The two-level system in a strong light field

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Usp. Fiz. Nauk **117**, 189–197 (September 1975)

PACS numbers: 32.10.–f

The section on Atomic Collisions (Chairman V. V. Afrosimov) of the USSR Academy of Sciences Council on Plasma Physics has recently shown excellent initiative in organizing conferences on specific problems that are of immediate importance for practice and new from the standpoint of basic research. Two excursion sessions were held in 1974. A conference on the topic "Coherence of Laser Radiation and Multiquantum Processes" (Chairman of Program Committee S. I. Anisimov) was held in February at the USSR Academy of Sciences Institutes of Theoretical Physics and Solid-State Physics (Chernogolovka, Moscow Oblast'). Another on the subject "The Two-Level System in a Strong Light Field" (Program Committee Chairman V. A. Kovarskiĭ) was held at the Moldavian Academy of Sciences Institute of Applied Physics (Kishinev) in December. The narrow specialization of the conferees who are working actively in this area, the use of invited papers in the basic format of the conferences, the original scientific communications presented by most of those in attendance, and the planned free discussions all combine to make such conferences highly productive.

The conference at Kishinev is a good example. At first glance, the two-level system is one of the most thoroughly studied models that have come into extensive use in quantum radiophysics. However, various new

phenomena that have again drawn attention to the two level model have recently been discovered. The first is resonant fluorescence in a strong field, the second is multiphoton resonance in atoms, and, finally, the third is composed of effects related to the nonmonochromaticity of the electromagnetic field. Nonmonochromaticity problems, which were discussed at both conferences, are of independent interest and require a separate discussion. We shall therefore concentrate only on the effects that arise under the action of a monochromatic field.

Substitution of a two-level system for the real atom is a very crude approximation, but often the only possible one. It pretends to qualitative description of the process in those cases in which the external field is resonant with the particular pair of levels. Needless to say, this resonance can be brought about with either one or several quanta (multiphoton resonance).

Not even the idealized problem of the behavior of the two-level system in one monochromatic field of arbitrary frequency has an exact analytic solution. The corresponding Schrödinger equation reduces to the so-called Whittaker equation [1]; it is a particular case of the well-known Hill equation in which the number of harmonics in the coefficient of the equation equals two, and it is incomparably more complex than the Mathieu equation (one harmonic). Given proximity to resonance, however, approximate solutions of the problem can be obtained; the solution for the case of resonance at the fundamental frequency is well known [2]. If, in addition to the external electromagnetic field, we take account of the interaction of the system with the field of the physical vacuum and also include levels of the system other than the two considered, the problem is greatly complicated.

Various approximations are naturally required to find solutions of real problems. Most theoretical studies have used one (or more) of the following approximations:

1) Theory of perturbations in the amplitude of the external electromagnetic field. In this approximation, the N-th order of nonstationary-perturbation theory is used to investigate N-photon ionization. Thus, for example, the probabilities of multiphoton nonresonant ionization and the probabilities of bound-bound transitions for hydrogen have been calculated. The case of the short-range atomic potential is also included here, since the external field can be neglected in the range of its action. An example of a system bound by short-range forces is the negative ion; the electromagnetic field in the effective range of the ion's potential is neglected in calculation of its ionization probability. This makes it possible to obtain a comparatively simple analytic expression for the probability [3].

2) Adiabatic approximation using the smallness of the external-field frequency compared to the atomic frequencies. A general theory of adiabatic perturbation of the states of the discrete spectrum was developed in [4]. It was used to solve the problem of electrical breakdown of semiconductors in an alternating electric field [5] and to solve the problem of multiphoton excitation in a two-level atom [6].

