Adiabatic pumping in a double quantum dot structure with strong spin-orbit interaction

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We theoretically investigate the adiabatic pumping in a double quantum dot structure in the presence of strong spin-orbit interaction. Pumping single electrons through a Pauli spin-blockade configuration in the presence of a transverse magnetic field allows to probe the spin-dynamics. We discuss how the pumping efficiency could quantitatively provide evidence of the spin-orbit interaction in double dots and renders appealing its presence for qubit operations.

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I. INTRODUCTION

A potentially revolutionary idea in spintronics is the possibility of using the two-level nature of electron spin to create a solid-state quantum computer.[1,2] Several "spin-based" quantum computer schemes have been proposed and extensively studied. A common theme in these proposals is the idea of manipulating the dynamics of a single (or a few) electron spin(s) in semiconductor nanostructures (e.g., quantum dots),[3] with the reasonable hope that the predicted behavior will extend to many-spin systems. The current architectures for spin-based quantum computing employ GaAs quantum dots[4] or Si (or Si-Ge) systems,[5] with different variations. The basic idea is to manipulate the spin states of a single electron using external magnetic fields (or microwaves) for single-qubit operations and to utilize the quantum exchange coupling between two neighboring electrons to carry out two-qubit operations.

Recently, especially appealing for a scalable technology is the possibility to perform the single-qubit operations with electric gate signals mediated by the spin-orbit interaction (SOI).[6] This has stimulated the interest in alternative quantum dots (QDs) systems with strong spin-orbit (SO) interaction, as QDs in InAs nanowires.[7,8] Apart being a complementary tool for single spin rotation,[9] SOI can have substantial influence on two-qubit operations via exchange gates[10,11] or direct spin-spin coupling,[12] thus it represents a powerful mean for fast control and coherent manipulation of coupled spin qubits.

A fascinating idea to analyze the dynamics of two coupled spins in the presence of strong SOI, is the use of QDs systems as spin pumps.[13] The basic principle of spin pumps is closely related to that of charge pumps. In a charge pump a dc current is generated by combining ac driving with either absence of inversion symmetry in the device, or lack of time-reversal symmetry in the ac signal. The range of possible pumps includes turnstiles, adiabatic pumps,[14] or nonadiabatic pumps based on photon-assisted tunneling (PAT).[15] In the case of nonadiabatic pump the periodic variation of gate potentials allows for a net dc current through the device even with no dc voltage applied: if the system is driven at a frequency corresponding to the energy difference between two time-independent eigenstates, the electron becomes completely delocalized and the system can pump electrons from left to right.[16]

Here, we pursue the idea of realizing a pump in a double quantum dot (DQD), in the spin-blockade (SB) regime and in the presence of SOI,[17] with time-dependent (harmonic) linewidths and in the presence of a uniform magnetic field. We focus on the adiabatic regime, where our device has the following characteristics: (i) The pumping can occur either through a singlet or triplet state depending on the spin-orbit interaction or the applied magnetic field; (ii) the pumped current is strongly reduced in the Pauli spin blockade configuration allowing to probe the dynamics of the two-coupled spins.

Our results of the pumped current permit us to probe the spin-dynamics leading to the same conclusions on the spin-dynamics as in the recent experiment of Pfund *et al.*[18]

The organization of the paper is the following: In Sec. II, we present the Hamiltonian and the general formulation to calculate the pumping current within the Green's function framework. In Sec. III, we present the results and give some conclusions.

II. HAMILTONIAN MODEL

We study a double dot structure in which the electron transport is activated by means of charge pumping. To fabricate the double dot structure, the source (left lead) and drain (right lead) regions are connected by using a nanowire (NW) patterned on a suitable substrate. In the middle of the NW the top gates G1, central gate (GC), and G2 are posi-

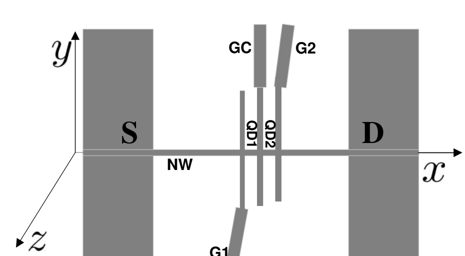

FIG. 1. The device considered in the main text: A double dot system coupled to two external leads.

