What you *must* know to pass the exam
2025

The examination starts with a quiz of 5 of these questions. Entry to the oral examination is granted only if at least 3 of them are answered correctly!

Each answer is usually just one short sentence. *The additional details given are not required at the entrance quiz, but should be known on the verbal part.*

1   Quantum Mechanics - QM

1. What device is the spectrometer?
   Solution:
   Spectrometers measure the intensity of an EM radiation as a function of the wavelength. Spectrometers in the optical range use optical gratings.

2. Value and unit of the elementary charge and of 1 electron volt
   Solution:

   $$e = 1.6 \times 10^{-19} C, \quad 1eV = 1.6 \times 10^{-19} J$$

3. Value of the thermal energy at room temperature in electron volts
   Solution:
   Room temperature $T_{room} = 300\,K$

   $$E_{thermal} = k_B \cdot T_{room} = 0.026 eV$$

4. How does the total energy of thermal radiation depend on the temperature?
   Solution:

   $$\mathcal{E}_{tot} = \sigma \times A \times T^4$$

   where σ is the Stephan-Boltzmann constant and A is the total radiating area.
   Need not know the value of σ. $\sigma = 5.67 \times 10^{-8} \dfrac{J}{m^2 K^4}$

5. Value and unit of the Planck constant
   Solution:

   $$h = 6.62 \times 10^{-34}\ Js$$

6. What is a wave vector?
   Solution:
   The direction of the wave vector $\mathbf{k}$ is the direction of propagation, its magnitude is $\dfrac{2\pi}{\lambda}$, where λ is the wavelength.

7. de Broglie wavelength formula, momentum expressed with the wave vector
   Solution:

   $$\lambda = \frac{h}{|\mathbf{p}|}, \quad \mathbf{p} = \hbar\mathbf{k}$$

8. How can the energy of a physical system change in classical physics and in quantum mechanics? What about electromagnetic waves?

   Solution:

   In classical physics the energy is continuous, while in quantum physics bound states have discreet energy levels. For EM waves the energy can only change in $\varepsilon = h\,\nu$ quanta, where h is the Planck constant.

   > *Detailed explanation (for the corresponding examination topics):*
   > *In classical physics the energy change can be arbitrarily small, therefore the energy of the system is continuously variable. In quantum mechanics this may still be the case for free particles, however in all other cases the energy may only change in discrete units. Such a unit is called a quantum.*

9. When do we need to use quantum mechanics instead of classical physics?

   Solution:

   When lengths and masses are so small that uncertainty relations must be used or when the potential changes rapidly over distances comparable with these lengths.

   > *Example (for the corresponding examination topics):*
   > *Electrons in a slowly varying EM field can be treated classically, while in atoms and solids where the change in the potential occurs on small scales quantum mechanics must be used.*

10. What quantity is called "potential' in quantum mechanics?

    Solution:

    The (operator of the) potential energy is called simply 'potential' in QM.

11. Particle-wave duality and what it means

    Solution:

    In experiments particles and EM radiation may behave as classical mass points or classical waves, however they are neither of these.
    > *Detailed explanation: (for the corresponding examination topics):*
    > *Electrons and EM radiation are neither classical waves, nor classical particles. They cannot be described by classical ideas. However under certain conditions they behave like they were one of these. Before realizing this people used to think that they have a dual (classical) nature, i.e. they may behave either as waves or as particles depending on the conditions in which they are being observed.*

12. What is the wave function?

    Solution:

    The wave function or state function describes the state of an elementary particle or microscopic system.

*Detailed explanation (*for the corresponding examination topics*):*
In some sense the wave function is the particle.
E.g. electrons are point like particles, and their wave functions determines how they are localized in space and what their momentum or velocity is.

13. Commutators and Uncertainty Relations between **p** and **r**, t and $\mathcal{E}$, L_x, L_y and L_z.

    Solution:

$$[\mathbf{r}_\ell, \mathbf{p}_m] = i\,\hbar\delta_{\ell m} \qquad \Rightarrow \Delta x\,\Delta p_x \geq \frac{\hbar}{2}, \ etc$$

$$[t, \mathcal{E}] = i\,\hbar \qquad \Rightarrow \Delta t\,\Delta\mathcal{E} \geq \frac{\hbar}{2}$$

$$[L_x, L_y] = i\,\hbar\,L_z \qquad \Rightarrow \Delta L_x\,\Delta L_y \geq \frac{\hbar}{2}\,L_z$$

*Detailed explanation (*for the corresponding examination topics*):*
Commutators are operator formulas that describe if the order of two operators matter. If it does then the commutator of the two operators is a third operator (which may be just a multiplication with a complex or real number). Each non zero commutator corresponds to an Uncertainty Relation.

