

Quantum Theory Matters

with thanks to John Clarke Slater (1900–1976),
Per-Olov Löwdin (1916–2000), and the many members of
QTP (Gainesville, FL, USA) and KUUU (Uppsala, Sweden)

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The periodic table of elements

Group→	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
↓Period																			
1	1 H																		2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo	
	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr			

All from H (1) to U (92), *except* Tc (43) and Pm (61) [their isotopes are all radioactive] are found on Earth. All isotopes of all transuranics are radioactive.

Correcting a common misconception

Scientific Theory: *not* a wild @\$\$#% guess, but rather a *mathematical framework* that allows *actual calculation* for known systems, and *prediction* for unknown ones.

- Theories should be based on *minimal sets of principles*, and be free of preconceived dogmas, no matter how widely accepted. [Remember Archimedes, Socrates, Hypatia, Galileo, Tartaglia, Kepler, Copernicus, Lavoisier, . . .]
- Open publication and free discussion of physical theories and experimental results, so that others can *criticize them, improve them, and reproduce them*.
- Know who pays for the work, and judge accordingly! Science *must* have public support. History shows that such support is paid back many times over.
- *If it ain't repeatable, it ain't science!*

Conservation principles of physical science

- energy (Lavoisier, Davy, Faraday)
- linear / angular / spin momentum
- (elementary particle) symmetry
- (elementary particle) parity
- baryon number
- ...

However, there are rare exceptions:

Nobel Prize in Physics for 1957 to Chen Ning Yang and Tsung-Dao (T.D.) Lee *“for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles”*

Impact of quantum theory on other fields

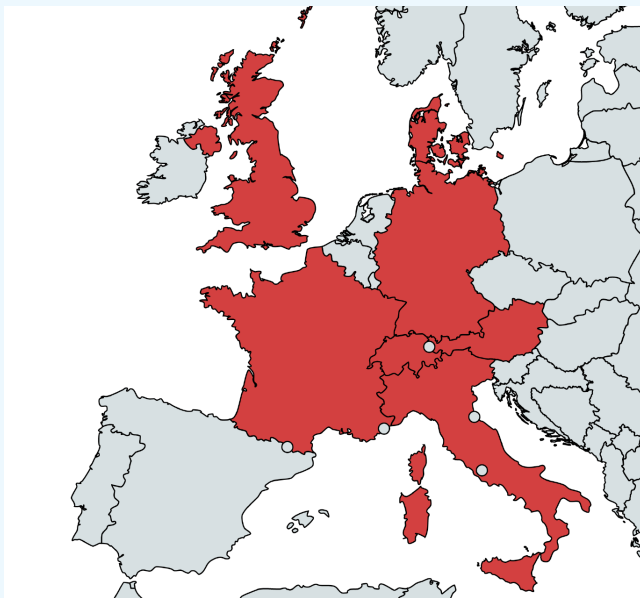
- biology,
- chemistry,
- computer science,
- cosmology,
- genetics,
- geophysics,
- medicine,
- paleontology,
- physics,
- . . . , and even
- Utah history, plus
- billions of consumer products.

Some geography and significant cities

Map of Europe with these 14 cities marked:

- Arosa, Switzerland
- Berlin
- Bern
- Cambridge
- Göteborg (Gothenburg)
- Göttingen
- Helgoland
- København (Copenhagen)
- Leipzig
- München (Munich)
- Paris
- Roma (Rome)
- Wien (Vienna)
- Zürich.

Map of western Europe



Some geography and significant cities

Map of US and Southern Canada with these 12 cities marked:

- Chalk River, ON
- Berkeley, CA
- Chicago
- Hanford, WA
- Los Alamos, NM
- Delta, UT (only beryllium mine in US; beryllium and boron are critical elements in nuclear technology)
- Boron, Kern County, CA (1/2 world source of boron, and CA's largest open pit mine)
- Moab, UT
- New York City (Columbia University)
- Oak City, UT
- Pasadena, CA
- Wendover, UT

Some important big numbers in science

12 g of pure ^{12}C contains *Avogadro's number* of atoms, **$6.022\,141\,29(27) \times 10^{23}$** .

The Universe contains about **10^{80}** elementary particles.

One *light year* is 9 460 730 472 580 800 m (exactly), or roughly **10^{16} m**, or 10^{13} km.

The Earth–Moon distance varies from 356, 000 km to 407, 000 km, or about **1.3 light-seconds**.

The median Earth–Sun distance is nearly the same as *one astronomical unit (AU)*, defined to be 149 597 870 700 m (exactly), or about 150 million km, or 150 Gm, or **8.3 light-minutes**.

1 light-year = 63 241 AU.

Solar system diameter is about **60 AU**.

Forces in nature found up to 1900

- gravity (known back to Nicolaus Copernicus (1473–1543), Tycho Brahe (1546–1601), Galileo Galilei (1564–1642), Johannes Kepler (1571–1630), and Isaac Newton (1642–1726))
- electricity and magnetism (quantitatively understood by Ole Rømer (1644–1710), Hans-Christian Ørsted (1777–1851), Michael Faraday (1791–1867), James Clerk Maxwell (1831–1879))

Notice that they all come *after* the discovery of the Western Hemisphere by Christopher Columbus (1451–1506).

Our current mathematical descriptions are due to Newton and Clerk Maxwell.