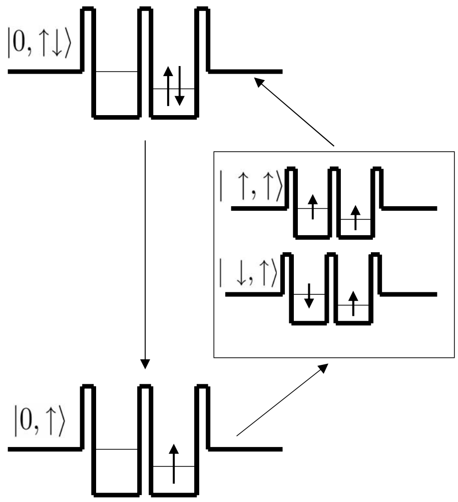

FIG. 2. The states involved in the pumping cycle.

tioned. The application of electrostatic potential to the gates depletes the electrons below the substrate creating two small regions, i.e., the quantum dots QD1 and QD2. The QDs are separated by the GC which controls the degree of hybridization of the QDs wave functions acting on the transparency of the central barrier. To have an additional tool to control the charge transport through the system, a magnetic field in the range of few mT may be applied in the plane xz (see Fig. 1).

The Hamiltonian of the system can be written as: $H = H_{\text{leads}} + H_{\text{2dot}} + H_{\text{tun}}$, where H_{leads}, H_{2dot}, and H_{tun} represent, respectively, the Hamiltonian of the free electrons in the leads considered in thermal equilibrium, the Hamiltonian of the double dot system and the tunneling Hamiltonian between the leads and the dots. The leads Hamiltonian is given by $H_{\text{leads}} = \sum_{k,\sigma,\alpha} \epsilon_{\sigma}^{\alpha}(k) c_{k\sigma\alpha}^{\dagger} c_{k\sigma\alpha}$, where $c_{k\sigma\alpha}^{\dagger}(c_{k\sigma\alpha})$ are the creation (annihilation) operators of the free electrons in the lead $\alpha = R,L$ with momentum k and spin σ. The tunneling Hamiltonian reads: $H_{\text{tun}} = \sum_{k,\sigma,\beta,j} [V_{\alpha,j}^{\sigma}(k,\tau) c_{k\sigma\alpha}^{\dagger} d_{j\sigma} + \text{H.c.}]$, where $d_{j\sigma}$ is the electron annihilation operator on the j-th dot while $V_{\alpha,j}^{\sigma}(k,\tau)$ is a time dependent tunneling amplitude, that for simplicity we assume a real quantity independent from the energy and spin, i.e., $V_{\alpha,j}^{\sigma}(k,\tau) = V_{\alpha}(\tau)$.

The Hamiltonian of the double dot in the presence of SO interaction and a transverse magnetic field is:

TABLE I. Model parameters

Parameters	Values	Dimensionless (unit of 6 μeV)
t	$(3-6)\times 10^{-3}$ meV	0.5–1
t_{so}	(0.2–0.3 meV)	33–50
Γ^0	$(1-3)\times 10^{-2}$ meV	$\frac{5}{3}-5$
$\Delta^{x/z}$	(0.51–0.65) meV/Tesla	$\sim$(85–108)/Tesla
U	(1.5–4) meV	$\sim$250–667
U'	$\leq U/2$	⋆

$$H_{\text{2dot}} = \sum_{j=\{1,2\},\sigma} \epsilon_{\sigma}^{j} d_{j\sigma}^{\dagger} d_{j\sigma} + U \sum_{j} n_{\uparrow}^{(j)} n_{\downarrow}^{(j)} + U' \sum_{\sigma,\sigma'} n_{\sigma}^{(1)} n_{\sigma'}^{(2)} + t \sum_{\sigma} (d_{1\sigma}^{\dagger} d_{2\sigma} + \text{H.c.}) + \sum_{j} \Delta^{x} (d_{j\uparrow}^{\dagger} d_{j\downarrow} + \text{H.c.}) - t_{so} (d_{1\uparrow}^{\dagger} d_{2\downarrow} - d_{1\downarrow}^{\dagger} d_{2\uparrow} + \text{H.c.}), \quad (1)$$

where $\epsilon_{\sigma}^{j} = \epsilon^{j} + \sigma \Delta^{z}$, $\Delta^{\lambda} = g^{*} \mu_B B_{\lambda} (\lambda = x,z)$ is the Zeeman energy induced by the magnetic field $\mathbf{B} = (B_x, 0, B_z)$, while t is the tunneling amplitude between the dots and $t_{so} = \alpha/(2d)$ is the spin-orbit interaction where α is the Rashba spin-orbit coupling constant (e.g., see Ref. 19) and d the distance between the QDs. The Coulomb repulsion on the same QD and on different dots, is represented by the terms U and U', respectively.

