Volume 9, Number 6
1009-1963/2000/09(06)/0419-05
CHINESE PHYSICS
June, 2000
© 2000 Chin. Phys. Soc.

LASER-ASSISTED e-Ar SCATTERING IN CO_2 LASER FIELD*

Zhu Zun-lüe(朱遵略), Jiang Yu-hai(江玉海), and Sun Jin-feng(孙金锋)

College of Physics and Information Engineering, Henan Normal University, Xinxiang 453002, China

(Received 8 November 1999; revised manuscript received 7 January 2000)

Electron scattering from argon in a laser field is investigated empolying the second-order perturbation theory. The absolute differential cross sections of e-Ar scattering with multiphoton exchange in special scattering geometries G1 (for small-angle scattering) and G2 are calculated. Our results are found to be better than other theoretical results as compared with the experimental data.

PACC: 3280

I. INTRODUCTION

With the development of lasers, electron scattering from atom (or molecule) in a laser field has become a new field in the 1970's. But in these processes three systems (electron, target and laser field) interact with one another. This makes the research so complicated that up to now only special cases and approximations have been investigated.[1] Recently, a set of experiments that were electron-atom scattering in the CO_2 laser field has been carried out by Wallbank and Holmes,[2−4] using two special scattering geometries (called G1 and G2 in the following). In geometry G1, the incident electron beam is parallel to the polarization direction of the laser field and the momentum transfer for small-angle scattering is nearly perpendicular to this direction; in geometry G2, the momentum transfer is perpendicular to the polarization direction. In the experimental geometries G1 (for small-angle scattering) and G2, the low-frequency approximation (LFA) formula,[5] which had been subsequently confirmed in details theoretically by many authors,[6,7] does break down. Wallbank and Holmes[4] thought the atom polarization potential induced by the laser field was extremely important for low-energy electron scattering from atom and might account for the discrepancies between LFA and experiments. But the theoretical estimations performed by some other authors[8,9] proved that the atomic polarization effect induced by a laser field is small enough to neglect. Madsen and Taulbjerg[10] formulated a soft-photon, weak-field approximation that was valid at small scattering angle. But there were also large differences between their results and experiments. Chen and Robicheaux[11] calculated the cross sections for scattering of electron from argon in the CO_2 laser field and found their results differed from the experimental results and were the same as the LFA. Later, many other authors[12,13] also studied the discrepancy between experiments and LFA in some ways but the agreements have not been improved.

Recently, we have employed the second-order perturbation theory to study laser-assisted electron-He scattering in geometry G1.[14,15] In this paper, the differential cross sections of the laser-assisted electron-Ar scattering with multiphoton exchange in geometry G1 and G2 are calculated and made comparisons with the experiment[3] and other theoretical results. In sec.Ⅱ, we will give briefly the second-order perturbation theory for the electron-atom scattering in a laser field. In sec.Ⅲ, we will present our results and discussion. Unless otherwise indicated, SI units are used throughout.

Ⅱ. THE SECOND-ORDER PERTURBATION THEORY

Since there are a large number of photons in a laser mode, we may describe the laser field as a classical electromagnetic field,[1] $\boldsymbol{E}(t) = \boldsymbol{E}_0 \sin\omega t$, and the corresponding vector potential is: $\boldsymbol{A}(t) = \dfrac{c\boldsymbol{E}_0}{\omega}\cos\omega t$. Therefore, the Schrödinger equation of an electron moving in the laser field and scattering from an atom potential $V(r)$ is

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Psi_{\boldsymbol{k}}(\boldsymbol{r},t) = \left[\frac{(\boldsymbol{p}+\dfrac{e}{c}\boldsymbol{A})^2}{2m} + V(r)\right]\Psi_{\boldsymbol{k}}(\boldsymbol{r},t). \quad (1)$$

The $A^2(t)$ term of Eq.(1) may be removed by the following transformation:

* Project supported by the Natural Science and the Education Committee Foundation of Henan Province, China (Grant No. 1999140009).