E&M *much* stronger than gravity: for two electrons, by about 4×10^{42} . Both fall off as $1/r^2$ (like inverse area of sphere).

However Newton's gravity force is instantaneous, while Clerk Maxwell's E&M force propagates at the speed of light (about 300,000 km/sec).

Albert Einstein in Bern, Switzerland, reconciles them in 1905–1910.

Forces in nature found after 1900

Nuclear forces that hold a cluster of like-charged particles together:

- weak nuclear force,
- strong nuclear force (10^{13} times larger than weak force).

Neither has much significance for day-to-day human experience, but we, and the Universe, are here because of them!

Both are *extremely* short range: about 1 to 2.5 fm (10^{-15} m); for comparison, atomic nucleus is about 1.75 fm (H) to 15 fm (U), and atomic radius is about 23 000 fm (H) to 145 000 fm (U).

Nobel Prize in Physics for 1979 to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *“for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current”*

The rest of this talk

We now look at some high points in science in a timeline from about 1890 to date.

1891–1897

Anglo-Irish physicist George Johnstone Stoney (1826-1911) names the fundamental unit of electricity an *electron* in 1891.

J. J. (Joseph John) Thomson (1856–1940) and his Cambridge team find it experimentally in 1897.

Nobel Prize in Physics for 1906 to Joseph John Thomson *“in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases”*

Nobel Prize in Physics for 1923 to Robert Andrews Millikan *“for his work on the elementary charge of electricity and on the photoelectric effect”*

Wilhelm Conrad Röntgen (1845–1923) discovers *X-rays* on 8-Nov-1895 in Würzburg, Germany.

Nobel Prize in Physics for 1901 (first!) to Wilhelm Conrad Röntgen *“in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him”*

1896

Henri Becquerel (1852–1908), Marie Skłodowska-Curie (1867–1934), and Pierre Curie (1859–1906) discover radioactivity in Paris, France.

Nobel Prize in Physics for 1903 to Antoine Henri Becquerel, Pierre Curie and Marie Curie, née Skłodowska *“in recognition of the extraordinary services he [HB] has rendered by his discovery of spontaneous radioactivity and in recognition of the extraordinary services they [PC & MC] have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel”*

Radioactivity depends on particular chemical element and isotope (then unknown).

Half life: time after which half of the reactants have become products. Thus, in ten generations: 10^{-3} left; twenty: 10^{-6} left, thirty: 10^{-9} left. Decay of certain isotopes allows accurate dating in medicine, anthropology, and paleontology (the late Frank Brown, and Thure Ceurling, are famous Utah experts in that area).

1900

To explain black-body radiation spectrum, Max Planck (1858–1947) in Berlin, Germany, introduces *quantum*, with energy of light proportional to frequency: $E = h\nu$, where *Planck's constant* $h = 6.626176(36) \times 10^{-27}$ erg sec.

A. D. Stone: ***h* is the signature of all things quantum.**

An *erg* is **tiny**: 41 868 000 ergs = 1 cal raises temperature of 1 g water by 1°C. [etymology: Greek *εργον* is English *work*]

1 *food calorie* = 1000 cal $\approx 4 \times 10^{10}$ ergs.

Planck accurately predicted *Avogadro's number*, the *mass of the hydrogen atom*, and the *charge on the proton*.

Nobel Prize in Physics for 1918 to Max Karl Ernst Ludwig Planck “*in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta*”

In 1948, the *Kaiser Wilhelm Society* is renamed the *Max Planck Society*, and ditto its Institutes (akin to US National Laboratories).

Einstein in Bern

Pictures from 20-Aug-2011:



1905: Einstein's Annus Mirabilis (Miracle Year)

- 18-Mar-1905: photoelectric effect.
- 11-May-1905: Brownian motion (giving first experimental proof of existence of atoms, and putting probability into physics, which he later tried very hard to avoid!).
- 30-Jun-1905: *Special Relativity* and *Principle of Equivalence*: light has constant velocity in all inertial frames, leading to *Lorentz length contraction*, *time dilation*, prediction of *perihelion advance of Mercury* (wrong by $2\times$), and *bending of light in gravitational field* [simple mathematics, and no literature references!]
- 19-Aug-1905: new determination of molecular dimensions (Ph.D. thesis).
- 27-Sep-1905: $E = mc^2$ (3 pages!)
The velocity of light is $c = 299\,792\,460$ m/sec *exactly*, because we now define the standard meter in terms of c , a symbol introduced in 1894 by Paul Drude (1864–1906), from Latin *celeris* (speed).

1905 (continued)

Nobel Prize in Physics for 1921 (awarded in 1922) to Albert Einstein *“for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect”*

In December 1922, Einstein was lecturing in Japan, and there was a diplomatic flap in Stockholm when both Swiss and German Ambassadors to Sweden showed up to accept the Prize on behalf of Einstein. Einstein's second 1905 paper on Brownian motion and theoretical prediction of atoms was found to be in close agreement with experiments by Jean Perrin.

Nobel Prize in Physics for 1926 to Jean Baptiste Perrin *“for his work on the discontinuous structure of matter, and especially for his discovery of sedimentation equilibrium”*

Nobel Prize in Chemistry for 1911 to Marie Curie, née Skłodowska *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*

Marie is thus *first person to win two Nobel Prizes!* She almost did not, because of a semi-secret love affair with unhappily-married Paul Langevin, a former student of Pierre Curie. [Pierre had been killed by a horse carriage in 1906.]

