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INTERACTION OF LASER RADIATION WITH ATOMS

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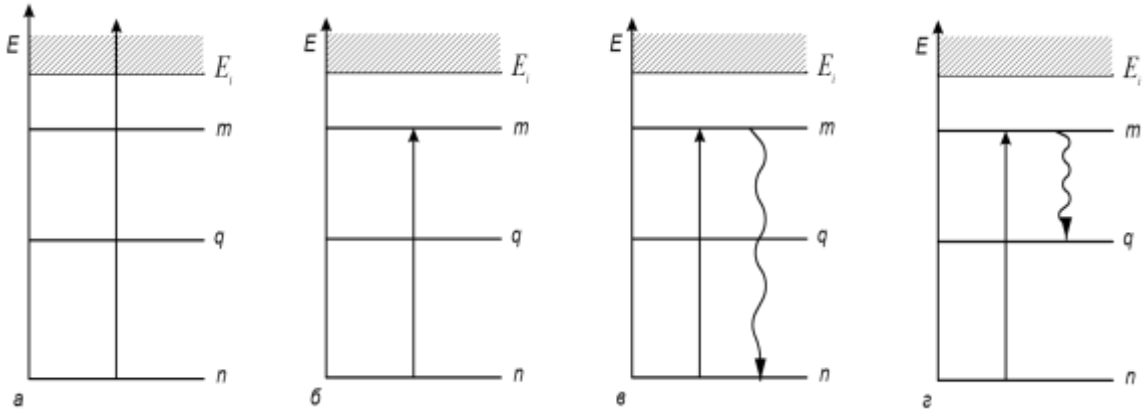
ABSTRACT

The article presents multiphoton (nonlinear) processes in liquids and modern views on single-photon processes as a result of the implementation of the limiting case when the interaction occurs at low light intensity

The law of the photoelectric effect opened the study of one of the main processes that occur during the interaction of electromagnetic radiation with matter. The atomic photoelectric effect, also called the process of atom photoionization, is a variant of the photoelectric effect at the atomic level of radiation interaction.

The main feature of the process of photoionization of an atom is its one-phton nature - the elementary act of detachment of an electron from an atom occurs as a result of the absorption of one photon. Accordingly, at the modern level, this process is also called single-photon ionization of an atom [2].



Picture 1. Schemes of single-photon processes. a - photoianization of an atom, b - photoexcitation of an atom, c - Rayleigh scattering of light by an atom, d - Romanov scattering of light by an atom. E is the energy of an electron in an atom, E_i is the

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ionization potential of an atom, n is the ground state, m, q are excited bound states of an electron in an atom, straight arrows are forced transitions of an electron as a result of photon absorption, wavy arrows are light scattered by atoms

At present, other elementary processes that occur during the interaction of light with an atom, such as photoexcitation of an atom, Rayleigh and Romanov (combined) scattering of light by an atom, have also been studied and described.

The advent of lasers gave experimenters monochromatic radiation of the optical frequency range of gigantic intensity, significantly exceeding the atomic intensity (I_a=3.61*10^{16}W/cm). Accordingly, the field strength of laser radiation significantly exceeds the atomic field strength (F_a=5.41*10^9V/cm). From a comparison of this value with the intensity up to laser sources of monochromatic radiation - spectral lamps - amounting to a value of the order of 1-10 W/cm^2, it is clear that a qualitatively new physics should arise during the interaction of laser radiation with matter.

Indeed, the use of laser radiation made it possible to discover the existence, in addition to the process of single-photon ionization of atoms, also of the process of multiphoton ionization of atoms. Foundation feature process of multiphoton ionization of an atom is the fact that the detachment of an electron from an atom occurs as a result of the absorption of several photons in one elementary act [1].

