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THE ROLE OF ELECTRON CORRELATIONS IN THE PROCESS OF PHOTOABSORPTION OF THE LIGHTEST ATOMS

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The contribution of diagrams of different order for the photoionization cross section and the oscillator strengths at the atoms of He, Li and Be in the framework of the Random Phase Approximation with Exchange (RPAE) is considered. The diagrams of the lowest order are shown to have the dominant role. This explains why the dense electron gas model deals equally well with electron correlations at lightest atoms as the rare electron gas model does. The dipole matrix element in the RPAE, developed in the series, is shown to have good convergence. The contribution of the exclusion principle violating (EPV) diagrams is calculated.

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1. Introduction

The study of the photoionization cross section and the oscillator strengths for the lightest atoms (He, Li, Be) is important for various applications, particularly in astrophysics. Since the measurements of these quantities are very delicate it is desirable to treat the problem theoretically. For many years various independent particle models have been used to consider this process for many atoms and they all gave results in strong disagreement with experiment[1,2]. The significant role electron correlations play in this process is pointed out. To take residual interaction into account the RPAE was employed in the calculations of the cross section and oscillator strengths primarily for heavier atoms, particularly noble gases[3-6]. Among the other advantages of this approximation is the coincidence of *length* and *velocity* forms for the cross section (oscillator strength)[3]. The obtained results were in good agreement with experiments[7]. Obviously, the lightest atoms cannot be considered as a dense electron gas. Though for these atoms the RPAE gives satisfactory results[8].

An approach opposite to the dense electron gas model was developed by Sinanoglu and collaborators to treat the electron correlations[9,10].

We wished to investigate why these two opposite approaches give equally good results. It is also interesting, in this connection, to examine the reasons for applicability of the RPAE to a small number of particles.

There exists a certain discrepancy between theoretical and experimental values for the photoionization cross section and oscillator strengths. Some authors ascribe this disagreement to the presence of the EPV diagrams[11] in the theoretical calculations. It is known that these diagrams do not describe any physical process. In this work we are interested in the computation of such diagrams.

Throughout the present paper atomic units are used except in figures where energy is expressed in electronvolts.

2. Theoretical aspects

In the present work we consider the photoexcitation (photoionization) of an unpolarized atom in the ground state by an unpolarized photon. The photon energy is of the order of magnitude of ionization energy of the studied subshell. Therefore it is possible to calculate the cross section in the dipole approximation. The relativistic effects and Compton scattering are neglected. The Russell-Saunders manner[12] of coupling angular momenta is adopted. The method developed in the papers cited here is applicable only to atoms with closed subshells or half-filled subshells. Only one-photon processes are considered so that the transition amplitudes are calculated in the first order in interaction hamiltonian (between the electrons of the atom and the external electromagnetic field).

We are interested in the photoionization cross section $\sigma(\omega)$ and the oscillator strengths f_n. They can be expressed by means of the current density correlation function in the dipole approximation[8] $S(\omega)$

$$\sigma(\omega) = -\frac{4\pi}{\omega c} \operatorname{Im} S(\omega) \tag{1}$$

and

$$f_n = \frac{2}{\omega_n} \operatorname{Res} S(\omega_n). \tag{2}$$

Res $S(\omega_n)$ is the residue of $S(\omega)$ at its pole $\omega = \omega_n \equiv E_n - E_o$; E_o and E_n are the energies of initial and final state of the atom. The correlation function $S(\omega)$ can be expressed by means of $\Pi_{hi,jk}(\omega)$[13] - Fourier transform of the polarization propagator, where h, i, j and k are the single-particle states; for example $| h > = | n\, l\, m\, s >$. It is convenient to write this relation in matrix form

$$S(\omega) = d^{\dagger} \Pi(\omega)\, d. \tag{3}$$

The one-column matrix d and the square matrix $\Pi(\omega)$ are labeled by an ordered pair of the particle-hole states

$$\alpha = (j, k)\ j > F,\ k < F \text{ or } j < F,\ k > F \tag{4}$$

(F is Fermi level; $j < F$ and $j > F$ denoting occupied (hole) and unoccupied (particle) states, respectively). The matrix d (in the dipole approximation) represents the operator of electron velocity (V-form) or electron position (L-form).

