General Physics 2

Date and time: Wednesday 15:15-16:00
Group code: Z00-32a
Student: Nykonchuk Illia, 245693

1. Fundamentals and principles of thermodynamics

Thermodynamics is a science that studies the general laws of the mutual transformation of energy from one form to another. It is a phenomenological science, based on a synthesis of experimental facts. The processes occurring in thermodynamic systems describe macroscopic quantities (temperature, pressure, components of components) that are introduced to describe systems consisting of a large number of particles and are not applicable to these molecules and atoms, in contrast, for example, to the values entered in mechanics or electrodynamics. The laws of thermodynamics are general in nature and do not depend on the specific details of the structure of matter at the atomic level. Therefore, thermodynamics is successfully applied in a wide range of issues of science and technology, such as energy, heat engineering, phase transitions, chemical reactions, transport phenomena, and even black holes.

Laws of thermodynamic

The Zeroth law

Says that if each of the two thermodynamic systems is in thermal equilibrium with some third, then they are in thermal equilibrium with each other.

Example: Suppose, that we have a glass of hot water and a glass of cold water and we place them in one room for a few hours. After that time water in this two glasses will reach thermal equilibrium with the room and eventually all 3 reach the same temperature

The First law

Represents a concretization of the general physical law of energy conservation for thermodynamic systems in which it is necessary to take into account thermal, mass transfer and chemical processes. In simple words it says that the total amount of energy in an isolated system is conserved.

The change ΔU of the internal energy of an uninsulated thermodynamic system is equal to the difference between the amount of heat Q transferred to the system and the work A, the perfect system on external bodies.

$$\Delta U = Q - A \qquad \text{or} \qquad Q = \Delta U + A$$

For example, you boil a water. The amount of heat is used to heat them (the energy of the particles increases, that is, the internal energy of the system), and then the cover is lifted - this is the work that the system performs.

Adiabatic process is the process of thermal insulation of the system from the environment, i.e.

$$Q = 0 \Rightarrow \Delta U = A$$

Change in internal energy occurs only due to the work of external forces. Or the work performed by the system occurs due to a decrease in internal energy. Almost all real processes occur with heat transfer: adiabatic processes are a rare exception.

The first law of thermodynamics for isoprocesses

In the **isothermal process**, the temperature does not change, so the internal energy does not change.

$$\Delta U = \frac{i}{2}\frac{m}{M} R\Delta \mathrm{T},\ \Delta T=0,\ \Delta U = 0, \text{ so } \mathbf{Q=A'}$$

The entire amount of heat that gas receives is spent on the work against external forces. Or, if the gas is compressed, the temperature does not change, external forces perform the work, and the gas gives off a certain amount of heat to the environment.

In the **isochoric process**, the volume does not change, so the work is zero

$$A = -p\Delta \mathrm{V},\ \Delta V = 0,\ A=0$$

$$Q = \Delta U \quad \Rightarrow \quad Q = \frac{i}{2}\frac{m}{M} \Delta R\mathrm{T}$$

If the gas is isochorically cooled, its internal energy decreases, and it gives off heat to the environment.

The Second law

The first law is one of the most general and fundamental laws of nature. No process is known where it would be violated. If any process is prohibited by the first law, then you can be sure that this process will never happen. But the first law does not explain anything in which direction the processes are taking place. **For example**, when a stone falls, all its kinetic energy disappears when it hits the ground, but the internal energy of the stone itself and the bodies around it increase, so that the law of conservation of energy is not violated. But the first law of thermodynamics would not contradict the reverse process, in which a certain amount of heat would pass to the stone lying on the ground from surrounding objects, as a result of which the stone would rise to a certain height. However, no one has ever observed such spontaneous jumping stones.

The second law of thermodynamics has several formulations:

1. The transition of heat from a body with a lower temperature to a body with a higher temperature is impossible.
2. A process is impossible, the result of which would be the completion of work due to the heat taken from one body (This formulation imposes a restriction on the conversion of internal energy into mechanical energy).
3. **Entropy** - an indicator of system disorder. The higher the entropy, the more chaotic the movement of material particles that make up the system. For example, in the liquid state, water is a rather disordered structure, since the molecules move freely relative to each other, and their spatial orientation can be arbitrary. Another thing is ice - in it water molecules are ordered, being included in the crystal lattice. The formulation, relatively speaking, states that ice, melted and turned into water (a process accompanied by a decrease in the degree of ordering and an increase in entropy) will never by itself be resurrected from water. **Entropy cannot decrease in closed systems - that is, in systems that do not receive external energy supply.**

For adiabatic processes: A->B

$S_B \geq S_A$

For quasi-static processes there exists sole temperature T scale n(absolute temperature):

$$\frac{\delta Q}{T} = \delta S$$

The Third law

Provides an absolute reference point for measuring entropy, saying that as the temperature of pure substances (chemical elements that are free from impurities) a system approaches absolute zero (−273.15°C, 0 K), then the value of the entropy approaches a minimum.

$$S \to 0 \text{ when } T \to 0$$

For other substances residual entropy remains which is an indication of the degree of disorder.