3) Theory of perturbations in the amplitude of the atomic field. This approach is used, for example, to take account of long-range Coulomb forces. In [7], the influence of the Coulomb field on the probability of multiphoton ionization of atoms was taken into account in this variant of perturbation theory. We should note that this method can be used only for ultrastrong fields. That is to say, the condition $\mathcal{E} \gg \omega^2$, where $\mathcal{E}$ is the strength of the electromagnetic field and ω is its frequency, must be satisfied in atomic units (which we shall henceforth use consistently). The ionization of noble-gas atoms in a light field is a real example to which this theory is applicable.

4. Resonant approximation. This approximation consists in the fact that if the energy difference between the two levels is close to the energy of several quanta, the strength $\mathcal{E}\cos\omega t$ of the electromagnetic field can, roughly speaking, be replaced by the simpler expression $\mathcal{E}e^{i\omega t}/2$, which contains only the exponent that does not result in rapid oscillations of the coefficients in the Schrödinger equation. This approximation often makes it possible to obtain analytic solutions. The simplest and best-known example is the two-level system in an external field whose frequency is close to the distance between the levels [2]. Here the probability of transition from one level to the other is of resonant nature. This treatment becomes meaningless at $d_{12}\mathcal{E} > \Delta E_{12}$, where ΔE_{12} is the distance between levels and d_{12} is the dipole matrix element connecting these levels.

After these introductory remarks, let us turn to the specific problems in which application of the two-level approximation has made it possible to describe and predict new physical phenomena.

Under the program of the conference, discussion was concentrated on definite physical phenomena. We shall attempt to adhere to this approach in our exposition. A review paper by P. L. Rubin and R. I. Sokolovskiĭ (Physics Institute, USSR Academy of Sciences), discussed the new phenomena that arise in one of the types of resonant scattering of strong light on the two-level system, namely on resonant fluorescence. In 1961—1969, various solutions of this problem had shown [8,9,15] that at high intensities, scattering cannot be regarded as reradiation of a single photon, since other photons are also scattered by the atom during its lifetime in the excited state. Allowance for multiphoton processes results in qualitative modification of the scattered-light spectrum as compared to the ordinary resonant fluorescence spectrum: satellite maxima whose amplitude and frequency depend on the intensity of the incident light and the degree of tuning of the resonance make their appearance. Figure 1 shows the theoretically predicted spec-

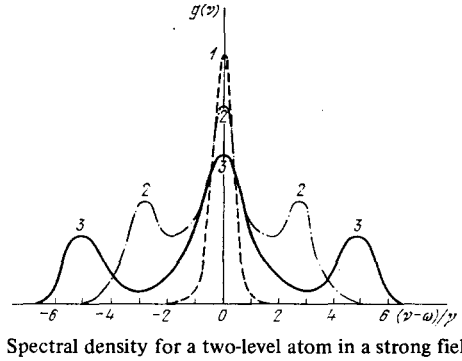

FIG. 1. Spectral density for a two-level atom in a strong field as a function of the ratio of the difference between the frequencies ν of the scattered light and ω of the incident light to the spontaneous decay probability γ [9]. The case in which the frequency of the incident light is tuned to exact resonance is illustrated. Curves 1, 2, and 3 correspond to different values of the field intensity $\mathcal{E}$ of the incident light: 1) $\kappa = 1$; 2) $\kappa = 3$; 3) $\kappa = 5$. Here $\kappa = d_{12}\mathcal{E}/\gamma$.

tral density $g(\nu)$ of the scattered light as a function of the difference between the frequencies ν and ω of the scattered and incident light.

The experiment of [10] qualitatively confirmed the general picture of the effect. Light from a tunable dye laser was directed perpendicular to a well-collimated beam of sodium atoms. The result was a sharp change in the role of the Doppler effect. The field-intensity amplitude was on the order of 10^5 V/cm. Radiation was observed in the direction normal to the intersection plane of the beams with a spectral resolution on the order of 10^{-2} cm^{-1}. When the lasing frequency was tuned to a selected transition in the sodium atom (to the transition $F = 2 \rightarrow 3$ in the D_2 doublet with energy ~ 3 eV), satellites were observed, and the spectrum of the scattered light was described approximately by the theoretical curve 2 in Fig. 1. Quantitative comparison of the theory with the experiment was made difficult by the large apparatus widths of this experiment, which were considerably larger than the spontaneous widths.

