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Quantum theory analysis of the action micromechanism exerted on bioparticles from laser microbeams*

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The effect of laser microbeam trapping the bioparticles has been applied widely in the biology .However the micromechanism of the acting that realizes the laser-microbeam trapping bioparticles is still lacking . In this paper ,the act microchenism of the gradiant force of laser microbeam for the bioparticles is analysed by means of quantum theory ,The result accords with our experiment.

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Since V S Latokhov advanced the thought on laser trapping of atoms[1],the research of laser cooling and trapping of atom by laser beams made considerable headway.Under inspiration of Latokhov thought,Ashkin ,A realtized that high convergent laser beams trap the bioparlicle(cell, spore or big biomolecule) [2,3].In laser biology ,the laser microbeam trapping maniputive the applications in the insertion of exogenous genes ,the exoteric assistant fertilisation,cellular fusion and micromanipulation of chromosomes or other biomolecules . Now ,one hold the action forces of laser microbeams ,that trap the bioparticles,are the scattering forces and the gradient forces, However the interaction between mechanism laser beam and He bioparticle is very complex. In this paper,an analytic theoretic analysis of the micromechanism for the gradient force of laser trapping the biomolecules was made by means of quantum theory.At the end of the paper,We explained the experiment[8] result in ref. [4]by means this theoretic analysis.

First , we must analyse the Hamiltonian of the laser-bioparticle (here we take biomolecule)interaction system.The Hamiltonian is:

$$H=H_{\mathrm{M}}+H_{\mathrm{L}}+V_{\mathrm{M\text{-}L}}+H_{\mathrm{R}}+V_{\mathrm{M\text{-}R}} \tag{1}$$

where, $\mathrm{H_M}$ is the free Hamiltonian of the biomolecules,$\mathrm{H_L}$ is the free Hamiltonian of laser field,$\mathrm{H_R}$ is the free Hamiltonian of radiation fields in vacuum;$\mathrm{V_{M\text{-}L}}$ is the interaction Hamiltonian of laser with biomolecules;and $\mathrm{V_{M\text{-}R}}$ is the interaction Hamiltonian of radiation fields with biomolecules.

Due to laser field is high convergent,we may take the dressed state to represent approximately the laser-micromolecule interaction system ,which is dressed by laser field[5,6].Under neglecting the action of H_R and $\mathrm{V_{M\text{-}R}}$, we can obtain the wave function Ψ_m^d of the dressed state (under the first order perturbation opproximation) [7]:

$$\psi_m^d=\psi_m^0+\exp[-i(E_m-\omega\hbar)t/\hbar]\times$$
$$\sum\nolimits_n' \frac{i\omega}{2c}\boldsymbol{D}_{nm}\cdot\boldsymbol{A}_0\frac{\phi_n}{E_n-E_m+\omega\hbar}-\exp[-i(Em+\omega\hbar)t/\hbar]\times$$
$$\sum\nolimits_n' \frac{i\omega}{2c}\boldsymbol{D}_{nm}\cdot\boldsymbol{A}_0\frac{\phi_m}{E_n-E_m+\omega\hbar} \tag{2}$$

where,$\psi_m^d=\phi_0 e^{-iE_m t/\pi}$ is the system state wave function when haven't laser field; $\boldsymbol{D}$ is the molecular dipole moment.
and $\boldsymbol{D}_{\mathrm{nm}}=\langle\phi_n|\boldsymbol{D}|\phi_m\rangle$
According to Heisenberg's motion equation $\frac{dA}{dt}=\frac{i}{\hbar}[H,A]$.
We can obtain the representation of the force that exerted on the biological molecules due to interaction of laser and the biomolecule , it is :

$$\boldsymbol{F}=\frac{d\boldsymbol{p}}{dt}=\frac{i}{\hbar}[H,\boldsymbol{P}] \tag{3}$$

$\boldsymbol{P}$ is the momentum operator .From (1) we can obtain:

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$$\boldsymbol{F} = -\nabla(V_{m-l} + V_{m-R}) = -\nabla(V_{m-l})$$

$$\nabla_R = (V_{m-R}) = 0 \tag{4}$$

Under rotating wave approximation[8] we have:

$$V_{m-l} = -\left\lfloor \boldsymbol{D} \cdot \varepsilon_l S_{+a_l} + \boldsymbol{D}^* \cdot \varepsilon^+{}_l S_{a_l^+} \right\rfloor \tag{5}$$

where α_L、α_L^+ are respectively annibilation operator and creation operator of laser field, $H_L = \hbar\omega\alpha^+\alpha$ ε_L is space distribution of laser field; ***P*** can take to as

$$\left[-\frac{m\omega_0}{e} D(S_+ + S_-)\right]$$

In general ,one only attend to the expectant value of the force ***f***. Analogous to our compute method in reference [9],we can obtain the expectant value of the force ***f***:

