a small surface area of a target are so large and the deposition

---

¹⁷ op. cit., p. 88
time so short that the change of phases induced by the deposition occurs before any material motion can occur. This means that the material within the target area reaches extremely high temperatures while still at the density of solids. Such methods allow the study of matter in these extreme conditions that may only occur in stars or in nuclear explosions. For the researcher there is the opportunity to understand the behavior of matter that is of relevance to fusion energy as well as to matter in exotic realms.

**Ultra-Fast Quantum Control**

Advances in laser and control technology have led to the possibility of observing the inner workings of atoms and molecules and have raised the prospect of controlling the processes within these systems. Figure 6 shows the range of timescales for subatomic to molecular processes and compares them to the timescales more familiar to normal human activity. Soon after the invention of the laser it was believed to be possible to directly control molecular processes, to excite desired bonds in order to force favorable reactions. The hope was short-lived however, because the internal dynamics of a molecule could redistribute energy appearing in one vibrational mode to all other vibrational modes more quickly than energy could be delivered to the desired mode. Effectively, then, the use of laser energy was not unlike raising the temperature of a set of reactants to produce a thermal equilibrium reaction leading to products.

Subsequently, the strategy that emerged for selective reaction was to recognize that pathways to end-products could occur through multiple quantum paths and states. If multiple paths existed between the starting state and the end state for a system, then the quantum solution could not in principle yield information about which of the paths were taken. In reality the principles of quantum mechanics state that all of the multiple states must be involved in the transition process. If paths allowed constructive interference at an end state, then the end state would be favored; for paths that led to destructive interference, there would be no practical yield of the end state. In order to control how molecular evolution to end states would occur, it is necessary to introduce pulse shaping.

Ultra-short pulses are the result of the superposition of wave components of widely different wavelengths or frequencies in order to achieve rapid rise and fall times at the front and back of a pulse. The frequency components can enable suitable couplings to the molecules whose preferred reactions are sought. To construct this, a pulse is first broken down into its frequency components. These are passed through controllable filters and then recombined to form the complex waveform that can excite modes of interest. As Figure 6 shows, outer shell electron motion is measured in femtoseconds ($10^{-15}$ s); at best, current technology can only change the outer electron orbits. But these control the forces that control the motions of the nuclei, and therefore control the chemical reaction process.

Figure 7 shows how to design appropriate waveforms. It is apparent that current experimental and theoretical capability is not sufficient to determine optimal pathways to new products when only very approximate models exist for complex molecular systems and the atomic structures within them. The method chosen to search for desired product states is to use a self-learning process in which the pulse

---

shaping and the experiment itself are part of a “learning loop.” Here, a random choice is first made for the structure of the initial pulse shape. The pulse is then fired at the target molecular material and the product state is evaluated after this shot. Another pulse is formed with a new waveform and this is fired at an identical initial sample. Using the results of these, a learning algorithm adjusts the controlling parameters for the pulse waveform to evolve the pulse formation towards enhanced product state yield. The looping process is continued until convergence criteria are met.

Quantum Engineering on the Nanoscale

The realm of nanoparticles lies above the scale of quantum systems such as atoms and molecules and below the realm of microscopic physics where light wavelengths range from about 400 to 700 nanometers. This means that particles on the size of nanometers are substantially below that of the wavelengths of visible light and are therefore microscopically not resolvable, i.e., invisible. If a large piece of obsidian is dropped on the floor, the resulting pieces retain the black color of the original piece. If the pieces are collected and ground, the small pieces will still retain the original color. As the broken pieces continue to be milled, eventually they acquire dimensions measured in microns, are no longer individually visible to the naked eye, but collectively exhibit the color of the unbroken piece. But, if further milling is pursued, eventually they reach the wavelengths of visible light whereupon their collective appearance takes on wonderful hues of color. This color property is no longer associated with the obsidian directly but with the physical dimensions of the particles that make up the collection. A behavior such as this is an example of a more comprehensive set of physical properties controlled by the nanostructure of the collection.

The explosion of interest over the last ten years in nanoscience and nanotechnology is attributable to the development of new tools for the construction and manipulation of nanostructures. This has involved basic research and development in atomic to molecular scales corresponding to scales up to a hundred nanometers, the construction of nanoscale structures and devices with new properties derived from their scales, and the growing ability to manipulate matter on the atomic scale and larger. The promise of the next decade is for rapid advances in visualization, manipulation, and control of the nanoworld.

In this context, visualization means the capability to “see what is unseen.” There are a number of ways by which this could be accomplished. One of these is by use of x-rays. Currently, x-rays are limited in resolution to about twenty nanometers, but this arises not from the wavelengths of the x-rays but from limitations in the design of x-ray lenses. The fabrication of nanomaterials that allow x-ray lenses that overcome this limitation is feasible and worthy of research. Another approach is to use the wave-particle...
properties of elementary particles. Already in use are beams of electrons in electron microscopes. Electrons with a mass of \( \frac{1}{2} \text{MeV} \) have very short de Broglie wavelengths, so that resolution is not an issue. On the other hand, electron scans depend on the interactions of the electrons with the matter that is to be visualized. Research is underway exploring the use of heavier particles with shorter de Broglie wavelengths and interaction properties different than those of the electrons. And a third approach is to map out surface structure by means of scanning probe microscopies that rely on molecular-scale effect for producing contrast, as shown in Figure 8. Here, the scan is similar in principle to the atomic force microscope (AFM) that generates a surface roughness map by dragging a finger across the surface, the ultra-fine finger displacement being magnified by a suitable cantilever.

Nanospheres can be constructed and they may have important properties for chemical sensors. The chemical properties of nanospheres can be interrogated through Raman scattering of light. The Raman effect occurs when light is scattered off a chemical; a small amount of energy is exchanged with the chemical and the scattered light has a slightly changed frequency compared to the light incident on the chemical. There is a direct correlation between the frequency change and the properties of the interrogated chemical. Nanospheres can be manufactured so that threat or hazard chemicals will attach to their surfaces and the response to Raman scattering can enhanced by many orders of magnitude compared to the chemical itself, when attached to the nanospheres. This offers the opportunity for rapid, accurate, and remote identification of these threat or hazard materials.