From the theoretical viewpoint, this experiment modelled a two level system in a resonant external field and a vacuum field. When the frequency of the light is close to the distance between levels, the light-scattering amplitude is of resonant nature. In fact, owing to the possibility of spontaneous decay, the upper level is quasi-discrete. Thus the resonant-fluorescence problem is essentially equivalent to the quantum-mechanical problem of resonant scattering on a quasidiscrete level [11]. This approach is valid when there is insufficient time for scattering of the next quantum on the atom during spontaneous emission. It can be shown that this occurs in sufficiently weak external fields, when $\kappa = d_{12}\mathscr{E}/\gamma_2 \ll 1$, where γ_2 is the probability of spontaneous emission of the upper level.

The picture becomes more complicated in a strong field ($\kappa > 1$). The appearance of the previously mentioned satellites (see Fig. 1) can be explained as follows. The wave function of a two-level system 1, 2 in the field $\mathscr{E}\cos\omega t$ can be represented in the following form in the resonant approximation [2, 12, 15] [1)]

$$\Psi(t) = A\left(e^{i\alpha_1 t}\Phi_1 - \frac{2\alpha_1}{V_{12}}e^{i\alpha_2 t}\Phi_2\right) + B\left(e^{-i\alpha_2 t}\Phi_1 + \frac{2\alpha_2}{V_{12}}e^{-i\alpha_1 t}\Phi_2\right);$$

here $V_{12} = d_{12}\mathscr{E}$; also

$$\alpha_1 = -\frac{\epsilon}{2} + \frac{\Omega}{2}, \quad \alpha_2 = \frac{\epsilon}{2} + \frac{\Omega}{2},$$

where $\Omega = \sqrt{\epsilon^2 + (d_{12}\mathscr{E})^2}$ and $\epsilon = E_2 - E_1 - \omega$. The quantities E_1, E_2 and Φ_1, Φ_2 are the unperturbed energies and wave functions of states 1 and 2 of the two-level system. The constants A and B are determined from the initial conditions. We see that the wave function $\Psi(t)$ is a superposition of four stationary states. Their energies are $E_1 - \alpha_1$, $E_1 + \alpha_2$, $E_2 - \alpha_2$, and $E_2 + \alpha_1$. Figure 2 shows these states and the possible spontaneous transitions between them. The central peak in Fig. 1 corresponds to the spontaneous transitions $E_2 + \alpha_1 \rightarrow E_1 + \alpha_2$ and $E_2 - \alpha_2 \rightarrow E_1 - \alpha_1$ with emission of a quantum of energy $\omega_0 = E_2 - E_1 + \alpha_1 - \alpha_2 = \omega$ (Rayleigh scattering). The right-hand and left-hand satellites are determined by the respective transitions $E_2 + \alpha_1 \rightarrow E_1 - \alpha_1$ ($\omega' = E_2 - E_1 + 2\alpha_1$) and $E_2 - \alpha_2 \rightarrow E_1 + \alpha_2$ ($\omega'' = E_2 - E_1 - 2\alpha_2$). Their energy distances from the central peak are $d_{12}\mathscr{E}$

[1)] Expression (3) for $\Psi(t)$ in Sec. 40 of the book [2b] (p. 176) contains a misprint: $e^{-i\epsilon t/2}$ should read $e^{i\epsilon t/2}$ in the second term in the right-hand side of (3).

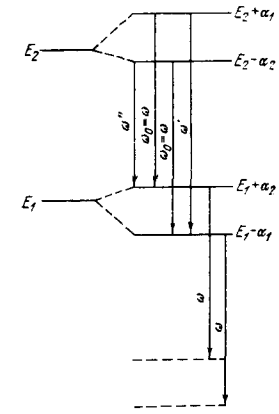

FIG. 2. Quasistationary states of two-level system in a resonant field. E_1 and E_2 are the unperturbed energies and $\omega_0 = \omega$, ω', ω'', ... are the energies of the quanta emitted on spontaneous transitions. The horizontal dashed lines indicate the quasi-energy levels.

