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Oxygen vacancy-driven orbital multichannel Kondo effect in Dirac nodal line metals IrO_2 and RuO_2

Juhn-Jong Lin 林志忠

A Long Journey into Exotic Kondo Physics

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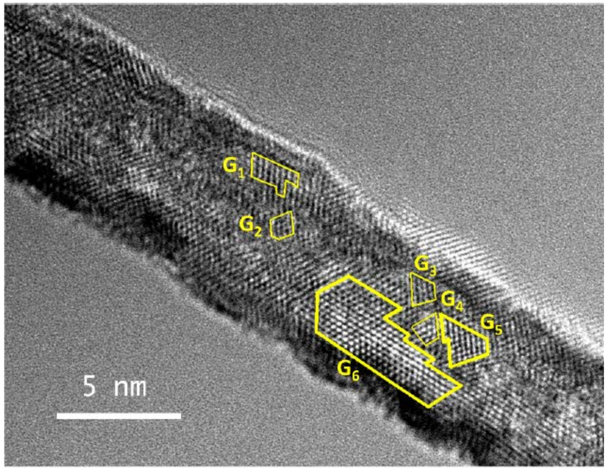
SCIENCE ADVANCES | RESEARCH ARTICLE

Sci. Adv. **3**, e1700135 (2017)

PHYSICAL SCIENCES

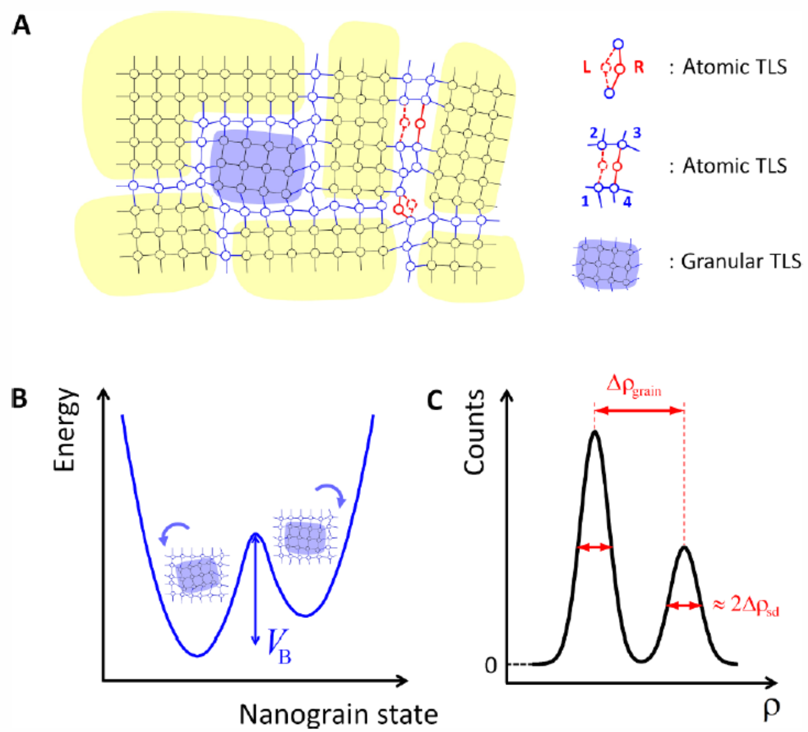
Probing nanocrystalline grain dynamics in nanodevices

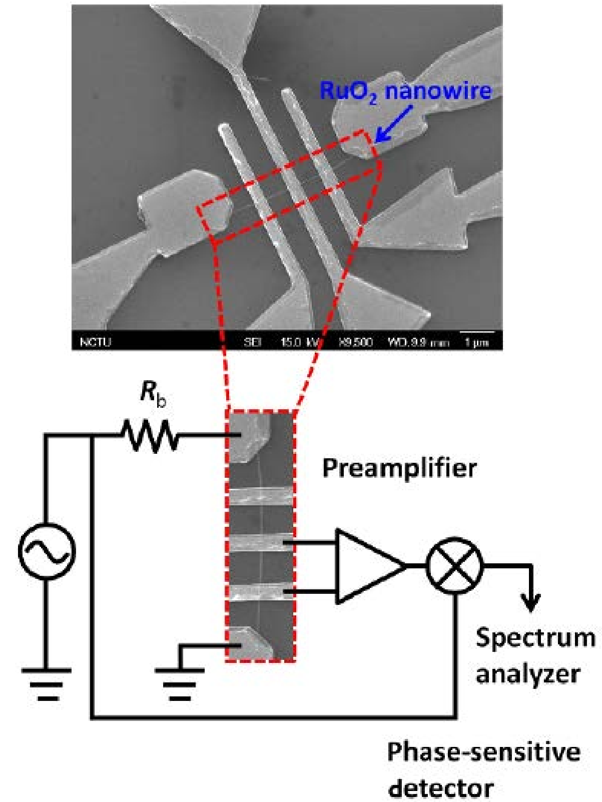
Sheng-Shiuan Yeh,[1] Wen-Yao Chang,[1] Juhn-Jong Lin[1,2]*



polycrystalline nanowire

We demonstrate theoretical conception and experimental method to quantitatively characterize nanocrystallite motion in RuO_2 nanowires.





Keywords:

Kondo physics

Magnetic spin-half Kondo effect

Nonmagnetic orbital Kondo effect

One-channel Kondo effect

Two-channel Kondo effect

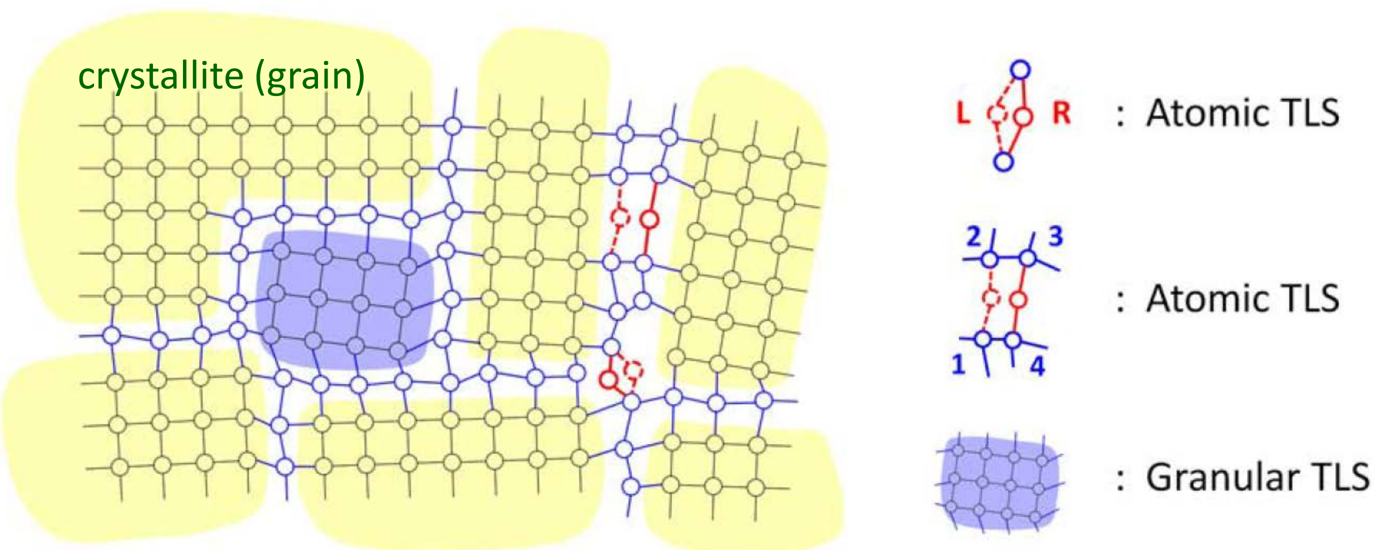
Dynamic defects

Dynamic scattering centers

Two-level systems

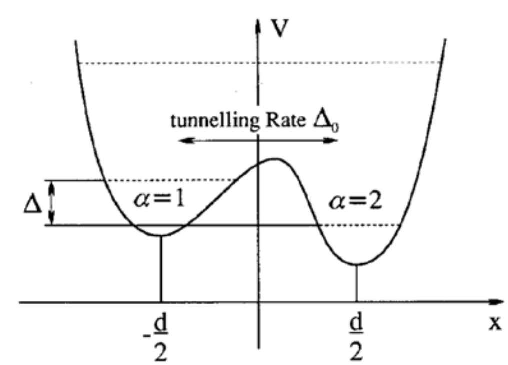
Fast two-level systems

Defect electrons



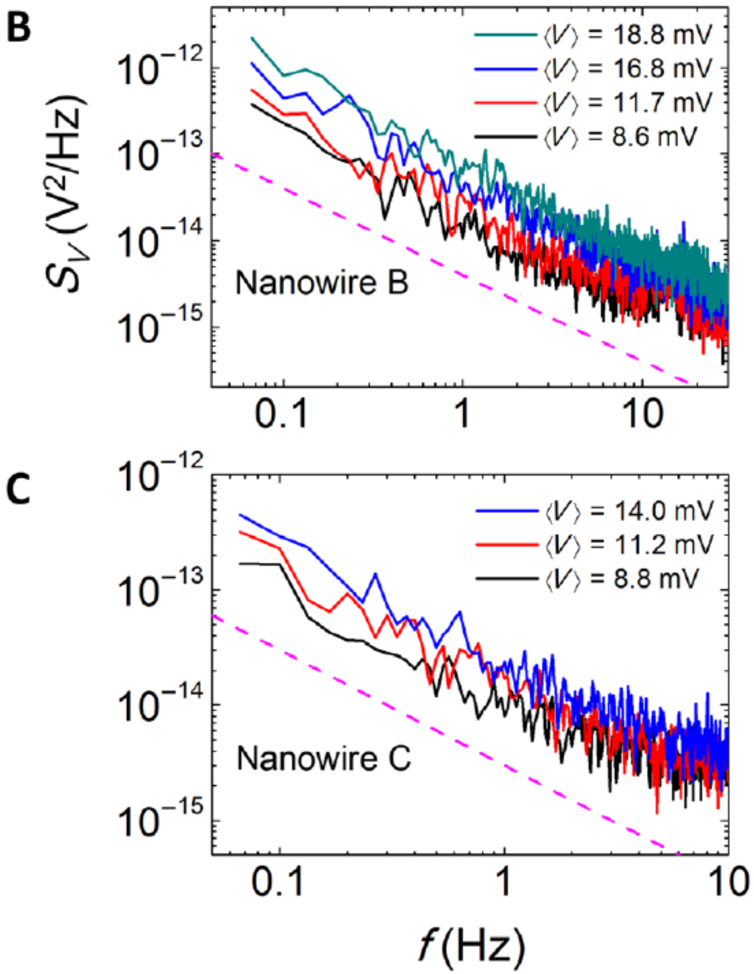
A defect having two equivalent (nearby) sites in a solid

