TIMELINE OF NUCLEAR PHYSICS

The table presented here is an attempt to present a timeline of discoveries that can be said to lead to the atomic bomb. The discoveries are listed in a chronological sequence and depend in some regards on a background that could be acquired through a high school course in chemistry.

Much of the material here can be expanded upon by examining the Wikipedia site found by searching on the name of the various discoverers. These articles not only describe the other discoveries made by these scientists but also describe their personalities and other activities. They make for very interesting reading. They weren’t all boy scouts.

The reader must understand that this is not a total outline of the development of physics but what I deem is the line of discoveries that leads directly to the development of atomic energy. As an example I offer thermodynamics. For this, I could develop a separate trail with some similar names such as Maxwell who besides work on electrodynamics did fundamental work on the kinetic energy of gasses. But in addition to Maxwell, that line would also include a large number of developments in the late 19th century, many with French names associated with them that do not appear here.

350 BC Aristotle defined an element as: Element – one of those bodies into which other bodies can decompose, and that itself is not capable of being divided into other. As time progressed, several materials such as iron and copper were identified as elements. Alchemists tried for centuries to prove that gold was not an element but could be synthized from other elements.

1784 Coulomb develops inverse square law of electrostatic force.

1750 Franklin proposes that electricity does not consist of two currents, positive and negative, but one. Shows by experiment that lightning is electricity.

1812 Faraday constructs first battery, demonstrates generation of electricity by moving conductor in magnetic field and vice versa.
1846 Laming suggests that atoms have a small core surrounded by electric particles with unit charge.

1861 Maxwell combines Faraday’s observations into a set of differential equations, showed existence of electromagnetic waves, predicted that light is EM wave with very great speed.

1864 Mendeleev, based on 28 known elements, shows that they fit into a table of columns and rows based on their chemical properties and successfully predicts existence of other unknown elements and their properties. His first version is a little difficult to understand but his second version, below, will appear familiar.

Modern table of the elements.
1881 **Stoney** invents name for electric particles surrounding atom center, “electrons”.

1887 **Michelson** shows that the speed of light is universal constant not requiring an Aether for its propagation.

1896 **Thompson** based on experiments following two decades of experimental work by Hittorf, Goldstein, Crooks, Schruster, and Lorentz conducted experiments demonstrating the existence of a small particle with negative charge. Fitzgerald pointed out that this was the electric charge proposed by Laming in 1846 (above). Thompson is credited with discovery of the electron.
1896 **Becquerel** accidentally discovers “uranic rays” from a uranium compound.

1897 **Rutherford** discovers uranic rays are a combination of two particles with equal but opposite electric charges which he named “alpha” and “beta”. The processes in which alpha and beta are emitted is termed “decay”, as in “beta decay”:

   Beta, (shortly recognized as the electron) with a negative charge, high penetrating power and lower mass  
   Alpha, with a positive charge, low penetrating power and larger mass.

1898 **Pierre and Marie Curie** discover polonium and radium from uranium ore and invent the term “radioactivity” to describe the process found by Rutherford. Both elements are much more radioactive than uranium. A market develops for radium for its glow-in-the-dark property. Piles of waste uranium collect here and there in Europe.

1900 **Villard** discovers and Rutherford names “gamma rays”, radiation with high penetrating power, later found to be very energetic EM waves with wavelength shorter than x-rays. They were usually found in association with nuclear reactions.

1905 **Einstein** publishes four significant works including special relativity based on the universal value of the speed of light. There were two results changing the basis of physics: simultaneity is not universal and mass has an energy equivalent. \( E = MC^2 \). Very strange results met with skepticism.

1906 **Rutherford** discovers that alpha particles become helium atoms when they slow down. Thus the positive Alpha particles become neutral helium atoms upon capturing two electrons.

1909 **Marsden and Geiger**, two students of Rutherford, discover the nucleus as a very small and positively charged core of the atom by bombarding gold foil with alpha particles. (More vindication of Laming, 1846)
1913 Bohr constructs his first model of the atom describing the emission of light by electrons changing their circular orbits while orbiting a positive nucleus. This model can actually predict wavelength of light based on equations representing his mechanical model of the atom. This was an incredible advancement in physics. This model, was very simple at first, electrons in circular orbits around a positive nucleus. As discoveries accumulated the model was expanded to offer a theoretical explanation for newly observed phenomena.

1913 Soddy and Richards discover the property of “atomic weight” and coin the term “isotope” to describe atoms of the same element that have different mass. In addition, they discover that some elements have radioactive “isotopes”, atoms of an element with different masses. They recognized that the term “Z” which has been used to denote the relative position of elements in the periodic chart actually denotes the number of protons in the atomic nucleus and this is equal to the number of electrons circling the nucleus and in turn determining the atom’s chemical properties. However, at this time the actual structure of the nucleus is not clear. It must contain Z protons but the atomic weight is something like twice this number and this difference has a range of values. It is proposed that in addition to Z protons, the nucleus contains various numbers of proton-electron pairs to establish the atomic weight. The neutron has yet to be discovered.