(in the case of exact resonance, i.e., when $\epsilon = 0$). We note that the spontaneous transitions $E_2 + \alpha_1 \rightarrow E_2 - \alpha_2$ and $E_1 + \alpha_2 \rightarrow E_1 - \alpha_2$ are forbidden, since $d_{11} = d_{22} = 0$. In the weak-field case ($\kappa \ll 1$), the distance $d_{12}\mathscr{E}$ from the satellites to the central peak is small by comparison with the peak width γ, and the satellites are not observed for this reason [15]. It is also natural that in the case $\epsilon = 0$ the amplitude of the central peak is twice as large as the satellite amplitudes (see Fig. 1). The theory indicates that the widths of the central peak and satellites, though they differ numerically, are literally always of the order of γ.

The coefficients of the time exponentials in (1) characterize the populations of the levels represented in Fig. 2. It is easily seen that when $\omega < E_2 - E_1$, the populations of the levels $E_1 - \alpha_1$ and $E_2 - \alpha_2$ are larger than those of $E_1 + \alpha_2$ and $E_2 + \alpha_1$. Thus, if the system under consideration is acted upon by another weak external electromagnetic field of variable frequency, the field will induce short-wave transitions $E_1 - \alpha_1 \rightarrow E_2 - \alpha_1$ associated with absorption of a quantum and long-wave transitions $E_2 - \alpha_2 \rightarrow E_1 + \alpha_2$ associated with emission of a quantum. The transitions $E_1 - \alpha_1 \rightarrow E_2 - \alpha_2$ and $E_1 + \alpha_2 \rightarrow E_2 + \alpha_1$, which correspond to the unshifted frequency, will be of low intensity owing to the similar populations. The existence of this effect was first demonstrated in [13]. At the Kishinev conference, a paper by A. M. Bonch-Bruevich et al. (State Optical Institute) reported the re-

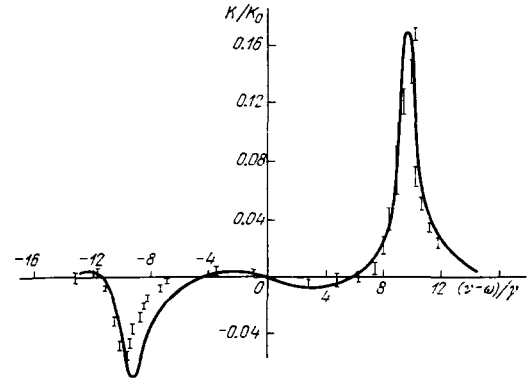

FIG. 3. Coefficient K of absorption of a weak external field of frequency ν by a two-level system situated in a strong resonant magnetic field $H = H_0 \cos\omega t$. The vertical lines correspond to the experimental data of [14] and the solid line to the theory [15]. K_0 is the coefficient of absorption of the weak external field by the two-level system in the absence of a strong field at the frequency $\nu = E_2 - E_1$. The detuning from resonance $\omega - E_2 + E_1 = 3\gamma$.

sults of an indirect investigation of this effect on a pair of ground-state Zeeman levels of cadmium atoms [14] situated in a constant magnetic field. A strong alternating magnetic field $H = H_0 \cos \omega t$ caused mixing of these levels. The result was the level picture shown in Fig. 2. Then a weak test radiation was switched on and caused transitions between the levels. The absorption spectrum of the test radiation is shown in Fig. 3. We see that the experimental results agree well with the theoretical predictions [15] discussed above.