An object switching in a double-well potential, modeled as a two-level system

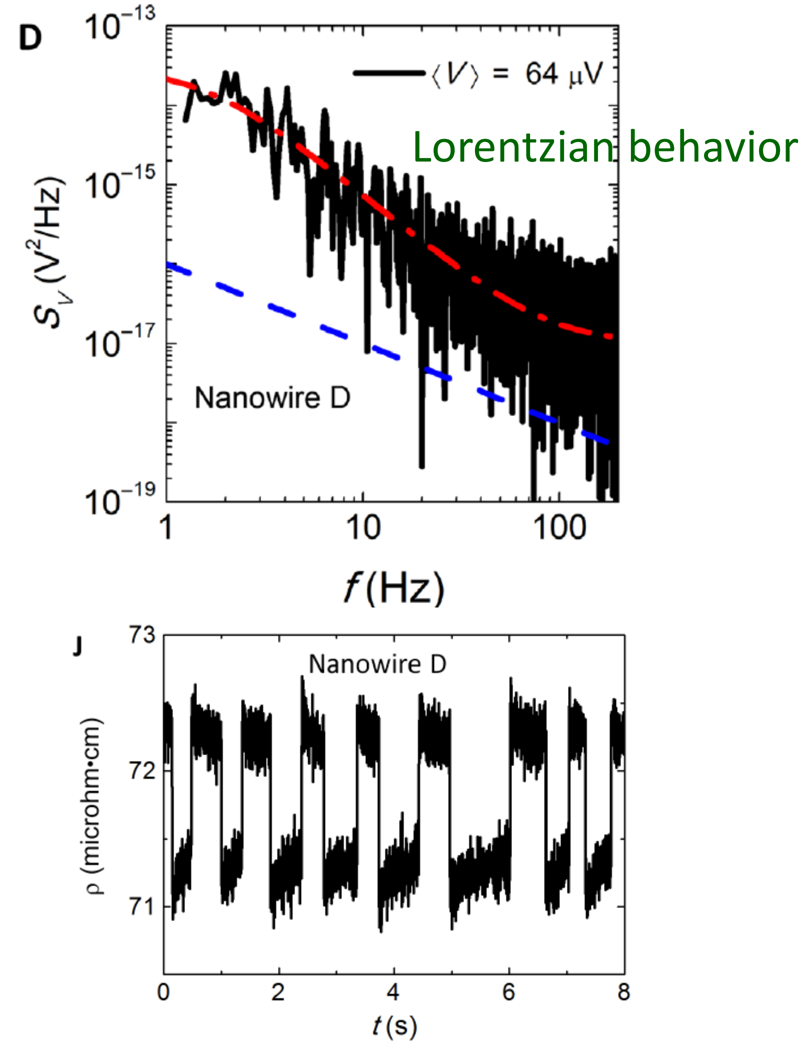


Noise due to atomic and granular dynamic defects

The motion of a large number of slow dynamic defects causes low-frequency (1/f) noise.



The motion of a single nanocrystallite leads to random telegraph noise.



nature COMMUNICATIONS

Vol. 11, 4749 (2020)

ARTICLE

Check for updates

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Oxygen vacancy-driven orbital multichannel Kondo effect in Dirac nodal line metals IrO_2 and RuO_2

Sheng-Shiuan Yeh[1,2,3], Ta-Kang Su[1], An-Shao Lien[1], Farzaneh Zamani[4], Johann Kroha[4], Chao-Ching Liao[1], Stefan Kirchner[5,6]✉ & Juhn-Jong Lin[1,2,7]✉

“**Strong electron correlations** may give rise to an **unconventional metallic state** accompanying non-magnetic Kondo scattering. Here, the authors report signatures of **orbital one- and two-channel Kondo physics** in Dirac nodal line metals RuO_2 and IrO_2 nanowires.”

Experimental realization of **non-Fermi liquid** behavior at low temperatures!

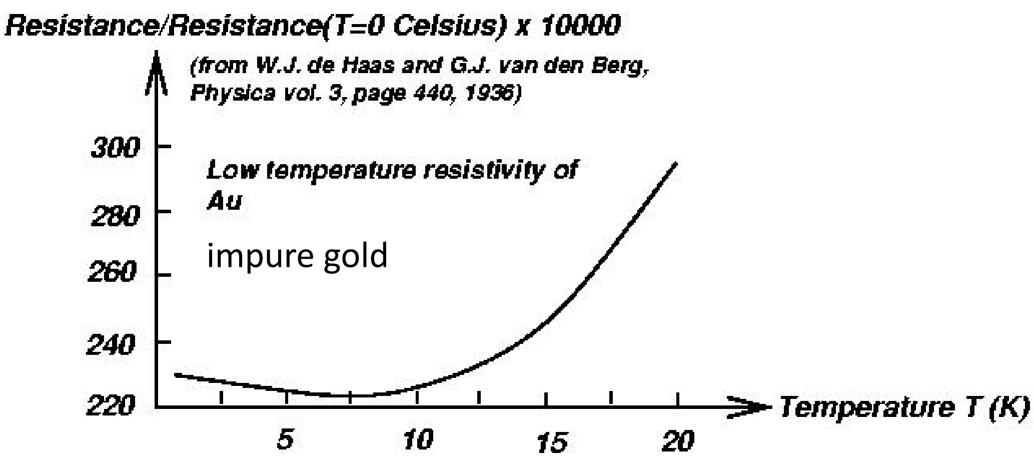
Spin-half magnetic Kondo effect

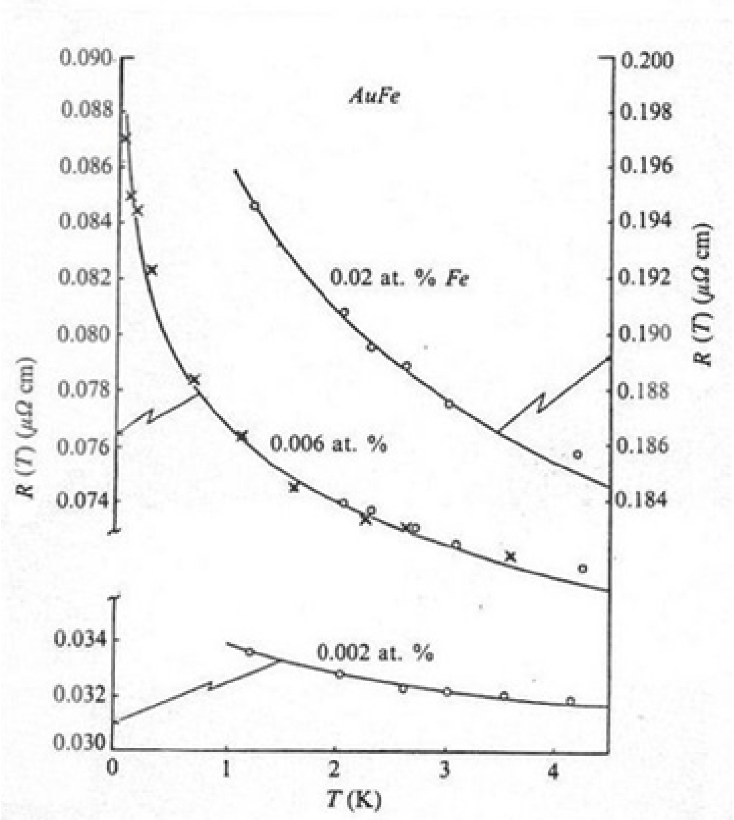
A localized S = ½ magnetic impurity causes the standard Kondo effect

Experimental discovery in 1930s at Kamerlingh Onnes' Lab. (Leiden)

Theoretical explanation in 1960s

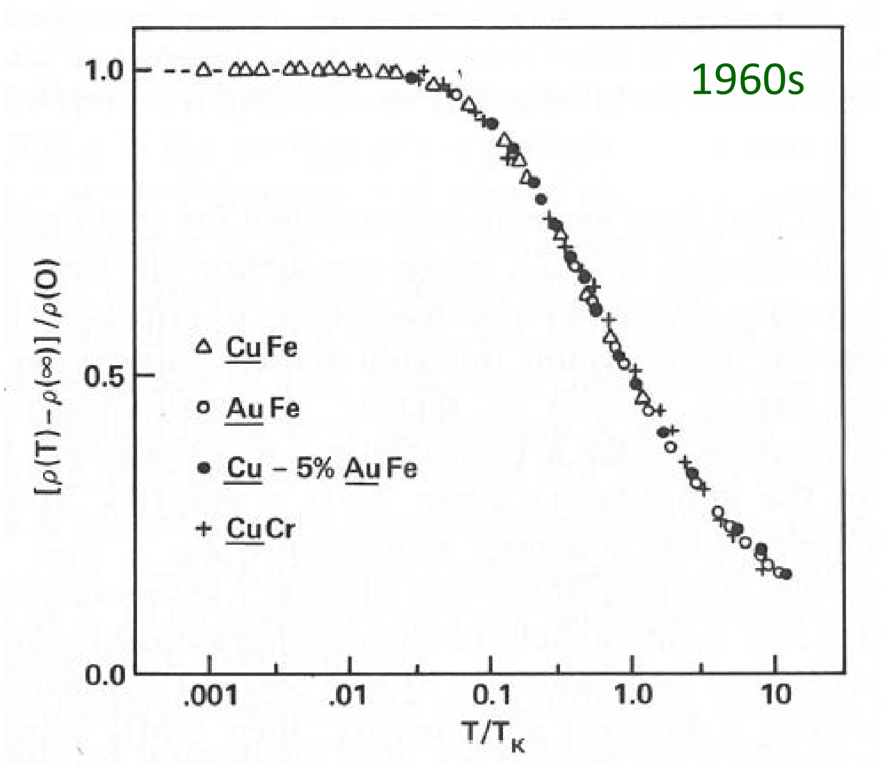
W.J. de Haas and G.J. van den Berg (1936)





Comparison of experimental and theoretical ρ(*T*) curves for dilute AuFe alloys [J. Kondo, Prog. Theor. Phys. **32**, 37 (1964)]

Kondo resistivity: universal temperature dependence

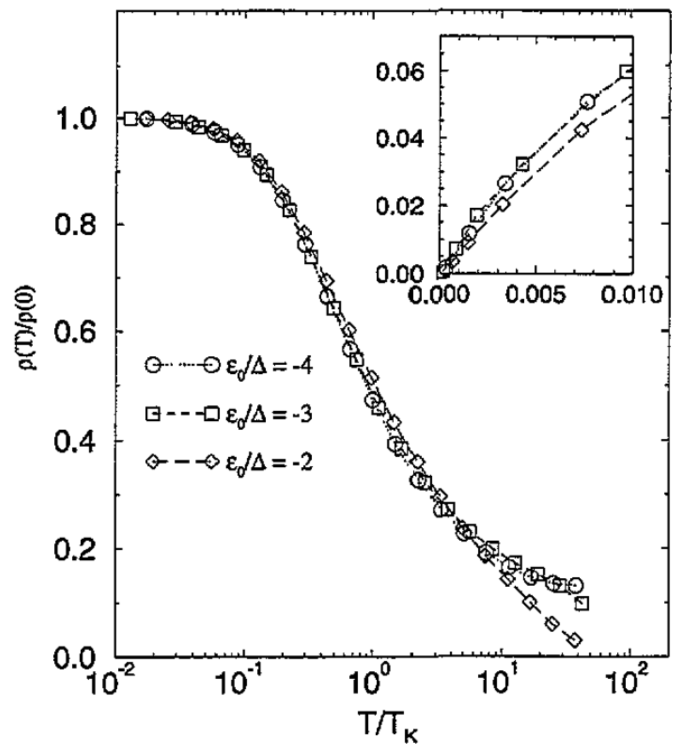


Normalized Kondo resistivity vs. reduced temperature T/T_K

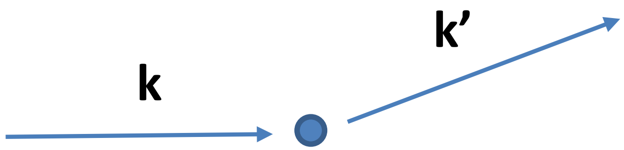
(Taken from "Long Range Order in Solids", by R. M. White and T. H. Geballe, Fig. VII.14)

Numerical renormalization group (NRG) calculations: one-channel Kondo (1CK) scaling form

