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TREATMENT OF THE PLASMA NONLINEAR ABSORPTION LAW AT LINEARLY POLARIZED LASER RADIATION OF RELATIVISTIC INTENSITIES

A. G. Ghazaryan

Centre of Strong Fields Physics, Yerevan State University, 1 A. Manoogian, Yerevan 0025, Armenia

e-mail: amarkos@ysu.am

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Abstract – On the base of previous analytical investigations of inverse laser-induced multiphoton bremsstrahlung of electrons on the ions/nuclei in the low-frequency approximation, and nonlinear absorption coefficient of linearly polarized laser radiation of relativistic intensities in plasma is treated via numerical simulations. Some dependences of absorption coefficient on the radiation intensity for moderately strong, as well as asymptotically large values of short laser pulses and high temperatures of plasma are revealed in case of radiation linear polarization. The latter exhibits different absorption law and nonlinear behavior of plasma absorption coefficient comparing with the case of circular polarization.

Keywords: relativistic superintense laser radiation, plasma, nonlinear absorption, bremsstrahlung.

At the propagation of an electromagnetic (e. m.) wave in the plasma, one of the dominant mechanisms of radiation absorption is the inverse stimulated bremsstrahlung (SB). The induced absorption process of strong e. m. radiation in plasma due to the multiphoton SB of electrons on the Coulomb scattering centers, in the limit of the low-frequency approximation, has been investigated with the appearance of laser sources (for earlier consideration of this process see the review [1]). At the ultrahigh intensities of super short laser pulses considerably exceeding nowadays the relativistic threshold value of radiation fields ($10^{18}\,Wcm^{-2}$ in optical domain), the nonlinear absorption process due to an electron beam SB on the Coulomb scattering centers has been investigated in the paper [2], and a new dependence on the wave intensity ($\approx 1/\xi_0^2$, $\xi_0 = eF_0/(m_e c\omega)$ is the dimensionless relativistic invariant parameter of intensity, e, m_e the electron charge and mass, F_0, ω the electric field amplitude and frequency of a laser radiation, c

the light speed in vacuum) of the absorption coefficient of a homogeneous monoenergetic electron beam on the wave intensity at asymptotically high values ($\xi_0 \geq 1$) has been revealed.

As the interaction of superintense laser pulses with any matter results to laser-plasma interaction and since the laser-produced plasmas are bright sources of X-ray emission, then due to the high laser absorption at the formation of laser plasmas, apart from plasma heating and related important processes or its practical applications, the conversion efficiency of laser field energy into the X-ray emission spectrum is significantly high. Besides the thermal sources of incoherent X-ray, during the last decades laser-produced plasmas are intensively discussed as the active media for generation of coherent X-ray, especially via high harmonic generation in the soft X-ray region (see, e.g. [3]). So, in the current stage of investigations of superstrong laser field-plasma interaction processes the problem of nonlinear absorption of electromagnetic wave energy by plasma becomes important.

As in the strong e. m. wave field SB process has significantly multiphoton nature, the task can be considered in the scope of classic theory [1]. First the study of the absorption of strong radiation in fully ionized plasma in the SB process was performed on the basis of the kinetic theory in [4]. In this paper we consider the plasma nonlinear absorption dependence on the intensity of external radiation using exact analytical expressions [2] for absorption coefficient in low frequency (LF) approximation. The conditions of the assumed LF approximation and the case of relativistic plasma in the circular polarization wave field have been considered by us earlier [5].

However, it is well known that the kinetics of an electron in the field of a strong e. m. wave essentially depends on the polarization of the wave. Thus, since the wave intensity for a circular polarization $\xi_0 = const$, then the longitudinal velocity of the electron in the wave: $V_{II} = const$ too, meanwhile in the wave of a linear polarization V_{II} oscillates with the wave harmonics $n\omega$, corresponding to inharmonic oscillatory motion of the electron. The latter leads to more complicated behavior of the dynamics of electron induced interaction with additional third body at the linear polarization of a stimulating strong wave. For example, in contrast to circular polarization [6], in case of a linearly polarized e. m. wave to obtain ultimate results for relativistic ATI rates, taking into account the photoelectron SB, is impossible analytically [7]. The analogous situation takes place for relativistic multiphoton SB in the strong linearly polarized radiation field, the consideration of which is the matter of the present paper. On the other hand, many important laser-assisted processes and nonlinear phenomena just occur at the linear polarization of the stimulating field (when conservation laws of the process require certain symmetry of the photon field). Thus, the high harmonic generation (HHG) process on the atoms takes place only in the linearly polarized laser fields [3]. To reveal dependence on the wave polarization, in this paper we study the nonlinear absorption coefficient in underdense plasma due to the mechanism of the nonlinear SB of electrons on the Coulomb scattering centers for the linearly polarized laser radiation of relativistic intensities. Due to the complexity of the task the investigations are performed by the numerical treatment of the issue.

