Matter and Light: Louis de Broglie and our current understanding of physics

for the special symposium

Louis de Broglie: 100 years of wave-particle duality
at the SPS Annual Meeting 2024

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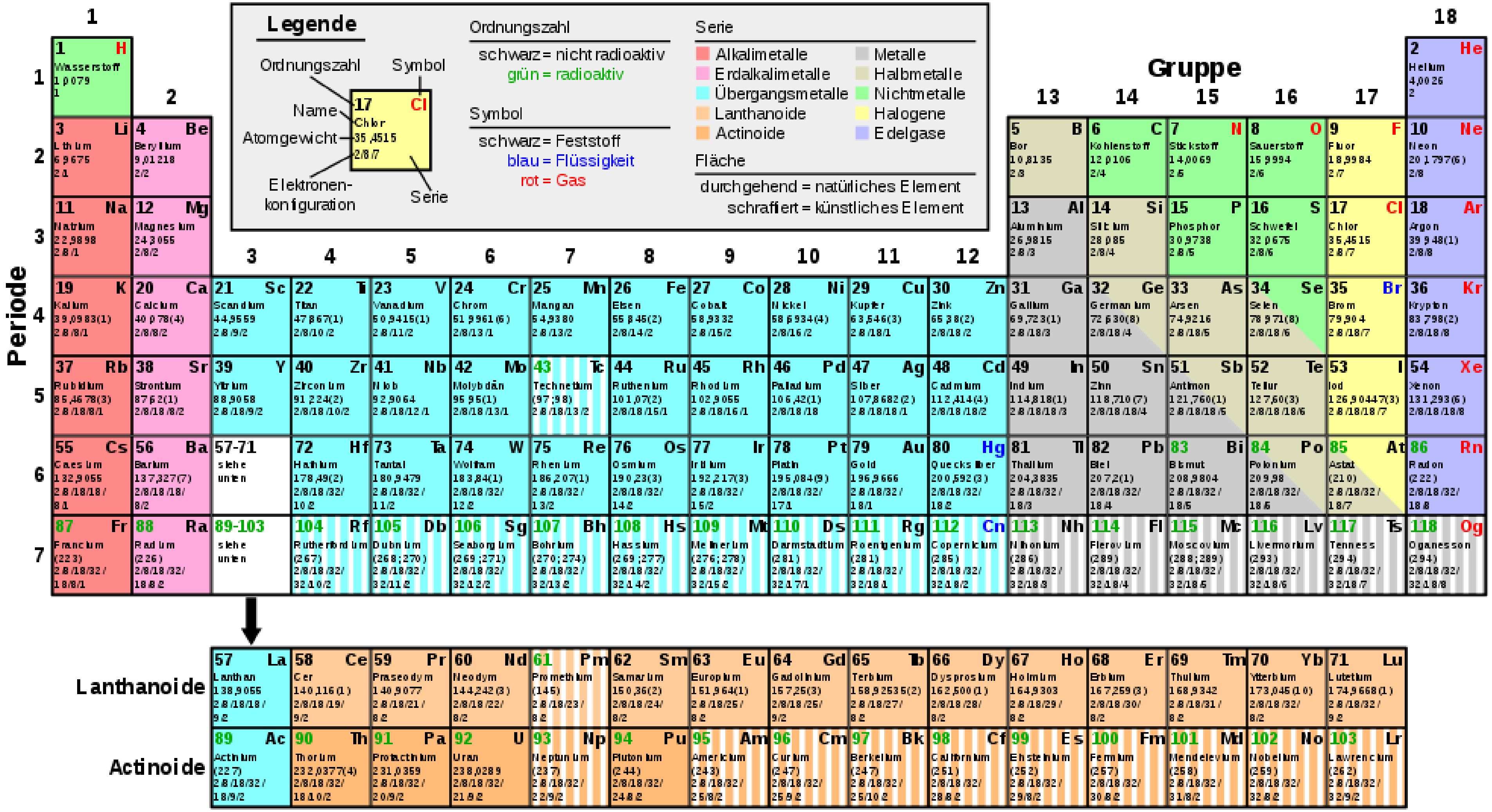
My apologies: I am not a quantum theorist, rather an «applied» theoretical physicsist, working on explaining the origin of the elements in the universe and their relation to stars and stellar explosions (but all this relies on quantum physics, my motivation)

Chemical Elements known today

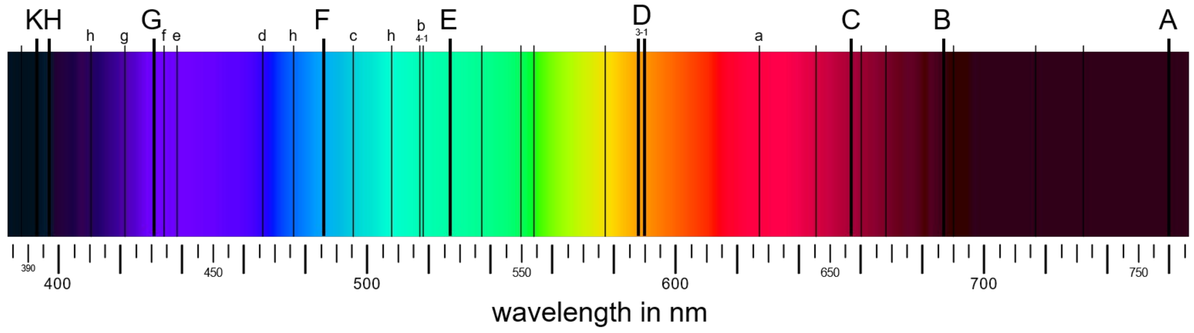
Up to Oganessan (Z=118), Elements with Z>94 (Plutonium) are unstable, short-lived and only created in nuclear accelerator labs

(wikimedia)

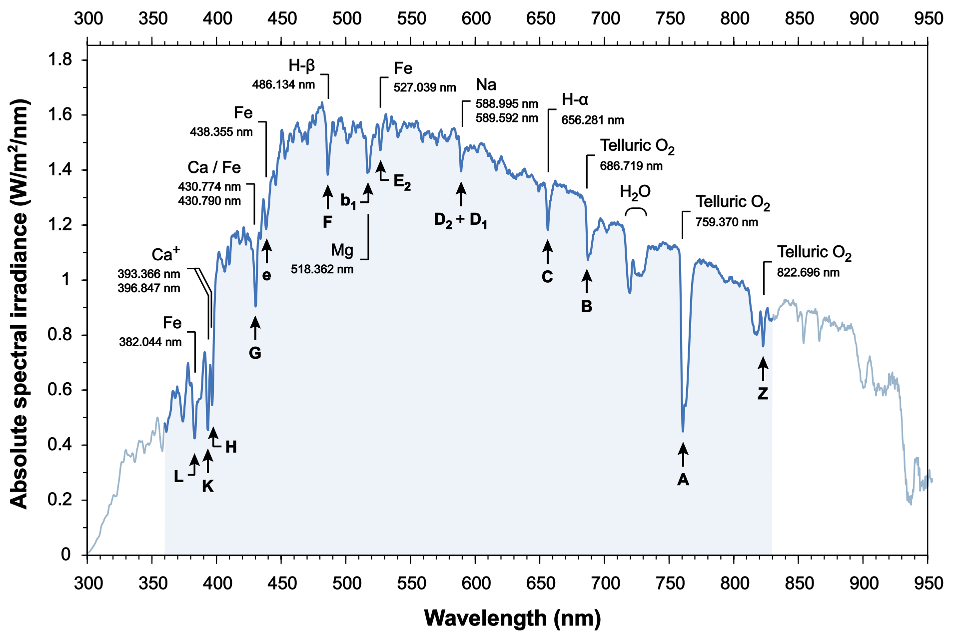


To understand the chemical elements and their orbital electron structure we need quantum mechanics

