UDC 539.192

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NONLINEAR STOCHASTIC DYNAMICS GOVERNING FOR QUANTUM SYSTEMS IN EXTERNAL FIELD: CHAOS THEORY AND RECURRENCE SPECTRA ANALYSIS

Nonlinear method of chaos theory and the recurrence spectra formalism are used to study quantum stochastic futures and chaotic elements in dynamics of atomic systems in the external electromagnetic (laser) field. Some illustrations regarding the recurrence spectra and chaos dynamics of lithium and magnesium atoms in the crossed electric and magnetic and laser fields are presented.

1. Introduction

In last years a great interest attracts studying a dynamics of quantum systems in external electric and magnetic field [1-18]. It has been discovered that dynamics of these systems in external electromagnetic fields 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 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, including the nano-optical ones. New field of investigations of the quantum and other (geophysical, chemical, biological, social etc) systems has been provided by a great progress in a development of a chaos theory methods [1,2] (c.f. review part in Refs.[19-22]).

Rydberg atoms in strong external fields have been shown to be real physical examples of non-integrable systems for studying the quantum manifestations of classical chaos both experimentally and theoretically. To describe these phenomena, one has to make calculating and interpreting the recurrence spectra which is the Fourier transformation of a photo absorption spectrum [2,13,14]. Consequently, the recurrence spectrum provides a quantum picture of classical behaviour. Studies of recurrence spectra have led to observations of the creation of new orbits through bifurcation's, the onset of irregular behaviour through core scattering and symmetry breaking in crossed fields [1-7,17,18]. In the past, many researchers have calculated the recurrence spectra of a Rydberg atom in an external field. But they only calculated the spectra in static electric or magnetic fields. In a recent experiment, the absorption spectrum of the lithium atom in a static electric field plus a weak oscillating field was measured and Haggerty and Delos gave some explanation for it theoretically (c.f.[2,13,14]). But as to the influence of an oscillating electric field on the absorption spectrum of the Rydberg atom in static magnetic field, none has given the calculation both experimentally and theoretically, besides the first classical estimate [14]. In previous our papers we have given a review of this approach in analysis of different systems of quantum physics, electronics and photonics. In this paper we have used the nonlinear method of chaos theory and the recurrence spectra formalism to study quantum stochastic futures and chaotic elements in dynamics of atomic systems in the external electroomagnetic fields.

2. Nonlinear analysis of quantum system dynamics in a field and a chaos theory methods

Following refs. [21,22] we briefly consider an analysis of nonlinear dynamics of some system in a field by means of a chaos theory methods. Usually some dynamical parameter $s(n) = s(t_0 + n\mathrm{D}t) = s(n)$, where t_0 is the start argument (for example, time), Dt is the argument step, and is n the number of the measurements. In a general case, $s(n)$ is any time series, particularly the amplitude level. Since processes resulting in the chaotic behaviour are fundamentally multivariate, the reconstruction results in a certain set of d-dimensional vectors $\mathbf{y}(n)$ replacing the scalar measurements. The standard method of using time-delay coordinates is usually used to reconstruct the phase space of an observed dynamical system. The direct use of the lagged variables $s(n + \mathrm{t})$, where t is some integer, results in a coordinate system in which a structure of orbits in phase space can be captured. Using a collection of time lags to create a vector in d dimensions,

$$\mathbf{y}(n) = [s(n), s(n + \mathrm{t}), s(n + 2\mathrm{t}), \ldots, s(n + (d\text{-}1)\mathrm{t})], \tag{1}$$

the required coordinates are provided. In a nonlinear system, the s(n + jt) are some unknown nonlinear combination of the actual physical variables that comprise the source of the measurements. The dimension d is also called the embedding dimension, dE. If any time lag t is chosen too small, then the coordinates s(n + jt) and s(n + (j + 1)t) are so close to each other in numerical value that they cannot be distinguished from each other. Similarly, if t is too large, then s(n + jt) and s(n + (j + 1)t) are completely independent of each other in a statistical sense. Also, if t is too small or too large, then the correlation dimension of attractor can be under- or overestimated respectively. It is therefore necessary to choose some intermediate (and more appropriate) position between above cases. First approach is to compute the linear autocorrelation function

