Intense Laser Phenomena

& Related Subjects

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Rector of the School: Professor A. M. Prokhorov

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PREFACE

This book includes the lectures given in the summer of 1989 at the IX International School on Coherent Optics (Uzhgorod, USSR) at the Multiphoton Processes Section, as well as interesting papers contributed by the participants of this section. The organization of the Multi-photon Processes Section at the School was stimulated by the noticeable increase in the number of researches, laboratories, universities and institutes in various countries engaged in investigations in this area of physics. The main reasons for the rapid development of the researches in multiphoton laser-atom physics are: progress in the experimental methods and technique, and the discovering and predicting of qualitatively new physical effects.

In the experimental technique the possibility of obtaining an extremely strong superatomic – light field is of prime importance. We must also point out the possiblity of carrying out experiments in a broad frequency range – from near infrared to ultraviolet, together with smooth freqency tuning. Finally, of principal importance in a number of experiments are supershort – pico and femtosecond – durations of laser pulses.

A number of qualitatively new phenomena were experimentally discovered in the last ten years. They are: multicharged ions formation in the process of multiphoton atom ionization, observation of the effective spin-forbidden multiphoton transitions in akaliearth atoms, above threshold absorption of photons in multiphoton ionization of atoms and molecules, and generation of extremely high optical harmonics in the interaction of laser light with noble gas atoms. The discovery of these effects opened up new areas of researches and obliged reconsideration of a number of basic statements, views and conclusions in the theory of multiphoton processes and atomic physics.

Qualitatively new phenomena are predicted by the theory of multiphoton processes as well. Of great and fundamental importance is, for example, the prediction of the field-induced Rydberg atom stabilization, with respect to ionization in a strong field, owing to the secondary population of nearby states accompanied by the interference of transitions from these states to the continuous spectrum.

The lectures presented in this book reflect new results and problems well and attracted the attention of both experimentators and theorists working in the field of physics of multiphoton processes in atoms and molecules.

In conclusion, further and rapid development of the researches on the elementary processes in laser field with the development of the experimental technique (laser intensity increasing first of all) is necessary. In the near future we expect an achievement of such high laser intensity, that the experiments on discovering and investigating vacuum quantum effects become a reality.

Rector of the School,
academician

A. M. Prokhorov

CONTENTS

Preface v

Lectures

Nonlinear Ionisation of Atoms (Short Review) 1
N. B. Delone

Resonant Multiphoton Ionisation Revisited with Femtosecond Pulses 20
P. Agostini, P. Breger, A. L'Huillier, H. G. Muller
G. Petite, A. Antonetti and A. Migus

High-Order Harmonic Generation in Rare Gases in Intense Fields 44
A. L'Huillier, L. A. Lompre, M. Ferray, X. F. Li and G. Mainfray

Quasiresonant Coherent Multi-photon Processes with Participation of Atomic Discrete and Continuum States – Simple Models 57
S. M. Gladkov and N. I. Koroteev

Coherent Effects in the Continuum 81
M. V. Fedorov

Multiphoton Microwave Resonances in Rydberg Atoms 100
I. M. Beterov, G. L. Vasilenko, I. I. Ryabtsev and N. V. Fateyev

Multiphoton Processes in Atomic Hydrogen within the Framework of Perturbation Theory 121
E. Karule

Semiclassical Approach for Matrix Elements of Above Threshold Ionization 133
I. Bersons

Semiclassical Dipole Matrix Elements of Atomic Transitions 144
V. P. Krainov, N. B. Delone, S. P. Goreslavsky and M. Yu. Ivanov

Complex Quasienergies and Autoionizing Atomic States in a Strong Resonant Field of Laser Radiation 163
A. E. Kazakov

Multiphoton Processes in Alkaline Earth Atoms 180
V. V. Suran

Role of Autoionizing States in Multiphoton Ionisation of Complex Atoms 194
V. I. Lengyel and M. I. Haysak