Fraunhofer Absorption Lines in the Sun and their interpretations

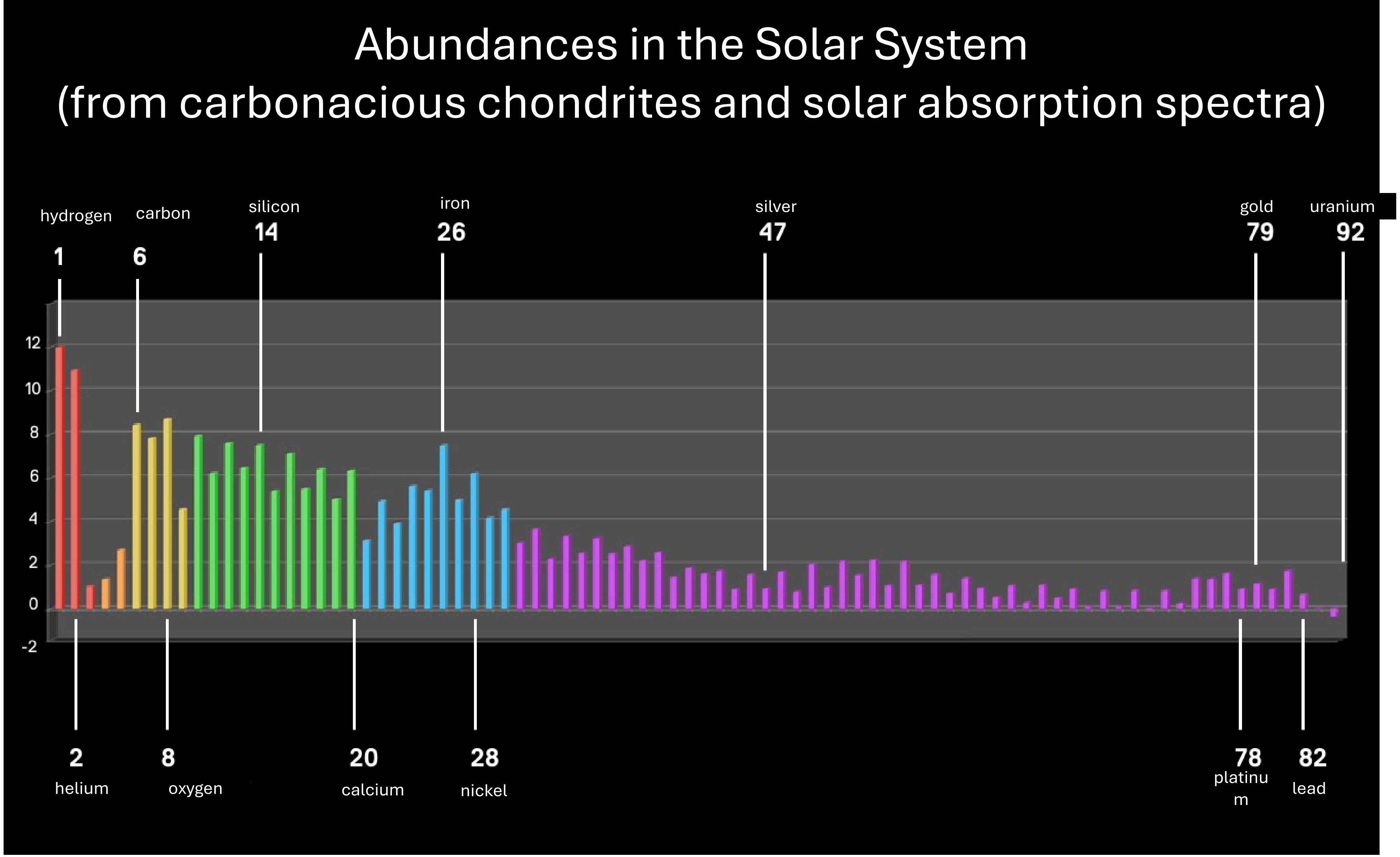


Classical notation



Relation to elemental absorption lines

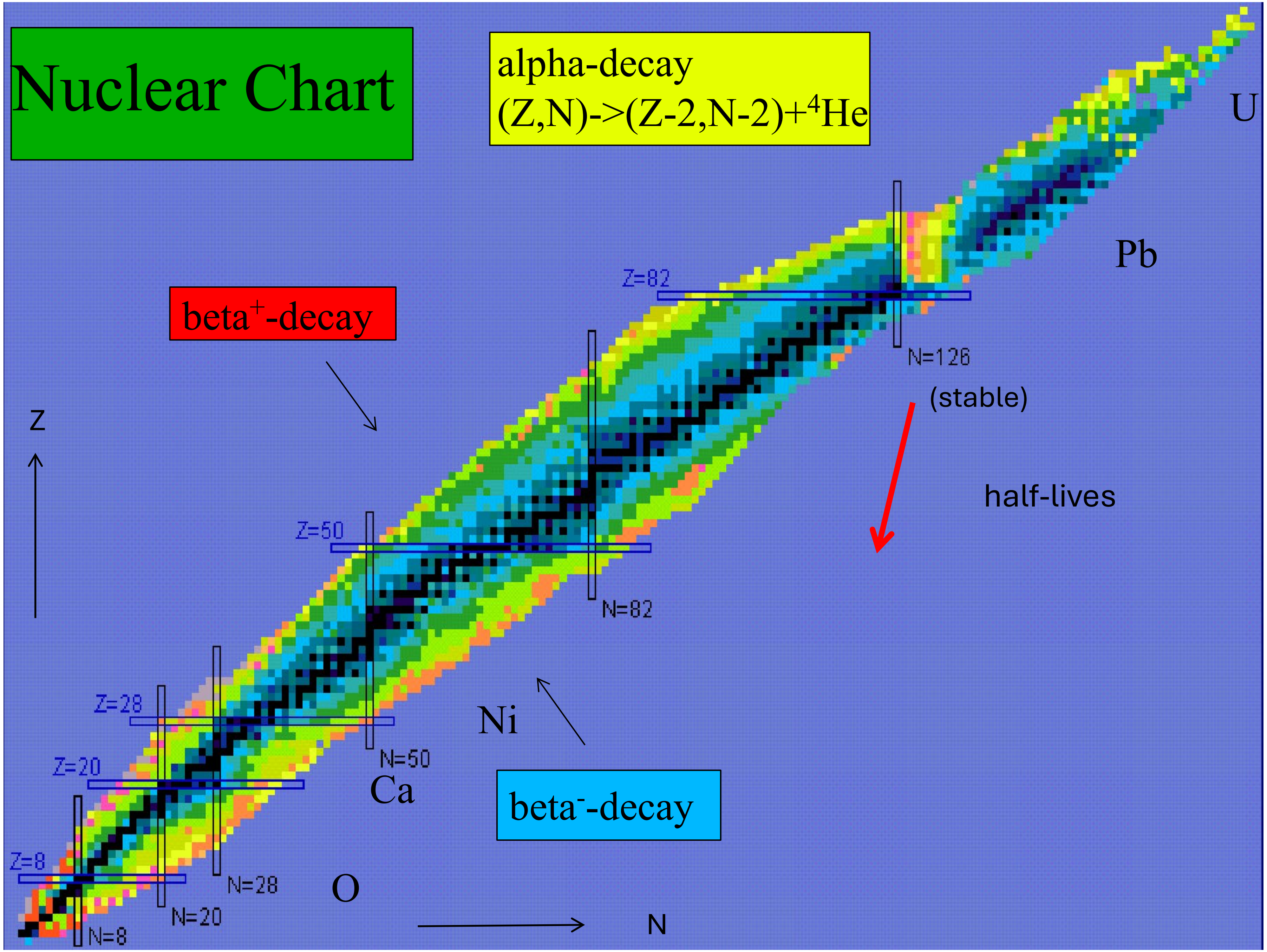
Absorption lines in stars (here especially the sun) are related to photon absorptions at wavelength/frequencies which correspond to transitions between or from electron orbits (bound-bound or bound-free transitions)



