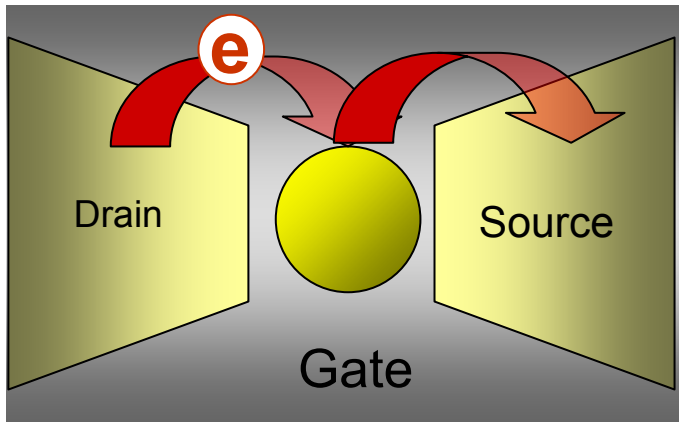
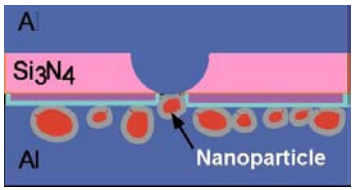
Measurements of electron-in-a-box level spectra in chemically-synthesized metal nanoparticles

Ferdinand Kuemmeth, Kirill I. Bolotin, Daniel C. Ralph



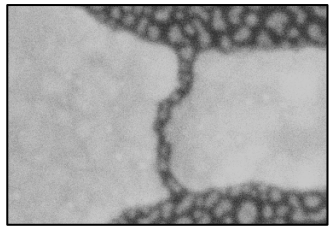
Laboratory of Atomic and Solid State Physics, Cornell University

spin orbit-scattering and g-factors



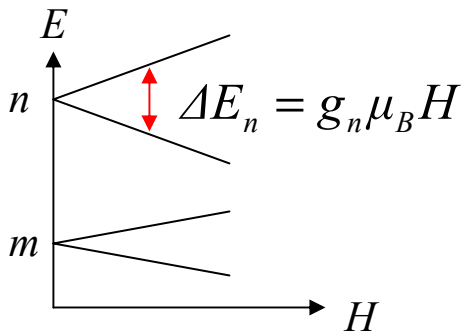
J. Petta et al
PRL. ***87****, 266801 (2001)*

$g \approx 0.15$ $(\delta \approx 0.2$ meV)



F. Kuemmeth et al
March Meeting 2004

$g \approx 1.3$ $(\delta \approx 1.0$ meV)

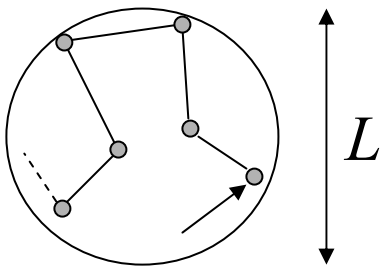


$$\Delta E_n = g_n \mu_B H$$

perturbation theory
*J. Vac.Sci.Technol. B****17****, 1708 (1999)*

$$g_n = 2 - 4 \sum_{m \neq n} \frac{\left| \left\langle \Psi_{m\downarrow} \middle| H_{SO} \middle| \Psi_{n\uparrow} \right\rangle \right|^2}{(E_n - E_m)^2}$$

