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Cross sections of electron excitation of atomic nuclei in plasma

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Within the frameworks of the nonrelativistic plane wave Born approximation (PWBA), the analytical formulas for cross sections of $E1$–$E3$ and $M1$–$M2$ excitation of nuclei to the low-energy isomeric state as a result of inelastic scattering of nonrelativistic electrons are derived in the present work. The PWBA cross section of $E1$ excitation of isomer ^{181}Ta^m ($9/2^-$, 6.237 keV) by electrons appeared to be two orders less than that one used in a number of works for calculation of isomeric nuclei yield under exposure of ^{181}Ta-target hot dense laser plasma. To test the PWBA method we have calculated excitation cross sections of the nuclei ^{181}Ta, ^{110}Ag, ^{169}Tm, and ^{201}Hg in a relativistic version of the Hartree-Fock-Slater method. It was established that the PWBA method overestimates $E1$ cross sections and underestimates $E2$ and $M1$ cross sections.

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I. INTRODUCTION

Studies of atomic nuclei excitation in plasma reached the experimental phase [1–7]. In this relation, the issues of theoretical interpretation of the obtained results are of primary importance.

A series of theoretical works is dedicated to the study of mechanisms for the excitation of nuclei in plasma: photoexcitation of nuclei by plasma photons [8], inelastic scattering of plasma electrons from nuclei [9], nuclear excitation by electron transition in atomic shell (NEET) [10], inverse internal electron conversion [11], many-photon excitation of nuclei [12], inverse electronic bridge [13], and so on. Systematics of these mechanisms within the framework of the perturbation theory for quantum electrodynamics was given in Ref. [14]. In recent years, some of most effective mechanisms such as photoexcitation, inelastic electron scattering, inverse internal electron conversion, and the NEET were used for theoretical studies and numerical simulations of the processes of the nuclei excitation and deexcitation in plasmas and in isolated atoms or ions (see, for example, the works [6,15–19] and references therein).

In the present work, data of numerical calculations [6] on excitation of the low-energy isomeric state $9/2^-$(6.237 keV, 6.05 μs) of the ^{181}Ta nuclei in hot dense laser plasma are analyzed. Two processes were used in Ref. [6] for calculation of number of formed ^{181}Ta^m isomers: photoexcitation of ^{181}Ta nuclei by thermal radiation of plasma and inelastic scattering of plasma electrons by ^{181}Ta. The key parameter, namely, the cross section of the process ^{181}Ta$(e,e')^{181}$Ta^m, was taken from [20]: $\sigma \simeq 10^{-31}$ cm^2. The numerical analysis led to the conclusion on dominating (on the average, by two orders of magnitude) character of the nuclei excitation by inelastic electron scattering within the entire studied range of plasma temperatures.

It will be shown in Sec. II that the cross section of ^{181}Ta^m isomer excitation by electrons given in Ref. [20] and, accordingly, in Ref. [6] appeared to be highly overestimated. In turn, using the real value of cross section of the process ^{181}Ta$(e,e')^{181}$Ta^m essentially changes the idea of the role of various mechanisms of nuclei excitation in hot dense laser plasma.

We shall give also the practical equations to calculate the cross sections of electron scattering by nuclei with magnetic transitions.

In addition, in Sec. III we shall present results of calculation of excitation cross sections of the nuclei ^{181}Ta, ^{110}Ag, ^{169}Tm, and ^{201}Hg in a relativistic version of the Hartree-Fock-Slater (RHFS) method [9,21], and compare these cross sections with the cross sections obtained in Ref. [18] in the framework of the distorted wave Born approximation (DWBA) method and the Wentzel-Kramers-Brillouin (WKB) approximation.

In the present work, we use the following system of units: $\hbar = c = k = 1$.