One unit on the y-axis corresponds to a factor of 10, i.e. hydrogen is about 10^{12} more abundant than uranium

With the help of stellar structure and conditions in the photosphere we can interpret absorption spectra in terms of element abundances

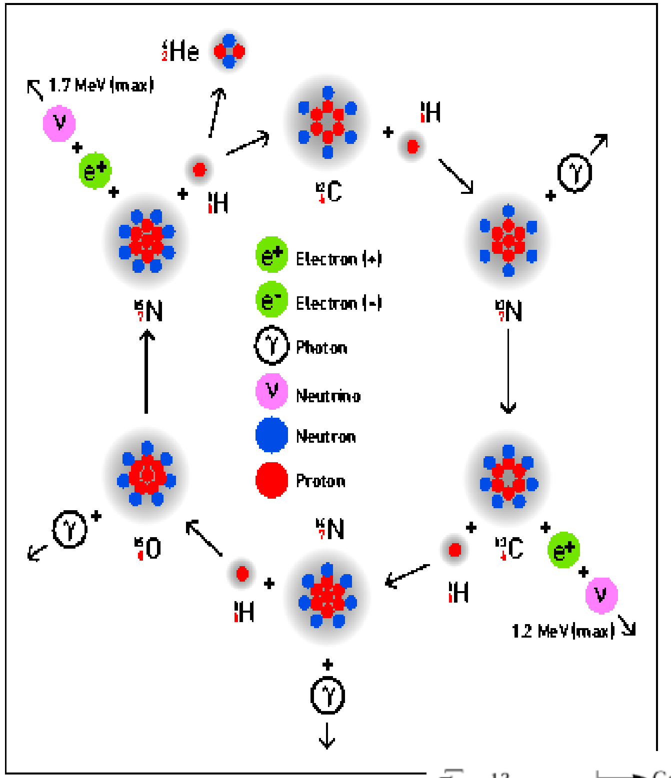
Quantum Mechanics and nuclear forces permit to understand the properties of atomic nuclei



