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Kondo resonance in a multiprobe quantum dot

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We present a theoretical analysis of a possible route for directly detecting Kondo resonances in local density of states (LDOS) of an interacting quantum dot. By very weakly coupling a third and/or a fourth lead to a two-probe quantum dot and measuring differential conductance through these extra links, we show that Kondo peaks directly map onto the differential conductance measured from the third link. We analyze the conditions by which this detection of Kondo peaks in LDOS is possible.

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The Kondo effect is a prototypical many-body correlation effect in condensed matter involving the interaction between a localized spin and free electrons. Recently it was observed in semiconductor quantum dots (QD's),[1–3] which has generated a great deal of theoretical and experimental interest. Experimental investigations of Kondo phenomenon in semiconductor QD's were mainly through two observations.[1–3] First, for cases of QD's confining an odd number of electrons, the differential conductance dI/dV is measured as a function of a gate voltage V_g. It was found that dI/dV in the Coulomb blockade region is enhanced[1,2] due to the Kondo effect. Second, there is a peak at bias $V=0$ in the dI/dV versus V curve, and this peak splits into two when there is a magnetic field.[1] Although dI/dV gives a measure of local density of states (LDOS) of the QD's in linear response, to the best of our knowledge the comprehensive shape of the LDOS of the QD's in the Kondo regime, namely the one (or a few) narrow Kondo peak on top of the ''shoulder'' of the broad peak corresponding to an intradot level, has so far not been directly detected in any experiment.

The outstanding features of the QD Kondo phenomenon are more prominent in LDOS than in the tunneling current I and its associated differential conductance dI/dV. For example, for a QD coupled to a normal lead and a superconducting lead (a NQDS device), three Kondo peaks arise in LDOS at the chemical potential of the normal lead and at the superconducting gap ($\pm\Delta$), respectively. On the other hand, the tunneling current hardly varies at all despite the presence of these Kondo peaks in LDOS.[4] As another example, in an asymmetric NQDS device under a finite on-site Coulomb interaction and a large superconducting gap, four Kondo peaks emerge in LDOS.[5] However, while the current is enhanced due to these features, it does not show clear characteristics of the narrow Kondo resonances. Therefore it is extremely useful to be able to directly detect the narrow Kondo resonance in the LDOS.

Given the importance of the physics of Kondo phenomenon in mesoscopic systems and the extensive investigations in both theory and experiments, it is indeed surprising to see the lack of direct observation of the Kondo resonance peaks in LDOS.[6] It is the purpose of this short paper to present a theoretical analysis of a possible route for solving this problem. We will investigate a different approach by which one or two extra leads are used to probe a typical two-terminal QD device. When conditions are controlled correctly, we show that the LDOS (including the narrow Kondo peaks) will directly map onto the current measured at the extra leads thereby providing a direct measurement of the narrow Kondo peaks elusive so far.

To begin, let us consider the hypothetical device consisting of a QD coupled to *four* leads fabricated by a split gate technique, as shown in the inset of Fig. 2, in a two-dimensional electron gas (2DEG). Here, leads 1 and 3 plus the QD form a typical two-probe QD device for which we assume to have a Kondo regime at low temperature, so that there are some Kondo resonances in the LDOS which is our target of measurement. Leads 2 and 4 are assumed to very weakly couple with the QD, much weaker than that of leads 1 and 3. Our hope is to probe the QD Kondo physics through lead 2. The purpose of the bias on lead 4, V_4, is to provide a voltage opposite in sign to that of V_2, so as to compensate the intradot energy altered by bias V_2. It has recently been demonstrated experimentally by Simmel *et al.*[3] that it is possible to fabricate a QD that is coupled rather asymmetrically to the two leads. Such an asymmetric NQDN device showed[3] a pinning effect of the Kondo resonance at the Fermi level of that lead which couples stronger to the QD. While it is more difficult to experimentally fabricate the proposed multiprobe QD device, our analysis demonstrates this possibility. Our results suggest that when conditions are right, the differential conductance dI_2/dV_2 versus its terminal bias V_2 gives an excellent measurement to the LDOS as a function of energy ϵ, thereby allowing us to observe the Kondo peaks directly. In addition, the Kondo peak splitting due to a nonequilibrium condition can also be detected using the multiprobe system. We note that the Kondo peak splitting at the nonequilibrium case cannot be observed in a two-terminal device even if the two terminals couple asymmetrically[3] to the QD.