II. CROSS SECTIONS OF INELASTIC SCATTERING OF ELECTRONS BY NUCLEI

A. General expressions for cross sections

The cross section of inelastic scattering of nonpolarized electrons by nonpolarized nuclei is calculated using the general equation [22]:

$$\sigma = \frac{1}{2I_I+1}\sum_{M_I,M_F}\int \frac{W_{fi}}{j_0}\frac{d^3p_f}{(2\pi)^3}, \tag{1}$$

where $\mathbf{p}_{i(f)}$ is the initial (final) momentum of electron, $I_{I(F)}$ and $M_{I(F)}$ are nuclear spin and its projection in the initial (final) state, j_0 is the flux density of scattered electrons, and W_{fi} is probability of transition of the interacting system "nucleus + electron" from the initial to the final state. Probability W_{fi} is usually represented as follows [22]:

$$W_{fi} = 2\pi e^4 \delta(\omega_N - (E_i - E_f))|H_{\text{int}}|^2, \tag{2}$$

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where ω_N is the energy of transition from the initial (this can be, e.g., the ground state of the nucleus) to the final state (for example, isomeric state), $E_{i(f)}$ is the initial (final) electron energy ($E^2_{i(f)} = \mathbf{p}^2_{i(f)} + m^2$, m is the mass of electron), and $H_{\rm int}$ is the Hamiltonian of interaction of the electron $j_\mu(\mathbf{r}) = -e\bar\psi_f(\mathbf{r})\hat\gamma_\mu\psi_i(\mathbf{r})$ and nuclear $J_\nu(\mathbf{R}) = e\Psi^+_F(\mathbf{R})\hat J_\nu\Psi_I(\mathbf{R})$ currents in the second order of the perturbation theory for quantum electrodynamics:

$$H_{\rm int} = \int d^3r\, d^3R\, j_\mu(\mathbf{r})D^{\mu\nu}(\omega_N, \mathbf{r}-\mathbf{R})J_\nu(\mathbf{R}). \quad (3)$$

In Eq. (3) $D_{\mu\nu}$ is the photon propagator in frequency-coordinate representation [22]: $D_{\mu\nu}(\omega_N, \mathbf{r}-\mathbf{R}) = g_{\mu\nu}\exp(i\omega_N|\mathbf{r}-\mathbf{R}|)/|\mathbf{r}-\mathbf{R}|$. (We assume that the electron interacts with each of Z nuclear protons. $\mathbf{R}_{\rm p}$ is the proton's coordinate. However, to simplify the text and the equations, we omit the sign of summation by nuclear protons $\sum_{\rm p=1}^{Z}$ and the corresponding index "p" at the $\mathbf{R}$ coordinate.)

Our task is to obtain the simple equations for the qualitative assessment of the cross-section value. Thus we shall use the plane waves as the wave functions (WF) of electron [22] $\psi(\mathbf{r}) = (u/\sqrt{2E})\exp(i\mathbf{pr})$. We are limited ourselves to the excitation of nuclei with lower (approximately up to 10 keV) isomeric state by electrons with energies up to tens kiloelectronvolts. This allows for the use of the nonrelativistic approximation. At low velocities, when the condition $u^*u = 2m$ is valid for the spin part, the electron WF are the following: $\psi(\mathbf{r}) = \exp(i\mathbf{pr})$. Such WF give the following flux density: $j_0 = p_i/m$ in Eq. (1).

B. Excitations of electric type

To describe the Coulomb excitation of nuclei we shall use the well-known multipole expansion for $D_{00}(\omega_N, \mathbf{r}-\mathbf{R})$ [23]:

$$\frac{\exp(i\omega_N|\mathbf{r}-\mathbf{R}|)}{|\mathbf{r}-\mathbf{R}|} = 4\pi i\omega_N\sum_{L,M} h_L^{(1)}(\omega_N r)Y_{LM}(\Omega_r)j_L(\omega_N R)Y^*_{LM}(\Omega_R), \quad (4)$$

where $h_L^{(1)}(x)$ and $j_L(x)$ are spherical Hankel functions of the first kind and spherical Bessel functions [24], correspondingly, $Y_{LM}(\Omega)$, are spherical functions.