The effective interaction matrix $\Gamma(\omega)$[14] satisfies in the RPAE the matrix equation

$$\Gamma(\omega) = U + U\, \Pi^0(\omega)\, \Gamma(\omega). \tag{5}$$

The matrix U is composed of the antisymmetrized Coulomb matrix elements, and $\Pi^0(\omega)$ is the Hartree-Fock (HF) polarization propagator. The equation (5) is to be understood in the same sense as (3). It is convenient to define here the renormalized photon vertex $\mathscr{D}(\omega)$[15] which satisfies the equation

$$\mathscr{D}(\omega) = d + U\, \Pi^0(\omega)\, \mathscr{D}(\omega), \tag{6}$$

or in terms of the matrix elements

$$\mathscr{D}_{\alpha}(\omega) = d_{\alpha} + \underset{\beta}{\mathrm{S}}\, U_{\alpha\beta}\, \Pi^0_{\beta}(\omega)\, \mathscr{D}_{\beta}(\omega) \tag{7}$$

where the symbol S denotes either the summation over the discrete particle-hole pairs β, or the integration over continuous spectrum of particle energy above the ionization threshold together with summation over hole states. The relation (6) corresponds to the graphical equation represented in Fig. 1. Now one can express the cross section by means of $\mathscr{D}(\omega)$[8]

$$\sigma(\omega) = \frac{4\pi^2}{\omega\, c} \sum_{\substack{j \leq F \\ k > F}} | \mathscr{D}_{kj}(\omega) |^2\, \delta(\omega - \varepsilon_k + \varepsilon_j) \tag{8}$$

(ε_k and ε_j are the one-particle energies). Upon iteration of the graphical equation from Fig. 1 one gets the corresponding series for the renormalized photon vertex. In this series all the diagrams are the Feynman diagrams, i. e., the time order of interaction is irrelevant. But the contribution of all corresponding Goldstone diagrams which are diagonal in a given hole and are time-forward directed contain divergences. This is so because $\Pi(\omega)$ contains one singular part (for $\omega = \omega_n$). In this connection, the equation (6) cannot be solved as it stands. On the other hand, to calculate the oscillator strengths, the energy differences $E_n - E_0$ must also be calculated consistently in the RPAE. One can resolve these problems by a special choice of excited one-particle states. Namely, the basic one-electron wave functions are computed by the self-consistent field code[16] for the ground state (occupied, hole) orbitals and by the program[17] which calculates excited states (unoccupied, particle) orbitals in the *frozen* core field of other electrons (the latter functions correspond to the definite LS state of the atom). We shall call these basic functions HF functions. This choice effectuates the summation of all time-forward Goldstone diagrams for $\Pi(\omega)$ diagonal in a given hole. Now it is convenient, because of the singularity of $\Pi^0(\omega)$, to define a new effective interaction $\Gamma'(\omega)$ and a new renormalized photon vertex $\mathscr{D}'(\omega)$. Then the pole of $\mathscr{D}(\omega)$ is displaced and excitation energy is determined as the solution of the equation

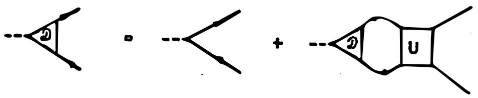

Fig. 1. Graphical equation satisfied by $\mathscr{D}(\omega)$.

$$\omega - \omega_\alpha - \Gamma'_{\alpha\alpha}(\omega) = 0. \tag{9}$$

$\Gamma'_{\alpha\alpha}$ is developed in the series around ω_α and only first-order term is retained. One should solve the matrix equation for $\Gamma'(\omega)$

$$\Gamma'(\omega) = U + U\Pi^{0\prime}(\omega)\,\Gamma'(\omega) \tag{10}$$

where $\Pi^{0\prime}_\alpha(\omega)$ is regular part of $\Pi^0(\omega)$. It is sufficient, however, to retain the second-order term in perturbation expansion. The first-order term $U_{\alpha\alpha}$ is set equal to zero due to the particular choice of excited single-particle states. One gets for the displaced pole

$$\omega_p \simeq \omega_\alpha + \sum_{\beta(\neq\alpha)} |\, U_{\alpha\beta}\,|^2\, \Pi^\circ_\beta(\omega) \left(1 - \frac{\partial \Gamma'_{\alpha\alpha}(\omega)}{\partial\omega}\bigg|_{\omega_\alpha}\right)^{-1} \tag{11}$$

and f_n becomes

$$f_n = \frac{2}{\omega_p}\, |\, \mathscr{D}'_\alpha(\omega_p)\,|^2 \left(1 - \frac{\partial \Gamma'_{\alpha\alpha}(\omega)}{\partial\omega}\bigg|_{\omega_\alpha}\right)^{-1}. \tag{12}$$