For the Hamiltonian above, we consider the Hilbert space made by the tensor products $|QD1,QD2\rangle = |QD1\rangle \otimes |QD2\rangle$ obtained using the complete set of eigenstates of the isolated QD1 and QD2, which correspond to an empty, single occupied with spin $\sigma = \uparrow, \downarrow$, and doubly occupied states. When considering a Pauli spin-blockade configuration as in Ref. 18, the dynamics of two-coupled spins can be probed by taking into account the four states: $|1\rangle \equiv |0,\uparrow\rangle$, $|2\rangle \equiv |\uparrow,\uparrow\rangle$, $|3\rangle \equiv |\downarrow,\uparrow\rangle$, $|4\rangle \equiv |0,\uparrow\downarrow\rangle$. The empty state $|0,0\rangle$ can be excluded by trapping permanently a spin up electron on the second QD. In this way the matrix elements $[H_{\text{2dot}}]_{ij} = \langle i|H_{\text{2dot}}|j\rangle$ of the isolated double dot system Hamiltonian can be written as follows:

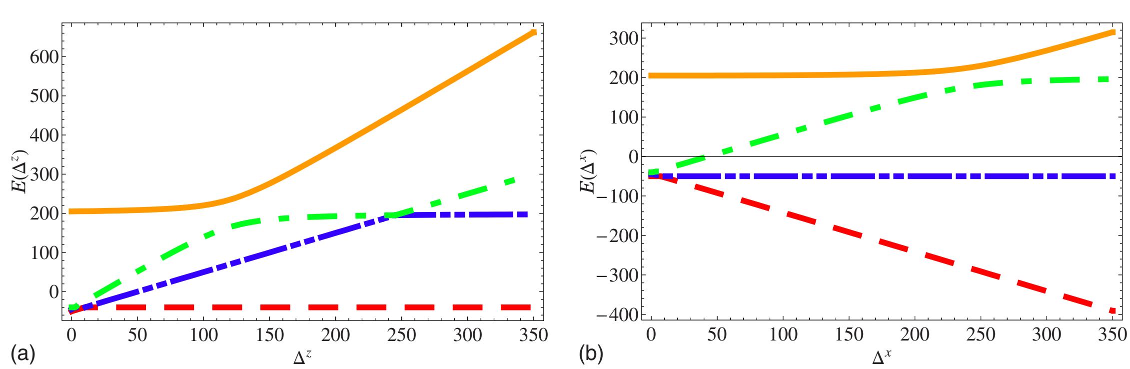

FIG. 3. (Color online) Eigenvalues of H_{2dot} plotted as a function of the Zeeman energy Δ^z (a) and Δ^x (b) by setting the remaining parameters as follows: $\epsilon^1 = 0$, $\epsilon^2 = -50$, $U = 250$, $U' = 10$, $t = 1$, $t_{so} = 35$, $\Delta^x = 0$ (a), and $\Delta^z = 0$ (b).

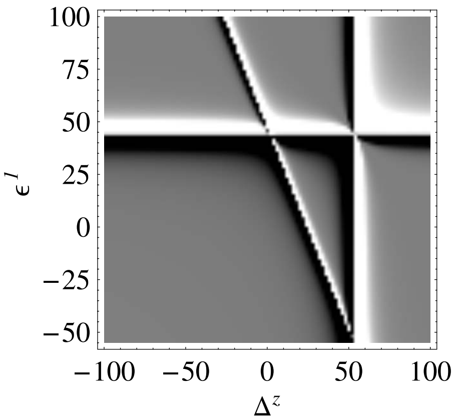

FIG. 4. Density plot of the pumped current I (in unit of $q\nu/(2\pi)$, being $\nu=\omega/(2\pi)$) as a function of the dot level ϵ^1 and the Zeeman energy Δ^z. The black (white) regions represent negative (positive) values of the current. The model parameters have been fixed as follows: $\epsilon^2=-55$, $U=250$, $U'=10$, $t=1$, $t_{so}=35$, $\Delta^x=0$, $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=4.9999$, and $\phi=\pi/2$.

