Static electric-field effects in the photodetachment of Cs^- at the ^3P resonance region

A. A. Khuskivadze and I. I. Fabrikant
Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska 68588-0111, USA

U. Thumm
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2604, USA
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We calculated near-threshold photodetachment cross sections for Cs^- in the presence of a dc electric field using three different approaches: the frame-transformation method with and without rescattering effects and the Kirchhoff-integral approach. Radial wave functions for the electronic motion were obtained using the Pauli equation method with a model potential describing the effective electron-atom interaction. Our results demonstrate the inadequacy of the frame-transformation method in the ^3P resonance region even for weak fields ($E<10$ kV/cm). We show that the triplet and singlet contributions to the total cross section can be manipulated by varying the external electric field. This can enhance spin-orbit effects in the photodetachment process and create more favorable conditions in the experiment for the observation of the lowest ^3P resonance in Cs^-.

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I. INTRODUCTION

A strong external static electric field affects the decay of negative ions and influences substantially the photodetachment (PD) dynamics. So far, most of the theoretical work performed in this field employed zero-range or short-range model potentials for the description of the interaction of the detached electron with the atomic residue. The zero-range potential model allows the exact analytical treatment of both negative-ion decay in a static field [1] and PD in a static field (see Ref. [2] and references therein). For short-range interactions, the frame-transformation theory [3,4] can be applied which assumes that the whole space can be separated into three regions: in the inner region the electron-atom interaction is dominant, in the outer region it can be neglected compared to the interaction of the electron with the external field, and in the intermediate region both are small compared to the electron binding energy. This approach was applied to the decay [4,5] and PD of negative ions [6–9]. However, the long-range polarization interaction between the detached electron and atomic residue might become important if the binding energy is small or the static field is strong. A typical example is the decay of alkali negative ions since alkali-metal atoms possess very large polarizabilities. If the final-state interaction is strong enough, it can cause the rescattering effect [7,9] whereby the electron wave reflected by the static-electric-field potential is scattered by the atomic residue. Although this effect has not been observed in PD of atomic anions [10], it was recently shown [11] that it can be substantial in PD of molecular anions due to the strong dipolar electron-molecule interaction. Similarly, the large polarizability of alkali-metal anions can enhance rescattering.

The spatial spreading of the electron wave function due to the reflection from the potential barrier formed by the static field can be estimated as [7] (atomic units are used throughout the paper) $2E/F$, where $E=k^2/2$ is the electron energy in the final state and F is the electric field. For a substantial rescattering effect this length should be of the order of (or smaller than) the effective range of the electron-atom interaction. In the case of scattering by the polarization potential this range is characterized by the Weisskopf radius [12]

$$r_W=\left(\frac{\pi\alpha}{4k}\right)^{1/3}, \tag{1}$$

where α is the atomic polarizability. From here we obtain the condition $k^2\leqslant(\pi\alpha F^3/4)^{2/7}$. For Cs $\alpha=402.2$ and, for example in the case $F=100$ kV/cm, we have $E<7$ meV. This energy corresponds to the effective (Weisskopf) radius of electron-atom interaction of about 20 a.u. However, the resonance scattering in the low-energy region can make the effective radius even larger, and the rescattering effect even more important than in the case of a pure potential scattering by a strong potential. The heavy alkali-metal atoms are particularly remarkable in this regard since the low-energy electron scattering in this case is strongly affected by a ^3P resonance. The cross section for e-Cs scattering reaches almost 10^{-12} cm^2 which corresponds to the effective radius 55 a.u. Therefore we expect the rescattering effects to be even more important in this region.

Incorporation of a realistic electron-atom interaction (including the polarization part) in the negative-ion decay problem is a complicated task because the polarization potential and the static field potential have different symmetries, spherical and cylindrical. It was shown in Refs. [13–15] that the electron wave functions in two different spatial regions where different symmetries prevail can be matched by using the Kirchhoff integral involving the Green's function for an electron in a long-range field. For example, in the problem of molecular Rydberg states [14,15] we employ the Coulomb Green's function whereas in the problem of negative-ion decay [13] the Green's function of Slonim and Dalidchik [16] is used.

In the present work we use accurately adjusted pseudopotentials [14,17] to describe the interaction of slow electrons with kinetic energies below 1 eV with Cs atoms and apply these potentials to the calculation of PD in the presence of a static external electric field. Heavy alkali-metal atoms are

interesting due to their relatively strong spin-orbit interaction which strongly affects electron scattering at low energies [18]. In particular, the fine-structure splitting of the low-lying $^3P^o$ negative-ion resonances is well pronounced in Cs^- [18]. The $^3P_1$ component of the $Cs^-(^3P)$ resonance was recently detected in PD measurements [19]. Its measured position and shape agree well with our recently calculated absolute PD cross section [20]. The theory developed in Secs. II–IV of this paper is followed by a numerical study of the influence of the static external electric field on the characteristics of the $Cs^-(^3P_1)$ resonance term (Sec. V). Our conclusions follow in Sec. VI. Unless indicated otherwise, we use atomic units throughout this work.