After the separation of the angular parts[18] in the renormalized photon vertex the cross section and the oscillator strengths can be expressed as

$$\sigma_{nl\to\varepsilon l'}(\omega) = \frac{4\pi^2}{\omega c}\frac{N_{nl}}{3(2l+1)}\,|\langle \varepsilon l' \| \mathscr{D}(\omega) \| nl\rangle|^2 \tag{13}$$

and

$$f_{nl\to n'l'} = \frac{2}{\omega}\frac{N_{nl}}{3(2l+1)}\,|\langle n' l' \| \mathscr{D}(\omega) \| nl\rangle|^2. \tag{14}$$

In the above equations $\langle \varepsilon l' \| \mathscr{D}(\omega) \| nl\rangle$ and $\langle n' l' \| \mathscr{D}(\omega) \| nl\rangle$ are the reduced dipole matrix elements in the RPAE for the transitions from the ground state to the state of the continuum and the discrete spectrum, respectively; n and n' are the principal quantum numbers of occupied (hole) and excited (unoccupied, particle) single-particle electronic states; l and l' are the corresponding orbital quantum numbers ($l' = l \pm 1$, because of the dipole approximation). In the case of continuous spectrum the single-particle energy ε is used instead of n'. N_{nl} is the number of electrons in the studied subshell. The reduced matrix element in the RPAE also satisfies the equation (6) provided that the polarization propagator is multiplied by $1/(2l+1)$, where l refers to l-th multipole component of the Coulomb interaction. The polarization propagator $\Pi^0(\omega)$ has a pole and integration in the equation (6) is replaced by numerical integration (Simpson's rule) in the vicinity of the pole on the function without a pole

$$f(x) - \frac{r}{x - x_s} \tag{15}$$

where r is the residue of the pole x_s of the function $f(x)$ under the integral[19].

We used our RPAE programs[20] to calculate the reduced dipole matrix elements in the RPAE and the corresponding photoionization cross section and oscillator strengths in both forms. The correlations are taken into account within the particle-hole reaction channel in which the atom is excited by photoabsorption process. The partice-hole channel is defined as a set of all particle-hole excitations (states) with definite (fixed) hole and defined (fixed) particle orbital angular momentum, i. e., the quantum numbers n, l and l' specify the particle-hole channel containing transitions (excitations) $nl \to \nu l'$ with all possible values of ν, from discrete ($\nu = n'$) and from continuous ($\nu = \varepsilon$) particle energy spectrum. These programs also compute the reduced dipole matrix elements and corresponding cross section and oscillator strengths in HF approximation, excitation energies, the reduced antisymmetrized matrix elements of Coulomb interaction and the time-forward and time-backward free polarization propagator matrix elements. Next we could calculate the contribution of diagrams one by one.

For the atom of He we consider the transitions

$$1s^2\,(^1S) \to 1s\,\nu p\,(^1P) \tag{16}$$

$$(\nu = n' \text{ or } \varepsilon).$$

Then the corresponding reduced dipole matrix element has the development as in Fig. 2. We calculated the contribution of the diagrams of the first and second order in interaction hamiltonian (second and third diagram on the right hand side of the graphical equation in Fig. 2). Furthermore we are interested here in the calculation of the EPV contribution of these diagrams. Namely, equation (5) can be deduced only by including the EPV diagrams which, clearly, lead to a physical error. In the development in Fig. 2 every member of the series, starting from the diagram of the first order, is EPV, provided that the diagram of the first order is partially EPV. The diagram of the second order is completely EPV and so are all higher-order diagrams. Let us consider the EPV contribution for the diagram of the first order (Fig. 3 (a)). Now i and i' are one-particle states $\left(1s\,0\,\frac{1}{2}\right)$ or $\left(1s\,0\,-\frac{1}{2}\right)$. We shall show that this diagram is apparently EPV. Let us write the contribution for this diagram

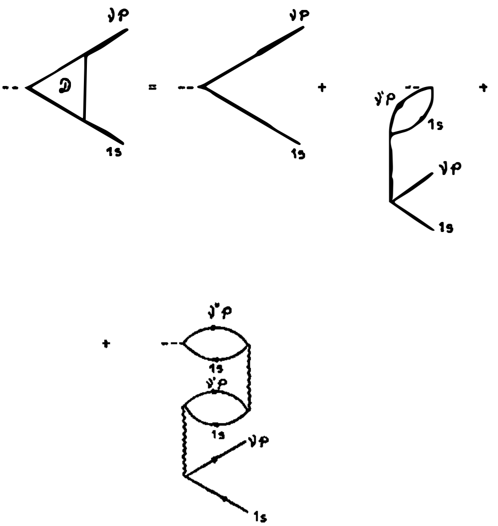

Fig. 2. Graphical relation representing the development of RPAE transition amplitude for He atom ($1s \to \nu p$) transition.