T. A. Costi, A. C. Hewson & V. Zlatic
JPCM **6**, 2519 (1994)



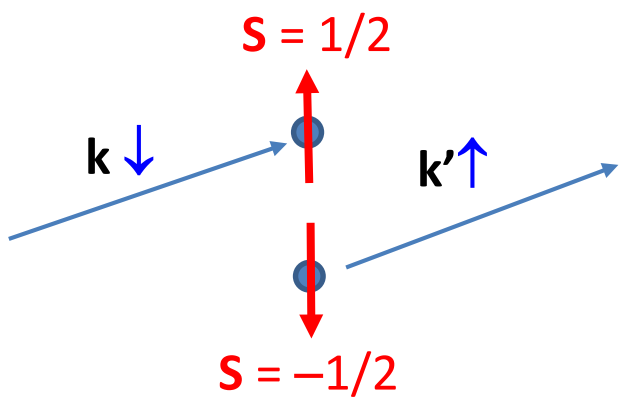
Scattering off a localized spin-half magnetic impurity



A **nonmagnetic** impurity (defect) in a metal

$\Rightarrow$ Elastic electron scattering

$\Rightarrow$ A constant, "residual resistivity" at low T



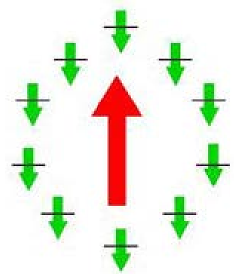
A localized **magnetic** impurity (S = ½) in a metal

$\Rightarrow$ Spin-spin coupling (**s-d exchange interaction**)

$\Rightarrow$ log(T) resistivity increase below a characteristic energy scale T_K

$\Rightarrow$ Fermi-liquid physics as $T \ll T_K$

$$H = \sum_{k,\sigma} \varepsilon_k c^{\dagger}_{k,\sigma} c_{k,\sigma} + J_K \vec{S} \cdot \vec{s}_c$$



One conduction-electron band (a Fermi sea) couples with the localized spin-½ magnetic moment, forming a spin-singlet ground state as $T \rightarrow 0$ K.

A quantum impurity with internal degree of freedom

Progress of Theoretical Physics, Vol. 32, No. 1, July 1964

Resistance Minimum in Dilute Magnetic Alloys

Physica 84B (1976) 40–49

Cf. Localized magnetic moments

LOCALIZED ATOMIC STATES IN METALS

Physica 84B (1976) 207–212

LOCALIZED ATOMIC STATES IN METALS

II. RESISTIVITY AND FREE ENERGY

J. KONDO

Electrotechnical Laboratory, Tanashi, Tokyo and Department of Applied Physics, Faculty of Engineering, University of Tokyo, Japan

Received 31 May 1976

"We investigate a case where the interaction is of the Coulomb type, which may vary depending on the states of the localized system. The simplest of such a system may be **an impurity atom, which can jump between two equivalent sites.**"

$$\Psi = \psi(\vec{r})\cdot\vec{s}_c \;\Rightarrow\; \psi(\vec{r}_L),\; \psi(\vec{r}_R)$$

A quantum impurity with internal degree of freedom

"The problem is similar to the **s-d problem** in that the conduction electrons interact with **an impurity system having an internal degree of freedom**. In the present case, the relevant interaction is the **orbital-orbital interaction**, since we are considering the Coulomb-type interaction."

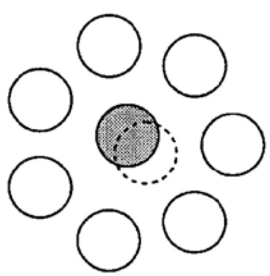
"Impurity-spin flipping" vs. "Impurity-site switching"

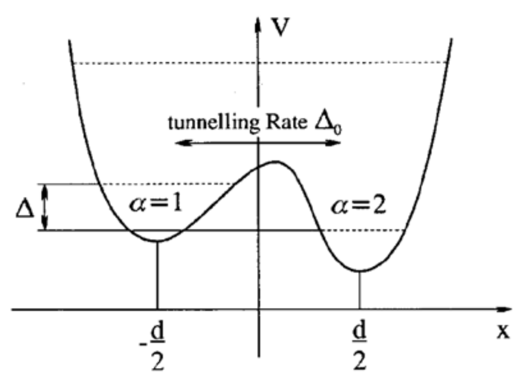
Two equivalent sites

Double-well potential $\Rightarrow$ "Two-level system" model

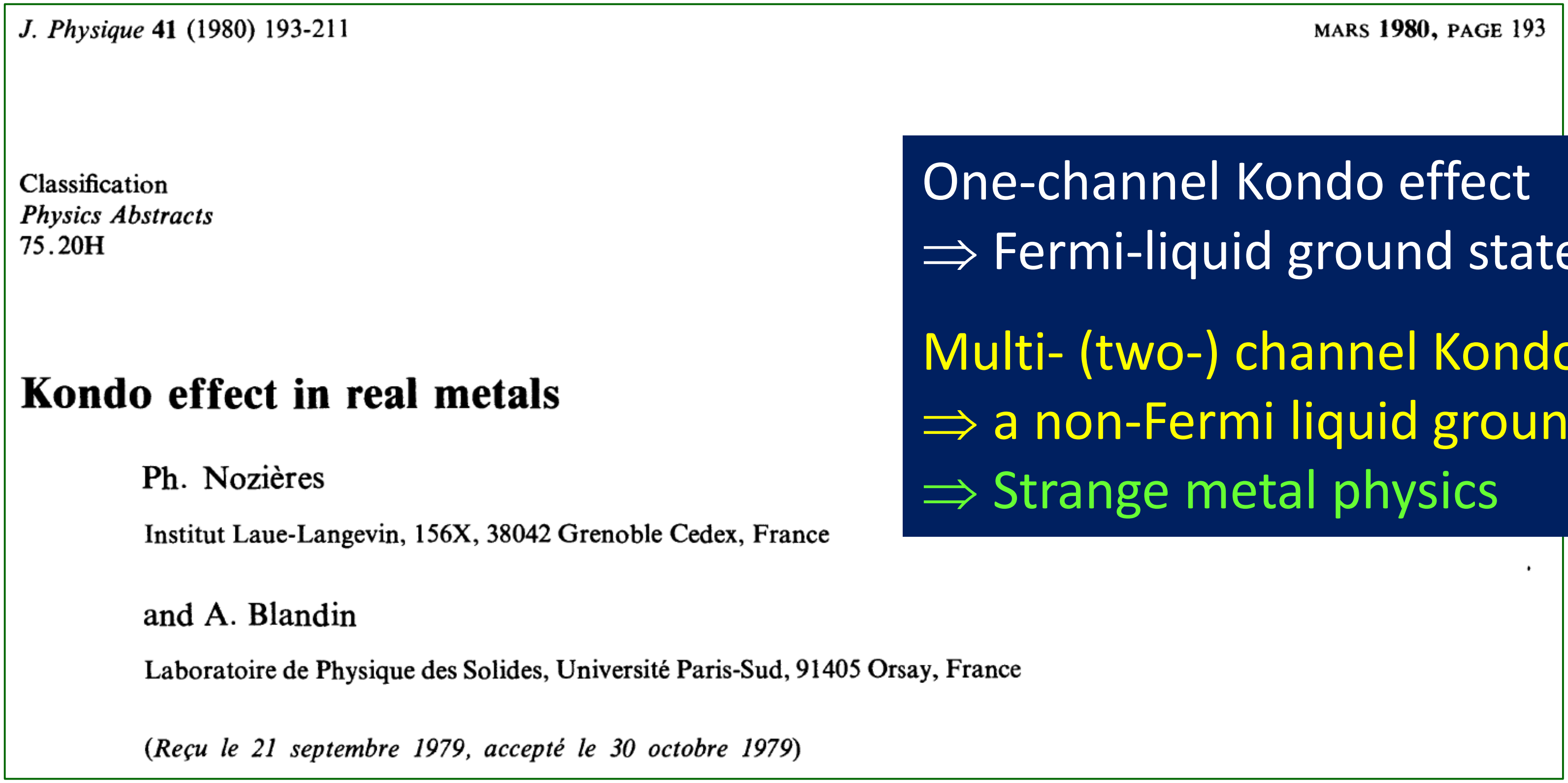
$\Rightarrow$ Non-magnetic orbital Kondo effect !

J. Kondo (1976)





Spin multi-channel Kondo effect


J. Physique **41** (1980) 193-211 MARS **1980**, PAGE 193

Classification
Physics Abstracts
75.20H

Kondo effect in real metals

Ph. Nozières
Institut Laue-Langevin, 156X, 38042 Grenoble Cedex, France

and A. Blandin
Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France

(*Reçu le 21 septembre 1979, accepté le 30 octobre 1979*)

One-channel Kondo effect
⇒ Fermi-liquid ground state

Multi- (two-) channel Kondo effect
⇒ a non-Fermi liquid ground state
⇒ Strange metal physics

The multichannel Kondo model:

A few conduction-electron bands interact with a localized quantum impurity which has internal degree of freedom.

"Over-screening" shall result in a non-Fermi-liquid ground state.

Orbital multi-channel Kondo effect

Exotic Kondo effects in metals: magnetic ions in a crystalline electric field and tunnelling centres

D. L. Cox

Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA and Department of Physics, University of California, Davis, California 95616, USA

and A. Zawadowski

Institute of Physics and Research Group of Hungarian Academy of Sciences,
Techn
Resea

344 pages

PHYSICAL REVIEW B VOLUME 28, NUMBER 3 1 AUGUST 1983

Theory of the interaction between electrons and the two-level system in amorphous metals. I. Noncommutative model Hamiltonian and scaling of first order

K. Vladár
Central Research Institute for Physics, Post Office Box 49, H-1525 Budapest, Hungary

A. Zawadowski*
Department of Physics, University of California, Los Angeles, California 90024
(Received 10 June 1982)

I. 18 pages
II. 14 pages
III. 17 pages

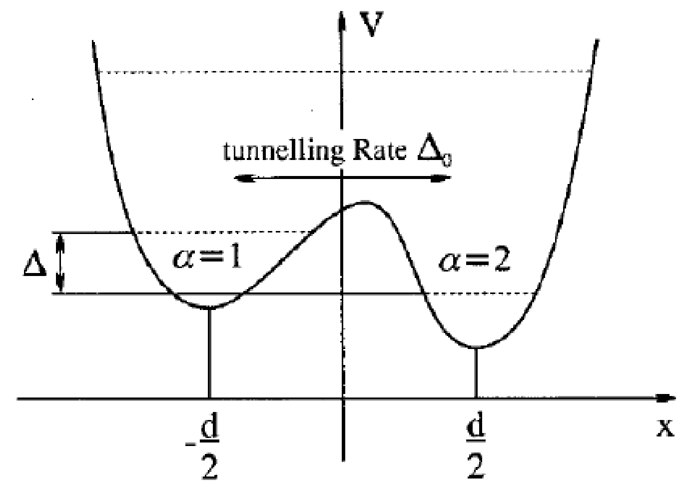
$$H = \sum_{i,k,\sigma} \varepsilon_k \psi^{\dagger}_{i,k,\sigma} \psi_{i,k,\sigma} + J_K \sum_{i=1}^{M=2} \vec{S} \cdot \vec{s}_c^{\,i}$$

- Two-channel Kondo effect
- non-Fermi-liquid ground state

M channels (M Fermi seas)

Vacancies in $ZrAs_{1.58}Se_{0.39}$ & two-level systems

Defect potential gives rise to several minima separated by a potential barrier: **two-level systems**



$$\left.\begin{array}{l} |\uparrow\rangle \\ |\downarrow\rangle \end{array}\right\} \text{ if atom is in} \left\{\begin{array}{c} \text{left} \\ \text{right} \end{array}\right\} \text{ position}$$

pseudospin algebra

coupling to conduction electrons induces ‘assisted’ tunneling

effective “spin-spin” interaction is very anisotropic

conduction electron spin acts as a bystander
– gives rise to 2 degenerate channels due to time-reversal symmetry

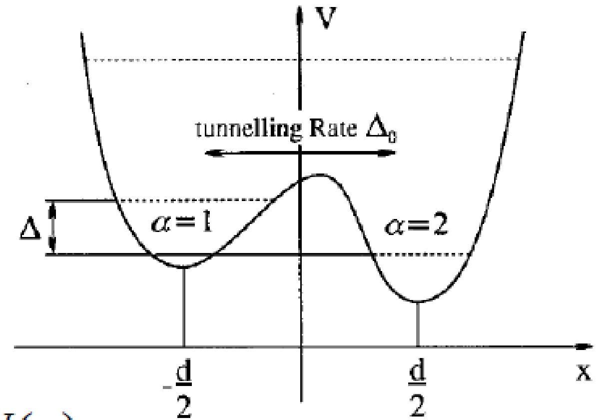
→ **system should flow to the non-magnetic two-channel Kondo fixed point**

→ **insensitivity to applied magnetic fields** (Vladar, Zawadowski, Zarand, von Delft ...)