Eliot-Yafet mechanism



spin-flips via lots of momentum scattering events

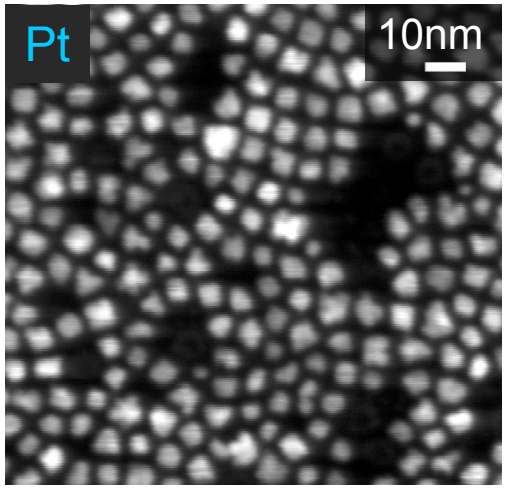
$$\tau_{SO} = \tau / \alpha$$

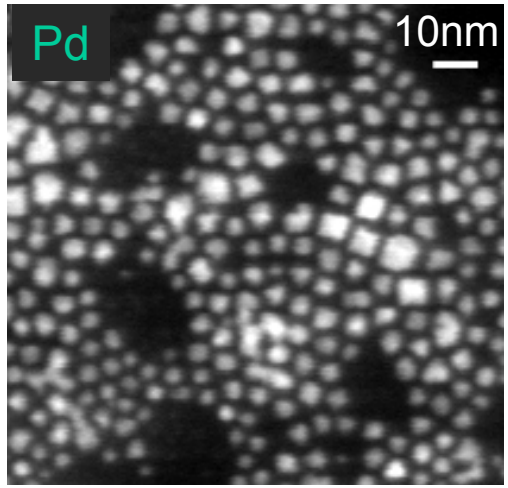
$$\tau_{SO}^{-1} \sim \frac{\alpha v_F}{L}$$

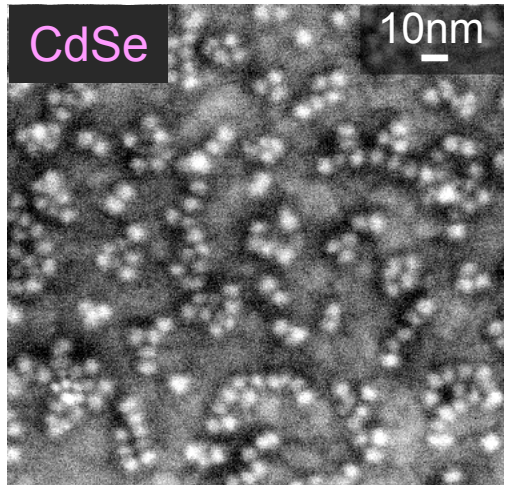
$$\delta \sim \frac{v_F \lambda_F^2}{L^3}$$

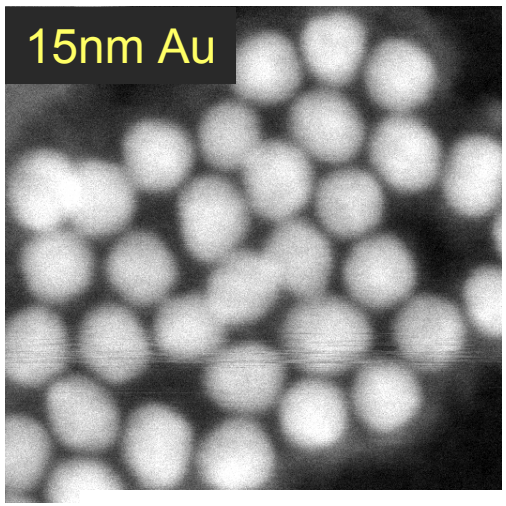
$$\frac{\text{SO-interaction}}{\text{level spacing}} \sim 1 \text{ for 10 nm gold particle}$$

