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SENSING SPECTRAL HIERARCHY, QUANTUM CHAOS, CHAOTIC DIFFUSION AND DYNAMICAL STABILISATION EFFECTS IN A MULTI- PHOTON ATOMIC DYNAMICS WITH INTENSE LASER FIELD

A. V. Glushkov, S.V. Malinovskaya,
A. A. Svinarenko and L. A. Vitavetskaya

Odessa National Polytechnic University, P. O. Box 116, Odessa-9, 65009, Ukraine

Abstract

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A. V. Glushkov, S.V. Malinovskaya, A. A. Svinarenko and L. A. Vitavetskaya

A new method for sensing a spectral hierarchy, quantum chaos, chaotic diffusion, dynamical stabilisation in atomic systems in the intense laser field in the multi-photon regime is developed. New method is based on QED perturbation theory approach to calculating multi-photon, above threshold ionization cross-sections, Focker-Plank evolutionary equation for studying quantum diffusion phenomena, Fedorov interference stabilisation model. It is at first found availability of the spectral hierarchy and separately quantum-chaotic range (satisfying to the Wigner distribution) in spectrum of multi-photon ionization for magnesium. It is discovered the phenomenon of chaotic diffusion in the multi-photon regime for this atomic system in a laser field. It is at first proposed consistent theoretical approach to modelling the dynamical stabilisation effect for atomic system in an intense laser field and theoretically predicted the cited effect in atom of neon in laser field with intensity ~10^{14} W/cm^2 in an excellent agreement with experiment. Presented theory of studied phenomena is the physical basis for construction of the new nano-atomic elements and devices, including quantum Carnot engine, single-atomic lasers, quantum computers elements etc.

Key words: sensing, atomic system, laser field, spectral hierarchy, quantum chaos, diffusion, stabilisation

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Аннотация

ДЕТЕКТУВАННЯ СПЕКТРАЛЬНОЇ ІЄРАРХІЇ, КВАНТОВОГО ХАОСУ, ЕФЕКТІВ ХАОТИЧНОЇ ДИФУЗІЇ ТА ДИНАМІЧНОЇ СТАБІЛІЗАЦІЇ У БАГАТОФОТОННІЙ АТОМНІЙ ДИНАМІЦІ З ІНТЕНСИВНИМ ПОЛЕМ ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ

О. В. Глушков, С. В. Малиновська, А. А. Свинаренко, Л. А. Вітавецька

Розвинуто новий метод детектування ефектів спектральної ієрархії, квантового хаоса, хаотичної дифузії і динамічної стабілізації в атомних системах у сильному полі лазерного випромінювання у багатофотонному режимі. В якості теоретичної основи нового методу детектування використується метод КЕД теорії збурень для розрахунку перерізів багатофотонної іонізації, рівняння Фокера-Планку для хаотичної дифузії. Вперше виявлені феномен спектральної ієрархії, наявність квантово-хаотичного діапазону у спектрі багатофотонної іонізації Mg, ефект хаотичної іонізації у багатофотонному режимі. Вперше запропонований теоретично послідовний підхід до моделювання ефекту стабілізації для атомних систем у понад інтенсивному полі лазерного випромінювання і теоретично завбачений шуканий ефект в атомі Ne у полі інтенсивності ~10^{14} W/cm^2 у добрій згоді з експериментом. Теорія ішуканих явищ може служити фізичною основою для побудування нових нано-атомних елементів і приладів (квантові машини Карно, одноатомні лазери, елементи квантових комп'ютерів тощо).

Ключові слова: детектування, атомна система, поле лазерного випромінювання, спектральна ієрархія, квантовий хаос, дифузія, стабілізація

Анотація

ДЕТЕКТИРОВАНИЕ СПЕКТРАЛЬНОЙ ИЕРАРХИИ, КВАНТОВОГО ХАОСА, ЭФФЕКТОВ ХАОТИЧЕСКОЙ ДИФФУЗИИ И ДИНАМИЧЕСКОЙ СТАБИЛИЗАЦИИ В МНОГОФОТОННОЙ АТОМНОЙ ДИНАМИКЕ С ИНТЕНСИВНЫМ ПОЛЕМ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ

А. В. Глушков, С. В. Малиновская, А. А. Свинаренко, Л. А. Витавецкая

Развит новый метод детектирования эффектов спектральной иерархии, квантового хаоса, хаотической диффузии и динамической стабилизации в атомных системах в сильном поле лазерного излучения в многофотонном режиме. В качестве основы метода детектирования используется метод КЭД теории возмущений для расчета сечений многофотонной ионизации, уравнение Фокера-Планка для хаотической диффузии. Впервые обнаружены феномен спектральной иерархии, наличие квантово-хаотического диапазона в спектре мультифотонной ионизации Mg, эффект хаотической ионизации в мультифотонном режиме. Впервые предложен теоретически последовательный подход к моделированию эффекта динамической стабилизации для атомных систем в сверх интенсивном поле лазерного излучения и теоретически предсказан искомый эффект в атоме Ne в поле интенсивности ~10^{14} W/cm^2 в хорошем согласии с экспериментом. Теория искомых явлений может служить физической основой для создания новых нано-атомных элементов и приборов (квантовые машины Карно, одноатомные лазеры, элементы квантовых компьютеров и т. д.).

Ключевые слова: детектирование, атомная система, поле лазерного излучения, спектральная иерархия, квантовый хаос, диффузия, стабилизация

1. Introduction

In last years a phenomenon of dynamical chaos attracts a great interest as a manifestation of this effect in photo-optical systems may in a significant degree change a functional regime (c. f. [1-7]). Cited effect is usually observed in the physical systems and related to a type of non-linear effects. As a rule, dynamical chaos is manifested in the quantum systems, which are not linear in a classic limit. Above especially effective manifestations of this effect in the quantum systems one could mention systems which interact with external, time dependent, for example laser, field. The dynamical chaos features are discovered near boundary of the discrete spectra and continuum [6,7]. It has been discovered that dynamics of atomic and molecular, cluster and nano-optical systems in a laser field has features of the random, stochastic kind and its realization does not require the specific conditions. The importance of studying a phenomenon of stochasticity or quantum chaos in dynamical systems in laser field is provided by a whole number of technical applications, including a necessity of understanding chaotic features in a work of different electronic devices and systems.

The important topic of the laser-atomic dynamics and hierarchy systems physics is connected with governing and control of quantum chaotic, diffusion and stabilisation effects in atomic systems in the intense laser field (especially important case is atoms in electromagnetic traps and heat bath) [1-28]. The principal aim of coherent control is to steer a quantum system towards a desired final state through interaction with light while simultaneously inhibiting paths leading to undesirable outcomes. Controlling mechanisms have been proposed and demonstrated for atomic and solid-state systems. Recently experimental work of Dudovich *etal* tests the effect of pulse-shaping on transient populations of the excited Rb atoms. Gibson performs calculations for three-level systems and 1D model of a two-electron molecule (c. f. [2-5]. Transitions to excited state occur via a 12-photon interaction for an 800 nm intense pulse of length 244 au, or just over 2 cycles. Theoretical studies of the laser-atom non-linear interactions are usually based on solving the time-dependent Schrödinger equation or using the time-independent Floquet formalism. In [9] authors extended the non-Hermitian multi-state Floquet dynamics approach of Day *et al* to treat one-electron atomic system to the case of general multi-electron ones. The result is a generalization of the R-matrix Floquet theory, developed by Burke *et al,* that allows for pulse shape effects whilst retaining the ab initio treatment of detailed electron correlation. In ref. [10] we develop a new method for sensing a structure of the stochastic, multi-mode laser pulse and chaotic, photon-correlation effects in the atomic, nano-optical systems in a laser and also laser and DC electric field. At the same time a problem of sensing and correct theoretical description of the new effects of spectral hierarchy, quantum chaos, chaotic diffusion and stabilisation in the multi-photon atomic dynamics in a intense laser field is quite far from the final solution. It requires developing principally new approaches to description of multi-photon dynamics and new scheme for sensing the cited effects. A new method for sensing a spectral hierarchy, quantum chaos, chaotic diffusion, dynamical stabilisation in atomic systems in the intense laser field in the multi-photon regime is developed. New method is based on QED perturbation theory (PT) approach to calculating multi-photon, above threshold ionization (ATI) cross-sections, the Focker-Plank evolutionary equation for studying quantum diffusion phenomena, Fedorov interference stabilisation model. It is at first found availability of the spectral hierarchy and separately quantum-chaotic range (satisfying to the Wigner distribution) in spectrum of multi-photon ionization for magnesium. It is discovered the phenomenon of chaotic diffusion in the multi-photon regime for this atomic system in a laser field. It is at first proposed consistent theoretical approach to modelling the dynamical stabilisation effect for atomic system in an intense laser field and theoretically predicted the cited effect in atom of neon in laser field with intensity ~10^{14} W/cm^2 in an excellent agreement with experiment. Presented theory of studied phenomena is the physical basis for construction of the new nano-atomic elements and devices (quantum Carnot engine, single-atomic lasers, quantum computers elements etc.