With increasing detuning from resonance, the nonresonant part of the external field becomes more important; in other words, instead of the field $\mathcal{E}e^{i\omega t/2}$, it is necessary to use the exact expression $\mathcal{E} \cos \omega t$. This results in the appearance of new levels with energies differing by $n\omega$ from those shown in Fig. 2, where n is any whole number. Some of them are shown in Fig. 2. These levels are called quasienergetic harmonics [16]. Spontaneous transitions between them give rise to additional satellites [17]. Their intensities are higher the greater the detuning from resonance.

Formulas (1) describe the resonant shifts of the atomic levels in the external field. We see from them that at $\epsilon = 0$ (exact tuning at resonance), the atomic-level shifts α_1 and α_2 are linear in the field. Far from resonance we have the usual square-law dependence. It is also necessary to remember that in addition to the two levels considered, all the other states of the atom, including states of the continuous spectrum, are just as significant in the nonresonant case.

In N-photon resonance, formulas (1) are easily modified by the substitutions $E - E_1 - \omega \to E_2 - E_1 - N\omega$ and $d_{12}\mathcal{E} \to c_N(d_{12}\mathcal{E})^N$. Since the nonresonant level shift that always exists is proportional to $\mathcal{E}^2$, the resonant shift can be of the same order of magnitude only at $N = 2$; at $N > 2$, the resonant splitting is small compared to the total nonresonant shift. Modified in this way, formulas (1) can be used to analyze N-photon resonant fluorescence with emission of a quantum of energy $\sim N\omega$.

There has recently been great practical interest in multiquantum spectroscopy and multiquantum selective excitation of atoms and molecules. Specific to the multiquantum resonant processes that must be brought about in either case is the limitation to fields and levels such that ionization of the resonant state can be neglected. We shall consider the external field to be weak if the relation

$$\gamma_{1,2}(\mathcal{E}) \ll \gamma_{1,2}, \qquad (2)$$

is satisfied, where $\gamma_{1,2}$ is the equivalent width for the transition 1, 2, determined by the spontaneous width of states 1 and 2, and $\gamma_{1,2}(\mathcal{E})$ is the change in the widths of states 1 and 2 under the action of the external field. The most promising method of two-photon spectroscopy, which was proposed in 1970 [18], consists in the use of colliding photon beams to bring about two-photon excitation and in observation of the spontaneous relaxation of the excited state. Thus the Doppler frequency shift that occurs in one photon-propagation direction is cancelled. The colliding-beam method, which is now being used in various modifications, has made it possible to verify the theory of atomic spectra on examples of the doublet fine structure of alkali-metal atoms (Fig. 4) [19,20] and the Paschen-Back (Fig. 5) [21] and Zeeman [22] effects. In these experiments, the resolution was determined for all practical purposes by the width of the laser line, and reached values on the order of 10^{-3} cm^{-1}. Bjorkholm and

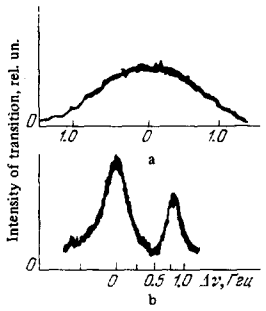

FIG. 4

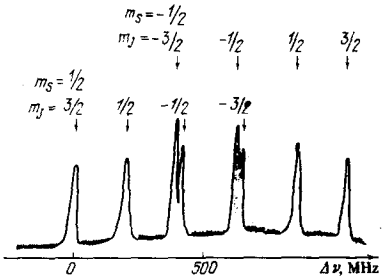

FIG. 5

FIG. 4. Intensity of two-photon transition 3S → 5S in sodium as a function of the light-frequency change $\Delta\nu$ [19]: a) one linearly polarized beam; b) two beams circularly polarized in opposite directions. In contrast to case (a), cancellation of the Doppler effect in case (b) results in separation of the fine structure of the atomic states.

FIG. 5. Spectrum of two-photon absorption $3S_{1/2} \to 4D_{3/2\,5/2}$ for sodium vapor in the presence of a strong magnetic field, $H_0 = 9860$ G [21]. The eight peaks correspond to different values of the spin projection m_S and the projection m_J of the total angular momentum.