So far there are some attempts in measuring the Kondo resonance in LDOS.[6–8] They use a scanning tunneling microscope (STM) to obtain spectroscopic data on individual magnetic impurities deposited onto the host metal. However, there exists electron transitions between the host metal, which provides conduction or free electrons, and the probing STM tip.[8,9] Since such transitions cannot be avoided, only Fano-like resonances were obtained, instead of the expected Lorentzian shape of the Kondo peaks. In contrast, in our device, there does not exist direct tunneling between the probe terminal lead 2 and the conduction electron channel leads 1 and 3. This important difference allows us to observe the original shape of LDOS including the Kondo resonances.

Our device is described by the following Hamiltonian:

$$H=\sum_{\alpha,k,\sigma}\epsilon_{\alpha k}a^{\dagger}_{\alpha k\sigma}a_{\alpha k\sigma}+\sum_{\sigma}\epsilon_{d\sigma}d^{\dagger}_{\sigma}d_{\sigma}+Ud^{\dagger}_{\uparrow}d_{\uparrow}d^{\dagger}_{\downarrow}d_{\downarrow}$$
$$+\sum_{\alpha,k,\sigma}(v_{\alpha k}a^{\dagger}_{\alpha k\sigma}d_{\sigma}+\text{H.c.}),\tag{1}$$

where $a^{\dagger}_{\alpha k\sigma}$ $(a_{\alpha k\sigma})$ $(\alpha=1,2,3,4)$ and $d^{\dagger}_{\sigma}$ (d_{σ}) are creation (annihilation) operators in the lead α and the QD, respectively. The QD includes a single energy level, but has spin index σ and intradot Coulomb interaction U. To account for a possible magnetic field, we allow $\epsilon_{d\uparrow}\neq\epsilon_{d\downarrow}$.

The current from lead α flowing into the QD can be expressed as (in units of $\hbar=1$) (Ref. 10)

$$I_{\alpha}=-2e\,\text{Im}\sum_{\sigma}\int\frac{d\epsilon}{2\pi}\Gamma_{\alpha}\left\{f_{\alpha}(\epsilon)G^{r}_{\sigma}(\epsilon)+\frac{1}{2}G^{<}_{\sigma}(\epsilon)\right\},\tag{2}$$

where $\Gamma_{\alpha}(\epsilon)=2\pi\Sigma_{k}|v_{\alpha k}|^{2}\delta(\epsilon-\epsilon_{\alpha k})$; $f_{\alpha}(\epsilon)$ is the Fermi distribution of lead α; $G^{r}_{\sigma}(\epsilon)$ and $G^{<}_{\sigma}(\epsilon)$ are the retarded and the Keldysh Green's functions of the QD, they are the Fourier transformation of $G^{r,<}_{\sigma}(t)$, and $G^{r}_{\sigma}(t)\equiv-i\theta(t)\times\langle\{d_{\sigma}(t),d^{\dagger}_{\sigma}(0)\}\rangle$, $G^{<}_{\sigma}(t)\equiv i\langle d^{\dagger}_{\sigma}(0)d_{\sigma}(t)\rangle$.

Using the standard equation of motion technique and taking the familiar decoupling approximation,[11] we have solved $G^{r}_{\sigma}(\epsilon)$ to be

$$G^{r}_{\sigma}(\epsilon)=\frac{1+UA_{\sigma}n_{\bar{\sigma}}}{\epsilon-\epsilon_{d\sigma}-\Sigma^{(0)}_{\sigma}+UA_{\sigma}(\Sigma^{(a)}_{\bar{\sigma}}+\Sigma^{(b)}_{\bar{\sigma}})},\tag{3}$$

