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THE YIELDS OF ^1P AND ^1D RESONANCES IN THE He(e,2e)He$^+$ REACTION

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1. Introduction

In refs.[1,2], the problem of interaction of the overlapping ^1P and ^1D autoionization states (AIS) in the He(e,2e)He$^+$ reaction has been considered in the first Born approximation (FBA) at incident energies E_0=4keV. It was shown[1] that in the vicinity of the quasielastic peak in the ejection angle range $-25^\circ<\theta_q<25^\circ$ and momentum transfer interval $1.2\leq Q<2$au the resonance profiles acquire a complicated asymmetric structure. In the region of the recoil peak the ^1P and ^1D resonances appear as well isolated symmetric structures.

At small momentum transfers ($Q<0.8$au), the ^1D resonance yield is small as compared with the maxima of the ^1P AIS yield in both peak regions. For a very low momentum transfer ($Q\sim0.01$au), the profiles of the ^1P AIS tend closely to the photoabsorption picture reproducing the experimental data[3] and theoretical estimates[4] in the optical limit (fig.2a). In early experiments[5] the neighbouring $(2s2p)^1P$ and $(2p^2)^1D$ AIS have not been resolved energetically. The ^1D AIS contribution was assumed to be negligible which turned out to be valid only at small momentum transfer[1]. Recently, in the coincidence measurements[6,7] carried out with higher energy resolution at incident energies of few hundred eV and certain kinematical conditions the ^1D resonance yield has been found to be larger than the ^1P AIS yield.

In this work, the dependence of the relation of these resonance yields on the momentum transfer Q at different ejection angles θ_q and incident energy E_0=1000eV is considered in the recoil peak region .

2. Formalism

The triple differential generalized oscillator strength (TDGOS) of transition to continuum with allowance for the ^1P and ^1D AIS interference (G) can be written down[1,8] as

$$f(E_b,\theta_q,Q)=f0(E_b,\theta_q,Q)+G(E_b,\theta_q,Q). \qquad (1)$$

The TDGOS for the noninteracting (f0) and isolated ^1P and ^1D AIS can be put in the following form

$$fO=C+V_P+V_D, \qquad fP=C+V_P, \qquad fD=C+V_D. \qquad (2)$$

Here

$$C(E_b,\theta_q,Q)=\frac{2E}{Q^2}|T_{dir}|^2 \qquad (3)$$

are TDGOS of the direct atomic ionization. The resonance contributions of the ^1P and ^1D AIS are described by

$$V_i=\frac{a_i\varepsilon_i+b_i}{1+\varepsilon_i^2}, \qquad (4)$$

Here the index i corresponds to the ^1P or ^1D AIS. The parameters a_i and b_i characterizing the asymmetry of the profiles allowed for in the ^1P and ^1D resonance calculations and the resonance "yields", respectively, can be expressed by the following formulas

$$a_i(E_b,\theta_q,Q)=\frac{4E}{Q^2}\,\mathrm{Re}\{T^*_{dir}(E_b,\theta_q,Q)T^i_{res}(E_b,\theta_q,Q)[q_i(Q)-i]\}, \qquad (5)$$

$$b_i(E_b,\theta_q,Q)=\frac{2E}{Q^2}\,\{|T^i_{res}|^2[q_i^2(Q)+1]+2\mathrm{Im}[T^*_{dir}T^i_{res}(q_i(Q)-i)]\}. \qquad (6)$$

