Modern Physics

Contents:

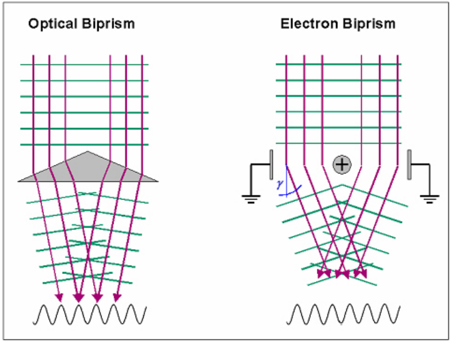
1. Classical Wave Phenomena
2. Essentials of Thermodynamics
3. Special Relativity
4. Wave-Particle Dualism
5. Atoms
6. Solids

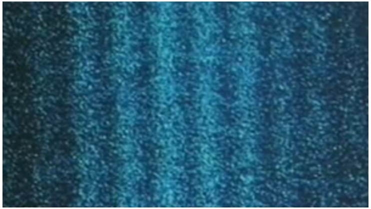
Matter waves

Wave-particle dualism

- Thermal radiation
- Planck’s radiation law
- Photoelectric effect
- Laser
- Compton effect
- Pair production
- Matter waves
- Uncertainty relations

Matter waves 19





(SingleElectronDoubleSlitWaveExperiment.mp4)

Matter waves 19 Comment 1

The video shows an interference experiment with electrons, in which the electron current is so small that the arrival of individual electrons on the luminescent screen can be observed.

In the experiment, an electron beam is guided past a positively charged electrode on the left and right.

As a result, the electrons are deflected somewhat and interference occurs.

The optical analog is a biprism shown on the left.

A light wave hits the two prisms, which deflect the light rays in such a way that interference occurs.

The astonishing result of the experiment is that an interference pattern forms even though the electrons fly past the electrode independently of one another.

Matter waves 19

Comment 2

The electron wave can be used to calculate the probability of where the electrons will arrive on the screen.

The square of the magnitude of the wave function determines the particle density and thus the probability.

This is similar to electromagnetic waves, where the square of the electric and magnetic field strength determines the energy density of the wave, i.e. the photon density.

This interpretation of the experiment leads to the problem that Newton wanted to solve in explaining the Newton rings with his corpuscular theory of light.

How do the particles know that there are forbidden areas because they fly past the electrode independently of each other?

Matter waves 19 Comment 3

The concept of the wave function seems to be an auxiliary mathematical construction which cannot answer the question of what determines the path of the particles.

The wave function is needed while the particle is traveling to calculate the probability of where the particle will end up on the screen.

If a luminous point on the screen signals that the electron has arrived, the concept of the wave function is instantly obsolete.

This property of a wave function is problematic. Since, if the wave function is to describe a physical phenomenon, the speed of light is the highest speed, so that the collapse of the wave function can propagate in space at the most at the speed of light.

Matter waves 19 Comment 4

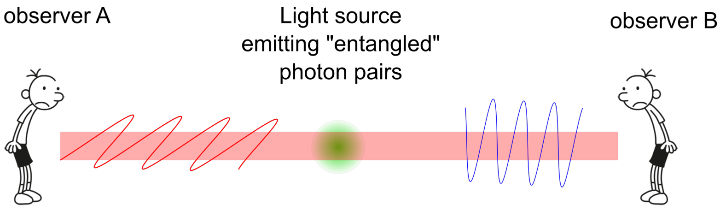
Einstein believed that the matter waves introduced by Louis de Broglie are preliminary and that there must be a more comprehensive theory that can actually explain the behavior of quantum particles.

Einstein summed up the problem by formulating the famous Einstein-Podolsky-Rosen Paradox (EPR Paradox) together with Podolsky and Rosen in 1935.

In this paradox it is shown that the concept of the wave function violates elementary physical principles that were generally accepted up to the point that wave functions (among other things) enable a remote interaction in which information can be transmitted at infinite speed.

Matter waves 20: Einstein Podolsky Rosen Paradox

- A non-linear light source emits pairs of photons that are polarized perpendicular to each other.
- Both photons of a pair are described by a common wave function. A wave function of two or more quantum particles is called an entangled state.
- As soon as one observer receives a photon and determines the polarization, the wave function collapses and the polarization measured by the second observer is fixed.



Matter waves 20 Comment 1

The paradox was formulated in various variants. In the following I am discussing a variant that is used in optics and that does not initially require any special knowledge of quantum physics.

The figure outlines the EPR paradox as it can be realized with a non-linear light source that emits pairs of photons polarized perpendicular to each other.

It is crucial that the light source emits a single wave function in which the polarization of the two photons is coded in such a way that every observer can measure one of the two polarizations with a 50 % probability.

