“Atom at 200: from Dalton till Today”

Compiled by-Mineesh Gulati
Happy Model Hr. Sec. School, Udhampur, J&K
IAPT- Life Member

Tiny-tiny little particle !
Which is not further divisible !

Tell me , tell me, what you are?
200 years of study on you, hope has not left your secrets far?

Tiny-tiny little particles ! OR tiny-tiny little waves !
Tell me , tell me, what you are?

From ancient Greek times of philosophy to today's technological era of quantum physics, scientists have been mesmerized by what is thought to be the smallest particle - the **Atom**. In Greek, the prefix "a" means "not" and the word "tomos" means “cut”. Thus, atomos or atom means uncutable or undividable.

All life whether in the form of whale, trees, mushrooms, amoeba or bacteria consist of cells. Similarly, all matter, weather in the form of Gold, aspirin, vitamins, water, minerals or air consists of atoms. It took us thousands of years to realize the structure of the atom. This understanding gave us enough power to mimic, harm and repair nature in ways never before possible.

Let’s go on a voyage of the discovery of the atom

In the beginning :

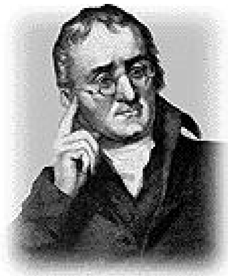
The Greeks and the Indians together they imagined that matter is made up of little unbreakable balls: the atoms. In 460 B.C a Greek philosopher, Democritus asked this question: If you break a piece of matter in half, and then break it in half again, how many breaks will you have to make before you can break it no further? Democritus thought that it ended at some point, a smallest possible bit of matter. He called these basic matter particles, atoms.

Unfortunately, the atomic ideas of Democritus had no lasting effects on other Greek philosophers, including Aristotle. In fact, Aristotle dismissed the atomic idea as worthless. People considered Aristotle's opinions very important and if Aristotle thought the atomic idea had no merit, then most other people thought the same also. (Primates have great mimicking ability.) In fact, the Catholic Church agreed with Aristotle's position and announced that atomistic ideas were equivalent to those of Godlessness.

The 5 points of **Democritus theory** are as follows...

Point #1 - All matter is made up of undividable particles called atoms.
Point #2 - There is a void, which is empty space between atoms.
Point #3 - Atoms are completely solid.
Point #4 - Atoms are homogeneous, with no internal structure.
Point #5 - Atoms vary in
1) Size
2) Shape.
3) Weight

For more than 2000 years nobody did anything to continue the explorations that the Greeks had started into the nature of matter. Not until the early 1800's did people begin again to question the structure of matter. The interest was rejuvenated due to Alchemy- The "grand plan" was transformation of "lowly" metals like "copper" to "noble" metals like "gold".



During this time of the "Gold rush" an English Chemist, John Dalton in 1800's performed experiments with various chemicals that showed that matter, indeed, seem to consist of elementary lumpy particles (atoms). Although he did not know about their structure, he knew that the evidence pointed to something fundamental.

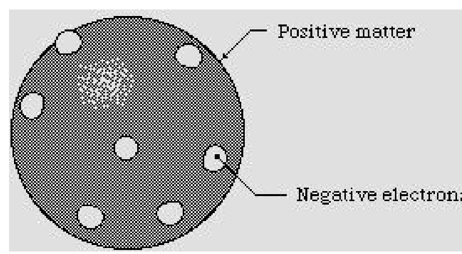
John Dalton is now called the **father of modern atomic theory** for his efforts. He published his work in a book called "**A New System of Chemical Philosophy" in 1808**. In it he was the first to propose that elements be identified with symbols. In this theory, there are five basic ideas...

1) chemical elements are made of atoms.
2) the atoms of an element are identical in their masses
3) atoms of different elements have different masses
4) atoms only combine in small, whole number ratios such as 1:1, 1:2, 2:3 and so on.
5) atoms can be neither created nor destroyed

Since he considered atoms to be perfect hard spheres having no internal structure therefore this theory came to be also known as the **"Billiard-balls theory".** Dalton's model could not explain cause of frictional electricity.