where $A_{\sigma}(\epsilon)=[\epsilon-\epsilon_{d\sigma}-U-\Sigma^{(0)}_{\sigma}-\Sigma^{(1)}_{\bar{\sigma}}-\Sigma^{(2)}_{\bar{\sigma}}]^{-1}$ and $\Sigma^{(0)}_{\sigma}=\Sigma_{k\alpha}|v_{\alpha k}|^{2}/(\epsilon-\epsilon_{\alpha k}+i0^{+})$ is the lowest-order self-energy for a noninteraction which is exactly the retarded self-energy for a noninteraction system; the higher-order self-energies $\Sigma^{(a)}_{\sigma}$, $\Sigma^{(b)}_{\sigma}$, $\Sigma^{(1)}_{\sigma}$, and $\Sigma^{(2)}_{\sigma}$ are: $\Sigma^{(a/b)}_{\sigma}=\Sigma_{k\alpha}|v_{\alpha k}|^{2}f_{\alpha}(\epsilon_{\alpha k})/\epsilon^{+/-}_{\sigma}$; $\Sigma^{(1/2)}_{\sigma}=\Sigma_{k\alpha}|v_{\alpha k}|^{2}/\epsilon^{+/-}_{\sigma}$; here $\epsilon^{+}_{\sigma}=\epsilon+\epsilon_{\alpha k}-\epsilon_{d\sigma}-\epsilon_{d\bar{\sigma}}-U+i0^{+}$ and $\epsilon^{-}_{\sigma}=\epsilon-\epsilon_{\alpha k}-\epsilon_{d\bar{\sigma}}+\epsilon_{d\sigma}+i0^{+}$. The quantity $n_{\bar{\sigma}}$ in Eq. (3) is the intradot electron occupation number of state $\bar{\sigma}$, which needs to be calculated self-consistently.[12] In the limit of having only two leads, the above results reduces to that of Refs. 11 and 13.

The Keldysh Green's function $G^{<}_{\sigma}$, for interacting systems, cannot be obtained from the equation of motion without introducing additional assumptions. We use the standard ansatz due to Ng,[14]

$$\Sigma^{<}_{\sigma}(\epsilon)=-\sum_{\alpha}\frac{\Gamma_{\alpha}f_{\alpha}(\epsilon)}{\Gamma}(\Sigma^{r}_{\sigma}-\Sigma^{a}_{\sigma}),\tag{4}$$

where $\Gamma=\Sigma_{\alpha}\Gamma_{\alpha}$. $\Sigma^{<}_{\sigma}$ and $\Sigma^{r}_{\sigma}(\Sigma^{a}_{\sigma})$ are the lesser and retarded (advanced) self-energies of the interacting system. Then from the Keldysh equation $G^{<}_{\sigma}=G^{r}_{\sigma}\Sigma^{<}_{\sigma}G^{a}_{\sigma}$ and $G^{a}_{\sigma}=(G^{r}_{\sigma})^{*}$, $G^{<}_{\sigma}$ can be obtained straightforwardly. With G^{r}_{σ} and $G^{<}_{\sigma}$ solved, from Eq. (2) the current can be obtained immediately:

$$I_{\alpha}=-2e\sum_{\sigma,\alpha'}\int\frac{d\epsilon}{2\pi}\frac{\Gamma_{\alpha}\Gamma_{\alpha'}}{\Gamma}[f_{\alpha}(\epsilon)-f_{\alpha'}(\epsilon)]\text{Im}\,G^{r}_{\sigma}.\tag{5}$$

In fact, if Γ_{α} are constant over energies comparable to the voltages, the Green's function $G^{<}_{\sigma}(\epsilon)$ in the current expression, Eq. (2), can be eliminated by using the current conservation.[10] Then Eq. (5) can be directly obtained without using the ansatz Eq. (4).

In the numerical calculation, we make a few further simplifications: (i) we assume square bands of width $2W$, so that $\Gamma_{\alpha}(\epsilon)=\Gamma_{\alpha}\theta(W-|\epsilon|)$, with $W=1000\gg\max(k_{B}T,eV_{\alpha},\Gamma_{\alpha})$; (ii) we take the large U limit $U\rightarrow\infty$; (iii) we take $\Gamma_{1}=\Gamma_{3}=1$ as energy unit; (iv) considering that the intradot level $\epsilon_{d\sigma}$ is affected by leads' bias voltage V_{α}, we assume this effect to be $\epsilon_{d\sigma}=\epsilon_{d\sigma}(0)+\gamma_{2}V_{2}+\gamma_{4}V_{4}$, with $\gamma_{\alpha}=C_{\alpha}/C$. Here C_{α} is the capacitance between lead α and the QD, and C is the total capacitance of the QD; $\epsilon_{d\sigma}(0)$ is the location of the intradot energy level at $V_{2}=V_{4}=0$. We set $V_{4}=-V_{2}$ to offset the level change, so that $\epsilon_{d\sigma}=\epsilon_{d\sigma}(0)+\gamma V_{2}$ where $\gamma=(C_{2}-C_{4})/C$.