14. What is the *Density of State?*

    Solution:

The density of state $g(\mathcal{E})$ determines the number of states in an energy interval $\Delta\mathcal{E}$ around a given energy value $\mathcal{E}$:

$$\mathcal{N} = g(\mathcal{E})\,\Delta\,\mathcal{E}$$

*Examples (*for the corresponding examination topics*):*
For electrons in a potential box:

$$g(\mathcal{E}) = \frac{8\,\pi\sqrt{2\,m^3}}{\hbar^3}\sqrt{\mathcal{E}}$$

For photons:

$$g(\nu) = \frac{4\,\pi\,V}{c^3}\nu^2 \qquad\qquad (1.1)$$

$$g(\mathcal{E}) = \frac{4\,\pi\,V}{h^3\,c^3}\mathcal{E}^2 \qquad\qquad (1.2)$$

15. Give both the time dependent and stationary Schrödinger equations in one dimension!

    Solution:

$$-\frac{\hbar^2}{2\,m_e}\frac{\partial^2\psi}{\partial x^2} + V(x)\,\psi = i\,\hbar\frac{\partial\psi}{\partial t}$$

$$-\frac{\hbar^2}{2\,m_e}\frac{d^2\phi}{dx^2} + V(x)\,\phi = \mathcal{E}\phi$$

16. Difference of the classical orbit and the QM orbital of an electron

    Solution:

    Orbit *denotes the classical image of a path an electron travels around the nucleus, while* orbital *is the wave function in an atom, molecule or solid.*

        (for the corresponding examination topics): In chemistry "orbital" denotes the range around an atom or molecule where the electron can be found with, say 90% probability.

17. Give definitions of the operators of p_x, x, $\mathbf{p}$ and $\mathbf{r}$!

    Solution:

$$\hat{p}_x := \frac{\hbar}{i}\frac{d}{dx},$$
$$\hat{x} := x\cdot$$
$$\hat{\mathbf{p}} := \frac{\hbar}{i},\nabla x, \;\; where \; \nabla \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$
$$\hat{\mathbf{r}} := \mathbf{r}\cdot$$

18. State both variations of the Pauli principle!

    Solution:

    (a) *No two electrons can be in the same state. (In an atom no two electrons can have the same 4 quantum numbers: n, ℓ, m and s).*

    (b) *The wave function of a many electron system is antisymmetric, i.e. it changes sign when coordinates of two electrons are exchanged:*

$$\psi(\mathbf{r}_1, \ldots \mathbf{r}_\ell, \ldots \mathbf{r}_m, \ldots) = -\psi(\mathbf{r}_1, \ldots \mathbf{r}_m, \ldots \mathbf{r}_\ell, \ldots)$$

19. What is the Boltzmann factor?

    Solution:

$$\frac{n_1}{n_2} = e^{-\frac{(\mathcal{E}1 - \mathcal{E}_2)}{k_B T}}$$

20. What are the statistical energy distributions formulas?

    Solution:

    Statistical energy distribution formulas describe the expected number of particles at a given energy (level).

21. In which conditions do we need to use quantum statistics?

    Solution:

    Quantum statistics must be applied when the density of the particles is high enough for the wave functions of the particles to overlap therefore the particles become "indistinguishable".

        Detailed explanation (for the corresponding examination topics):

        (The density limit is where the thermal deBroglie wave function is equal to the inter-particle distance.)

22. When should the Maxwell-Boltzmann (M-B) energy distributions formula be applied?

Solution:

$f_{M-B}(\mathcal{E})$ is used when the wave functions do not overlap therefore the particles are distinguishable.

The corresponding formulas (for the corresponding examination topics to know them)

$$f_{M-B}(\mathcal{E}) = \frac{1}{Z}\,e^{-\frac{\mathcal{E}}{k_B T}},\ \ where\ Z = \int\limits_0^\infty g(E)\,e^{-\frac{\mathcal{E}}{k_B T}}\,d\mathcal{E}$$

23. When should the Bose-Einstein (B-E) energy distributions formula be applied?

    Solution:

    $f_{B-E}(\mathcal{E})$ must be applied to bosons: indistinguishable integer spin particles for which the Pauli principle is not valid.
    The corresponding formula (for the corresponding examination topics to know it)

    $$f_{B-E}(\mathcal{E}) = \frac{1}{A\,e^{\frac{E}{k_B T}} - 1}$$

24. When should the Fermi-Dirac (F-D) energy distributions formula be applied?

    Solution:

    $f_{F-D}(\mathcal{E})$ must be applied to fermions: indistinguishable half spin particles for which the Pauli principle must be used.
    The corresponding formula (for the corresponding examination topics to know them)

    $$f_{F-D}(\mathcal{E}) = \frac{1}{e^{\frac{E-E_F}{k_B T}} + 1}$$

2 Relativity Theory - REL

1. Define the Galilean Principle of Relativity!

   Solution:

   Any physics experiment gives the same results in all inertial reference frames.