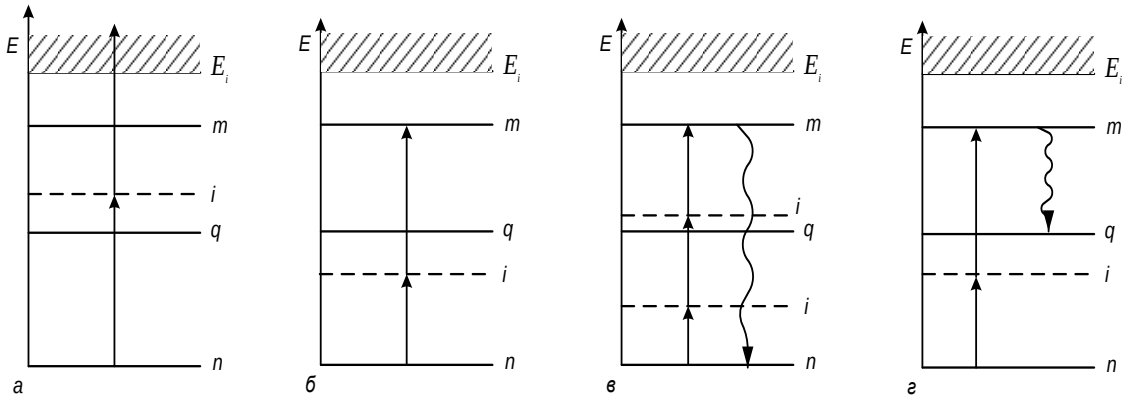

Figure 2. Schemes of multiphoton processes. a - multiphoton photoanization of an atom, b - multiphoton excitation of an atom, c - excitation of the highest (third) harmonic of the incident radiation, d - hyper-Raman scattering of light by an atom. The designations are the same as in Fig. 1 I is the state of an electron that has absorbed one or more photons.

Using laser radiation, multiphoton analogs of other basic single-photon processes were also discovered - multiphoton excitation of an atom, excitation of higher harmonics during light scattering (multiphoton Rayleigh scattering of light) and hyper Raman (multiphoton Raman) scattering of light by an atom.

Thus, the use of high-intensity laser radiation has led to the emergence of a new chapter in physics - the nonlinear (multiphoton) interaction of electromagnetic radiation with matter at the atomic level.

The discovery of multiphoton (nonlinear) processes led to the modern

view of single-photon processes as a result of the realization of the limiting case when the interaction occurs at low light intensity [2].

During the second half of the 20th century, the processes of multiphoton (nonlinear) ionization of atoms were studied in detail experimentally and comprehensively described theoretically. To date, this chapter of physics is a study completed in its main features. Hundreds of works, dozens of reviews and a number of monographs are devoted to this issue.

Since laser radiation has unique properties (frequency and monochromaticity, power, coherence, and small angular divergence), there is a need to elucidate the features of its interaction with atoms. Let us now proceed to a description of some of the effects arising in the interaction of laser radiation with atoms.

The ionization of a substance under the action of light is called photoionization.

Basic laws of the photoelectric effect

1. The number of electrons N knocked out of a substance under the action of light is proportional to the intensity of the light flux I:

2. Photoelectrons are not formed if the radiation wavelength is greater than a certain critical value (the red border of the photoelectric effect), which is characteristic of each specific substance.

The presence of the red border of the photoelectric effect means that the substance is characterized by a certain minimum energy (ionization potential) that must be expended in order to pull out one electron from the substance. The energy of each photon is determined by its wavelength using the formula , where c is the speed of light. This shows that if the wavelength is too long, then the photon energy may not be enough to knock out an electron [2].

From the proportionality of the number of photoelectrons to the intensity of the light flux, it follows that photons "give birth" to electrons independently of each other.

The ionization potentials of different substances vary greatly. From several tens to several units. Therefore, it would seem that optical radiation cannot lead to ionization of atoms.

However, such a conclusion follows from the classical laws of the photoelectric effect. If the optical radiation is strong enough, then ionization can occur due to the simultaneous absorption of several photons. In other words, a high power of light cancels the law of the presence of a red border of the photoelectric effect: ionization can occur under the action of radiation with a large wavelength, if the power of this radiation is large enough. This phenomenon is called multiphoton ionization [2].