$$\underset{k'i'}{S} \langle i' \mid d \mid k' \rangle \langle k' k \mid U \mid i' i \rangle \Pi^{0<}_{i'k'} (\omega) \tag{17}$$

(the factors in the above expression are ordinary matrix elements not reduced ones). But $\langle k' k \mid U \mid i' i \rangle$ denotes the antisymmetrized Coulomb matrix element

$$\langle k' k \mid U \mid i' i \rangle = \langle k' k \mid V \mid i' i \rangle - \langle k' k \mid V \mid i i' \rangle . \tag{18}$$

The second term in the right hand side of (18) corresponds to the exchange diagram (Fig. 3 (b)). The EPV contribution is obtained when $i = i'$ and the matrix element (18) becomes zero. Then the EPV contribution in the given diagram is zero. One can get the same result for more complicated higher-order diagrams. More precisely, whenever a diagram contains two hole states entering the same antisymmetrized matrix element of Coulomb interaction, the corresponding EPV contribution is zero. Finally we can subtract the contribution of zero and first order from the RPAE amplitude, to get the complete EPV part of the transition amplitude in RPAE.

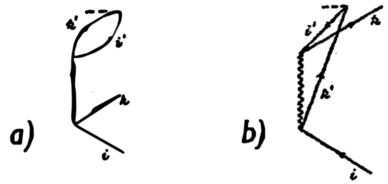

Fig. 3. First-order diagram in the series, from Fig. 2 for the dipole matrix element in RPAE for He atom. (a) direct diagram; (b) exchange diagram.

The situation is not so simple for the atoms of Li and Be due to the existence of two channels of interaction. For Li we consider the following transitions

$$1s^2\,2s\,(^2S) \rightarrow \begin{cases} 1s^2\,\nu p\,(^2P) \\ 1s\,\nu p\,(^1P)\,2s\,(^2P). \end{cases} \tag{19}$$

The reduced dipole matrix element in RPAE corresponding to the considered transitions (19) can be represented by the graphical series in Fig. 4, where $n = 2$ for the transitions from the outer subshell ($n' = 1$, $n'' = 1$ in this case) and $n = 1$

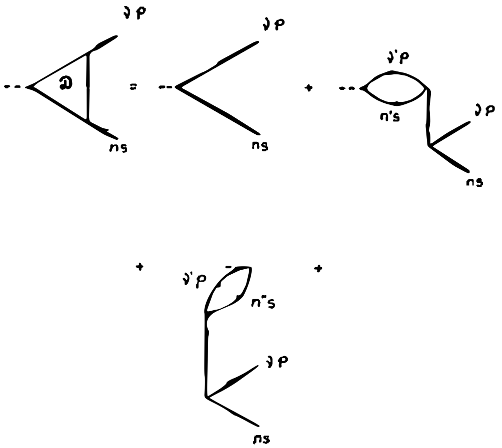

Fig. 4. The graphical series for the reduced dipole matrix element in RPAE corresponding to the transitions (19) and (20).

for the transitions from the inner subshell ($n' = 2$, $n'' = 1$). The contribution of the diagrams up to the second order (corresponding to the transitions from the outer and inner subshell, respectively) is calculated. The EPV contribution of these diagrams (up to the second order) is found too. There do not exist EPV diagrams up to the second order for the transitions from the outer subshell. For the transitions from the inner subshell we have (besides apparently EPV diagrams) one completely EPV diagram (Fig. 5 (a)) and one partially EPV diagram (Fig. 5 (b)).

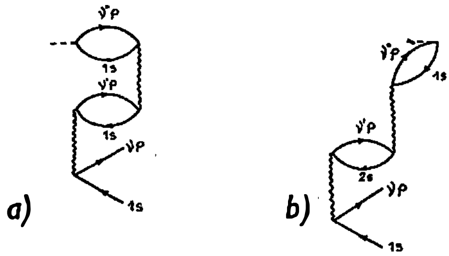

Fig. 5. EVP diagrams up to the second order in the series from Fig. 4 corresponding to the transitions from the inner subshell of Li atom. (a) completely EPV diagram; (b) partially EPV diagram.