II. FRAME-TRANSFORMATION APPROACH WITH SPIN-ORBIT EFFECTS

Because of the strong signature of the low-energy ^3P resonance in the PD of heavy alkali-metal atoms, we reformulate the frame-transformation theory [8,9] to include the spin-orbit interaction. If we neglect rescattering effects, the PD cross section can be written in the form [9]

$$\sigma=\frac{4\pi^2\omega}{c}\sum_{ll'}\mu^m_{ll'}X^{(\tau)}_{lmSM_S}X^{(\tau)*}_{lmSM_S},$$

where $X^{(\tau)}_{lmSM_S}$ is the matrix element of the dipole operator between the initial bound state ψ_i and the final state $\Phi^{(-)}_{lmSM_S}$,

$$X^{(\tau)}_{lmSM_S}=\langle\Phi^{(-)}_{lmSM_S}|\mathbf{r}\cdot\boldsymbol{\varepsilon}|\psi_i\rangle.$$

Here l, m, S, and M_S are the total orbital momentum, the projection of orbital momentum, the total spin of the Cs^- ion, and its projection along the static electric field that defines our quantization and z axis. $\boldsymbol{\varepsilon}$ is the polarization of the incident photon, τ is the photon angular momentum along the quantization axis, $\mathbf{r}$ is the radius vector of the valence electron. Information about the electric field is contained in the coefficients

$$\mu^m_{ll'}(k,F)=\int_{-\infty}^{k^2/2}s_{lm}(k,q,F)s_{l'm}(k,q,F)d\left(\frac{q^2}{2}\right),$$

where the functions s_{lm} are determined as solutions of the equation

$$\left(\frac{2^{1/3}}{F^{1/6}}\mathrm{Ai}(-\eta)\cos qz-\frac{2^{2/3}F^{1/6}}{q}\mathrm{Ai}'(-\eta)\sin qz\right)\times J_m(\sqrt{k^2-q^2}\rho)\frac{e^{im\phi}}{\sqrt{2\pi}}=\sum_l s_{lm}(k,q,F)j_l(kr)Y_{lm}(\theta,\phi). \quad (2)$$

In this equation, $k^2/2$ is the total energy of the ejected electron, $q^2/2$ the energy of the electron's motion along the electric field, ρ and z are the electron's cylindrical coordinates, F is strength of the static electric field, Ai the regular Airy function, J_m a Bessel function, and Y_{lm} a spherical harmonic.

The functions $\Phi^{(-)}_{lmSM_S}$ have the asymptotic behavior

$$\Phi^{(-)}_{lmSM_S}\overset{r\to\infty}{\to}j_l(kr)Y_{lm}(\hat{r})\chi_{SM_S}+(\text{incoming wave}), \quad (3)$$

where

$$\chi_{SM_S}=\sum_{\mu_1\mu_2}C^{SM_S}_{(1/2)\mu_1(1/2)\mu_2}\left|\frac{1}{2}\mu_1\right\rangle\left|\frac{1}{2}\mu_2\right\rangle.$$

is the spin wave function of the two-electron system for the total spin S and its projection M_S, and $C^{jm}_{lml'm'}$ is a Clebsch-Gordon Coefficient.

This allows us to write the close-coupling expansion in the form

$$\Phi^{(-)}_{lmSM_S}=\sum_{LM_LJM_J}A^{JM_J}_{LM_LSM_Slm}\sum_{S'}|LS'JM_J\rangle R^J_{LS'S}(r), \quad (4)$$

with

$$|LSJM_J\rangle=\sum_{M_L}C^{JM_J}_{LM_LSM_S}Y_{LM_L}(\hat{r})\chi_{SM_S}.$$

Thus, the wave function $\Phi^{(-)}_{lmSM_S}$ includes spin and angle coordinates of both electrons, but only the radial coordinate of the detached electron. We do not mix different L components in the expansion (4) since at low energies only $L=1$ is involved. The asymptotic form of the incident-wave part of $R_{LSS'}$ is $\delta_{SS'}\sin(kr-L\pi/2)/r$. This allows us to write the asymptotic expression for $\Phi^{(-)}_{lmSM_S}$ as

$$\Phi^{(-)}_{lmSM_S}=\sum_{LM_LJM_J}A^{JM_J}_{LM_LSM_Slm}|LSJM_J\rangle\frac{1}{r}\sin(kr-L\pi/2)+(\text{incoming wave}). \quad (5)$$