**Quantum Information**

Although machines have been invented throughout history that embodied the rudiments of computational control (e.g., Heron of Alexandria, nineteenth century looms, player pianos, etc.), the development of the general purpose computer in the last century led to an explosive development of an information industry that reaches far beyond manufacturing and product details. Today, information is a commodity that is created, transmitted, modified, and stored at a rate inconceivable only decades ago. The basic building block of stored information is the *bit* – a register built on some sort of physical substrate that can store one of two possible values. If, for example, a capacitor has a charge stored within it, the simple task of measurement of the voltage between its plates reveals whether the charge is present or not; it is customary to regard a voltage beyond a threshold value as corresponding to the value 1, and a voltage near zero or below the threshold to correspond to the value 0, although other definitions could be consistently applied. In the case of the physical hard drives in personal computers, data are stored on the magnetic surfaces of the plates in the form of local magnetization regions, which can be read by a recording head floating just above the spinning plates. Here too, threshold conditions allow a read of a data value of one or zero from any given region of the plates.

Of course, the use of the two numbers 0 and 1 are logical representations of the physical state conditions meant to represent these two distinct numbers. What is of great importance is that the manipulations of the data values in the computational process be kept as error free as possible. In fact, the computers we use today surprise us with their ability to perform so well with so many operations (the Core Duo processor computer on which this document has been prepared has a speed of approximately \( 10^{10} \) floating point operations per second).

\[ \textit{op. cit.}, \text{ p. 125} \]
In spite of processor speeds that have evolved from the IBM personal computer of 3.5MHz to personal computer processors running at 3GHz, there are some problems that are practically unsolvable. The encryption technology in existence today is based on the use of prime numbers (numbers that have as factors only themselves and unity) to create large composite numbers. The RSA protocol was devised in 1977 by Rivest, Shamir, and Adleman as a public-key cryptosystem. It depends on the use of products of relatively large primary numbers. While it is easy to produce a number M that is the product of the two prime numbers p and q, the inverse problem of finding the prime number factors when given M is extraordinarily difficult. For example, a number that is 250 digits long would require a computer performing at a rate of 200 million instructions per second (200 MIPS) about ten million years to perform the factorization. An improvement in processing speed to 10 GIPS is an increase by a factor of fifty in processing speed resulting in a reduction of processing time to two hundred thousand years. On the other hand, the security of the world’s encryption methodology in place today relies completely on the inability of systems to perform this factorization.

While not the raison d'être of quantum computing, there appears to be a sense of urgency in the realm of quantum research to demonstrate the capability to expeditiously break the RSA protocol and to supplant it with a scheme that is inherently unbreakable. This depends fundamentally on the at times counterintuitive properties of quantum matter.

As said previously, a classical register of one-bit length can store one of two numbers, which are taken to be represented as 0 and 1. A classical register of length two can store any one of $2^2$, or four possible numbers. And a register of length N can store any of $2^N$ numbers. The qubit (quantum bit) is a register that is built on the property of superposition of quantum states. In the case of a register of length 1, as we have said, there are only two possible values (0, 1) that can be stored. If we consider any quantum system that has only two possible states, then we can establish a correlation between the bit whose value is either 0 or 1 and the two possible quantum number values for the two quantum states that can be assigned to the qubit. Electrons are known to have only two possible measured values of internal spin. We can associate the +spin with 1 and the –spin with 0. The wave function for an electron for which the spin hasn’t been measured is

$$|\Psi\rangle = a|0\rangle + b|1\rangle, \quad |a|^2 + |b|^2 = 1. \quad (1)$$

Here, $a$ and $b$ are complex numbers that represent the probability amplitudes of observing the electron in a –spin or +spin state, respectively; their squared magnitudes represent the probabilities of observing either of the spin values and, of course, the probability of measuring any spin at all is unity. The classical register stores one of two values, the qubit register stores the two possible states simultaneously as a superposition of the base states, as shown in Eq. (1). Correspondingly, a classical N-bit register can store any one of $2^N$ binary digits, while an N-qubit register can store $2^N$ quantum states simultaneously. It is believed that there are approximately $10^{80}$ baryons (heavy particles like protons or neutrons) in existence throughout the universe. Since $\log(2) \approx 0.3$, this number is about $2^{267}$. This means that a 300-qubit register can simultaneously store more states than all the baryons in the universe. The implication of this is that a vast amount of information can be simultaneously processed in a quantum computer constructed of a fairly modest number of components.

The reality is that the wave function for the single qubit as given in Eq. (1) supports an infinite number of values, since the quantities $a$ and $b$ can be any complex numbers, subject only to the constraint that the

---


squares of their magnitudes must add up to unity. For utility in a quantum computer it is necessary to perform measurements on the wave function in such a way as to extract useful information – here, the probability amplitudes. Since a single measurement only yields one of the possible eigenvalues and not the probabilities, a possible strategy is to perform repeated measurements on identically prepared initial wave functions. This process yields a distribution of outcomes from which the values of \( a \) and \( b \) can be obtained. Although this may seem to compromise the advantage of quantum computers, the tradeoff of the exponential growth in classical computing for large numbers promises to be a most favorable one.

A quantum computer must be able to accept programming in such a way as to manipulate the input variables, the input here being the initial wave function. The wave function for the state of the \( N \) electrons as given in the example represents an entanglement of the \( N \) electrons as it evolves through the quantum computer. The propagation is regarded as a Hermetian process, the practical consequence of which is the fact that the process is temporally reversible and is therefore non-dissipative. The challenge of quantum computer engineering is to control the coherence of the wave function for a sufficiently a long time to allow the computation to be completed, which means the forestalling of decoherence.

The view of measurement in the formative years of quantum mechanics was that the human observer’s process of measurement led to the reduction of a wave function to one of the eigenstates of the measurement operator and the realization of one of the eigenvalues. This is frequently called the collapse of the wave function. In contradistinction to classical physics, prior to the observation of the system it is untrue that the system is in any one of the eigenstates but, in fact, was a superposition of the possible eigenstates. On the other hand, for an observer who treats another observer as part of a larger quantum system it would seem that the other observer would have to share in the superposition of possible states. The thinking that is emerging is that the observation process is the result of entanglement of a small, quantum system with a large, very complex system and that the many-variable mixing with the large system induces a decoherence of the smaller system’s wave function. The philosophical paradoxes then are resolved by the interactions of large measurement systems with the smaller quantum systems whether the measurement apparatus is a magnetometer or a human.