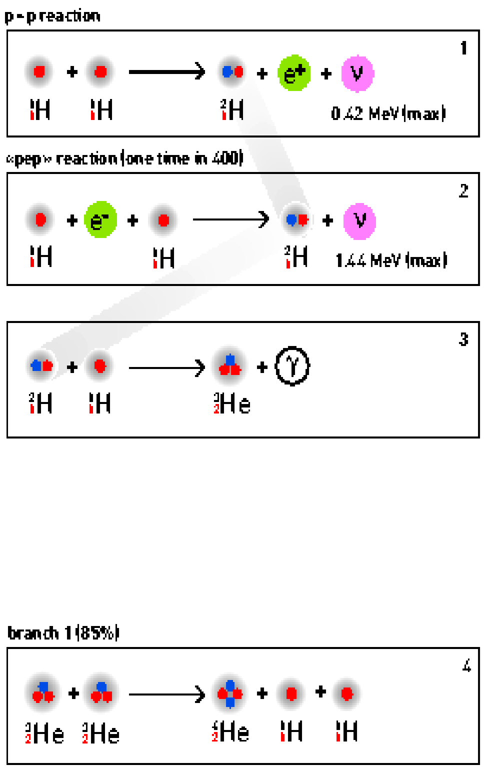
Stellar Burning Stages

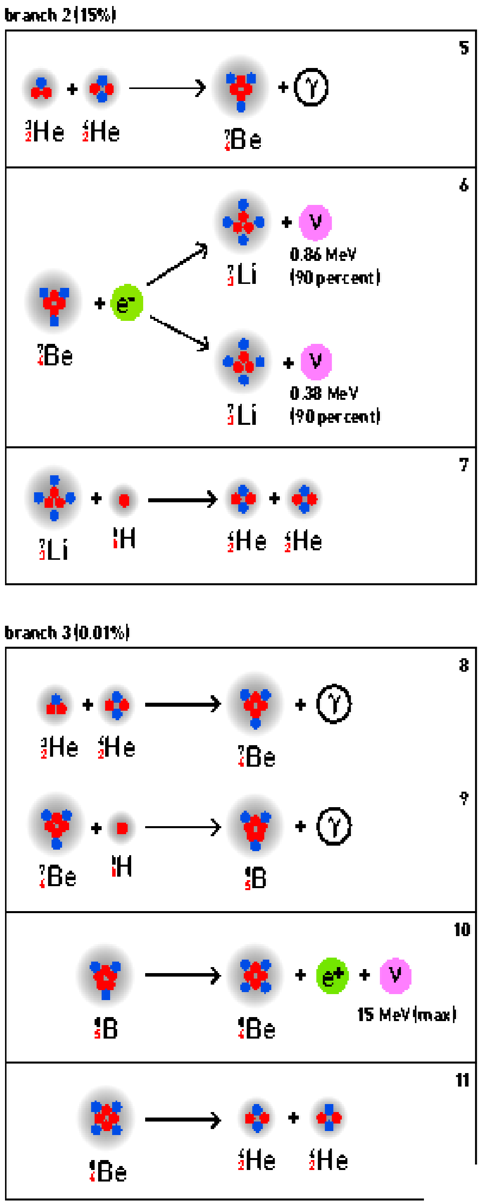
Hydrogen Burning

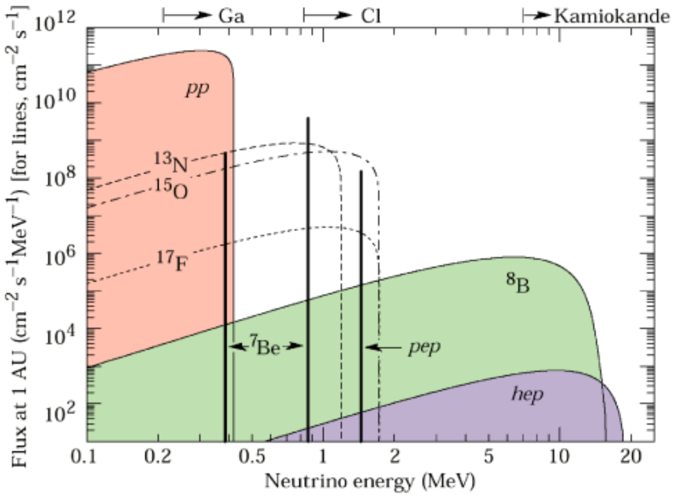
The CNO Cycle



P-P Cycles

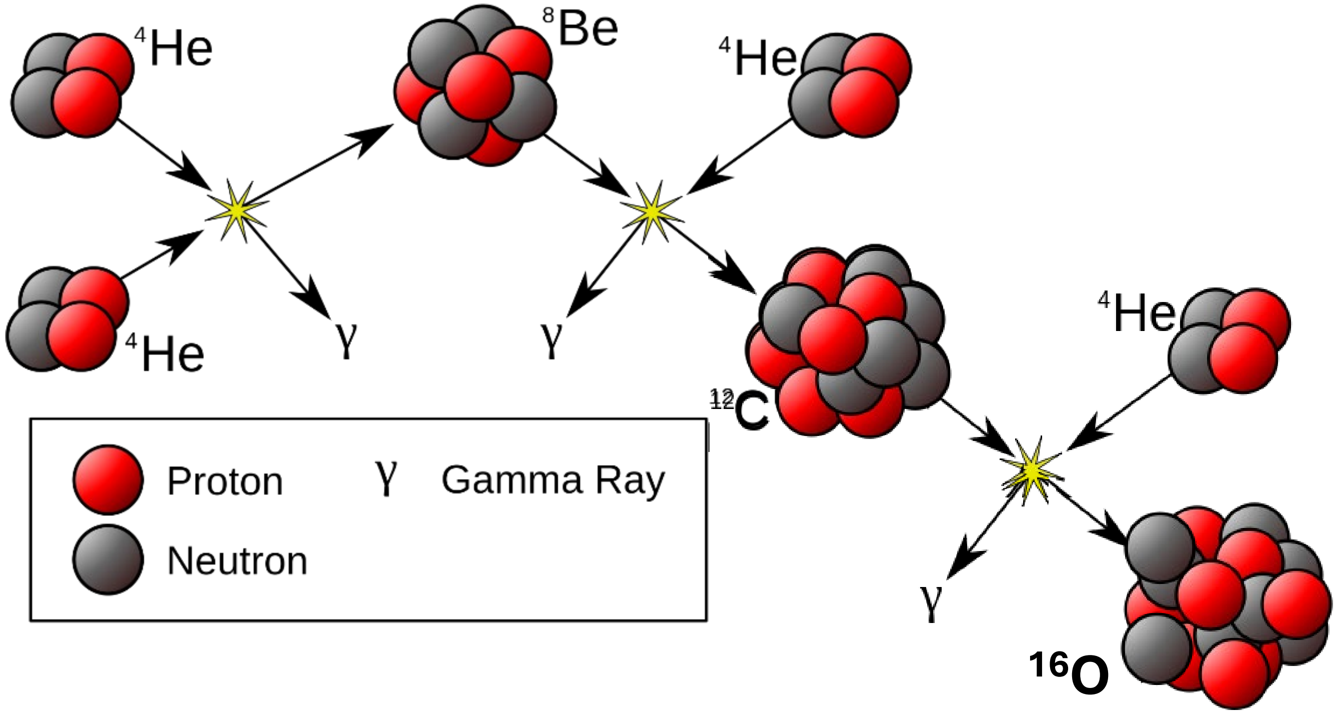


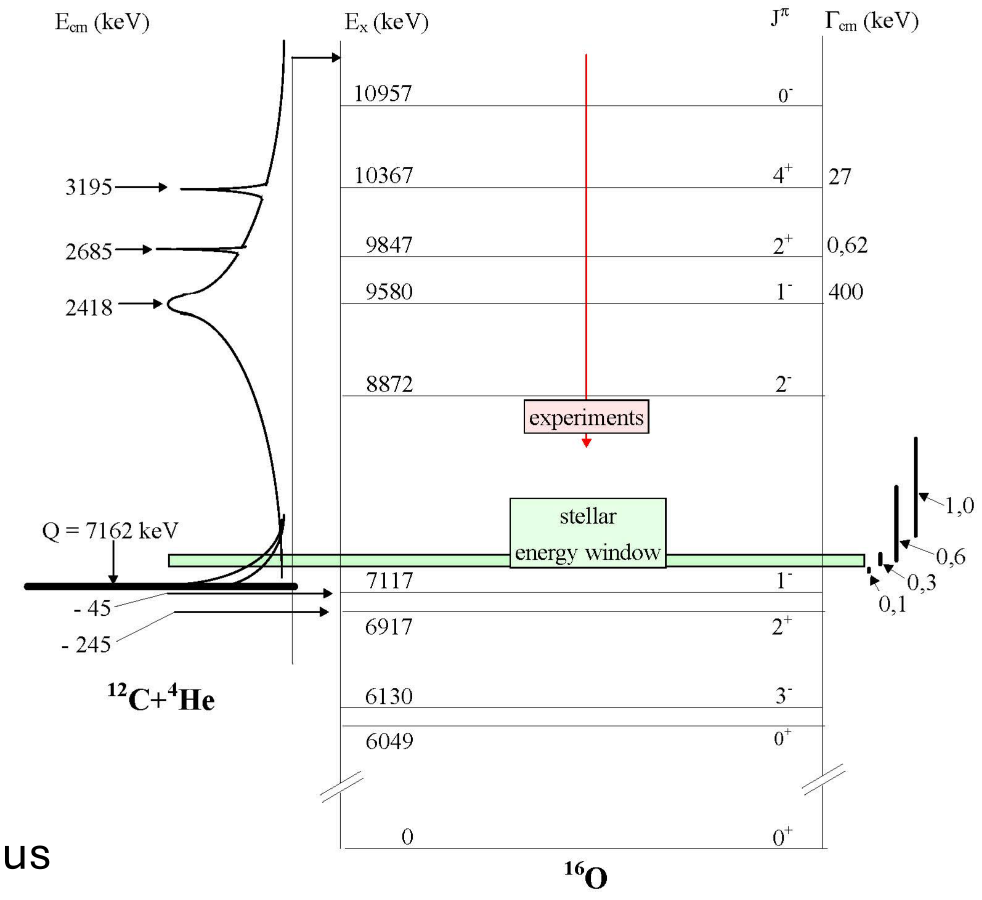




Nuclear fusion reactions lead to nuclear energy generation in stars, the escape of neutrinos, and via photon/radiation transport to the overall luminosity of a star plus its observed spectra

He-burning and $^{12}C(\alpha,\gamma)^{16}O$





Here the nuclear resonances/excited states in the compound nucleus ^{16}O involved in the $^{4}He + ^{12}C$ reaction in stellar helium burning

