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Competing interests statement

The authors declare that they have no competing financial interests.

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Kondo resonance in a single-molecule transistor

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When an individual molecule[1], nanocrystal[2–4], nanotube[5,6] or lithographically defined quantum dot[7] is attached to metallic electrodes via tunnel barriers, electron transport is dominated by single-electron charging and energy-level quantization[8]. As the coupling to the electrodes increases, higher-order tunnelling and correlated electron motion give rise to new phenomena[9–19], including the Kondo resonance[10–16]. To date, all of the studies of Kondo phenomena in quantum dots have been performed on systems where precise control over the spin degrees of freedom is difficult. Molecules incorporating transition-metal atoms provide powerful new systems in this regard, because the spin and orbital degrees of freedom can be controlled through well-defined chemistry[20,21]. Here we report the observation of the Kondo effect in single-molecule transistors, where an individual divanadium molecule[20] serves as a spin impurity. We find that the

Kondo resonance can be tuned reversibly using the gate voltage to alter the charge and spin state of the molecule. The resonance persists at temperatures up to 30 K and when the energy separation between the molecular state and the Fermi level of the metal exceeds 100 meV.

We prepared devices by an extension of the methods previously used in constructing single-C_{60} (ref. 1) and single-nanocrystal transistors[3]. Using electron-beam lithography, a narrow gold bridge was fabricated on an aluminium pad with a ~3-nm oxide layer serving as a gate electrode[22]. The electromigration-induced break-junction technique[1,3] was then used to create two closely spaced gold electrodes (Fig. 1). Scanning electron microscope imaging and tunnel current measurements reveal that the narrowest gap between the two electrodes is consistently ~1 nm.

Single-molecule transistors containing individual divanadium (V_2) molecules ([(*N*,*N*′,*N*″-trimethyl-1,4,7-triazacyclononane)$_2$-$V_2(CN)_4(\mu\text{-}C_4N_4)$]: Fig. 1)[20] were prepared by depositing a dilute methanol solution of the V_2 molecule onto the gold bridge. To minimize the probability of multiple V_2 molecules bridging two electrodes, we controlled the coverage of molecules on an array of gold electrodes such that <20% of the junctions—7 in an array of 42 broken junctions—showed current–voltage (I–V) characteristics different from a simple tunnel junction.

Figure 2 shows plots of differential conductance ($\partial I/\partial V$) as a function of bias voltage (V) and gate voltage (V_g) for two single-V_2 transistors, designated D1 and D2. Two distinct characteristics, which are shared by all seven single-V_2 transistors studied to date, are evident in the behaviour of both devices. Each displays two conductance-gap regions, I and II, bounded by two broad $\partial I/\partial V$ peaks that slope linearly as a function of V_g. These peaks cross at $V_g = V_c$, at which point the conductance gaps vanish. Moving away from this point, the gaps in both regions continue to widen even beyond $V = 100$ mV. Most significantly, the devices also exhibit a sharp zero-bias $\partial I/\partial V$ peak in region I, whereas this peak is clearly absent in region II. The zero-bias $\partial I/\partial V$ peak was generally found to persist up to $T \geq 10$ K. Other features observable in D2, such as the enhanced conductance within region I and the $\partial I/\partial V$ peaks outside the conductance gaps, were not shared by all devices (see below).

The observation of conductance gaps that vary linearly with V_g provides strong experimental evidence that an individual molecule is responsible for the device behaviour. A conductance gap arises from the finite energy required to add (remove) an electron to (from) the molecule, which is a consequence of single-electron charging and the quantized molecular level spacing. The conductance gap changes linearly and reversibly as a function of V_g because a more positive V_g stabilizes an additional electron on the V_2 molecule. At the charge degeneracy point, $V_g = V_c$, where the total energy is the same for two different charge states of the molecule, the conductance gap disappears. As V_g traverses V_c in the positive direction, the equilibrium number of charges on the molecule increases by one electron.