$$C_L(\delta) = \frac{\frac{1}{N}\sum_{m=1}^{N}[s(m+\delta)-\bar{s}][s(m)-\bar{s}]}{\frac{1}{N}\sum_{m=1}^{N}[s(m)-\bar{s}]^2} \tag{2}$$

where $\bar{s}$ is an averaged value and to look for that time lag where C_L(d) first passes through 0. This gives a good hint of choice for t at that $s(n + j\mathrm{t})$ and $s(n + (j + 1)\mathrm{t})$ are linearly independent. However, a linear independence of two variables does not mean that these variables are nonlinearly independent. It is therefore preferably to utilize approach with a nonlinear concept of independence, e.g. the average mutual information. Let there are two systems, A and B, with measurements a_i and b_k. The mutual information I of two measurements a_i and b_k is symmetric and nonnegative, and equals to zero if only the systems are independent. The average mutual information between any value a_i from system A and b_k from B is the average over all possible measurements of $I_{AB}(a_i, b_k)$,

$$I_{AB}(\tau) = \sum_{a_i, b_k} P_{AB}(a_i, b_k) I_{AB}(a_i, b_k)\,. \tag{3a}$$

To place this definition to a context of observations from a certain physical system, let us think of the sets of measurements $s(n)$ as the A and of the measurements a time lag t later, $s(n + \mathrm{t})$, as B set. The average mutual information between observations at n and n + t is then

$$I_{AB}(\tau) = \sum_{a_i, b_k} P_{AB}(a_i, b_k) I_{AB}(a_i, b_k)\,. \tag{3b}$$

Now we have to decide what property of I(t) we should select, in order to establish which among the various values of t we should use in making the data vectors $\mathbf{y}(n)$. It is necessary to choose that t where the first minimum of I(t) occurs.

The goal of the embedding dimension determination is to reconstruct a Euclidean space R^d large enough so that the set of points d_A can be unfolded without ambiguity. According to the embedding theorem, the embedding dimension, d_E, must be greater, or at least equal, than a dimension of attractor, d_A, i.e. $d_E > d_A$. There are standard approaches to reconstruct the attractor dimension, for example, the correlation integral method. It was shown in refs. [23,24] in studying chaos in the vibrations dynamics of the autogenerators and similar analysis for geophysical systems [19-21, 24, 25], the low, non-integer correlation dimension value indicates on an existence of low-dimensional chaos. The embedding phase-space dimension is equal to the number of variables present in the evolution of the system. To verify data obtained by the correlation integral analysis, it is often used a surrogate data method.

This an approach makes use of the substitute data generated in accordance to the probabilistic structure underlying the original data [19-21]. The next step is an estimating of the Lyapunov exponents (LE). These parameters are the dynamical invariants of the nonlinear system and defined as asymptotic average rates. So, they are independent of the initial conditions, and therefore they do comprise an invariant measure of attractor. In fact, if one manages to derive the whole spectrum of LE, other invariants of the system, i.e. Kolmogorov entropy and attractor's dimension can be found. The Kolmogorov entropy, *K*, measures the average rate at which information about the state is lost with time. An estimate of this measure is the sum of the positive LE. The inverse of the Kolmogorov entropy is equal to an average predictability. The estimate of the dimension of the attractor is provided by the Kaplan and Yorke conjecture: $d_L = j + \sum_{\alpha=1}^{j} \lambda_\alpha / |\lambda_{j+1}|$, where *j* is such that $\sum_{\alpha=1}^{j} \lambda_\alpha > 0$ and $\sum_{\alpha=1}^{j+1} \lambda_\alpha < 0$, and the LE l_a are taken in descending order. The known approach to computing the LE is based on the Jacobin matrix of the system function [3]. The detailed description of the whole approach (our version) to analysis a nonlinear dynamics of chaotic systems can be found in refs. [19-25].