A wave function of two or more quantum particles is called an entangled state.

The concept of entanglement was introduced by Schrödinger to meet the requirements of the Pauli principle for electrons. But entanglement is general.

Matter waves 20 Comment 2

Well noticed! The polarization of the photons is not determined in the light source. The light source only determines the entangled wave function of the two photons.

Only when one observer determines the polarization of his photon does the polarization of the other photon appear immediately, which the second observer can determine. This is the collapse of the wave function.

This information has to get from one observer to another at an infinitely high speed, which is paradoxical.

There is a second problem with this experiment. Usually a measurement can only determine what is actually there.

Matter waves 20 Comment 3

When measuring the polarization of the photon, however, the polarisation is determined by the measurement, since the light source does not determine which photon should receive which observer.

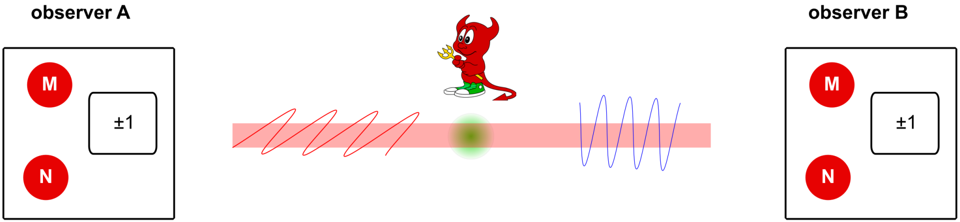
The paradox of Einstein, Podolski and Rosen shows that the concept of the wave function violates two fundamental and generally accepted principles.

The first is called the reality principle (Einstein asks: Is the moon in the sky even when nobody is looking?).

The second is called the locality principle (no signal propagation faster than the speed of light).

Matter waves 21: Bell's inequality

James Bell (1964): Is there a hidden theory?



E.g. button M of observer A gives the result $M_A = +1$ or $M_A = -1$, etc.

$$S = \langle M_A M_B - M_A N_B + N_A M_B + N_A N_B \rangle$$

Matter waves 21 Comment 1

Einstein, Podolski and Rosen argue that there must be a “hidden” theory that already determines within the light source which polarization each observer will receive.

One can imagine a demon in the light source, which determines which polarization of the photon observers A and B will receive.

Instead of polarized photons, one can imagine the demon unpacking shoe boxes and sending one shoe to observer A and the other shoe to observer B.

If the demon throws the pairs of shoes randomly, then there is a 50 % probability that every observer will receive a left or right shoe.

The result corresponds exactly to the prediction of quantum mechanics, whereby - thanks to the demon - no laws of physics have to be disregarded.

Matter waves 21 Comment 2

In 1964 James Bell found a way to test experimentally whether this hidden theory could exist. Thereby the details of the hidden theory not have to be known. The hidden theory only needs to satisfy two principles:

The first principle is the reality principle. The value of a measurand is independent of whether it is measured or not.

The second principle is the principle of locality. If two parts of an object are so far apart that communication even at the speed of light is impossible, the manipulation of one part cannot affect the other.

Quantum physics violates both principles to the maximum.

Matter waves 21 — Comment 3

The sketch shows an experiment proposed by James Bell to test the EPR paradox.

Each observer is equipped with an analyzer that has two setting options, which are marked M and N in the sketch.

If the polarization of the photon corresponds to the orientation of the analyzer, the device displays the number +1, or -1 if the polarization does not match.

The positions M and N of the analyzers can be chosen arbitrarily and the apparatus of the two observers do not have to be aligned relative to one another.

But it is crucial that both observers analyze the same pair of photons.

The experimental difficulty lies in ensuring this condition in the experiment.

Matter waves 21 Comment 4

The observers note their measurement results and come together after the experiment and use their joint results to calculate the correlation function S, underlined in red.

If, for example, both observers have pressed button M for a photon pair, then they calculate with their experimental results $\langle M_A M_B \rangle$.

For example, if observer A pressed button M and observer B pressed button N, then they calculated with their experimental results $\langle M_A N_B \rangle$, etc.

(For more details see the book: A. I. Lvovsky “Quantum Physics: An Introduction Based on Photons” chapter 2.3.2 The Bell inequality. (Springer-Verlag GmbH Germany, part of Springer Nature 2018))

Matter waves 22: Bell's inequality

Bell inequality : $|S| \leq 2$

quantum mechanics

$|S| > 2$

Matter waves 22 Comment 1

For any theory that follows the reality and locality principle, the value of $|S|$ must be less than or equal to 2.

For any theory that violates the reality and locality principle, the value of $|S|$ is always greater than 2.