In the formula (1) the term G presenting the interference between the amplilitudes of ^1P and ^1D resonances is given by the expression

$$G(E_b,\theta_q,Q)=\frac{2E}{Q^2}\,\frac{[(1+\varepsilon_p\varepsilon_d)\mathrm{Re}(T^{d*}_{res}T^{p}_{res}Z)+(\varepsilon_p-\varepsilon_d)\mathrm{Im}(T^{d*}_{res}T^{p}_{res}Z)]}{2(\varepsilon_p^2+1)(\varepsilon_d^2+1)}, \qquad (7)$$

where $Z=1+q_p(Q)q_d(Q)+i(q_p(Q)-q_d(Q))$,

$$\varepsilon_i=(E-E^i_{res})/\Gamma_i, \qquad (8)$$

Γ_i and ε^i_{res} are the widths and positions, respectively, of the resonance ^1P or ^1D; $q_i(Q)$ are the profile indices of the resonances; $E=E_0-E_a=E_b+I$ is the energy loss suffered by the scattered electron; in the latter relation E_0,E_a and E_b are the energies of the incident, scattered and ejected electrons respectively. I is the ionization potential of the Helium atom.

Note that the parameters a_i, b_i, C and G are functions of the energy (E_b), the ejection angle (θ_q) and the momentum transfer (Q).

In (7), T_{dir} is the direct ionization amplitude in the coordinate system with the z-axis directed along the momentum transfer Q, and it is written[1,8] as

$$T_{dir} = \sum_L t_L(E_b, Q) P_L(\cos\theta_q), \tag{9}$$

where the partial amplitude t_L is

$$t_L = (2L+1)\, e^{i\delta_L}\, I_{E_bL}(Q). \tag{10}$$

Here $P_L(\cos\theta_q)$ is the Legendre polynomial, θ_q is the ejection angle determined by the angle between the wave number vector $\mathbf{k}_b$ of the ejected electron and the z-axis; L is the angular momentum transfer and

$$I_{E_bL} = \sqrt{\frac{1}{2\pi}} \int_0^\infty U_{E_bL}(r)\, j_L(Qr) \langle \Phi_{1s}(r') | \Phi_0(r, r') \rangle dr \tag{11}$$

Here $\Phi_0(r,r')$ and $\Phi_{1s}(r)$ are the ground-state wave functions of the Helium atom and the residual ion, respectively; $j_L(Qr)$ is the Bessel function; $U_{E_bL}(r)$ is the wave function of the ejected electron in the He^+ ion field. The latter is obtained by solving the Schrödinger radial equation with the boundary condition

$$U_{E_bL} \to \sqrt{\frac{2}{\pi k_b}}\, \mathrm{Sin}(k_b r + \frac{1}{K_b} \ln(2k_b r) - \frac{\pi}{2}L + \delta_L), \qquad \text{at} \quad r \to \infty,$$

where

$$\delta_L = \eta_L + \sigma_L\ , \qquad \eta_L = \arg(L + 1 - \frac{i}{k_b}) \tag{12}$$

and σ_L is the phase shift with respect to the pure Coulomb wave. The function U_{E_bL} is forced to be orthogonal to the occupied ground state orbitals of the Helium atom. For the resonance amplitudes which allow for the ^1P and ^1D resonances

$$T^i_{res} = t_{L_i} P_{L_i}(\mathrm{Cos}\theta_q), \qquad L_1 = 1, \qquad L_2 = 2. \tag{13}$$

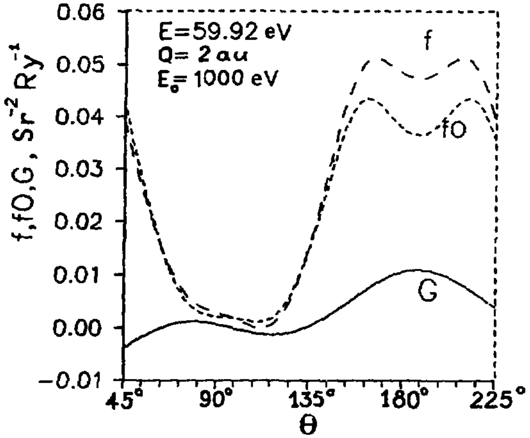

Fig.1. The dependence of the ^1P and ^1D resonance yields in the TDGOS f, fO, and of the interference term G on the ejection angle θ_q. The angle θ_q is counted off the direction of the ejected electron.