The problem of decoherence that is likely to persist for distributed quantum computer components or for concepts of quantum communications has a potential solution in teleportation. Teleportation is a device that is commonly used in science fiction plots and employed by Gene Roddenberry as a plot-accelerating device in his Star Trek series of the 1960s (no presentation time wasted by the portrayal of the transport of the series characters from spacecraft to planetary surface). For all practical purposes it is an infeasible concept for the transport of humans: the Bekenstein Bound is a fundamental limitation on the possible number of quantum states in a bounded region and this can be described as a bound on the number of bits that can be coded in a bounded region.\(^{24}\) If the information is characterized by \( I = \log_2 N \), then the information that can be encoded in a sphere of radius \( R \) containing energy \( E \) is

\[
I \leq 2\pi ER/\hbar c \ln 2. \tag{2}
\]

Assuming that a human has a mass less than 100kg and can fit into a sphere of 1m radius leads to

\[
I_{\text{human}} \leq 2.7 \times 10^{45} \text{ bits.} \tag{3}
\]

This is far too much information to conceivably transmit for reconstruction of a human in any practical time period. On the other hand, it is possible to transmit relatively small quantum systems by this method.

Figure 9 is a representation of the demonstration of teleportation of a two-qubit measurement over a distance of 600m. The teleport of the quantum state at Alice’s location is mediated by quantum entangled particles sent to both Alice and Bob via the underground channel. The particles used need not be the same kind as the particles that are used to establish the entanglement. Alice allows entanglement of the (to her) unknown quantum state to be teleported and inserts one of the entangled pair in the channel. She then performs a special kind of measurement that yields a two-bit classical outcome without knowing anything about the original wave function. She sends Bob the result of her measurement to Bob by way of conventional communications (here, a microwave link).

Figure 9. Quantum teleportation experiment demonstrated using an 800-m-long optical fiber fed through public sewer system tunnels under a river. In a quantum teleportation only the quantum state is transferred and not the qubit itself – that is, the atom or photon constituting the two-level quantum system is not transferred. Quantum teleportation cannot occur instantaneously, unlike the commonly assumed science fictional mode of intergalactic personnel teleportation. The speed of quantum teleportation is limited by factors such as the speed at which the necessary entanglement can be generated and measurements made, as well as classical transmission of the result of the two-qubit measurement. Thus, there is no violation of the laws of relativity.25

---

Principles of Teleportation*

Teleportation of quantum state requires transmission of classical information from A to B
Quantum state vanishes at A, reappears at B

A teleportation scheme has been worked out for systems that can have only two basic states, such as the polarization of a photon or the spin of an electron. The scheme follows this procedure:

- An entangled pair of particles are prepared prior to performing the teleportation and are sent to two participants – Alice and Bob, who want to send an unknown quantum state to one another by teleportation
- Alice allows a particle (#1) in an unknown state to interact with one of the two particles previously entangled (#2)
- Alice performs a special measurement – called a Bell operation - involving both particles #1 & #2
- Alice gets a number that tells her she got one of the four basis states for the Bell operator in the measurement
- Alice transmits the result of her measurement (one of 4, or \(2^2\) choices that is represented as a two-bit number) to Bob – a classical transmission such as by radio
- Bob receives this information and can then tell which of the four possibilities for particle #3 are correct
- Bob then can reconstruct the original wave function for Alice’s particle that from here on is carried by particle #3
- This process in reality destroys the wave function of particle #1 (it doesn’t exist after Alice’s measurement) but is recreated when Bob gets the classical information from Alice – the essence of teleportation
- Speed-of-light is not exceeded but information has been sent from one point in space to another without continuous propagation in the intervening interval

Construct EPR singlet state:

\[ \Psi_{\text{EPR}} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \]

Construct complete Bell operator orthonormal basis with 1 & 2:

\[ \Psi^{(\uparrow\downarrow)}_1 = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle) \quad \Phi^{(\uparrow\downarrow)}_1 = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle) \]

Unknown state:

\[ |\phi\rangle = a|\uparrow\rangle + b|\downarrow\rangle \]

(123) state before A’s measurement:

\[ \Psi^{(\uparrow\downarrow)}_2 = \frac{a}{\sqrt{2}} (|\uparrow\rangle |\uparrow\rangle - |\downarrow\rangle |\downarrow\rangle) + \frac{b}{\sqrt{2}} (|\downarrow\rangle |\uparrow\rangle - |\uparrow\rangle |\downarrow\rangle) = \frac{1}{2} \begin{bmatrix} |\uparrow\rangle & |\downarrow\rangle & |\uparrow\rangle & |\downarrow\rangle \\ |\downarrow\rangle & |\uparrow\rangle & |\downarrow\rangle & |\uparrow\rangle \end{bmatrix} \]

After A’s measurement, B’s particle 3 projected into one of four pure states:

\[ |\phi\rangle = \begin{bmatrix} a \\ b \end{bmatrix} \]

B receives A’s information about which basis vector found. This tells B which of these states he has received. B uses an appropriate inverse matrix to obtain the teleported quantum state.

Bob receives the quantum particle in the channel, the state of which has been modified by the entanglement at Alice’s location. He receives the classical information from Alice, here two classical bits of information, and this allows him to select the correct basis state from the four possible states. The result is that Bob’s particle received through the channel now carries the entire quantum state of the original particle that began at Alice’s location. An essential feature of this process is that the quantum state that first arrived at Alice’s location must vanish as a mathematical necessity in the creation of the same state at Bob’s location. No such state exists in the interval between Alice’s measurement and Bob’s use of the classical information received from Alice by conventional means. The potential application of teleportation in quantum
computing is the circumvention of decoherence effects in components and the potential for quantum communication.

The goal of quantum computing research requires development of the physics and engineering of the substrates, the quantum particles that will be used to store qubit information, the construction of suitable control gates, and the theoretical foundation for constructing functional quantum computers. Methods will need to be advanced for controlling decoherence of the system wave functions in the computing construct, as well, but much confidence exists in the quantum computing community in overcoming these obstacles.