$$H_{2\text{dot}}=\begin{pmatrix}\epsilon_\uparrow^2 & 0 & 0 & 0\\ 0 & \epsilon_\uparrow^1+\epsilon_\uparrow^2+U' & \Delta^x & t_{so}\\ 0 & \Delta^x & \epsilon_\downarrow^1+\epsilon_\uparrow^2+U' & -t\\ 0 & t_{so} & -t & \epsilon_\uparrow^2+\epsilon_\downarrow^2+U\end{pmatrix}. \tag{2}$$

For the system above we are interested in the generation of a net charge transfer through the two dots by using a charge pumping scheme in which the pumping cycle is determined by the two out-of-phase time-dependent tunneling amplitudes and involves the states drawn in Fig. 2. In order to calculate the pumped charge, we consider the following expression for the pumped current in the lead α valid in the adiabatic regime:[20,21]

$$I^\alpha=\frac{\omega}{2\pi}\int dE\int_0^{2\pi/\omega} d\tau I^\alpha(E,\tau)[-\partial_E f(E)]$$

$$I^\alpha(E,\tau)=\frac{q}{2\pi}[\text{Im}\{-i\,\text{Tr}[\dot{\mathbf{\Gamma}}^\alpha\mathbf{G}^r(E,\tau)]\}+\text{Im}\{\text{Tr}[\dot{\mathbf{\Gamma}}^\alpha\mathbf{G}^r(E,\tau)]\text{Tr}[\mathbf{\Gamma}^\alpha\mathbf{G}^a(E,\tau)]\}], \tag{3}$$

where ω is the pumping frequency, and $f(E)$ stands for the Fermi function. The time dependent current $I^\alpha(E,\tau)$ depends on the advanced (retarded) Green's function of the double-dot structure $G^{a(r)}$ in the time-average approximation,[20] and on the time-dependent linewidths $\Gamma^\alpha(\tau)$, which we assume to vary cyclically in time with frequency ω:

$$\Gamma^\alpha(\tau)=\Gamma_0^\alpha+\Gamma_\omega^\alpha\sin(\omega\tau+\phi_\alpha), \tag{4}$$

where ϕ_α is some phase. Explicitly, $\Gamma^\alpha(\tau)=2\pi\rho V_\alpha(\tau)V_\alpha^*(\tau)$, where ρ is the density of states of the leads at the Fermi level. The boldface notation in Eq. (3) stands for a matrix representation. Since in the pumping scheme, the two time-dependent parameters must be out of phase, the lead phase ϕ_α is chosen as $\phi_L=0$ and $\phi_R=\phi$. For the explicit calculation, we determine the retarded Green's function of the double-dot structure $\mathbf{G}^r$ by means of the Dyson's equation: $\mathbf{G}^r(E,\tau)=[\mathbf{1}-\mathbf{G}_0^r(E)\mathbf{\Sigma}^r(E,\tau)]^{-1}\mathbf{G}_0^r(E)$, where $\mathbf{G}_0^r(E)=[\mathbf{1}(E+i\eta)-\mathbf{H}_{2\text{dot}}]^{-1}$ is the Green's function of the double-dot uncoupled to the leads, whose poles are obtained by the exact diagonalization of Eq. (2), while $\mathbf{\Sigma}^r(E,\tau)$ is the tunneling self-energy obtained in the wide band limit (WBL) and whose expression is $\mathbf{\Sigma}^r(E,\tau)\simeq-\frac{i}{2}\sum_{\alpha=L,R}\Gamma^\alpha(\tau)\mathbf{A}$; $\mathbf{A}$ is a 4×4 matrix whose elements are $A_{24}=A_{42}=0$ for a spin-blockade configuration and $A_{ij}=1$ otherwise, for $i,j=1,\ldots,4$.