Heike Kamerlingh Onnes in Leiden, The Netherlands, discovers *superconductivity*. Its theoretical explanation took another 46 years (1957).

1913

Niels Bohr (1885–1962) (Cambridge, Manchester, and Copenhagen) publishes three ground-breaking papers that are the peak of '*old quantum mechanics*', all under the main title *On the Constitution of Atoms and Molecules*, and subtitled

- *The binding of electrons by positive nuclei* (July 1913);
- *Systems containing only a single nucleus* (September 1913);
- *Systems containing several nuclei* (October 1913).

They are inspired by Planck's *quantum*, and provide the first successful description, and high-accuracy *prediction*, of the spectra of one-electron systems, with electrons moving in quantized fixed *orbits* about the nucleus.

Nobel Prize in Physics for 1922 to Niels Henrik David Bohr
"for his services in the investigation of the structure of atoms and of the radiation emanating from them"

1914–1918: World War I

On 28-Jul-1914, Germany and Austria-Hungary declare war on rest of Europe, following assassination of Archduke Franz Ferdinand on 28-June-1914 in Sarajevo.

Almost none of the four-and-half-year long war is fought on German territory: Poland, Belgium, France, and Russia have most of the battles. The USA does not join until 6-Apr-1917.

Russian Revolution in October/November 1917 kills Czar, creates USSR. The war ends on Armistice Day, 11am 11-Nov-1918, and the next year-and-a-half of peace settlements that are negotiated personally in Paris by US President Woodrow Wilson, British Prime Minister David Lloyd George, French Prime Minister Georges Clemenceau, and Italian Prime Minister Vittorio Emanuele Orlando, cripple Germany, and lay the grounds for the next terrible war in 1939. [The US post-1945 Marshall Plan did *much* better!]

Mention Ho Chi Minh in Paris and Boston.

Inspired by Frederick Soddy's popular writings on radioactivity, Herbert George (H. G.) Wells (1866–1946) publishes the book *The World Set Free* about an invention that speeds up radioactive decay of radium, allowing production of what he called *atomic bombs*, the first known use of that phrase in print.

[In 1897–1898, Wells had written the book *The War of the Worlds*, about the hostile invasion of Earth by Martians. A 1938 radio dramatization of that book by Orson Welles caused widespread panic in the US.]

1915

Albert Einstein's work in (peaceful) Berlin from 1905 to 1915 leads finally to his papers on the field equations of *General Relativity* that extend Special Relativity to handle acceleration.

The equations are ten coupled differential equations in curved space, using mathematics that is unfamiliar, then and now, to most scientists outside small areas of pure mathematics.

The field equations reduce to Newton's three Laws in the weak field ('small' mass) limit.

Newton's Laws work fine for satellites and rockets (so far, their velocities are $\ll c$, so Special Relativity and General Relativity are not needed).

Matter tells space how to curve, and space tells matter how to move.

John A. Wheeler (1990)

1915 (continued)

Einstein (like most physicists and astronomers) believes in 1915 that the Universe is static. Einstein's field equation solutions are found to be unstable for a static Universe, so Einstein adds a fudge term, which he calls the 'cosmological constant' (Λ). He later retracts it, calling it his *Greatest Blunder* (see events of late 1924).

On 22-Dec-1915, Karl Schwarzschild (1873–1916) reports to Einstein an exact solution of the General Relativity field equations.

1916

Karl Schwarzschild publishes paper on a critical radius, now called the *Schwarzschild radius*, at which a massive body suffers a gravitational collapse and becomes a '*black hole*', a term usually credited to John Wheeler in 1967.

Schwarzschild dies on 11-May-1916 on Russian front, likely from poison gas exposure.

Nobel Prize in Chemistry for 1918 to Fritz Haber "*for the synthesis of ammonia from its elements*"

Ammonium nitrate fertilizers from Haber's process save millions of human lives from starvation, but can be used for explosives too.

Fritz Haber (1868–1934) also develops poison gas in World War I, and is a close friend of Albert Einstein.

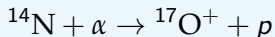
1914–1924

Efforts by many in Denmark, England, and Germany on why Bohr's atomic model does not work for two or more electrons.

Niels Bohr and Wolfgang Pauli (1900–1958) develop the *Aufbauprinzip* (building-up principle, or *Aufbau principle*) to explain the periodic table of elements.

Niels Bohr develops the *Correspondence Principle* relating classical and quantum mechanical behavior, and guiding the future philosophical development of quantum mechanics.

Ernest Rutherford in Manchester, UK, demonstrates the first-ever *artificially-induced radioactivity* by bombardment of nitrogen atoms with alpha particles (more in slides for 1920 and 1928):



At the time, the proton was not yet known, or named.

On 9-Nov-1919, the New York Times reports that solar-eclipse observations confirm Einstein's General Theory of Relativity:

Lights All Askew in the Heavens: Men of Science More or Less Agog over Results of Eclipse Observations. Einstein Theory Triumphs. Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry. A Book for 12 Wise Men. No More in All the World Could Comprehend it, said Einstein When His Daring Publishers Accepted It.

Nobel Prize in Chemistry for 1908 to Ernest Rutherford “for his investigations into the disintegration of the elements, and the chemistry of radioactive substances”

New Zealander Rutherford (1861–1937) did his Ph.D. under J. J. Thomson at Cambridge (1895–1898).