**Quantum Physics and Energetic Materials**

For the sake of completeness we turn to several topics that are perhaps unique to DTRA and its mission and that are intimately related to the questions of quantum mechanics – either in their suggestion of new physics mechanisms or in engineering obstacles, or both. These do not fall specifically into the AMO scope as just outlined and they are not areas of research as such, but are special concepts that should be addressed. If these were shown to have adequate foundation, credibility, or feasibility, they would provide dramatic new capabilities to the field of energetic materials.

**Nuclear Isomers**

The paradigm shift in the understanding of quantum matter in the last century evolved through the first atom bomb test in New Mexico on July 16, 1945 and reached maturity in the first proof-of-principal test of the Teller-Ulam design “staged” hydrogen bomb on November 1, 1952, in which hydrogen fusion depended critically on quantum tunneling through the Coulomb barrier.

Since that time scientists have continued to look for ways to exploit the energy bound within the nucleus. One attractive possibility results from the fact that some elements of nature occur as nuclear isomers. These nuclei have energy stored in excited rotational states or in deformation states that sometimes persist for anywhere from seconds to, in the case of tantalum, greater than $10^{15}$ years. Unlike fissionable materials, the decay of a nuclear isomer yields none of the neutrons or radioactive fission products; instead, the decay of a nuclear isomer produces photons. The kinetics of nuclear rotation is such that a transition from an excited state to the ground state requires a much larger change in spin angular momentum than a single photon can carry (a photon always has the spin $\pm \hbar$) and so the decay process is generally inhibited by the momentum conservation law, leading to the longevity of these excited states. Nonetheless, when transition paths exist, the photons that are released carry energies that are at least tens of keV or higher, i.e., the release of this nuclear energy is in the form of gamma radiation. For example, the isomer of the hafnium nucleus (hafnium-178) has a half-life of 31 years and an excitation energy of 2.5MeV. Figure 10 shows the excitation energy of hafnium-178 and the transition energies that range from 200 to 500keV, which have considerable penetration power in solid matter.

The hafnium bomb was a concept that generated interest in the feasibility of triggering the release of isomer-stored energy in the late 1990s. The concept was an outgrowth of work by Collins in which Hf-178 was irradiated with x-rays and claims were made of observation of enhanced release of gamma rays from the sample. In 1997, the JASONs were commissioned by DARPA to look into a possible scheme for such a bomb. Their conclusions included: “There was no scientific justification of how such a process might possibly be obtained with high enough efficiencies to be useful in any practical purpose.” In 1998 the JASONs were commissioned to consider whether isomers could be made into a weapon within the next twenty years. The JASONs looked at four fundamental questions: 1) Did Collins demonstrate that an enhanced yield really occurred? 2) What was the physical mechanism that would allow triggering to take

---

place? 3) Could enough hafnium be manufactured in the next twenty years to make the concept useful? and 4) Could a triggering mechanism be produced in the next twenty years? The JASONs concluded that the claims of hafnium triggering are *a priori* implausible and that the experiments conducted to date were unconvincing.27

The Department of Energy became interested in the isomer issue because of concerns that, if the hafnium claims could be verified, the possibility of isomeric energetic systems would become a national security issue. To investigate the claims DOE funded Lawrence Livermore, Los Alamos, and the Argonne national laboratories to perform experiments to reproduce earlier results. Using a broad-band x-ray source to stimulate hafnium-178, samples showed that there was no evidence of triggered decay.28

Earlier this year, scientists at the Livermore National Laboratory studied the isomer Thorium-229. This isomer has an excitation energy that is near optical energies suggesting that transitions might be achievable with small-scale lasers. Livermore scientists have accurately measured the energy difference between the excited state energy and ground state levels. The Livermore results differ significantly from prior results. These scientists first hope to use a laser tuned to this precise energy difference to observe the transition to the excited state and then to explore triggering from this state.30

Nuclear isomers remain an interest to the scientific community. The physical principles are understood and naturally occurring nuclear isomers are catalogued with a wide range of half-lives. The difficulty in producing isomers is great, requiring accelerator technology that produces the nuclei with low mass yields. And the mechanisms that govern the decay process do not offer clear pathways to triggering. That is to say, it is difficult to make meaningful amounts of isomers and it is not known how to extract the energy in a useful way. But research continues and work such as that at Livermore probes the isomer phenomena for clues as to how to accomplish this level of control.

**Low Energy Nuclear Reactions**

The fusion process that powers stars (see Figure 11) is a multi-step process that in essence combines four protons into a helium nucleus while releasing energy and neutrinos, with a total energy release of about 27MeV as determined by comparing the masses of the four protons before reaction to the single helium nucleus in the product. In the terrestrial scheme proposed for fusion the deuterium-tritium reaction produces about 14MeV of energy in the form of neutron kinetic energy and about 3.5MeV in the kinetic energy of the helium nucleus. The announcement by Stanley Pons and Martin Fleischmann in 1989 of the discovery of heat generation in a table-top laboratory experiment at the University of Utah chemistry department met with

---

immediate public interest; the announcement included the claim that a nuclear fusion process was operative in deuterated palladium electrodes.

There was considerable interest generated in the scientific community by this announcement but few details were forthcoming from the Utah group in these early months. Nuclear physicists were most skeptical of the claims since no Department of Chemistry personnel suffered radiation sickness from the huge neutron flux that would have been present, if the power observed were to be explained by terrestrial nuclear processes. The Pons and Fleischman claim was then weakened by the assertion that the absence of neutron flux implied a wholly new and undiscovered nuclear fusion process. After the expenditures of considerable peer theoretical and experimental effort, and even careers, the consensus of the physics community was that there was no fusion “in a bottle” and that the appearance of energy had to originate from the highly complex electrolytes in the system.

More recently, Widom and Larsen have concurred that the process hidden in the Pons and Fleischmann experiments could not be based on nuclear fusion but have advanced the notion that a different form of nuclear reactions is responsible for the observed energy release. The reaction process is governed by the weak interaction alone without strong interactions between protons.32 Perhaps the most intriguing feature of this proposition is the experimental identification of transmutation products in metal electrodes made of metals such as nickel, titanium, and palladium immersed in electrolytes containing light water (see Figure 12). These data reveal the presence of nuclei with atomic masses both above and below that of the host electrode and they suggest that proton-metal initiated reactions occur in such cells.