Extracting the J dependence as

$$A^{JM_J}_{LM_LSM_Slm}=C^{JM_J}_{LM_LSM_S}B_{LM_Llm}, \quad (6)$$

we obtain the asymptotic expression

$$\Phi^{(-)}_{lmSM_S}=\sum_{LM_L}B_{LM_Llm}Y_{LM_L}(\hat{r})\chi_{SM_S}\frac{1}{r}\sin(kr-L\pi/2)+(\text{incoming wave}). \quad (7)$$

Comparing this expression with Eq. (3), we obtain

$$B_{LM_Llm}=\frac{1}{k}\delta_{Ll}\delta_{M_Lm}.$$

For the dipole matrix elements we obtain

$$X^{(\tau)}_{lmSM_S}=\frac{1}{k}C^{l\tau}_{lmSM_S}\langle Y_{l\tau}R^l_{l0S}|\mathbf{D}\cdot\boldsymbol{\varepsilon}|\psi_i\rangle,$$

where **D** is the dipole moment operator.

We will now consider two important cases: the case of linear polarization parallel to the static field and the case of perpendicular (linear or circular) polarization. The first case corresponds to $\tau=M_J=0$ and the second to $|\tau|=|M_J|=1$. Assuming that the initial state ψ_i is spherically symmetric, we obtain for the PD cross section (partial in m, S, and τ)

$$\sigma_{mS\tau}=\frac{4\pi^2\omega}{3ck^2}|\mathcal{M}_S|^2(C^{1\tau}_{1mSM_S})^2\mu^m_{11},$$

where $\mathcal{M}_S=\int_0^\infty R^1_{10S}(r)rR_i(r)r^2\,dr$ is the radial dipole matrix element for the zero static field. In the weak-field limit $F\to 0$, $\mu^m_{11}=2k/\pi$, and we recover the PD cross section for no static field [17]. More explicitly, for linear polarization, the cross sections are

$$\sigma_{00}=\frac{\pi}{2k}\sigma^{(0)}_0\mu^0_{11},\quad \sigma_{10}=\frac{\pi}{2k}\sigma^{(0)}_1\mu^1_{11},$$

where $\sigma^{(0)}_S$ is the cross section for $F=0$ and $\sigma_{S\tau}=\Sigma_m\sigma_{mS\tau}$. In the case of circular polarization we have

$$\sigma_{01}=\frac{\pi}{2k}\sigma^{(0)}_0\mu^1_{11},\quad \sigma_{11}=\frac{\pi}{4k}\sigma^{(0)}_1(\mu^0_{11}+\mu^1_{11}).$$

III. RESCATTERING EFFECT

For high enough electric fields F, the frame-transformation equations are not valid. In this case correction terms of higher order in F need to be calculated. Their inclusion leads to the following expression for the PD cross section [8,9]:

$$\sigma_{S\tau}=\frac{4\pi^2\omega}{c}\sum_{l,l',m}\mu^m_{l'}Q^{(\tau)}_{lmSM_S}Q^{(\tau)*}_{l'mSM_S},$$

with

$$Q^{(\tau)}_{lmSM_S}=X^{(\tau)}_{lmSM_S}+\frac{\pi iy}{k}\times\sum_{l',m',l'',S',M'_S}i^{l'+l''}\sqrt{(2l'+1)(2l''+1)}\times T_{(l''0S'M'_S)(lmSM_S)}X^{(\tau)}_{l'm'S'M'_S}\qquad(8)$$

and

$$y=\frac{(2F)^{1/3}}{2}[\mathrm{Ai}'(-\eta)\mathrm{Ci}'(-\eta)+\eta\,\mathrm{Ai}(-\eta)\mathrm{Ci}(-\eta)]-\frac{ik}{2\pi},$$

where $\eta=k^2/2F^{2/3}$ and Ci is the Airy function that satisfies outgoing-wave boundary conditions. Equation (8) has a simple physical meaning: The first term describes PD without the external field and the second term describes PD with the formation of an intermediate atomic state $|l'm'S'M_S\rangle$, followed by rescattering to the state $|lmSM_S\rangle$.