From the standpoint of interelectron correlations the outer subshell is the most interesting because the characteristic features of the atom are determined by the outer electrons. When the outer subshell contains exactly one electron, the intrachannel correlations do not exist. In the case of Be the correlations between the electrons in the outer subshell (intracross) are much more greater than the correlations between electrons from different subshells. Therefore we consider in this paper only the correlations between electrons in the outer subshell of Be. So we are interested in the transitions

$$1s^2\,2s^2\,(^1S) \to 1s^2\,2s\,\nu p\,(^1P). \tag{20}$$

The corresponding dipole matrix element in RPAE satisfies the graphical equation represented in Fig. 4. The contribution of the diagrams up to the second order within the RPAE as well as their EPV contribution is calculated. In this case we have, besides apparently EPV diagrams, one completely EPV diagram (Fig. 6 (a)) and two partially EPV diagrams (Figs. 6 (b), 6 (c)).

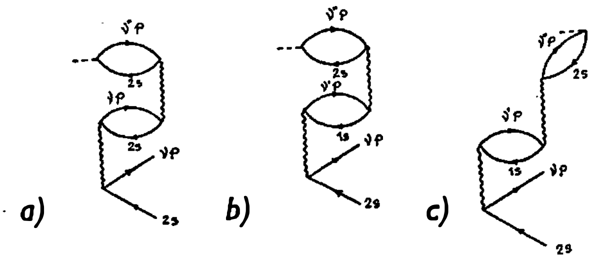

Fig. 6. EPV diagrams up to the second order in the graphical series from Fig. 4 corresponding to the transitions from the outer subshell of Be atom. (a) completely EPV diagram; (b) partially EPV diagram; (c) partially EPV diagram.

The integral over energy variable ε in the expression for the contribution of considered diagrams has been replaced by a sum according to Simpson's rule, the sum being finite. The integration points were equidistant in free-particle momentum $\varkappa$ ($\varkappa = \sqrt{2\varepsilon}$). The integral has to be understood in the sense of a principal value and has been calculated using the already mentioned procedure[19].

3. *Results and discussion*

The contribution to transition probability amplitude from the ground state of the He atom to the state of the discrete spectrum has been presented in Table 1, in HF, in the first and second order of the RPAE, and in the RPAE, together with the corresponding EPV part of the contribution (only the real part of the contribution is presented). The transition probability amplitude decreases with increasing photon energy. The EPV part is very small and is also decreasing when the energy of the quantum increases. The dipole matrix element in RPAE shows good convergence. The non-EPV part of the contribution has only a real part, because the time-forward free polarization propagator emerges starting from the second-order term.

TABLE 1

Transition	Zero order		First order	
	L	*V*	*L*	*V*
$1s \to 2p$	—0.4948	—0.3705	0.0104	—0.0139
$3p$	—0.2521	—0.2039	0.0058	—0.0078
$4p$	—0.1601	—0.1329	0.0038	—0.0051
$5p$	—0.1135	—0.0953	0.0027	—0.0037
$6p$	—0.0859	—0.0726	0.0021	—0.0028
	Second order		RPAE	
$1s \to 2p$	—0.0098	—0.0120	—0.4870	—0.3870
$3p$	—0.0014	—0.0016	—0.2472	—0.2131
$4p$	—0.0010	—0.0011	—0.1567	—0.1388
$5p$	—0.0007	—0.0008	—0.1108	—0.0994
$6p$	—0.0002	—0.0003	—0.0837	—0.0755
	EPV			
$1s \to 2p$	—0.0026	—0.0026		
$3p$	—0.0008	—0.0014		
$4p$	—0.0003	—0.0008		
$5p$	—0.0006	—0.0004		
$6p$	0.0001	—0.0001		

The calculated values of the reduced dipole matrix elements (for the transitions $1s \to np$), in both forms, for He atom, in HF approximation, in first and second order of RPAE, respectively, and in the RPAE. The EPV contribution to amplitude is given too. We give here only the real part of the contribution.

Table 2 contains the calculated values of oscillator strengths for the He atom (for the transitions $1s \rightarrow np$) in both forms, in HF, up to the first and second order of RPAE, respectively, values of oscillator strengths in the RPAE and experimental ones. The experimental values are taken from Ref. 21.

TABLE 2.

Transition	in zero order		up to first order	
	L	*V*	*L*	*V*
$1s \rightarrow 2p$	0.2603	0.2296	0.2495	0.2471
$3p$	0.0732	0.0642	0.0699	0.0692
$4p$	0.0303	0.0266	0.0289	0.0286
$5p$	0.0154	0.0135	0.0147	0.0145
$6p$	0.0089	0.0078	0.0085	0.0084
	up to second order		In RPAE	
$1s \rightarrow 2p$	0.2620	0.2580	0.2598	0.2520
$3p$	0.0707	0.0703	0.0704	0.0702
$4p$	0.0293	0.0291	0.0291	0.0290
$5p$	0.0149	0.0149	0.0147	0.0147
$6p$	0.0084	0.0084	0.0084	0.0084
	Experiment			
$1s \rightarrow 2p$	0.276	(1%)		
$3p$	0.0734	(1%)		
$4p$	0.0302	(3%)		
$5p$	0.0153	(< 10%)		
$6p$	0.0085	(< 10%)		

The oscillator strengths (for the transitions $1s \rightarrow np$) for He atom in both forms, in HF approximation, in the first and second order of RPAE, respectively, and in the RPAE, together with the corresponding experimental values[21]. The errors of measurements are in the brackets.