There is some evidence of transmutation in exploding wire research extending as far back as 1922.33 This may be attributable in the case of low voltage/high current limits to collective electron transfers of energy to nuclei.

Figure 11. The proton-proton cycle dominates the fusion process in stars with masses smaller than, or equal to, our sun

Figure 12. Reaction product yield vs. mass number

31 Miley, G.H. On the Reaction Product and Heat Correlation for LENRs. in 8th International Conference on Cold Fusion. 2000. Lerici (La Spezia), Italy: Italian Physical Society, Bologna, Italy
The field of low energy nuclear reactions (LENR) has expanded since the early days of cold fusion, there are over a thousand papers published in this area, and there is a growing body of experimental evidence of isotopes appearing in reaction cells and power yields (without significant prompt radiation or residual radioactivity) to suggest actual applications.

**BlackLight Power**

BlackLight Power is the product of the early days of the cold fusion era. The founder of BlackLight Power, Inc. was unconvinced that the experiments of Pons and Fleischmann were demonstrations of a fusion process operating in the tabletop cells. The alternative explanation that he offered was that hydrogen itself was not sufficiently understood and that, in fact, hydrogen had quantum states below the traditional quantum states. If it were possible to stimulate decay into these lower energy states, then much more energy could be extracted from the sea of hydrogen that surrounds us on this planet. BlackLight Power, Inc. is an operating business and wholly owned subsidiary of Millsian, Inc. The championing of this new source of energy is distinctly different from LENR and is apparently exclusively within the purview of the corporation.

It is useful here to discuss the traditional solution of the Schrödinger equation for the hydrogen atom. The wave function for the spherically symmetric potential field can be written as

\[ \psi(r, \theta, \varphi) = \frac{u(r)}{r} Y_l^m(\theta, \varphi) \]  

(4)

in which the angular functions are eigenfunctions and the eigenvalues are integers. The equation for the radial component of the wave function for the case of a spherically symmetric potential becomes

\[ \frac{\hbar^2}{2\mu} \frac{d^2}{dr^2} u + \left( \frac{\hbar^2}{2\mu} \frac{l(l+1)}{r^2} + V(r) \right) u = Eu. \]  

(5)

It is necessary to consider the boundary conditions that can arise for \( u \). For most problems the potential should have a finite value everywhere except possibly at the origin and should vanish infinitely far from the origin. Near the origin we could assume that

\[ V(r) \sim r^\alpha, \quad \alpha \geq -1. \]  

(6)

It is important to note that Eq.(5) is valid only for non-zero values of \( r \) and that the solutions of that equation must be supplemented by a boundary condition for \( u \) at \( r = 0 \). The appropriate boundary condition is arrived at by ensuring that the Hamiltonian is self-adjoint with respect to admissible eigenfunctions. This ensures that the probability interpretation of quantum mechanics is upheld. Then we must have

\[ \int \int \psi^* \psi r^2 dr d\Omega = \int_0^\infty u^* u dr = 1. \]  

(7)

If the Hamiltonian operator is written as

\[ H = -\frac{\hbar^2}{2\mu r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial}{\partial r} \right) + \frac{L^2}{2\mu r^2} + V(r), \]  

(8)

then

\[ H u_k = E_k u_k. \]  

(9)

---

34 Merzbacher, E. Quantum Mechanics, New York: John Wiley & Sons, Inc. 1961, p.186ff
If Eq. (9) is multiplied by \( u_m \), the same equation is written with \( k \) and \( m \) interchanged, and then the two equations subtracted from one another, then an integration over all of \( r \) shows that

\[
\lim_{r \to 0} \left( u_k^* \frac{du_m}{dr} - du_k^* \frac{du_m}{dr} u_m \right) = 0. \tag{10}
\]

The assumption that \( u_{k,m}(0) = 0 \) provides a sufficient but not necessary condition to satisfy Eq. (10). This traditional assumption leads to eigenvalues for the energy that are proportional to an integer equal to, or greater than, unity. The assumption that satisfies Eq. (10) leads to the traditional quantization of the hydrogen atom for which the ground state is well defined.

BlackLight Power has proposed a different set of boundary conditions for the wave function: for non-radiative states, the current density function must not possess space-time Fourier components that are synchronous with waves traveling at the speed of light. This leads to the conclusion that there are energy levels below the energy levels traditionally associated with hydrogen.

Although BlackLight Power offers a set of data on the behavior of matter with hydrogen as described, the astrophysical community has yet to discern any discrepancy in astrophysical hydrogen spectra. On the other hand, BlackLight Power identifies the hypothetical lower energy states as corresponding to fractional energy-level quantum numbers; these states could not make simple transitions through the emission or absorption of single photons, since the conservation of angular momentum would be violated. That is, the hypothetical state transitions would be forbidden. However, the conventional point of view is that energy levels below what is accepted as the ground state must inevitably be reached under natural conditions, these levels being energetically favored. The absence of such ready observation raises questions about the physical correctness of the BlackLight Power model of hydrogen.
ASSESSMENT

It has been established that:

- It is DoD policy that basic research is essential to the Department of Defense’s ability to carry out its missions,
- The Department of Defense is mandated to conduct a vigorous program of high quality basic research in DoD component laboratories, support high quality basic research in institutions of higher education, other nonprofit research institutions, laboratories of other Federal agencies, and industrial research laboratories,
- Results of quantum mechanics research have been laid the foundation for many technologies now in military and civilian use,
- Quantum mechanics basic research may be on the verge of unprecedented discoveries, using new techniques and instrumentation capable of exploring the limits of measurement and quantum control,
- Basic research in quantum mechanics can be expected to generate surprising new discoveries of use to the DoD and civilian sector, and
- Basic research in quantum mechanics is broadly consistent with the DTRA mission.

These factors taken together support the conclusion that DTRA should participate in quantum mechanics basic research and that products of this research will meet the DTRA mission objective.