Certainly the most prominent feature of the data is the appear-

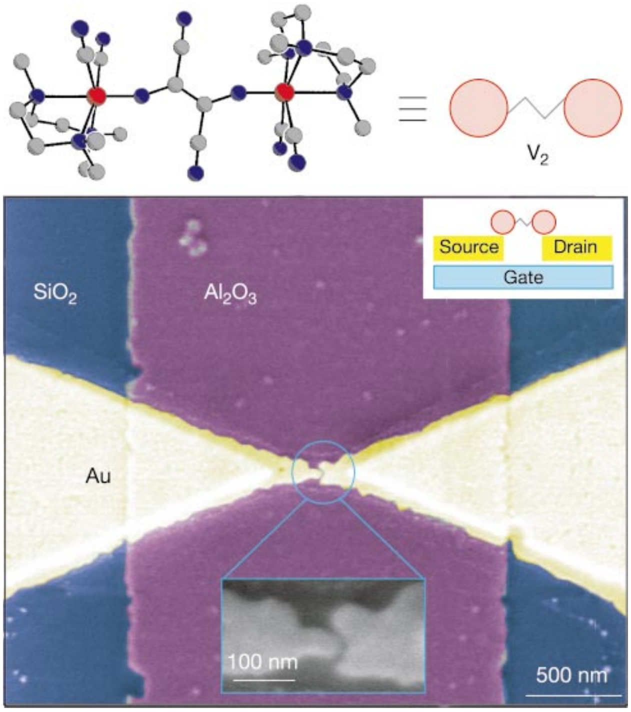

Figure 1 Fabrication of single-molecule transistors incorporating individual divanadium molecules. Top left, the structure of [(*N*,*N*′,*N*″-trimethyl-1,4,7-triazacyclononane)$_2V_2(CN)_4(\mu\text{-}C_4N_4)$] (the V_2 molecule) as determined by X-ray crystallography; red, grey and blue spheres represent respectively V, C and N atoms. Top right, the schematic representation of this molecule. Main panel, scanning electron microscope image (false colour) of the metallic electrodes fabricated by electron beam lithography and the electromigration-induced break-junction technique. The image shows two gold electrodes separated by ~1 nm above an aluminium pad, which is covered with an ~3-nm-thick layer of aluminium oxide. The whole structure was defined on a silicon wafer. The bright yellow regions correspond to a gold bridge with a thickness of 15 nm and a minimum lateral size of ~100 nm. The paler yellow regions represent portions of the gold electrodes with a thickness of ~100 nm. Main panel inset, schematic diagram of a single-V_2 transistor.