2. Energy approach to atomic system in a intense laser field and above threshold ionization

Now let us consider a new approach to calculation of the characteristics of multi-photon ionization in atomic systems, which is based on the QED PT[17-24]. Below we calculate numerically the ATI cross-sections for atom of magnesium in a intense laser field. The two-photon excitation process will be described in the lowest QED PT order. This approach is valid away from any one-photon intermediate-sate resonance. We start from the two-photon amplitude for the transition from an initial state Ψ_0 with energy E_0 to a final state Ψ_f with energy $E_f = E_0 + 2\omega$ is:

$$T_{f0}^{(2)} = \lim_{\eta \to 0+} = \int d\varepsilon < \Psi_f \mid D \cdot e \mid \varepsilon > \\ > (E_0 + \omega - \varepsilon + i\eta)^{-1} < \varepsilon \mid D \cdot e \mid \Psi_0 > \quad (1)$$

Here $\boldsymbol{D}$ is the electric dipole transition operator (in the length $\boldsymbol{r}$ form), e is the electric field polarization and ω is a laser frequency. It's self-understood that the integration in equation (1) is meant to include a discrete summation over bound states and integration over continuum states. Usually an explicit summation is avoided by using the Dalgarno-Lewis by means the setting:

$$T_{f0}^{(2)} = C_f < \Psi_f \| D \cdot e \| \Lambda_p > \quad (2)$$

where <|| ||> is a reduced matrix element and C_f is an angular factor depending on the symmetry of the Ψ_f, Λ_p, Ψ_0 states. Λ_p, can be founded from solution of the following inhomogeneous equation [16,17]:

$$(E_0 + \omega - H) \mid \Lambda_p > = (D \cdot e) \mid \Psi_0 > \quad (3)$$

at energy $E_0+\omega$, satisfying outgoing-wave boundary condition in the open channels and decreasing exponentially in the closed channels. The total cross section (in cm^4W^{-1}) is defined as:

$$\sigma/I = \sum_J \sigma_J / I = 5{,}7466 \times 10^{-35} \cdot \omega_{au} \sum_J | T_{J,0}^{(2)} |^2 \quad (4)$$

where I (in W/cm^2) is a laser intensity. To describe two-photon processes there can be used different quantities [16]: the generalized cross section $\sigma^{(2)}$, given in units of cm^4s, by

$$\sigma_{cm^4 s}^{(2)} = 4{,}3598 \times 10^{-18} \omega_{au} \sigma / I_{cm4/W} \quad (5)$$

and the generalized ionization rate $\Gamma^{(2)}/I^2$, (and probability of to-photon detachment) given in atomic units, by the following expression:

$$\sigma / I_{cm4/w} = 9{,}1462 \times 10^{-36} \omega_{au} \Gamma_{au}^{(2)} / I_{au}^2 \quad (6)$$

Described approach is realized as computer program block [18] in atomic numeric code "Super-atom" (c. f. [10,22-24]), which includes a numeric solution of the Dirac equation and calculation of the matrix elements of the (17)-(18) type. The original moment is connected with using the consistent QED gauge invariant procedure for generating the atomic functions basis's (optimized basis's) [17-21]. This approach allows getting results in an excellent agreement with experiment and they are more precise in comparison with similar data, obtained with using non-optimized basis's.