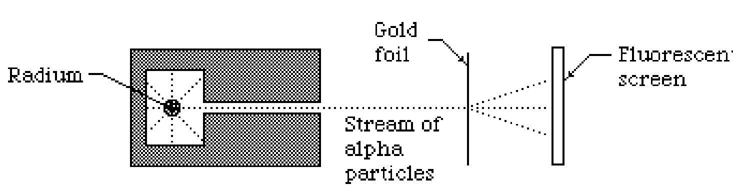
J.J Thompson's : Plum Pudding Model

On April 30, 1897, the English physicist John Joseph Thomson discovered the electron and proposed a model for the structure of the atom. Thomson knew that electrons had a negative charge and thought that matter must have a positive charge. His model looked like raisins stuck on the surface of a lump of pudding. Thomson designed the famous "plum pudding model" shown to the right. He was honored with the noble prize in Physics in 1906.

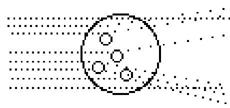


Ernest Rutherford: discovers the nucleus

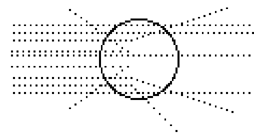
Henry Becquerel had by this time had discovered radioactivity i.e. emission of alpha, beta and gamma radiations. The alpha particles had a positive charge and physicists thought it consisted of positive part of the Thompson's atom while beta-rays were considered as the emission of the negative rasins of the Thompson's "Plum-pudding model"



In **1911 Ernest Rutherford** thought it would prove interesting to bombard atoms with these alpha rays, figuring that this experiment could investigate the inside of the atom (sort of like a probe). He used Radium as the source of the alpha particles and shinned them onto the atoms in thin gold foil. Behind the foil sat a fluorescent screen for which he could observe the alpha particles impact.



Expected result

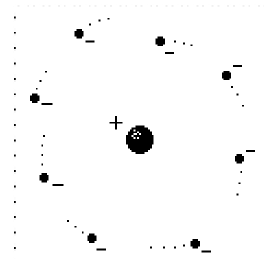


Actual result

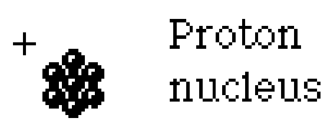
The results of the experiments came unexpected. Most of the alpha particles went smoothly through the foil. Only an occasional alpha veered sharply from its original path, sometimes bouncing straight back from the foil! Rutherford reasoned that they must get scattered by tiny bits of positively charged matter. He reasoned that most of the space around the tiny positive centers is empty! He thought that the electrons must exist somewhere within this empty space. Rutherford thought that the negative electrons orbited a positive center in a manner like the planets orbit the sun in the solar system.

Rutherford's Solar System Model

Rutherford's atom

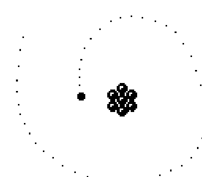


Rutherford knew that atoms consist of a compact positively charged nucleus, around which circulate negative electrons at a relatively large distance. The nucleus occupies less than one thousand million millionths (10) of the atomic volume, but contains almost all of the atom's mass. If an atom had the size of a football stadium then the nucleus would be of the size of the tossing coin!.



Not until 1919 did Rutherford finally identify the particles of the nucleus as discrete positive charges of matter. Using alpha particles as bullets, Rutherford knocked hydrogen nuclei out of atoms of six elements: boron, fluorine, sodium, aluminum, phosphorus, and nitrogen. He named them **"Protons",** from the Greek for **'first'**, for they consisted of the first identified building blocks of the nuclei of all elements. He found the protons mass at 1,836 times as great as the mass of the electron.

Failure of the Rutherford's model:



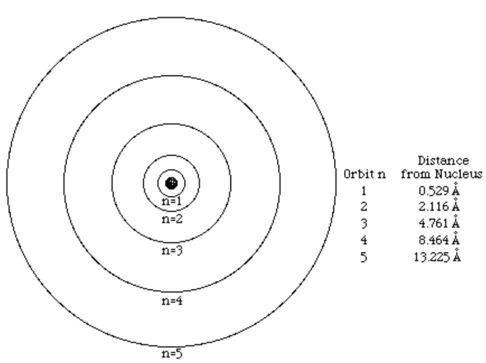
But there appeared something terribly wrong with Rutherford's model of the atom. The electrons revolving around the positive nucleus are accelerating and according to the theory of electromagnetism such an atom should radiate electromagnetic waves (rainbow of colours). As the energy of the radiating electron decreases it should spiral in and eventually bombard into the nucleus. But no experiment could verify this rainbow or observe the suicide of the electrons into the nucleus. The Rutherford's solar system model did not appear to be in resonance with the laws of classical Physics.