III. RESULTS

We consider a double dot in the weakly coupled regime (i.e., small t) arranged in serial configuration as in Fig. 1, obtained by creating three top gates on an InAs nanowire and operating at 100 mK.[8,18] In this material the spin-orbit interaction has been shown to play an important role.[7,8] To be specific in Table I we list the range of the relevant parameters included in our model [Eq. (1)] and deduced by Refs. 8, 18, 22, and 23.

Let us note that the spin-blockade regime is characterized by U larger than $2U'$ as shown in the experiment[22] and from energy arguments.

Considering the DQD in an initial (0,1) state, a second electron can be loaded into either a singlet $S(1,1)$ or a triplet $T_\sigma(1,1)$ ($\sigma=0,\pm$ denotes the S_z spin component, while the notation (n,m) indicates the number of electrons on the left and right dot). The ground state of the (0,2) configuration at zero magnetic field is a singlet $S(0,2)$. Sequential transport is therefore blocked due to spin conservation, once the second

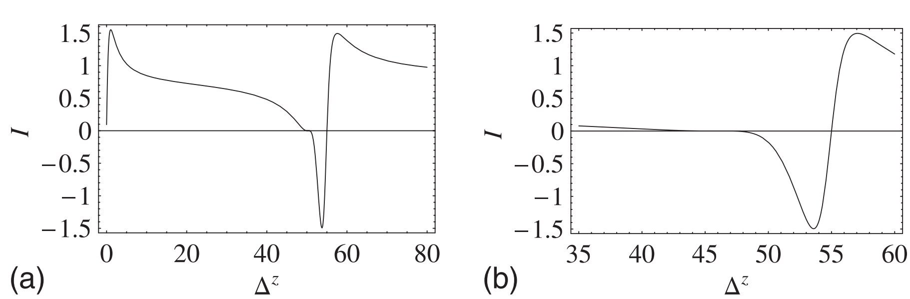

FIG. 5. Plot of the pumped current I (in unit of $q\nu/(2\pi)$, being $\nu=\omega/(2\pi)$) as a function of the Zeeman energy Δ^z. In (a) the model parameters have been fixed as follows: $\epsilon^1=50$, $\epsilon^2=-55$, $U=250$, $U'=10$, $t=1$, $t_{so}=35$, $\Delta^x=0$, $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=4.9999$, and $\phi=\pi/2$; for (b) we set $\epsilon^1=55$, while the remaining parameters are the same as in (a).

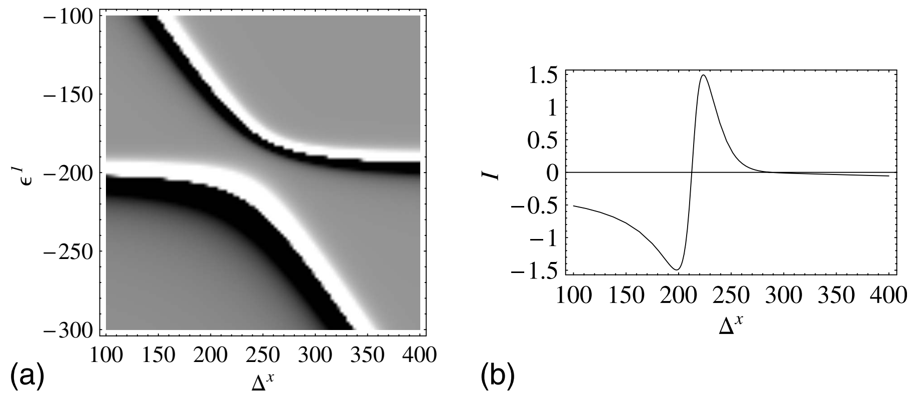

FIG. 6. (a) Density plot of the pumped current I (in unit of $q\nu/(2\pi)$, being $\nu=\omega/(2\pi)$) as a function of the dot level ϵ^1 and the Zeeman energy Δ^x. The black (white) regions represent negative (positive) values of the current. The model parameters have been fixed as follows: $\epsilon^2=-55$, $U=250$, $U'=10$, $t=1$, $t_{so}=35$, $\Delta^z=0$, $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=4.9999$, and $\phi=\pi/2$. In (b) the current I is plotted as a function of the Zeeman energy Δ^x by fixing $\epsilon^1=-210$ while the remaining parameters are chosen as in (a). An energy gap of order $\sim 2t_{so}$ is visible in (a).

electron entered the DQD in a (1,1) triplet. This SB is lifted, if the mutual detuning of the states in the two dots (defined by the difference of the dots energy levels $\varepsilon=\epsilon_1-\epsilon_2$) exceeds the (0,2) singlet-triplet splitting, which gives rise to the strong current. In particular, this is the case for negative detuning $\varepsilon<0$.