The electron-atom interaction potential is parametrized in the $|LSJM_J\rangle$ representation [14,17]. Solving the close-coupling equations in this representation leads to the transition matrix $T_{(LSJM_J)(L'S'J'M_J)}$, which we transform into the $|LM_LSM_S\rangle$ representation according to

$$T_{(l'm'S'M'_S)(lmSM_S)}=\sum_{JM_J}C^{JM_J}_{l'm'S'M'_S}C^{JM_J}_{lmSM_S}T_{(l'S'JM_J)(lSJM_J)}.$$

In a good approximation, in Eq. (8) we can keep only terms with $l=1$. Then, final expression for the cross section takes the form

$$\sigma_{S\tau}=\frac{4\pi^2\omega}{3k^2c}\sum_{mM_S}\mu^m_{11}(C^{1\tau}_{1mSM_S})^2\left|\mathcal{M}_S-y\mathcal{M}_\tau\frac{3\pi i}{k(1+\tau)}\times[T_{(1S1\tau)(1\tau1\tau)}+(-1)^mT_{(1S2\tau)(1\tau2\tau)}S\tau]\right|^2.$$

IV. KIRCHHOFF-INTEGRAL APPROACH

In the Kirchhoff-integral approach [13–15], the whole space is divided in two regions. In the region close to the atom both electric field and short-range interaction of an electron with the Cs atom are taken into account, and the Schrödinger equation is solved numerically. This solution is matched to the solution in the outer region where only electric-field effects are important. The Schrödinger equation for the valence electron is

$$\left(-\frac{1}{2}\boldsymbol{\nabla}^2-\mathbf{F}\cdot\mathbf{r}+\hat{V}(\mathbf{r})-E\right)\psi(\mathbf{r})=0\qquad(9)$$

with

$$\hat{V}(\mathbf{r})=\sum_\alpha\left(V_{LS}(r)+\frac{1}{2c^2r}\frac{dV_{LS}}{dr}(\mathbf{l}\cdot\mathbf{s})\right)|\alpha\rangle\langle\alpha|$$

and $|\alpha\rangle=|LSJM_J\rangle$. V_{LS} is a short-range potential representing the electron-Cs interaction. The corresponding Lippman-Schwinger equation has the form

$$\psi^{(-)}_{mSM_S}(\mathbf{r})=\psi^{(0)}_{mSM_S}(\mathbf{r})-\int G^{(-)}(\mathbf{r},\mathbf{r}')\hat{V}(\mathbf{r}')\times\psi^{(-)}_{mSM_S}(\mathbf{r}')d\mathbf{r}',\qquad(10)$$

where $\psi^{(0)}_{mSM_S}$ is the solution of the Schrödinger equation in the electric field F,

$$\psi^{(0)}_{mSM_S}(r)=\frac{2^{1/3}e^{im\varphi}}{\sqrt{2\pi}F^{1/6}}\mathrm{Ai}(\xi)J_m(\sqrt{k^2-q^2}\rho)|SM_S\rangle,$$

$$\xi = -(2F)^{1/3}\left(z + \frac{q^2}{2F}\right),$$

and $G^{(-)}(\mathbf{r},\mathbf{r}')$ is the Green's function in the electric field,

$$\left(-\frac{1}{2}\boldsymbol{\nabla}^2 - \mathbf{F}\cdot\mathbf{r} - E\right) G^{(-)}(\mathbf{r},\mathbf{r}') = \delta(\mathbf{r}-\mathbf{r}'), \qquad (11)$$

satisfying incoming-wave boundary conditions. Using Eqs. (9)–(11) and the Kirchhoff-integral transformation, we obtain the matching condition at $r = r_0$ in the limit $r' \to r + 0$,

$$\psi^{(0)}_{mSM_S}(\mathbf{r}') + \frac{r_0^2}{2}\oint_S \left(G^{(-)}(\mathbf{r},\mathbf{r}')\frac{d}{dr}\psi^{(-)}_{mSM_S}(\mathbf{r}) - \psi^{(-)}_{mSM_S}(\mathbf{r})\frac{d}{dr}G^{(-)}(\mathbf{r},\mathbf{r}')\right) d\Omega = \psi^{(-)}_{mSM_S}(\mathbf{r}').$$