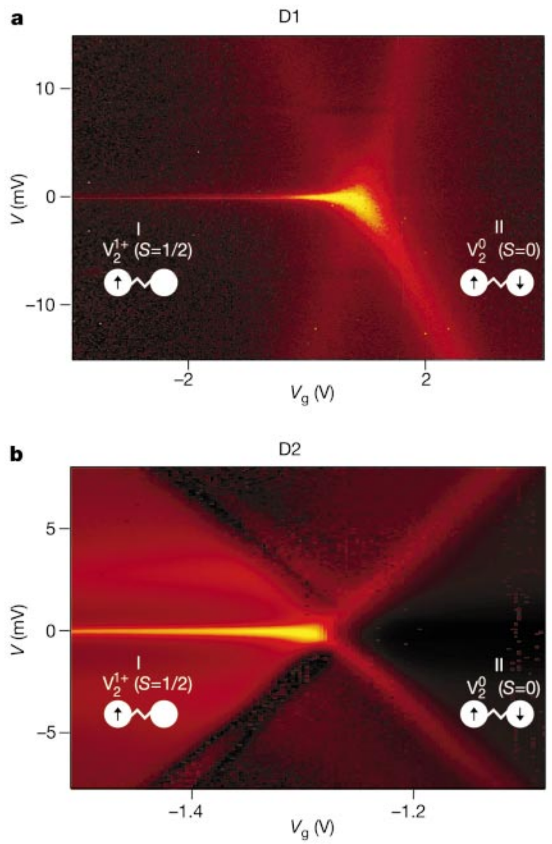

Figure 2 Plots of differential conductance ($\partial I/\partial V$) as a function of bias voltage (V) and gate voltage (V_g) obtained from two different single-V_2 transistors D1 (**a**) and D2 (**b**). Both measurements were performed at $T = 300$ mK. The $\partial I/\partial V$ values are represented by the colour scale, which changes in **a**, from dark red (0) to bright yellow ($1.55e^2/h$) and in **b**, from dark red (0) to bright yellow ($1.3\,e^2/h$). The value of e^2/h is 38.8 μS or $(25.8\ \text{k}\Omega)^{-1}$. The labels I and II mark two conductance-gap regions, and the diagrams indicate the charge and spin states of the V_2 molecule in each region.

ance of the sharp zero-bias $\partial I/\partial V$ peak in region I. This feature is strongly reminiscent of the Kondo resonance observed previously in lithographically defined quantum dots[10–14] and single-walled carbon nanotubes[15,16]. The Kondo resonance is a many-electron phenomenon resulting from the exchange interaction between a localized spin and the conduction electrons in metallic electrodes[17–19,23,24], and it appears only when the electronic state of a quantum dot has non-zero spin (S) or degeneracy.

One signature of a Kondo resonance arising from non-zero S is the splitting of its peak position in an applied magnetic field, B, by twice the ordinary Zeeman splitting[19]. Figure 3a depicts a plot of $\partial I/\partial V$ versus V and B, and clearly shows that the zero-bias $\partial I/\partial V$ peak in region I splits in V under a magnetic field. The magnitude of this splitting is 230 $\mu\mathrm{V\,T}^{-1}$ or $2g\mu_{\mathrm{B}}B/e$ (where $g = 2$ is the g-factor of the molecule[20], and μ_{B} is the Bohr magneton), consistent with the expected splitting of a Kondo resonance. As the temperature is raised, the peak height of the resonance is expected to decrease in a characteristic fashion while its peak width increases (see below for further discussion)[12,17,24]. Such behaviour is evident in the data presented in Fig. 4. These observations therefore firmly establish that the zero-bias $\partial I/\partial V$ peaks in region I arise from a Kondo resonance in the single-V_2 transistors.

The absence of a Kondo resonance in region II suggests, on the other hand, that the requisite spin degeneracy is lost when the charge state of the V_2 molecule changes by the addition of one electron. Insight into the origin of this behaviour can be obtained by inspecting Fig. 3b, which displays a $\partial I/\partial V$–V–V_{g} plot analogous to those in Fig. 2, but with data measured at $B = 8$ T. In particular, Fig. 3b shows that the $\partial I/\partial V$ peaks defining region II exhibit an ordinary Zeeman splitting of $g\mu_{\mathrm{B}}B/e = 115\,\mu\mathrm{V\,T}^{-1}$, whereas the peaks defining region I show no such splitting. This splitting pattern is characteristic of the ground-state spin change of $\Delta S = -1/2$ upon the addition of one electron[25]. Comparison of Figs 2b and 3b further shows that the charge degeneracy point ($V_{\mathrm{g}} = V_{\mathrm{c}}$) moves in the positive V_{g} direction as the magnetic field is increased, signifying that the ground state of the molecule in region I is stabilized relative to that in region II. Analysis of this shift on the basis of the known electrostatic coupling to the gate electrode indicates that the energy stabilization amounts to $\sim 100\,\mu\mathrm{V\,T}^{-1}$, again consistent with a reduction of the spin by 1/2.