(courtesy of S. Kirchner)

Two-level systems: the no-go theorem

Problem: a tunneling term between the two minima appears, not forbidden by symmetry



effect of excited states cannot be ignored

Aleiner, et al (2002):

Consider heavy particle in a general double well potential V(q):

-bosonization of the action
-integrating out conduction electrons

One-dimensional Coulomb gas of kinks, anti-kinks which describe tunneling events between the solutions of

$$M\frac{d^2q}{d\tau^2} = V'[q]$$

Tunneling rate Δ_0 and effective magnetic field h are not independent $h_{\rm eff} \gg T_K$

The two-channel Kondo fixed point can never be reached!

(courtesy of S. Kirchner)

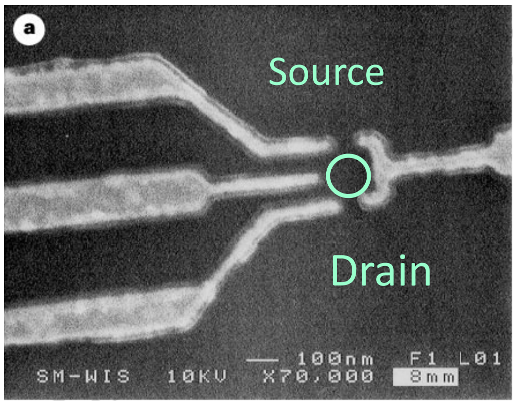
PHYSICS WORLD, January 2001

Nanotechnology has rekindled interest in the Kondo effect, one of the most widely studied phenomena in condensed-matter physics

Revival of the Kondo effect

Leo Kouwenhoven and Leonid Glazman

The theory that describes the scattering of electrons from a localized magnetic impurity was initiated by the work of Jun Kondo in 1964



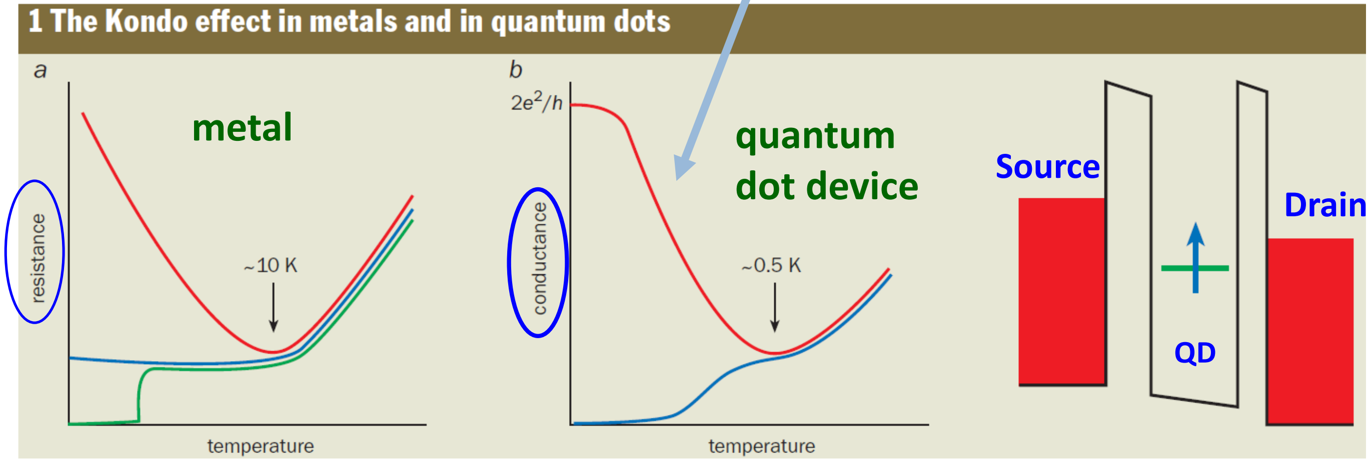
A semiconductor quantum dot (~ 100 nm) containing an **odd** number of electrons can act as a localized spin- ½ magnetic impurity, giving rise to Kondo physics

$\Rightarrow$ **Kondo "conductance" G(T)**

$T_K \sim 0.2$ K

A quantum dot (*S*=1/2) coupled to source-drain electrodes

Goldhaber-Gordon et al., Nature 391, 156 (1998)



1 The Kondo effect in metals and in quantum dots

Motivation

two-channel

Nanotechnology has rekindled interest in the Kondo effect,
one of the most widely studied phenomena in condensed-matter physics

Revival of the Kondo effect

Leo Kouwenhoven and Leonid Glazman

The theory that describes the scattering of electrons from a localized magnetic impurity was initiated by the work of Jun Kondo in 1964

Phys. World **14**, 33 (2001)

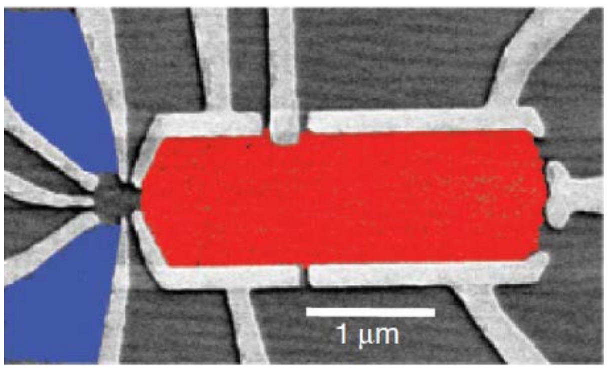
A suggested route to 2CK effect

Vol 446 | 8 March 2007 | doi:10.1038/nature05556 nature

LETTERS

Observation of the two-channel Kondo effect

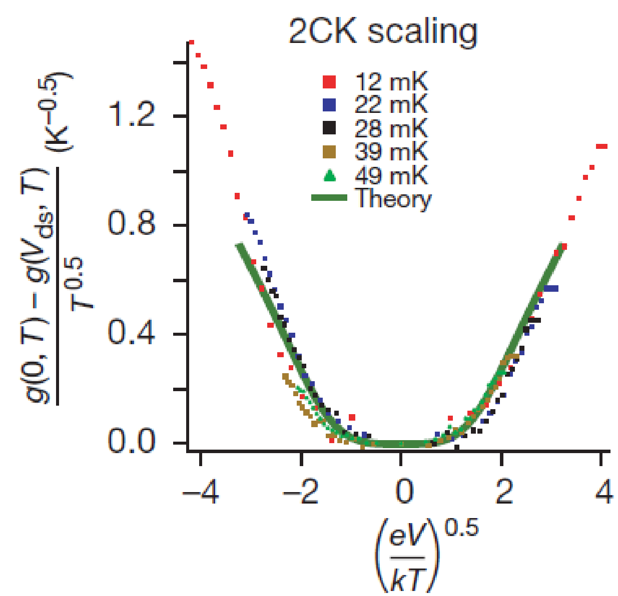
R. M. Potok[1,3]†, I. G. Rau[2], Hadas Shtrikman[4], Yuval Oreg[4] & D. Goldhaber-Gordon[1]



$$G(V,T) = \frac{dI(V,T)}{dV}$$

$\sqrt{T}$ temperature behavior

A non-Fermi-liquid signature



Problems and difficulties:

1) Fine-tuning is required.

2) Implications for real solids and topological quantum materials is unclear.

3) T_K value is very small.

Orbital two-channel Kondo effect in real materials

Experimental signature:

A $\sqrt{T}$ resistivity increase at low temperatures (in the residual-resistivity regime). The resistivity increase is independent of an applied magnetic field.

$$\Delta\rho_{2CK}(T,B) \propto -n_d\sqrt{T}$$

n_d : dynamic defect density

Altshuler & Aronov:

An ubiquitous effect in real conductors !

Electron-electron interaction (EEI) effect causes a $\sqrt{T}$ resistivity increase at low temperatures in 3D weakly disordered metals.

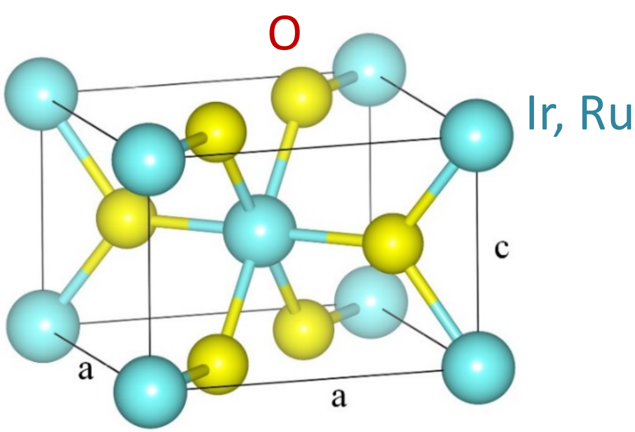
$$\frac{\Delta\rho(T)}{\rho_0} = -\frac{0.915e^2}{4\pi^2\hbar}\left(\frac{4}{3}-\frac{3}{2}F\right)\rho_0\sqrt{\frac{k_B T}{\hbar D}}$$

D: electron diffusion constant

$0 \leq F \leq 1$: a screening factor

The presence of impurities cause multiple elastic scattering, leading to quantum interference of electronic waves, which in turn results in enhanced e-e interaction. $\Rightarrow$ The density of states at E_F is suppressed.