3. Spectral hierarchy and quantum chaos in spectrum of magnesium in a laser field

Let us present the results of calculating the multi-photon resonances spectra characteristics for atom of magnesium in a laser field and show the possibilities for sensing a whole number of non-linear laser-atomic dynamical effects for atomic (and nano-optical) systems in this field. Let us note that to calculate spectral properties of atomic systems different methods are used: relativistic R-matrix method (R-метод; Robicheaux-Gao, 1993; Luc-Koenig E. etal, 1997), added by multi channel quantum defet method, K-matrix method (K-method; Mengali-Moccia,1996), different versions of the finite L^2 method (L^2 method) with account of polarization and screening effects (SE) (Moccia-Spizzo, 1989; Karapanagioti et al, 1996), Hartree-Fock configuration interaction method (CIHF), operator QED PT (Glushkov-Ivanov, 1992; Glushkov-Svinarenko et al; 2004) etc. (c. f. [2,5,16]. In table 1 we present results of calculating characteristics for $3p^{2}\,{}^1S_0$ resonance of Mg; E- energy, counted from ground state ($см^{-1}$), Γ-autoionization width ($см^{-1}$), σ/I- maximum value of generelized cross-section ($см^4W^{-1}$). R-matrix calculation with using length and velocity formula led to results, which differ on 5-15%, that is evidence of non-optimality of atomic basis's.

This problem is absent in our approach and agreement between theory and experiment is very good. Further let us consider process of the multi-photon ATI from the ground state of Mg. The laser radiation photons energies ω in the range of 0,28-0,30 a. u. are considered, so that the final autoionization state (AS) is lying in the interval between 123350 $см^{-1}$ and 131477$см^{-1}$. First photon provides the AS ionization, second photon can populate the Rydberg resonance's, owning to series *4snl,3dnl,4pnp* с J=0 and J=2 [16]. In table 2 we present energies ($см^{-1}$; counted from the ground level of Mg $3s^2$) and widths ($см^{-1}$) of the AS (resonance's) *4snl,3dnl,*$4p^2$ ${}^1D_2$, calculated by the K-, R-matrix and our methods. In a case of ${}^1S_0$

Table 1.

Characteristics for $3p^{2\,1}S_0$ resonance of atom of the magnesium: E- energy, counted from ground state (см$^{-1}$), Γ- autoionization width (см$^{-1}$), σ/I- maximum value of generalized cross-section (см^{4}W^{-1}).

Methods	E	Γ	σ/I
Luc-Koenig E. etal, 1997	without	account	SE
Length form	68492	374	$1{,}96\ 10^{-27}$
Velocity form	68492	376	$2{,}10\ 10^{-27}$
Luc-Koenig E. etal, 1997	with	account	SE
Length form	68455	414	$1{,}88\ 10^{-27}$
Velocity form	68456	412	$1{,}98\ 10^{-27}$
Moccia and Spizzo (1989)	68320	377	$2{,}8\ 10^{-27}$
Robicheaux and Gao (1993)	68600	376	$2{,}4\ 10^{-27}$
Mengali and Moccia(1996)	68130	362	$2{,}2\ 10^{-27}$
Karapanagioti et al (1996)	68470	375	$2{,}2\ 10^{-27}$
Our calculation	68281	323	$2{,}0\ 10^{-27}$

Table 2.

Energies and widths (см$^{-1}$) of the AS (resonance's) *4snl,3dnl,4p²* $^1D_2$ for Mg (see text)