In the neutral V_2 molecule, both vanadium atoms exist in a 4+ oxidation state, each possessing one valence d electron[20] (Fig. 3c). Electrochemical studies show that in organic solvents three oxidation states of the V_2 molecule are accessible[20]: neutral V_2^0, positive V_2^+, and negative V_2^-. Magnetic measurements performed on bulk samples indicate that the ground state of V_2^0 is a spin-singlet ($S = 0$) owing to the antiferromagnetic coupling between vanadium centres, while that of V_2^- is a spin-quadruplet ($S = 3/2$) owing to the resonant exchange of the added electron[20]. Although the V_2^+ ion has not yet been isolated in bulk, the ground state of V_2^+ is expected to be a spin-doublet ($S = 1/2$) as it possesses only one d electron. These results, combined with the information that the ground-state spin value reduces by 1/2 upon one-electron addition, indicate that the V_2^+ and V_2^0 species are responsible for the device behaviour in regions I and II, respectively, as shown in Fig. 2.

Determination of the spin multiplicity permits a quantitative analysis of the temperature dependence of the Kondo effect (Fig. 4). Previous theoretical[17–19,23,24] and experimental[10–16] studies have shown that the Kondo physics of a non-degenerate spin-1/2 system is characterized by a single temperature scale known as the Kondo temperature (T_{K}). In the limit of a large charging energy U ($U > 1$ eV in the V_2 molecule) and $\varepsilon \gg \Gamma$, T_{K} is expected to follow the functional form[7,26] $T_{\mathrm{K}} = 0.5(\Gamma U)^{1/2}\exp(-\pi\varepsilon/\Gamma)$. Here Γ is the level width due to the tunnel coupling to metallic electrodes, and $-\varepsilon$ is the energy of the localized electron measured relative to the metal Fermi level. Although this expression is derived in the Kondo regime ($\varepsilon/\Gamma \gg 1$), previous experimental studies have shown that the expression also adequately describes data in the crossover region between the mixed-valence ($\varepsilon/\Gamma \leq 0.5$) and the Kondo regimes[12,14]. The temperature dependence of the Kondo peak height (G_{K}) follows an approximate scaling form given by $G_{\mathrm{K}}(T) = G_0/(1 + (2^{1/s} - 1)T^2/T_{\mathrm{K}}^2)^s$, where G_0 is a constant[12]. The value of s depends on the value of ε/Γ, and it attains its asymptotic value of 0.22 when $\varepsilon/\Gamma \gg 1$. At low temperatures, the width of the Kondo peak is expected to saturate at $\sim k_{\mathrm{B}}T_{\mathrm{K}}/e$, where k_{B} is the Boltzmann constant[11].

T_{K} and the resonance width extracted from device D3 are presented as a function of ε/Γ in Fig. 4b. The value of T_{K} was determined by fitting the measured G_{K}–T curves to the above scaling expression using G_0 and s as fit parameters, and the peak width was measured at the full-width at half-maximum. We note that the T_{K} value close to $V_{\mathrm{g}} = V_{\mathrm{c}}$ exceeds 30 K, representing (to our knowledge) the highest Kondo temperature reported to date for a quantum-dot type system. Far away from $V_{\mathrm{g}} = V_{\mathrm{c}}$, the peak widths converge to an asymptotic value owing to thermal broadening. The Kondo resonance nevertheless persists even when ε exceeds 100 meV ($\varepsilon/\Gamma > 3$).

Figure 4b shows that, as ε is tuned away from the Fermi level, both T_{K} and the peak width decay as expected, but they do not follow a single-exponential form. The values of ε/Γ range from 0.1 to 2, thus spanning the mixed-valence regime ($\varepsilon/\Gamma \leq 0.5$) and crossing over to the Kondo regime ($\varepsilon/\Gamma \gg 1$) (refs 12, 24, 26, 27). As shown by two lines in Fig. 4b, the decay can be approximated by $\exp(-3\varepsilon/\Gamma)$ for $0 < \varepsilon/\Gamma < 0.5$ and then rolls over to $\exp(-1.3\varepsilon/\Gamma)$