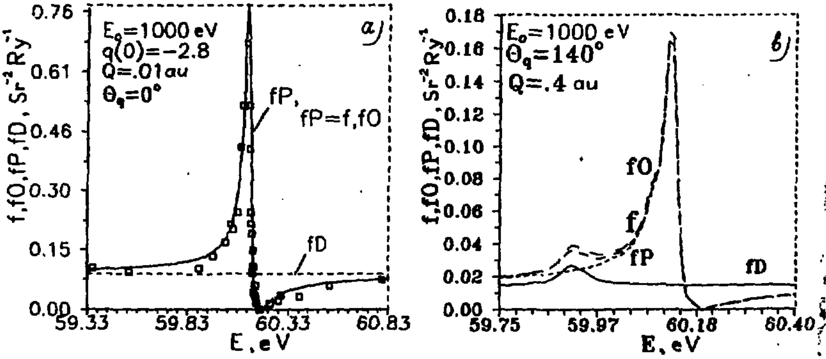

Fig.2. The spectra of the ^1P and ^1D AIS yields in the TDGOS f in a vicinity of the optical limit for different kinematical conditions 2a and 2b. □ is the experimental data of the photoabsorption(3), q(o)=-2.8 the is profile index value(3).

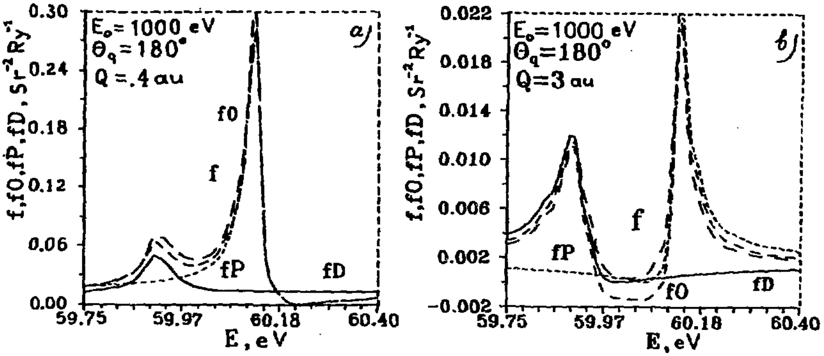

Fig.3. The relation between the ^1P and ^1D AIS yields in the spectra of the TDGOS f, fO at different momentum transfers at recoil peak θ_q=180°.

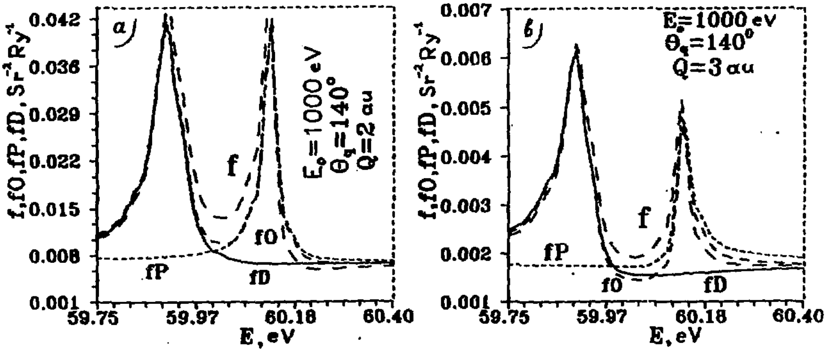

Fig.4. The relation between the ^1P and ^1D AIS yields in the spectra of the TDGOS f and fO for large momentum transfers at the ejection angle θ_q=140°.

3. Results and discussion

In calculations of the TDGOS as the wave functions of the helium initial and final states we use the six-parameter Hylleraas function[9] and the solutions of the Schrödinger radial equation for a static potential, respectively.

Our previous estimations have shown[1,10] that the combination of these functions is sufficient for describing the direct and resonance He(e,2e)He$^+$ reaction at high incident ($E_0 \geq 4$keV) and large ejection ($E_b \geq 20$eV) energies . The characteristics of the ^{1}P and ^{1}D resonances (E^R_i, Γ_i) and, also, the corresponding profile indices with allowance for the Q-dependence ($q_i(Q)$) were taken from ref[3,11,12].