For intermediate, as well as at high temperatures of electrons and asymptotically large values of laser fields with relativistic laser intensities ξ_0, as it has been shown in [2], the SB process is well enough described by the classical theory, in the LF approximation. Hence, the absorption coefficient α for a radiation field of arbitrary intensity, in general case of the homogeneous ensemble of electrons with the arbitrary distribution function $f(\mathbf{p})$ over relativistic momentum $\mathbf{p}$, at the inverse-bremsstrahlung on the scattering centers with concentration n_i can be represented in the form (cm^{-1}):

$$\alpha = \frac{n_i}{2\pi I}\int f(\mathbf{p})d\mathbf{p}\int_0^{2\pi}\frac{d}{dt}W(\mathbf{p},\tau_0)d\tau_0 \quad , \tag{1}$$

where $n_i W$ is the classical energy absorbed by a single electron per unit time due to SB process on the Coulomb scattering centers; τ_0 is the scattering phase in the e. m. wave, and $I = \omega^2 A_0^2 / 8\pi c$ is the wave intensity of linear polarization (the integration is performed over the initial phase τ_0).

For the generality, we assume Maxwellian plasma with the relativistic distribution function of electrons by momenta:

$$f(\mathbf{p}) = \frac{n_e}{4\pi m_e^2 ckT_e K_2\left(m_e c^2 / k_B T_e\right)}\exp\left(-\frac{E(\mathbf{p})}{kT_e}\right), \tag{2}$$

where k_B is Boltzmann's constant, T_e and n_e the temperature and concentration of electrons in plasma respectively, $E(\mathbf{p})$ is the relativistic energy–momentum dispersion law of electrons and $K_2(x)$ is McDonald's function; $f(\mathbf{p})$ is normalized as

$$\int f(\mathbf{p})d\mathbf{p} = n_e. \tag{3}$$

According to the work [2], the change of energy of one electron due to the scattering on Coulomb centers (in LF approximation) in the strong e. m. wave field of linear polarization with the vector potential:

$$\mathbf{A}(\tau) = A_0 \hat{\mathbf{e}} \cos(\tau), \tag{4}$$

($\hat{\mathbf{e}}$ is the unit vector; $\hat{\mathbf{e}} \perp \mathbf{k}$, $\mathbf{k}$ and τ are the wave vector and phase, respectively) at a certain phase τ_0 is given by the relation (taking into account the definitions $\mathbf{p}_0 \equiv \mathbf{p}_0(\tau_0)$, $E_0 \equiv E_0(\tau_0)$):

$$\begin{gathered} \frac{dW}{dt}(\mathbf{p},\tau_0) = 2\pi \frac{Z_a^2 e^4 m_e^2 c^2}{(\mathbf{np}')^2} \frac{E_0}{p_0^3} \left\{ \left(1 + E_0 \frac{\mathbf{np}'}{m_e^2 c^3} \right) \left[-\Lambda\cos(\tau_0) - 2(Z + Z\cos 2\tau_0) \right] \right. \\ - \frac{\mathbf{p}_{0\perp}^2}{m_e^2 c^2}(Z + Z\cos 2\tau_0) + \left\{ \Lambda\cos(\tau_0) + (Z + Z\cos 2\tau_0)\left(1 - E_0 \frac{\mathbf{np}'}{m_e^2 c^3} \right) \right\} \\ \left. \times \ln\left(1 + E_0 \frac{\mathbf{np}'}{m_e^2 c^3} - \frac{c\,\mathbf{np}'}{\omega m_e^2 Z_a e^2} \frac{p_0^3}{E_0} \right) \right\}, \end{gathered} \tag{5}$$