chemical control over size, density, tunnel barrier

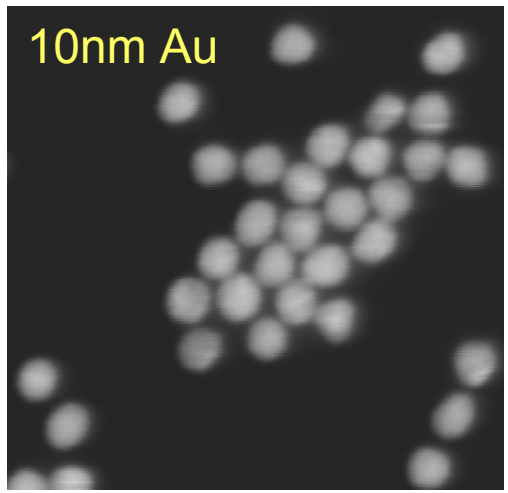




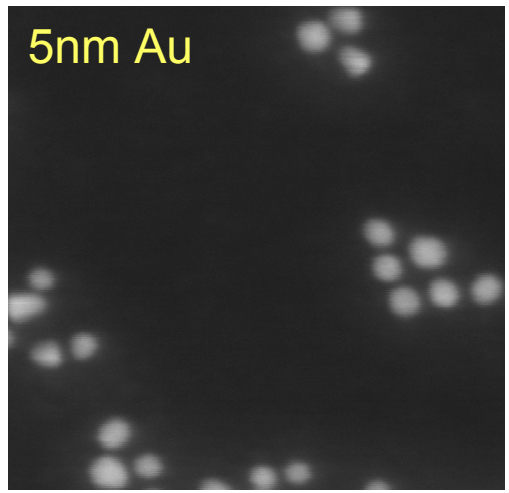




$\delta \sim 0.07$ meV



$\delta \sim 0.25$ meV

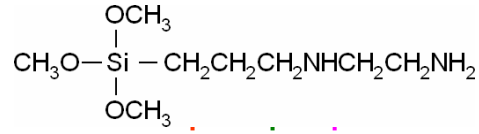


$\delta \sim 2$ meV

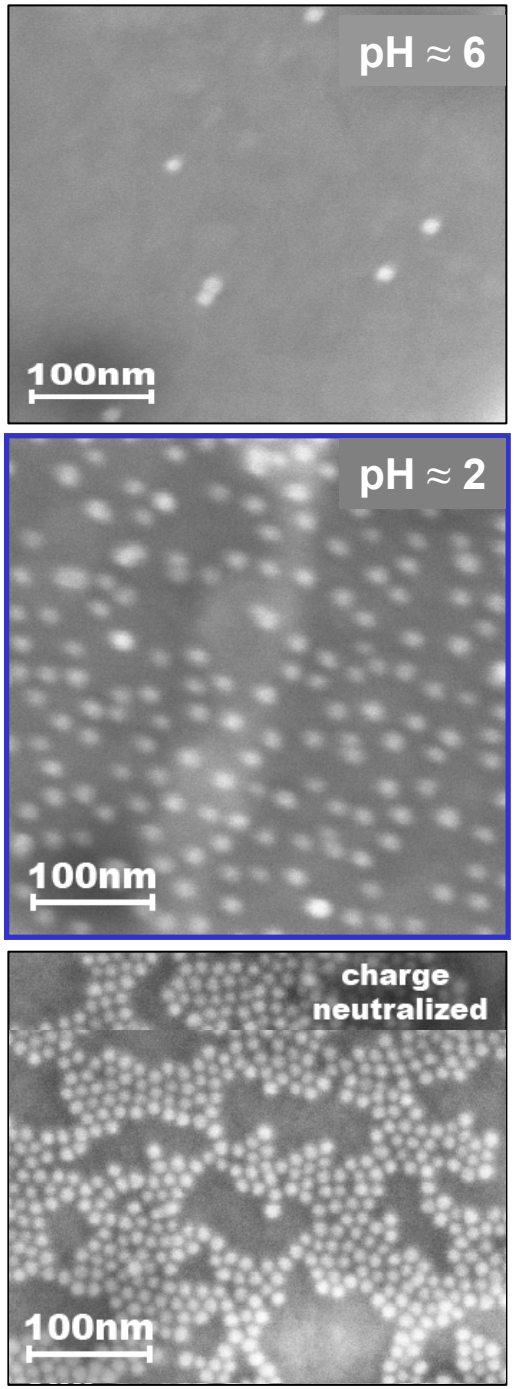
fabrication of the single electron transistor