Application of Hyperspherical Coordinates Method for the Description of Multiphoton Processes in Complex Atoms 221
M. I. Haysak

Multiphoton Phenomena in the Field of a Strong Focused Laser Pulse 243
S. P. Goreslavsky

Nonperturbative Multiphoton Transitions in Molecules – A Coupled Equations Approach Study of LiF 259
A. D. Bandrauk

Three-Photon Resonant Ionisation and Above-Threshold Dissociation of Diatomic Molecules in Intense Laser Field 287
I. I. Tugov, A. I. Pergakov and L. P. Rapoport

Non-Perturbative Approaches of Laser Interaction with Matter: From Atoms to Solids 299
N. S. Brandi, L. Davidovich, G. Jalbert, B. Koiller and N. Zagury

Fractional Revivals of Wave Packets during the Long-Term Evolution of Highly Excited Quantum Systems 316
I. Sh. Averbukh and N. F. Perelman

Major Peculiarities of Squeezed Light 330
V. P. Bykov

Nonlinear Collective Plasma Interactions in Laser Multi-Photon Ionisation 360
F. Giammanco

Energy Pooling Collisions in Resonantly Laser Excited Vapors 388
L. Moi, C. Gabbanini and S. Gozzini

Contributed Papers

Influence of Laser Radiation Field on Spectrum of Ba Atoms 404
I. I. Bondar' and V. V. Suran

The Stepwise Process of Doubly-Charged Barium Ions Creation in Visible Spectra Range 412
I. I. Bondar', M. I. Dudich, V. V. Suran and L. L. Shimon

Probability of Four-Photon Ionisation of Mg Atom in Spectrum Region 16300–18000 cm^{-1} 419
I. I. Bondar' and V. V. Suran

Anomalies in the Six-Photon Ionisation of Sr Atom in Infrared Spectrum Region (8100–9150 cm^{-1}) 424
T. T. Bernat, I. I. Bondar', V. V. Suran and L. L. Shimon

Formation of Double-Charged Sr^{2+} Ions in the Frequency Region 8100–9100 cm^{-1} 431
T. T. Bernat, I. I. Bondar', V. V. Suran and M. A. Preobrazhensky

Absolute Values of the Multiphoton Ionization Cross-Section of the Alkali-Earth Atoms 437
D. Sh. Akramova and V. K. Medvedeva

Correlation Role in the Nonlinear Ionization of Atomic Systems 442
I. Yu. Kiyan, P. A. Golovinsky, M. A. Preobrazhensky and V. S. Rostovtsev

Ionization with Excitation in Superstrong Fields 449
P. A. Golovinsky

Autoionizing-Like Resonances in Multiphoton Ionization Spectra 453
Yu. I. Heller

Above-Threshold Multiphoton Detachment: Adiabatic Theory and Keldysh Approximation 461
D. A. Telnov

Critical Intensities for Ionisation of Hydrogen 469
S. P. Goreslavsky and O. V. Shcherbachev

Interaction of Atoms with Supershort Laser Pulses and Supercontinuum Generation 477
M. V. Fedorov, M. Yu. Ivanov and P. B. Lerner

Quantum Systems Behaviour in the Field of a Strong Ultrashort Pulse 484
P. A. Golovinsky and M. A. Preobrazhensky

Multiply Charged Ions Formation in the Field of Laser Radiation 493
I. A. Wojciechowski, M. V. Medvedeva and E. S. Parilis

Diffusion in Multiphoton Multielectron Ionisation of Atoms 498
P. A. Golovinsky and M. A. Preobrazhensky

Amplification of Radiation at the Electron Scattering on Atoms in Laser Field 506
E. A. Beilin and B. A. Zon

Electron Spectrum of Multiphoton Bremsstrahlung in a Spatially Inhomogeneous Laser Pulse 514
S. P. Goreslavsky and A. V. Solomatin

Saturation of Third Harmonic Generation in Laser Produced Plasma in Intense Laser Field 522
A. B. Fedotov, S. M. Gladkov and A. M. Zheltikov