where

$$E_0 = E + c^2(\Lambda\cos(\tau_0) + Z + Z\cos 2\tau_0),\ \mathbf{p}_0 = \mathbf{p} - \frac{e\mathbf{A}(\tau_0)}{c} + \mathbf{n}c(\Lambda\cos(\tau_0) + Z + Z\cos 2\tau_0) \tag{6}$$

are the energy and momentum of an electron in the wave, $\mathbf{p}' = \mathbf{p} - \mathbf{n}E/c$, $\mathbf{n} = \mathbf{k}/|\mathbf{k}|$. The parameters Z and Λ have the form:

$$Z = -e^2 A_0^2 / (4c^3 \mathbf{np}'), \qquad \Lambda = eA_0(\mathbf{p}\hat{\mathbf{e}})/(c^2 \mathbf{np}'). \tag{7}$$

The relation for the absorption coefficient in the case of linearly polarized wave is very complicated and even for not so large ξ_0 one cannot integrate it analytically. Therefore, for the analysis we have performed numerical investigations, making also analytic interpolation. For the numerical simulations in (1) we have taken $Z_a = 10$, ω= 1 eV. Numerical calculation of the inverse-bremsstrahlung absorption coefficient (1) has been made for intermediate, as well as at large values of laser fields and high temperatures of electrons. To show the dependence of the inverse-bremsstrahlung absorption rate on the laser radiation intensity for moderate wave intensities $\xi_0 = 0.1 - 1$, in figure 1, the scaled rate $\alpha(\xi_0, T_n)/\alpha_0$ versus plasma temperature for various wave intensities is shown ($T_n = k_B T_e / mc^2$). Here,

$$\alpha_0 = 4 Z_a^2 r_e^3 \lambda^2 n_i n_e \,, \tag{8}$$

where λ is the laser radiation wavelength, r_e is the electron classical radius.

For the comparison, in Fig. 1 the numerical results for the nonrelativistic absorption coefficient (1) are also shown. As expected for small values of ξ_0 both results coincide, in the meantime, the absorption rate for a moderately large ξ_0 at the inverse-bremsstrahlung, given by the nonrelativistic formula (1), is suppressed due to dependence $1/I^{3/2}$ [1].