Representing the wave function in the close-coupling expansion $\Sigma_\alpha A_\alpha^{mSM_S}(q)\Sigma_{\alpha'}R_{\alpha\alpha'}(r)|\alpha'\rangle$ and projecting onto states $\langle\alpha''|$, we get an inhomogeneous algebraic system for the coefficients $A_\alpha^{mSM_S}(q)$ (α stands for $LSJM_J$),

$$Q^{mSM_S}_{\alpha''}(q) - \sum_\alpha A^{mSM_S}_\alpha(q) M_{\alpha\alpha''} = 0, \qquad (12)$$

where

$$M_{\alpha\alpha''} = \frac{r_0^2}{2}\sum_{\alpha'} \delta_{S''S'} \sum_{M''_L M''_S} C^{J''M''_J}_{L''M''_L S''M''_S} C^{J'M'_J}_{L'M''_L S'M''_S} \times \left(\langle L''M''_L|G|L'M''_L\rangle \frac{dR_{\alpha\alpha'}}{dr} - R_{\alpha\alpha'}\left\langle L''M''_L\left|\frac{dG}{dr}\right|L'M''_L\right\rangle\right) + R_{\alpha\alpha''} \qquad (13)$$

and

$$Q^{mSM_S}_\alpha(q) = \langle\alpha|\psi^{(0)}_{mSM_S}\rangle.$$

Radial wave functions $R_{\alpha\alpha'}(r)$ are evaluated at $r = r_0$. Finally, the cross section for PD in an external electric field F follows as

$$\sigma_{S\tau} = \frac{4\pi^2\omega}{c}\sum_{mM_S}\int_{-\infty}^{k^2/2} |z^{(mSM_S\tau)}_{fi}(q)|^2 d\left(\frac{q^2}{2}\right)$$

with

$$z^{(mSM_S\tau)}_{fi}(q) = \int \psi^{(-)*}_{mSM_S}(\mathbf{r})(\mathbf{r}\cdot\boldsymbol{\varepsilon})\psi_i(\mathbf{r})d\mathbf{r} = \sum_\alpha A^{mSM_S*}_\alpha(q)\sum_{\alpha'}\langle\alpha'|\mathbf{n}\cdot\boldsymbol{\varepsilon}|\alpha\rangle \times \int_0^\infty R_{\alpha\alpha'}R_i r^3 dr,$$

where $\mathbf{n} = \mathbf{r}/r$.

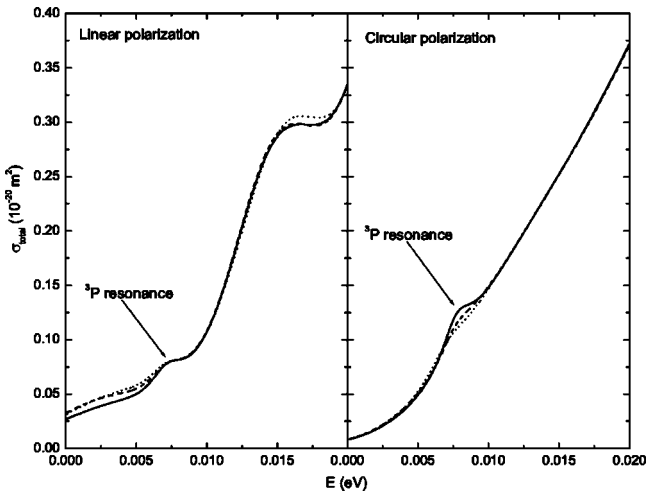

FIG. 1. Total cross section for photodetachment of Cs anions in a static external electric field $F = 20$ kV/cm as a function of the detached electron's energy. Full lines denote exact calculations within the Kirchhoff-integral approach, dotted lines correspond to frame-transformation calculations, and dashed lines stand for the calculation which takes the rescattering effect into account.

V. RESULTS AND DISCUSSION

We performed numerical calculations of the PD cross section for Cs anions in the presence of an external electric field. Figure 1 presents results for the total cross section as a function of the energy of the detached electron. The electric field is taken to be $F = 20$ kV/cm. Full lines denote exact calculations with the Kirchhoff-integral approach, dotted lines correspond to frame-transformations calculations, and dashed lines stand for the calculation which takes the rescattering effect into account. These results were obtained for different photon polarizations. As expected, for linear polarization there are oscillations caused by the presence of the external electric field.

All models agree quite well, except in the region close to the ^3P resonance, which is caused by differences in the results for the triplet component of the cross section. The triplet contribution to the cross section, corresponding to the final total spin $S = 1$, is shown in Fig. 2. For the electric-field strengths above 30 kV/cm, the difference between the exact (the Kirchhoff-integral approach) and the approximate frame-transformation technique including rescattering effects becomes significant (Fig. 3). This difference is particularly important in the ^3P resonance region (Fig. 1) for the triplet component of the cross section (Figs. 2 and 4). From Fig. 4 we conclude that the frame-transformation model does not work for even very small electric fields. Inclusion of the rescattering effect significantly improves the result, but does not lead to the complete agreement with the exact calculation. This is related to the fact that, in the resonance region, the detached electron rescatters from the Cs atom many times. In this case, Eq. (8), which takes into account only single rescattering, is not quite valid, and higher-order terms in the external field have to be taken into account.