Radiative-Collision Processes in Intense Laser Field. The Quantum Mechanical Generalization 527
A. I. Pegarkov and L. P. Rapoport

Multiphoton Transitions in Molecules on the Base of the Frequency Effect 545
A. V. Belousov, V. A. Kovarsky and V. N. Chebotar

Multiphoton Satellites of Allowed and Forbidden Atomic Optical Transitions in Stochastic Quasichromatic Fields 550
N. F. Perelman and A. A. Mosyak

The Resonant Internal Conversion Stimulated by the Laser Radiation as a Method of ^{235}U Decay Accelerating 556
B. A. Zon and F. F. Karpeshin

Threshold Resonance Fluorescence 563
A. B. Voitkiv and V. A. Pazdzersky

"Drag" of Electron in Interaction of Laser Radiation with Weakly Ionised Gas 569
V. K. Dolmatov and A. S. Baltenkov

The Interaction of Coherent Light with Electrons 576
B. G. Sherman

Excitation of Optical Transitions from Quartet Autoionizing Levels of Alkali-Metal Atoms in their Mixtures with Rare Gases 582
Yu. K. Gabrielyan, A. E. Mailyan, G. Ts. Nersisyan, V. O. Papanyan and S. A. Ter-Avetissyan

NONLINEAR IONIZATION OF ATOMS

(Short review)

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Abstract. The results of studying of multiphoton laser-atom interaction over the past ten years are reviewed briefly. The last findings, such as multicharged ions formation, high-order harmonics generation and above threshhold ionization in the field of optical and near-infrared frequency regions are emphasized.

INTRODUCTION

The main purpose of this lecture is to review the results of study of the process of nonlinear ionization of atoms. It is assumed to call nonlinear ionization of quantum system the process of an ejection of the bound electron under irradiation with quantum energy ω less than the energy of electron coupling $\mathcal{E}$, i.e. when the following condition is satisfied:

$$\omega < \mathcal{E} \tag{1}$$

(Herein after we use the atomic system of units).

Since a spectrum of the bound electron states in any real quantum system (in atom, molecule and ion) is unharmonic, the process of nonlinear ionization under the action of monochromatic radiation is a result of a number of virtual electron transitions rather than transirions via real bound states. The possibility of virtual transitions is stipulated by the energy-time uncertainty relation, $\Delta\mathcal{E}\Delta\tau \sim 1$. Resonance detunings $\Delta\mathcal{E}=|K\omega-\mathcal{E}_n|$, where $\mathcal{E}_n$ are the energies of the bound electron states, are large as compared with the natural width of atomic levels γ_n. This gives rise to rather small values $\Delta\tau$, and rather high radiation intensity (i.e. number of photons transmitted through a single section per unit time), under which the probability of nonlinear ionization can reach such a large value, at which the process should be taken into account and can be revealed.

One should imply that the presence of nonlinear ionization qualitatively modifies the main position of linear optics, according to which a "red boundary" of radiation frequency ω_r separates the absorption ($\omega > \omega_r$) and the transparency ($\omega < \omega_r$) regions. Taking into account the process of nonlinear ionization, the region of transparency is absent, and the absorption occurs at any ratio between ω and ω_r. The transparency region occurs practically for $\omega < \omega_r$ and small radiation intensities, when the probability of nonlinear ionization is so small that this process can be ignored.

The works by Einstein[1], Dirack[2], Geppert-Mayer[3] and Frenkel[4] have indicated on the possibility of the nonlinear ionization; however, this process was studied only after lasers were constructed as they enabled one to produce sufficiently high quasimonochromatic radiation intensities.

THE FUNDAMENTAL LAWS

A general pattern of the process of nonlinear ionization became clear from the work by Keldysh (1964)[5], that was devoted to the description of the nonlinear electron ejection from a short-range potential. As compared to the Coulomb potential, this potential is a quite simple one, as at the final state electron is subjected only by the light wave field. In his work Keldysh derived the expression for the nonlinear ionization probability ω as a function of the adiabaticity parameter

$$\gamma = \sqrt{2\mathcal{E}}\,\omega/E \qquad (2)$$

where E is the radiation field strength.