The term G describing interference of the ^{1}P and ^{1}D AIS is small within a wide range of the kinematic variables (fig.1). In the vicinity of the recoil peak and of the position of ^{1}D AIS the angular dependence of the TDGOS f and f_0 has[2] maxima in a certain range of ejection angles (fig.1) for large momentum transfer values. This behaviour of the resonance yield is due to the mutually destructive interference of the terms a_i, c_i and b_i in the resonance contributions V_i (formula (4)).

In the optical limit Q→0, the calculated spectra of the TDGOS f and f0 approach the photoabsorption profile and reproduce the experimental data[3] (fig.2a). At small momentum transfers (Q~0.4au) the yield of the optically allowed ^{1}P resonance is much greater than the yield of the ^{1}D AIS at any ejection angle θ_q (The angle θ_q is counted off the direction of the ejected electron, fig.2b).

With increasing momentum transfer the yield of the optically forbidden ^{1}D resonance grows relatively to the yield of the ^{1}P AIS (fig3a,b). Note that for the momentum transfer Q>2au the profile index q(Q) was taken as constant equal to it's value at Q=2au. Our calculations show, that for a large momentum transfer (Q>2au) the relation between the ^{1}P and ^{1}D resonances drastically varies in the certain range of the ejection angle θ_q. Under these conditions the yield of the ^{1}D resonance turns out to be large than the ^{1}P AIS yield just in the ejection angle range where the TDGOS f and f0 have maxima (fig.4a,b). Physically this means that in these situations the contribution of the higher multipole (D) in TDGOS dominates over the contribution of the lower one (P).

We note, that such behaviour of the ^1P and ^1D AIS yields is retained at different incident energies. But, when the incident energies increase, the domination of the ^1D AIS yeild over the ^1P AIS one was achieved, as a rule, at relatively large momentum transfers.

A similar pattern of the relation between the ^1P and ^1D resonance yields was revealed in coincidence experiments[6] at somewhat differing values of the kinematical variables, than in our calculations: incident energies of 200eV, a 10° scattering angle and ejection angle ~130°. The experimental data were given in arbitrary units.

4. Conclusion

The dependence of the relation between the yields of the ^1P and ^1D resonances in the $He(e,2e)He^+$ reaction upon the momentum transfer and ejection angle in the recoil peak region at incident energies E_0=1000eV is considered. This relation varies noticeably as the momentum transfer is enhanced for different ejection angles θ_q.

At small momentum transfers the yield of the optically allowed ^1P resonance yield is greater than the ^1D AIS yield for any ejection angle.

In a certain range of ejection angles, $\theta_q \sim (140^\circ - 170^\circ)$, and at large momentum transfers (Q>2au) the yield of the ^1D AIS dominates over the ^1P resonance yield. Physically, this is due to domination of the higher multipole contribution (D) in the TDGOS of the transition to continuum over the lower one (P) for these kinematical conditions.

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Лхагва О. и др. E4-91-303

Выходы ^1P и ^1D резонансов в He(e,2e)He$^+$ реакции

В первом борновском приближении изучается соотношение выходов ^1P и ^1D резонансов в He(e,2e)He$^+$ реакции в зависимости от переданного импульса при разных углах эжекции и энергии падающего электрона E = 1000 эВ. Показано, что при больших переданных импульсах в определенном интервале угла эжекции выход ^1D резонанса доминирует над выходом ^1P резонанса.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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The Yields of ^1P and ^1D Resonances in the He(e,2e)He$^+$ Reaction

In the first Born approximation the dependence of the yields of the ^1P and ^1D resonances in the He(e,2e)He$^+$ reaction on the momentum transfer in the recoil peak region at incident energies E_0 = 1000 eV is studied. It is shown that in a certain range of the ejection angle and for the large momentum transfer the yield of the ^1D resonance dominates over the ^1P resonance one.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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