1915 Harkins points out that the mass of a helium atom is slightly less than that of two hydrogen atoms and suggests that this is an example of $E = MC^2$. The difference in mass was converted to energy in the process of combining the two hydrogen nuclei into one helium nucleus. This is the first suggestion of nuclear energy.

1919 Rutherford, bombarding nitrogen (atomic number 7) with alpha particles (atomic number 2) creates oxygen (atomic number 8) and hydrogen, (atomic number 1). This is the first transformation of one element into another: $7 + 2 = 8 + 1$. This was another important nuclear process leading to atomic energy.

1924 De Broglie publishes thesis predicting wave behavior of electrons. Thus electrons could be thought of as waves as well as particles.
1925 **Heisenberg** publishes first papers on quantum mechanics. Methodology not generally in use today.

1926 **Schrodinger** publishes first of series of papers establishing quantum mechanics based on the wave properties established by De Broglie. The resulting atomic model describes atomic phenomena not resulting from even advanced Bohr model.

1927 **Heisenberg** publishes **Uncertainty Principle**.

1930 **Dirac** cleverly combines relativity and quantum mechanics, predicting existence of positive electrons, later recognized as positrons (antimatter). This was accomplished by adding $E = MC^2$ to the energy term in the Schrodinger equation describing the electron. This resulted in the prediction of new phenomena including the positron, a positive mirror image of the electron that was soon identified as antimatter.

1932 **Chadwick** bombards beryllium with alpha particles producing neutral particles with a mass close to that of a proton. This is a milestone in constructing a model of the nucleus. The new particle was named “neutron”. This discovery results in new model of nucleus as a combination of $Z$ protons and $N$ neutrons varying in number about $Z$. The atoms with various numbers of neutrons were recognized as ‘isotopes’ of the element described by Soddy and Richards, (1913)

1932 **Lawrence** invents the **Cyclotron** a instrument that accererate charged particles to very high energies to bombard atomic targets resulting in nuclear processes for nuclear research.

1932 **Cockcroft and Walton** build a particle accelerator and cause the disintegration of lithium atoms with high-speed protons, confirming the equivalence of mass and energy.

1934 **Joliot and wife, Irene Curie** bombard aluminum with alpha particles to produce phosphorus-30, the first man-made radioactive element. Phosphorus-30 has a nucleus with 15 protons and 15 neutrons. ($Z =$
15, N =15, A =30). Phosphorus has 22 isotopes ranging from A = 24 to A = 46, of these only A = 31 is considered stable.

1934 Szilard realizes chain reaction could lead to bomb, patents it, and assigns patent to the British government. No one pays much attention. A patent not very easy to enforce.

1935 Yukawa proposes the nucleus is held together by short-range nuclear force that overpowers electrostatic repulsion of positive protons. The force is proportional to 1/e raised to the r power, where e= 2.718….. This explains many aspects of the nucleus.

1938 Bethe calculates how nuclear fusion of hydrogen into helium could explain the sun’s energy production. (see Harkins, 1915)

1939 Collectively, Hahn, Meitner, Strassman and Frisch discover induced atomic fission and coin the term “chain reaction” thus letting the nuclear cat out of the bag.

Note. At this time a working model of the atom has developed wherein the atom consists of a positive nucleus surrounded by a quantum mechanical cloud of probability describing the electron structure.

The number of cloud electrons, determining chemical nature of the element, equals the number of protons in the nucleus.

Thus the nucleus consists of Z protons (Z = atomic number) that determine the chemical nature element, plus N neutrons to define the atomic weight, A, of the atom. ( A = Z+N )

However, the number of neutrons in the nucleus can vary somewhat around the number of protons. Although these nuclei are all of the same element, they can have different nuclear properties and are called “isotopes”. Although there are often a few stable isotopes of a given nucleus, there are also unstable isotopes whose nuclei have various “lifetimes” defined is the time by which half the nuclei in a sample will undergo splitting or “fission”.
In a fission process, a nucleus will undergo one of a number of disintegration patterns ranging from an atom splitting into two lighter elements to an isotope changing into a “lighter” isotope of lower atomic weight.

For instance, uranium with an atomic number $N = 92$ can have nuclei with a variety of atomic weights, some of which are radioactive.

Nuclei can have their contents changed by bombardment of accelerated nuclear particles. One of these processes is the creation of radioactive isotopes from stable isotopes.

1939 **Einstein - Szilard** letter to Roosevelt urging nuclear program.
1941 **Heisenberg visits Bohr** in Copenhagen in September. Later neither Heisenberg nor Bohr can agree on contents of their discussion. Bohr came away with the idea that Heisenberg was actively working on atomic bomb and he (Bohr) worked to transmit this knowledge to U.S. and Britain.

1942 **Fermi** constructs first atomic pile where natural Uranium-235 decay neutrons induce additional decays that produce enough neutrons that even more decays take place, a chain reaction. This reactor was capable of “going critical” like a melt-down reactor. However it produced needed numbers of daughter neutrons in chain reaction and helped predict “critical mass”.

Now. Almost all power reactors are capable of going critical.