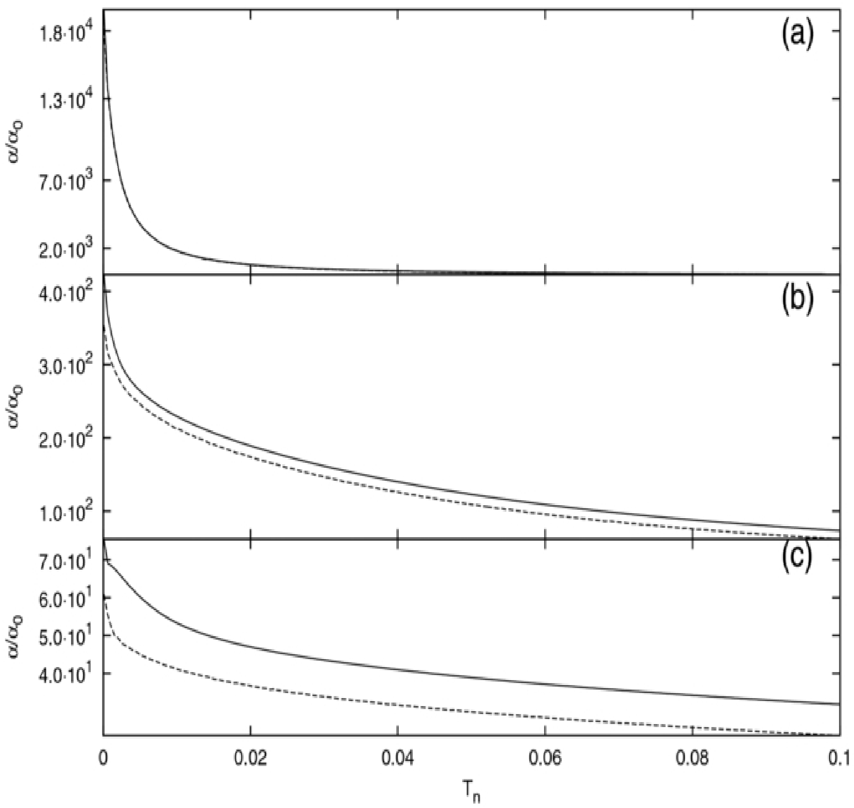

Fig. 1. Total scaled rate of inverse-bremsstrahlung absorption (in arbitrary units) of linearly polarized laser radiation in plasma, as a function of the plasma temperature (in units of an electron rest energy mc^2) is shown for various wave intensities: (a) $\xi_0 = 0.1$, (b) $\xi_0 = 0.5$ and (c) $\xi_0 = 1$ for the range $T_n = k_B T_e / mc^2 = 10^{-4} - 10^{-1}$. Numerical results for the nonrelativistic absorption coefficient [1] are shown by the dashed lines.

In Fig. 2, the dependence of the inverse-bremsstrahlung absorption rate on the laser radiation intensity for the linearly polarized wave is shown for various plasma temperatures. As seen from this figure, the SB rate is considerably suppressed with the increase of the wave intensity and plasma temperature. The results of numerical investigations of equation (1) for the large values of laser fields and high temperatures of electrons are illustrated in Figs. 3-5. In Fig. 3, the scaled rate $\alpha(\xi_0, T_n)/\alpha_0$ versus the relativistic invariant parameter of the wave intensity for various plasma temperatures is shown. As seen from Fig. 3, the SB rate strictly depends on the wave polarization; it is suppressed with an increase of the wave intensity, and for large values of ξ_0 it exhibits a tenuous dependence on the plasma temperature. This behavior is also seen from Fig. 4, where the total scaled rate of the inverse-bremsstrahlung absorption as a function of the plasma temperature T_n (in the units of an electron rest energy mc^2) is shown for various wave intensities. Here, for the large values of ξ_0, we have a weak dependence on the temperature, which is a result of the laser-modified relativistic scattering of electrons, irrespective of the initial state of electrons. As it was shown in [5], in the case of circularly polarized wave the absorption coefficient α decreases as $1/\xi_0^2$ at the increase of intensity, in accordance with the analytical results [2].

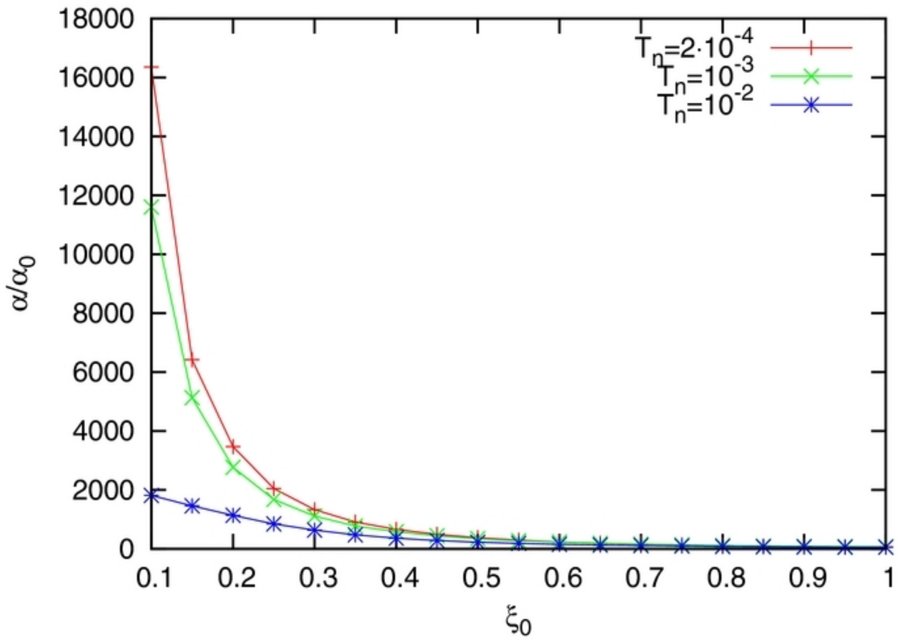

Fig. 2. Total scaled rate of inverse-bremsstrahlung absorption (in arbitrary units) of linearly polarized laser radiation in plasma versus the dimensionless relativistic invariant parameter of wave intensity in the range $0.1 \le \xi_0 \le 1$ for various plasma temperatures.