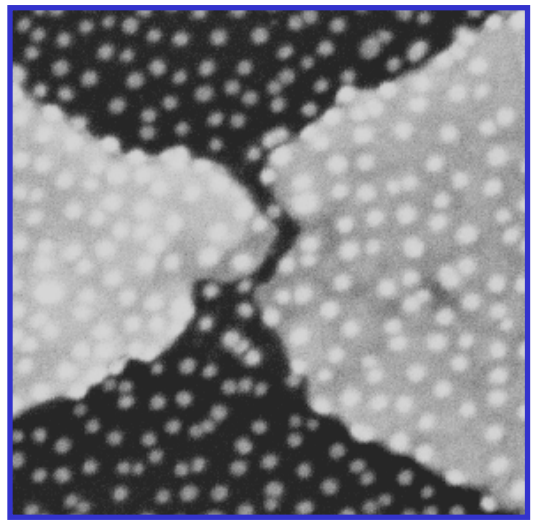
1) form nm sized gap in gold wire (electromigration)

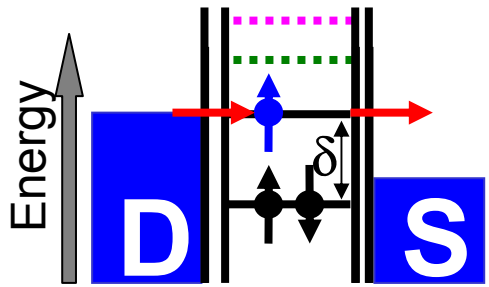
2) self assemble monolayer of APTS [(Aminoethylamino)propyl]trimethoxysilane