2. Define Einstein's principle of Special Relativity!

   Solution:

   The results of any physics experiment and the value of constants of nature are the same in every inertial reference frame.

3. What are the invariants in Galilean Relativity?

   Solution:

   Distances of points and time.
   The results of physics experiments.

4. What are the invariants in Galilean and Special Relativity?

   Solution:

   The constants of nature
   The (square of the) interval between events. The results of physics experiments.

5. What is the 'Addition of Velocities' in Galilean Relativity?

   Solution:

   It gives the transformation formula of velocities between two inertial reference frames $\mathcal{K}$ and $\mathcal{K}'$: $v = v' + v_o$ where v_o is the velocity of $\mathcal{K}$ relative to $\mathcal{K}'$.

6. What is the 'Addition of Velocities' in Einstein's Special Relativity?"

   Solution:

   It gives the transformation formula of velocities between two inertial reference frame $\mathcal{K}$ and $\mathcal{K}'$:
   $$v = \frac{v' + v_o}{\sqrt{1 - \frac{v_o^2}{c^2}}}$$
   where v_o is the velocity of K' relative to K.

7. What are Constants of Nature?

   Solution:

   Physical quantities which are invariant, (i.e. they have the same value) in every reference frame like the speed of light in vacumm (c) or Planck's constant (h),

8. Write down the Lorentz transformation formula using the notation of $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ for motion along the x axis!

   Solution:

   $$x = \gamma(x' + v_o \cdot t') \qquad t = \gamma(t' + \frac{v_o}{c^2})$$
   or
   $$x' = \gamma(x - v_o \cdot t) \qquad t' = \gamma(t - \frac{v_o}{c^2})$$
   and $y = y', z = z'$

9. What is the light cone?

   Solution:

   The light cone describes the paths of all light rays starting from and ending in the same 4D space-time event $E(\equiv (t, x, y, z))$, which divides space time for four regions: the light cone itself, the absolute past and future of event E and all other regions, called elsewhere. It looks like a double cone in 3D (t,x,y).

10. Define the square of the space-time interval!

    Solution:
    $s^2 = c^2 t^2 - \mathbf{r}^2$
    It can be positive, negative or zero.

11. What is proper time?

    Solution:
    The time measured by a clock which is stationary in a given reference frame (i.e. a co-moving clock).

12. What is time dilation?

    Solution:
    If $\mathcal{K}'$ moves relative to $\mathcal{K}$ the time difference measured in $\mathcal{K}$ between the same two events is larger in $\mathcal{K}'$, i.e. $\Delta t = \gamma \cdot \Delta t' > \Delta t'$

13. What is length contraction?

    Solution:
    If $\mathcal{K}'$ moves relative to $\mathcal{K}$ the spatial distance measured in $\mathcal{K}$ between the same two events is smaller in $\mathcal{K}'$, i.e. $\Delta x = \Delta x'/\gamma < \Delta x'$

14. **Solution:**

15. What is the solution of the 'Twin Paradox'?

    Solution:
    Twin paradox: if one of two twins travel somewhere and back they the stationary twin ages more because of time dilation, although seemingly from the point of view of the traveling twin the other should age less. The solution: to come back the traveling twin must change reference frames so they can't see much of the aging of the remaining twin.

16. Classical physics has conservation laws for energy and momentum. So does relativity. What is the difference between these two?

    Solution:
    In classical physics these two laws are independent, while in relativity theory they are part of the energy-momentum 4-vector and not independent.

17. What is the general formula that includes $E = mc^2$?

    Solution:
    $\mathcal{E}^2 - p^2 c^2 - m^2 c^4$
    where $\mathcal{E}$ is the energy, p is the momentum and m is the (rest) mass. When $p = 0$ this reduces to $E = m\,c^2$

18. What is the mass energy equivalence?

    Solution:
    Even massive objects stationary in a reference frame have energy (calculated as $\mathcal{E} = m\,c^2$) and energy not associated with any mass (e.g. in an EM wave (light)) are affected by gravity.