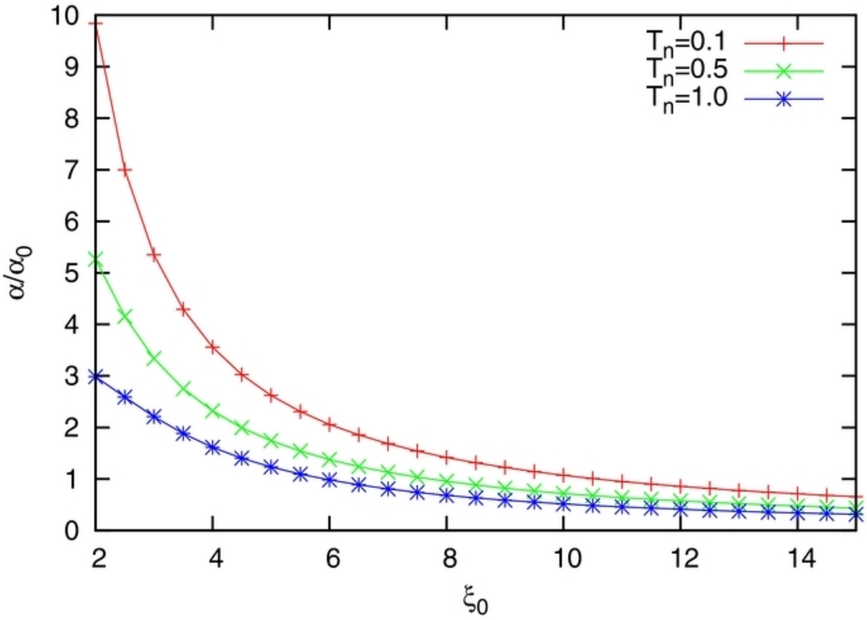

Fig. 3. Total scaled rate of inverse-bremsstrahlung absorption (in arbitrary units) of linearly polarized laser radiation in Maxwellian plasma versus the dimensionless relativistic invariant parameter of the wave intensity for various plasma temperatures.

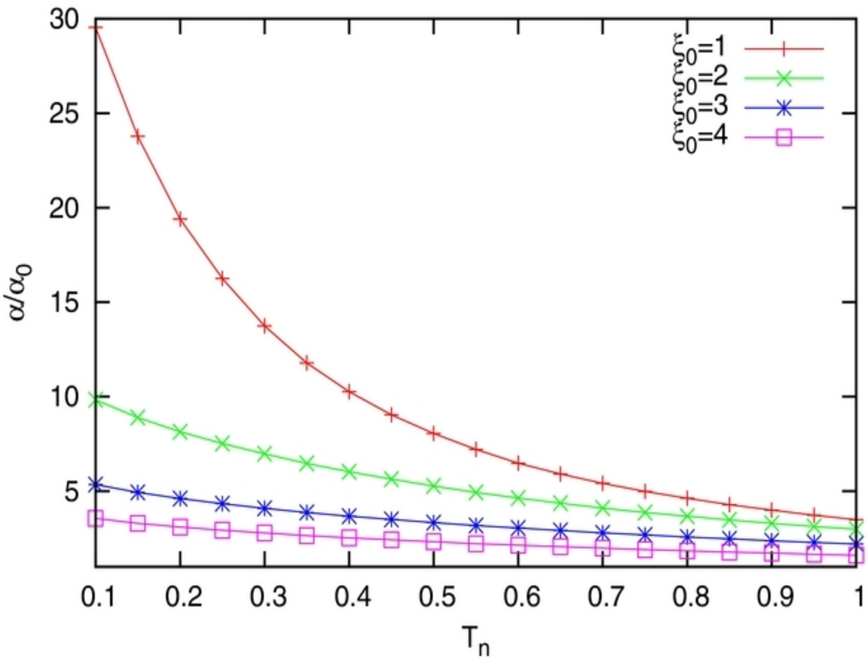

Fig. 4. Total scaled rate of inverse-bremsstrahlung absorption (in arbitrary units) of linearly polarized laser radiation in plasma, as a function of the plasma temperature (in units of an electron rest energy mc^2) is shown for various wave intensities.