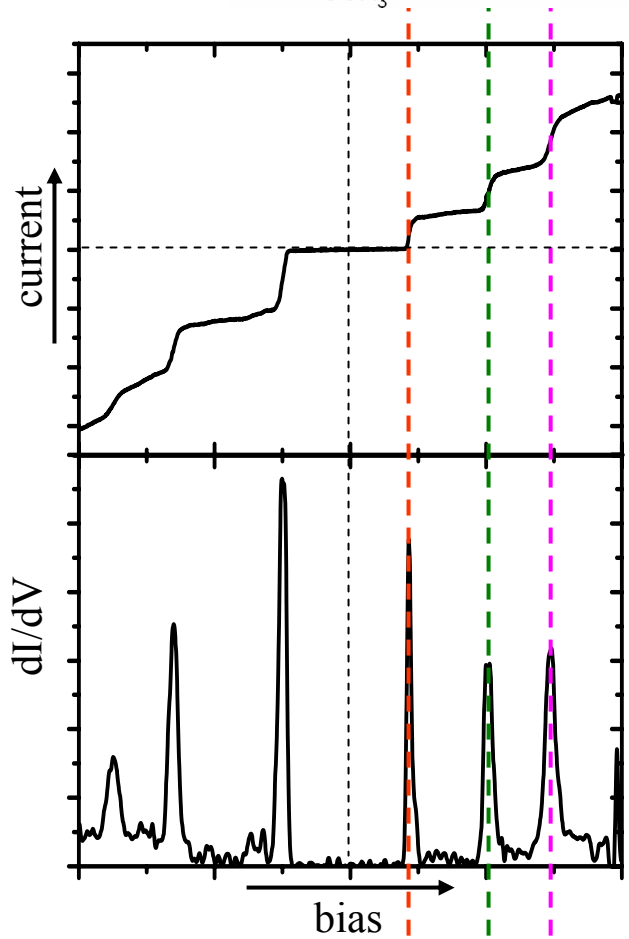


3) apply colloid with appropriate acidity



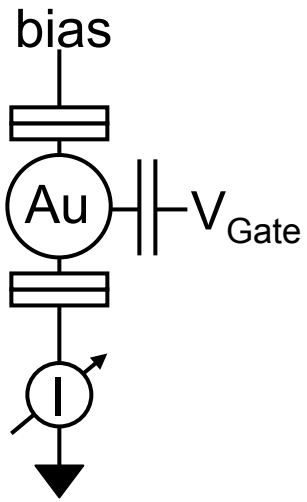


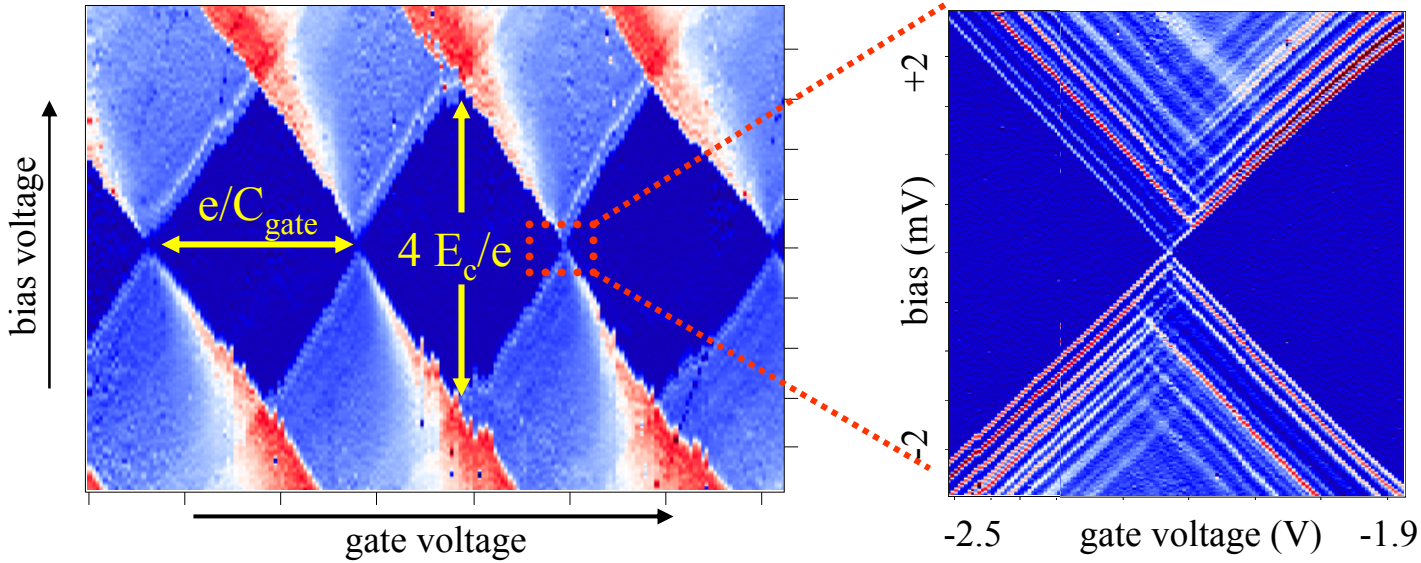




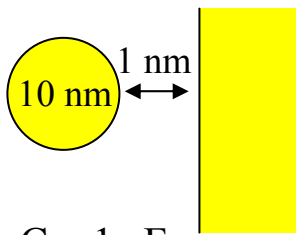
Coulomb blockade and single electron tunneling at low temperatures

Single electron tunneling (dilution refrigerator)





model:



C ~ 1 aF

<δ> ~ 0.25 meV

$E_{charging} \approx 30\,\text{meV}$

$C_{gate} \approx 0.03\,\text{aF}$

$C_{source,drain} \approx 1.3\,\text{aF}$

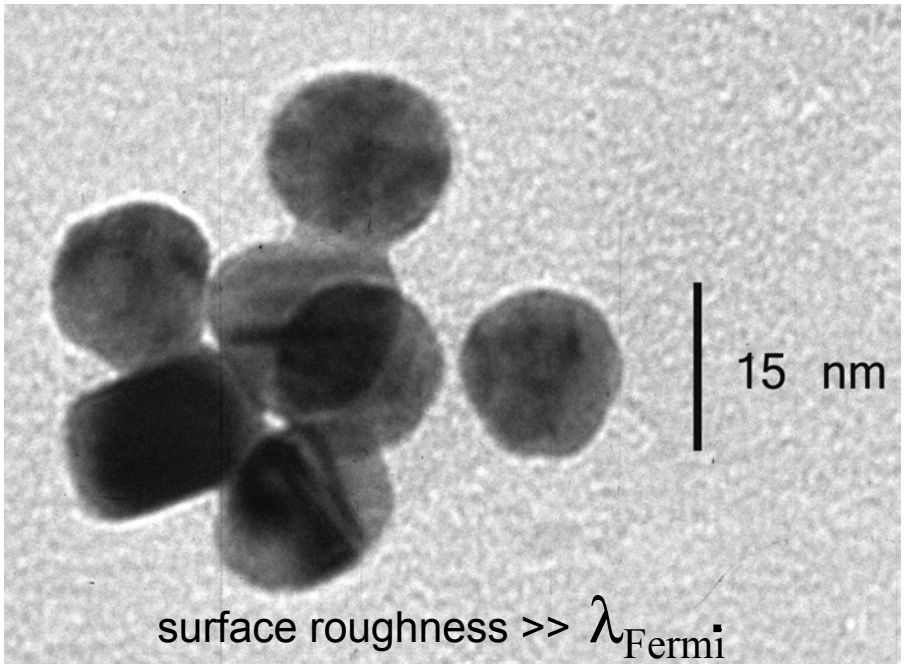
mean level spacing

$<\delta> \approx 0.31\,\text{meV}$

(corresponds to a 9.1 nm particle)