Hamiltonian of interaction $\int d^3r\, d^3R j^0(\mathbf{r})D_{00}(\omega_N, \mathbf{r}-\mathbf{R})J^0(\mathbf{R})$ in nonrelativistic approximation, taking into account expansion of $h_L^{(1)}(\omega_N r)$ and $j_L(\omega_N R)$ at the low values of argument (see [24]), is the following:

$$H_{\rm int} = \sum_{L,M}\frac{4\pi}{2L+1}\langle I_F M_F|R^L Y^*_{LM}(\Omega_R)|I_I M_I\rangle \times \int d^3r\, e^{i\mathbf{qr}}\frac{Y_{LM}(\Omega_r)}{r^{L+1}}, \quad (5)$$

where $\mathbf{q} = \mathbf{p}_i - \mathbf{p}_f$ is the momentum transfer, and $\langle I_F M_F|R^L Y^*_{LM}(\Omega_R)|I_I M_I\rangle$ is nuclear matrix element, related to the experimentally measured reduced probability $B(EL; I_I \to I_F)$ of nuclear electric-type transition with multipolarity L under the following law [25]:

$$B(EL; I_I \to I_F) = \sum_{M_F,M}|\langle I_F M_F|eR^L Y^*_{LM}(\Omega_R)|I_I M_I\rangle|^2. \quad (6)$$

After calculation of the electron coordinate integral in Eq. (5) and substitution of the obtained expression into (2), taking (6) into account, one can obtain the following equations for cross sections of electric-type excitation of nucleus for three main multipoles:

$$\sigma_{E1} = \frac{16\pi^2}{9}e^2\frac{m}{\mathcal{E}_i}\ln\frac{\sqrt{\mathcal{E}_i}+\sqrt{\mathcal{E}_f}}{\sqrt{\mathcal{E}_i}-\sqrt{\mathcal{E}_f}}B(E1; I_I \to I_F), \quad (7)$$

$$\sigma_{E2} = \frac{64\pi^2}{225}e^2m^2\sqrt{\frac{\mathcal{E}_f}{\mathcal{E}_i}}B(E2; I_I \to I_F), \quad (8)$$

$$\sigma_{E3} = \frac{128\pi^2}{11025}e^2m^3(\mathcal{E}_i+\mathcal{E}_f)\sqrt{\frac{\mathcal{E}_f}{\mathcal{E}_i}}B(E3; I_I \to I_F), \quad (9)$$

where $\mathcal{E}_i = p_i^2/2m$ is the kinetic energy of the scattering electron in nonrelativistic approximation, $\mathcal{E}_f = \mathcal{E}_i - \omega_N$.

The reduced probability of nuclear transition is usually represented as follows:

$$B(EL, I_I \to I_F) = B(W; EL)B_{\rm W.u.}(EL, I_I \to I_F),$$

where $B(W; EL)$ is the reduced probability in Weisskopf model for EL transition in a nucleus with atomic number A and radius $R_0 = 1.2A^{1/3}$ fm [25]:

$$B(W; EL) = \frac{e^2}{4\pi}\left(\frac{3}{3+L}\right)^2 R_0^{2L},$$

and $B_{\rm W.u.}$ is the so-called reduced probability in Weisskopf units, the parameter, which takes into account the features of particular nuclear transition. Functions $B_{\rm W.u.}$ are tabulated in Nuclear Data Sheets as characteristics of nuclear transition intensities.

Usually the tables contain the values of $B_{\rm W.u.}(L, I_{\rm is} \to I_{\rm gr})$ for the transitions from the isomeric level (is) to the ground state (gr). To calculate the excitation cross sections, it is necessary to take the value of $B_{\rm W.u.}(L, I_{\rm gr} \to I_{\rm is})$ associated with $B_{\rm W.u.}(L, I_{\rm is} \to I_{\rm gr})$ by the relation

$$B_{\rm W.u.}(L, I_{\rm gr} \to I_{\rm is}) = \frac{(2I_{\rm is}+1)}{(2I_{\rm gr}+1)}B_{\rm W.u.}(L, I_{\rm is} \to I_{\rm gr}).$$