Bohr's Model

In 1912 a Danish physicist, Niels Bohr came up with a theory that said the electrons do not spiral into the nucleus and came up with some rules for what does happen. Bohr said, "Here's some rules that seem impossible, but they describe the way atoms operate, so let's pretend they're correct and use them." Bohr came up with two rules which agreed with experiment:

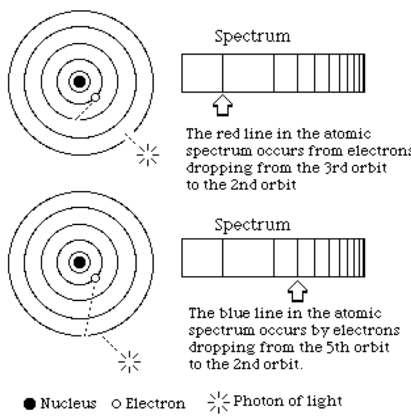
RULE 1: Electrons can orbit only at certain allowed distances from the nucleus.

RULE 2: Atoms radiate energy when an electron jumps from a higher-energy orbit to a lower-energy orbit. Also, an atom absorbs energy when an electron gets boosted from a low-energy orbit to a high-energy orbit.



Bohr's atom for Hydrogen

The electron can exist in only one of the orbits. (The diagram shows only five orbits, but any number of orbits can theoretically exist.)

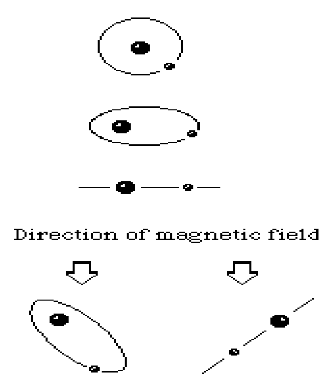


Light (photons) is emited whenever an electron jumps from one orbit to another. The jumps seem to happen instantaneously without moving through a trajectory.

By the 1920s, further experiments showed that Bohr's model of the atom had some troubles. Bohr's atom seemed too simple to describe the heavier elements. In fact it only worked roughly in these cases. The spectral lines did not appear correct when a strong magnetic field influenced the atoms. There was a need for a better model.

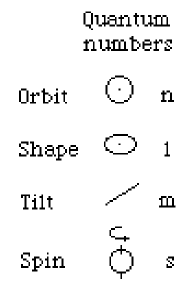
Bohr-Sommerfield's Model: Vector Atom Model.

Bohr and a German physicist, **Arnold Sommerfield** expanded the original Bohr model to explain these variations. According to the Bohr-Sommerfield model, not only do electrons travel in certain orbits but the orbits have different shapes and the orbits could tilt in the presence of a magnetic field. Orbits can appear circular or elliptical, and they can even swing back and forth through the nucleus in a straight line.



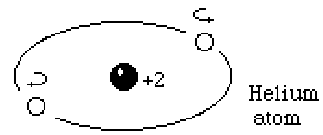
Bohr- Sommerfield model of the atom

The orbit shapes and various angles to the magnetic field could only have certain shapes, similar to quantization of the electrons orbital radius. These added states allowed more possibilities for fine structure of the spectral lines to appear.



The conditions of the state of the orbit got assigned **quantum numbers**. The three states discovered so far consist of: orbit number (n), orbit shape (l) and orbit tilt (m).

In 1924 an Austrian physicist, **Wolfgang Pauli** predicted that an electron should spin (kind of like a top) while it orbits around the nucleus. The electron can spin in either of the two directions clockwise or anti-clockwise. This spin consisted of a fourth quantum number: electron spin (s).

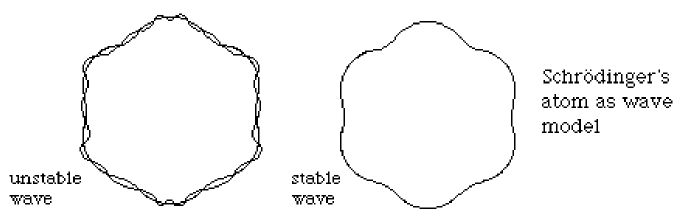


Pauli's Exclusion principle

Pauli gave a rule governing the behavior of electrons within the atom that agreed with experiment. If an electron has a certain set of quantum numbers, then no other electron in that atom can have the same set of four quantum numbers. Physicists call this **"Pauli's exclusion principle."** This principle later helped to classify elementary particles in two groups the fermions (which obey the exclusion principle) and the bosons (which don't)

The Wave Model

In 1924 a Frenchman named **Louis de Broglie** thought about particles of matter. He thought that if light can exist as both particles and waves, why couldn't atom particles also behave like waves? In a few equations derived from Einstein's famous equation, ($E=mc^2$) he showed what matter waves would behave like if they existed at all. (Experiments later proved him correct.)