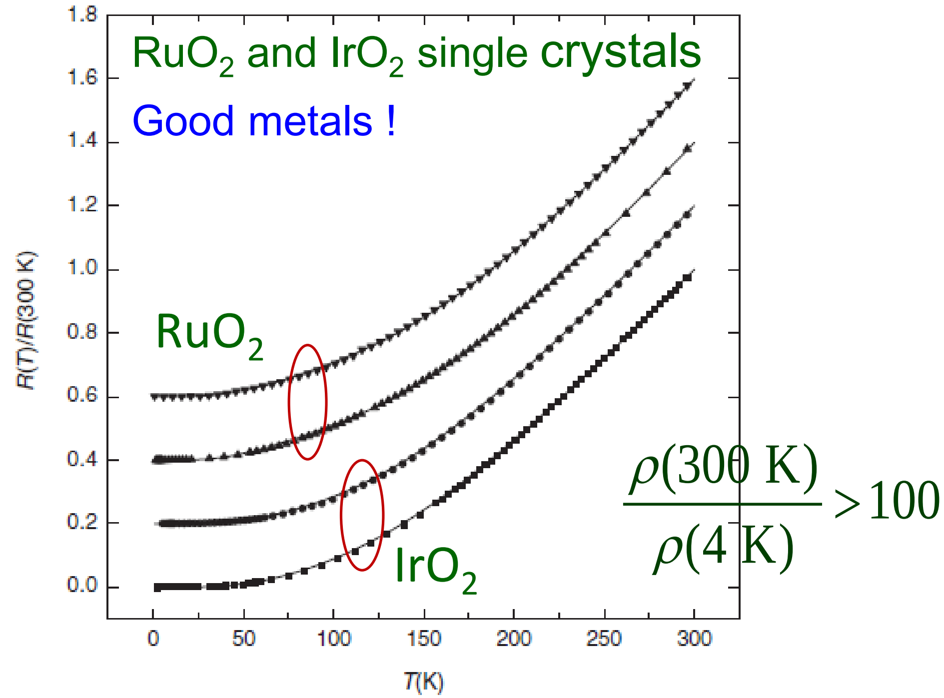
IrO_2 and RuO_2 crystalizes in the rutile structure

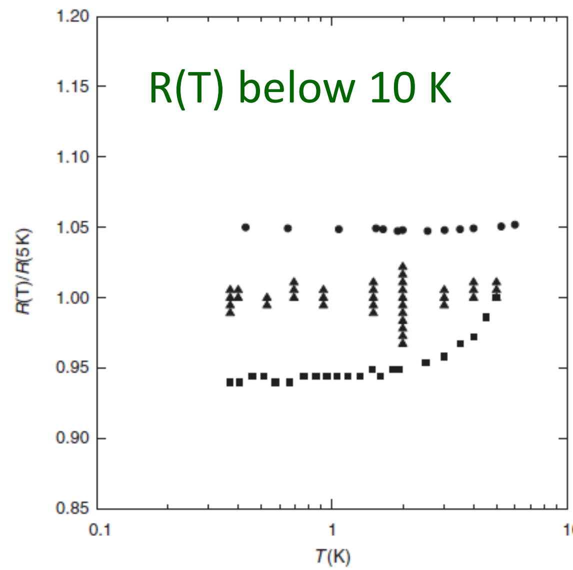


Ir: [Xe]$4f^{14}5d^{7}6s^{2}$

Ir^{+4}: [Xe]$4f^{14}5d^{5}$

5*d* orbitals are half-filled in IrO_2





J. J. Lin et al., JPCM 16, 8035 (2004)

Recent discovery: Dirac nodal line metals IrO_2 and RuO_2

nature COMMUNICATIONS

Large spin Hall resistivity

ARTI

Received

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det

Kohei F
YoshiC

PHYSICAL REVIEW B **99**, 195106 (2019)

Strong spin-orbit coupling and Dirac nodal lines in the three-dimensional electronic structure of metallic rutile IrO_2

X. Xu,[1,*] J. Jiang,[2,3,4,*] W. J. Shi,[5] Vicky Süß,[5] C. Shekhar,[5] S. C. Sun,[1] Y. J. Chen,[1] S.-K. Mo,[4] C. Felser,[5] B. H. Yan,[5]
H. F. Yang,[2] Z. K. Liu,[2] Y. Sun,[5] L. X. Yang,[1,6,†] and Y. L. Chen[1,2,3,‡]
[1]*State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University,*

PHYSICAL REVIEW MATERIALS **3**, 064205 (2019)

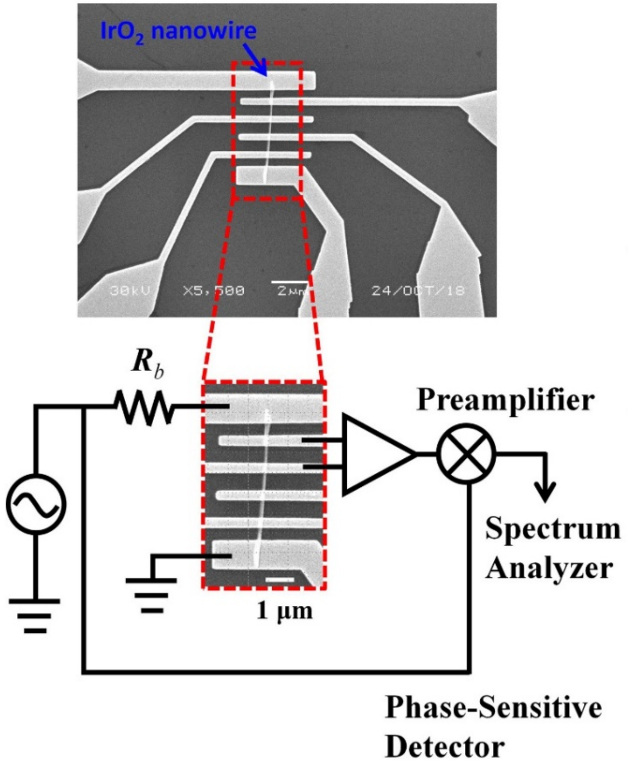
Editors' Suggestion

Dirac nodal lines protected against spin-orbit interaction in IrO_2

J. N. Nelson,[1] J. P. Ruf,[1] Y. Lee,[1] C. Zeledon,[2] J. K. Kawasaki,[3] S. Moser,[4] C. Jozwiak,[5] E. Rotenberg,[5] A. Bostwick,[5]
D. G. Schlom,[2,6] K. M. Shen,[1,6,*] and L. Moreschini[2,†]
[1]*Laboratory of Atomic and Solid State Physics, Department of Physics, Cornell University, Ithaca, New York 14853, USA*
[2]*Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14853, USA*
[3]*Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA*
[4]*Physikalisches Institut, Universität Würzburg, D-97074 Würzburg, Germany*
[5]*Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[6]*Kavli Institute at Cornell for Nanoscale Science, Ithaca, New York 14853, USA*

Low-temperature Kondo resistivity in rutile nanowires

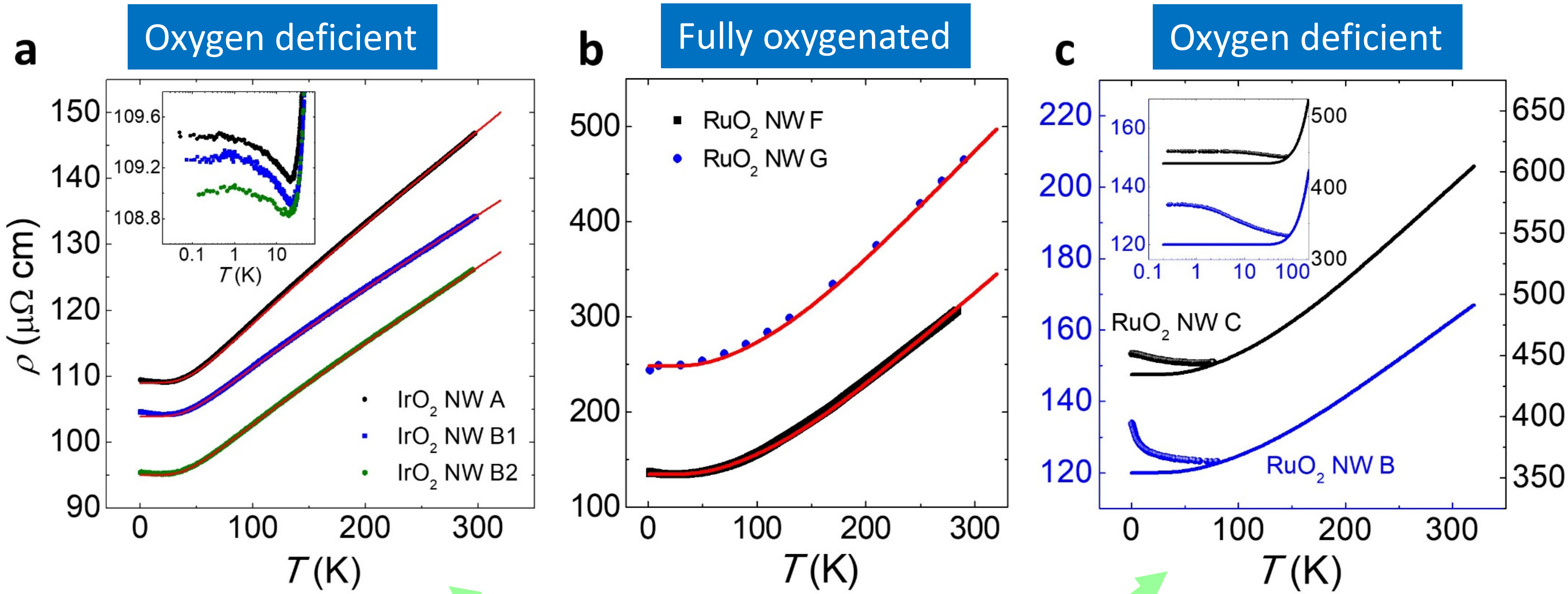
nanowire diameter
≈ 50 – 190 nm



- IrO_2 nanowires were grown via MOCVD. RuO_2 nanowires were grown via thermal evaporation.
- Four-probe R(T) measurements down to 50 mK, in applied magnetic field up to 9 T.
- Nanowires were measured as-grown, after annealing in vacuum, and after oxygenation.
- **Thermal annealing in vacuum generates oxygen vacancies which generate dynamic scattering defects, causing orbital Kondo effect.**
- **The orbital Kondo effect is suppressed in (fully) oxygenated nanowires.**

Nanowires were grown by Y.S. Huang's group (NTUST), and F.R. Chen & J.J. Kai's group (NTHU).

Resistivity vs. temperature for IrO_2 and RuO_2 nanowires

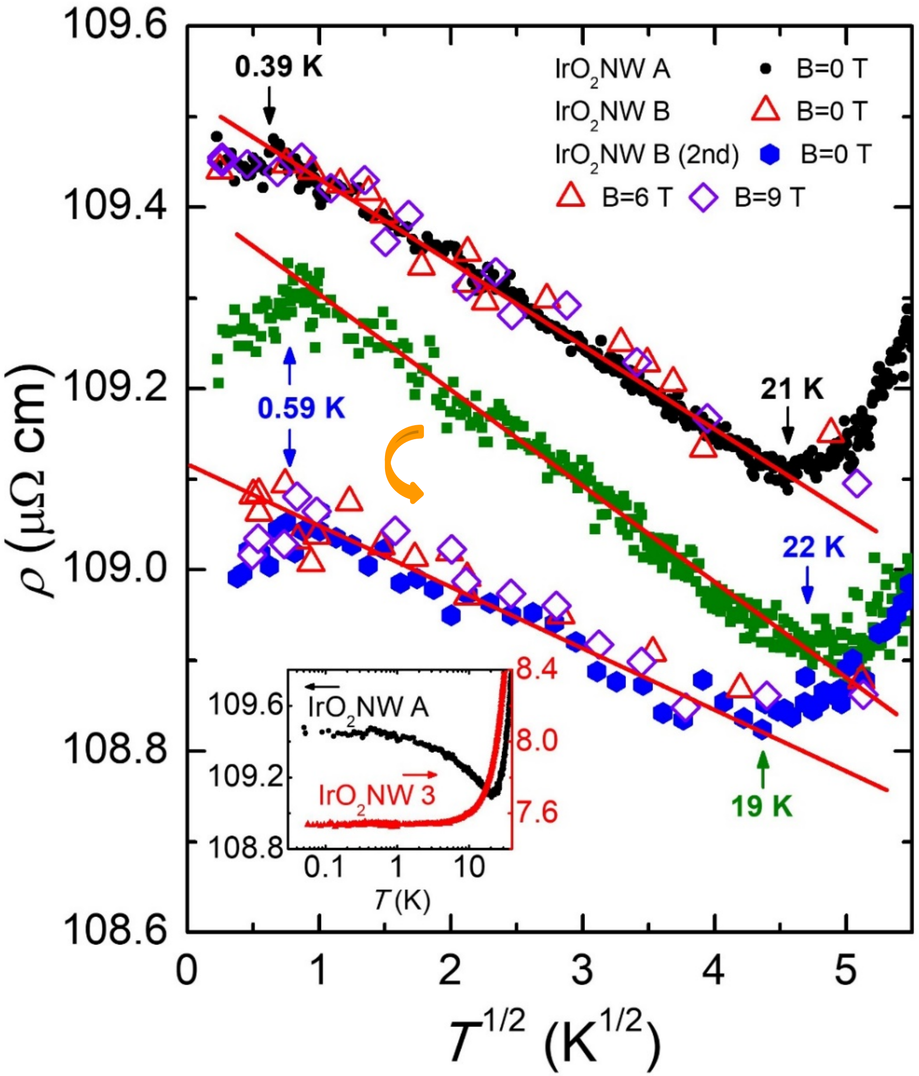


Thermal annealing in vacuum
caused a low-T resistivity increase

The overall resistivity curve $\rho(T)$ reveals Boltzmann-transport behavior.