Various experiments confirm the singlet-triplet picture described above in *GaAs* quantum dots.[22]

For our calculation of the current we have performed an exact diagonalization of the Hamiltonian $H_{2\text{dot}}$ to analyze its energy spectrum and to obtain information on the states close to the Fermi level (chosen as the zero of energy) that participate in the transport. In Figs. 3, the magnetic field dependence of the eigenvalues is plotted by fixing the other parameters as: $\epsilon^1=0$, $\epsilon^2=-50$, $U=250$, $U'=10$, $t=1$, $t_{so}=35$, $\Delta^x=0$ (a), and $\Delta^z=0$ (b).

The two upper curves in the figures (straight and dashed-dotted) correspond to the hybridized states $T_+(1,1)$ and $S(0,2)$, the dashed-double-dotted line corresponds to the (0,1) state which depends linearly on the magnetic field along z in Fig. 3(a) and is independent from the transverse field [see Fig. 3(b)]. Finally the dashed curve corresponds to a (1,1) state and is independent from the magnetic field along z [Fig. 3(a)] while depends linearly on the transverse magnetic field [Fig. 3(b)].

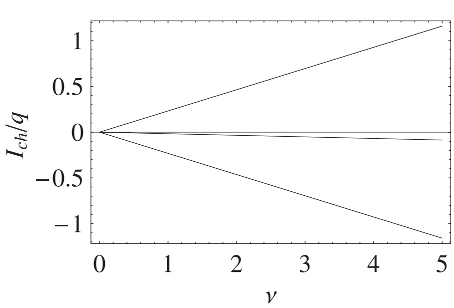

FIG. 7. I_{ch}/q as a function of the pumping frequency ν. The model parameters are fixed as follows: $\epsilon^1=15$, $\epsilon^2=-55$, $U=250$, $U'=10$, $t=1$, $t_{so}=35$, $\Delta^z=0$ and $\Delta^x=0$ (middle line), $\Delta^x=30$ (upper and lower line). The pumping cycle has parameters $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=4.99$ and $\phi=\pi/2$ for lower and middle line (anticlockwise cycle) and $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=-4.99$, $\phi=-\pi/2$ for the clockwise cycle (upper curve).

An important aspect related to the presence of the SOI is the opening of a gap due to the hybridization of the $T_+(1,1)$ state and the $S(0,2)$ state, which considerably influences the pumped current. When $t_{so}=0$ the gap closes and a simple crossing of the levels occurs for a specific value of Δ^z or Δ^x.

In Fig. 4, a density plot of the pumped current as a function of the dot level ϵ^1 and of the Zeeman energy Δ^z is reported while a section of the figure is reported in Fig. 5 for $\epsilon^1=50$. Here, the current clearly shows two resonances in correspondence of the level crossings and a plateaux at around $\Delta^z\simeq 45$ which we have verified to be a linear function of the SOI.

In Fig. 6(a), the density plot of the pumped current is reported as a function of the dot level ϵ^1 and the longitudinal magnetic field Δ^x. When the detuning $(\epsilon_1-\epsilon_2)$ (in dimensionless units) is around 150 the pumped current is essentially zero due to the energy gap in the spectrum of the order t_{so}. In Fig. 6(b), where $\epsilon_1=-210$, due to the SO gap the pumped current is strongly suppressed above $\Delta^x\simeq 250$ and is maximum where the SO gap is suppressed.