From general ratio $w(\gamma)$ there follows two limiting cases corresponding to parameters $\gamma \gg 1$ and $\gamma \ll 1$.

For $\gamma \gg 1$ (Multiphoton case) the probability of nonlinear ionization is related with the field strength by degree relation:

$$w^{(K_o)} = \alpha'^{(K_o)} E^{2K_o} = \alpha^{(K_o)} F^{K_o} \qquad (3)$$

where $K_o = \langle E/\omega + 1\rangle$ is the number of quanta whose absorption is required for the fulfillment of the energy conservation law, $\alpha^{(K_o)}$ is the multiphoton (K_o-photon) cross-section of the ionization process.

For $\gamma \ll 1$ (tunneling case) the probability of nonlinear ionization is related with the field strength by exponential relation with the index analogous to that for tunnel ionization in the constant field:

$$w = C_1 \exp(-C_2 \mathcal{E}^{3/2}/E) \qquad (4)$$

Many works were carried out after the Keldysh's work, which were devoted to the ionozation from short-range potential. As for the ionization from a Coulomb potential we have no yet general analytical description of this process because one should take into account a simultaneous influence of two strong fields upon the electron in finite state - long-range Coulomb field and radiation field. However, both the numerical calculations and analytical solution[6] derived by Perelomov et al. for a very strong field, imply that the before mentioned general relations are also valid for the Coulomb potential ionization, i.e. for atoms, molecules and positive ions.

From eq.(2) it is a simple matter to estimate that the ionization of atoms, molecules and positive ions from the ground state in the visible frequency radiation field with the strength E, which is less than the atomic strength E_a, is multiphoton ($\gamma \gg 1$). Tunnel ionization takes place at $E < E_a$ for infrared radiation. Thus, a general relationship $w(\gamma)$ has the form represented by Fig.1.

Let us turn now to the experiment. Delone et al. in 1965[7] were first to observe nonlinear ionization of atoms and molecules in a multiphoton limiting case. Till now, many experiments were made on multiphoton atom ionization. Atom ionization in the tunneling limiting case was observed by Chin et al.[8] in 1985. All set of these experiments confirms the general laws which were already said.

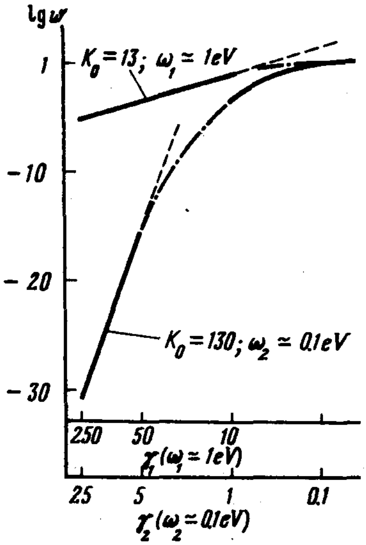


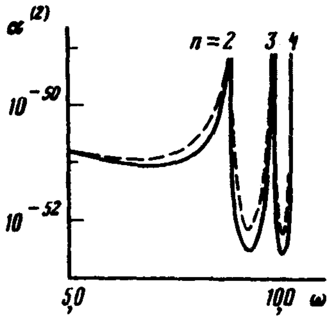
Fig.1. The probability (in arbitrary units) W of nonlinear ionization of quantum system with the electron bound energy $\mathcal{E}$ = 10 eV versus adiabaticity parameter for two radiation frequencies.

As for the short-range potential, the previous plans to employ negative atomic ions as an object for the experiments seems to be ungrounded now as a number of secondary effects (e.g. dynamic polarizability of ions[9]) are essential.

By resuming now we can confirm that the fundamental laws of the process of nonlinear ionization seemed to be undoubtful and may form the basis for a detailed analysis of the special laws of this process and different evaluations of its role in interaction of laser radiation with matter.