3. The recurrence spectra for atomic systems in an electromagnetic fields: Sensing chaos

For quantum systems in an external field there is very useful method, based on the analysis of the recurrence spectra. To calculate the energy spectra of atomic systems in the electric and magnetic fields one should use an approach, which combines solution of the 2D Schrödinger equation [16-18] for atomic system in crossed fields and operator perturbation theory [8,9]. The detailed description of such an approach is presented in these refs.[8,17,18], so here we briefly discuss the key moments. For definiteness, we consider a dynamics of the non-coulomb atomic systems in a static magnetic field and oscillating electric filed. The Hamiltonian of the system in a static magnetic field and an oscillating electric field is (in atomic units) is as follows:

$$H = 1/2(p_\rho^2 + l_Z^2/\rho^2) + \gamma l_Z/2 + (1/8)\gamma^2\rho^2 + $$
$$+ (1/2)p_Z^2 + F_1 z \cdot \sin(\omega t) + V(r) \qquad (4)$$

where the electric field and magnetic field B are taken along the z-axis in a cylindrical system; g=B/2.35×10^5; *V(r)* is a one-electron model potential, which is as follows:

$$V(r) = -1/r + (2/Zr)[1 - \exp(-2b_1 r)(1+r)]. \qquad (5)$$

Here Z is a nuclear charge, and *b* is a free length parameters, which are chosen to give the energy spectrum of free atom. In fact, the second term in (5) is the corresponding potential of the K-shell (in a case of the Li atom). We consider only the m=0 state, thus $l_z=0$. The Hamiltonian obeys a classical scaling rule and can be written as:

$$\tilde{H} = \tilde{p}^2/2 + (1/8)\tilde{\rho}^2 + $$
$$+ f \cdot \tilde{z} \cdot \sin(\tilde{\omega} \cdot \tilde{t}) + V(r) = E(t)\gamma^{-2/3} \qquad (6)$$

Here $\tilde{r} = r\gamma^{2/3}$, $\tilde{p} = p\gamma^{-1/3}$, $\tilde{f} = F_1\gamma^{-4/3}$, $\tilde{l} = l\gamma$, $\tilde{\alpha}_i = \alpha_i\gamma^{-2/3}$ and $\tilde{\omega} = \omega\gamma^{-1}$.

In the oscillating field, the electron energy *E(t)* is not constant. We define $e = E^{out} g^{-2/3}$ as it leaves the atom. The useful method is a scaled recurrence spectroscopy, which allows to analyse the photo absorption amplitude as a function of the parameter $g^{-1/3}$ while varying the external fields frequency simultaneously in such a way that *e* and *f* remain constant. To account for an electric field (under supposition that an electric field is quite weak) one can use the perturbation theory. For solution of the Schrödinger equation the finite differences scheme is usually used. To find the resonances width and absorption spectrum one should use the golden Fermi rule (see details in refs. [2,3,8]).

4. Some results and discussion

We have studied a dynamics of the lithium atom in a crossed electric and magnetic fields. The transition from the lithium 3s state to final states corresponding to the principle quantum numbers around n =125 and m =0 is considered. Following to ref. [14,16-18], because the ionic core produces important dynamical effects, we can split the whole space into two characteristic spatial regions: (1) The core region, where the laser field and the ionic core potential dominate while the external magnetic field can be eliminated. It should be noted here that the standard semi classical closed orbit theory provides an efficient treating the motion of a Rydberg electron far from the nucleus, but it fails when the electron is close to the nucleus. Because this region extends for only a few Bohr radii around the atomic nucleus, one must deal with this region by using a quantum method; (2)

The external region typically lies beyond 30 Bohr radii from the nucleus, so one can treat this region using standard semi classical methods or approximations to quantum approaches [14-18]. Using equation (4-6), we calculate the photo absorption spectrum of lithium in a magnetic field plus an oscillating electric field, with B =4.7T, F_1 =10V/cm and w=10^8 Hz. The corresponding data are presented in figure 1. In figure 2 we present the data on the photoabsorption spectrum of the LiI in a magnetic field without electric field. One should conclude that, when the oscillating field was added, the photo absorption spectrum was weakened greatly. This is fully corresponding the analysis within the standard closed orbit semi-classical calculation [5,14]. In figures 3(b),(d) we list the results of calculating the recurrence spectra of the Li atom in a magnetic field plus an oscillating field, with e=-0.03, v=0.32 ,$g^{-1/3}$ in the range 35–50 and f= 0.0035 and 0.07, respectively.