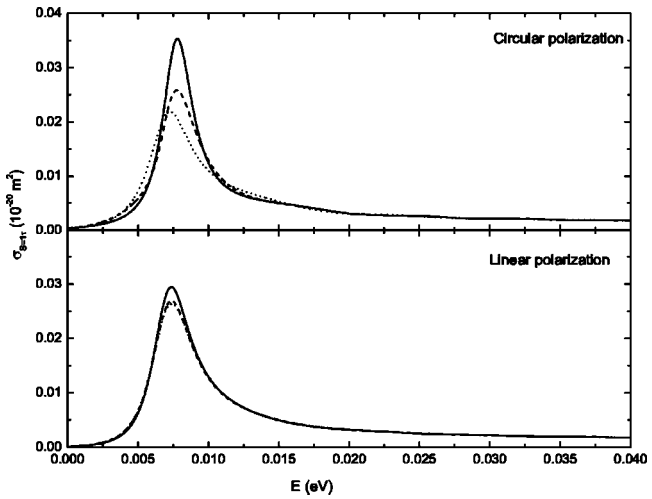

FIG. 2. Triplet component of the cross section for photodetachment of Cs anions in an external electric field $F=20$ kV/cm as a function of the detached electron's energy. Line types as in Fig. 1.

For comparison, singlet and triplet components of the PD cross section as functions of the external field strength at an energy of the detached electron of $E=8$ meV are presented in Fig. 3 and Fig. 4, respectively. Figure 4 shows partial in m PD cross section. For detachment into the singlet state, the projection of the orbital angular momentum m of the detached electron is the same as the projection of the incident photon momentum τ. This means that for circular polarization the electron is detached perpendicularly to the field direction, so that there is no interference between different electronic paths which could produce oscillations in the cross section. In the case of detachment into the triplet state, circularly polarized photons produce electrons with $m=0,\pm1$ and linearly polarized photons create electrons with $m=\pm1$. We therefore expect oscillations in the PD cross section for circularly but not for linearly polarized light. Inclusion of the rescattering effect leads to oscillations also in the case of

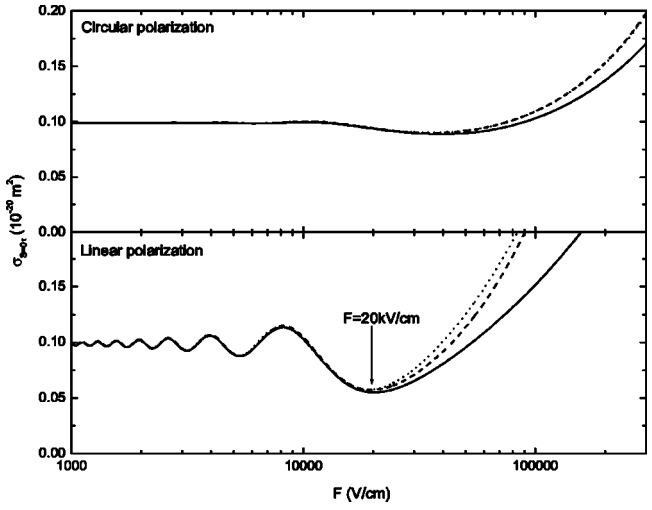

FIG. 3. Singlet component of the cross section for photodetachment of Cs anions at an energy of the detached electron of $E=8$ meV as a function of external field F. Line types as in Fig. 1.

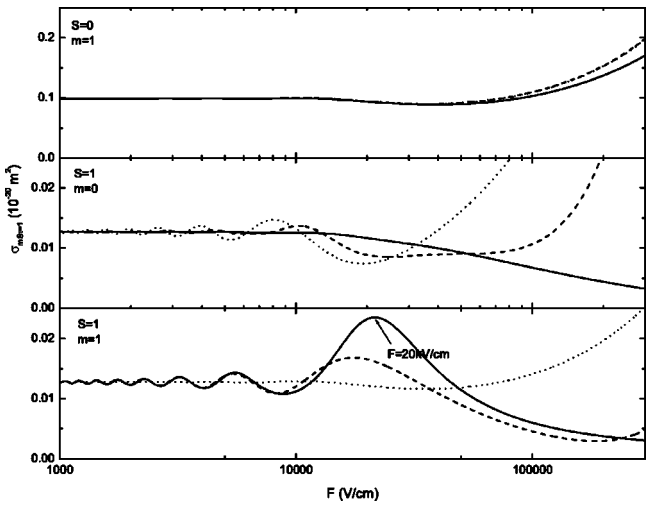

FIG. 4. Singlet and triplet components of the cross section for the photodetachment of Cs anions at an energy of the detached electron of $E=8$ meV as a function of the external field strength F for different projections m of the electron angular momentum for the case of circular polarization. Line types as in Fig. 1.

detachment into the triplet state with linearly polarized photons. This is a manifestation of the fact that electrons can be detached into the singlet state with subsequent rescattering into the triplet state.