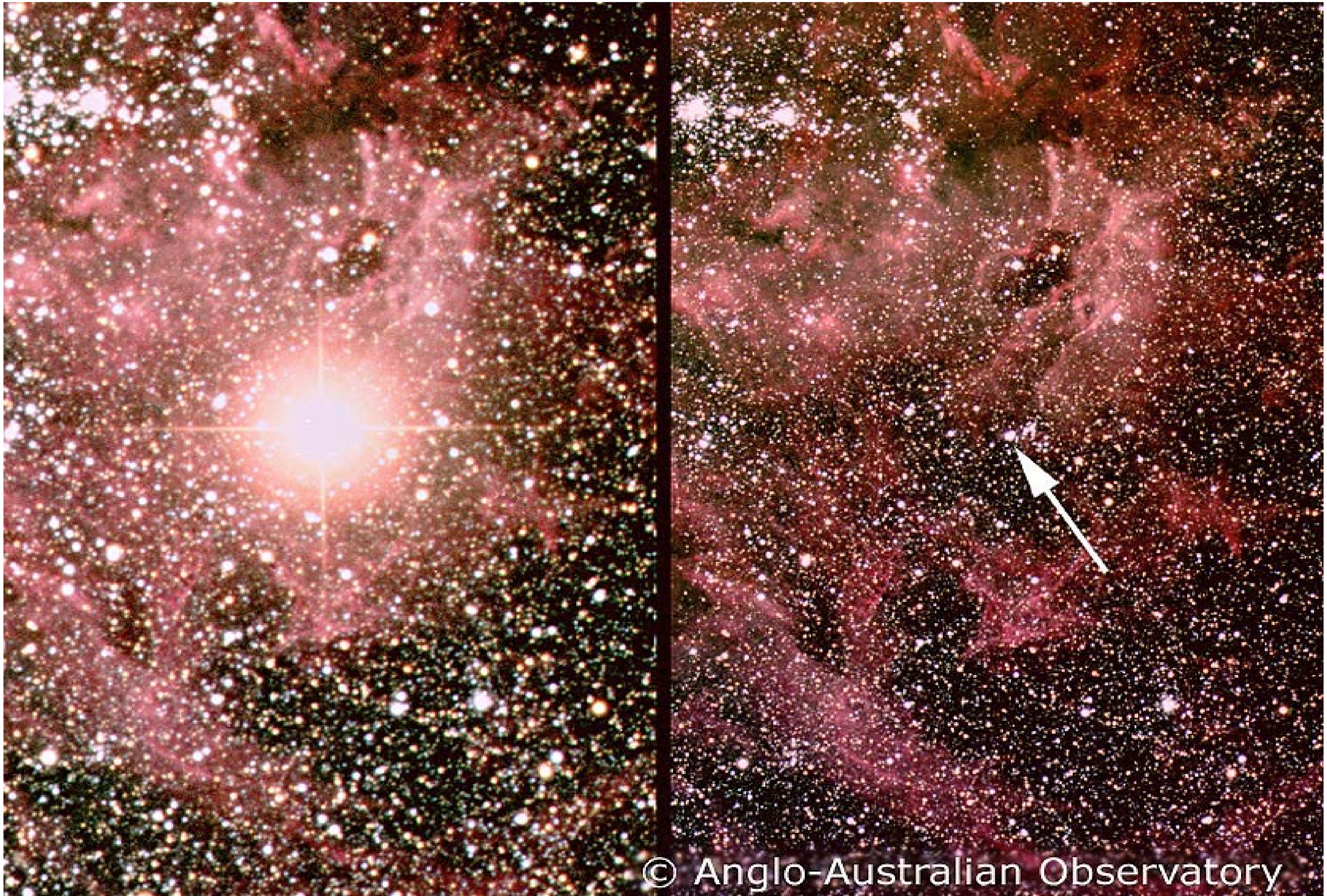
Supernova 1987A (originating from a $20M_\odot$ star)

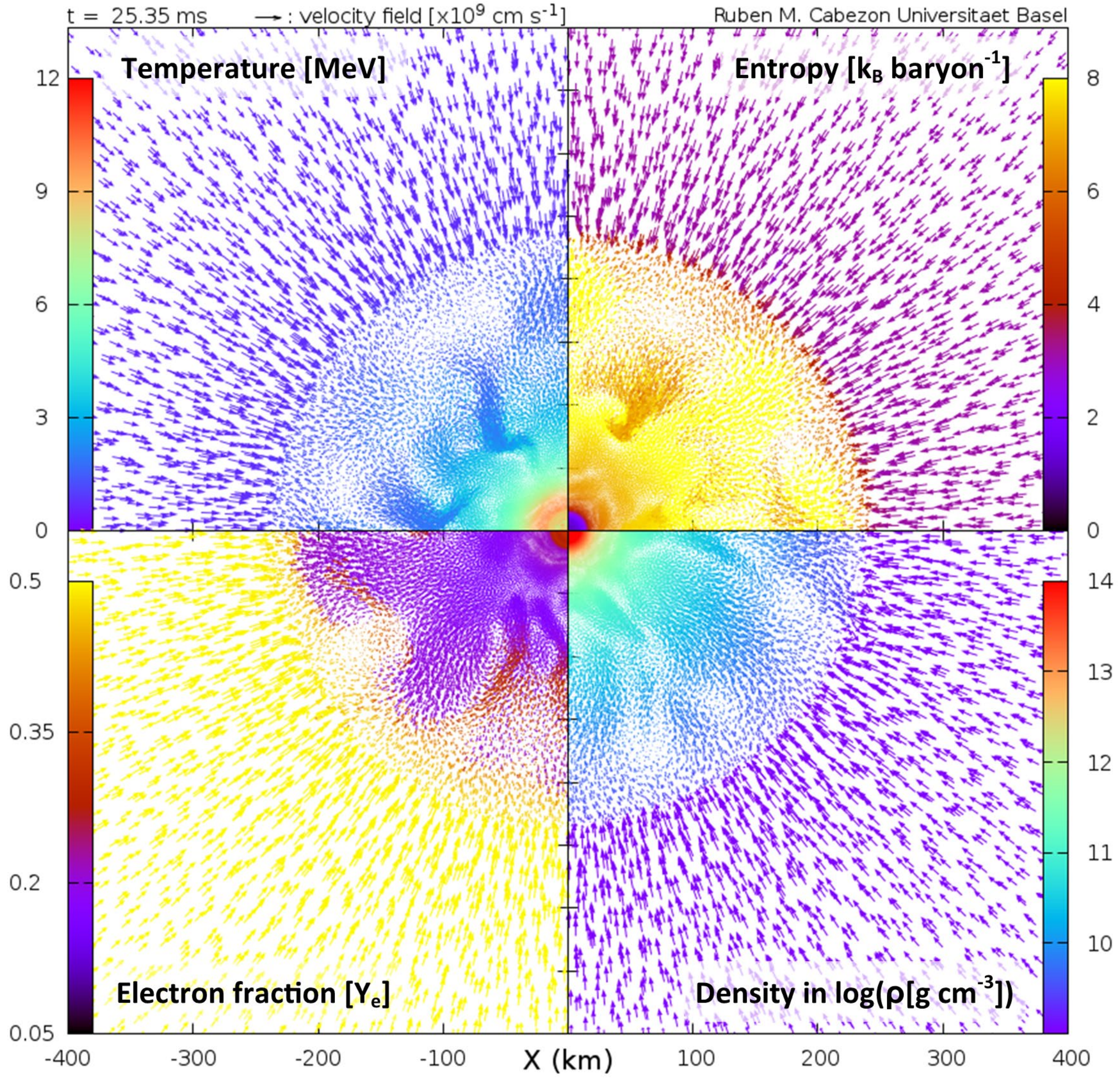
after and before explosion

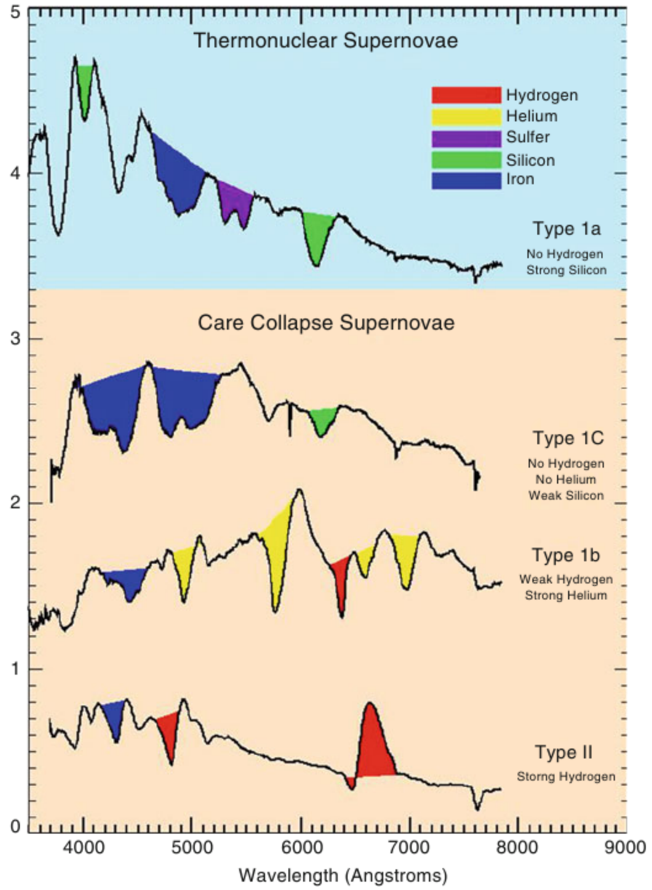
Stellar explosions, like supernovae are powered by the gravitational binding energy when the central 1-2 solar masses are compressed to an object of about 10 km size, stabilized by repulsive nuclear forces.