Our objective system is the QD plus leads 1 and 3, it is recovered by setting $\Gamma_{2}=\Gamma_{4}=0$ so that leads 2 and 4 are decoupled from the QD. The dotted curves of Fig. 1 shows the intradot LDOS of the objective system.[15] A broad peak at $\epsilon=-2$ (in units of Γ_{1}) is due to the intradot renormalized level. In nonequilibrium and at zero magnetic field ($\epsilon_{d\uparrow}=\epsilon_{d\downarrow}$), there exhibit two narrow Kondo resonance peaks at

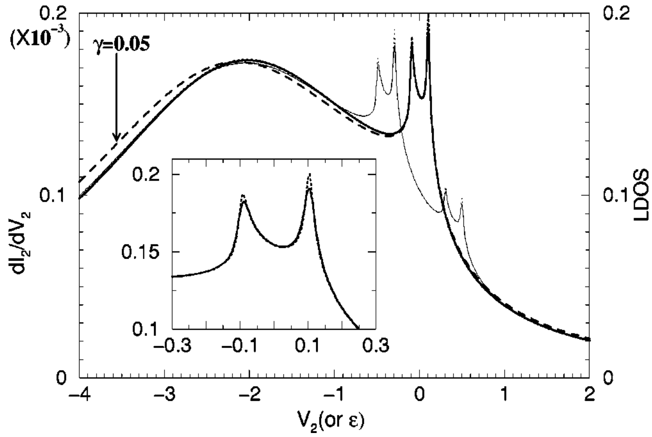

FIG. 1. Two solid curves are the differential conductance dI_{2}/dV_{2} versus V_{2}, with $\Gamma_{2}=\Gamma_{4}=0.001$ and $\gamma=0$. Two dotted curves are the LDOS versus energy ϵ for the two-probe objective system (obtained by setting $\Gamma_{2}=\Gamma_{4}=0$). The thick dashed curve is dI_{2}/dV_{2} versus V_{2} with $\Gamma_{2}=\Gamma_{4}=0.001$ and $\gamma=0.05$. Other parameters are: $\Gamma_{1}=\Gamma_{3}=1$, $V_{1}=-V_{3}=0.1$, and $T=0.005$. The thick curves and thin curves correspond to $\epsilon_{d\uparrow}(0)=\epsilon_{d\downarrow}(0)=-4.0$ and $\epsilon_{d\uparrow}(0)=-4.2$, $\epsilon_{d\downarrow}(0)=-3.8$, respectively. Notice that the dotted curves almost overlap perfectly with the solid curves so that they almost cannot be seen in the figure. The inset amplifies the two Kondo resonance peaks at zero magnetic field [by setting $\epsilon_{d\uparrow}(0)=\epsilon_{d\downarrow}(0)=-4.0$].

μ_1 and μ_3 in the LDOS. With a nonzero magnetic field ($\epsilon_{d\uparrow} \neq \epsilon_{d\downarrow}$) and in nonequilibrium, four narrow Kondo peaks emerge at $\mu_{1/3} \pm \Delta\epsilon$ where $\Delta\epsilon = \epsilon_{d\downarrow} - \epsilon_{d\uparrow}$ is the level difference. These familiar characteristics of LDOS have been known[13] in theory; our task is to "experimentally" measure them.

Let us now turn on a nonzero Γ_2 and Γ_4. Note that these couplings must be greatly weaker than those of leads 1 and 3, i.e., $\Gamma_2, \Gamma_4 \ll \Gamma_1, \Gamma_3$, so that they do not affect the QD significantly. We first consider the $\gamma = 0$ case for which there is a complete compensation of V_2 by V_4 so that the level $\epsilon_{d\sigma}$ does not change with V_2. The differential conductance dI_2/dV_2 versus V_2 is shown in Fig. 1 by the solid curves; they overlap almost identically with the dotted curves of the two-probe LDOS (the objective system) so that the dotted curves are barely seen in Fig. 1. In other words, the dI_2/dV_2-V_2 data and the LDOS-ϵ data of the objective system map into each other essentially perfectly. To better see the comparison, data in the vicinity of Kondo peaks for zero magnetic field are amplified in the inset of Fig. 1. Although the Kondo peaks of dI_2/dV_2 is slightly lower than those of LDOS, they not only agree in their position but also in the Lorentzian shape which is a very important characteristic of Kondo phenomenon. Therefore the nonequilibrium splitting and nonzero magnetic-field splitting of the Kondo resonance peak in the LDOS can be detected by measuring the differential conductance dI_2/dV_2.