Rutherford and Frederick Soddy (1877–1956) work together at McGill University in Montréal (1898–1907), and Rutherford then moves to Manchester, UK. [Eyring anecdote.]

Rutherford names the second elementary particle (after the 1891 *electron*) the *proton*, and finds it experimentally in atomic collisions of nitrogen.

His Bakerian Lecture on 1-Jul-1920 predicts a third elementary particle, the *neutron* (confirmed in 1932). That lecture does not use the term *neutron*; he first published that word five months later.

Rutherford becomes *Sir Ernest* in 1914, and *Baron Rutherford of Nelson* in 1925.

Arthur H. Compton (1892–1962) at Washington University in St. Louis, MO, publishes experimental results that prove that electromagnetic radiation behaves as *particles of zero mass*, as Einstein predicted in 1905. Thus, light exhibits *wave–particle duality*, and we can speak of particles of light, called *photons*, a name introduced in 1926 by Frithiof Wolfers and Gilbert N. Lewis.

Nobel Prize in Physics for 1927 to Arthur Holly Compton
“for his discovery of the effect named after him”

The controversy over whether light consists of particles or waves goes back to the late 1600s, with Isaac Newton favoring particles, and René Descartes, Robert Hooke, and Christiaan Huygens advocating waves.

1924

Enrico Fermi (1901–1954) in Rome publishes December 1924 paper on *Fermi–Dirac statistics*, and almost discovers Pauli's *Exclusion Principle* (1925).

Fermi is the most-cited pioneer physicist: $1.2\times$ Einstein, and his name is attached to many important concepts in physics, to about half the particles in the Universe (fermions), and to element 100 (fermium).

Wolfgang Pauli (1900–1958) in Zürich predicts electron spin and nuclear spin.

Electron spin is proposed independently, and confirmed experimentally, by George Uhlenbeck (1900–1988) and Samuel Goudsmit (1902–1978) in November 1925.

Nuclear spin is confirmed experimentally by S. Goudsmit and E. Back in 1927, in papers received 8-Apr-1927 and 1-Dec-1927

No Nobel Prize to U & G, however!

1924 (continued)

Einstein translates to German two papers from Satyendra Nath Bose (1894–1974) in Dacca, East Bengal, India, and publishes them. The first is the origin of *Bose–Einstein statistics*. Bose's name is now attached to the other half of the particles in the Universe: *bosons*, a name suggested by Paul Dirac.

Nobel Prize in Physics for 2001 to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *“for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates”*

Prince, later Duke, Louis de Broglie (1892–1987) postulates *wave–particle duality* in his 1924 doctoral thesis.

Nobel Prize in Physics for 1929 to Prince Louis-Victor Pierre Raymond de Broglie *“for his discovery of the wave nature of electrons”*

1924–1925

23-Dec-1924 and 2-Jan-1925: Astronomer Edwin Hubble (1889–1954) reports that Universe is *expanding* in New York Times story and American Astronomical Society meeting; thus, Einstein's fudge term, the cosmological constant Λ , is *not* needed!

[No Nobel Prize, because astronomy is not covered by Nobel's will; that rule of the Nobel Committee is changed after Hubble's death.]

1929: Hubble publishes Redshift distance law.

Georges Lemaître (1894–1966) in Louvain, Belgium, theoretically predicts expanding Universe, derives Hubble's Law, red shift, and estimates Hubble's constant, but publishes in little-read journal.

1925–1926

Werner Heisenberg (1901–1976) publishes three papers on matrix mechanics, the beginning of the *'new quantum theory'*:

- 1st received 29-Jul-1925 (after visions on Helgoland recovering from severe allergies);
- 2nd received 27-Sep-1925;
- 3rd received 16-Nov-1925.

Nobel Prize in Physics for 1932 to Werner Karl Heisenberg
"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen"

Albert Einstein says: "Heisenberg has laid a big quantum egg. In Göttingen they believe in it (I don't). . . . A veritable witches' multiplication table . . . exceedingly clever and because of its great complexity, safe against refutation."

In February 1925, Wolfgang Pauli publishes his *Exclusion Principle* that governs build-up of atoms: *no two fermions (particles with half-integral spin, such as electrons and protons) can occupy the same quantum state at the same time.*

Nobel Prize in Physics for 1945 to Wolfgang Pauli *“for the discovery of the Exclusion Principle, also called the Pauli Principle”*

1926

Austrian Erwin Schrödinger (1887–1961) at Universität Zürich, while on a ski holiday in Arosa, Switzerland, in December 1925 discovers *wave mechanics*:

- Quantization as an eigenvalue problem (4 papers): 1st paper received 27-Jan-1926, 4th on 21-Jun-1926 (140 pages total).
- Wave-mechanics equation *much* easier for traditional physicists to understand than matrix mechanics, and dominates the field ever since.
- 18-Mar-1926: Schrödinger demonstrates equivalence of matrix mechanics and wave mechanics.

Nobel Prize in Physics for 1933 to Erwin Schrödinger and Paul Adrien Maurice Dirac *“for the discovery of new productive forms of atomic theory”*

In December 1928, Max Born (1882–1970) in Göttingen interprets Schrödinger wavefunction's 'square' $|\Psi\Psi^*|$ as a *probability*, causing his close friend Albert Einstein much grief and anguish.