Since, in multiphoton ionization, several quanta are required to knock out one electron, the photoflux ceases to depend linearly on the light intensity. Thus, the second law of the classical photoelectric effect is also canceled.

At the beginning of studies of multiphoton ionization, it was believed that the dependence of the photocurrent on the intensity should be a power law. According to quantum mechanics, electrons in atoms can only be in states with certain well-defined values of energy. Therefore, after absorbing the first photon, whose energy is insufficient for ionization, the atom cannot

wait for the second photon to fly up to it, since the energy of the waiting state is forbidden by quantum mechanics. Nevertheless, by chance (and due to the complexity of atomic spectra, such cases are quite probable) it may turn out that after the absorption of a photon, the energy of an atom will approach the allowed energy state [1].

And then it should be taken into account that the energy position of this state itself depends on the intensity of laser radiation, since the intensity is high. There is a phenomenon called the dynamic Stark effect, which consists in changing the atomic spectrum by the laser field. As a result, the positions of the atomic levels begin to change with a change in the laser intensity.

Depending on the frequency dependence of the nonlinear photocurrent, the multiphoton excitation manifests itself in the form of a resonance. Therefore, multiphoton ionization with intermediate excitation of real atomic states is called resonant, while ionization with no intermediate resonances is called direct [2].

Structure of liquids

Prior to the use of X-ray analysis, the theory of the liquid state of substances was based on the concept that follows from the van der Waals equation, according to which a certain gradual transition from a gaseous state to a liquid state was established. Under strong compression, the intermolecular cohesive forces between gas particles become so significant that the substance itself retains its volume, regardless of external pressure. There is a change in the state of aggregation and a liquid is formed, which, according to these ideas, can be considered as a highly compressed gas.

However, X-ray analysis showed that the condensed gas particles form small groups with an ordered structure. This did not follow directly from the concept of compressed gas.

If the electrons of individual atoms had a relatively weak connection with the latter, then when approaching distances comparable to the size of the electron orbits, “socialization” of these electrons should occur. This state will be typical for metals. In the case of a strong connection of electrons with individual atoms, this kind of approach will not cause the “socialization” of electrons, in which the connection with their atoms will be preserved to some extent. The substance will then be a dielectric. Therefore, the latter must consist of individual atoms whose force fields hold their electrons. When absorbing energy quanta, for example, during irradiation, electrons can leave the scope of their atoms and form a conduction current [3].

With this kind of irradiation, it may turn out that the absorbed energy quantum will not be enough to completely detach the electron from its atom. The electron will enter an excited state, i.e. will revolve around its atom in a larger orbit. When atoms collide, the excited state can be transferred to other atoms, i.e. excitons will form, but conduction will not occur. Such a phenomenon is observed in experience and is easily explained from the point of view of the classical concept, which consists in the idea of a dielectric as a compressed gas. It is difficult to explain this phenomenon from the zone point of view [3].

At present, it is generally accepted that a liquid at temperatures close to those at which crystallization occurs has many features in common with crystals than with gases, and at temperatures or pressures close to “critical”, a liquid is more like a gas. Thus, the liquid state is intermediate. Features and differences appear especially clearly in the nature of thermal motions. In gases, molecules move rapidly and randomly, and the interaction of particles occurs mainly only during collisions, which impart certain characteristic features to gases (diffusion, thermal conductivity and viscosity).

In solids, atoms perform thermal vibrations for a long time in the same environment, but this environment is not constant: atoms move from one equilibrium position to another (sites and interstices), and thus, although slowly, but also as in gases , there is a continuous mixing of atoms. In this regard, there are already some features of similarity between a gas and a solid body [4].