The differences in the behavior of the cross section, calculated by different methods, can be understood quantitatively. In the case of circular polarization, Eq. (12) can be solved approximately. The main contribution to the expression for the cross section is due to the states $|LSJM_J\rangle = |1011\rangle$ and $|1111\rangle$. We define corresponding states by $\alpha=0$ and $\alpha=1$. We use the approximate expression for the Green's function [7,8]

$$G^{(+)}(\mathbf{r},\mathbf{r}')=G_0^{(+)}(\mathbf{r},\mathbf{r}')+y(F)e^{ik(z+z')}, \tag{14}$$

where $G_0^{(+)}(\mathbf{r},\mathbf{r}')$ is the Green's function of a free electron. Neglecting the electric-field dependence in $R_{\alpha\alpha'}$ we obtain

$$A_\alpha^{mSM_S}\approx B_\alpha^{mSM_S}s_{1m}(q,F)\frac{1+b_\alpha\delta_{S0}y^*(F)}{1+ay^*(F)}, \tag{15}$$

where the coefficients $B_\alpha^{mSM_S}$, b_α, and a are given in the Appendix.

Thus, the dependence of the cross section on electric field originates in the frame-transformation function $s_{1m}(q,F)$ and function $y(F)$. For small fields, when $|ay(F)|\ll1$, the dependence on the electric field in Eq. (15) is completely determined by $s_{1m}(q,F)$, which corresponds to the frame-transformation model. In the next approximation, we can expand Eq. (15) in a Taylor series in $ay(F)$. The first term in this expansion corresponds to the rescattering model. The function $y(F)$ is monotonically increasing for large F. The integral over q of the square of the frame-transformation function is also monotonically increasing for large electric fields. This together with Eq. (15) explains the behavior of the cross section at large electric field (Fig. 4).

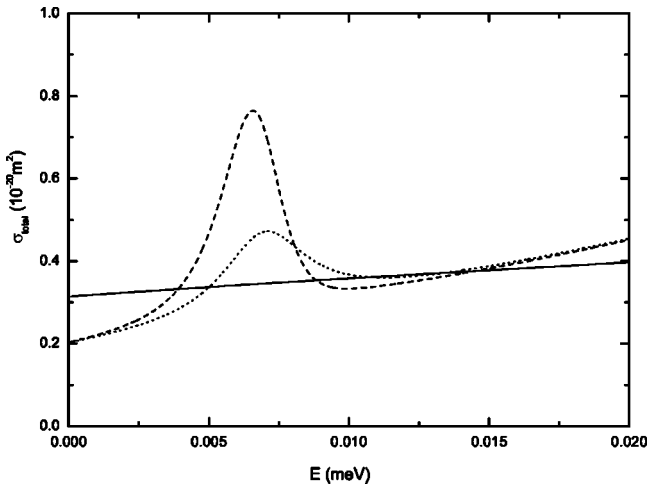

FIG. 5. Total cross section for photodetachment of Cs anions in a static external electric field $F=500$ kV/cm as a function of the detached electron's energy. Line types as in Fig. 1.

The Kirchhoff-integral approach is valid over a large energy range and for external fields up to $F=1$ MV/cm. For field strength above 1 MV/cm, distortions of the initial state due to the static field need to be taken into consideration [2].

The drastic difference between frame-transformation model and our exact calculation is demonstrated in Fig. 5 for $F=500$ kV/cm. According to the frame-transformation model, the increase of the electric-field strength leads to the enhancement of the resonance contribution in the total cross section, while the exact calculation gives the opposite result.

Figure 6 shows the ratio of the triplet component of the cross section to the singlet component. We can adjust the electric field in order to change the contribution of the ^3P resonance state to the total cross section. Interestingly, this ratio reaches a maximum at $F=20$ kV/cm, where it is two times larger than the corresponding ratio without the electric field.