In Fig. 7 the photoionization cross section for the He atom is plotted against photon energy. RPAE cross section is between two forms of cross section in HF approximation. The first and second order of RPAE practically coincides with RPAE. The experimental values are taken from Refs. 7 and 22.

From what has been said it follows that the dipole matrix element in RPAE has good convergence. The greatest contribution to probability amplitude within RPAE comes from the zero and first-order diagrams. Since higher-order diagrams represent interelectron correlations, it is shown that these are small. In fact, one would expect it because the correlations grow with the number of the particles in the system. The more complicated interelectron correlations one considers, as the contribution in the expression for the total amplitude, the smaller is the corresponding probability.

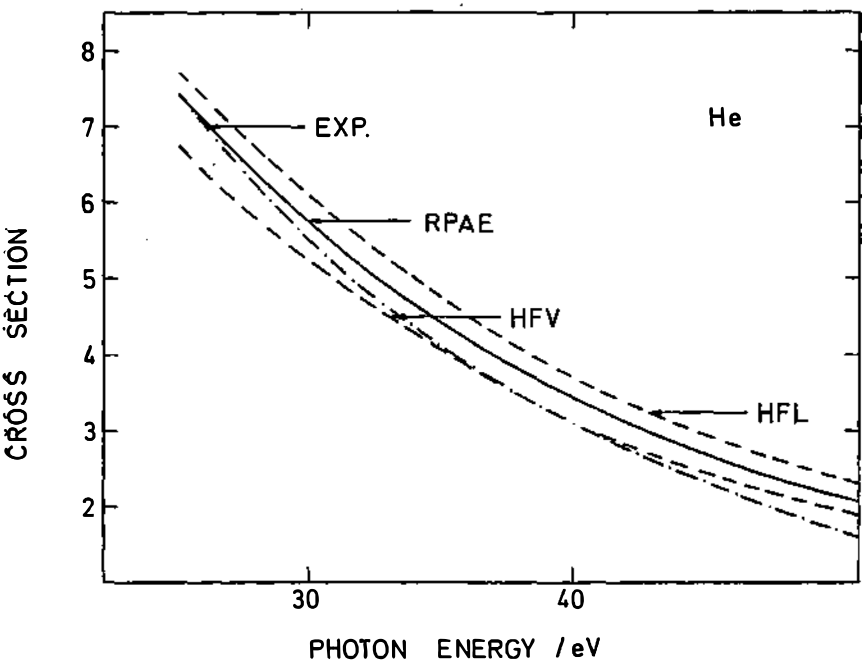

Fig. 7. The photoionization cross section (expressed in $10^{-22}\,m^2$) of He atom in the ground state versus photon energy in HF approximation (both forms). The cross section up to the first and second order of the RPAE practically coincides with RPAE curve, also plotted in the figure. The experimental curve (EXP.) represents the averaged results of Refs. 7 and 22.

Summing up the *ladder* diagrams in the case of rare electron gas one gets the corresponding amplitude in the framework of this approximation. The diagrams with dominant contribution in this approximation are up to the first order. So in RPAE and in rare gas approximation we get practically the same diagrams playing the dominant role. This explains why these two opposite approaches have equally good success. EPV contribution is negligible, so that omission of this part in the total amplitude does not improve theoretical results as some authors believed.

In the case of Li and Be atoms the convergence of the RPAE is not so explicit as in the case of He atom due to the more complicated interelectron correlations. The number of different correlations grows with the number of electrons in the atom and so does the number of EPV diagrams. The EPV contribution up to the second order for the atom of Li is negligible. But for the Be atom the situation is somewhat different. The lowest members of the series for the dipole matrix element in RPAE show satisfying convergence and we believe that the destructive interference at higher-order diagrams does not significantly effect the behaviour of the series. So we expect that the EPV contribution in the second order would be the greatest. The calculated values of oscillator strengths for Be atom in RPAE corresponding to the transition $2s \rightarrow 2p$ are 1.4496 (*L*-form) and 1.2707 (*V*-form), while ommiting EPV contribution we get for oscillator strengths (in RPAE) 1.4023