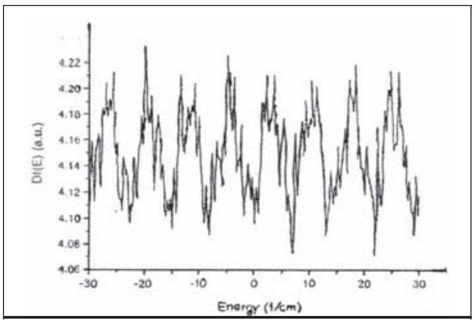

Figure 1. Absorption spectra of the Li atom in magnetic field plus an oscillating electric field

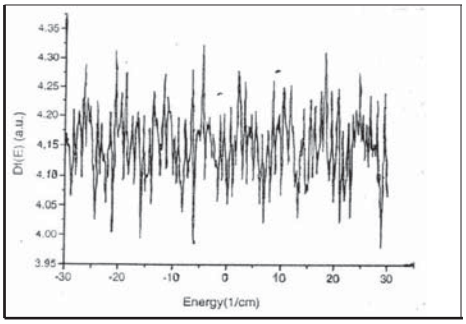

Figure 2. Absorption spectra of the Li atom in magnetic field, B =4 7 T.

This data are similar to parameters of the semi-classical approximation analysis [17]. As analysis of received data shows, when the value of f increases, the strength of all the peaks decreases. Some recurrences dropped rapidly and vanished as f increased; others remained even at much higher f. As the oscillating field gets stronger, some of the peaks re-appear, some more than once. Because when the oscillating field is strong, one can not consider it as a perturbation, the method described in this paper [14] is no longer suitable. Note that besides the semi-classical closed-orbit theory in versions [2-6,13,14], the other standard methods, for example, based on the perturbation theory [2,3], are not also acceptable for large values of field strengths. At the same time, the approach applied can be used even in a case of strong field. Availability of multiple resonances with little widths in atomic spectra in external fields is described within quantum chaos theory and provided by interference and quantum fluctuations, which characterize chaotic systems [1,9]. The chaos theory analysis fully confirms this conclusion. The mutual information approach, the correlation integral analysis, the false nearest neighbour algorithm, the LE analysis were used in analysis. The main conclusion is that the system exhibits a nonlinear behaviour and low-D chaos. The LE analysis supported this conclusion. Really, the first two LE have the following positive values: l_1=0.0242; l_2=0.0039. In conclusion, let us note that there is of a great interest to perform the similar analysis of chaotic dynamics and recurrence spectra for more heavy alkali systems in a microwave field. In conclusion we present also another remarkable example of the chaos phenomenon for quantum systems in an external electromagnetic (laser) field, namely, the multi-photon above threshold ionization (ATI) process for magnesium atom (from the ground state).

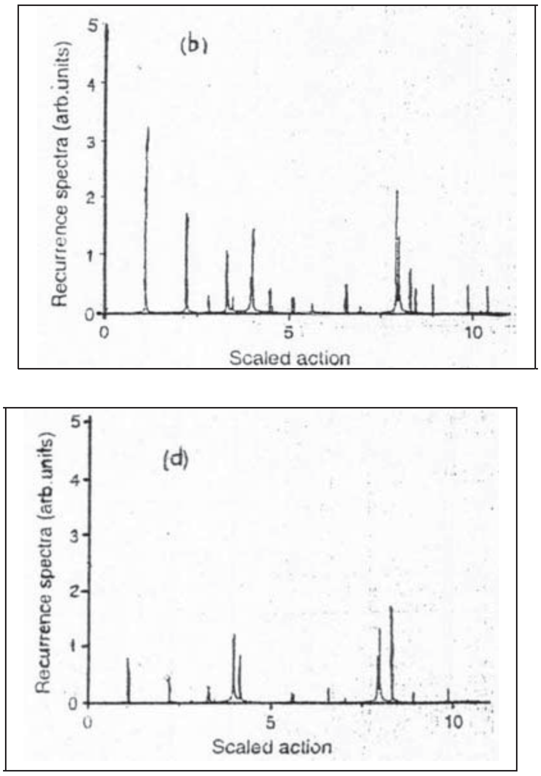

Figure 3. The recurrence spectra of Li in magnetic field plus an oscillating electric field: (b) scaled field *f* =0 0035; (d) scaled field *f* =0 07.