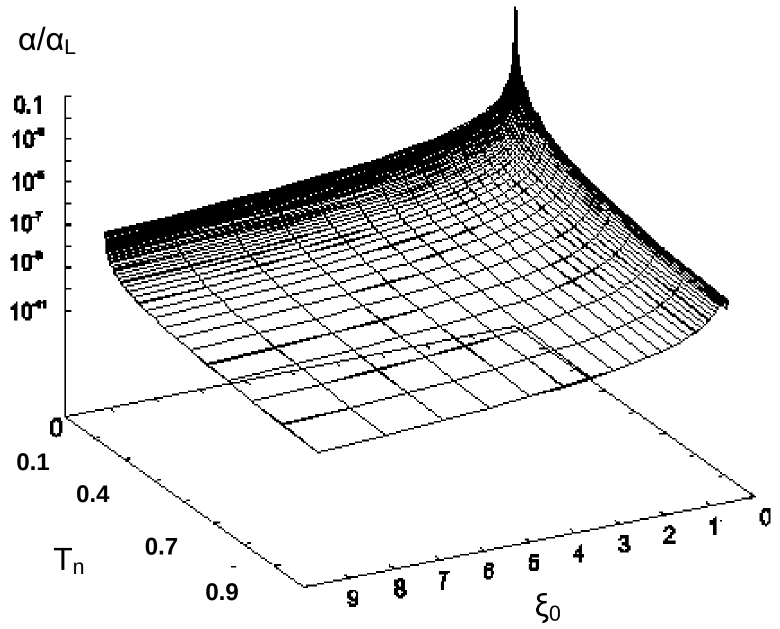

Fig. 5. Plot of the total rate of inverse-bremsstrahlung absorption scaled to the asymptotic rate α_L (in arbitrary units), as a function of the plasma temperature (in units of an electron rest energy mc^2) and the dimensionless relativistic invariant parameter of the linearly polarized laser beam.

In the case of linearly-polarized wave from Fig. 5 with the interpolation, we have seen that α decreases as $1/\xi_0^{5/4}$ at the increase of the wave intensity and exhibits a tenuous dependence on the plasma temperature. For the large ξ_0 we can interpolate α by the following formula. As seen from Fig. 5, in the case of linearly-polarized wave and for the moderate temperatures, with the well enough accuracy one can apply the asymptotic rate (9):

$$\alpha \cong \alpha_L = \frac{\alpha_0}{\xi_0^{5/4}}. \tag{9}$$

Concluding, we have presented numerical treatment of relativistic theory of the inverse-bremsstrahlung absorption of a superintense laser radiation in the LF approximation. The coefficient of nonlinear inverse-bremsstrahlung-absorption in plasma has been calculated considering, in general, the relativistic Maxwellian distribution. The simple analytical formula (9) has been obtained for the absorption coefficient at asymptotically large values of laser fields for linearly polarized e. m. wave. The obtained results demonstrate that the SB rate is suppressed with the increase of the wave intensity and temperature of plasma. If for large values of ξ_0, the absorption coefficient α decreases as $1/\xi_0^2$ for circularly polarized wave [5], for a linearly polarized e. m. wave α decreases as $1/\xi_0^{5/4}$, in contrast to the nonrelativistic case where one has the dependence $1/\xi_0^3$ [1]. The SB rate is suppressed with the increase of the plasma temperature, but for the relativistic laser intensities it exhibits a tenuous dependence on plasma temperature.

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References

1. F. V. Bunkin, A. E. Kazakov, M. V. Fedorov, Sov. Phys. Usp. **15**, 416 (1973).

2. H. K. Avetissian, A. K. Avetissian, H. A. Jivanian, S. V. Movsissian, J. Phys. B **25**, 3217 (1992); ibid B **25**, 3201 (1992).

3. T. Brabec and F. Krausz, Rev. Mod. Phys. **72**, 545 (2000).

4. V. P. Silin, Sov. Phys. JETP **20**, 1510 (1965).

5. A. G. Ghazaryan, Armenian Journal of Physics **7 (1),** 1 (2014).

6. H. K. Avetissian, A. G. Markossian, G. F. Mkrtchian, Phys. Rev. A **64**, 053404 (2001).

7. H. K. Avetissian, A. G. Markossian, Phys. Rev. A **76**, 053407 (2007).