$$\Psi_{\boldsymbol{k}}(\boldsymbol{r},t)=\exp\left(-\frac{\mathrm{i}}{\hbar}\int_{-\infty}^{t}\frac{e^2}{2mc^2}\boldsymbol{A}^2(t')\mathrm{d}t'\right)\Phi_{\boldsymbol{k}}(\boldsymbol{r},t). \tag{2}$$

So Eq.(1) may be rewritten as

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Phi_{\boldsymbol{k}}(\boldsymbol{r},t)=\left[\frac{p^2}{2m}+\frac{e}{mc}\boldsymbol{p}\cdot\boldsymbol{A}(t)+V(r)\right]\Phi_{\boldsymbol{k}}(\boldsymbol{r},t). \tag{3}$$

We consider $V(r)$ in Eq.(3) as a perturbation and the unperturbation solution of Eq.(3) is just the Volkov solution[16]

$$\chi_{\boldsymbol{k}}(\boldsymbol{r},t)=\exp\left[\mathrm{i}\left(\boldsymbol{k}\cdot\boldsymbol{r}-\frac{\hbar k^2}{2m}t-\frac{e}{m\omega^2}\boldsymbol{k}\cdot\boldsymbol{E}_0\sin\omega t\right)\right], \tag{4}$$

where $\boldsymbol{k}$ is the wave vector of the electron. Using the Green function representation

$$G(\boldsymbol{r},t;\boldsymbol{r}',t')=-\frac{\mathrm{i}}{(2\pi)^3\hbar}\int\mathrm{d}\boldsymbol{k}\chi_{\boldsymbol{k}}(\boldsymbol{r},t)\chi^*_{\boldsymbol{k}}(\boldsymbol{r}',t')u(t-t'), \tag{5}$$

$u(t-t')$ denoting the step function, and the solution of Eq.(3) is

$$\Phi_{\boldsymbol{k}}(\boldsymbol{r},t)=\chi_{\boldsymbol{k}}(\boldsymbol{r},t)+\int\mathrm{d}\boldsymbol{r}'\int_{-\infty}^{t}\mathrm{d}t'G(\boldsymbol{r},t;\boldsymbol{r}',t')V(r')\Phi_{\boldsymbol{k}}(\boldsymbol{r}',t'). \tag{6}$$

According to standard time-dependent scattering theory, the scattering matrix from initial state $\boldsymbol{k}_\mathrm{i}$ to final state $\boldsymbol{k}_\mathrm{f}$ is

$$S_\mathrm{fi}=-\frac{\mathrm{i}}{\hbar}<\chi_{\boldsymbol{k}_\mathrm{f}}|V|\Phi_{\boldsymbol{k}_\mathrm{i}}>, \tag{7}$$

where $\Phi_{\boldsymbol{k}_\mathrm{i}}$ is the solution of Eq.(3) and the brackets denote the integration over all space and time. We only consider the first and the second terms of the scattering matrix

$$S_\mathrm{fi}^{<2>}=S_\mathrm{fi}^{(1)}+S_\mathrm{fi}^{(2)}, \tag{8}$$

where

$$\begin{aligned}S_\mathrm{fi}^{(1)}&=-\frac{\mathrm{i}}{\hbar}<\chi_{\boldsymbol{k}_\mathrm{f}}|V|\chi_{\boldsymbol{k}_\mathrm{i}}>\\&=-2\pi\mathrm{i}\sum_\nu\delta(E_\mathrm{f}-E_\mathrm{i}+\nu\hbar\omega)J_\nu(\lambda_\mathrm{fi})\tilde{V}(k_\mathrm{fi}),\end{aligned} \tag{9}$$