C. Excitations of magnetic type

Let us proceed to the formulas for cross sections of magnetic type. To calculate the excitation of nuclei with magnetic transition, the known magnetic multipole expansion [23] of integration element in the Hamiltonian of interaction (3) is to be used:

$$j^\alpha(\mathbf{r})D_{\alpha\beta}(\omega_N, \mathbf{r}-\mathbf{R})J^\beta(\mathbf{R}) = 4\pi i\omega_N\sum_{L,M}\mathbf{j}(\mathbf{r})\cdot\mathbf{B}^M_{LM}(\omega_N, \mathbf{r})\mathbf{A}^M_{LM}(\omega_N, \mathbf{R})\cdot\mathbf{J}(\mathbf{R}),$$

where $\alpha, \beta = 1$–3. Magnetic multipoles are defined by equations: $\mathbf{A}^M_{LM}(\omega_N, \mathbf{R}) = j_L(\omega_N R)\mathbf{Y}_{LL;M}(\Omega_R)$, $\mathbf{B}^M_{LM}(\omega_N, \mathbf{r}) = h_L^{(1)}(\omega_N r)\mathbf{Y}_{LL;M}(\Omega_r)$, where $\mathbf{Y}_{LJ;M}(\Omega)$ are vector spherical harmonics: $\mathbf{Y}_{LJ;M}(\Omega) = \sum_{m,\kappa} C^{JM}_{Lm1\kappa} Y_{Lm}(\Omega)\xi_\kappa$, $C^{JM}_{Lm1\kappa}$ are the Clebsch-Gordan coefficients, and ξ_κ is the standard spherical basis set [23]: $\xi_{\pm 1} = \mp(\mathbf{e}_x \pm i\mathbf{e}_y)/\sqrt{2}$, $\xi_0 = \mathbf{e}_z$.

The reduced probability of nuclear magnetic transition is defined similar to the probability of electric type transition by substituting: $EL \to ML$ and $R^L Y^*_{LM}(\Omega_R) \to \hat{\mathbf{J}} \cdot \mathbf{A}^M_{LM}(\omega_N, \mathbf{R})$ in Eq. (6). The reduced probability in the Weisskopf model $B(W; ML)$ is calculated in accord with the following relation:

$$B(W; ML) = B(W; EL) \times 10/(M_N R_0)^2,$$

where M_N is the mass of nucleon.

Simple calculations, which are similar to those presented above for the electric type transitions, lead to expressions for cross sections of excitation in the case of magnetic multipoles $M1$ and $M2$:

$$\sigma_{M1} = \frac{16\pi^2}{9} e^2 \frac{\mathcal{E}_i + \mathcal{E}_f}{\mathcal{E}_i} \ln \frac{\sqrt{\mathcal{E}_i} + \sqrt{\mathcal{E}_f}}{\sqrt{\mathcal{E}_i} - \sqrt{\mathcal{E}_f}} \times B(M1; I_I \to I_F), \tag{10}$$

$$\sigma_{M2} = \frac{8\pi^2}{25} e^2 m(\mathcal{E}_i + \mathcal{E}_f)\sqrt{\frac{\mathcal{E}_f}{\mathcal{E}_i}} B(M2; I_I \to I_F) \times \left[1 - \frac{1}{6} \frac{(\mathcal{E}_i - \mathcal{E}_f)^2}{\sqrt{\mathcal{E}_i \mathcal{E}_f}(\mathcal{E}_i + \mathcal{E}_f)} \ln \frac{\sqrt{\mathcal{E}_i} + \sqrt{\mathcal{E}_f}}{\sqrt{\mathcal{E}_i} - \sqrt{\mathcal{E}_f}}\right]. \tag{11}$$

The second term in the square brackets in the expression for σ_{M2} is small in comparison with unity at $\omega_N \ll \mathcal{E}_i$. However, near the reaction threshold, when $\omega_N \approx \mathcal{E}_i$, this correction reaches the value $-1/3$.