These laws of thermodynamics, as the basis of phenomenological thermodynamics) are considered as axioms.

2. The Ohm's law and two its equivalent formulations

Ohm's Law - physical law that defines the relationship of the electromotive force of a source (or electrical voltage) with the strength of the current flowing in a conductor and the resistance of a conductor

There are three formulations of this Law:

1. The **current** in the circuit is directly proportional to the voltage and inversely proportional to the electrical resistance of this circuit section.

   $I = \frac{V}{R}$, where I - current, V – voltage, R – resistance

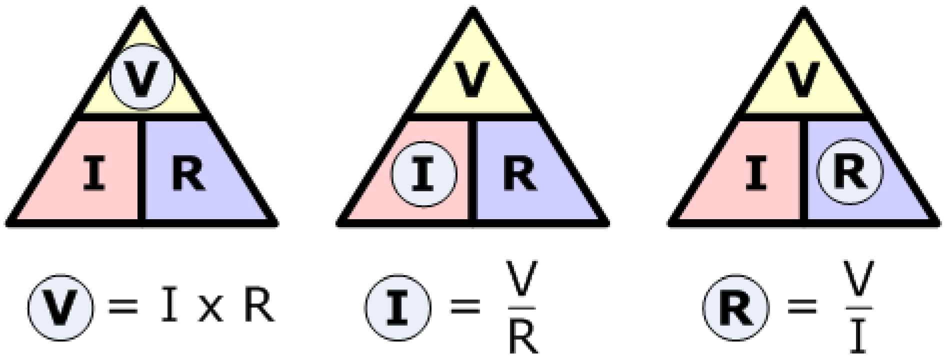
2. The **potential difference** on the conductor is equal to product of the current in the conductor and its resistance.

   $V = IR$, where I - current, V – voltage, R – resistance

3. The value of **resistance** equals ratio of potential difference across the resistor and the current flow through the resistance

   $R = \frac{V}{I}$, where I - current, V – voltage, R – resistance

To easily find which formulation needed to be used we can use Ohm's law triangle:



3. Superconductivity

Superconductivity is the property of some materials to have **strictly zero electrical resistance** when they reach a temperature below a certain value (critical temperature). Several hundred compounds, pure elements, alloys and ceramics are known to pass into the superconducting state. Superconductivity is a quantum phenomenon. It is also characterized by the **Meissner effect**, which consists in the complete displacement of the magnetic field from the volume of the superconductor. The existence of this effect shows that superconductivity cannot be described simply as ideal conductivity in the classical sense.

Most metals or amalgams become superconductors at temperatures underneath 1/10K (-273.05 C)

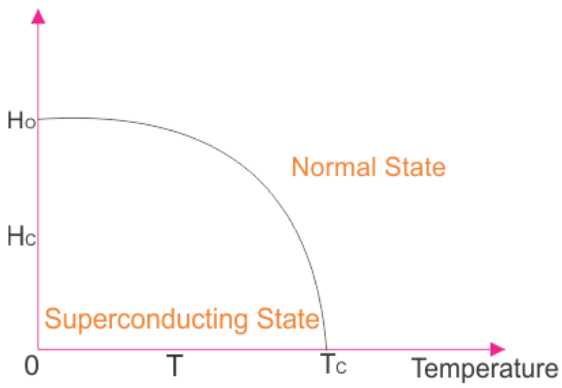
Properties of superconductors:

1. Zero Electric Resistance or Infinite Conductivity

   In the superconducting state, the superconducting material shows zero electrical resistance (infinite conductivity). When a sample of a superconducting material is cooled below its critical temperature / transition temperature, its resistance suddenly drops to zero. For example, Mercury shows zero resistance below 4k.

2. Superconductors in a high-frequency field

   Strictly speaking, the statement that the resistance of superconductors is zero is valid only for direct electric current. In an alternating electric field, the resistance of a superconductor is nonzero and increases with increasing field frequency.