The first convincing experimental results were published in 1982 by Alain Aspect.

The measurements show that the quantum mechanics describes the experiments correctly and that there is no hidden theory.

Since then, this type of experiment has been repeated in many variations, and the predictions of quantum physics have always been confirmed.

Matter waves 22 Comment 2

In the meantime, people have come to terms with the fact that quantum physics disregards the plausible principles of reality and locality and recognized that this opens up completely new possibilities, e.g. quantum cryptography and quantum computing.

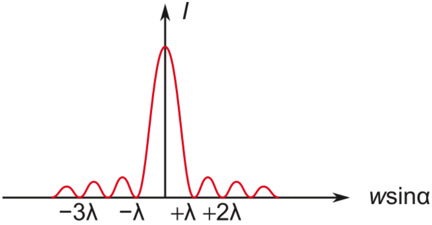
In 2022 the Nobel prize was awarded to Alain Aspect, John Clauser and Anton Zeilinger ”for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

Uncertainty relations

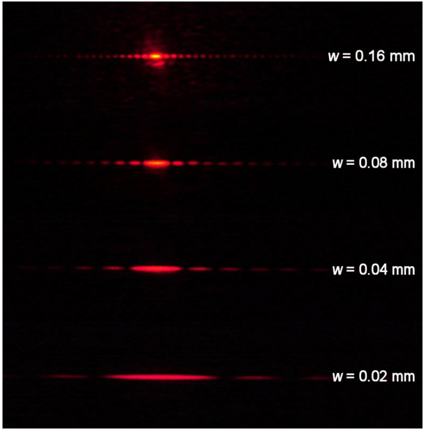
Wave-particle dualism

- Thermal radiation
- Planck’s radiation law
- Photoelectric effect
- Laser
- Compton effect
- Pair production
- Matter waves
- Uncertainty relations

Uncertainty relations 1: Diffraction on a single slit



minima: $n\lambda = w \sin \alpha_n$



Uncertainty relations 1 Comment

The uncertainty relations are very useful for predicting the behavior of quantum systems.

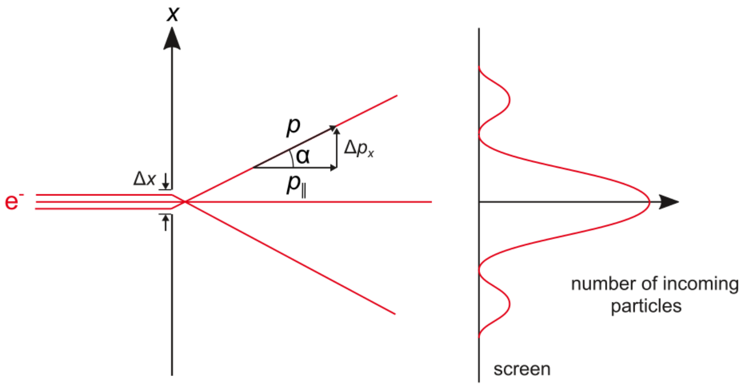
The strictly mathematical derivation of the uncertainty relations was given in 1927 by Werner Heisenberg.

The essence becomes apparent when the particle image is used to describe diffraction at a single slit.

The figures show the intensity after a single slit.

The distance between the minima increases as the width of the slit decreases.

Uncertainty relations 2: Diffraction on a single slit



the particles get a transversal momentum Δp_x after the slit

Uncertainty relations 2 — Comment

The momentum of the particles in front of the slit is parallel to the direction of the beam.

After the slit, some particles get a transverse momentum, so that the diffraction pattern of a single slit results when many particles are observed.

Uncertainty relations 3

Estimate of the transversal momentum with the 1st diffraction minimum

$$\Delta x \sin\alpha_1 = \lambda \quad \text{und} \quad \sin\alpha_1 = \frac{\Delta p_x}{p}$$

and with the de Broglie wavelength $\lambda = h/p$

$$\Delta x \sin\alpha_1 = \lambda = \frac{h}{p} = \Delta x \frac{\Delta p_x}{p} \qquad \text{und} \qquad \Delta x \Delta p_x = h$$

the exact Heisenberg's uncertainty relation is

$$\boxed{\Delta x \Delta p_x \geq \frac{\hbar}{2}}$$

Uncertainty relations 3 — Comment 1

The first diffraction minimum can be used to estimate the relationship between the width of the slit and the uncertainty of the transverse momentum Δp_x.

The first equation gives the diffraction condition for the 1st minimum.

The underlined equation gives the sinus of this deflection angle as the quotient of the corresponding Δp_x for α_1 and the total momentum of the electron.

The second underlined equation results when the de Broglie wavelength is used.