19. What is the Equivalence Principle?

    Solution:
    Gravity is indistinguishable from acceleration, i.e. a 1kg mass weights the same on Earth as it would in a rocket far from any planet if the rocket is accelerating with g.

20. What is a geodesic?

    Solution:
    Geodesic is a curve an object moves on without any other object acting on it in a curved space-time.

3 Solid State Physics - SSP

1. Define short range ordering
   Solution:
   first- or second-nearest neighbors of an atom are arranged in the same structure.

2. Define long range ordering!
   Solution:
   once the positions of any atom and its neighbors are known at one point, the place of each atom is known precisely throughout the material.

3. What are solids?
   Solution:
   Solids are composed of atoms or molecules at fixed relative positions in which either short or long range ordering is present.

4. What is a crystal?
   Solution:
   Crystals are solids with long range ordering.

5. What are cells in a crystal?
   Solution:
   Cells are regions of space from which the whole infinite (perfect / ideal) crystal lattice can be built up by translations in all directions without overlap and without leaving any gaps.

6. What are primitive cells?
   Solution:
   A primitive cell is a cell which contains a single lattice point only.
   *Elaboration: (*for the corresponding examination topics*)*
   If a lattice point is shared by N cells only $1/N$-th of it belongs to any one of them.

7. What are conventional unit cells?
   Solution:
   A conventional unit cell reflects all but the translational symmetries of the crystal.

8. What is a point lattice?
   Solution:
   The point lattice describes the geometric structure of a crystal.

   *Detailed explanation (*for the corresponding examination topics*):*
   This description separates the physical lattice into a point lattice *that determines the cells and a* basis, *which is the arrangement of a single atom or molecule or a group of atoms or molecules put into the points of the point lattice. The same crystal lattice can be described with many different selection of these.*

9. What is the basis?
   Solution:
   It is the arrangement of a single atom or molecule or a group of atoms or molecules that must be put into the points of the point lattice to describe the physical crystal.

*Elaboration (*for the corresponding examination topics*):*
The same crystal lattice can be described with many different selection of these.

10. What is a Bravais lattice?

    Solution:

    A Bravais lattice is a lattice in which all points are equivalent.
    *Detailed explanation (*for the corresponding examination topics*):*
    The orientation of each neighboring points viewed from any point of the lattice is the same. With suitable selection of a basis any physical crystal lattice can be described with a Bravais lattice.

11. What kind of symmetry must all crystals have?

    Solution:

    All crystals must have translational symmetry.

12. What is the reciprocal lattice?

    Solution:

    Def. #1
    The reciprocal lattice of a crystal with base vectors $\mathbf{a}_i$ is also a crystal lattice with base vectors $\mathbf{b}_i$ for which

    $$\mathbf{a}_i \cdot \mathbf{b}_i = 2\pi$$

    Def. #2
    The reciprocal lattice of a crystal is the Fourier transform of the crystal.
    *Elaboration (*for the corresponding examination topics*):*

    $$\mathbf{b}_1 = 2\pi\frac{\mathbf{a}_2 \times \mathbf{a}_3}{\mathbf{a}_1(\mathbf{a}_2 \times \mathbf{a}_3)}, \ \mathbf{b}_2 = 2\pi\frac{\mathbf{a}_3 \times \mathbf{a}_1}{\mathbf{a}_1(\mathbf{a}_2 \times \mathbf{a}_3)}, \ \mathbf{b}_3 = 2\pi\frac{\mathbf{a}_1 \times \mathbf{a}_2}{\mathbf{a}_1(\mathbf{a}_2 \times \mathbf{a}_3)}$$

13. What is the dispersion relation for electrons?

    Solution:

    the $\mathcal{E}(\mathbf{k})$ function, where $\mathcal{E}$ is the energy and $\mathbf{k}$ is the wave vector.

14. What is the dispersion relation for phonons?

    Solution:

    It is the $\omega(\mathbf{k})$ function
    *Elaboration (*for the corresponding examination topics*):*
    Valid for phonons and any other cases when $\mathcal{E}(\mathbf{k}) = \hbar\omega(\mathbf{k})$),

15. What solids are called conductors?

    Solution:

    Materials that do not have any gap between the valence and conduction bands.

16. What solids are called insulators?

    Solution:

    Materials with $\mathcal{E}_g \gg k_B T$ between the valence and conduction bands.

17. What solids are called semiconductors?

    Solution:

    Materials with $\mathcal{E}_g \geq k_B T$ between the valence and conduction bands, that still somewhat conduct electricity, whose resistivity falls with increasing temperature.