The low-T resistivity increase can be repeatedly introduced (suppressed) by thermal annealing in vacuum (oxygen).

$\sqrt{T}$ resistivity increase in paramagnetic IrO_2 nanowires



- A $\sqrt{T}$ resistivity increase is found after annealing in vacuum.
- The $\sqrt{T}$ resistivity increase shows insensitivity to magnetic field.
- After aging in air, the $\sqrt{T}$ behavior persists, but showing a smaller resistivity increase.
- Oxygenation reduces dynamic scattering defects, producing a smaller orbital Kondo effect.
- A deviation from the $\sqrt{T}$ behavior occurs around 0.5 K !

Ruling out 3D electron-electron interaction effect

- A deviation from the $\sqrt{T}$ dependence at ~0.5 K is incompatible with the 3D EEI effect.

- The observed resistivity increase (~0.5%) is more than one order of magnitude as would be predicted by the 3D EEI effect (~0.03%).

- The residual resistivities ρ_0(B1) = 73.9 μΩ cm and ρ_0(B2) = 75.0 μΩ cm differ by ≈1%. The 3D EEI effect predicts a ≈3% difference in resistivity increase. But, experiment shows ≈50% difference.

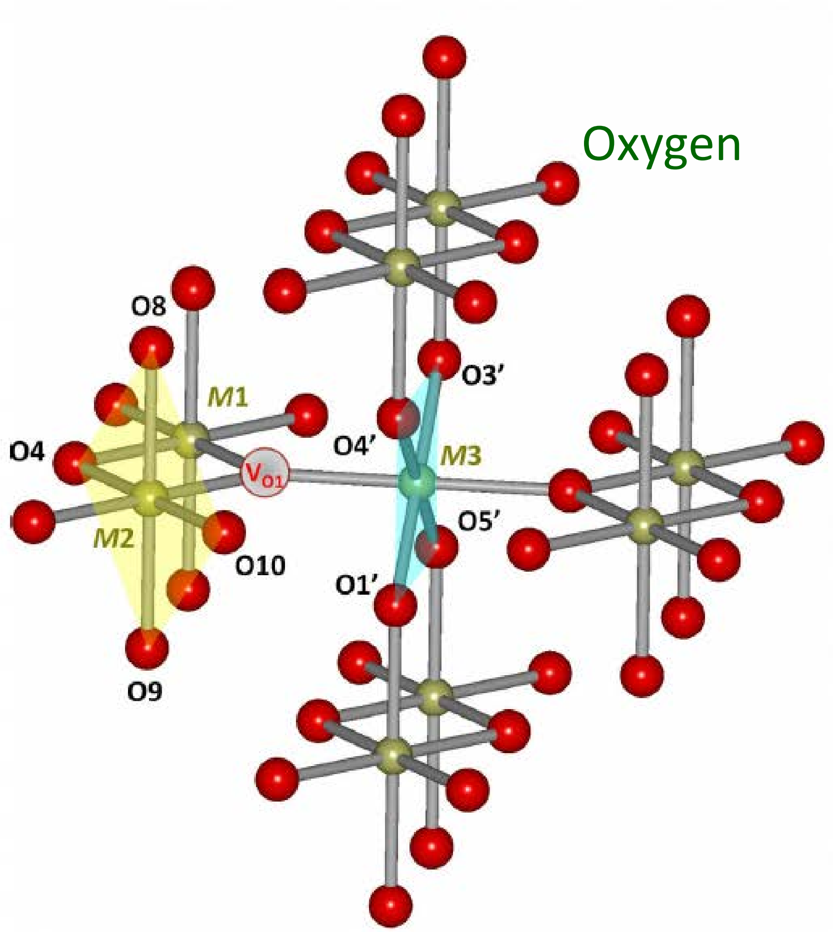
$$\frac{\Delta\rho(T)}{\rho(T_0)} = -\frac{0.915e^2}{4\pi^2\hbar}\left(\frac{4}{3}-\frac{3}{2}\tilde{F}\right)\rho(T_0)\sqrt{\frac{k_B}{\hbar D}}\left(\sqrt{T}-\sqrt{T_0}\right)$$

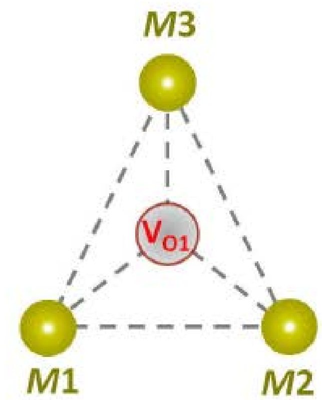
≈ 3×10^{-4} in our MO_2 nanowires

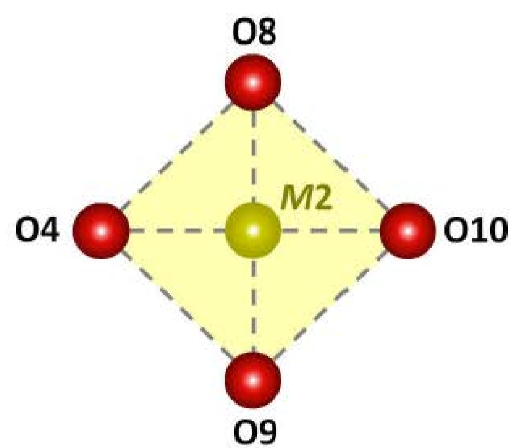
Independence of applied magnetic field of the resistivity increase is in accord with nonmagnetic orbital 2CK effect !

Crystal Structure of MO_2 & Oxygen Vacancies

Oxygen vacancies lead to an almost perfect C_4-symmetry around the transition metal ions M1 & M2 next to the vacant site:

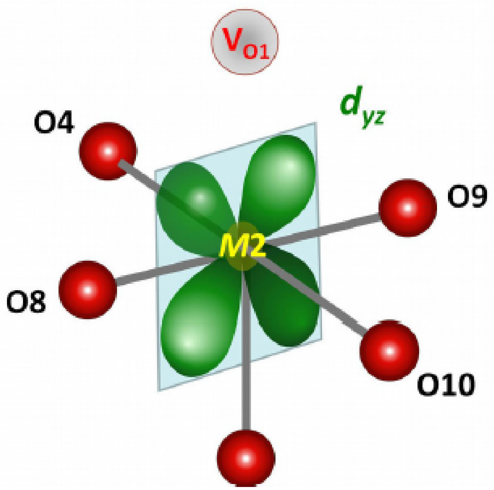


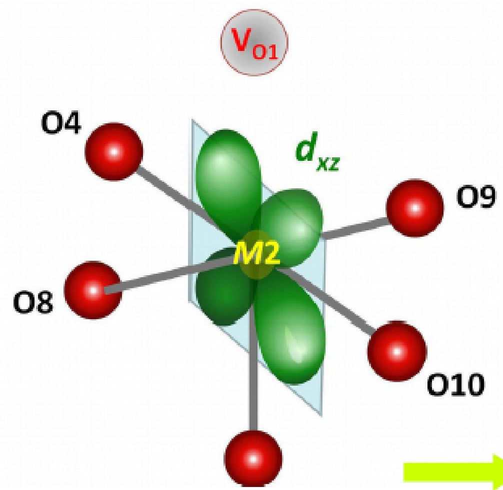


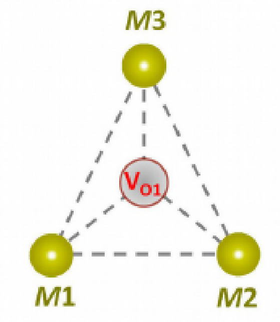


(courtesy of S. Kirchner)

Orbital two-channel Kondo effect in MO_2







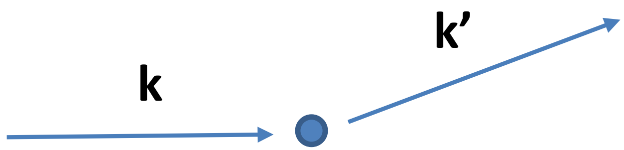
→ d_{xz}- and d_{yz} -orbitals are degenerate

- Every oxygen vacancy generates two *defect electrons* due to charge neutrality.
- Coulomb repulsion forces the *defect electrons* to localize at different transition metal ion sites near the vacancy site.
- For Ir-ions in IrO_2: 5d-shell is half-filled
- The defect electron at M2 (M1) can localize in the d_{xz}-orbital or d_{yz}-orbital – equivalent to spin-up and spin-down state → orbital Kondo effect
- Spin-degenerate conduction band: two independent scattering channels

→ **Orbital two-channel Kondo effect**

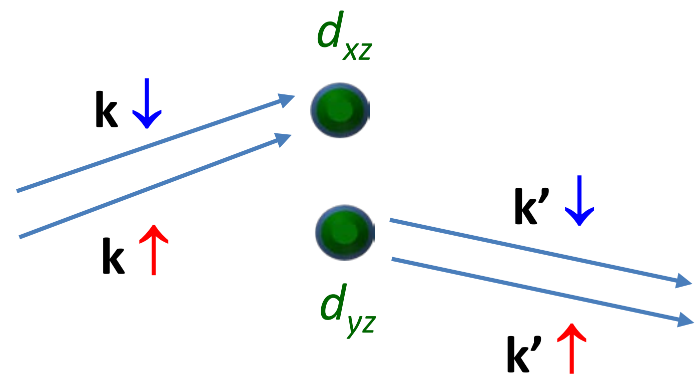
(courtesy of S. Kirchner)

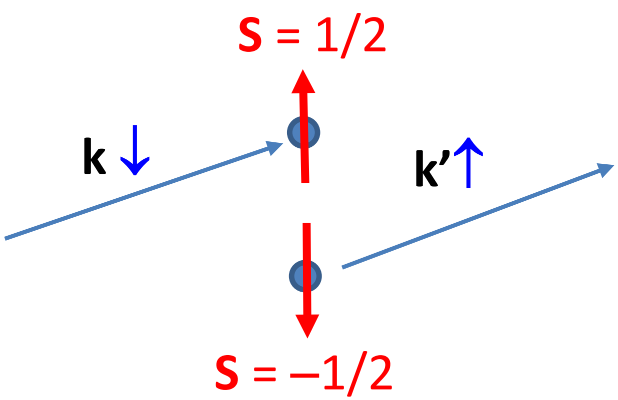
Heuristic picture for electron-quantum impurity scattering



Elastic electron-impurity scattering

⇒ “residual resistivity”





Magnetic spin-flip scattering

⇒ Standard 1CK effect

S =±1/2 degenerate doublet states

Electron-quantum impurity scattering:

The quantum impurity M^{+3} contains a defect electron which tunnels between the two-fold degenerate d_{xz} and d_{yz} orbitals.

The spin-up and spin-down conduction electrons act as two independent and equivalent channels.

⇒ Nonmagnetic orbital 2CK effect !