Liao [20] report the results of experiments with resonant excitation of an intermediate level in a two-photon transition brought about by colliding light beams of different frequencies. The cross section for two-photon excitation increases by a factor of approximately 10^7 when resonance with the intermediate level is obtained. Thus, the probability of selective excitation of atoms and molecules can be increased sharply.

The main thing required from the theory is estimation of the conditions under which multiphoton mixing of resonant states can occur. It is obvious that the unperturbed atomic spectrum, which is the object of study in the given case, will be perturbed when mixing occurs.

The solution is well known for the case of single-photon resonance and was discussed above for the case of resonant fluorescence. We note that strong mixing can also occur in weak fields in this case provided that tuning to resonance is exact ($E_2 - E_1 - \omega \to 0$). Mixing in the case in which the $1 \to 2$ transition frequency of the system is a multiple of the excitation frequency was discussed in [23,24]. It was found possible to apply all relationships for resonance at the fundamental frequency (see formula (1)) if the matrix element of the field perturbation $V_{12} = d_{12}\mathcal{E}/2$ is replaced by the standard matrix element of the N-photon transition:

$$V_{12}^{(N)} = \sum_{s_1, s_2, \ldots, s_{N-1}} \frac{V_{1s_1} V_{s_1 s_2} \cdots V_{s_{N-1}2}}{[(N-1)\omega - \omega_{s_1 1}][(N-2)\omega - \omega_{s_2 1}] \cdots (\omega - \omega_{s_{N-1}1})}.$$

The quantity $V_{12}^N \sim \mathcal{E}^N$. In addition, in contrast to the case of resonance at the fundamental frequency, the level shift due to perturbation, which is quadratic in $\mathcal{E}$ (see above) must be taken into account in the detuning from resonance ($E_2 - E_1 - N\omega$). The resonant-mixing effect changes the unperturbed spectrum of the atom significantly when the admixture of state 2 in state 1 is significant. The quantity (see formula (1)) $V_{12}^{(N)}/\Omega_N$, where $\Omega_N = \sqrt{(E_2 - E_1 - N\omega + \Delta E)^2 + (V_{12}^{(N)})^2}$, is a measure of the mixing. A more complex situation arises when the times considered are large compared to the spontaneous-transition times. It is then necessary to take account of the intrinsic width γ of the upper energy level. The result of phenomenological allowance for γ [24] is that the resonant denominators in $\Psi(t)$ (see (1)) assume the form $(E_2 - E_1 - N\omega + \Delta E_{12})^2 + (\gamma/2)^2 + (V_{12}^{(N)})^2$; here ΔE_{12} is

the level shift due to perturbation. Mixing is strong if $V_{12}^{(N)}/\Omega_N$ is of the order of unity. In N-photon resonance (N = 1, 2, ...), the quantum system oscillates periodically between resonating states with the frequency Ω_N (see (1)). Consequently, mixing now requires a relatively long time of action T of the perturbation: $\Omega_N T > 1$.

After all of the above, there remains only the problem of calculating the matrix elements of the bound-bound multiphoton transitions. At $(d_{12}\mathscr{E})^2 < \omega$, it is natural to use the methods of nonstationary perturbation theory[25]. The difficulties that arise in this calculation are of mathematical rather than physical nature. They arise from the need to perform infinite summations and the need to choose sufficiently well-conditioned atomic wave functions. Meanwhile very few digits are obtained in the calculations and, in particular, there is not even a qualitative general picture of how the matrix elements vary with the quantum numbers of the states and with the perturbation frequency. If $(d_{12}\mathscr{E})^2 > \omega$, ordinary temporal perturbation theory is inapplicable. It is then possible to calculate multiphoton matrix elements by using the adiabatic approximation[6]. The criterion for applicability of the latter has the form $N \gg 1$ (which is equivalent to $\omega \ll \omega_{12}$). In addition, it goes without saying that the external field must be small compared to the atomic field. Papers by D. F. Zaretskiĭ (I. V. Kurchatov Institute of Atomic Energy) and V. P. Kraĭnov (Moscow Engineering Physics Institute) and also by P. A. Apanasevich (Institute of Physics Belorussian Academy of Sciences) were devoted to the problem of calculating the matrix elements.