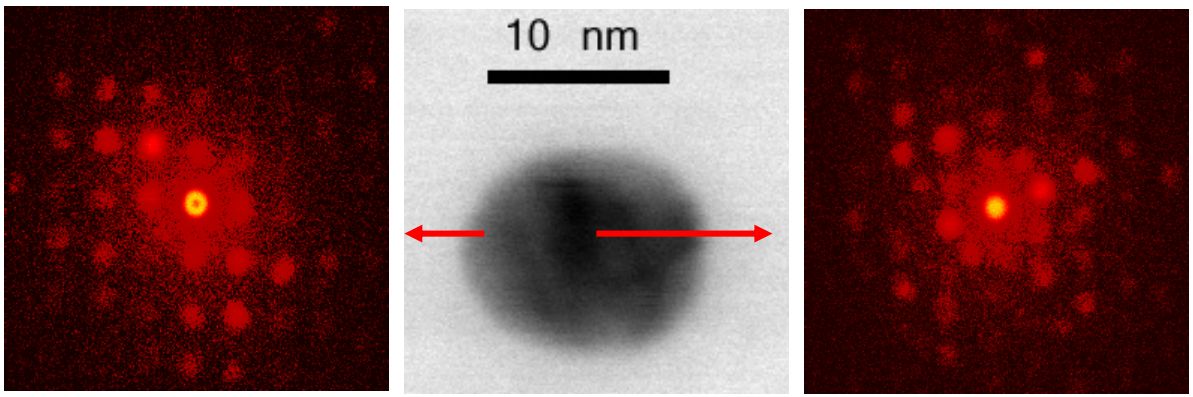
note: symmetric tunnel barriers

TEM images of gold colloid



no perfect spheres →

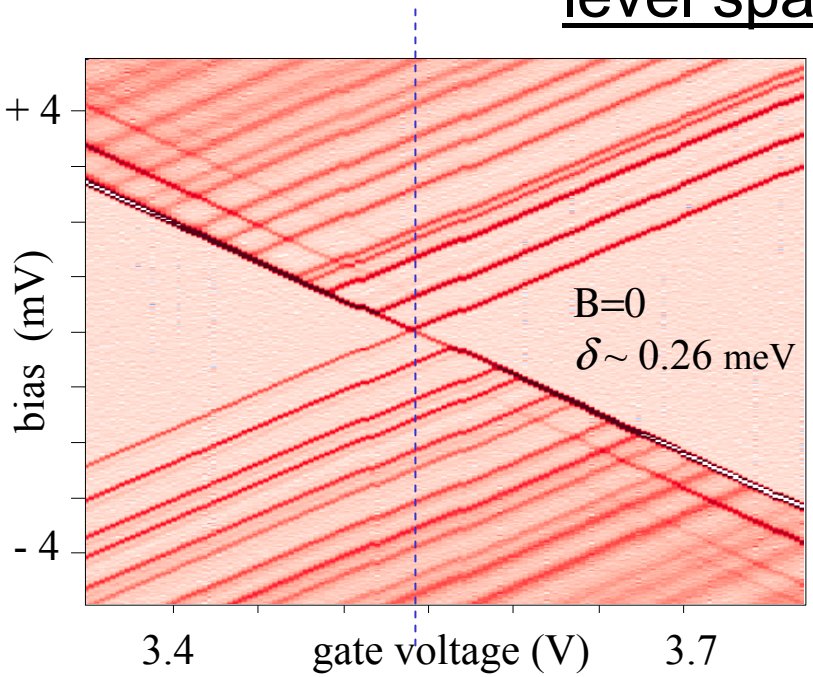
random level spectrum
(no shell structure)