	R-method			Our approach			*K*-method	
$^1D_2$	E	Γ	$^1D_2$	E	Γ		E	Γ
4s3d	109900	2630	4s3d	109913	2645		110450	2600
$3d^2$	115350	2660	$3d^2$	115361	2672		115870	2100
4s4d	120494	251	4s4d	120503	259	(ds)	120700	170
3d5s	123150	1223	3d5s	123159	1235	(ds)	123400	2000
$4p^2$	124290	446	$4p^2$	124301	458		124430	500
3d4d	125232	400	3d4d	125245	430		125550	590
4s5d	126285	101	4s5d	126290	113	(ds)	126250	120
3d6s	127172	381	3d6s	127198	385	(ds)	127240	350
4s6d	127914	183	4s6d	127921	215		127870	1900
3d5d	128327	208	3d5d	128344	215			
4s7d	128862	18	4s7d	128874	24	(ds)	128800	30
3d5g	128768	4,5	3d5g	128773	5,2	3d5g	128900	2,2
3d7s	129248	222	3d7s	129257	235		129300	160
4s8d	129543	114	4s8d	129552	125	(ds)	129500	140
			3d6d	129844	115			
			4s9d	129975	64			
			4s10d	130244	5			
			3d8s	130407	114			
			4s11d	130488	118			
			4s12d	130655	28			
			3d7d	130763	52			
			4s13d	130778	36			
			4s14d	130894	14			
			4s15d	130965	7			

resonance's one can see an excellent identification of these resonance's. Let us note that calculated spectrum of to-photon ATI is in a good agreement with the R-matrix data and experiment, but our results are more precise than data of Luc Koenig etal [16]. Calculated spectrum of two-photon ATI to final states with J=2 is presented on fig. 1. Situation is drastically changed. Only three resonance's are identified. Other resonance's and ATI in a whole demonstrate non-regular behaviour. Studied system is corresponding to a status of quantum chaotic system with stochastization mechanism. It realizes through laser field induction of the overlapping (due to random interference and fluctuations) resonance's in spectrum, their non-linear interaction, which lead to a global stochasticity in the atomic system and quantum chaos phenomenon. The quantum chaos is well known in physics of the hierarchy, atomic and molecular physics in external electromagnetic field. Earlier it has been found in simple atomic systems H, He, and also Ca (c. f. [6,7,10]). Here we at first discover it in atom of Mg. Spectrum of resonance's can be divided on three intervals: 1). An interval, where states and resonance's are clearly identified and not strongly perturbed; 2) quantum-chaotic one, where there is a complex of the overlapping and strongly interacting resonance's; 3). Shifted one on energy, where behavior of energy levels and resonance's is similar to the first interval. Quantitative estimate shows that the resonance's distribution in the second quantum-chaotic interval is satisfied to Wigner distribution $W(x)=x\exp(-\pi x^2/4)$. At the same time, in the first interval the Poisson distribution is valid.

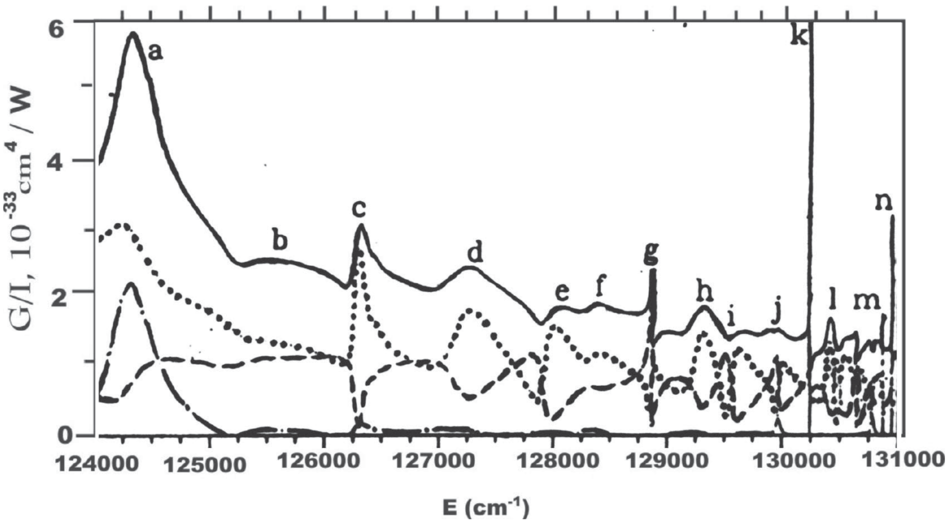

Fig. 1. Two-photon ATI from the ground state Mg to states J=2; The full cross-section σ/I (solid line) and partial cross-sections, corresponding to ionization to 3sεd (dashed line) or to 3pεp opened channels (dotted line). Identification of the $^1D_2$ resonance: a- 4p4p; b-3d4d; c-4s5d;d-3s6d;e-4s6d;f-3d5d; g-4s7d; h-3d7s; i-4s8d; j-4s9d; k-4s10d; l-4s11d; m-4s14d; n-4s15d;