$$\begin{aligned}S_\mathrm{fi}^{(2)}&=-\frac{\mathrm{i}}{\hbar}\int_{-\infty}^{+\infty}\mathrm{d}t\int\mathrm{d}\boldsymbol{r}\int\mathrm{d}\boldsymbol{r}'\int_{-\infty}^{t}\mathrm{d}t'\chi^*_{\boldsymbol{k}_\mathrm{f}}(\boldsymbol{r},t)V(r)G_{\boldsymbol{k}_q}(\boldsymbol{r},t;\boldsymbol{r}',t')V(r')\chi_{\boldsymbol{k}_\mathrm{i}}(\boldsymbol{r}',t')\\&=-\frac{1}{(2\pi)^3\hbar^2}\int_{-\infty}^{+\infty}\mathrm{d}t\int\mathrm{d}\boldsymbol{k}_q\tilde{V}(k_{\mathrm{f}q})\tilde{V}(k_{q\mathrm{i}})\sum_l\sum_n\exp\left[\frac{\mathrm{i}}{\hbar}[E_\mathrm{f}-E_\mathrm{i}+(l+n)\hbar\omega]t\right]\\&\quad\times[(E_\mathrm{i}-E_q-n\hbar\omega)+\mathrm{i}0^+]^{-1}\mathrm{J}_l(\lambda_{\mathrm{f}q})\mathrm{J}_n(\lambda_{q\mathrm{i}}).\end{aligned} \tag{10}$$

Here $\mathrm{J}_n(\lambda)$ is the Bessel function of the first kind and order n, $\tilde{V}(k_{\alpha\beta})$ is the Fourier transform of the atom potential

$$\tilde{V}(k_{\alpha\beta})=\int\mathrm{d}\boldsymbol{r}\exp(-\mathrm{i}(\boldsymbol{k}_\alpha-\boldsymbol{k}_\beta)\cdot\boldsymbol{r})\cdot V(r). \tag{11}$$

Other parameters are

$$\begin{aligned}&E_\alpha=\frac{\hbar^2k_\alpha^2}{2m},\quad E_\mathrm{f}=E_\mathrm{i}+\nu\hbar\omega,\ \lambda_{\alpha\beta}=(\boldsymbol{k}_\alpha-\boldsymbol{k}_\beta)\cdot\boldsymbol{\alpha}_0,\\&\boldsymbol{\alpha}_0=\frac{e\boldsymbol{E}_0}{m\omega^2},\quad\alpha,\beta=\mathrm{i},q,\mathrm{f}.\end{aligned} \tag{12}$$

So T matrix of the second-order perturbation theory with ν being photon exchange ($\nu>0$ for absorption and $\nu<0$ for emission) is found to be

$$\begin{aligned}T_\mathrm{fi}^{<2>}(\nu)=&T_\mathrm{fi}^{(1)}(\nu)+T_\mathrm{fi}^{(2)}(\nu)\\=&\mathrm{J}_\nu(\lambda_\mathrm{fi})\tilde{V}(k_\mathrm{fi})+\sum_n\int\mathrm{d}\boldsymbol{k}_q(2\pi)^{-3}\tilde{V}(k_{\mathrm{f}q})\tilde{V}(k_{q\mathrm{i}})\mathrm{J}_{(\nu-n)}(\lambda_{\mathrm{f}q})\mathrm{J}_n(\lambda_{q\mathrm{i}})\\&\times[(E_\mathrm{i}-E_q-n\hbar\omega)+\mathrm{i}0^+]^{-1}.\end{aligned} \tag{13}$$

The corresponding differential cross section with photon exchange ν is

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\nu} = \frac{k_{\mathrm{f}}(\nu)}{k_{\mathrm{i}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 |T_{\mathrm{fi}}^{<2>}(\nu)|^2. \qquad (14)$$

In this paper, we do not consider the polarization potential that describes the atom polarization effect induced by the incident electron and presents less contribution to differential cross sections, but only consider the analytic screening electric static potential in the following form:[17]

$$V(r) = -\frac{Ze^2}{r}\sum_{i=1}^{3} A_i \exp(-\alpha_i r), \qquad (15)$$

where Z is the nuclear charge number, the parameters A_i and α_i are taken from Ref.[17]. Then

$$\tilde{V}(k) = -4\pi Ze^2 \sum_{i=1}^{3} \frac{A_i}{\alpha_i^2 + |\boldsymbol{k}|^2}. \qquad (16)$$

Only taking the first-term of Eq.(13), we can obtain the first-order perturbation theory formula (usually called the Born approximation formula in the presence of a laser field) with photon exchange ν