It is clear that the six broad research areas in atomic, molecular, and optical sciences have sound physical foundations and have broad implications for domestic, security, and military applications. The specific research areas that could impact the discipline of energetic materials are more uncertain in the fundamental physics:

- Nuclear isomers are understood when described in the language of quantum mechanics, are known to exist in nature, have transition energies hundreds to thousands of times greater than chemical bond energies when compared on an atom-to-atom basis, but are likely to have a long development time to achieve even rudimentary production and triggering methods.
- Low energy nuclear reaction is becoming a discipline of its own, and many individual efforts are being invested into experimental and theoretical investigations, often encouraged by tantalizing claims of transmutations in tabletop electrode experiments; while the concepts of BlackLight power seem at odds with accepted thinking about the fundamental behavior and experimental characterization of hydrogen.
- Many of the AMO research areas will require new theoretical, experimental, and manufacturing insights to realize capabilities that could potentially emerge from such research. Some of these appear to have much longer developmental times than is suggested and others, like quantum control, are much more at hand.

In some sense all the sound approaches have potential relevance to the DTRA mission, but those that have more concrete applications in sight warrant a clear interest, as suggested by Figure 13. For example, the capabilities promised in quantum computing can impact all areas of sensor processing, threat materials identification and discrimination with processing speeds in extremely small components far in excess of current computer miniaturization technology. Furthermore, the use of the principles of quantum mechanics can lead to new forms of communications technology that can include encryption techniques that are not only unbreakable but alert the users if interception is attempted. For quantum optimization, opportunities exist in the near term; work is underway exploring new reaction products by means of ultra-short laser pulse shaping and optimization and work is proceeding in developing theoretical techniques that help to understand
the efficiencies that can be achieved by optimization search algorithms. For nano-structure fabrication, opportunities exist to explore new kinds of materials with unprecedented strength, or dynamic materials whose properties could be altered “on the fly” by contributions from electronic control and nanoparticles components. For energetic materials that have unique interest to DTRA, the special projects summarized here present unique theoretical physics challenges; much work needs to be done in both the nuclear isomer and low energy nuclear reaction areas – to find ways to both manufacture and control nuclear isomers and to uncover the truth of low energy nuclear reactions as a potential basis for energy-producing cells.

Although only the broadest relationship between basic research areas in quantum mechanics is suggested in Table 1, it is nonetheless tempting to draw more specific connections between the areas of quantum mechanics research summarized here and some potential applications to the DTRA mission.

Not discussed here are a number of exotic, quantum mechanics concepts that have not so far met the standards of scientific credibility but which may yet be demonstrated. The concept of teleportation presented earlier arises from the property of entanglement that enforces the collapse of the wave function for one part of an entangled system upon measurement performed on another part of the system. Faster-than-light concepts point to the requirement of instantaneous collapse of the wave function for parts of a system far away from the measured system; this suggests that communication might circumvent the light limitations of relativity. Arguments are advanced that such a concept cannot be possible – sometimes based on quantum mechanical argument and sometimes based on the violation of causality. However, the meaning of quantum mechanics is still under debate and other consequences of quantum mechanics have been no less astounding than the supposition of faster-than-light communication. Further theoretical work and experimentation would need to be successful before this concept would be of value to a national security need.
Table 1. Quantum research technologies and potential DTRA application

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Potential DTRA Application</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Dot</td>
<td>Manufactured “atom”</td>
<td>Radiation detectors</td>
<td>Tailored molecule with large energy bandwidths could revolutionize explosive chemistry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Artificial molecule</td>
<td></td>
</tr>
<tr>
<td>Revolutionary space/time</td>
<td>GPS accuracy improvement</td>
<td>Weapon hit accuracy can dramatically improve weapon performance. Enables optimum multi-weapon delivery (e.g., “pile-driver” penetration)</td>
<td></td>
</tr>
<tr>
<td>measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>At low temperatures de Broglie wavelengths overlap neighbors</td>
<td>Atomic laser used as gravity sensor</td>
<td>High resolution visualization. Detection/mapping of underground facilities</td>
</tr>
<tr>
<td>Bose-Einstein condensates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-Ray laser</td>
<td>Intense burst of radiation in x-ray spectrum/delivers very energetic photons</td>
<td>Bio-agent kill</td>
<td>Intense beam can destroy agent DNA and cause electronic burn-out/upset on electronic systems</td>
</tr>
<tr>
<td>Ultrafast quantum control</td>
<td>Control non-equilibrium molecular states</td>
<td>Chemical reaction control</td>
<td>Can explore unconventional reaction paths to enhanced energetic molecules</td>
</tr>
<tr>
<td>Nanoscale engineering</td>
<td>Manipulation of matter at atomic scale/ fabricate materials with new properties</td>
<td>Fabrication of x-ray or gamma ray lenses Nanospheres for attachment to molecules of chemical agents</td>
<td>Useful for WMD detection and defeat</td>
</tr>
<tr>
<td>Quantum information</td>
<td>Quantum computing based on quantum bit register – superposition of states gives rise to very large computing power</td>
<td>Encryption Quantum computing Non-local communication</td>
<td>Applications to sensors, secure communications</td>
</tr>
<tr>
<td>Nuclear isomers</td>
<td>Nuclear energy stored in shape or spin of nucleus</td>
<td>Bio-agent kill</td>
<td>100,000 times greater energy density than chemically based explosives</td>
</tr>
<tr>
<td>Low energy nuclear reactions</td>
<td>Proposed nuclear reactions mediated by weak interaction</td>
<td>Nuclear but clean energy source</td>
<td>Mounting evidence of transmuted species in tabletop reactors without traditional nuclear radiation</td>
</tr>
</tbody>
</table>

There is considerable interest in the subject of AMO research, as evidenced by even a cursory listing of groups and institutions that have formed in recent years, both nationally and internationally, as shown in the sidebar. And there is support from DoD organizations as well. However, the National Research Council’s Committee on AMO noted with some concern the general decline in basic research funding at the DoD agencies, since basic research has been so important to the nation’s defense strategy during the last fifty years. The committee’s interactions with agencies have revealed that there are many more good research proposals than could be supported by available funds.35 Since funding difficulty may more easily be remediated than would be a paucity of good ideas, the prospects for healthy advancement of new technologies are good. Also noted was the rapid rise in technical capabilities and associated increase in the cost of scientific instrumentation, which added pressures on research group budgets. New paths to increased technical capabilities can be imagined, but the tools needed to achieve these capabilities come with increased cost, and funding pressures can only grow.