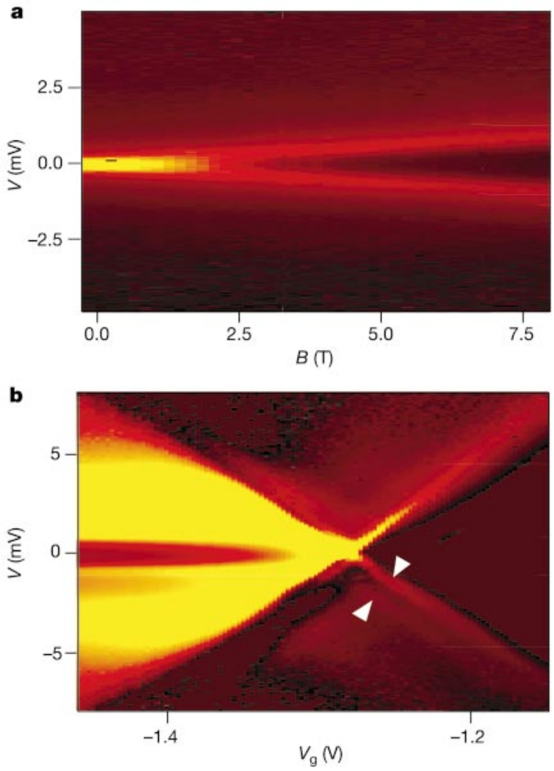

Figure 3 Transport data obtained from single-V_2 transistors in an applied magnetic field (B). **a**, A $\partial I/\partial V$ plot as a function of V and B obtained from D1 at $V_{\mathrm{g}} = -0.1$ V and at $T = 300$ mK. The $\partial I/\partial V$ values are represented by a colour scale that varies from dark red (0) to bright yellow (1.3 e^2/h). **b**, A $\partial I/\partial V$ plot as a function of V and V_{g} obtained from D2 at $B = 8$ T and at $T = 300$ mK. White arrows indicate the two $\partial I/\partial V$ peaks that arise from a Zeeman splitting. To clearly illustrate weak Zeeman-split features, the colour scale has been changed from that in Fig. 2a and varies from dark red (0) to bright yellow (0.55 e^2/h).

for $0.5 < \varepsilon/\Gamma < 2$. In the range of $0.5 < \varepsilon/\Gamma < 2$, the decay is approximately a factor of two slower than what has been observed previously for a non-degenerate spin-1/2 system[12,14].

One possible explanation for this behaviour is that not only the spin but also orbital degrees of freedom may be required to explain the Kondo physics observed in single-V_2 transistors. As discussed previously, the V_2^+ ion contains two equivalent vanadium sites and hence it can provide doubly degenerate orbitals for a single *d* electron. Such degeneracy is known to be important from studies of lanthanide impurities in metal hosts[23,28,29], and theoretical calculations predict that the Kondo temperature scales as $T_K \propto \exp(-\pi\varepsilon/2\Gamma)$ for doubly degenerate orbital cases[23,28,29], therefore accounting for our experimental data in a satisfactory fashion. Nevertheless, given the experimental and theoretical uncertainties, this conclusion remains speculative, and further investigation is necessary to resolve the role of orbital degeneracy in the single-V_2-transistor system.