DIRECT PROCESS OF MULTIPHOTON ATOM IONIZATION

The process of multiphoton ionization in the lack of intermediate resonances is usially called direct. The probability of direct process is described by the degree relation (3). The problem of interest are multiphoton cross-section $\alpha^{(K_0)}(\omega,\rho)$, their absolute values and their dependences on frequency ω and radiation polarization ρ. The typical dependence for the hydrogen atom is illustrated in Fig.2.



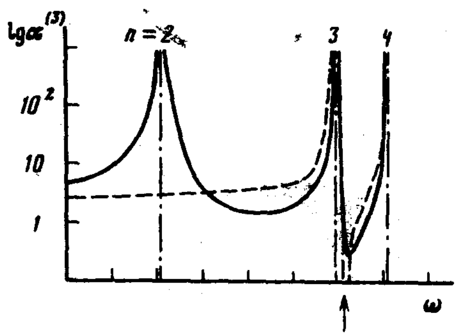


Fig.2. Dependence of two-photon ionization cross-section $\alpha^{(2)}$ of hydrogen atom in linearly polarized field (in photons per $cm^{-4}sec^{-1}$) on radiation frequency ω (eV); |n> are the main quantum numbers of intermediate resonances. Solid line corresponds to calculations, dashed line - to approximated quasiclassical calculation[14].

Fig.3. Dependence of three-photon ionization cross-section $\alpha^{(3)}$ of hydrogen atom (in arbitrary units) on radiation frequency (in arbitrary units); solid line corresponds to calculations for linearly polarized radiation, dashed line - for circularly polarized radiation; arrow indicates the "transparency window".

A direct process of multiphoton hydrogen atom ionization is still studied only theoretically.

Many experimental and theoretical data were obtained for alakali atoms [10,11]. The calculations were made by Rapoport et al.[12] in the framework of nonstationary perturbation theory in the K_0- order and in one-electrone approximation. The wave functions of an electron in a complex atom were constructed approximately by the methods of quantum defect and model potential. The calculatuions agree well with the experimental data.

A special attention should be made to a theoretical prediction that each interresonance interval at circular radiation polarization has "transparency window" - frequencies for which w = 0 (Fig.3). The presence of such frequencies means that the statement on the absence of transparency at nonlinear ionization is not general, strictly speaking, it is valid only for the linear polarized radiation. The transparency windows are not still revealed experimentally because of the difficulties connected with clearing of the alkali atom target from molecular dimers.

The great number of experimental data is obtained also for different atoms having a few equivalent electrons in the external shell, first of all for alkali-earth atoms[13]. A relatively not high accuracy of experimental measurement of multiphoton cross-sections does not enable one to make the difference between multiphoton cross-sections for alkali atoms and, thereby, to obtain the data on the applicability of one-electron approximation.

In general, all set of experimental data within the experimental accuracy is well described by Berson's quasiclassical formula[14] which has a simplified form:

$$\alpha^{(K_o)} = B^{(K_o)}\omega^{-\frac{7K_o+2}{3}} \qquad (5)$$

where $B^{(K_o)}$ is tabulated in the Table:

K_o	2	3	4	5	6
$B^{(K_o)}$	1.0×10^{-45}	3.4×10^{-77}	7.0×10^{-109}	1.0×10^{-140}	8×10^{-173}

The orientation on eq. (5) is rather useful since the calculations by the methods of perturbation theory requires complicated methods and special programs.

While such an integral characteristic as the absolute value of multiphoton cross-section is independent of a sort of an atom within the experimental accuracy, investigation of the particular characteristics displays a qualitative difference. Such a difference is observed, for example, in radiation polarization dependence of the cross-section of direct ionization process. Thus, for alkali atoms at $K_o < 4$ the following factorial relation[16]

$$\frac{W_c^{(K_o)}}{W_L^{(K_o)}} = \frac{(2K_o - 1)!!}{K_o!!} \qquad (6)$$