Variation In Critical Magnetic Field with The Temparature

3. Phase transition in superconducting conditions

   The temperature interval of the transition to the superconducting state for pure samples does not exceed thousandths of Kelvin and therefore it makes sense to have a certain value of Tc - the temperature of the transition to the superconducting state. This value is called the critical transition temperature. The width of the transition interval depends on the heterogeneity of the metal, primarily on the presence of impurities and internal stresses

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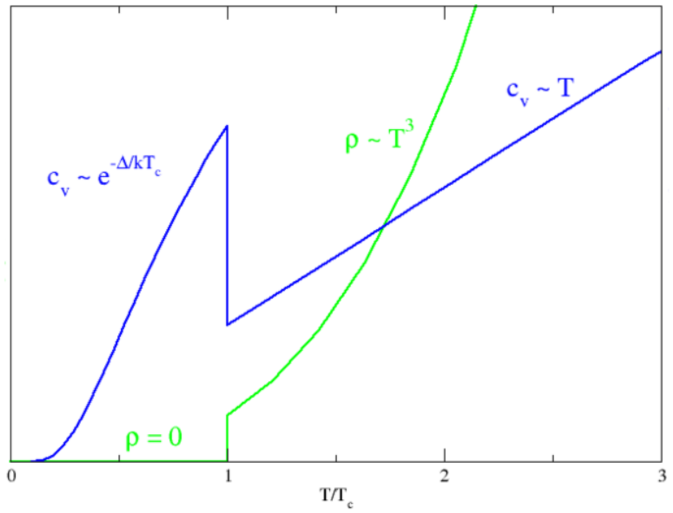
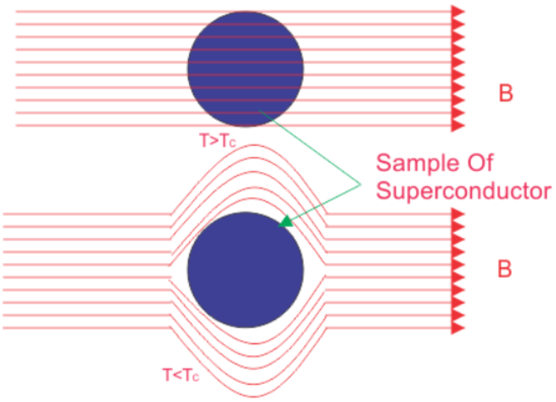


The nature of the change in heat capacity (cv, blue graph) and resistivity (ρ, green) during a phase transition to the superconducting state

4. Meissner effect



An even more important property of a superconductor than zero electrical resistance is the so-called Meissner effect, which consists in displacing a constant magnetic field from a superconductor. From this experimental observation, the conclusion is drawn about the existence of undamped currents inside the superconductor, which create an internal magnetic field that is oppositely directed to the external, applied magnetic field and compensates for it.

A sufficiently strong magnetic field at a given temperature destroys the superconducting state of matter. A magnetic field with intensity Hc, which at a given temperature causes a transition of a substance from a superconducting state to a normal one, is called a critical field. With decreasing superconductor temperature, the value of Hc increases. The temperature dependence of the critical field with good accuracy is described by the expression: $H_c(T) = H_{c0}(1 - \frac{T^2}{T_c^2})$
Where H_c critical field at zero temperature. Superconductivity also disappears when an electric current with a density greater than critical passes through the superconductor because it creates a magnetic field larger than critical.

The destruction of the superconducting state under the influence of a magnetic field is different for type I and type II superconductors.

5. Isotopic effect

The isotopic effect of superconductors is that the temperatures Tc are inversely proportional to the square roots of the atomic masses of the isotopes of the same superconducting element. As a consequence, monoisotopic preparations differ somewhat in critical temperatures from the natural mixture and from each other

Usage of superconductors:

The phenomenon of superconductivity is used to obtain strong magnetic fields (for example, in cyclotrons), since when passing through the superconductor strong currents that create strong magnetic fields, there is no heat loss.

Also there are photon detectors on superconductors, superconducting cables for electricity delivery, miniature superconducting ring devices – SQUID and so on.