The slit width determines the transverse momentum Δp_x of the particles.

Uncertainty relations 3 Comment 2

With the slit, the particles are localized along the x-direction.

The width of the slit determines the uncertainty of the localization.

The smaller Δx , the larger Δp_x becomes.

The equation outlined in red shows Heisenberg’s exact result.

Uncertainty relations 4

uncertainty relation of energy: with $\Delta E = c\Delta p$ and $\Delta t = \Delta x/c$

$$\Delta t \Delta E \geq \frac{\hbar}{2}$$

uncertainty relation of angular momentum: with $\Delta L = r\Delta p$ and $\Delta \varphi = \Delta x/r$

$$\Delta \varphi \Delta L \geq \frac{\hbar}{2}$$

Uncertainty relations 4 — Comment 1

There are also uncertainty relations for other physical quantities.

The time-energy uncertainty and the angle-angular momentum uncertainty are particularly important.

Here, too, a strict derivation of the uncertainty relations would go beyond the scope of this lecture.

The formulas given are intended to make the uncertainty relations at least plausible.

A photon can be considered for the time-energy uncertainty relation. The photon moves with the speed of light c and the energy-momentum relation is $E = cp$.

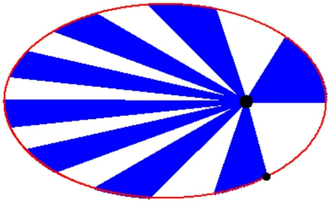
Uncertainty relations 4 Comment 2

For the angle-angular momentum uncertainty relation, a particle moving on a circular path with radius r can be considered.

The angular momentum is $L = rp$ and the variation of the angle is $\Delta\varphi = \Delta x / r$. Here, Δx denotes a certain distance on the circumference of the circle.

Uncertainty relations 5: Consequences

Planets move in orbital planes around the sun



uncertainty relations of a quantum particle $\Delta z \to 0$ $\Delta p_z \to \infty$ or $\Delta p_z \to 0$ $\Delta z \to \infty$.

The electrons of an atom cannot move in orbital planes!

Uncertainty relations 5 — Comment

It has been known since Johannes Kepler (1571-1630) that planets move in orbital planes around the sun.

The figure illustrates the 2nd Kepler law: A line connecting a planet and the sun sweeps over the same areas at the same time intervals.

Newton showed that this is a direct consequence of conservation of angular momentum.

If the plane of the orbit is within the xy-plane, then the uncertainty of Δz is zero and consequently the momentum uncertainty Δp_z is infinitely large.

On the other hand, the position uncertainty along the z-axis is infinitely large when the momentum in the z-direction is zero.

Therefore, the movement of a quantum particle cannot be restricted to one plane.

Uncertainty relations 6: Consequences

Estimation of the kinetic energy of a proton in the atomic nucleus

nuclear diameter $d \approx 2 \cdot 10^{-15}$ m

$$\Delta p \geq \frac{\hbar}{2d} = \frac{h}{4\pi d}$$

energy uncertainty

$$\Delta E \geq \frac{\Delta p^2}{2m_\mathrm{P}} = \frac{c^2 \Delta p^2}{2m_\mathrm{P} c^2} = \frac{(3 \cdot 10^8\,\mathrm{m/s})^2 (4.14 \cdot 10^{-15})^2\,(\mathrm{eVs})^2}{2 \cdot 16\pi^2\,(2 \cdot 10^{-15})^2\,\mathrm{m}^2\,940 \cdot 10^6\,\mathrm{eV}}$$

$$= 5.2\,\mathrm{MeV}$$

For comparison: the binding energy of the electron of the hydrogen atom is 13.6 eV

→ nuclear forces are very much stronger than the Coulomb force

Uncertainty relations 6 — Comment 1

Protons and neutrons make up the atomic nucleus.

The diameter of the nuclei is between 10^{-15} m for helium and $16 \cdot 10^{-15}$ m for uranium.

The core diameter indicates the positional uncertainty of the nucleons (i.e. protons and neutrons) and the momentum of the nucleons can be estimated using the uncertainty relation.

The formula $E_{\text{kin}} = p^2/2m$ of classical physics can be used to estimate the kinetic energy of nucleons, since the energy uncertainty ΔE is very much smaller than the rest energy of a proton ($m_{\text{p}}c^2 = 940 \cdot 10^6$ eV).

Uncertainty relations 6 Comment 2

The kinetic energy of the nucleons is large compared to the binding energy of the electrons.

It is obvious that the nuclear forces that bind the nucleons are much stronger than the Coulomb force that determines the properties of the electron cloud.