$$\boldsymbol{f}(\boldsymbol{r}) = \left\langle \left| S_{+a_L} \cdot [\varepsilon_L^*(\boldsymbol{r})] + S_{+a_L^+} + \nabla[\boldsymbol{D} \cdot \varepsilon_L^*(\boldsymbol{r})] \right| \right\rangle =$$

$$\frac{\hbar}{2} \sum_n \{ < e, n | \rho | g, n+1 > \nabla[\omega_R(\boldsymbol{r}) e^{i\varphi(\boldsymbol{r})}] \} =$$

$$\frac{i\hbar\omega_R}{2} \nabla\varphi(\boldsymbol{r})(\rho_{eg} e^{-i\varphi(\boldsymbol{r})} - \rho_{ge} e^{-i\varphi(\boldsymbol{r})}) - \frac{\hbar\nabla\omega_R}{2}(\rho_{eg} e^{-i\varphi(\boldsymbol{r})} - \rho_{ge} e^{-i\varphi(\boldsymbol{r})}) \tag{6}$$

where ω_R is Rabi frequency, ω_R is directly proportional to laser electric field intensity and relate to the interaction of laser and biomolecule; ρ relates to the biomolecule population.

Transfering ρ_{eg} and ρ_{ge} into representation of dressed state[10],we can be obtain:

$$\rho_{eg} = e^{i\phi}[\sin\theta\cos\theta\pi - \sin\theta\cos\theta\pi_2 + \cos^2\theta\rho_{12} - \sin^2\theta\rho_{21}]$$

$$\rho_{ge} = e^{-i\phi}[\sin\theta\cos\theta\pi_1 - \sin\theta\cos\theta\pi_2 + \cos^2\theta\rho_{21} - \sin^2\theta\rho_{12}] \tag{7}$$

where

$\cos 2\theta = -\delta / \sqrt{\omega_R^2 + \delta^2}$,$\delta = \omega_l - \omega_0$, ω_l is laser frequency, $\omega_0 = (E_0 - E_1)/\hbar$, E_0 is the basic state energy of the molecule, E_1 is first excited state energy of the molecule,δ is called the disarrangement guantity; $\pi_i = \sum_n < i, n, r | \rho | i, n, r >$. Hence we can obtain ***f*** :

$$\boldsymbol{f}(\boldsymbol{r}) = \frac{-\hbar\nabla\omega_R}{2}[\sin 2\theta(\pi_1 - \pi_2) - \cos 2\theta(\rho_{12} - \rho_{21})] \tag{8}$$

From the formula (8) we can see $\boldsymbol{f}(\boldsymbol{r}) \propto \nabla\omega_R$,however $\omega_R \propto$ laser electric field strength $|\boldsymbol{E}_l|$ and ∇ is gradient operator.Hence the formula (8)can explain the force ***f*** (***r***),which acts on the biomolecules due to the nonuniformity of laser field,is a gradient force .If the bioparticle is bigger, the total resultant Force which acts on the bioparticle is:

$$\boldsymbol{F}(\boldsymbol{r}) = \sum_n \left\{ \frac{-\hbar\nabla\omega_R}{2} \sin 2\theta(\pi_1 - \pi_2) - \frac{\hbar\nabla\omega_R}{2} \cos 2\theta(\rho_{12} - \rho_{21}) \right\} \tag{9}$$

From the formula (9) we can see that the total resultant $F(r)$ still possess the feature of gradient force.

In our laser trapping experiment[4],we find that most bioparticles are attracted to laser field centre,only less bioparticles are repeled.From formula (8) and attend to

$$\nabla[\omega_R^2 + \delta^2]^{1/2} = \sin 2\theta \nabla\omega_R$$

$$\nabla\omega_R \cos\theta = 2\sqrt{\omega_R^2 + \delta^2}\nabla\theta$$

we cen obtain: $\boldsymbol{f}(\boldsymbol{r}) = -\frac{\hbar\delta\nabla\omega_R^2}{4\delta^2 + 2\omega_R^2}$, under the velocity of the mass center motion of the bioparticle is slow ,light field is a standing wave field: ($i.e\omega_l(\boldsymbol{r}) = \omega_l \cos \boldsymbol{k} \cdot \boldsymbol{r}$) and the system state is a stable state .From

$$\boldsymbol{f}(\boldsymbol{r}) = -\frac{\hbar\delta\nabla\omega_R^2}{4\delta^2 + 2\omega_R^2}$$

We can explain the phenonmenon in our experiment[9].When $\delta < 0$ the bioparticle tend to where laser strength is stronger; when $\delta > 0$ the bioparticle is repelled .Due to laser frequance in our experiment is minor , hence in the experiment the ω_0 of most molecule $> \omega_l$,i.e.the disarrangement guatity $\delta < 0$,so most molecule are attended to the center of laser field , but less molecule are repelled from the center.

In addition, we find yet that a few bioparticles can rotate by laser action in our experiments[4]. In fact ,due to the laser field is nonuniform, hence when the bioparticlesis bigger , the action of laser field can form a moment act to the bioparticles.

To sum up ,we can see that our theoretic analysis results accords with the result of our experiment research.

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