In 1926 the Austrian physicist, **Erwin Schrödinger** had an interesting idea: Why not go all the way with particle waves and try to form a model of the atom on that basis? His theory worked kind of like **standing waves theory** for a guitar string except that the vibrations traveled in circles.

The world of the atom, indeed, began to appear *very* strange. It proved difficult to form an accurate picture of an atom because nothing in our world really compares with it. **Schrödinger's wave mechanics** did not question the makeup of the waves but he had to call it something so he gave it a symbol:

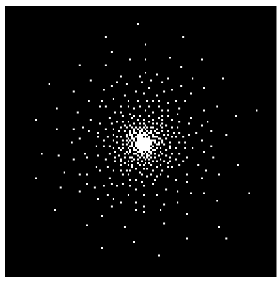
$$\Psi$$

The "psi" symbol of Schrödinger's wave came from the Greek lettering system.

In 1926, a German physicist, **Max Born** had an idea about 'psi'. Born thought they resembled **waves of chance**. These ripples moved along waves of chance, made up of places where particles may occur and places where no particles occurred. The waves of chance ripple around in circles when the particle appears like an electron in an atomic orbit, and they ripple back and forth when the electron orbit goes straight through the nucleus, and they ripple along in straight lines when a free particle moves through inter-atomic space. You can think of them as waves when traveling through space and as particles whenever they travel in circles. However, they cannot exist as both waves and particles at the same time.

Just before Schrödinger proposed his theory, a German physicist **Werner Heisenberg,** in 1925, had a theory of his own called matrix mechanics which also explained the behavior of atoms. The two theories seemed to have entirely different sets of assumptions yet they both worked. Heisenberg based his theory on mathematical quantities called matrices that fit with the conception of **electrons as particles** whereas **Schrödinger based his theory on waves**. Actually, the results of both theories appeared mathematically the same.

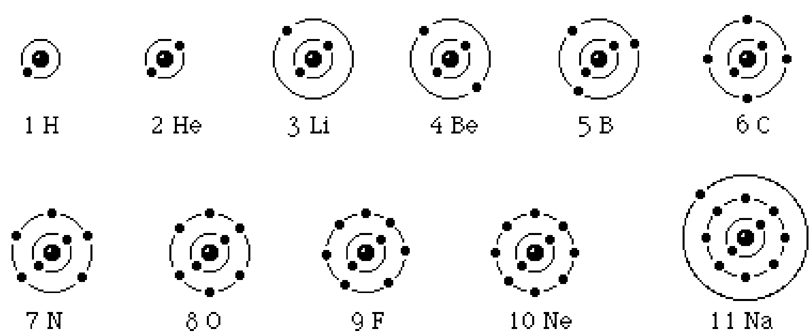
In 1927 Heisenberg formulated an idea, which agreed with tests, that no experiment can measure the position and momentum of a quantum particle simultaneously. Scientists call this the **"Heisenberg uncertainty principle."** This implies that as one measures the certainty of the position of a particle, the uncertainty in the momentum gets correspondingly larger. Or, with an accurate momentum measurement, the knowledge about the particle's position gets correspondingly less.



The visual concept of the atom now appeared as an **"electron cloud"** which surrounds a nucleus. The cloud consists of a probability distribution map which determines the most probable location of an electron, like the view at the top. Higher dot density indicates a greater chance of finding an electron in that region.

Although the mathematical concept of the atom got better, the visual concept of the atom got worse. These models of the atom simply served as a way of thinking about them, albeit they contained limitations (all models do).

Regardless, even simplistic visual models can still prove useful. Chemists usually describe the atom as a simple solar system model similar to Bohr's model but without the different orbit shapes. (The example below shows the first eleven elements.) **Aufbu** gave us rules which govern how the electrons get filled around in the various orbitals.

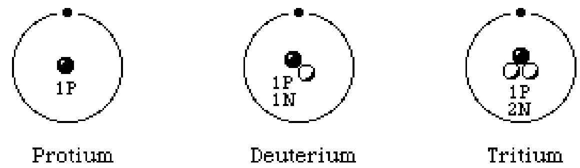


Nature of the Nucleus

A mystery of the nature of the nucleus remained unsolved. The nucleus contains most of the atom's mass as well as the positive charge. The protons supposedly accounted for this mass. However, a nucleus with twice the charge of another should have twice the number of protons and twice the mass.