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\nu}_{\mathrm{B}} = \frac{k_{\mathrm{f}}(\nu)}{k_{\mathrm{i}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 |T_{\mathrm{fi}}^{(1)}(\nu)|^2 = \frac{k_{\mathrm{f}}(\nu)}{k_{\mathrm{i}}} \mathrm{J}_{\nu}^2(\lambda_{\mathrm{fi}}) \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{el}}_{\mathrm{B}}, \qquad (17)$$

where $\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{el}}_{\mathrm{B}} = \left|\frac{m}{2\pi\hbar^2}\tilde{V}(k_{\mathrm{fi}})\right|^2$ is the Born approximation elastic differential cross section in the absence of a laser field. Equation (17) was obtained by Bunkin *et al.*[18]

Ⅲ. RESULTS AND DISCUSSION

In geometries G1 (for small-angle scattering) and G2, we have employed the second-order perturbation theory to calculate the differential cross sections of e-Ar with multiphoton exchange. The parameters are the same as those used in the experiment.[3] The laser field frequency is $\omega = 0.117\,\mathrm{eV}$ and its intensity is $I = 1.5 \times 10^8\,\mathrm{W/cm^2}$. For comparison, we have also calculated the results of LFA using the following formula:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\nu} = \frac{k_{\mathrm{f}}(\nu)}{k_{\mathrm{i}}} \mathrm{J}_{\nu}^2(\lambda_{\mathrm{fi}}) \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{el}}, \qquad (18)$$

where $\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\nu}$ denotes the elastic differential cross section with ν being the photon exchange; $\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{el}}$ is the elastic differential cross section in the absence of a laser field. Other parameters are the same as in Eq.(12). In our calculation, the field-free elastic differential cross section by the LFA formula is obtained using our previous optical potential method.[19] These results along with the experimental results obtained by Wallbank and Holmes[3] are shown in Figs.1–6.

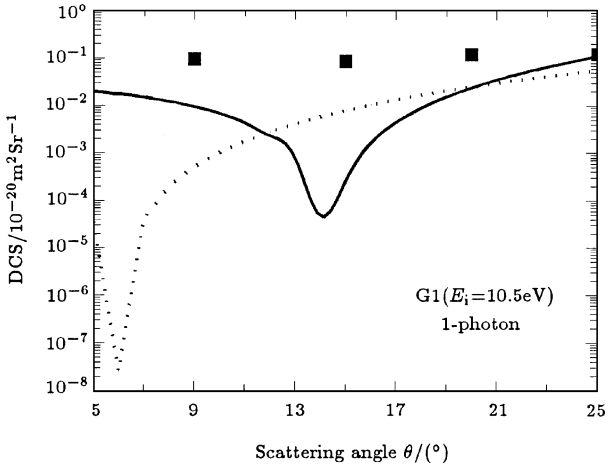


Fig.1. One-photon absorption differential cross section (DCS) in G1. The incident electron energy is $E_{\mathrm{i}} = 10.5\,\mathrm{eV}$. Solid line, SBA result; dotted line, LFA result; box, experiment.

From Figs.1–6, we can see that our results differ by orders of magnitude from those obtained by the LFA, and the former is better than the latter, as compared with the experimental results. For small argument λ in geometries G1 (for small-angle scattering) and G2, $\mathrm{J}_n(\lambda) \approx \lambda^n/2^n n!$, the LFA either is not valid or predicts much smaller cross sections. In addition, comparing Eq.(17) with Eq.(18), we can see that the LFA is similar to the first-order perturbation theory in that they only consider the electron transformation

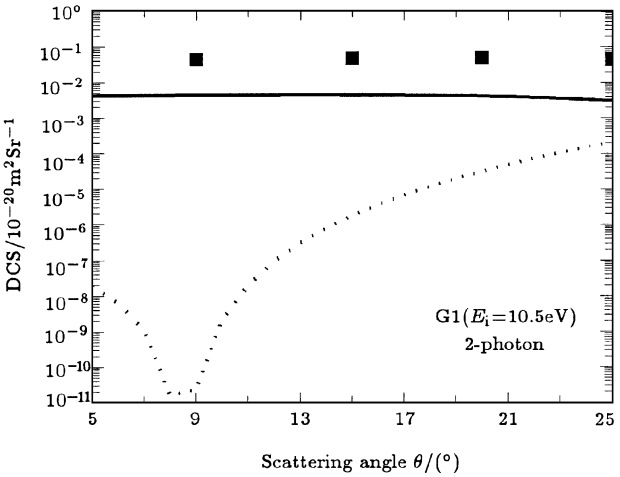


Fig.2. Same as Fig.1, but for two-photon absorption.