For the movement of particles in a liquid, there is much more room than in a solid, because, for example. When melting crystals, their volume increases by 3-10%. However, particles of liquids, as well as particles of a crystalline body, oscillate around a temporary equilibrium position. With sufficient energy, a liquid particle leaves this position and passes into a new environment. Such transitions happen very often, and in this liquids differ significantly from solids. During transitions, due to thermal motion, microcavities can spontaneously form in liquids due to the expansion of particles to the sides (cavitation processes). These cavities, as can be assumed, play a certain role in the scatter in determining the values of breakdown voltages, which is usually attributed to the influence of impurities and some random factors.

The duration of oscillations of liquid particles around one equilibrium position depends on temperature. With an increase in the latter, this number of oscillations decreases.

When studying the regularities of the scattering of X-rays by liquids, certain maxima of the scattered radiation were found, although diffused. Based on this, one could assume the presence of some order in the structure of liquid bodies [3].

Thus, the existence of microvolumes with an ordered structure in liquids can be considered established. In this respect, a liquid also has a certain resemblance to a solid. It turns out that against the background of the general disorder, liquids still have a certain order in their arrangement at small distances (short-range order).

X-ray analysis, however, does not make it possible to determine the nature of such quasicrystallite groups to the same extent as it can be done for crystals. At present, two assumptions can be made about the nature of these transformations.

According to the first of them, in microregions with sizes of 10-20 A there is a certain orderly structure of scattering centers, very closely resembling a crystalline structure. Based on this idea, a liquid can be considered as consisting of a very large number of small crystals (crystallites) separated by amorphous interlayers [3].

According to the second proposal, the molecular ordering of liquids corresponds to the so-called sybotactic

state. At a certain point in time, a liquid can also be represented as consisting of small ordered groups. But the molecules in these sybotactic groups are not firmly fixed, but are constantly shifting. And the groups themselves do not exist for a long time, but break up and are created again. This is how sybotactic groups differ from solid crystallites. When the temperature changes, the structure of the sybotactic groups can also change. As the crystallization point is approached, due to the action of forces that determine the crystalline structure, the structure of these groups can approach the crystalline one. This is also confirmed by X-ray data. The intensity curves of scattered rays in liquids at a temperature close to the crystallization point are made similar to the same curves for the solid crystalline state. Apparently, the average arrangement of scattering centers in liquids is then the same as in a crystal.

It follows from the data presented that the breakdown strength of liquids depends on their structure and that it is still impossible to predict in advance the nature of the change in E during the transition of substances from a gaseous state to a liquid one. The basic electrical properties of liquids seem to be determined by the "short range order", i.e. the nature of the interaction of molecules with nearest neighbors, as is the case with semiconductors [3].

Breakdown of liquids under the action of laser radiation

If a sufficiently high voltage is applied to metal electrodes separated by a liquid, extremely rapid ionization occurs in the liquid, as a result of which the liquid turns into gas a, then into plasma, acquiring electrical conductivity. This phenomenon is called electrical breakdown of the liquid. As a rule, the breakdown can be observed with the naked eye, it is accompanied by a light flash, sometimes very bright, and the evaporation of the liquid. Breakdown is the result of avalanche ionization, which starts from a small number of random seed electrons [4,5].

Electrons, accelerated by an electric field, acquire energy sufficient to detach an electron from a molecule or atom, and produce ionization, giving the acquired energy to this. From each energetic electron, two slow electrons are obtained, they, in turn, acquire energy from the field, ionize atoms, it turns out four, and so on. This is how an electron avalanche develops, the liquid is ionized to one degree or another, which depends on many factors, in particular, on what current the external circuit can pass. Ionization processes are always accompanied by acts of excitation of atoms, which are highlighted and give a visible flash [6].

The main processes of electrical breakdown of a liquid in the initial stage are multiphoton ionization, cascade, or avalanche ionization. The first electrons appear due to a frequency-dependent tunneling effect, at high frequencies the tunneling mechanism is equivalent to multiphoton ionization [5].

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