Atoms

Modern Physics

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1 Classical Wave Phenomena
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Atoms

1. Early atomic physics
   - The electron and the elementary charge
   - The nucleus
   - The spectrum of the hydrogen atom
   - Bohr's model of the hydrogen atom
   - The spectra of the alkali metals
   - X-ray spectra
   - The Frank-Hertz experiment
2. The Schrödinger equation as a wave equation
3. Quantum mechanics
4. Atoms with many electrons

Early atomic physics 1 Introduction

The idea that atoms form the smallest units of matter comes from ancient Greece.

It was not until the beginning of the 19th century that this idea was seriously studied.

With the ideal gas laws, and in particular Avogadro's law of 1811 (i.e. the product of pressure and volume of a gas is determined by the temperature and by the number of particles in the gas) it became possible to measure the relative masses of chemical compounds.

Since there are innumerable chemical compounds, it was not until 1869 that Dmitri Mendeleev and in the same year Lothar Meyer formulated the first version of the periodic table of the elements.

Early atomic physics 2 — Introduction

The early versions of the periodic system enabled the discovery of a large number of new, unknown elements.

The noble gases in particular were discovered.

The noble gases were completely absent from the first version of the periodic table.

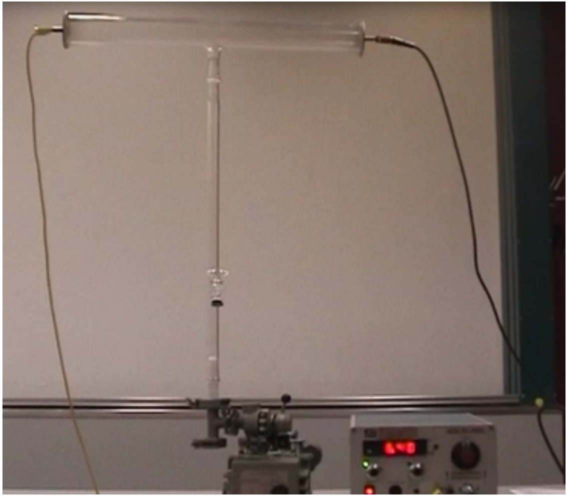
Based on the atomic mass, it had been assumed since the beginning of the 19th century that the atoms are composed of the lightest element, i.e. hydrogen.

Electron

Early atomic physics

- The electron and the elementary charge
- The nucleus
- The spectrum of the hydrogen atom
- Bohr’s model of the hydrogen atom
- The spectra of the alkali metals
- X-ray spectra
- The Frank-Hertz experiment

The electron and the elementary charge 1



(Gasentadungsroehre.mp4)

The electron and the elementary charge 1 Comment

The starting point for the physical investigation of atoms and molecules were experiments with gas discharge tubes.

A gas discharge tube is a tube with electrodes at the ends to which a very high voltage is applied.

In the video, the tube is filled with air and you can see that the air starts to emit light during evacuation.

The emission spectrum is an important source of information.

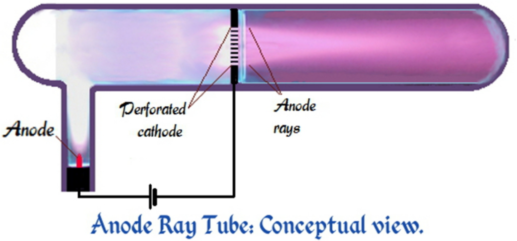
The study of the hydrogen spectrum by Johannes Balmer in 1885 is famous.

In 1896, Pieter Zeeman discovered that the spectral lines of atoms split and shift when a magnetic field is applied.

This discovery is significant because Hendrik Lorentz was able to conclude in 1899 that the spectral lines of atoms and molecules are caused by electrons.

The electron and the elementary charge 2

Eugen Goldstein (1886)



The electron and the elementary charge 2 Comment

Eugen Goldstein modified the simple discharge tube in 1886.

He used grids as electrodes and discovered that there were rays behind the grids, which were then called canal rays.

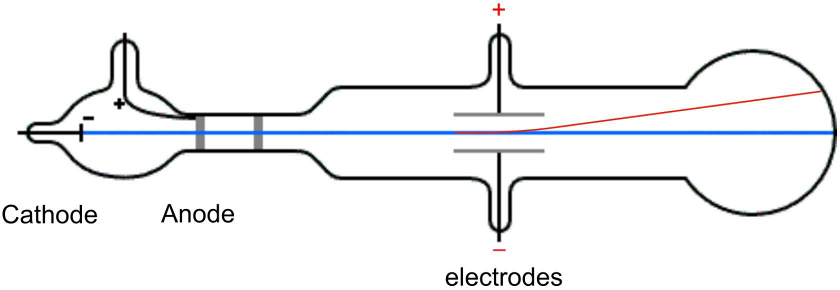
In the figure, a grid is used as the cathode.