It is clear that the required relation between cross sections of electric and magnetic types is valid in nonrelativistic approximation ($\mathcal{E}_i \ll m$) and at small values of imparted energy ($\omega_N \ll \mathcal{E}_i$):

$$\frac{\sigma_{ML}}{\sigma_{EL}} \approx v_i^2 \frac{B(ML, I_I \to I_F)}{B(EL, I_I \to I_F)},$$

where $v_i = \sqrt{2\mathcal{E}_i/m}$ is the electron velocity.

III. RESULTS

In this section we consider some numerical examples and compare the plane wave Born approximation cross sections of (7),(8), and (10) with excitation cross sections obtained in the framework of other models.

The nucleus ^{181}*Ta*. We begin our consideration from the nucleus ^{181}Ta. This nucleus has the value $B_{\mathrm{W.u.}}(E1, 9/2^- \to 7/2^+) = 2.01 \times 10^{-6}$ for the transition $9/2^-(6.237$ keV$) \to 7/2^+(0.0)$ with the energy 6.237 keV from isomeric to the ground state in ^{181}Ta [26]. This value indicates that the $E1$ transition is considerably hindered in comparison with its assessment made using the Weisskopf single-particle model.

Dependence of the cross section of nuclei ^{181}Ta excitation to the isomeric state $9/2^-(6.237$ keV) is shown in Fig. 1. One can see that the maximum value of plane wave Born approximation (PWBA) cross section is 3.5×10^{-33} cm^2. This is approximately 100 times less than the value given

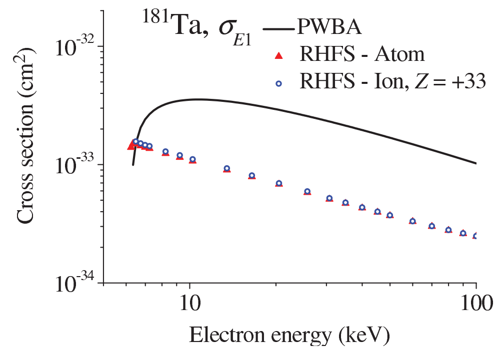

FIG. 1. (Color online) Cross sections for isomer ^{181}Ta^m($9/2^-$, 6.237 keV) excitation by electrons in the framework of the PWBA and RHFS methods.

in Ref. [20] and used in Ref. [6] for numerical modeling and planning of the future experiment. Moreover, the cross section calculated in the framework of RHFS method is even less—about 3–4 times (see in Fig. 1) for both the atom and the ion with the degree of ionization $Z = +33$. (In RHFS method [9,21], the atomic shell is calculated in a relativistic version of the Hartree-Fock-Slater method and the wave functions of the scattering electron in the initial and final states are taken in relativistic form as a solution of the Dirac equation in a self-consistent potential of the nucleus and the electron shell.)

The corresponding correction of data shown in Fig. 8 of the work in Ref. [6] for the expected yield of the excited nuclei ^{181}Ta^m as a function of laser radiation intensity showed that the conclusion of the authors of the paper [6] about the total domination of the inelastic electron scattering process at excitation of nuclear isomer ^{181}Ta^m in plasma seems to be premature. The calculation with the correct value of cross section of the ^{181}Ta$(e, e')^{181}$Ta^m process testifies that, in a wide range of the intensities of laser radiation, which creates plasma, the processes of photoexcitation and Coulomb excitation by electrons will give approximately identical contributions to the generation of isomeric nuclei ^{181}Ta^m.

The nucleus ^{169}*Tm*. In Fig. 2 we present the $E2$ and $M1$ excitation cross sections of the nucleus ^{169}Tm in the framework of PWBA and RHFS methods. In the calculations we used the tabular values of the reduced probabilities for the isomeric nuclear transition $3/2^+(8.41$ keV$) \to 1/2^+(0.0)$ from [27]:

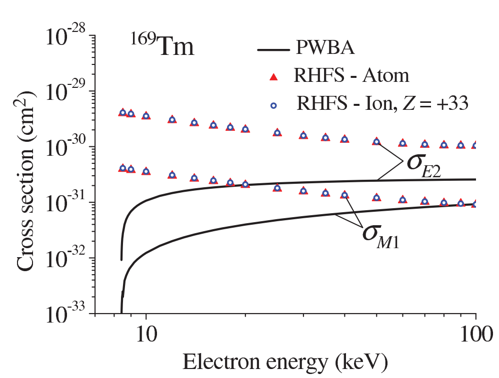

FIG. 2. (Color online) Cross sections for excitation of the isomer ^{169}Tm^m($3/2^+$, 8.41 keV).

