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Toward the possibility of ^{229}Th isomeric nuclear state excitation by two-color laser field

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Abstract. The process of high harmonic generation (HHG) has a wide area of different applications, in particular, in nanoscale imaging, study the nanoscale energy transport in complex molecules and solids, probe the charge and spin dynamics with the femtosecond time resolution, etc. Here we discuss a possible application of HHG effect related with the study of nuclear transition dynamics. We analyse the efficiency of excitation of the isomeric nuclear state ^{229m}Th by the fifth harmonic of Ti: Sa laser generated in thorium by two-color femtosecond pulse consisting of the fundamental and thensecond harmonic of Ti: Sa laser (ω+2ω). It is shown that the rate of isomeric state excitation can be enhanced significantly with respect to other nucleus excitation processes in laser plasma or by an external coherent source at the resonance wavelength. This enhancement is due to the discussing process of "nonlinear laser nuclear excitation".

The thorium isomer ^{229m}Th which has an anomalously low excitation energy lying in the UV range attracts the attention of researchers for quite long time [1]. Recently the energy of this level has been estimated as 7.8±0.5 eV [2]. The lifetime of isomeric state depends essentially on the chemical environment of atom, because in the non-ionized atom the process of internal conversion is the most probable [3]: it is equal to 7 μs for the decay through an internal conversion channel and more than 60 s through a photon channel [4, 5]. The unusual properties of this isomer give rise to a number of possible applications [5].

The energy of nuclear transition is comparable with the energy of atomic electron transitions. As a result a number of different mechanisms associated with the energy transfer between the electron and nuclear have been discussed (please, see[6] for example).. However, direct excitation of this isomer from the ground state has not yet been realized. This is due to the lack of reliable data on the excitation energy and absence of spectrally bright tunable UV sources in required energy range.

Here we discuss the mechanism of electron-nuclear energy transfer, presented in [7]. The external laser field induces the electron current in atom. The atomic current produces the response e.m. field. In far field zone this response field is arranged the spectrum of harmonics. However the atomic current produces the field at its own nucleus as well. If the frequency of some harmonic of atomic current coincides with frequency of nuclear transition then the nuclear transition can be effectively induced. Hence, due to electron-nuclear energy transfer the nucleus transitions can be resonantly stimulated by the external laser fields acting

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on the electron subsystem of atom. The probability of nuclear transitions depends on the mutual orientation of nucleus angular momentum and the polarization of the driving e.m. field. At the same time, the polarization of e.m. field produced by an electron at nucleus depends on the mutual orientation of the polarization vector of driving laser field and the angular momentum of an atomic electron [8]. The advantage of the proposed excitation mechanism is in possibility of the precise adjustment not only to the energy of the exotic ^{229m}Th excited state (the photon energy of the 5th harmonic can be easily tuned within 7-9 eV due to peculiar properties of the Ti:Sa medium), but also to the nucleus angular momentum polarization direction [7]. To increase the 5th harmonic generation efficiency we suggest to use ω+2ω field.

To analyse the problem of atomic electron response in ω+2ω field we apply the recently developed approach [9]. In numerical simulations the model structure of the ^{229m}Th atom included the following discrete spectrum states: 6d, 7s, 5f, 7p. Calculations were carried out for the case of the ω+2ω orthogonally polarized femtosecond laser pulses with the intensities of both components assumed to be ~ 10^{12} W/cm^2.

All three components of the atomic current on the Cartesian set of coordinates have been calculated in numerical experiments. The polarization of the 5th harmonic field at nucleus strongly depends on the propagation direction of the driving field. So, if the thorium target is polarized, then by varying the propagation direction of the driving field we can control the amplitude and polarization of the 5th harmonic field at nucleus. The spectra of the atomic current projections where calculated for different values of the Euler angles (θ_0, ψ_0, φ_0), connecting the axes of atomic configurational space and coordinate set associated with configuration of the ω+2ω field [8, 10]). The spectrum of the three atomic current components contains even and odd field harmonics, including the 5th harmonic. By changing the Euler angles (θ_0, ψ_0, φ_0) we can optimize it parameters to precisely adjust to the nucleus transition. As a result, to the angles θ_0~ ψ_0~0.5 rad and φ_0=0 is supposed to be optimal to have all three projections (two of them coincide with polarization direction of the components of the ω+2ω field, and the third is the longitudinal one) of the 5th harmonic with comparable values.

We have studied possibility of the isomeric state ^{229m}Th excitation under action of ω+2ω laser field. The results of simulations have shown the possibility of high efficiency of excitation. This enhancement is due to the process of "nonlinear laser nuclear excitation" [7]. Results of numerical calculations demonstrate ways of the 5th harmonic generation properties optimization to adjust the nucleus transition.

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