Nobel Prize in Physics for 1954 to Max Born and Walther Bothe *“for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction [MB] and for the coincidence method and his discoveries made therewith [WB]”*

Werner Heisenberg's paper on *Unschärferelation* or *Ungenauigkeit* (in English, the **Uncertainty Principle**) received 23-Mar-1927:

$$\Delta x \Delta p \geq h / (2\pi) \quad \text{position–momentum form}$$

$$\Delta E \Delta t \geq h / (2\pi) \quad \text{energy–time form}$$

Drastically different from expectations of Newton mechanics!
 However, h is tiny, so we do not see its limits in human-sized objects, and certainly not on cosmological scales.

1928

George Gamow (1904–1968) is first to apply quantum mechanics to nucleus, and that year, discusses nuclear disintegration, and proposes liquid-drop model of nuclear structure. Also describes (1) quantum nature of alpha decay, (2) theory of the hot initial state of the Universe, (3) existence of cosmic microwave background radiation, (4) clue to the genetic code in biology. Gamow never got the Nobel Prize, but he often got there first in research.

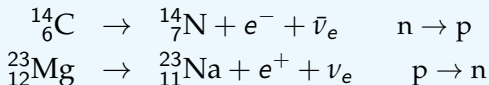
Oppenheimer, and Gamow, and Gurney & Condon, independently discover phenomenon of 'quantum tunneling', which explains alpha decay (atom \rightarrow new-atom + He⁺⁺), and is critical for modern electronics design.

Oppenheimer leads by 5 months with paper received 28-Mar-1928.

Paul Dirac (1902–1984) at Cambridge extends Schrödinger's wave equation with Einstein's Relativity to produce *relativistic quantum mechanics*, albeit only for single particle (papers: 2-Jan-1928, 2-Feb-1928). His equations predict a *positive electron*, later called a *positron*.

Dirac book *Principles of Quantum Mechanics* introduces 'quantum of action' notation: $\hbar = h/(2\pi)$.

4-Dec-1930: Pauli writes letter "*Dear Radioactive Ladies and Gentlemen*", to Tübingen conference participants, proposing a small neutral particle, which he calls a *neutron*, (later renamed *neutrino* by Edoardo Amaldi), to carry away energy in beta decay ($p \leftrightarrow n$, so atom \rightarrow new-atom + (electron or positron)),



and preserve the *Principle of Conservation of Energy*.

Neutrino is confirmed in 1953 by Frederick Reines and Clyde Cowan.

Nobel Prize in Physics for 1995 to Martin L. Perl and Frederick Reines "*for the discovery of the tau lepton (MLP) and for the detection of the neutrino (FR)*"

1931

5-Dec-1931: Harold Urey (1893–1981) reports discovery of heavy isotope of deuterium, $D = {}^2_1\text{H}$. D is stable & about 0.02% of all hydrogen on Earth.

Nobel Prize in Chemistry for 1934 to Harold Clayton Urey
“for his discovery of heavy hydrogen”

Wikipedia: “Tritium [$T = {}^3_1\text{H}$] was first produced in 1934 from deuterium, . . . , by Ernest Rutherford, working with Mark Oliphant and Paul Harteck. Rutherford was unable to isolate the tritium, a job that was left to Luis Alvarez and Robert Cornog, who correctly deduced that the substance was radioactive [half life \approx 12 years]. Willard F. Libby discovered that tritium could be used for dating water, and therefore wine.”

Nobel Prize in Chemistry for 1960 to Willard Frank Libby *“for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science”*

[Leona Woods Marshall Libby anecdote and book *The Uranium People* (1979).]

1932 (Miracle year in nuclear physics)

Three huge developments in nuclear physics:

- James Chadwick (1891–1974) at Cambridge discovers neutron; (possible existence: 27-Feb-1932; confirmed existence: 10-May-1932).
- Frédéric Joliot-Curie (1900–1958) and Irène Curie (1897–1956) in Paris produce first artificially induced nuclear transmutations by charged-particle bombardment.
- Carl Anderson (1905–1991) at Caltech, Pasadena, CA, discovers positron.

Free electron and proton are stable indefinitely (experimentally, for more than 10^{26} years, and 10^{29} years, respectively; the Universe is about 10^{10} years old).

Neutrons are stable inside the nucleus, but a free neutron decays with a half life of about 15 minutes to a proton, an electron, and an electron antineutrino: $n \rightarrow p + e + \bar{\nu}_e$.

1932 (continued)

Nobel Prize in Chemistry for 1935 to Frédéric Joliot and Irène Joliot-Curie *“in recognition of their synthesis of new radioactive elements”*

Thus, 5 members of the Curie family shared 3 Nobel Prizes!

Nobel Prize in Physics for 1935 to James Chadwick *“or the discovery of the neutron”*

Nobel Prize in Physics for 1936 to Victor Franz Hess and Carl David Anderson *“for his discovery of cosmic radiation (VHF) and for his discovery of the positron (CDA)”*

U of Utah Physics & Astronomy *Cosmic Ray Project* is a world leader in that area.

1933

30-Jan-1933 Adolf Hitler becomes Chancellor of Germany and proclaims Third Reich will last a thousand years.

Persecution of Jews and other ethnic minorities increases in Germany, and many such flee (e.g., Einstein to IAS, Princeton, NJ).