Another aspect of the problem is also urgent: the dependence of transitions in the two-level system on the method of switching on the field. The paper by S. P. Goreslavskiĭ and V. P. Yakovlev (Moscow Engineering Physics Institute) analyzed multiphoton transitions in the two-level system under the action of low-frequency fields ($\omega \ll \Delta E_{12}$) that were switched on both adiabatically and suddenly. Suddenness and adiabaticity of the switching on of the perturbation mean that the switching-on time is small and large, respectively, compared to $1/\Omega_N$. It was shown how the population of the levels ceases to oscillate as we go from sudden to adiabatic switching-on. The results were similar to those in the case of resonance at the fundamental frequency[26], except that the transition matrix element V_{12} is replaced by $V_{12}^{(N)}$. Let us assume for the sake of argument that the particle was in the lower state, 1, before the interaction was switched on. Then in the case of sudden switching-on, the average probability n_2 that the particle will be on the upper level is given by the relation $n_2 = (1/2)(V_{12}^{(N)}/\Omega_N)^2$, whereas in the case of adiabatic perturbation, n_2 is constant at $n_2 = (\Omega_N - E_{21} + N\omega)/2\Omega_N^2$. In the case of two-quantum resonance, which is the one of greatest practical interest and whose realization requires field intensities $E \geq 10^4$ V/cm, the time $1/\Omega_2$ is found to be much larger than the leading-edge length of the pulse of any high-power laser operating in the Q-switched mode. Sudden switching-on always occurs.

Mixing of multiplet states in an external electromagnetic field was the subject of a paper by B. A. Zon and B. G. Katsnel'son (Voronezh State University). It is easy to formulate conditions under which nonresonant mixing of fine-structure components occurs. For this it is necessary that the interaction with the field, which, in atomic units, has the estimate $\mathscr{E}$, not be small compared to the typical fine-structure interval $\sim 1/c^2 \sim 10^{-4}$, i.e.,

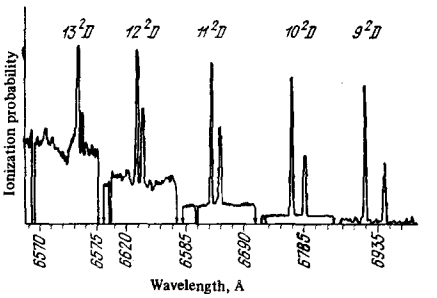

FIG. 6. Resolution of doublet fine structure of D states of the cesium atom with principal quantum numbers from 9 to 13 [28]. The ion yield is represented as a function of the wavelength of the electromagnetic field.