from the initial state $\boldsymbol{k}_{\rm i}$ to the final state $\boldsymbol{k}_{\rm f}$. Nevertheless, in the second-order perturbation theory, we consider not only the electron transformation from the initial state $\boldsymbol{k}_{\rm i}$ to the final state $\boldsymbol{k}_{\rm f}$, but also that from the initial state $\boldsymbol{k}_{\rm i}$ to the intermediate state $\boldsymbol{k}_q$ and then from $\boldsymbol{k}_q$ to $\boldsymbol{k}_{\rm f}$. The contribution of the latter transformation to the cross section is larger in geometries G1 (for small-angle scattering) and G2. Therefore, our results are better than the LFA ones. In Fig.4, we also give Chen's results[11] that are different from the experimental ones.

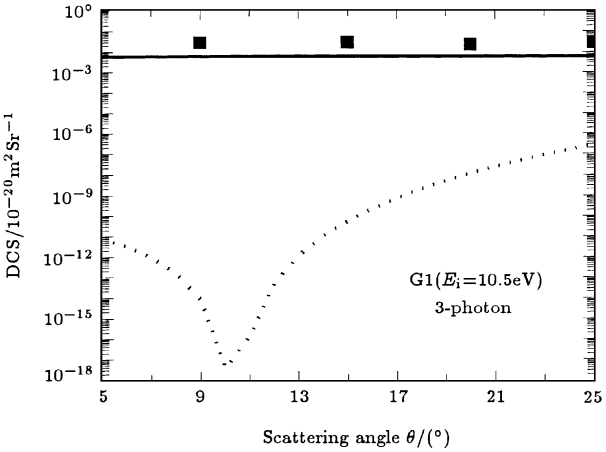


Fig.3. Same as Fig.1, but for three-photon absorption.

One can find that the discrepancies between our results and the experimental ones still exist, especial for scattering geometry G2. The reasons are as follows: (a) The experiment[3] contained some errors. Wallbank and Holmes reported that the errors in the measurement of absolute cross sections in each experiment were estimated to be less than 10%, but the discrepancies between the different experiments could exceed 40% at particular energies and angles. This reflects the experimental difficulties inherent in such absolute measurements. Hence we see that some errors in the experiment could not be avoided. (b) Some factors have not been considered in our theory. For example, we ignore the atom polarization effect induced by the incident electron; we only consider the homogeneous, linearly polarized laser field that does not conform to the experimental conditions completely.

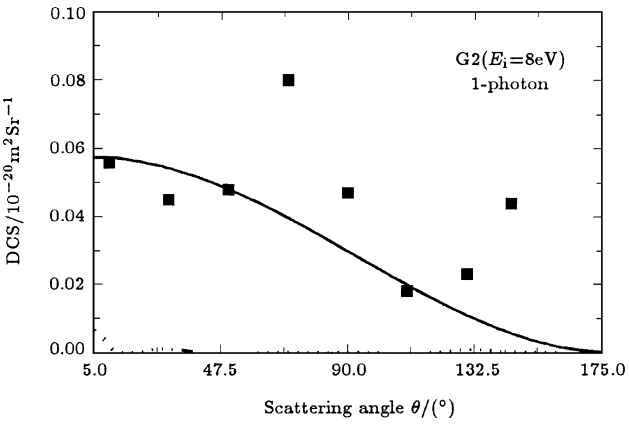


Fig.4. One-photon absorption DCS in G2. The incident electron energy is $E_{\rm i} = 8$ eV. Solid line, SBA result; dotted line, Chen's result; box, experiment.