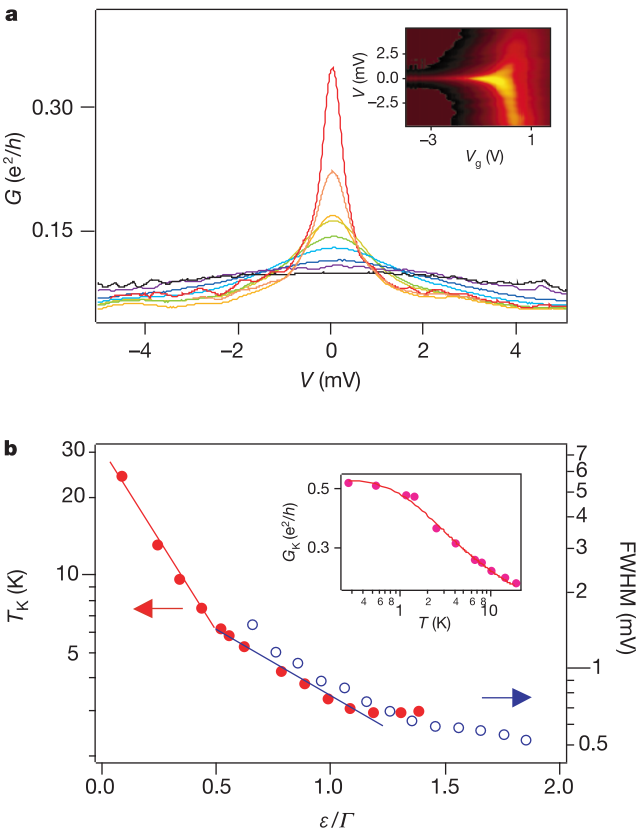

Figure 4 Temperature-dependent transport data from device D3. **a**, A plot of conductance (G) versus V with $V_g = -2.25$ V at various temperatures. The temperatures of the measurements (in K) are $T = 0.3$, 1.0, 2.0, 3.1, 4.2, 6.3, 9.0, 14 and 20, in order of decreasing peak height. Inset, a $\partial I/\partial V$ plot as a function of V and V_g at $T = 300$ mK. The colour scale changes from dark red (0) to bright yellow ($0.55\ e^2/h$). **b**, The Kondo temperature (T_K: filled red circles) and the Kondo peak width determined by the full-width at half-maximum (open blue circles) plotted against ε/Γ in a logarithmic scale. Here $-\varepsilon$ is the energy of the localized electron measured relative to the Fermi level of the metal, and Γ is the level width due to the tunnel coupling to the metallic electrodes. Measurements of the $\partial I/\partial V$ peak widths and slopes that define conductance gaps (inset in **a**) show that Γ is ~30 mV and the gate coupling is $\alpha = C_g/C_\Sigma = 30\,\mathrm{meV}\,V_g^{-1}$ (C_g is the capacitance to the gate, and C_Σ is the total capacitance). This value of α allows the conversion of V_g to ε, because $\varepsilon = \alpha(V_c - V_g)$. We estimate that the values of Γ and ε are accurate to within 20%. Red and blue lines are proportional to $\exp(-3\varepsilon/\Gamma)$ and $\exp(-1.3\varepsilon/\Gamma)$, respectively. As ε/Γ exceeds 2, T_K and the peak widths approach respective asymptotic values. Inset, plot of the Kondo peak height (G_K) as a function of temperature at $\varepsilon = 0.43\Gamma$. The line is a fit to the formula $G_K(T) = G_0/(1 + (2^{1/s} - 1)T^2/T_K^2)^s$, yielding $T_K = 12.2$ K and $s = 0.19$.

Overall, the behaviour of a single-V_2 transistor is well described by the Coulomb blockade model and a Kondo resonance originating from the V_2^+ ion. However, certain transport characteristics of these transistors remain to be explained. As noted previously, device D2 exhibits strongly enhanced conductance values within the nominal conductance-gap region I. The bias position of this feature does not depend on V_g, suggesting that it arises from inelastic cotunnelling events[16,30]. In addition, some devices exhibit one or more $\partial I/\partial V$ peaks outside the conductance gaps. Both observations suggest that the excited electronic or vibrational states may participate in electron transport[1].

The present study shows that molecules can provide a Kondo system where critical parameters of Kondo physics, such as the spin and orbital degrees of freedom, are defined by chemical synthesis. With the recent advances of synthetic methodology, the preparation of molecular clusters possessing adjustable magnetic properties is becoming feasible[21]. Future investigations of such species are expected to provide detailed insight into electron transport through a molecular system where the spin and orbital degeneracies are precisely controlled. ☐

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