The channel rays must consist of positive charges and are called anode rays.

When the grid is positively charged there are also rays called cathode rays.

The electron and the elementary charge 3

The cathode ray tube of Joseph John Thomson (1897)



$\vec{F} = m\vec{a} = q\vec{E}$ acceleration $\vec{a} = \frac{q}{m}\vec{E}$

The electron and the elementary charge 3 Comment 1

The experiments of Sir Joseph John Thomson, in which he discovered the electron in 1897, were decisive.

Thomson expanded the simple canal tube by installing two more electrodes and a magnetic field in the space behind the electrode so that the beams could be deflected by an electric and magnetic field.

The underlined equation gives Newton’s equation of motion and it turns out that the acceleration of the charges depends on the ratio of the charge to the mass of the particles.

A corresponding result is obtained in the case of the Lorentz force.

The picture shows the cathode ray tube with which Thomson discovered the electron.

The electron and the elementary charge 3 Comment 2

The blue line shows the beam when no voltage is applied to the deflection electrodes.

The red line shows the case with the voltage applied so that the beam is deflected.

When comparing his measurements with anode and cathode ray tubes, Thomson found that the mass of the particles that make up the cathode ray must be much smaller than the mass of the particles of the anode ray.

He also found that the ratio q/m is always the same for the cathode ray, while different ratios q/m can occur with the anode ray.

The electron and the elementary charge 3 Comment 3

Since the mass of the electrons is more than a factor of 1000 smaller than the mass of the atoms and molecules, the behaviour of the cathode rays differs from the anode rays not only due to the charge of the particles.

Thomson soon realized that he had discovered the first subatomic particle.

A year later, in 1898, Wilhelm Wien discovered the proton in a similar experiment.

In his reflections on the Zeeman effect in 1899, Hendrik Lorentz came to the conclusion that the light emission of the atoms must be caused by electrons.

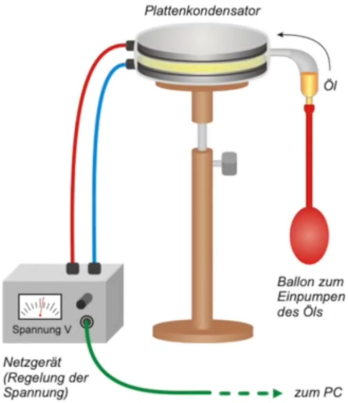
The electron and the elementary charge 3 Comment 4

In 1902 Hendrik Lorentz and Pieter Zeeman were awarded the Nobel Prize “in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena”.

In 1906 Joseph John Thomson was awarded the Nobel Prize “for his theoretical and experimental investigations on the conduction of electricity by gases”.

The electron and the elementary charge 4

The Millikan experiment (1910)



(MillikanVersuch.mp4)

The electron and the elementary charge 4 Comment 1

With the anode and cathode rays only the ratio q/m could be determined, since the mass of the particles was unknown at that time.

Robert Millikan and Harvey Fletcher therefore introduced a new method of charge measurement in 1910.

Instead of the unknown particles of the anode and cathode rays, they used macroscopic oil droplets.

The diameter of the droplets and thus the mass of the droplets can be determined with a microscope.

The illustration shows the experimental setup. Oil droplets are blown through a nozzle between the charged plates of a capacitor.

The electron and the elementary charge 4 — Comment 2

There the oil droplets can be observed with a microscope.

The oil droplets carry an electrical charge, which is created by natural radioactivity or the disintegration of the oil.

If there is no voltage applied on the plates, the droplets slowly sink to the bottom.

When a voltage is applied, the speed of the droplets changes due to the Coulomb force.

The evaluation of the measurements shows that the charge is quantized in units of the elementary charge.

The numerical value of the elementary charge can also be determined fairly precisely.

The electron and the elementary charge 4 Comment 3

The work of Robert Millikan and Harvey Fletcher made mass spectroscopy possible.

Since the numerical value of the elementary charge is known, the mass of atoms and molecules can be determined in channel beam experiments.

In 1923 Robert Millikan was awarded the Nobel Prize Robert “for his work on the elementary charge of electricity and on the photoelectric effect”.