And finally, the Committee noted36: “…it is important not to lose sight of the essential role played by theoretical research.” Theoretical research is the foundation of understanding and it is the guiding principle for future development.

36 op. cit., p 28
### Selected Quantum Mechanics Research Institutions

<table>
<thead>
<tr>
<th>Domestic Groups/Institutions</th>
<th>International Groups/Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice Quantum Institute - Rice University</td>
<td>Institute for Quantum Optics - Zurich</td>
</tr>
<tr>
<td>Range of effects from atomic to interstellar</td>
<td>Quantum photonics</td>
</tr>
<tr>
<td>Mathematical Sciences Research Institute – Berkeley</td>
<td>Quantum/non-linear optics</td>
</tr>
<tr>
<td>Quantum computation</td>
<td>Ultra-fast laser physics</td>
</tr>
<tr>
<td>Quantum Technologies Group – Cambridge-MIT Institute</td>
<td>Institut für Quantenoptik und</td>
</tr>
<tr>
<td>Communication</td>
<td>Quanteninformation – Austria</td>
</tr>
<tr>
<td>Computation</td>
<td>Quantum optics &amp; spectroscopy</td>
</tr>
<tr>
<td>Metrology</td>
<td>Quantum information &amp; computation</td>
</tr>
<tr>
<td>Photonic reagents</td>
<td>Ultracold atoms &amp; quantum gases</td>
</tr>
<tr>
<td>Georgia Tech Quantum Institute (GTQI)</td>
<td>Max Planck Institute of Quantum Optics</td>
</tr>
<tr>
<td>Quantum information &amp; technology</td>
<td>Attosecond &amp; High Fields</td>
</tr>
<tr>
<td>Institute for Quantum Sciences – MSU</td>
<td>Quantum Dynamics</td>
</tr>
<tr>
<td>Quantum computing &amp; information sciences</td>
<td>Laser Chemistry</td>
</tr>
<tr>
<td>Institute for Quantum and Complex Dynamics – UCSB</td>
<td>Quantum Information Theory Group – Imperial College</td>
</tr>
<tr>
<td>Non-linear, terahertz, sciences</td>
<td>Quantum computation &amp; entanglement</td>
</tr>
<tr>
<td>Free electron lasers</td>
<td>Quantum Information Group at IITIS PAN – Poland</td>
</tr>
<tr>
<td>Institute for Quantum Science and Engineering – Harvard University</td>
<td>Quantum computing simulation</td>
</tr>
<tr>
<td>Mathematics/computer science</td>
<td>Quantum programming languages</td>
</tr>
<tr>
<td>Quantum physics/nanoscience/device engineering</td>
<td>Quantum games</td>
</tr>
<tr>
<td>Institute for Nanoscience and Quantum engineering – Yale</td>
<td>Institute of Quantum Optics – University of Hannover</td>
</tr>
<tr>
<td>Nanoscale fabrication of materials/devices</td>
<td>Molecules &amp; lasers</td>
</tr>
<tr>
<td>Quantum design processes/engineering on scale of atoms and subatomic particles</td>
<td>Ultra-fast laser optics</td>
</tr>
<tr>
<td>Joint Quantum Institute – NIST/UMD</td>
<td>Institute for Quantum Computing – University of Waterloo</td>
</tr>
<tr>
<td>Superconducting qbits</td>
<td>Quantum information &amp; processing</td>
</tr>
<tr>
<td>Entanglement</td>
<td></td>
</tr>
<tr>
<td>Decoherence /coherence</td>
<td></td>
</tr>
<tr>
<td>Topological quantum computing</td>
<td></td>
</tr>
<tr>
<td>Quantum/classical interface</td>
<td></td>
</tr>
<tr>
<td>Quasi one-dimensional superconductors as optical lattices</td>
<td></td>
</tr>
<tr>
<td>Quantum Optimization – Princeton University</td>
<td></td>
</tr>
<tr>
<td>Photonic reagents</td>
<td></td>
</tr>
</tbody>
</table>

### U.S. Government Organizations/Agencies

| LANL – Quantum Institute                                          | Quality Information Theory Group – Imperial College                   |
| Quantum traps                                                     | Quantum Information Group at IITIS PAN – Poland                       |
| Quantum computing & cryptography (quantum key distribution – QKD) | Quantum computing simulation                                          |
| Decoherence                                                       | Quantum programming languages                                         |
| Materials science                                                 | Quantum games                                                         |
| Atom cooling & trapping techniques                                | Institute of Quantum Optics – University of Hannover                   |
| LLNL                                                              | Molecules & lasers                                                    |
| EOS & Materials Theory Group                                      | Ultra-fast laser optics                                              |
| Scientific Discovery through Advanced Computing (SciDAC)          |                                                                        |
| Quantum Simulations Group (QSG)                                   |                                                                        |
| New materials/States of Matter prediction                        |                                                                        |
| Argonne National Laboratory                                       |                                                                        |
| Atomic theory & fundamental quantum mechanics                     |                                                                        |
| Pacific Northwest National Laboratory                             |                                                                        |
| Magnetic semiconductors & quantum computing                       |                                                                        |
| SNL                                                               |                                                                        |
| Quantum dots, wires, wells                                       |                                                                        |
| Quantum transistors                                               |                                                                        |
| Quantum computing                                                |                                                                        |
| DARPA                                                             |                                                                        |
| Fundamental physics                                               |                                                                        |
| Novel physics-based devices & applications                        |                                                                        |
| Cognitively augmented Design for quantum technology               |                                                                        |
| Quantum sensors                                                   |                                                                        |
| AFOSR                                                             |                                                                        |
| Quantum electronic solids                                         |                                                                        |
| ARL                                                               |                                                                        |
| Physical sciences – atomic/molecular dynamics, quantum information science | |
RECOMMENDATIONS

The results presented in this report represent the product of a preliminary investigation of short duration and of limited resources. The recommendations presented here must therefore be regarded as preliminary in themselves. However, several can be made at this early date and several courses of action can be entertained by DTRA/ASCO.