The gained binding energy is released in form of neutrinos.

A shock wave powered by energy from neutrino absorptions emerges and leads to nuclear burning and the production of heavy elements.







Element identifications in supernova spectra

A 3-dim simulation of the central collapse and emerging explosion shock (R. Cabezon, U. of Basel)

All of this would not be explainable without quantum mechanics,

***but how did it all come about, and what was the role of deBroglie*?**

Louis de Broglie 15.8.1892 (Dieppe) – 19.3.1987 (Louveciennes)

was stemming from an aristrocrate family, going back to Italien nobility from Piemont (with the Name Broglia).
Francesco Broglia (1671-1745, already *Comte*) settled in France, due to military achievements became *Marquis* and later *Maréchal de France*.

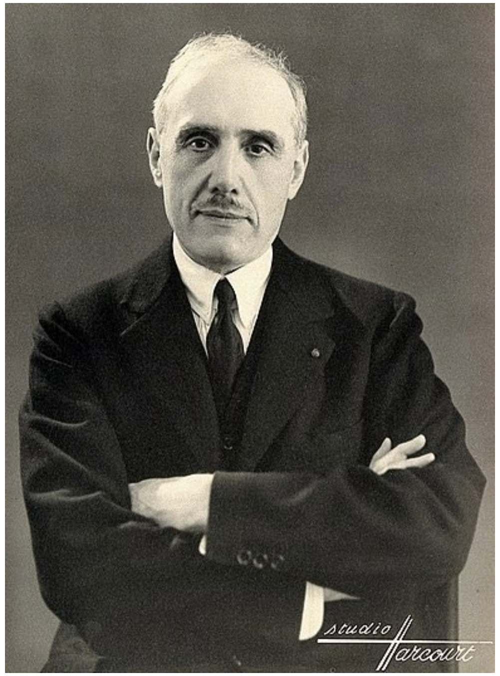
The two next generations were known as successful generals, the family obtained the Castle Chambrais in Normandie as a gift and called themselves de Broglie, since 1742 also the oldest son had regularly the title *Duc*.

After the French Revolution Charles Louis Victor died by the guillotine.
Leonce Charles Victor (1785-1879) became one of the most important French statesmen, Grandfather Charles Victor Albert (1821-1901) and father Victor (1846-1906) were active polititians.

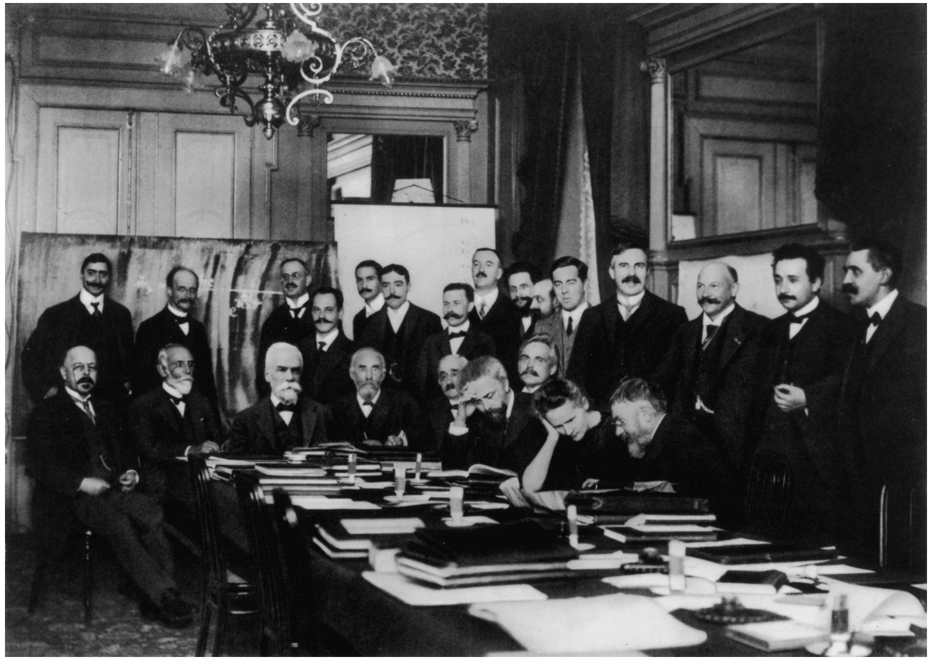
Louis was one of four siblings, three of them being 4, 17, and 20 years older than him. He grew up somewhat isolated, cared for by a nanny, and educated by tutors, spent a lot of his time by reading literature.

After the early death of his father in 1906, his much older brother Maurice started to play the role to be in charge of his education and future.

Maurice had started a career in the French Marine Corps and got in touch with science during the accompanying education. During high school (lycée) days he got to know Prof. Brizard and learned about electrons and X-rays, later started to have his own laboratory, began studying physics and undertook his own experiments, finally deciding to stop his military career *(studying spectroscopy at the Observatoire de Meudon and the College de France)*. For his experiments with X-rays and the photo effect he received high recognition in scientific circles. **The impact of his brother Maurice led Louis to start at the Lycée Janson de Sally, where Prof. Brizard taught, and he choose the science branch, but initially still very open to history and law studies, later turning to the history of sciences.**



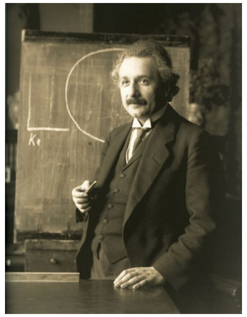
The 1911 Solvay Congress in Brussels



had as participants the most prominent physicists of that time: among them *Planck, Sommerfeld, Wien, Nernst, Rutherford, Perrin, Marie Curie, Einstein …*
They joined under the title «The Theory of Radiation and Quanta».
It turned out that Maurice de Broglie had the honor to be secretary of the congress and was in charge to publish the results and discussions (more than 400 pages).
Louis had the chance to read all that, which turned him definitely to Physics, not continuing his history and law studies.

However, he was not really convinced by the quality of physics and mathematics professors at the Sorbonne and focused mostly on reading primary literature himself (Appell, Poincaré, Drude, Lorentz, Boltzmann, Gibbs, Planck, Einstein).
He finished his (undergraduate) studies with excellent exams after only two years, before missing the direct contact with new developments in physics during six years of military service due to military mobilization and WW I.
As part of his WW I obligations he was stationed on the Eiffel Tower in charge of radio operations / signalling. After the end of WW I, since 1919, he began to get involved in science again.

The situation around 1920: Today's understanding of physics is not possible without the concept of quantum mechanics, but how did it all come about?