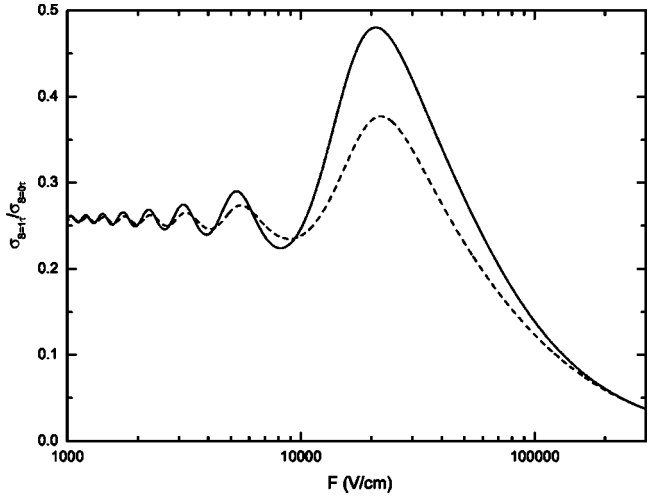

FIG. 6. The ratio of the triplet component of the cross section to the singlet component at $E=8$ meV as a function of electric field. Full line corresponds to the linear polarization and dashed line corresponds to the case of circular polarization.

VI. CONCLUSIONS

The near-threshold PD cross sections for Cs^- in the presence of a dc electric field F show an interesting oscillatory behavior as functions of F. The amplitude of these oscillations is noticeably different for the singlet and triplet contributions to the PD cross section. Near the ^3P resonance in Cs^-, the dependence of the PD cross section on F is particularly sensitive to the quality of the theoretical approach and is significantly different for the approximative frame-transformation results as compared with our exact Kirchhoff-integral calculations. In general, except near resonances, we find our frame-transformation results sufficiently accurate. Rescattering contributions to the PD cross section are found to be significant near the ^3P resonance in Cs^- and for electric fields $F>500$ V/cm.

The manipulation of the triplet and singlet contributions to the total PD cross section with a variable static external electric field tends to magnify spin-orbit effects in the PD process and may enable a more convenient and accurate observation of the lowest ^3P resonance in Cs^-.

ACKNOWLEDGMENTS

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APPENDIX

The matrix elements (13) can be evaluated explicitly if we use an approximate expression for the Green's function (14) and the following expansions:

$$G_0^{(+)}(\mathbf{r},\mathbf{r}')=\frac{e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}}{2\pi|\mathbf{r}-\mathbf{r}'|}$$
$$=2ik\sum_{l=0}^{\infty}\sum_{m=-l}^{l} j_l(kr_<)h_l^{(1)}(kr_>)$$
$$\times Y_{lm}(\hat{\mathbf{r}})Y_{lm}^*(\hat{\mathbf{r}}'),$$

$$e^{i\mathbf{k}\cdot(\mathbf{r}+\mathbf{r}')}=4\pi\sum_{ll'} i^{l+l'}j_l(kr)j_{l'}(kr')$$
$$\times\sqrt{(2l+1)(2l'+1)}Y_{l0}(\hat{\mathbf{r}})Y_{l'0}^*(\hat{\mathbf{r}}'),$$

where we choose the direction of the vector $\mathbf{k}$ along z axis. j_1 and $h_1^{(1)}$ are spherical Bessel and Hankel functions, respectively. After integration over the angles we obtain the following from Eq. (13):

$$M_{\alpha\alpha'}=K_{\alpha\alpha'}+y^*(F)N\delta_{\alpha 1}\delta_{\alpha' 1},$$

where

$$K_{\alpha\alpha'}=ikr_0^2h_1^{(2)}(R_{\alpha\alpha'}kj_1'-j_1R_{\alpha\alpha'}')+R_{\alpha\alpha'},$$

and

$$N=3\pi r_0^2 j_1(R_{\alpha\alpha'}kj_1'-j_1R_{\alpha\alpha'}').$$

The coefficients $Q_\alpha^{mSN_S}(q)$ can be calculated explicitly:

$$Q_\alpha^{mSM_S}(q)=C^{11}_{1mSM_S}\delta_{S1S1m}(q,F)j_1.$$

Thus, we can solve system of equations (12) for two states $|LSJM_J\rangle=|1011\rangle$ and $|1111\rangle$ and obtain the coefficients $A_\alpha^{mSM_S}(q)$ in Eq. (15), with

$$B_\alpha^{mSM_S}=(-1)^{S+\alpha}C^{11}_{1mSM_S}j_1\frac{K_{\alpha0}\delta_{S1}+K_{1\alpha}\delta_{S0}}{K_{11}K_{00}-K_{10}K_{01}},$$

$$b_\alpha=\frac{N}{K_{1\alpha}}\delta_{\alpha0},\quad a=\frac{K_{00}N}{K_{00}K_{11}-K_{10}K_{01}}.$$

Radial wave functions are taken at $r=r_0$, and Bessel and Hankel functions are evaluated at kr_0.

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