12-Sep-1933: New York Herald-Tribune reports quotes Ernest Rutherford: *'The energy produced by the breaking down of atoms is a very poor kind of thing, Any one who expects a source of power from the transformations of these atoms is **talking moonshine.**'*

Also on 12-Sep-1933: After reading a London Times article that quoted Rutherford's *'talking moonshine'* comment, Leo Szilard (1898–1964) becomes the first to conceive of the possibility of a *neutron chain reaction*. In March 1934, Szilard files a British patent application on the neutron chain reaction, the first in that new area of physics.

Discuss chain reaction.

1934

Enrico Fermi and his group in Rome begin experiments to bombard all available elements with neutrons, discovering more than 60 new radioactive nuclei.

Nobel Prize in Physics for 1938 to Enrico Fermi *“for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons”*

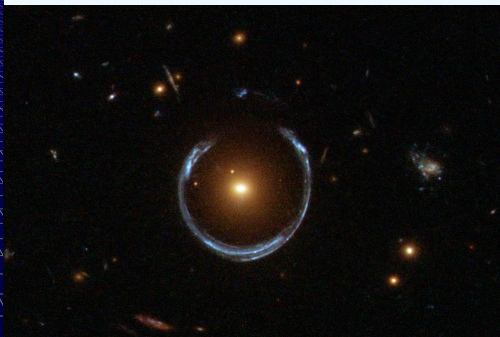
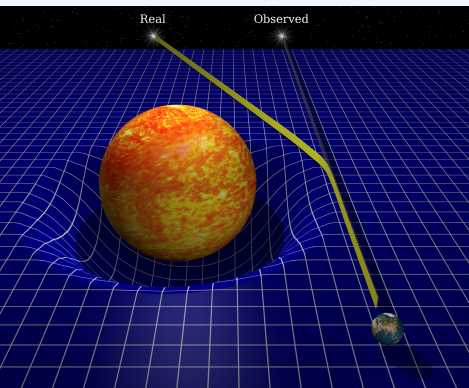
Fermi and his family leave Nobel celebration in Stockholm in December 1938 for the UK and then the US, never to return to Italy.

25-Mar-1935: Albert Einstein, Boris Podolsky, Nathan Rosen (EPR) submit paper *Can quantum mechanical description of physical reality be considered complete?* to *Physical Review* journal.

The EPR paper is one of most cited in all of physics, and still the most downloaded from APS archives.

1936

Einstein predicts gravitational lensing effect; confirmed experimentally in 1979.



On 13-July-1938, nuclear physicist Lise Meitner escapes from Berlin, Germany via The Netherlands to Stockholm, Sweden, where she is grudgingly, and barely, supported by Manne Siegbahn.

Nobel Prize in Physics for 1924 to Karl Manne Georg Siegbahn *“for his discoveries and research in the field of X-ray spectroscopy”*

Nobel Prize in Physics for 1981 to Nicolaas Bloembergen, Arthur Leonard Schawlow, and Kai M. Siegbahn *“for their contribution to the development of laser spectroscopy (NB & ALS) and for his contribution to the development of high-resolution electron spectroscopy (KMS)”*

Manne's (1886–1978) son is Kai (1918–2007), and three of Kai's sons are also physicists.

1938 (continued)

Hans Bethe (1906–2005) in two papers received 7-Sep-1938 and 15-Dec-1938 publishes quantitative description of energy production in stars, leading to models of stellar evolution: white/brown/black dwarfs, red giants, neutron stars, quasars, pulsars, and black holes, and ultimately, answering the deep question: *Where do the 90 other chemical elements come from, if stars contain mostly H and He?*

Nobel Prize in Physics for 1967 to Hans Albrecht Bethe “for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars”

1938 (continued)

Otto Hahn (1879–1968) and Fritz Strassmann (1902–1980) in Berlin: two papers received 22-Dec-1938 on unexpected low-mass products from neutron bombardment of uranium. On 24-Dec-1938, in Göteborg, Sweden, Lise Meitner (1878–1968) and her nephew Otto Robert Frisch (1904–1979) explain this as *nuclear fission*, using George Gamow's liquid-drop model (often miscredited to Niels Bohr). Frisch carries news back to Bohr's group in Copenhagen, Denmark.

Nobel Prize in Chemistry for 1944 (delayed to 1945) to Otto Hahn "*for his discovery of the fission of heavy nuclei*"

Sadly, neither Strassmann nor Meitner share in the Prize; both deserve it too. Despite decades of close collaboration between Hahn and Meitner, after 1945, Hahn shamefully discredits her critical contributions: see Ruth Lewin Sime's papers and books.

1939: Physics heats up!

2-Jan-1939: Enrico Fermi arrives at Columbia University in NYC.

16-Jan-1939: Niels Bohr and Leon Rosenfeld arrive in NYC; fission news is supposed to be suppressed until H&S and M&F papers are published, but Rosenfeld is not told that, so he spills the beans, and within two weeks, uranium fission is reproduced at a few US labs. First public story in New York Times on 29-Jan-1939.

Early 1939: Enrico Fermi and his Columbia group, and another group at the University of Minnesota, show that the rare uranium-235 isotope is the fissile component of natural uranium, which is mostly composed of uranium-238 (99.3% U-238 and 0.7% U-235).

April 1939: Nazi Germany starts *Uranverein* (Uranium club).