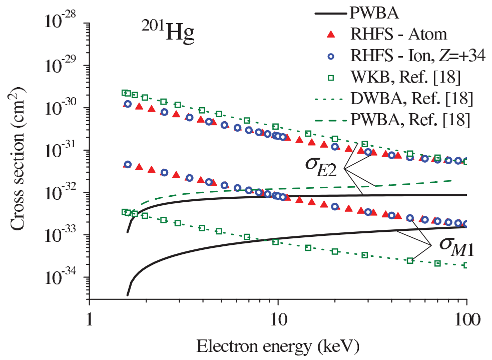

FIG. 3. (Color online) Cross sections for excitation of the isomer ^{201}Hg^m($1/2^-$, 1.5648 keV).

$B_{\mathrm{W.u.}}(M1; 3/2^+ \to 1/2^+) = 0.0342$ and $B_{\mathrm{W.u.}}(E2; 3/2^+ \to 1/2^+) = 241$. (This transition occurs within the rotational band $K^\pi[Nn_Z\Lambda] = 1/2^+[411]$ [27]. This explains the high intensity of the $E2$ component and the cross section as a whole.) The $E2$ PWBA cross section coincides with the corresponding PWBA cross section from the work in [20]. On the other hand, the graphs show clearly that PWBA cross sections and cross sections obtained by RHFS method have little in common.

It is interesting to compare RHFS cross sections and cross sections obtained in the framework of the distorted wave Born approximation method and the Wentzel-Kramers-Brillouin approximation (see [18]). In Figs. 3 and 4 we show PWBA and RHFS cross sections of inelastic electron scattering from the ^{201}Hg and ^{110}Ag nuclei.

The nucleus ^{201}*Hg*. In the calculations we used the following parameters of the isomeric nuclear transition $1/2^-(1.5648\ \mathrm{keV}) \to 3/2^-(0.0)$ in ^{201}Hg: $B_{\mathrm{W.u.}}(M1; 1/2^- \to 3/2^-) = 0.00151$ and $B_{\mathrm{W.u.}}(E2; 1/2^- \to 3/2^-) = 25$ [28]. Our $E2$ RHFS cross section, σ_{E2}, is well consistent with the $E2$ cross sections in DWBA and WKB approximation in Fig. 4 of the work in [18] (see graphs in Fig. 3). The small difference between the results is explained by different values for the reduced probability of the nuclear transition. The similar difference between PWBA graphs clearly indicates this. At the same time our $M1$ RHFS cross section, σ_{M1}, is one order of magnitude greater than corresponding DWBA and WKB cross sections in Fig. 4 in [18]. The authors [18] do not give the cross section σ_{M1} in the framework of PWBA; therefore, we cannot identify the causes of this discrepancy.

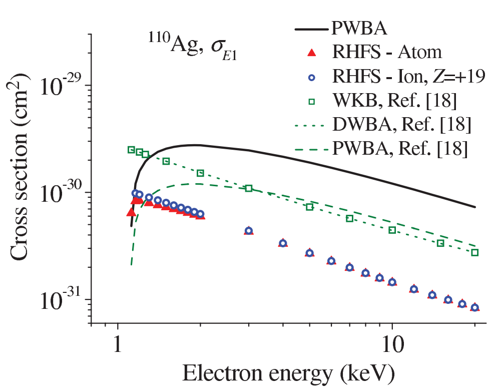

FIG. 4. (Color online) Cross sections for excitation of the isomer ^{110}Ag^m(2^-, 1.113 keV).