4. Sensing effect of the chaotic ionization on spectrum of highly excited Rydberg states and Focker-Plank approach.

Chaotic diffusion phenomenon for atomic systems in the low frequency electromagnetic field in the tunnelling regime was studied in many papers (c. f. [2-5]). Its essence results in diffusion of electron on the strongly perturbed atomic states by the external field. In order the stochastic motion of electron covers many energy levels it is necessary fulfilling the condition for electric field strength: $E>n^{-6}$ [1]. Experimentally this effect is realized for hydrogen atom from the state n=60 in electromagnetic field with frequency w=9,9GGz by Koch et al (c. f. [3]). A number of qualitative models of chaotic ionization process was proposed and based on simplified diffusion equation (Delone-Kraynov model). More complicated theories are based on models of chaotic draft of the Coulomb electron in he microwave field (Jensen R. etal; c. f. [2-5]). The cited papers are related to so called regime of the tunnelling ionization, when the Keldysh parameter $\gamma^2<<1$. Here we consider the opposite case, when $\gamma^2>>1$. Speech is about multi-photon chaotic ionization. Critical value of laser field strength, when splitting states of the shell n reaches value of order of the distance to nearest shell n+1 and mixing of states of the different shells occurs, is a follows: $E_{cr}\sim 1/n^5$. Multi-photon ionization of atomic systems has a diffusion character for conditions [1]: $1/n^2>>\omega>Fn.\ 1/n^4$. With increasing n region of realization of the diffusion mechanism increases. We develop at first consistent, Focker-Plank approach to stochastic diffusion of electron on spectrum of highly lying states. The Focker-Plank equation is [25]:

$$\partial f(n,t)/\partial t=\partial/\partial n\,[\Theta(n-N_{min})wn^3\partial f(n,t)/\partial n]- \\ -[\Theta(n-N_{max})W(n)f(n,t) \qquad (7)$$

Here function $f(n,t)$ gives distribution of Rydberg electron on space of effective quantum numbers n; $w=W_{n,n}\pm_1$— velocity of radiation transitions, $W_{n,n}\pm_1=\sigma_{n',n\pm1}\cdot I(t)$, $\sigma_{n',n\pm1}$— cross-sections of radiation transitions above and down; $I(t)$— intensity of laser radiation (in photon $cm^{-2}c^{-1}$);,$\Theta(n-N_{min})$ — is the Heviside function. The last function appears as additional multiplier in the diffusion coefficient $D(R)n^3$, which realizes "freezing" the stochastic processes in interval of the low-lying states according to the Chirikov criterion. It separates the interval above some value $n=N_{min}$. This interval is corresponding to the deterministic one and diffusion process is forbidden. In the interval of highly lying states, when $n>N_{max}$ $\{f(n=N_{max})=0\}$ a channel of direct, multi-photon ionization is opened. Here one can suppose that there is 100% ionization, and autoionization width $W(n\geq N_{max})=\infty$. Eq. (7) was solved numerically for atom of Mg by means of the Eihler method. All necessary values for constants are taken from ref. [16] and our calculations. The set accounts for 1500 equally lying points n_k in the interval $n\in[0\text{-}50]$. The initial distribution of Rydberg electron on level $n=n_0$ was chosen as: $f_{n0}(n_k,t=-\infty)=N\exp[-10(n_0-n_k)^2]$. In fig. 2 we present solution of eq. (7). It gives temporary evolution of the distribution function $f(n,t)$ of Rydberg electron under chaotic diffusion on spectrum of highly lying states and resonance's. Solid lines give the map of levels of the values for $\ln[f(n,t)]$. The dashed lines are corresponding to positions of low reflecting wall N_{min} and above absorbed wall N_{max}. Initially Rydberg electron was in state n_0=10 (3s10s). Received result is qualitatively corresponding to similar results of the chaotic draft theory (tunnelling mechanism) and stochastic ionization of Rydberg electron in the collision process (c. f. [2-5,25,26,28]). So, we make modelling the stochastic diffusion of electron on spectrum of highly lying, Rydberg states and resonance's in the multi-photon regime. Results are in reasonable agreement with statistic nature of diffusion processes. Estimate for diffusion time is ~10^{-8}s. Let us note that the diffusion motion of Rydberg electron occurs especially effectively in the quantum-chaotic interval, where there is a complex of the overlapping and strongly interacting resonance's.

