High-order harmonic spectra generated by atoms in a strong laser field: a new heuristic theoretical model

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In this paper we presented the current results of our new elaborated model approach for theoretical treatment of high-order harmonic generation (HHG) by atoms and negative ions, i.e. nonlinear phenomenom of coherent emission of electromagnetic (EM) radiation of frequencies $\Omega_N = N \cdot \omega$ which are multiplies of the fundamental laser frequency ω ($\omega \ll I_p$, where I_p is the ionization potential of a laser exposed atomic or atomic ion system and N is a positive integer odd number, $N \gg 1$; the atomic system of units is used throughout this paper unless otherwise stated). Our "*heuristic*" approach is developed to fast numerical calculation of atom HHG spectra with a rather good accuracy and based on three main key presumptions, namely:

i) the active (optical) atomic electron being released from atom does not interact with its parent residual core, but with ionizing laser field only, therefore, its movement in atomic continuum can be described by nonrelativistic Volkov's wavefunction (see, e.g., [1]);

ii) the total amplitude $A^{(N)}_{HHG}(\Omega_N)$ of HHG process of emission of high order N-th harmonic may be represented in the factorized form, i.e., as a product of atom photoinization amplitude - $A_{PI}(p_m, E)$ and $A_{SR}(p_m, \Omega_N)$ - the amplitude of subsequent spontaneous photorecombination of released active atomic electron into the final atomic (ground) state;

iii) only a narrow region of values of photoelectron momentum determined by expression $p_m = \sqrt{2(m \cdot \omega - I_p - U_p)}$ (here m is a positive integer number and $U_p = E^2/(4 \cdot \omega^2)$ is the ponderomotive or "quiver" energy of electron driven by laser field of strength E) of released electron being in atomic continuum intermediate states are taken into primary account to give the main contribution to the total HHG amplitude.

Like other various different SAE approaches developed before (e.g., the TDSE -approach or the famous "*simple-man model*" (SMM) and its diverse modifications, see also [2] for more details), our proposed model describes purely non-perturbative (nonlinear) single-atomic response. Despite of our results *a fortiori* are of a bit less precision (mostly in the low-frequency region of HHG spectra) than ones corresponding to most of mentioned general models, nonetheless, unlike the latter ones, our results are obtained with not so much intensive and annoying numerical computation work. Therefore, our model seems to be especially appropriate and extremely useful for numerical calculations of HHG spectra with *plateau* of too large extent (the magnitude of which is proportional to $\eta = U_p/\omega$) that appear if the applied laser field is either too strong (the strength E is comparable of intraatomic one) or (for the case of moderate field intensities) sufficiently low-frequency, so that U_p takes very large values ($\eta \geq 50$).

As an example of the results obtained within our developed model approach, the calculated HHG spectra of various noble atoms in the field of Nd:YAG laser ($\hbar\omega = 1.165$ eV) are presented on the figure below 1 for the same value of laser field intensity $I = 1.11 \cdot 10^{14}$ W$\cdot$cm^{-2} ($\eta = 10$) at which the tunneling regime of atom photoionization is realized (the value of the Keldysh parameter $\gamma = (\omega \cdot \sqrt{2 \cdot I_p})/E \approx 1$). It is easy to make sure that all the calculated and presented HHG spectra demonstrate quite a "reasonable" behavior and, particularly, are in a good agreement with the famous "$I_p + 3.2 \cdot U_p$" rule for both the extent of plateau and the position of its *cut-off* frequency even though the applied *heuristic* HHG model is rather rough approximation (especially for low- frequency region of spectra as mentioned above). As expected, the intensities of HHG peaks within the plateau region fluctuate by up to one or two order of magnitude from one harmonic to the next and in some cases even more, moreover, at the fixed laser field intensity the height of the plateau (that is, the average efficiency of HHG) decreases noticeably with increasing I_p (from Xe to He), in contrast to the extent of plateau and its cut-off frequency) which both increase too.

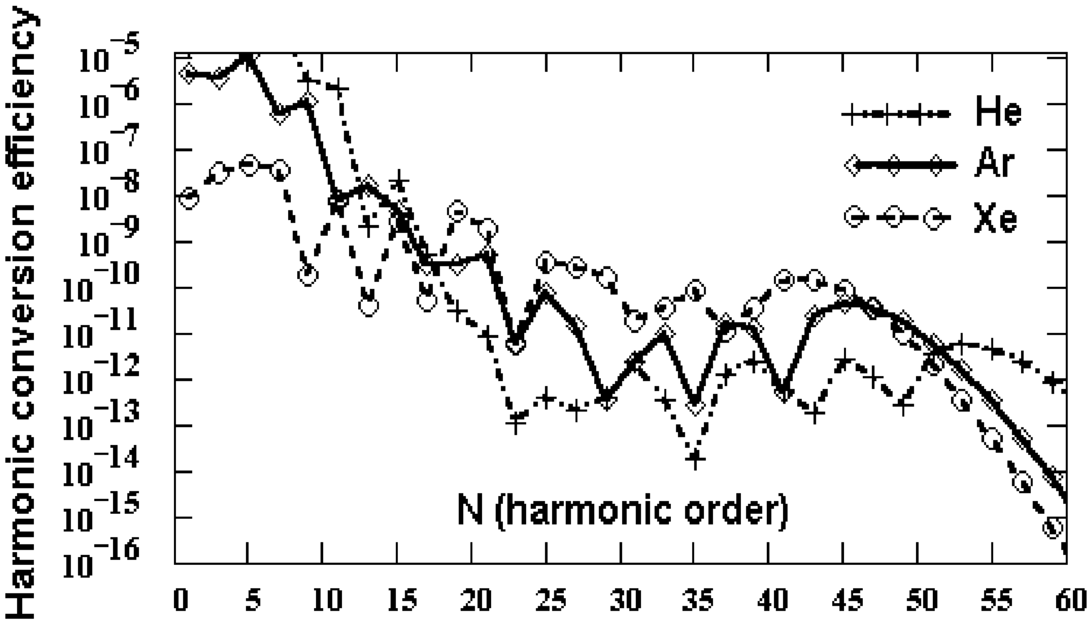

Figure 1: The calculated HHG spectra generated by noble atoms (crosses - for He, diamonds - for Ar and circles - for Xe) in the field of Nd:YAG laser ($\hbar\omega = 1.165$ eV) and intensity $I = 1.11 \cdot 10^{14}$ W $\cdot$cm^{-2} corresponding to the value $U_p = 11.7$ eV. The symbols are joined by lines to help the eye to distinguish each spectrum from other ones.

[1] Delone N.B. and Krainov V.P. *Atoms in Strong Fields* (Springer-Verlag, Heidelberg, 1985).
[2] Protopapas M., Keitel C.H. and Knight P.L. *Rep. Progr. Phys.*, **60**, 389-486 (1997).