In ref.[9] it has presented the detailed theoretical description of the cited process and listed the data about the theoretical spectrum of two-photon ATI to final states with J=2 (figure 4). The laser radiation photons energies w 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 131477см$^{-1}$. First photon provides the AS ionization, second photon can populate the Rydberg resonance's, owning to series *4snl,3dnl,4pnp* c J=0 and J=2 [9,25]. In a case of $^{1}S_{0}$ resonance's there is observed an excellent identification of these resonance's. Situation is drastically changed in a case of spectrum of two-photon ATI to final states with J=2. Only three resonance's are identified.

Other resonance's and ATI in a whole demonstrate non-regular behavior. Studied system is corresponding to a status of quantum chaotic system.

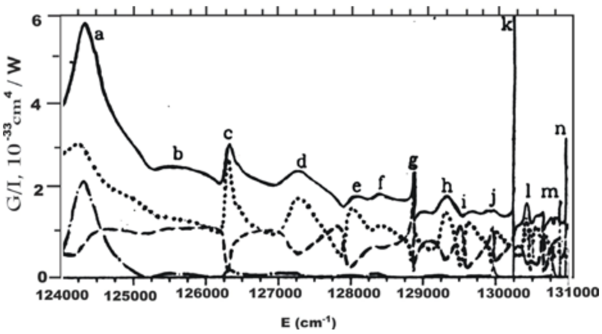

Figure 4. Two-photon ATI from the ground state Mg to states J=2; The full cross-section s/I (solid line) and partial cross-sections, corresponding to ionization to 3sed (dashed line) or to 3pep opened channels (dotted line). Identification of the $^{1}D_{2}$ resonance: a-4p4p; b-3d4d; c-4s5d;d-3s6d;e-4s6d;f-3d5d;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

It realizes through the electromagnetic 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 and quantum chaos phenomenon. Spectrum of resonance's is divided on three intervals: 1). the 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. Analysis shows that the resonance's distribution in the second quantum-chaotic interval is satisfied to the Wigner distribution W(x)=xexp(-px^{2}/4), however, in the first interval the Poisson distribution is valid. The chaos theory analysis fully confirms this conclusion.

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UDC 539.192

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Abstract.

Nonlinear method of chaos theory and the recurrence spectra formalism are used to study quantum stochastic futures and chaotic elements in dynamics of atomic systems in the electromagnetic (laser) field. Some illustrations regarding the recurrence spectra and chaos dynamics of lithium and magnesium atoms in the crossed electric and magnetic and laser fields are presented.

Key words: atomic system, electromagnetic field, chaos, recurrence spectrum

УДК 539.192

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НЕЛИНЕЙНАЯ СТОХАСТИЧЕСКАЯ ДИНАМИКА КВАНТОВЫХ СИСТЕМ ВО ВНЕШНЕМ ПОЛЕ: АНАЛИЗ НА ОСНОВЕ ТЕОРИИ ХАОСА И РЕКУРРЕНТНЫХ СПЕКТРОВ

Резюме.

На основе нелинейных методов теории хаоса и формализма рекуррентных спектров изучены квантово-стохастические особенности и элементы хаоса в динамике атомных систем во внешнем электромагнитном (лазерном) поле. В качестве примера приведены данные по рекуррентным спектрам и хаотической динамике атомов лития и магния в скрещенных электрическом и магнитном.а также лазерном полях.

Ключевые слова: атомная система, электромагнитное поле, хаос, рекуррентный спектр

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НЕЛІНІЙНА СТОХАСТИЧНА ДИНАМІКА КВАНТОВИХ СИСТЕМ У ЗОВНІШНЬОМУ ПОЛІ: АНАЛІЗ НА ОСНОВІ ТЕОРІЇ ХАОСУ ТА РЕКУРЕНТНИХ СПЕКТРІВ

Резюме.

На підставі нелінійних методів теорії хаосу та формалізму рекурентних спектрів досліджені квантово-стохастичні особливості та елементи хаосу в динаміці атомних систем у зовнішньому електромагнітному (лазерному) полі. В якості приклада наведені дані по рекурентним спектрам та хаотичній динаміці атомів літію та магнію у схрещених електричному та магнітному, а також лазерному полях.

Ключові слова: атомна система, електромагнітне поле, хаос, рекурентний спектр