Why does dI_2/dV_2 versus V_2 give such an excellent mapping of the original LDOS of the objective system? First, lead 2 is very weakly coupled to the QD so that the original QD LDOS is not significantly affected by it. Second, because the QD is coupled much stronger to leads 1 and 3, e.g., $\Gamma_1, \Gamma_3 \gg \Gamma_2$, resonance tunneling from lead 2 to leads 1 and 3 cannot occur with any substantial probability. Therefore an incident electron with energy ϵ from lead 2 has a probability of tunneling into the QD that is given by the intradot LDOS(ϵ), leading to the excellent agreement between dI_2/dV_2 and the LDOS. We conclude that the LDOS versus energy ϵ can be obtained by measuring dI_2/dV_2 versus V_2.

It is worth mentioning that although we have assumed symmetric couplings between leads 1 and 3 to the QD, $\Gamma_1 = \Gamma_3$, and assumed a large e-e interaction $U \to \infty$, it is straightforward to confirm, as we did, that if $\Gamma_1 \neq \Gamma_3$ and U is finite, our results still hold. In fact, these parameters of the objective system only affect its LDOS, they do not destroy the excellent agreement between the signal dI_2/dV_2 and the LDOS. In addition, the physics dictating this excellent agreement is independent of what theoretical methods one uses to derive the Green's functions $G^r_\sigma(\epsilon)$. In other words, if one uses another method to solve $G^r_\sigma(\epsilon)$ rather than the equation of motion method we used here,[16] or even if one gives an arbitrary LDOS of the target system, our proposed detection technique can still give the excellent agreement between dI_2/dV_2 and the LDOS.

Other important issues concerning our proposal are the ranges of parameters associated with leads 2 and 4 which we use to probe the LDOS. If the resistance provided by lead 1 to the QD is a typical 10 KΩ, then if lead 2 couples 1000 times weaker, its contact to the QD will have a resistance of 10 MΩ which is experimentally realizable. When voltages on leads 2 and 4 do not exactly compensate, i.e., when $\gamma \neq 0$, the intradot level $\epsilon_{d\sigma}$ will change with V_2, hence features in LDOS will be changed which affects the proposed measurement of the Kondo peaks by dI_2/dV_2. Our investigation shows that this is actually a weak effect on the Kondo resonances, as shown in Fig. 2 where dI_2/dV_2 is plotted against V_2 at several values of γ. The background differential conductance does change with γ. However, the important result is that the narrow Kondo peaks still keep the original shape, and their locations do not vary at all as shown in Fig. 2. Even when $\gamma = 0.5$ or larger, these Kondo characters remain. Therefore we believe that the condition on parameter γ is not strict for our proposal to work. It should be stressed that if γ is not very large, e.g., $\gamma = 0.05$, the broad peak which corresponds to the intradot renormalized level only shifts slightly but it retains its line shape (dashed line of Fig. 1). This analysis strongly shows that the comprehensive shape of LDOS in the Kondo regime, the one (or a few) narrow Kondo peak on top of the shoulder of the broad peak, can be detected.

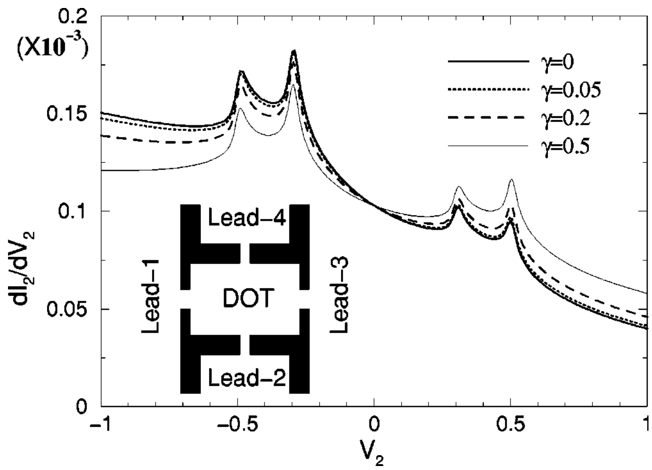

FIG. 2. dI_2/dV_2 versus V_2 at different parameters γ. Other parameters are same as those of the thin solid line of Fig. 1. The inset is a schematic diagram for the four-probe quantum dot device.