Nucleus

Early atomic physics

- The electron and the elementary charge
- The nucleus
- The spectrum of the hydrogen atom
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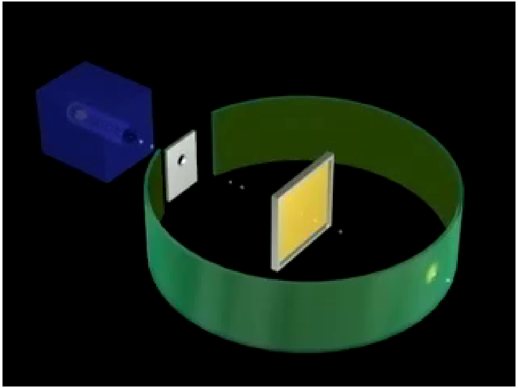
The nucleus 1

Rutherford scattering (1909-13): scattering of α-particles on a thin gold foil

→ most α-particles are not at all scattered

(RutherfordExperiment.mp4)



The nucleus 1 — Comment

The animation illustrates Rutherford’s scattering experiment.

α-particles are the nuclei of helium atoms.

For most α-particles, the gold foil is no obstacle.

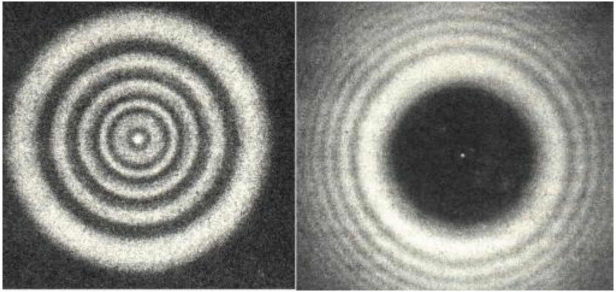
Only a few α-particles are scattered.

From the number of scattered α-particles as a function of the scattering angle, Rutherford was able to show that the α-particles were scattered at quasi point-like atomic nuclei.

The diameter of the atomic nuclei is so small that it could not be determined with this experiment.

The nucleus 2

diffraction on a hole and on a pinhead



(FresnelbeugungFreiburg.mp4)

Diffraction experiments with electrons on the nucleus $d \approx 10^{-14}$ m

$$\lambda = \frac{h}{p} = \frac{hc}{eU} = \frac{12.42 \cdot 10^{-7}\,\text{Vm}}{U} \quad \rightarrow \quad \lambda << 10^{-14}\,\text{m} \rightarrow U >> 124\,\text{MV}$$

The nucleus 2 Comment 1

If you want to determine the diameter of an atomic nucleus, you have to make use of the wave character of the particles.

The pictures demonstrate the optical analogue. The left picture shows the scattering of photons at a pinhole. The picture on the right shows the scattering of photons at the head of a pin.

The video shows an experiment with an expanded laser beam. The light is collected on a screen behind the objects (pin head, edge and two pinholes).

With the pin head you can also see that there are maxima and minima of the intensity due to the interference of diffracted light waves in the vicinity of the pin but also in the shadow area.

The nucleus 2 — Comment 2

If you want to observe the diffraction pattern of an atomic nucleus instead of the head of a pin, you can use electron waves, for example, whose wavelength is smaller than the diameter of the atomic nucleus.

Since the core diameter is in the range of 10^{-14} m, high-energy relativistic electrons must be used.

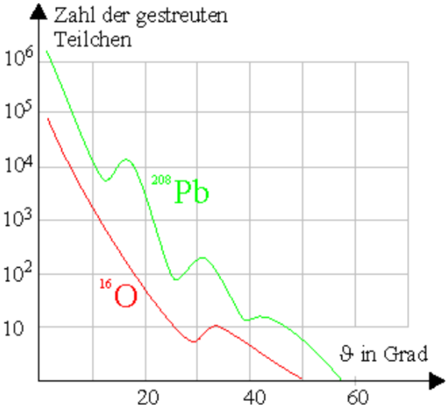
The rest energy of the electron can be neglected and the energy of the electron is given by the product of the speed of light and momentum, i.e. $E = cp$

If the electron is accelerated with the voltage U, then the kinetic energy results from the product of the voltage and the elementary charge, i.e. $E_{\text{kin}} = eU$ and the formula for the de Broglie wavelength results in the formula underlined in red for the wavelength of relativistic electrons.

If the wavelength is to be smaller than 10^{-14} m, the voltage must exceed 100 MV.

The nucleus 3

elastic electron scattering



the kinetic energy of the electrons is 500 MeV

The nucleus 3 — Comment 1

The figure shows the experimental results of elastic electron scattering on the nuclei of oxygen and lead.

The acceleration voltage is 500 MV and the kinetic energy of the electron therefore very much larger than the rest energy of $m_0c^2 = 500$ keV.

In the forward direction there is a very large number of electrons, since most of the electrons penetrate the sample, as in the Rutherford experiment, without being deflected by the nuclei.

Outside the electron beam, the interference of the diffracted electron waves is observed.

In case of oxygen, the diffraction minimum of 1st order can be resolved.