- **DTRA/ASCO should advocate, and DTRA should participate in, the funding of quantum research.** This is consistent with Department of Defense instructions and it makes sound business sense. The evolution of scientific research is not unlike punctuated equilibrium: research will develop for a time, perhaps a protracted time, with predictable progress, but on occasion a new breakthrough in understanding or experimentation that will lead to dramatic progress in a comparatively short interval. The outsider who monitors progress is hampered by the relative slowness of conventional reporting (such as journal articles, meetings, and even newspaper reporting) while those intimately involved share progress through the Internet, with the speed of thought. If DTRA is to remain an intelligent consumer of the products of quantum research, it must maintain focus as a participant in this research. Its mechanism for accomplishing this is to participate in the funding of research projects.

- **DTRA should establish channels of communications with other agencies invested in quantum research.** As mentioned previously, there are many organizations and agencies currently involved in basic research in quantum mechanics. Many efforts are focused on the six areas in atomic, molecular, and optical sciences. Where there is overlap of interests, these relations avoid duplication, provide a mechanism for awareness of new developments, and provide a vehicle for adopting advocacy for those high risk, high potential payoffs of relevance to the DTRA mission.

- **DTRA should consider focused participation in quantum research.** The field of quantum research is broad. It is not advisable, nor is it possible, to attempt wide-ranging support: the mechanics of management is complicated by the numerous efforts implied and it is difficult to maintain technical congnizance over progressing, disparate projects. DTRA should select areas of special interest and participate in funding in activities related to these areas of emphasis. These areas are quantum research areas that are likely to have implications for utility to a number of applications technologies. The focus of effort on critical concepts that enable the research areas provides much more economy of purpose than does the approach of selecting applications technologies first and then assigning a subset of these to quantum issues.

- **DTRA/ASCO should regard concepts that depend on counterintuitive quantum properties such as teleportation as feasible and potentially exploitable for defense applications.** The six areas described in the National Research Council’s Committee on AMO research describes opportunities for the next decade that spring from new understanding in quantum research, new

---

37 Punctuated equilibrium, a concept advanced by Stephen Gould, stands in contrast to the belief that evolution was slow, gradual, accumulating change in species. It states that species show long periods of stasis, interrupted by brief but significant evolutionary steps.
instrumentation, and tools that can explore control of phenomena down to components of the atom and up to extremely high energy densities and powers.

- **DTRA/ASCO should consider nuclear isomers as a potential, long term research interest with high potential payoff.** There is fundamental soundness in understanding the structure and behavior of nuclear isomers but that the physics of triggering and bulk manufacturing are intertwined and not understood. Clearly, the field would benefit from continued investigation such as that conducted at Lawrence Livermore National Laboratory.

- **DTRA/ASCO should maintain a healthy skepticism with regard to LENR and BlackLight Power.** DTRA/ASCO should wait until more progress is made with experimental data, yet be receptive to consideration of new ideas in quantum-based energetic materials. For low energy nuclear reactions, there is uncertainty in the basic physics that is purported to provide practical yield of nuclear energy in tabletop cells through the process of transmutation to lower energy products, rather than any claim of fusion and there needs to be further investigation to substantiate claims of data revealing transmuted elements in electrodes. And the concept of BlackLight Power appears to be inconsistent with the widely accepted notions of ground state behavior and the absence of hydrogen spectra consistent with its concept. But here, too, data are offered that purport to substantiate the proposed concept.

- **DTRA/ASCO should commission a more comprehensive assessment of quantum research opportunities.** The assessment provided in this report was inherently proscribed by limitations in time and resources. For the special projects in energetic materials a more comprehensive evaluation should be made of the experimental evidence that has been proffered by the prononers of the technologies, either to validate the physics or to lay to rest their further consideration. Areas of AMO research should be evaluated more thoroughly to provide a better assessment of the projected timescales for achieving progress. Concomitant with this is the need for a development of a comprehensive investment plan, including strategies for selecting research offerings for possible funding as well as strategies for leveraging resources through partnerships.
E1. ENCLOSURE 1

PRINCIPLES FOR THE CONDUCT AND SUPPORT OF BASIC RESEARCH

E1.1.1. Basic research is an investment. The DoD Components are to view and manage basic research investments as a portfolio, with assessments of program success based on aggregate returns. There should be no expectation that every individual research effort will succeed because basic research essentially is an exploration of the unknown and specific outcomes are not predictable.

E1.1.2. Basic research is a long-term activity that requires continuity and stability of support. Individual basic research efforts sometimes return immediate dividends, with transitions directly from research laboratories to defense systems in the field. However, most often the full benefits of basic research are not apparent until much later. Therefore, the DoD Components must engage in long-term planning and funding of basic research to the maximum possible extent.

E1.1.3. Balance is essential in the portfolio of basic research investments. A wide range of scientific and engineering fields is of potential interest to the Department of Defense and the DoD Components. It is important to develop a balanced portfolio that includes investments not only in established research areas with promise for evolutionary advances, but also in areas that entail higher risk and offer potential for revolutionary advances with correspondingly higher benefits.

E1.1.4. Coordination with other Federal agencies is important. The DoD Components are to consider other Federal agencies’ basic research investments when making investment decisions, both to avoid unintended overlapping of support and to leverage those agencies’ investments as appropriate.

E1.1.5. Merit review is used to select basic research projects for support. It is crucial that the Department of Defense invest in the highest quality research for defense needs. Merit review relies on the informed advice of qualified individuals who are independent of the individuals proposing to do the research. The principal merit review factors used in selecting among possible projects are technical merit and potential long-term relevance to defense missions.
In quantum mechanics all physical states are represented by a wave function or Hilbert space state vector. Electrons, photons, and other physical objects can be described by these wave functions as functions of space and time. The wave functions consist of complex numbers; the square of the amplitude of the wave function gives the probability density of observation of the position of the particle and can be used to calculate the probability density of other characteristics such as momentum. The propagation of the wave function exhibits the effect of interference, as depicted by the regular appearance of light and dark bands on this cover. The sphere represents the Bloch sphere—a mathematical sphere of unit radius that represents all possible wave functions for a two-state system such as the spin of an electron or the polarization of a photon. Each wave function can be represented by a vector pointing from the origin of the Bloch sphere to its surface. Only two quantities are needed to completely represent a wave function vector—the polar and axial angles. A classical bit register can store only two values—zero or unity—while a qubit can store any two of an infinite number of values.