Let us estimate the value of γ. The total capacitance C includes each terminal capacitance C_α ($\alpha = 1,2,3,4$), it also includes, perhaps, some gate capacitances C_g. In general, $C_\alpha / C_{\alpha'}$ is approximatively proportional to $\Gamma_\alpha / \Gamma_{\alpha'}$, and C_g is larger than C_α.[17] Because $\Gamma_2 \ll \Gamma_1$ and Γ_3 (in Figs. 1 and 2, $\Gamma_1 = \Gamma_3 = 1000\Gamma_2$), a conservative estimate is that C_1 and C_3 should be larger than $10C_2$. Then, even if we neglect C_g in the total C and even if we completely remove the compensating terminal 4, we still have $\gamma = C_2/C < 0.05$. Hence by results of Fig. 2 such a small γ will not cause any trouble to our proposed measurements of the Kondo peaks.

Next, we discuss the range of temperature T where the excellent agreement of dI_2/dV_2 and LDOS can be kept. We fix $\gamma = 0.05$, as discussed above this value of γ is easily realized even without the compensating lead 4. Therefore we set, in our theory, $\Gamma_4 = 0$ and $C_4 = 0$, and we propose to replace lead 4 by a gate to control the intradot level position

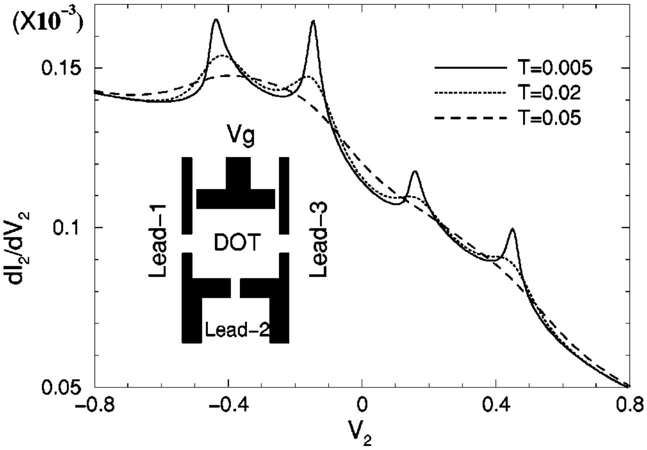

FIG. 3. dI_2/dV_2 versus V_2 for three different temperatures *T*, where the parameters are: $\Gamma_1=\Gamma_3=1$, $\Gamma_2=0.001$, $\gamma=0.05$, $\epsilon_{d\uparrow}(0)=-4.15$, $\epsilon_{d\downarrow}(0)=-3.85$, and $V_1=-V_3=0.15$. The inset is a schematic diagram for a proposed three-terminal quantum dot device.

(see inset of Fig. 3). The signal dI_2/dV_2 versus V_2 is shown in Fig. 3 for three temperatures. At low temperature, there are four Kondo peaks at $\mu_{1/3}\pm\Delta\epsilon$ in dI_2/dV_2. Increasing temperature causes the Kondo peaks to go down until they completely disappear. On the other hand, we found that the broad peak which corresponds to the intradot level essentially does not change in this range of temperatures (not shown). These characters are in excellent agreement with those of the LDOS. In fact, our investigations show that when $k_BT<\Gamma_1+\Gamma_3$, the excellent agreements between dI_2/dV_2 and LDOS are always maintained. At last, we estimate the range of the voltages V_2 where the excellent agreement holds. With V_2 increasing, the intradot level will move, leading to a difference between the conductance dI_2/dV_2 and the LDOS. When γeV_2 reaches $e^2/C=U$, the similarity between them will be broken down. However, if $\gamma eV_2 <e^2/10C$, the excellent similarity is maintained.

To summarize, we have proposed and analyzed a possibility to experimentally directly observe the local density of states of a quantum dot, and thereby directly detect Kondo resonance peaks in it. In particular, using an extra weak link to the quantum dot, we showed that curves of dI_2/dV_2 versus V_2 can map out perfectly the curves of LDOS versus energy, if experimental conditions are set in the correct range. We also provided an analysis to these conditions and found them to be reasonable and therefore should be realizable. Indeed, it will be extremely interesting to experimentally test these predictions.

Note added. After submission of this manuscript, we noticed that E. Lebanon and A. Schiller also addressed a very similar problem (cond-mat/0105488, 25 May 2001).

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