Light had been understood (apart from ancient corpuscle interpretations by Demokrit, Platon, Aristoteles, Lukrez, Seneca) in terms of waves since Huygen's in 1690 (and Fresnel's extension in 1818, with precursors by Grosseteste, Kepler, Galilei, Descartes, Rømer, Fermat), but *Planck (in 1900, Verh. Deutsch. Phys. Ges. 2, 237) and Einstein (in 1905, Annalen der Physik 17, 132; 18, 639) postulated particle behaviors (light quanta, later called photons).*

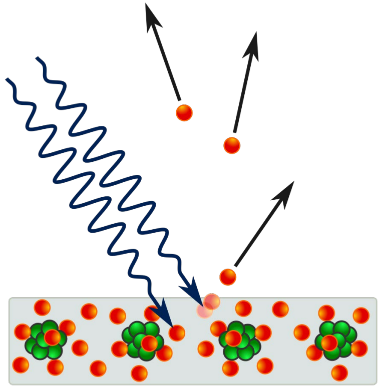
Black body radiation was interpreted as a gas of light quanta with $E = h\nu = hc/\lambda$, $p = h\nu/c = h/\lambda$, where the frequency or wavelength was related to their energy or momentum, confirmed by Compton's experiments in the early 1920s.

The Bohr model of the atom (1913, extending ideas of Thomson, Rutherford, Haas and Sommerfeld) still considered electrons as particles, but with quantized angular momentum (Sommerfeld later explained fine structure by including relativistic effects) .

de Broglie’s new scientific activities after finishing the WW I duties

He started to follow lectures by Langevin on relativity and quantum physics at the College de France. He also was in constant contact with members of his brother’s (Maurice) experimental laboratory, which had reached international recognition. *Jointly they published articles on atomic spectra, the photo effect, X-rays:*

Sur le modèle d’atome de Bohr et les sprectres corpusculaires (1921, Comptes Rendus 172, 746
Sur la structure électronique des atomes lourds (1921), Compt. Rend. 172, 1650
Sur la distribution des électrons dans les atomes lourds (1921), Compt. Rend. 173, 137
Sur le spectre corpusculaire des élements (1921), Compt. Rend. 173, 527
Remarques sur le travail de E. Hjalma concernant le série M des élements (1922), C. R. 175, 1139
Remarques sur les spectres corpusculaires de l’éffect photoélectrique (1922), C.R. 175, 1922
Sur le système spectral des rayons Roentgen (1922), C. R. 175, 685
Sur les analogies de structure entre les séries optiques et les séries Roentgen (1922), C.R. 175, 755
Sur la vérification expérimentale des projections d’électrons prévus lors de la dissusion des rayons X par les considerations de Compton et Debye (1924), C. R. 178, 383



With the experiments on the photo effect the debate on the nature of light as well as X-rays was rejuvenated and led to the conclusion that the particle nature of light could not be neglected.

de Broglie was the first after Einstein who engaged in discussing the properties of light quanta in two articles in 1922:

Rayonnement noir et quanta de lumière, Journal de Physique (1922) VI, III, 422
Sur les interférence et la théorie des quanta de lumière (1922) C. R. 175, 811

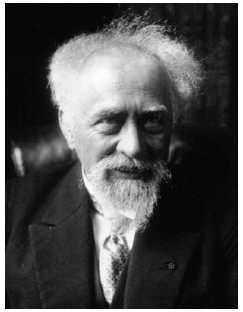
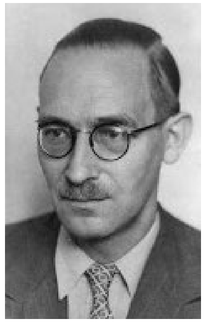
In 1923 he published three articles which revolutionized physics and secured his scientific reputation:

Onde et Quanta (1923), C. R. 177,517
Quanta de lumière, diffraction et interférences (1923), C. R. 177, 548
Les quanta, la thèorie cinètique des gaz et le principe de Fermat (1923), C. R. 177, 630

In 1924 he extended these ideas and published them in his doctoral thesis:

Récherches sur la theorie des quanta (1925), Annales de Physique X, III, 22-128

The PhD committee (Jean Perrin, Charles Mauguin, Langevin ..) was enthusiastic about the brilliant thoughts of the candidate, but at that point still very sceptical about the idea of matter waves.


The basic idea was to translate the properties of light quanta/photons with

$$E = h\nu = hc/\lambda \qquad p = h\nu/c = h/\lambda$$

to particles with mass, combined with Einsteins relation $E=mc^2$.
For particles with rest mass m_0 the total energy

$$E = \sqrt{(m_o c^2)^2 + (cp)^2} = \frac{m_0}{\sqrt{1-v^2/c^2}} c^2 = mc^2$$

can also be expressed in this way with the relativistic mass m. In fact, de Broglie always still thought of photons having a rest mass, and that c would only be the limiting (but never fully attained) velocity. With a relativistic mass $m=h\nu/c^2$ he came with $m_0 = m\sqrt{1 - v^2/c^2}$ to a limiting photon rest mass of $m_0 < 10^{-50}$g.

For particles with rest mass, like electrons, neutrons, protons, ... he introduced the de Broglie wavelength, according to the relation for photons $p=h/\lambda$, by utilizing the relativistic particle momentum p and $\lambda_{DB}=h/p$.

In 1927, experiments provided finally the proof of the theory: Davisson and Germer (Phys. Rev. 30, 705) found interference phenomena of electron beams for the first time. The beams could be diffracted by crystal lattices, i.e. the electrons (particles) showed the behavior of waves.

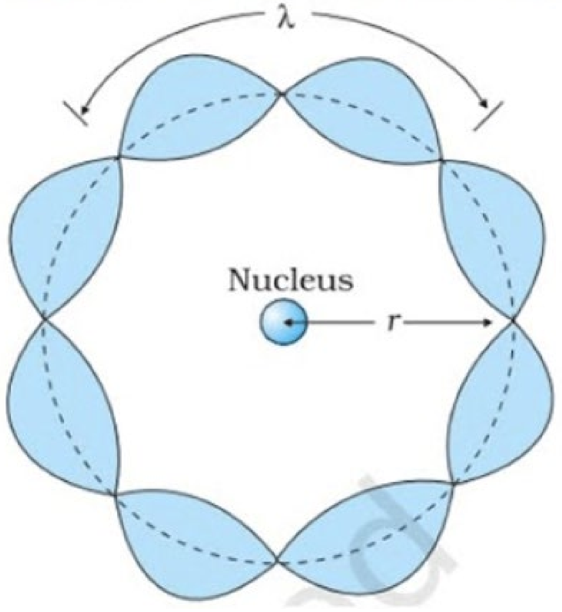
de Broglie Wavelength and Bohr’s quantization rule for electron orbits

With the introduction of the wavelength $\lambda=h/p$ for electrons, Bohr’s quantization rule for atomic electron orbits $L=nh/2\pi$, i.e. quantized angular momentum, is consistent with $n\lambda = 2\pi r$ and the rule became easy to understand:

a wave propagates along the “orbit of the electron” around the atomic nucleus.

Stable “orbits” are those in which the waves do not get erased through interference, i.e. (standing waves) for which the following applies $n\lambda = 2\pi r$ (in the case of circular orbits).

This condition corresponds to Bohr's postulate, so that de Broglie could write: “Nous croyons que c'est la première explication physiquement plausible proposée pour ces conditions de stabilité de Bohr-Sommerfeld.”



Frequencies of moving matter waves, phase and group velocity:

For a particle with restmass m_0, applying Einstein's relation, this leads to a frequency ν_0, i.e. $h\nu_0 = m_0 c^2$.

In its proper reference system (where the particle is at rest) with proper time t_0, the particle can be represented by a stationary wave (e.g. along the x-axis) via $\sin\omega_0 t_0 = \sin 2\pi\nu_0 t_0$ or in case of an initial time τ_0 via $\sin\omega_0(t_0 - \tau_0) = \sin 2\pi\nu_0(t_0 - \tau_0)$.