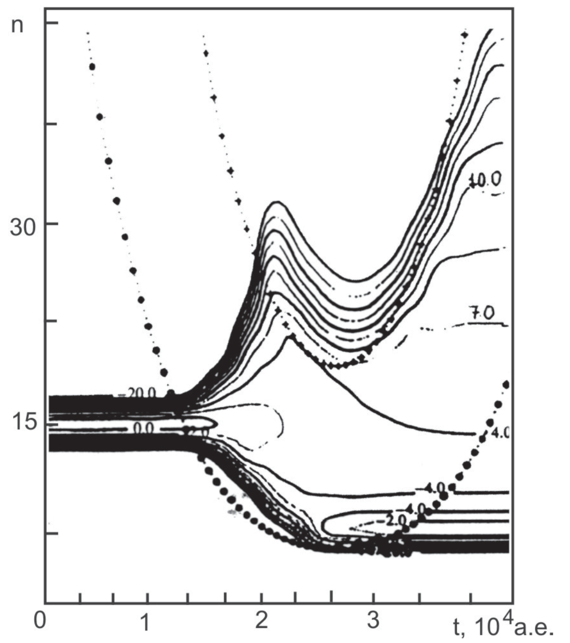

Fig 2. Temporary evolution of the distribution function $f(n,t)$ of Rydberg electron under chaotic diffusion on spectrum of highly lying states and resonance's.

5. Sensing effect of dynamical stabilisation for neon atom in the super intense laser field and QED interference stabilisation model

Here we present new approach to modelling and sensing multi-photon stabilisation of atomic systems in an intense laser field, based on the Fedorov interference stabilisation model and QED PT to calculating of the multi-photon matrix elements. Further we theoretically confirm effect of dynamical stabilisation for atom of neon in laser field with intensity ~10^{14}W/cm^2. Different models for description of the stabilisation effect in the tunnelling regime has been proposed (c. f. [2-10]). Here we consider a case of the multi-photon stabilisation. The essence of effect is as follows [2,5]: Rydberg electron absorbs a photon of frequency $\omega>E_n$, moves to continuum and further can reach indefiniteness (ionization) or transit to one of the Rydberg states, radiating a stimulated photon. Further electron can again absorb a photon of field and such a process can repeat many times. (c. f. fig. 3). To get full amplitude of ionization it is necessary to make summation of amplitudes of all PT orders. Interference of these partial amplitudes is destructive, so full amplitude is less each term on module. Ionization probability decreases with a growth of laser filed intensity. In result, the Rydberg states of atomic system are stabilised in super intense laser filed. In the first PT order a matrix element of bound-free transition is [5]: $V_{nE} = z_{nE}F$. Here z_{nE} — dipole element of transition (for supposition, external field is linearly polarized along axe Z), F — amplitude of filed strength. In the next

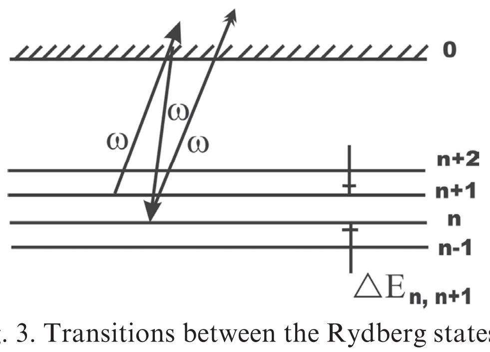

Fig. 3. Transitions between the Rydberg states of atomic system (third order of PT)

order the 3-photon matrix element is, which is corresponding to transition: $n \rightarrow E' \rightarrow n' \rightarrow E$:

$$V_{nE}^{(3)} = \sum_{n'} \int \mathrm{d}\,E' \frac{V_{nE'} V_{E'n'} V_{n'E}}{(E' - E_{n'} - \omega)(E' - E - \mathrm{i}\delta)} \quad (8)$$