28-Jun-1939: Niels Bohr and John Wheeler (1911–2008) publish quantitative liquid drop model of nuclear fission and predict that U-235 and Pu-239 are the fissile isotopes.

Summer 1939: Werner Heisenberg lectures in Ann Arbor, MI, but refuses urging by friends and colleagues to remain in the US.

1939 (continued)

2-Aug-1939: Albert Einstein signs letter, written by Leo Szilard with Eugene Wigner (1902–1995) and Edward Teller (1908–2003), to US President, warning of danger of German nuclear bomb project (Franklin Roosevelt does not see letter until 11-Oct-1939).

1-Sep-1939: World War II begins when Nazi Germany invades Poland.

1941

September 1941: Enrico Fermi suggests to Edward Teller that a fission bomb might be used to ignite deuterium sufficiently to produce a fusion weapon.

6-Dec-1941: US President Franklin Roosevelt authorizes nuclear research project.

7-Dec-1941: Japan attacks Pearl Harbor, and US enters World War II.

1942

September 1942: General Leslie Groves initiates Manhattan Project to construct an atomic bomb: ultimately, 140,000 people work on that *top-secret* project in Oak Ridge, TN, Hanford, WA, and Los Alamos, NM.

Mention Oak City, UT, 14 miles east of Delta.

Enrico Fermi group of 43 under the University of Chicago football stadium demonstrate first working nuclear pile on 2-Dec-1942. The pile is then moved from Stagg Field to Argonne, IL (later named Argonne National Laboratory) and later reproduced in large scale in Hanford, WA for production of fissile isotopes of synthetic element 94, plutonium.

First American use of nuclear power for commercial electrical use on 17-Jul-1955 in Arco, ID.

Nuclear fission power now provides 13% of world-wide energy supply, and for France, over 70%. It produces **zero** CO₂ emissions, but has serious radioactive-waste disposal problem.

Despite 70 years of effort, *controlled nuclear fusion* remains elusive, yet it may be mankind's only hope of long-term survival!

1945

12-Apr-1945: Franklin Roosevelt dies in Warm Springs, GA. VP Harry Truman becomes President that day, and is shortly thereafter informed of Manhattan Project, of which he knew *nothing* until then.

16-Jul-1945: First atomic bomb test at Trinity, NM.

6-Aug-1945: U-235 Little Boy bomb dropped on Hiroshima, Japan. Bomber crews trained at Wendover, UT.

9-Aug-1945: Pu-239 Fat Man bomb dropped on Nagasaki, Japan.

2-Sep-1945: Japan surrenders unconditionally, and WW II ends.

World Wars I and II had huge loss of life on all sides, but technology won World War II: (1) cryptography and cryptanalysis in UK and US (notably, Alan Turing, Bletchley Park), (2) radar in UK and US, (3) atomic weapons (US).

Wartime computations needed for (1) and (3), and for artillery tables, spurred development of electronic computers, but British *Official Secrets Act* hid much of UK work for 50+ years.

Sam Goudsmit leads *Alsos* team to capture German atomic scientists, who are interned first in Belgium, and then at *Farm Hall* near Cambridge, UK. Physicist Luis Alvarez (1911–1988) is scientist on board Hiroshima plane. Son Walter and father Luis in 1977–1980 find iridium isotope in ash layer in Gubbio, Italy (**home of TV mystery series 'Dom Matteo' on local KUEN channel 9.2**). That leads to discovery in 1978 of Chicxulub Crater off Yucatan in Gulf of Mexico; the meteor impact wipes out the dinosaurs, and most life on Earth, in the Cretaceous–Tertiary (K–T) extinction event about 66 Mya.

Nobel Prize in Physics for 1968 to Luis Walter Alvarez *“for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis”*

1945–1991

Iron Curtain and the Cold War between Western Allies and the USSR and its 'allies', notably, the People's Republic of China.

Hot wars, including Korean War (1950–1953) and Vietnam War (1955–1975), numerous minor wars and coups in Latin America, Asia, and Africa, and Hungarian uprising in 1956.

Significant threat of nuclear war and *nuclear winter*.

Alpha-beta-gamma ($\alpha\beta\gamma$: Alfer, 'Bethe', Gamow) paper on origin of chemical elements: details later shown to be wrong, but Penzias (1979) and Turner (2008) describe its influence.

Gamow adds Bethe as a joke, but Bethe does not mind, and the paper gets remembered and cited!

Late 1940s and early 1950s

Bethe/Feynman/Tomonaga/Schwinger: quantum electrodynamics (QED).
Richard P. Feynman (1918–1988), Julian Schwinger (1918–1994), Sin-Itiro Tomonaga (1906–1979).

Nobel Prize in Physics for 1965 to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *“for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles”*

Freeman Dyson (1923–) in 1948–1949 combines F/S/T work into consistent theory.

Some predictions of QED now agree with experiment to **ten decimal digits**, surpassing any previous theories in the history of humankind.

1949

28-Mar-1949: British astrophysicist Fred Hoyle (1915–2001), a supporter of a static Universe model, coins the term *Big Bang* for the projection backward-in-time of Hubble's expanding Universe.

29-Aug-1949: USSR explodes its first atomic bomb.

Fermi Paradox: Where are they? [extraterrestrials]

Lunch-time question by Enrico Fermi to Emil Konopinski (1911–1990), Edward Teller, and Herbert York (1921–2009) later spawns SETI (*Search for Extraterrestrial Intelligence*) project.