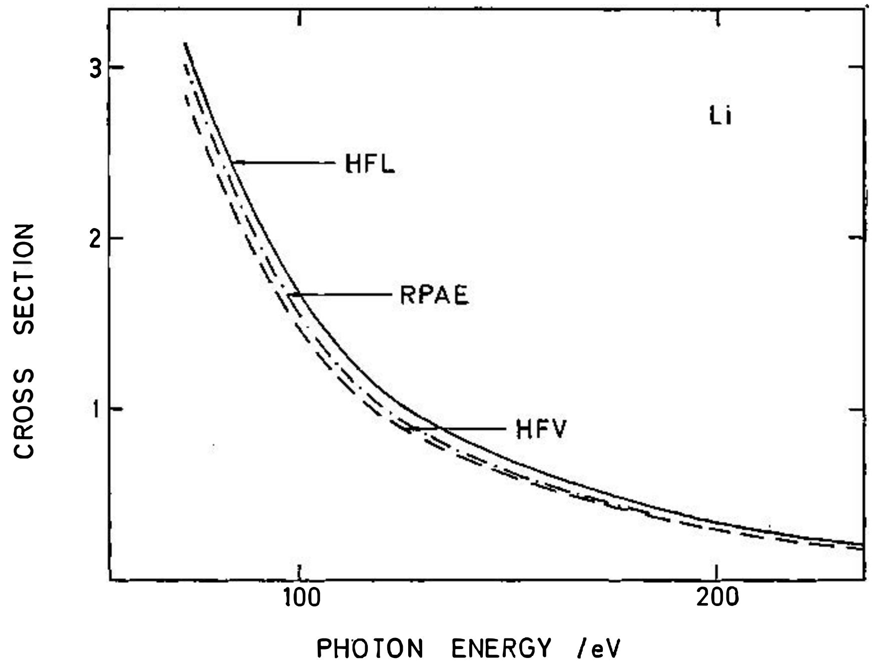

Fig. 8. The photoionization cross section (expressed in 10^{-22} m^2) for the inner subshell of Li atom plotted against energy of the photon in two forms of HF approximation and in RPAE. The cross section up to the first and second order of RPAE cannot be distinguished from RPAE cross section.

(*L*-form) and 1.2508 (*V*-form). The experimental value for oscillator strength of Martinson et al.[23] is 1.34 ± 0.05.

The photoionization cross section of the inner subshell of Li atom is plotted versus the energy of the incident photon (Fig. 8), showing similar behaviour as the cross section of He. In the case of the outer subshell the situation is somewhat different (Fig. 9). The highest theoretical curve is RPAE. For greater photon energies the curves approach each other. The situation is much more different for the cross section of the outer subshell of Be (Fig. 10) due to the presence of more complicated interelectron correlations in this case. The cross section calculated up to the second order in RPAE practically coincides with the RPAE cross section. For greater energies the RPAE curve joins the first-order RPAE curve.

4. *Conclusion*

Many-body perturbation theory diagrams within RPAE which give contribution to the transition probability amplitude from the ground state to the discrete spectrum or to the continuum for the atoms of He, Li and Be have dominant con-