Transport anomalies in MO_2

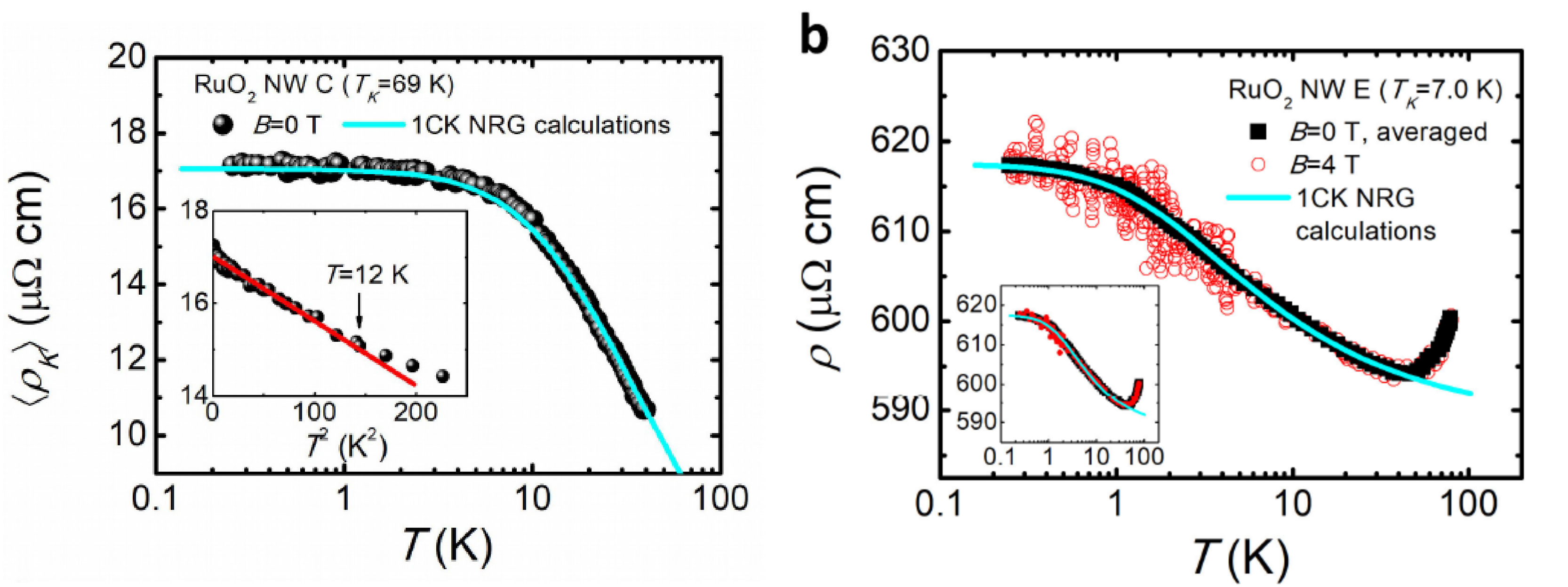
Can we test that model?

Lifting the spin degeneracy would lead to an orbital one-channel Kondo effect

→ study anti-ferromagnetic RuO_2 (same structure as IrO_2)

In RuO_2 the $4d_{xz}$ and $4d_{yz}$ orbitals are half filled while the $4d_{x^2-y^2}$ orbital is located well below the Fermi energy and is completely filled.

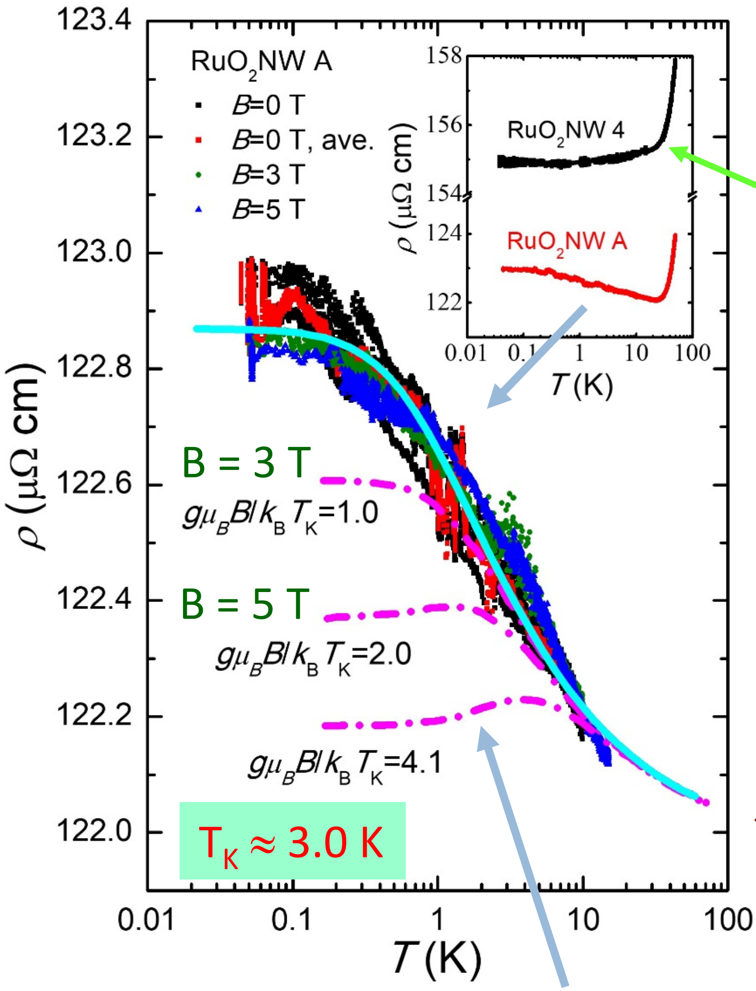
[Berlijn et al. "Itinerant antiferromagnetism in RuO_2" Phys.Rev.Lett. (2017)]



(courtesy of S. Kirchner)

The low-T resistance increase is insensitive to **large** magnetic fields !

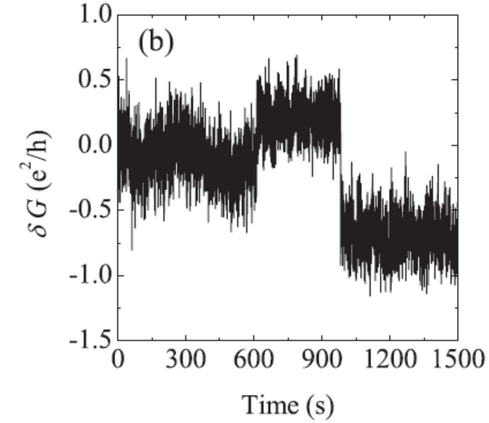
$$g\mu_B B / k_B T_K \geq 1, \quad T_K = 3.0\ \mathrm{K}$$

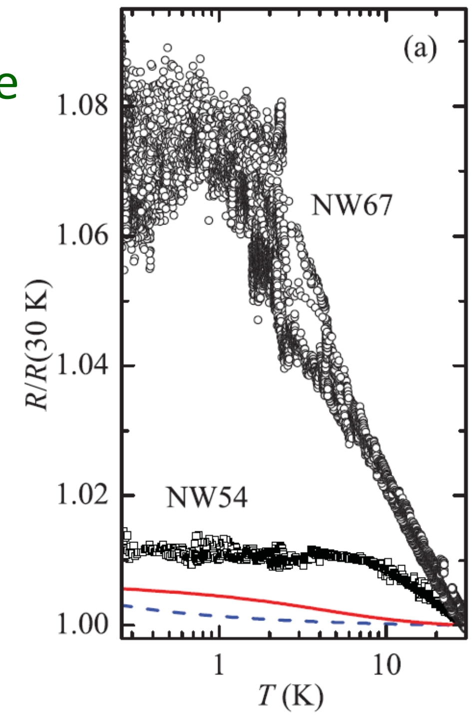


Oxygenated NW 4

$$\frac{\Delta\rho}{\rho} \simeq 0.65\%$$

Temporal universal conductance fluctuations (UCFs) in RuO_2 wires



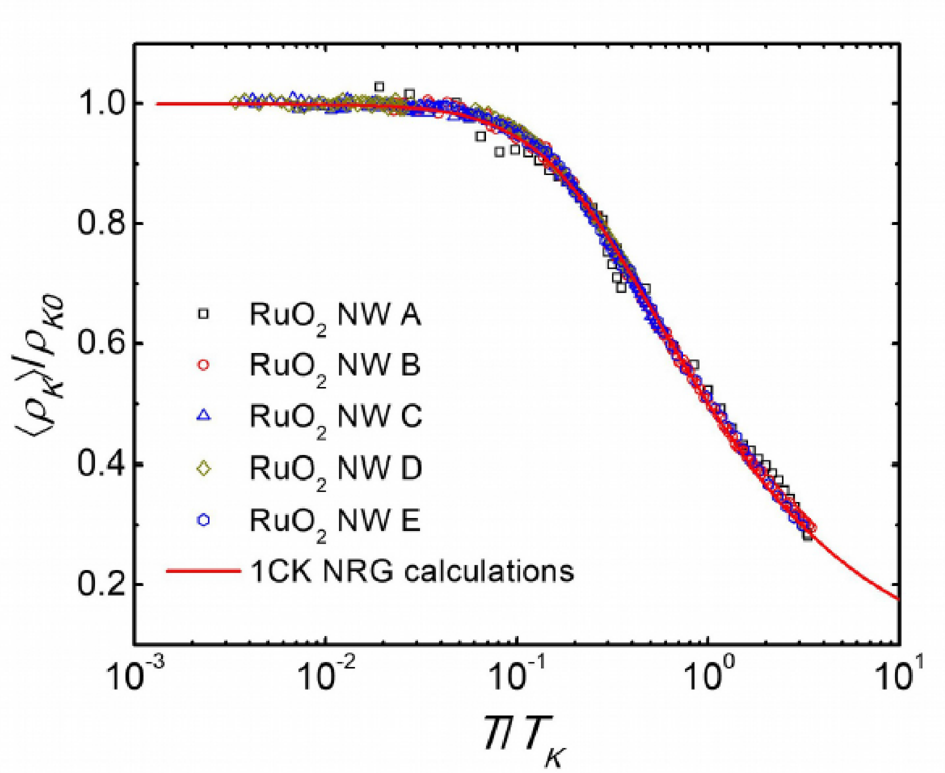


Magnetoresistance for magnetic spin-1/2 Kondo effect by NRG calculations.
T. A. Costi, PRL 85, 1504 (2000)

Lien et al., PRB 84, 155432 (2011)

Transport anomalies in MO_2

Orbital one-channel Kondo effect in anti-ferromagnetic RuO_2



Single-channel Kondo scaling over three decades in T/T_K !

T_K values vary from 3 to 80 K. The Kondo resistivities conform to the universal 1CK scaling function !

Oxygen vacancies drive an orbital one-channel Kondo effect in RuO_2 !