The nucleus 3 Comment 2

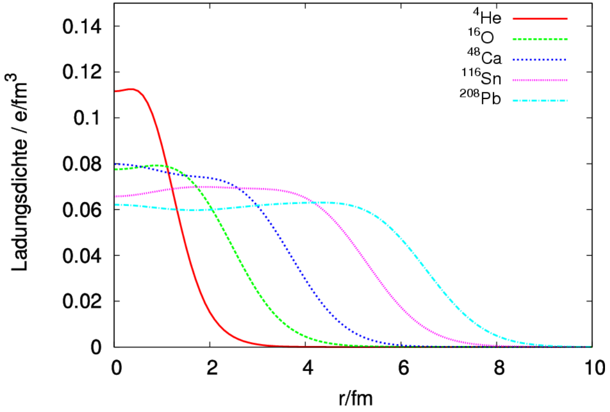
In the case of lead, three diffraction maxima can be observed.

As with the gap or the pinhole, the minima shift to larger deflection angles when the core radius is reduced.

Even without a detailed evaluation, the figure shows that the core radius of lead is larger than the core radius of oxygen.

The nucleus 4

nuclear charge density



$\rightarrow$nuclear radius $\approx 10^{-15}$ m (atomic radius $\approx 10^{-10}$ m)

The nucleus 4 Comment

The distribution of the charge density in the atomic nucleus can be determined from such measurements of elastic electron diffraction.

The figure shows the distribution of the nuclear charge density for different nuclei.

The core radius is in the range of a few femtometers, i.e. a few 10^{-15} m.

The radius of the electron shell can be derived from measurements of the crystal structure.

The atomic radius is about five orders of magnitude larger than the radius of the atomic nucleus.

If you take the radius of the Adenauerring (1.1 km) for comparison, then the atomic nucleus corresponds to a marble ($\approx$1 cm) lying in the tower of the castle.

The nucleus 5

Linear accelerator
from Stanford University

The nucleus 5 Comment

These experiments were largely carried out and directed by Robert Hofstadter in the 1950s at Stanford University.

The left figure shows the elongated hall of the linear accelerator of the university and on the right a photo of the experiment hall with the target (left yellow box), the deflection magnets (blue structures) and the detector (right yellow box).

The accelerator has been continuously developed so that the electrons currently reach an energy of 50 GeV.

Robert Hofstadter was awarded the Nobel Prize in 1961 “for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons”.

The nucleus 6

A nucleus contains Z protons with the charge (Z is the atomic number)

$$q_P = +e$$

and N neutrons which carry no electric charge

$$\text{mass of proton} \approx \text{mass of neutron}$$

The notation for nuclei is

$$^{A}_{Z}\text{nuclide}$$

$A = Z + N$ is the mass number

Isotops denote nuclei with the same Z but different values of A e.g.

$$^{12}\text{C},\ ^{13}\text{C and } ^{14}\text{C}$$

The nucleus 6 Comment 1

The atomic number Z determines the electronic properties of an atom and can be determined directly from the characteristic X-ray spectrum of the element.

In 1920 Rutherford concluded from a comparison of the atomic number Z with the mass of the nucleus that the nucleus must contain neutral particles in addition to the positively charged protons.

These neutral particles are called neutrons.

The nucleus 6 Comment 2

However, direct detection of the neutron was difficult and was only achieved by Rutherford's student James Chadwick in 1932.

James Chadwick was awarded the Nobel Prize as early as 1935 “for the discovery of the neutron”

The neutron is slightly heavier than the proton and is only stable in the atomic nucleus.

As a free particle, the neutron uses its rest energy to transform itself into the lighter proton and an electron with a lifespan of 880 seconds.

With the discovery of the neutron, the basic structure of an atomic nucleus was understood.

The nucleus 6 Comment 3

An atomic nucleus consists of Z protons.

Z denotes the atomic number.

There are also N neutrons.

The sum of the atomic number and the number of neutrons is called the mass number $A = Z + N$.

Nuclei are denoted by the chemical name of the element.

The mass number is given as the index at the top left.

The atomic number is sometimes given as an index at the bottom left.

The nucleus 6 Comment 4

Since the nuclear charge is already clearly determined by the name of the element, this index is often omitted.

Most elements can be formed with different numbers of neutrons.

The different nuclei of an element are called isotopes.

Revision

Summary in questions

1. What does the collapse of the wave function mean?
2. Give the uncertainty relations of momentum, energy, and angular momentum.
3. Give reasons for the fact that atomic orbitals differ so much from the orbits of planets.
4. Calculate the wavelength when electrons are accelerated with a voltage of 500 MV.
5. Give the general notation for the description of nuclei.