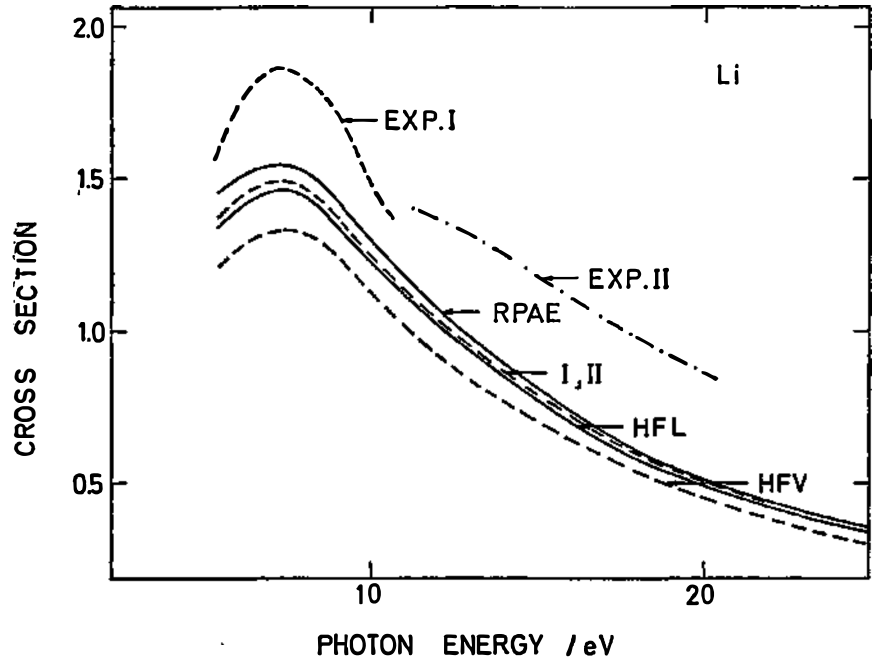

Fig. 9. The photoionization cross sections (expressed in 10^{-22} m^2) for the outer subshell of Li atom up to the first and second order of RPAE (mutually coinciding) are plotted against photon energy. The curves of the cross section in HF approximation (two forms) and in the RPAE are also plotted. The experimental curves EXP. I and EXP. II give the results of Refs. 24 and 25.

tribution up to the first order in interaction hamiltonian. This is the reason fo- applicability of the RPAE to a system with small number of particles. Higherr-order diagrams represent (different) interelectron correlations and are small for a system with small number of particles, because residual interaction grows with increase of the number of particles. So the diagrams in this approximation with dominant contribution are the same as in the *ladder* approximation. This accounts for having equally good results when applying these two methods. The dipole matrix element in RPAE has the satisfactory convergence. The EPV contribution to the amplitude is negligible for the atoms of He and Li. For the atom of Be the EPV contribution cannot be responsible for discrepancy between theoretical (the mean value of two forms) and experimental result.

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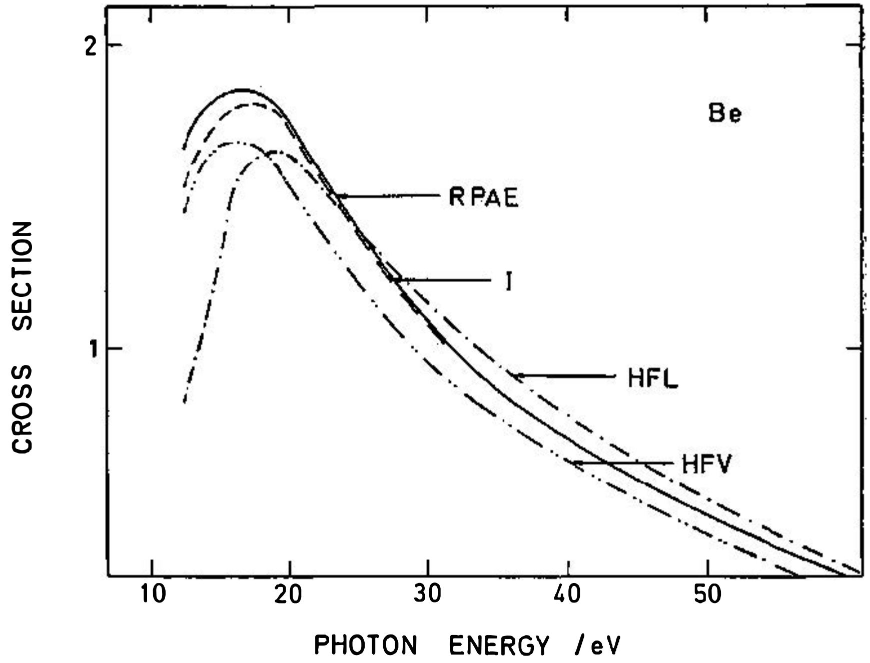

Fig. 10. The photoionization cross section (expressed in 10^{-22} m^2) for the outer subshell of Be atom is plotted against photon energy. The values of cross section up to the first and second order are mutually differing, but the second order of RPAE practically coincides with RPAE curve. The cross section in the HF approximation is plotted too.

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ULOGA ELEKTRONSKIH KORELACIJA U PROCESU FOTOAPSORPCIJE NAJLAKŠIH ATOMA

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Doprinos dijagrama različitog reda efikasnom presjeku fotojonizacije i oscilatornim jačinama za atome He, Li i Be razmatra se u okviru Aproksimacije slučajnih faza sa izmjenom (RPAE). Pokazano je da dijagrami najnižeg reda imaju preovlađujući doprinos. To objašnjava zašto model gustog elektronskog gasa tretira podjednako dobro elektronske korelacije kod najlakših atoma kao što to čini model rijetkog elektronskog gasa. Dipolni matrični element u RPAE pokazuje dobru konvergenciju u okviru ove aproksimacije. Izračunat je doprinos dijagrama koji narušavaju Paulijev princip (EPV).

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