The particle, however, moves with velocity v (and β=v/c) with respect to the reference system x,t of an observer. Then, when utilizing the observer system, the proper time in the reference system of the particle can be expressed as $t_0 = (t - \beta x/c)/\sqrt{1-\beta^2}$. When expressing $\sin 2\pi\nu_0(t_0 - \tau_0)$ by the space and time coordinate in the observer system it would turn to $\sin[2\pi\nu_0/\sqrt{1-\beta^2}(t - \beta x/c - \tau_0)]$ with an apparent frequency $\nu = \nu_0/\sqrt{1-\beta^2}$.

Thus, the frequency noticed in the observer system, where the particle moves with relative velocity v=β/c
Is

$$\nu == \frac{m_0 c^2}{h} / \sqrt{1-\beta^2}.$$

The observer sees this as an oscillating wave with frequency ν which propgates in direction of the particle velocity and whose frequency increases with the particle speed.

The wave propagates with the **phase velocity**

$$v_{ph}=\nu\lambda=(E/h)\,(h/p)=E/p=mc^2/mv=c^2/v=c/\beta$$

The relativistic mass m cancels out in this expression.

The phase velocity can be larger than c for v<c.

The particle moves with the group velocity v (in other applications first introduced by Hamilton 1839 and Rayleigh 1877).

at an earlier point the introduction of the de Broglie wavelength was motivatied parallel to the photon wavelength λ=p/h, but de Broglie found this relation also by expressing p in a different way.

$$p=\frac{m_0 v}{\sqrt{1-\beta^2}}=\frac{E}{c^2}v=\frac{h\nu}{v_{ph}}=\frac{h}{\lambda}$$

by identifying c^2/v with the phase velocity $v_{ph}=\nu\lambda$, which *is consistent with the relation for the particle wavelength*

λ=p/h

Waves and Quanta.

The quantum relation, energy $= h \times$ frequency, leads one to associate a periodical phenomenon with any isolated portion of matter or energy. An observer bound to the portion of matter will associate with it a frequency determined by its internal energy, namely, by its "mass at rest." An observer for whom a portion of matter is in steady motion with velocity βc, will see this frequency lower in consequence of the Lorentz-Einstein time transformation. I have been able to show (*Comptes rendus*, September 10 and 24, of the Paris Academy of Sciences) that the fixed observer will constantly see the internal periodical phenomenon in phase with a wave the frequency of which $\nu = \frac{m_0 c^2}{h\sqrt{1-\beta^2}}$ is determined by the quantum relation using the whole energy of the moving body—provided it is assumed that the wave spreads with the velocity c/β. This wave, the velocity of which is greater than c, cannot carry energy.

A radiation of frequency ν has to be considered as divided into atoms of light of very small internal mass ($< 10^{-50}$ gm.) which move with a velocity very nearly equal to c given by $\frac{m_0 c^2}{\sqrt{1-\beta^2}} = h\nu$. The atom of light slides slowly upon the non-material wave the frequency of which is ν and velocity c/β, very little higher than c.

The "phase wave" has a very great importance in determining the motion of any moving body, and I have been able to show that the stability conditions of the trajectories in Bohr's atom express that the wave is tuned with the length of the closed path.

The path of a luminous atom is no longer straight when this atom crosses a narrow opening; that is, diffraction. It is then *necessary* to give up the inertia principle, and we must suppose that any moving body follows always the ray of its "phase wave"; its path will then bend by passing through a sufficiently small aperture. Dynamics must undergo the same evolution that optics has undergone when undulations took the place of purely geometrical optics. Hypotheses based upon those of the wave theory allowed us to explain interferences and diffraction fringes. By means of these new ideas, it will probably be possible to reconcile also diffusion and dispersion with the discontinuity of light, and to solve almost all the problems brought up by quanta.

LOUIS DE BROGLIE.

Paris, September 12.

Publication:

Nature, Volume 112, Issue 2815, pp. 540 (1923).

de Broglie's kind of a summary of his 1923 work

In 1924 de Broglie introduced the theory of electron waves, before understood as particles, and proposed (more generally) that particles are wave packets which move with group velocity, having an effective mass.

Following de Broglie's proposal, leading to the wave-particle duality of electrons, modern quantum mechanics was born when in 1925 Werner Heisenberg, Max Born and Pascal Jordan developed matrix mechanics and Erwin Schrödinger invented wave mechanics as solutions of the Schrödinger equation in 1926.

From the wider acceptance at
the Fifth Solvay Conference in 1927

to further refinements, and unified formalizations by David Hilbert, Paul Dirac, and John von Neumann, until 1930 only a few years would pass.

Bohr won the Nobel prize in 1922, de Broglie in 1929, Heisenberg in 1932, Schrödinger in 1933, followed by many other quantum physicists since then.

Einstein and Schrödinger were both very impressed by de Broglie's thesis which actually motivated Schrödinger to extend the theory of matter waves mathematically towards wave mechanics and the Schrödinger equation, which led to exactly the same solutions as Heisenberg's matrix mechanics.

However, it was non-relativistic and utilized only fields, i.e. the particle nature was kind of lost. This inspired de Broglie to think about how phase waves could lead to the transport of energy.
In a 1924 article he searched for solving this problem
Sur la dynamique du quantum de lumière et les interférences (1924), C.R. 179, 1039
"This property allows the material point to be regarded as a singularity of the wave group. [...].
rays envisaged by the wave theories would therefore in all cases be the possible paths of the quantum."

He further worked on his idea of the "double solution",
Sur le parallélisme entre la dynamique du point matériel et l'optique géometrique (1926), J. de Physique, VI, VII,1-6
The basic idea of this theory is that in addition to the regular solution of the Schrödinger equation ψ, there must be a further solution u, which has a singularity where the particle is located. *Then the Schrödinger wave ψ would not only have the statistical significance assigned to it by Born, but would also represent all theoretically conceivable paths of the particle, while the solution u would represent the individual motion of a particle.* De Broglie postulated that both waves had to be in phase and that the singularity propagates in the direction in which the phase grows fastest.
He called this relationship the "law of guidance".

de Broglie presented these ideas at the 1927 Solvay Conference, but did not find much approval, while it was rather centered around the "Copenhagen School" of Heisenberg and Bohr. Pauli made a comment: "I read your article in the Journal de France, it is very interesting, but wrong" (not explaining properly inelastic scattering, but see next slide).
These experiences stopped de Broglie's research for several years.

While de Broglie remained with a high scientific recognition in France and related posts in academic life, he was not extremely active in scientific research until he received a publication by David Bohm (Quantum Theory, Prentice Hall) in 1951, in which he found again his idea of the “Law of Guidance” or the “pilot wave theory”. This theory, also known as Bohmian mechanics, was the first known example of a hidden-variable theory (as presented first by de Broglie in 1927). [a **hidden-variable theory** is a deterministic physical model which seeks to explain the probabilistic nature of quantum mechanics by introducing additional (possibly inaccessible) variables.]

This encouraged him to restart his early ideas (Sur la possibilité d’une interpretation causale et objective de la méchanique ondulatoire (1952), C.R. 234, 265). *Its more modern version, the de Broglie–Bohm theory, interprets quantum mechanics as a deterministic theory, and avoids issues such as wave–particle duality, instantaneous wave function collapse, and the paradox of Schrödinger's cat by being inherently nonlocal (also explaining inelastic scattering in its many-particle extension).* This turning away from the Copenhagen School led him, however into scientific isolation.[The de Broglie–Bohm pilot wave theory is one of several interpretations of (non-relativistic) quantum mechanics.]

So far my attempt to present an overview of de Broglie’s ideas and break-throughs, plus also his later inclinations. *Thank you for your attention!*
My colleagues in this symposium will discuss modern research and advances in this field, I focused on the role of de Broglie, a few main aspects and the history behind it.