18. Differential Ohm's law formula

    Solution:

    $$\mathbf{j} = \sigma\,\mathbf{E}$$

    where $\mathbf{j}$ is the current density ($[A/m^2]$), $\mathbf{E}$ is the electric field ($[V/m]$) and σ is the conductivity ($[1/\Omega\,m]$).

19. Define the crystal momentum of Bloch electrons

    Solution:

    $\mathbf{p}_{crystal} = \hbar\,\mathbf{k}$ – *where $\mathbf{k}$ is the wave vector of the electron.*

    Elaboration (for the corresponding examination topics):
    The total momentum of Bloch electrons is

    $$\mathbf{p} = \mathbf{p}_{crystal} + \mathbf{p}_{lattice}$$

20. Define the mobility of charge carriers

    Solution:

    Is the proportionality factor μ between the velocity of the charge carrier and the applied electric field.

    $$\mathbf{v} = \mu \cdot \mathbf{E}$$

    Its dimension is $\dfrac{m^2}{s\,V}$.

21. What is the Fermi energy in metals?

    Solution:

    In metals the energy below which all states are occupied and above which all states are empty at 0K.

22. What is the Fermi energy in insulators and intrinsic semiconductors?

    Solution:

    The Fermi energy is the chemical potential of the electrons. It lies in the energy gap.

    Elaboration (for the corresponding examination topics):
    The constant E_F appears in the Fermi-Dirac distribution function. At absolute 0K is usually in the middle of the gap between the valence and conduction bands.

23. Give the effective mass formula in 1D!

    Solution:

    $$\frac{1}{m_{eff}} = \frac{1}{\hbar^2}\frac{d^2 E}{dk^2}$$

24. Give the effective mass formula in 3D!

    Solution:

    $$\left(\frac{1}{m_{eff}}\right)_{i,j} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k_i\,\partial k_j}$$

25. What are holes?

    Solution:

    Holes are positively charged charge carriers that correspond to missing electrons.

26. Can you use both holes and electrons together to describe conduction in metals?

    Solution:

    Not together. Either holes or electrons can be used though.

        Detailed explanation (for the corresponding examination topics):

        Conduction in any single band can be described equivalently as either the current of electrons or the current of holes, but not with both together. Usually holes are used to describe the current in bands where there is a dominance of electrons, or where the mobility of the holes is larger than that of the electrons. In transition metals holes conduct electricity.

27. Can you use both holes and electrons together to describe conduction in semiconductors?

    Solution:

    Yes, usually the charge carriers in conduction bands are electrons while in valence bands holes.

        Detailed explanation (for the corresponding examination topics):

        Holes are positively charged charge carriers that correspond to missing electrons. Conduction in any single band can be described equivalently as either the current of electrons or the current of holes. This is the case for metals. Usually holes are used to describe the current in bands where there is a dominance of electrons. In materials where more than one band contribute to conduction (e.g. semiconductors and some metals where there are separate conduction and valence bands) the charge carriers in conduction bands are the electrons while in valence bands holes are used.

28. What are majority charge carriers?

    Solution:

    Majority charge carriers are mobile electrons or holes with the larger current determined by their mobility and/or concentration.

        Detailed explanation (for the corresponding examination topics):

        In crystals where both electrons and holes are present (in their separate bands) the total current is the sum of the current of these. Holes and electrons move in opposite directions, but the current of both of them flows in the same direction. The magnitude of the corresponding concentrations and the velocities (i.e. the mobilities) of these may be different. Majority charge carriers are the ones whose current is larger.

29. What are minority charge carriers?

    Solution:

    mobile electrons or holes with the smaller current determined by their mobility and/or concentration.

*Detailed explanation (*for the corresponding examination topics*):*

In crystals where both electrons and holes are present (in their separate bands) he total current is the sum of the current of these. Holes and electrons move in opposite directions, but the current of both of them flows in the same direction. The magnitude of the corresponding concentrations and the velocities (i.e. the mobilities) of these may be different. Majority charge carriers are the ones whose current is larger.

30. How can we measure the sign of the majority charge carriers?

    Solution:

    The sign of the majority charge carriers can be determined by using the Hall effect.

31. What are the *space charge* region and the *depletion region*?

    Solution:

    These two concepts are equivalent and denotes the region around the interface in a p-n structure.

    *Elaboration (*for the corresponding examination topics*): around the interface between the n- and p-type parts. The name "space charge region" refers to the fact the region contains ionized dopant atoms, while the name "depletion region" reflect the fact this region is depleted of (movable) charge carriers.*

32. What is the p-n junction?

    Solution:

    The p-n junction is a junction between p and n doped parts of a semiconductor material.