it is necessary that $\mathscr{E} > 10^5$ V/cm in ordinary units. According to the indeterminacy principle, the mixing time is determined by the reciprocal of the fine-structure interval. Moreover, to ensure that the perturbation will be nonresonant (that none of the distances between the numerous fine-structure components is close to the perturbation frequency ω), the perturbation frequency ω must be large compared to the fine-structure interval. As a rule, this condition is satisfied. When all of these conditions are met, the problem of realignment of the multiplet in a strong field is solved[27]. In a weak field, states with definite total angular momentum and definite projections of this momentum onto the direction of the field greatly exceeds the spin-orbit interaction responsible for the fine structure, spin-orbit coupling is broken and the set of quantum number changes. Total angular momentum is not conserved in a strong field, and the projection of the orbital angular momentum and the projection of the spin onto the field direction are good quantum numbers. At perturbations corresponding to the typical distance in the multiplets (field $\mathscr{E} \sim 10^5$ V/cm), estimation[27] of the period of the oscillations gives $\tau \sim 10^{-10}$ sec, which is comparable with the typical duration of laser pulses. We see from this estimate that while mixing should occur in the radiation field of a nanosecond laser, it may not occur in the field of a picosecond laser. Use of resonant multiphoton ionization of atoms as one method of multiquantum spectroscopy was the subject of a review by G. A. Delone and N. B. Delone (Physics Institute, USSR Academy of Sciences). When relation (2) is satisfied and the method of crossing light and atomic beams is used, it is possible, by observing the dependence of ionization probability on the frequency of the radiation, to register the resonant state with high accuracy. The method of resonant multiphoton ionization has certain advantages over the colliding-photon method: it can be used to observe the structure of higher states in the atomic spectrum, for whose excitation the energy of two laser photons is inadequate, or states the probability of ionization from which exceeds the spontaneous relaxation probability. The actual possibilities of this method are seen from the results of studies of the fine structure of doublets in the cesium atom with principal quantum numbers from 9 to 13.[28] The doublets are resolved with an accuracy on the order of 0.1 cm^{-1}, which is determined by the width of the laser's emission line (Fig. 6). From the theoretical standpoint, a new problem arises here, that of accounting for the perturbation of the resonant state. It requires analysis of a peculiar three-level system, ground state—resonant state—continuous spectrum, under the conditions of perturbation of the resonant state by the field and with consideration of the stimulated nature of the transitions. A number of papers[3,29,30] have been de-

voted to examination of this three-level system. An adiabatic solution of the analogous problem for the case in which the third state is also bound was reported by V. P. Kraĭnov (Moscow Engineering Physics Institute). We cannot discuss the results because the problem goes beyond the framework of the two-level approximation.

The promise of using the two-level model to describe multiphoton problems that arise on the interaction of a strong light field with molecules is obvious. The possibility of using this method results, in particular, from the possibility of separating the electronic and nuclear variables. This separation is always possible in weak fields. Relatively-few-photon processes can therefore be described within the framework of standard perturbation theory, when the unperturbed molecular spectrum is taken as the basis. Strong coupling of these variables may arise when the field intensity is sufficiently high. However, as was shown in the paper by M. V. Fedorov (USSR Academy of Sciences Physics Institute), separation of the variables is also possible at rather strong fields when the condition $d_{12}\mathcal{E} \gg \omega_{vib}$ (ω_{vib} is the vibrational frequency of the molecules) is met. It follows from solution of the problem [31] that strong modification of electronic terms occurs, with preservation of their adiabatic nature. It is interesting that the theory predicts a new branch of the vibrational spectrum that is absent in the unperturbed spectrum. It could be determined in experiments with absorption of infrared light.

The paper by A. M. Bonch-Bruevich et al. dealt with the applicability of the two-level approximation to resonant molecular fluorescence. The cross section of the two-level system for absorption of light at frequency ω contains a resonant denominator of the form $(E_{12}-\omega)^2 + (\gamma/2)^2 + (1/2)(d_{12}\mathcal{E})^2$. In a strong field, when $d_{12}\mathcal{E} > \gamma$, absorption occurs in a frequency range $\Delta\omega \sim d_{12}\mathcal{E}$. A similar relationship was observed experimentally in [32] following irradiation of molecular rubidium vapor with the red light emitted by a ruby laser. Such experiments can be used to determine the dipole matrix elements of molecular transitions.

If we now think back to the beginning of this brief review of the Kishinev conference, there can be no doubt as to the validity of our announcement of the appearance of a new range of physical phenomena that can be interpreted with the two-level approximation. We note that, although the principal applications discussed in the review were problems of multiquantum spectroscopy, use of the two-level approximation may be promising for various other practical problems of the present and future: laser separation of isotopes, the development of ultraviolet lasers, and the investigation of self-action in resonant media.

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Translated by R. W. Bowers