4. Bloch’s Theorem

Bloch's theorem is an important theorem of solid-state physics, establishing the form of the wave function of a particle located in a periodic potential

Formulation:

According to Bloch's theorem, the Eigen functions of a wave equation with a periodic potential have the form of the product of a plane wave function by a function that is a periodic function in the crystal lattice:

$$\psi_{\vec{k}}(r^{\rightarrow}) = u_{\vec{k}}(r^{\rightarrow}) * e^{ikr}, \text{ where}$$

$$u_{nk}(r+R) = u_{nk}(r)$$

For all R belonging to the Bravais lattice. Index n is called the zone number. Its appearance is due to the fact that for an arbitrary fixed wave vector of a particle k, the system can have many independent eigenstates

Electronic wave functions in the form $u_{nk}(r+R) = u_{nk}(r)$ are called Bloch functions. But it’s important to understand that the Bloch functions themselves are not periodic functions, since the other term in this work describes a plane wave.

The theorem considers an ideal infinite crystal. This means that there are no defects in it and it has translational symmetry. In the further construction of the theory, violations of the periodicity of the lattice are usually considered small perturbations. In addition, in a real crystal, electrons interact with each other, which should be reflected in the Hamiltonian of the system by adding the corresponding term. In the statement of the theorem, however, the approximation of non-interacting electrons is used, which allows us to consider the single-particle Hamiltonian.

Proof:

Let T_R denote the operator of translation of an arbitrary function to the vector R. By the periodicity of the Hamiltonian, we have:

$$\widehat{T_R}\widehat{H}_{\psi} = H(r+R)\psi(r+R) = \widehat{H}(r)\psi(r+R) = \widehat{H}\,\widehat{T}_{R\psi}$$

Thus, the operator of translation into an arbitrary Brave lattice vector commutes with the Hamiltonian of the system. In addition, the translation operators on arbitrary two vectors commute with each other:

$$\widehat{T_R}\widehat{T}_{R'}\psi(r) = \widehat{T_{R'}}\widehat{T}_R\psi(r) = \psi\left(r+R+R^{'}\right) = T_{R+R^{'}}\psi(r)$$

It follows from the fundamental theorem of quantum mechanics that in this case the states of the Hamiltonian H can be chosen so that they are simultaneously the eigenstates of all the operators T_R:

$$H_{\psi} = E_{\psi}$$

$$\widehat{T_R}\psi = c(R)\psi$$

The eigenvalues c (R) are interconnected by the relation c (R) c (R ') = c (R + R'), because, on the one hand:

$$\widehat{T_R}\widehat{T}_{R'}\psi = c(R)\widehat{T_{R'}}\psi(r) = c(R)c(R^{'})\psi$$

With another:

$$\widehat{T_R}\widehat{T}_{R'}\psi = \widehat{T}_{R+R'}\psi = c(R+R^{'})\psi$$

Let a_i be the three main vectors of the Bravais lattice. We can always represent with (a_i) in the form:

$$c(a_i) = e^{2\pi i x}$$

For an arbitrary vector $R = n_1a_1 + n_2a_2 + n_3a_3$, the equality:

$$c(R) = c(a_1)^{n_1} * c(a_2)^{n_2} * c(a_3)^{n_3}$$

Equivalent to:

$c(R) = e^{ikR}$, where $k = x_1b_1+x_2b_2+x_3b_3$,

b_i = reciprocal lattice vectors satisfying the relation:

$$b_i a_j = 2\pi\delta_{ij}$$

Thus, the eigenvalues ψ of the Hamiltonian H can be chosen so that for each vector R of the Bravais lattice the equality holds:

$$\widehat{T_R}\psi(\mathrm{r}) = \psi(r+R) = c(R)\psi(r) = e^{ikR}\psi(R)$$

Which exactly corresponds to the statement of the theorem.

5. Bosons and fermions

Boson

A boson is a particle or quasiparticle with an integer spin (intrinsic angular momentum) expressed in units of the Dirac constant. Bosons, unlike fermions, allow an unlimited number of identical particles to be in a single quantum state. Systems of two or more identical bosons are described by wave functions that are even with respect to particle permutations.

There are elementary (fundamental) bosons and composite:

1. Elementary bosons:

   Most elementary bosons are quanta of gauge fields, with the help of which elementary fermions (leptons and quarks) interact in the Standard Model. These calibration bosons include:

   a. photon (electromagnetic interaction),
   b. gluon (strong interaction)
   c. W ± - and Z-bosons (weak interaction).

   In addition, the Higgs boson, responsible for the mechanism of the appearance of masses in the electroweak theory, and the graviton not discovered so far, belong to elementary bosons.

All elementary bosons, with the exception of W ± bosons, do not have an electric charge. Gluons are electrically neutral, but carry a color charge.