Finally in Figs. 7 and 8 the pumped current is shown as a function of the pumping frequency ω for the cycle (0,1)-(1,1)-(0,2) of Fig. 2. The current is linear in the pumping frequency, as expected in the adiabatic regime,[24] and the behavior looks different for the two pumping directions, in particular there is a sign change of the current. The two lowest curves in both Figs. 7 and 8 correspond to the anticlockwise cycling, while the upper curves correspond to the clockwise cycling. As shown, the pumping efficiency is sensitive to both the magnetic field or the spin-orbit interaction. In Fig. 7, for $\Delta^x=0$ (middle curve), we find a significantly reduced pumped current compared to the other curves. If the magnetic field is applied, charge is again pumped with finite efficiency ($\sim 1/4$ per cycle). Thus, the current is significantly reduced by the Pauli spin-blockade for zero magnetic field since the transition from the triplet (1,1) state to the singlet (0,2) is forbidden. When the magnetic field is applied, and in the presence of the SOI, the states $T_+(1,1)$ and $S(0,2)$ hybridize, thus, lifting the spin blockade; moreover the trip-

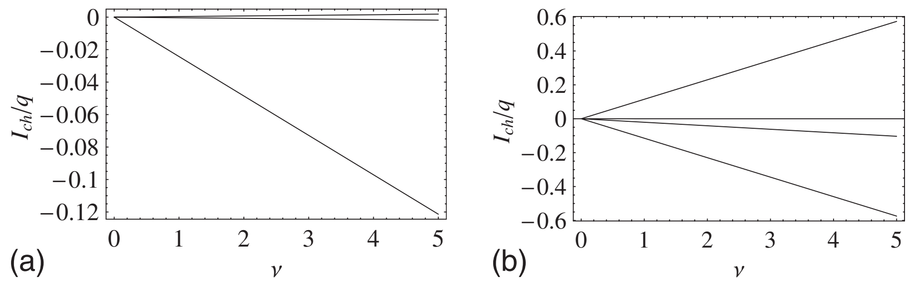

FIG. 8. (a) I_{ch}/q as a function of the pumping frequency ν. In (a), the model parameters are fixed as follows: $\epsilon^1=15$, $\epsilon^2=-55$, $U=250$, $U'=10$, $t=1$, $t_{so}=0$, $\Delta^z=0$, $\Delta^x=0$ (lower line), and $\Delta^x=30$ (upper and middle line). The pumping cycle has $\Gamma_0^{L,R}=5$, $\Gamma_\omega^{L,R}=4.99$, and $\phi=\pi/2$ (lower and middle line), while the upper line is a path-reversed pumping cycle. (b) I_{ch}/q vs ν curves obtained by setting $t_{so}=20$ and taking the remaining parameters as in (a).

let state $T_+(1,1)$ is lowered in energy thus reducing the gap between the (1,1) triplet and the singlet and bringing more states close to the Fermi energy. Both factors increase the pumped current. The above characteristics for the pumped current observed in an experiment would permit to probe the physics of the spin-Coulomb blockade.

Similarly, as shown in Fig. 8(a) when the SOI is set to zero the efficiency is considerably reduced. The efficiency of almost 1/10-charge per cycle is restored as soon as t_{so} is nonzero [Fig. 8(b)] due to the hybridization of the triplet state $T_+(1,1)$ and the singlet $S(0,2)$. Since the efficiency of the pump is increased in the presence of the SO interaction, this quantity could be taken as a quantitative probe of the SOI when the experiment is performed on double dots patterned on different materials (e.g., InAs or GaAs) or to disregard materials with and without SO interaction.

IV. CONCLUSIONS

In conclusion, we showed that the adiabatic pumping in a double dot is a powerful mean to probe the Pauli-spin blockade physics and the presence of the spin-orbit interaction. In particular, we have shown that in the absence of a transverse magnetic field, since the transition between the triplet (1,1) and the singlet (0,2) state is blocked, the efficiency of the pump is remarkably reduced while it reaches a rate of almost 1/4-charge per cycle[25] in applied magnetic field.

On the other hand the presence of the spin-orbit interaction hybridizes the (1,1) and (0,2) state favoring the sequential tunneling in the presence of an external magnetic field and increasing the efficiency of the pump. Due to the different order of magnitude of the efficiency in the presence and not of the spin-orbit interaction, this quantity could be used in an experiment to disregard materials with and without spin-orbit interaction.

The above characteristics with pumping render particular appealing to perform single and two qubit operations via electric gate signals mediated by the spin-orbit interaction and are close to reach within current technology.

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