1950–1953

During the Manhattan Project work at Los Alamos (1943–1945), Edward Teller vigorously campaigns for work on *'the super'*, a fusion bomb whose ultimate size is unlimited, unlike that of an atomic fission bomb.

1-Feb-1950: President Harry Truman issues Executive Order: *"I have directed the Atomic Energy Commission to continue its work in all forms of atomic weapons, including the so-called super bomb."*

1-Nov-1952: first hydrogen bomb test by US (main designers: Edward Teller, Stan Ulam (1909–1984), John von Neumann (1903–1957)).

12-Aug-1953: first hydrogen bomb test by USSR.

In London, UK, Peter Higgs (1929–) and six others predict a new super-fundamental particle.

Higgs boson is found at CERN in the Large Hadron Collider on 4-Jul-2012.

Nobel Prize in Physics for 2013 to Peter Higgs and François Englert *“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”*

1964 (continued)

Nobel Prize in Physics for 1964 to Charles Hard Townes, Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov *“for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle”*

Lasers used in CDs and DVDs, much experimental equipment, in long-distance communication in optical fibers, and for accurate interplanetary distance measurements.

Tom Stockham (1933–2004) founds Soundstream in 1975, with first commercial digital recordings.

“In 1974 he [Stockham] investigated President Richard Nixon’s White House tapes. It was he who discovered that the 18 minutes of erasures were not accidental, as Nixon’s secretary Rosemary Woods claimed. Stockham was able to discern several distinct erasures and even determined the order of erasure.”

Nixon resigned 9-Aug-1974, preceded by VP Spiro Agnew 10-Oct-1973.

Nobel Prize in Physics for 1986 to Ernst Ruska, Gerd Binnig, and Heinrich Rohrer *“for his fundamental work in electron optics, and for the design of the first electron microscope (ER) and for their design of the scanning tunneling microscope (GB & HR)”*

Scanning tunneling microscope (STM) (1981) and its successor, the atomic force microscope (AFM) (1986, with Calvin Quate (1923–), from Baker, NV, (5 miles west of Utah border and Great Basin National Park) and Professor Emeritus at Stanford University, and Christoph Gerber (Basel)), make possible imaging of single atoms.

Nobel Prize in Physics for 2011 to Saul Perlmutter, Brian P. Schmidt, and Adam G. Riess *“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”*

Possible explanations of acceleration: dark matter (Jan Oort, 1932, and Fritz Zwicky, 1933) and dark energy (US and Australia groups, 1998).
The mystery of the Universe continues!

Wrap up: Spinoffs of physical science

- DNA and modern molecular biology, genetics, and pharmaceuticals.
- Global-Positioning System (GPS): needs corrections from both Special and General Relativity.
- Electronics and transistor, replacing vacuum tubes ('valves' in the UK).

Nobel Prize in Physics for 1956 to William Bradford Shockley, John Bardeen and Walter Houser Brattain *“for their researches on semiconductors and their discovery of the transistor effect”*

- 2nd (and later) generation computers, including CPUs, storage devices, and local networks.
- ARPAnet (started with SRI, UC/Berkeley, UC/Los Angeles, **University of Utah**, and UC/Santa Barbara), and the Internet.

Wrap up: Spinoffs of physical science

- Explanation of superconductivity.

Nobel Prize in Physics for 1972 to John Bardeen, Leon Neil Cooper and John Robert Schrieffer *“for their jointly developed theory of superconductivity, usually called the BCS-theory”*

Hope for high-temperature superconductivity for lossless long-distance energy transmission.

- Mobile phones, tablets, laptops, and computer sensors.
- Prediction, and manufacture, of post-uranic elements (up to 118 now).
- Quantum cryptography and quantum computers.
- Lasers and masers and accurate communication.

Wrap up: Spinoffs of physical science (continued)

- LCD/LED displays for TVs, computers, mobile devices.

Nobel Prize in Physics for 2014 to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *“for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources”*

- Accurate timing and accurate standards of length.
- Medical imaging (X-ray, NMR, EPR, ...).

Nobel Prize in Chemistry for 2014 to Eric Betzig, Stefan W. Hell and William E. Moerner *“for the development of super-resolved fluorescence microscopy”*

- Medical use of isotope tracers.
- Probably: space program, satellites, astronauts on the moon, ...

Literature resources

Autobiographies, biographies, books, original papers, and much more, are recorded in bibliography archives at

<http://www.math.utah.edu/pub/tex/bib>

<http://www.math.utah.edu/pub/bibnet>

The start of each tells how to mirror the collections: please do!

Nobel Prize citations used in these slides are taken verbatim from

http://www.nobelprize.org/nobel_prizes/chemistry

http://www.nobelprize.org/nobel_prizes/physics

Final words from the masters

If we are going to stick to those damned quantum jumps, then I regret that I ever had anything to do with the quantum theory!

Erwin Schrödinger (1926)

If anybody says he can think about quantum theory without getting giddy, it merely shows that he hasn't understood the first thing about it!

Niels Bohr (1927)

I have thought a hundred times as much about the quantum problems as I have about general relativity theory.

Albert Einstein (1940s)

All the fifty years of conscious brooding have brought me no closer to the answer to the question: "what are light quanta?" Of course today every rascal thinks he knows the answer, but he is deluding himself.

Albert Einstein (1951)