i. e.
$$V_{nE}^{(3)} = \mathrm{i}\, f(E) V_{nE}\,, \quad (9)$$

where
$$f(E) = \sum_{n'} \frac{|V_{n'E}|^2}{E - E_{n'} - \omega}\,. \quad (10)$$

Next 5-photon matrix element can be written similarly. A set of matrix elements represents indefinite geometric progression and its sum is:

$$\tilde{V}_{nE} = \frac{V_{nE}}{1 + \mathrm{i}\, f(E)}\,. \quad (11)$$

Ionization probability of Rydberg system after averaging on all quantum numbers is:

$$\tilde{w}_{nE} = \frac{w_{nE}}{1 + f^2(E)} < w_{nE}\,. \quad (12)$$

Here w_{nE} –is probability of one-photon ionization of Rydberg state according to Fermi golden rule. We make modelling the dynamical stabilisation effect in atom of Ne in the super intense laser field with intensity ~10^{14}W/cm^2 and compared the results of modelling with data of experiment by de Boer M., Hoogenraad J., Vrijen B. et al (c. f. [2,5]). Atom of Ne was excited from the ground state $2p^6$ (m=-1) by absorbing five photons of laser radiation to excited state $5g$ (m=l=n-1=4). Energy of bond is E_{5g}=0,55 eV, the Kepler period t_{5g}=0,6ps. Photo ionization from circular state $5g$ Ne realized by laser radiation of frequency ω=2eV>E_{5g} and pulses duration t_l =0,1ps and t_l =1,0ps. The results of the de Boer M., Hoogenraad J., Vrijen B. Et al experiment are presented in fig. 4 (dotes). For more large pulse duration (t_l =1,0ps) and maximum intensity I=1,2×10^{13}Wcм$^{-2}$ the photo electrons output is approximately increased due to linear law with growth of laser field intensity. But, for more small pulse duration (t_l=0,1ps) and maximum intensity I=1,2×10^{14}Wcм$^{-2}$ the photo electrons output is not practically dependent upon the laser filed intensity that is an evidence of the stabilisation effect. Our data are also presented in fig. 3 (solid lines: curve 1 is got with using gauge invariant atomic basis's; curve 2 — with using atomic basis's without optimization) (c. f. [18,21, 22]). So, theory gives sufficiently good agreement with experiment.

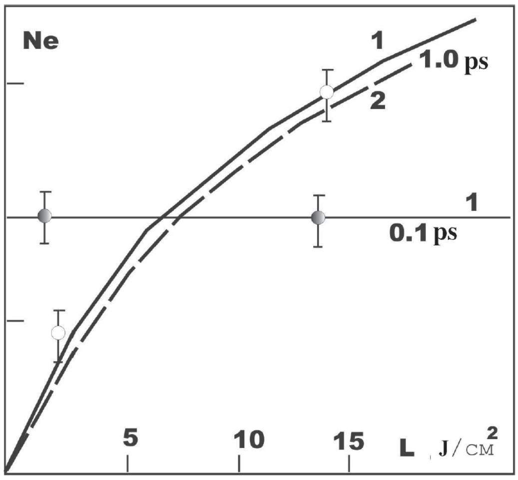

Fig. 4. Dependence of the photo-electron output from the state 5g Ne upon intensity of laser field for two duration's of laser pulse (see text).

So, we presented new approaches to sensing spectral hierarchy, quantum chaos, chaotic diffusion, dynamical stabilisation in atomic systems in the intense laser field in the multi-photon regime. We have at first found availability of the spectral hierarchy and separately quantum-chaotic range in spectrum of multi-photon ionization for Mg. We have discovered the phenomenon of chaotic diffusion in the multi-photon regime for Mg and proposed consistent approach to modelling the stabilisation effect for atoms in intense laser field. The important result is theoretically found stabilisation in Ne in field with I~10^{14} W/cm^2 in a good agreement with experiment. We believe that presented studying can be used as a physical basis for construction of new nano-atomic elements and devices (quantum Carnot engine, single-atomic lasers, quantum computers elements etc.).

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