But this did not prove correct. Rutherford speculated in 1920 that there existed electrically neutral particles with the protons that make up the missing mass but no one accepted his idea at the time.

Not until 1932 did the English physicist **James Chadwick** finally discoverd the **neutron**. He found it to measure slightly heavier than the proton with a mass of 1840 electrons and with no charge (neutral). The proton-neutron together, received the name, **"nucleon."**



Isotopes of Hydrogen

Although scientists knew that atoms of a particular element have the same number of protons, they discovered that some of these atoms have slightly different masses. They concluded that the variations in mass result, more or less, from the number of neutrons in the nucleus of the atom. Atoms of an element having the same atomic number but different atomic masses get called "isotopes" of that element.

Advent of the Nuclear Force:

When scientists found out about the atomic nucleus, they questioned why the positively charged protons should remain so close without repelling. The scientists realized that there must exist new forces at work and the secrets must lie within the nucleus. They knew that the force which holds the protons together has to be much stronger than the electrostatic force of repulsion between the protons and that the force must act over very small distances (otherwise they would have noticed this force in interactions between the nucleus and the outer electrons).

In **1932, Werner Heisenberg** concluded that charged particles bounce photons of light back and forth between them. This exchange of photons provides a way for the electromagnetic forces to act between the particles. The theory says that a proton shoots a photon at the electron, and the electron shoots a photon back at the proton. These photon exchanges go on all the time, very rapidly. However, because no one can see them (measure them), Heisenberg called these exchange particles, **virtual photons**. (Virtual meaning, not exactly 'real'.)

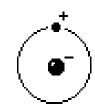
In **1935 a Japanese physicist, Hideki Yukawa**, suggested that exchange forces might also describe the strong force between nucleons. However, virtual photons did not have enough strength for this force, so he thought that there must exist a new kind of virtual particle. Yukawa used Heisenberg's uncertainty principle to explain that a virtual particle could exist for an extremely small fraction of a second. Since its time of existence is known exactly, there would occur a great uncertainty in the energy of the virtual particle (since $\Delta \mathbf{E} \, . \, \Delta \mathbf{t} \geq \hbar$.) This uncertainty allowed the particles to exist very strongly but only at certain times and the particles could slip in and out of existence. He also calculated that these particles should be about 250 times as heavy as an electron. Later, in 1947, the physicist **Cecil F. Powell** detected this particle and called it the **"pion."**

Physicists presently think that all the forces in the universe get carried by exchange of some kind of a quantum field particle. This theory started in 1928 with **Paul Dirac** stating that photons transmit the electromagnetic force. The theory called **"quantum electrodynamics," or QED**, developed from work by Richard Feynman, Julian Schwinger, and Sin-Itiro in the late 1940s. The four known forces and their particles appear as follows:

PARTICLE	NATURE AND ROLE
Photon	Carrier of the electromagnetic force (magnetisim, light, heat, EMR, electricity)
W+, W-, Z	Carrier of the weak force (radioactivity)
Gluon (8 types)	Carriers of the strong force (holds the quarks)
Gravition	Carrier of the gravitational force (undetected so far at the time of this writing)

Discovery of the Anti-matter:

Anti-matter



In **1928, Paul Dirac** produced equations which predicted an unthinkable thing at the time- a positive charged electron. He did not accept his own theory at the time. In 1932 in experiments with cosmic rays, **Carl Anderson** discovered the anti-electron, which proved Dirac's equations. Physicists call it the **positron.**

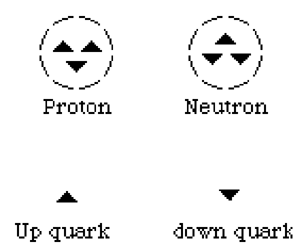
For each variety of matter there should exist a corresponding 'opposite' or antimatter. Physicists now know that antimatter exists. However, because matter and antimatter annihilates whenever they come in contact, it does not stay around for very long. There exists not only anti-electrons but in 1955, physicists found the anti-proton, and later the anti-neutron. This allows the existence for anti-atoms, a true form of antimatter.

From 1947 until the end of the 1950's, physicists discovered many more new particles (dozens of them). The various types of particles needed a new theory to explain their strange properties.