2. Composite bosons:

Composite particles (such as hadrons, nuclei, and atoms) can be bosons or fermions depending on their constituents. More precisely, because of the relation between spin and statistics, a particle containing an even number of fermions is a boson, since it has integer spin.

a. Any meson, since mesons contain one quark and one antiquark.
b. The nucleus of a carbon-12 atom, which contains 6 protons and 6 neutrons.
c. The helium-4 atom, consisting of 2 protons, 2 neutrons and 2 electrons; also the tritium atom, consisting of 1 proton, 2 neutrons and 1 electron.
d. The nucleus of deuterium, known as a deuteron, and its anti-particle

The number of bosons within a composite particle made up of simple particles bound with a potential has no effect on whether it is a boson or a fermion.

Boson stars

A bosonic star is a hypothetical astronomical object consisting of bosons (in contrast to ordinary stars, consisting mainly of fermions - electrons and nucleons). In order for such a type of stars to exist, stable bosons with a small mass must exist (for example, axioms are hypothetical light particles considered as one of the candidates for the role of dark matter components)

Quasiparticles

Quasiparticles, described as quanta of collective excitations in multiparticle systems (for example, in condensed matter), can also carry spin and are classified as bosons and fermions. In particular, bosons are phonons ("quanta of sound"), magnons (quanta of spin waves in magnets), and rotons (excitations in superfluid helium-4).

Fermion

A fermion is a particle or quasiparticle with a half-integer spin value (that is, equal to (n+1/2) ħ, where n is an integer, and ħ is the Planck constant). All particles can be divided into two groups depending on the value of their spin: particles with a whole spin belong to bosons, with half-integer - to fermions.

Fermions are also quantum-mechanical systems consisting of an odd number of fermions (and an arbitrary number of bosons).

Properties of fermions:

1. Fermions, unlike bosons, in a single quantum state can be no more than one particle
2. Pauli's Inhibition Principle is responsible for the stability of the electron shells of atoms, making it possible for complex chemical elements to exist. It also allows degenerate matter to exist under the influence of high pressures (neutron stars).
3. The wave function of a system of identical fermions is antisymmetric with respect to the permutation of any two fermions.

There are two types of fermions: elementary and composite:

1. The Standard Model recognizes two types of elementary fermions: quarks and leptons. In all, the model distinguishes 24 different fermions. There are six quarks (up, down, strange,

charm, bottom and top quarks), and six leptons (electron, electron neutrino, muon, muon neutrino, tau particle and tau neutrino), along with the corresponding antiparticle of each of these. Mathematically, fermions come in three types:

a. Weyl fermions (massless)
b. Dirac fermions (massive)
c. Majorana fermions (each its own antiparticle).

Most fermions of the Standard Model are believed to be Dirac fermions, although it is not currently known whether neutrinos are Dirac or Majorana fermions (or both). Dirac fermions can be considered as a superposition of two Weil fermions.

2. Composite particles (such as hadrons, nuclei, and atoms) can be bosons or fermions depending on their constituents. More precisely, because of the relation between spin and statistics, a particle containing an odd number of fermions is itself a fermion. It will have half-integer spin.

   Examples:

   a. A baryon, such as the proton or neutron, contains three fermionic quarks and thus it is a fermion.
   b. The nucleus of a carbon-13 atom contains six protons and seven neutrons and is therefore a fermion.
   c. The atom helium-3 (^3He) is made of two protons, one neutron, and two electrons, and therefore it is a fermion; also the deuterium atom is made of one proton, one neutron, and one electron, and therefore it is a fermion as well.

   Fermionic or bosonic behavior of a composite particle (or system) is only seen at large (compared to size of the system) distances. At proximity, where spatial structure begins to be important, a composite particle (or system) behaves according to its constituent makeup.

Fermions can exhibit bosonic behavior when they become loosely bound in pairs. This is the origin of superconductivity and the super fluidity of helium-3: in superconducting materials, electrons interact through the exchange of phonons, forming Cooper pairs, while in helium-3, Cooper pairs are formed via spin fluctuations.

Skyrmions

In a quantum field theory, there can be field configurations of bosons which are topologically twisted. These are coherent states (or solitons) which behave like a particle, and they can be fermionic even if all the constituent particles are bosons.

Skyrme's original example involved fields which take values on a three-dimensional sphere, the original nonlinear sigma model which describes the large distance behavior of pions. In Skyrme's model, reproduced in the large N or string approximation to quantum chromodynamics (QCD), the proton and neutron are fermionic topological solitons of the pion field.