(courtesy of S. Kirchner)

PRL **118,** 077201 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

Itinerant Antiferromagnetism in RuO_2

T. Berlijn,[1,2] P. C. Snijders,[3,4] O. Delaire,[3,5] H.-D. Zhou,[4] T. A. Maier,[1,2] H.-B. Cao,[6] S.-X. Chi,[6] M. Matsuda,[6]
Y. Wang,[3] M. R. Koehler,[7] P. R. C. Kent,[1,2] and H. H. Weitering[4,3]
[1]*Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[7]*De*

PHYSICAL REVIEW LETTERS **122,** 017202 (2019)

Anomalous Antiferromagnetism in Metallic RuO_2 Determined by Resonant X-ray Scattering

Z. H. Zhu,[1,*] J. Strempfer,[2] R. R. Rao,[3] C. A. Occhialini,[1] J. Pelliciari,[1] Y. Choi,[2] T. Kawaguchi,[4]
H. You,[4] J. F. Mitchell,[4] Y. Shao-Horn,[3,5] and R. Comin[1,†]
[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA*
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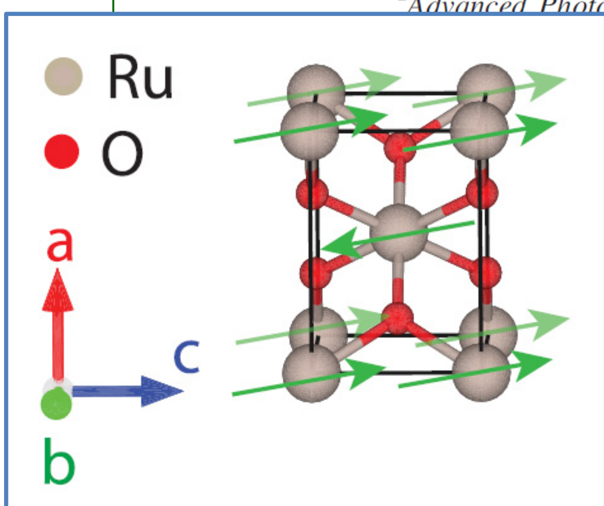
e Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
aterial Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA



Ruling out 3D electron-electron interaction effect

- Conformation to the one-channel Kondo scaling form for three decades in T/T_K rules out the 3D EEI effect

- The observed resistivity increase is more than one order of magnitude as would be expected from the 3D EEI effect

$$\frac{\Delta\rho(T)}{\rho(T_0)} = -\frac{0.915e^2}{4\pi^2\hbar}\left(\frac{4}{3}-\frac{3}{2}\tilde{F}\right)\rho(T_0)\sqrt{\frac{k_B}{\hbar D}}\left(\sqrt{T}-\sqrt{T_0}\right)$$

$\approx 3\times10^{-4}$ in our MO_2 nanowires

The insensitivity to applied magnetic field indicates nonmagnetic orbital one-channel Kondo effect !

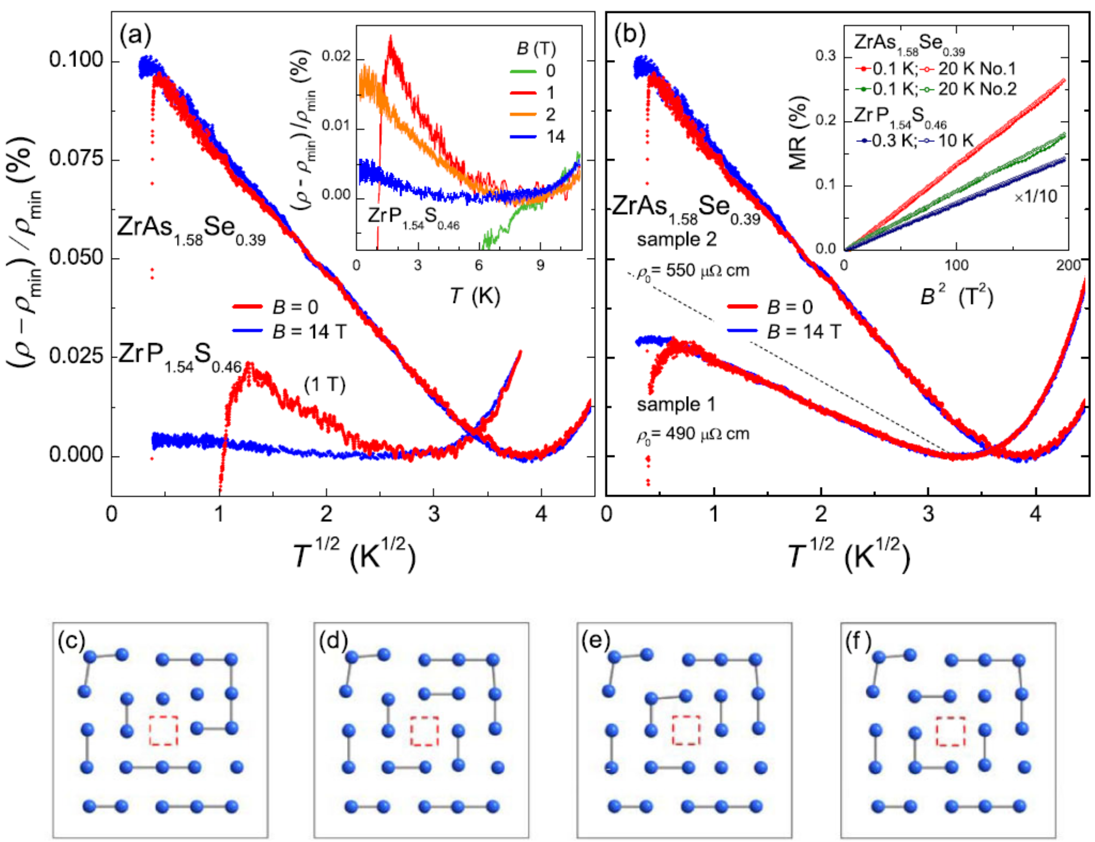
Recent 2CK experiment of layered compound Zr-As-Se (?)

PRL **117,** 106601 (2016) PHYSICAL REVIEW LETTERS week ending 2 SEPTEMBER 2016

Two-Channel Kondo Physics due to As Vacancies in the Layered Compound $ZrAs_{1.58}Se_{0.39}$

T. Cichorek and L. Bochenek
Institute of Low Temperature and Structure Research, Polish Academy of Sciences, 50-950 Wroclaw, Poland

in collaboration with MPI Dresden, Zhejiang University



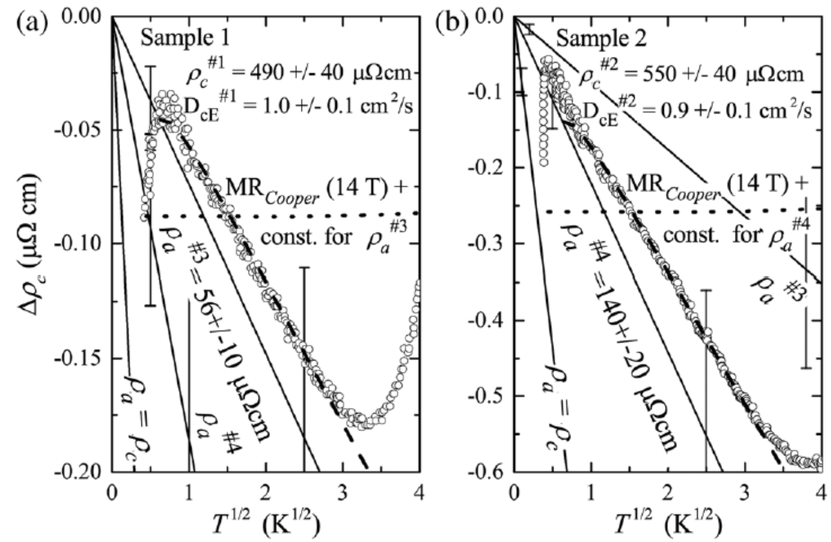
For the layered compound $ZrAs_{1.58}Se_{0.39}$, the authors argue that vacancies in the square nets of As give rise to the low-*T* transport anomaly in line with the nonmagnetic version of the 2CK effect.

Recent 2CK experiment of layered compound Zr-As-Se (?)

PRL **118,** 259701 (2017) PHYSICAL REVIEW LETTERS week ending 23 JUNE 2017

Comment on "Two-Channel Kondo Physics due to As Vacancies in the Layered Compound $ZrAs_{1.58}Se_{0.39}$"

In a recent Letter [1], Cichorek *et al.* reported that a magnetic field independent $AT^{1/2}$ term in the low-temperature resistivity of $ZrAs_{1.58}Se_{0.39}$ could not be caused by electron-electron interaction (EEI) and could only be explained by a two-channel Kondo effect (2CKE). This statement was formulated on the basis of quantitative analysis of experimentally obtained A-coefficient values in light of the Altshuler-Aronov theory of EEI in disordered conductors [2]. The authors argue that even when the electron screening factor $F = 0$, the values of the A coefficient for samples 1 and 2 of single-crystalline $ZrAs_{1.58}Se_{0.39}$ give unrealistic diffu-

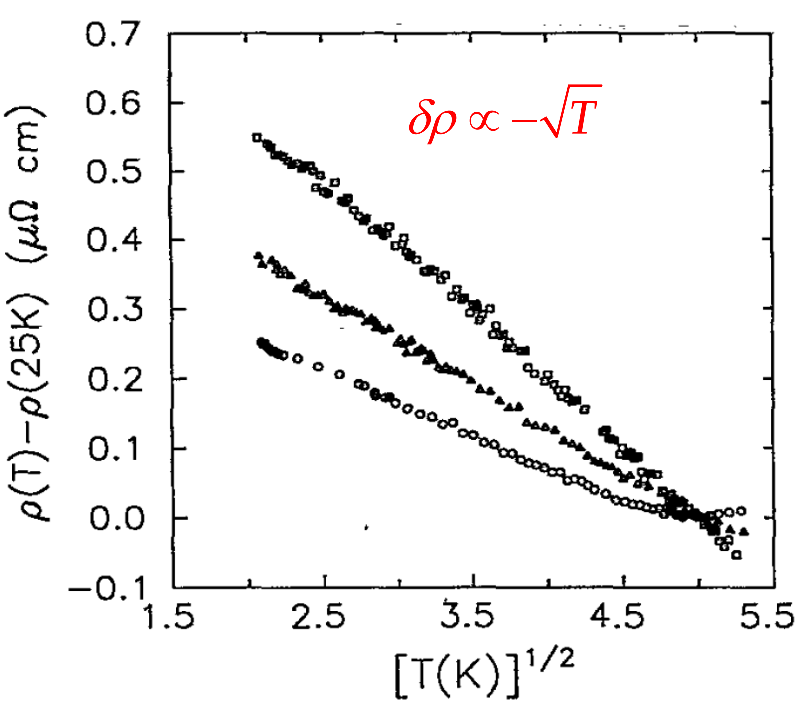


PHYSICAL REVIEW B **97**, 134201 (2018)

Origin of the $-|A|T^{1/2}$ term in the resistivity of disordered $ZrAs_{1.58}Se_{0.39}$

Daniel Gnida
Institute of Low Temperature and Structure Research, Polish Academy of Sciences, P.O. Box 1410, 50-950 Wrocław, Poland

3D electron-electron interaction effect in Ti-Al alloys



Resistivity increase for Al-doped Ti alloys with ρ_0 = 143, 167 and 204 μm cm.
Phys. Rev B 48, 5021 (1993)

吳至原副教授 (輔仁物理系)
PhD in 1996, NTU Physics

CONCLUSION

- IrO_2 and RuO_2 crystalize in the rutile structure, with approximate C_4 symmetry. Properties of the C_4 group imply **two-fold degeneracy** of the nonmagnetic impurity.
- In **paramagnetic** IrO_2, the spin-degeneracy of the conduction bands is preserved. $\Rightarrow$ **Orbital 2CK effect !**
- In **antiferromagnetic** RuO_2, the conduction band is (locally) spin-polarized. $\Rightarrow$ **Orbital 1CK effect !**
- The symmetries that that enforces the existence of Dirac nodal lines also promote the formation of non-magnetic Kondo correlation.
- Both the emergence of the strange metallic state that accompanies unconventional superconductivity and the formation of the 2CK effect originate from strong electron interactions.

A quantum impurity (a localized spin, a moving electron or atom, etc.) with internal degree of freedom (two-fold degeneracy) generates the Kondo effect.

Kondo, 1976
Nozieres, 1980
Zawadowski, 1980s
Many more ……