Classification of Elementary Particles: The Eightfold way

In 1960, **Murray Gell-Mann and Yuval Ne'man** independently proposed a method for classifying all the particles then known. The method became known as **the Eightfold Way**. What the periodic table did for the elements, the Eightfold Way did for the particles. In 1964 Gell-Mann went further and proposed the existence of a new level of elementary particles and called them **"quarks"**

Gell-Mann thought there existed at least **three types of quarks**. They have the names, "**up**," "**down**," and "**strange**." From 1974 thru 1984 the theory predicted three more quarks called "**charm**," "**bottom**" (or beauty), and "**top**" (or truth). And each quark has their corresponding anti-quark.



Quarks do not exist by themselves but only in pairs (mesons) or triplets (baryons).

The theory of the quark explains the existence of several particles including the nucleus of the atom. In fact the proton and neutron each get made up of three quarks and the force which holds the quarks together come from particles called **"gluons."**

The emergence of Particle Physics as a separated discipline in the second half of the last century has had a strong impact on atomic physics. It is no longer protons, neutrons and electrons which are thwe basic building block of matter, but, according to the **"Standard Model"** the building blocks are quarks and leptons. Further, the strong interaction is not the nuclear force between nucleons but rather Quantum Chromo-Dynamics (QCD), the exchange of gluons between quarks.

Applications and Spinoff's of Atomic Physics

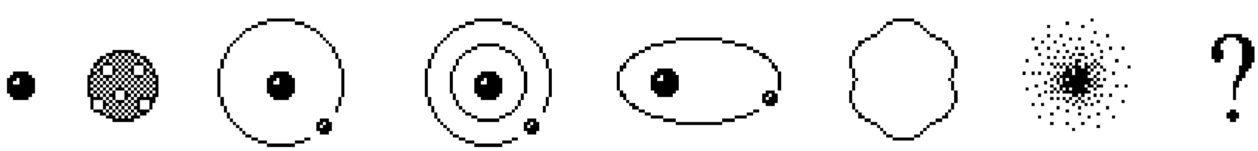
Since 1901, 32 times Noble Prizes in Physics have been related to the discovery of the various aspects of the Atom. Atomic Physics has a long record of developing novel techniques for presicion measurements. In 1940's N.Ramsey developed the so-called separated oscillatory fields method that is now the basis of the cesium atomic clock. The SI units are based on some property of an atom which makes it easier to reproduce them in the laboratory and remain invariant with time place and changes in physical conditions.

The Magnetic Resonance Imaging (MRI) techniques is a fantastic tool to look closely at the human body.Quantum cryptography and quantum computing are revolutionizing the developments of super-computers.

During the 1990's, Bose-Einstein Condensation (BEC) was observed using magnetic traps and evaporative cooling. This has helped in demonstration of the so called atom laser. Recently there has been work on exploring ultra-cold fermions. L.Hau showed in the late 1990's that light interacting with BEC can be slowed and even stopped.
Richard P. Fynmann's famous lectures "There is plenty of room at the bottom" and " if I could swallow a surgeon" has led to the development of miniaturization and nano-technology. The AFM - atomic force microscope- moves individual atoms around using the tip of a sharp needle and dip-pin lithography. STM can also move atoms around. The "Top-Down" approach of manufacturing of our industries which leads to generation of wastes and pollutants would be replaced by the benign "Bottom-Up" approach wherein small nono-robots would be able to build products at the atomic scale, the way the plants make their food. These developments are leading to implications for a wide variety of disciplines including bio-technology, astrophysics, condensed matter physics, nuclear physics, photonics, quantum optics etc.

From the time of the ancient Greeks until today, the visual concept of the atom has proved elusive and obscure, yet the mathematical concepts have grown stronger. Although nothing has yet proven absolute, humans can now predict the behavior of atoms with great accuracy. But the world of the atom, the quanta of particles, appears so strange that we can no longer visualize what we think and talk about. The particles have a quality of complete random existence and non-existence about them; and yet the methods of quantum electrodynamics (QED), quantum chromodynamics (QCD), and the whole of quantum mechanics provide such precise, useful, and powerful tools, that it encompasses all of the classical physical laws. The predictions of quantum mechanics have verified themselves many times and to a precision of better than one part in a billion. No predictive method has yet come as close. It is safe to assume that atomic physics will remain a hotbed of active research for the foreseeable future.

"Nothing is indifferent, nothing is powerless in the universe;
an atom might destroy everything, an atom might save everything!"
- Gérard de Nerval



And this only describes the beginning!