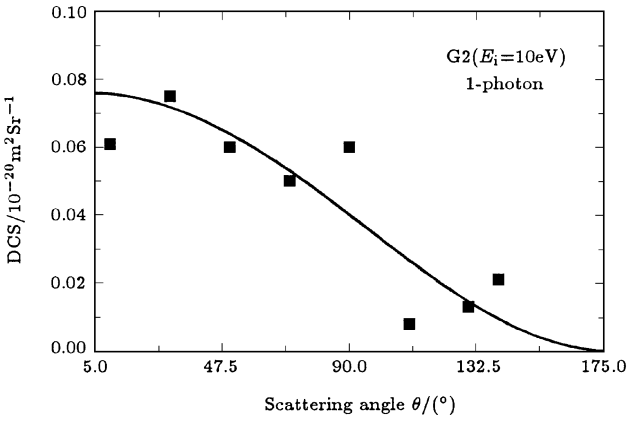


Fig.5. One-photon absorption DCS in G2. The incident electron energy is $E_{\rm i} = 10$ eV. Solid line, SBA result; box, experiment.

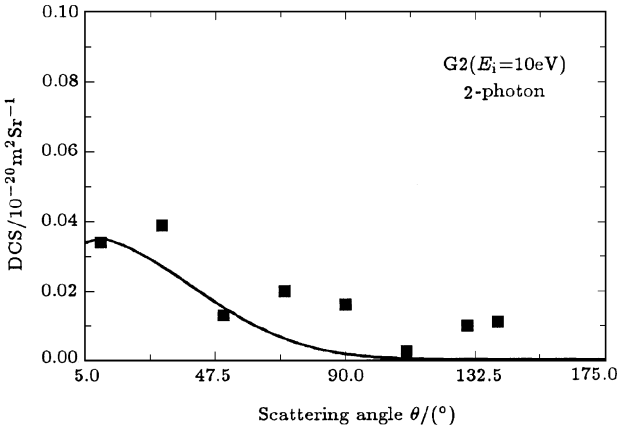


Fig.6. Same as Fig.5, but for two-photon absorption.

In general, our results are proved to be better than other theoretical results as compared with the experimental data.

ACKNOWLEDGMENT

We are pleased to acknowledge discussions with Professor Z. X. Liu.

REFERENCES

[1] M. H. Mittleman, 1993 Introduction to the Theory of Laser-Atom Interactions (Plenum, New York).

[2] B. Wallbank, J. K. Holmes, *Phys. Rev.*, **A48**(1993), R2551.

[3] B. Wallbank, J. K. Holmes, *J. Phys.*, **B27**(1994), 5045.

[4] B. Wallbank, J. K. Holmes, *J. Phys.*, **B27**(1994), 1221.

[5] N. M. Kroll, K. M. Watson, *Phys. Rev.*, **A8**(1973), 804.

[6] H. Krüger, Ch. Jung, *Phys. Rev.*, **A17**(1978) , 1706.

[7] L. Rosenberg, *Phys. Rev.*, **A23**(1981), 2283.

[8] S. Varró, F. Ehlotzy, *Phys. Lett.*, **A203**(1995), 203.

[9] S. Geltman, *Phys. Rev.*, **A51**(1995), R34.

[10] L. B. Madsen, K. Taulbjerg, *J. Phys.*, **B28**(1995), 5327.

[11] C. T. Chen, F. Robicheaux, *J. Phys.*, **B29**(1996), 345.

[12] A. Cionga, L. Dimou, F. M. Faisal, *J. Phys.*, **B30**(1997), L361.

[13] N. J. Kylstra, C. J. Joachain, *Phys. Rev.*, **A58**(1998), R26.

[14] J. F. Sun, S. H. Zhang *et al., Phys. Rev.*, **A58**(1998), 2225.

[15] J. F. Sun *et al., Acta Physica Sinica*, **48**(1999), 1628(in Chinese).

[16] D. M. Volkov, *Z. Phys.*, **94**(1935), 250.

[17] F. Salvat, J. D. Martine, R. Mayol, J. Parellada, *Phys. Rev.*, **A36**(1987), 467.

[18] F. V. Bunkin, M. V. Fedorov, *Zh. Eksp. Teor., Fiz.*, **49**(1965), 1215.

[19] X. Z. Zhang, J. F. Sun, Y. F. Liu, *J. Phys.*, **B25**(1992), 1893.