The nucleus ^{110}*Ag*. Isomeric transition from the first excited state in the nucleus ^{110}Ag is not well studied [29]. First, the internal conversion coefficient, α, is unknown. Secondly, we are not sure that we know all decay channels of the level. That is why to evaluate the cross sections for excitation of the level $2^-(E = 1.113\ \mathrm{keV}, T_{1/2} = 660\ \mathrm{ns})$ in ^{110}Ag we must accept some assumptions. According to our calculation, the internal conversion coefficient for the $E1(1.113\ \mathrm{keV})$ isomeric transition $2^- \to 1^+$ in ^{110}Ag is $\alpha = 1.1 \times 10^3$. Using the known half-life of the isomeric level, $T_{1/2}$, we can compute the reduced probability of the isomeric transition. The result is: $B_{\mathrm{W.u.}}(E1; 2^- \to 1^+) = 2.9 \times 10^{-4}$. [We assume that the isomeric transition to the ground state is the sole (or dominant) decay channel of the level $2^-(1.113\ \mathrm{keV})$.]

The excitation cross sections of the process ^{110}Ag$(e, e')^{110m}$Ag as functions of electron energy in the range 1–12 keV are shown in Fig. 4. Our PWBA cross section is approximately two times greater than the corresponding PWBA cross section in Fig. 2 of the work in Ref. [18]. Apparently the authors [18] used other values for the internal conversion coefficient α, and for the reduced probability of nuclear isomeric transition $B_{\mathrm{W.u.}}(E1; 2^- \to 1^+)$. As concerns the RHFS $E1$ cross section, it lies systematically below the PWBA cross section in contrast to WKB and DWBA cross sections (see in Fig. 4 and in Ref. [18], where the PWBA, WKB, and DWBA methods exhibit the same behavior for the wide energy range excluding only the neighborhood of threshold).

Thus the results of our calculations show that the use of the Born approximation to estimate the excitation cross sections of atomic nuclei by electrons can lead to significant errors. This is especially true for $E2$ and $M1$ cross sections whose behavior has nothing to do with the cross sections obtained in the framework of RHFS or DWBA, and WKB methods (see [18]). $E1$ cross section may be used to estimate the number of excited nuclei in a hot dense plasma with some caution. The reaction rate averaged over the spectrum of plasma electrons $\langle \sigma v_i \rangle$ is not very sensitive to the behavior of the cross section near the reaction threshold. In this sense, the difference near the reaction threshold in the behavior of the $E1$ cross section calculated in the framework of the PWBA and all other methods is not critical for determining the number of excited nuclei. As for the systematic differences between the PWBA and RHFS cross sections throughout the energy range, it can affect more strongly the result of calculation of the number of excited nuclei. Therefore, the use of the PWBA requires caution, even for the case of $E1$ nuclear transition.

At the end of this section, let us note also that numerical calculations in the framework of relativistic plane wave Born approximation [formulas (II E.41)–(II E.46) in Ref. [30]] give the same values for the σ_{E1} and σ_{E2} near the threshold as the PWBA method. In the energy range near 100 keV the relativistic PWBA cross sections σ_{E1} and σ_{E2} are approximately two times bigger than corresponding PWBA cross sections.

IV. CONCLUSION

In conclusion, the results of the work can be summarized as follows. (1) The simple analytical formulas were obtained for calculation of cross sections of inelastic scattering of electrons by nuclei in nonrelativistic Born approximation for multipoles $E1$–$E3$ [Eqs. (7)–(9)] and $M1$–$M2$ [Eqs. (10) and (11)]. (2) The excitation cross sections of the nuclei ^{181}Ta, ^{110}Ag, ^{169}Tm, and ^{201}Hg were calculated in the framework of PWBA and relativistic version of the Hartree-Fock-Slater method. It was shown that PWBA systematically overestimates the $E1$ cross section and underestimates the $E2$ and $M1$ cross sections. (3) Using the experimental spectra of photons and electrons in high-temperature laser plasma [6], it was established that inelastic scattering of electrons by ^{181}Ta nuclei and photoexcitation of ^{181}Ta by thermal plasma radiation resulted in approximately the same number of ^{181}Ta^{m} ($9/2^{-}$, 6.237 keV) isomers.

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