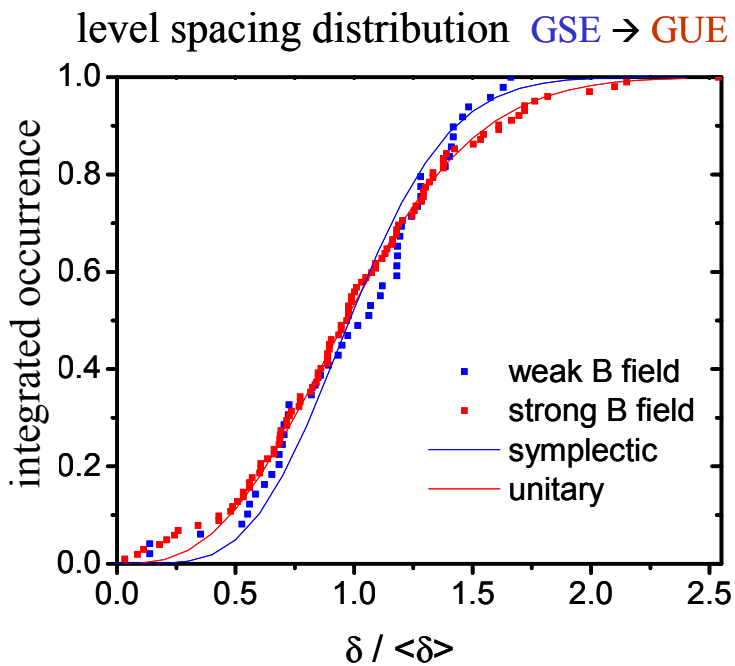


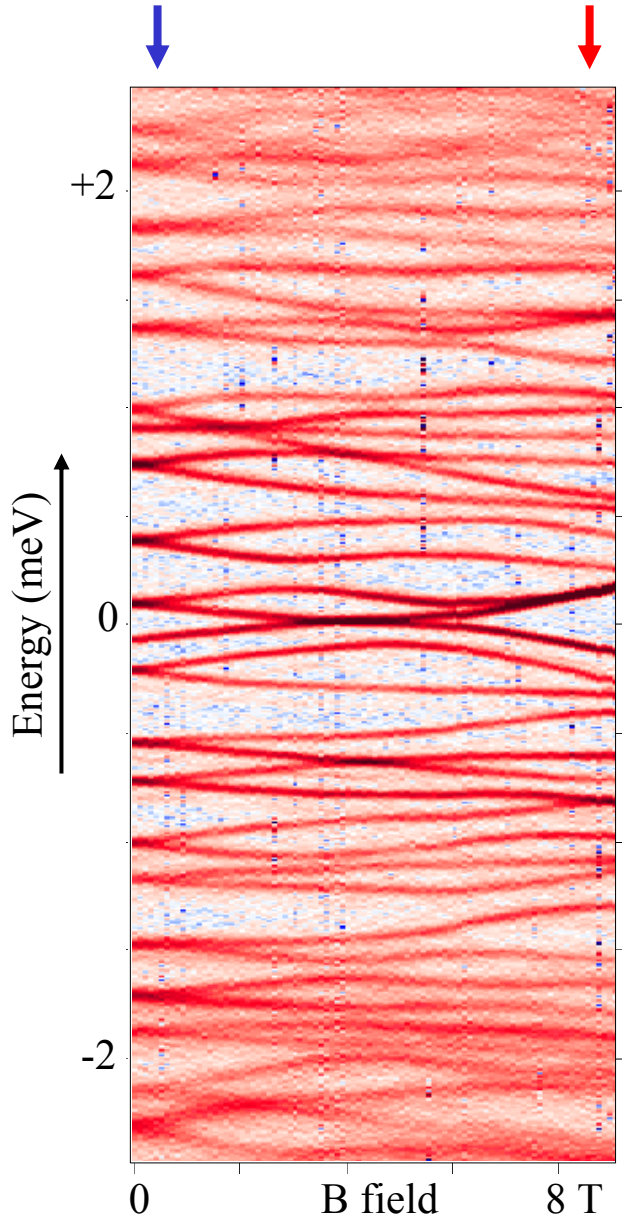
electron diffraction →

nanoparticles are not
single crystal

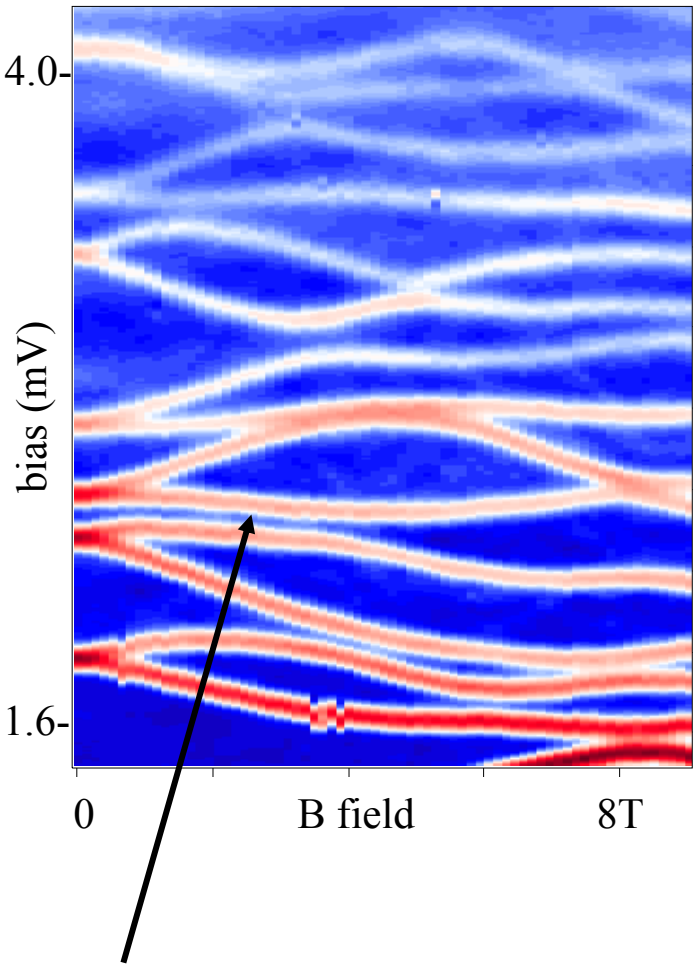
level spacing statistics



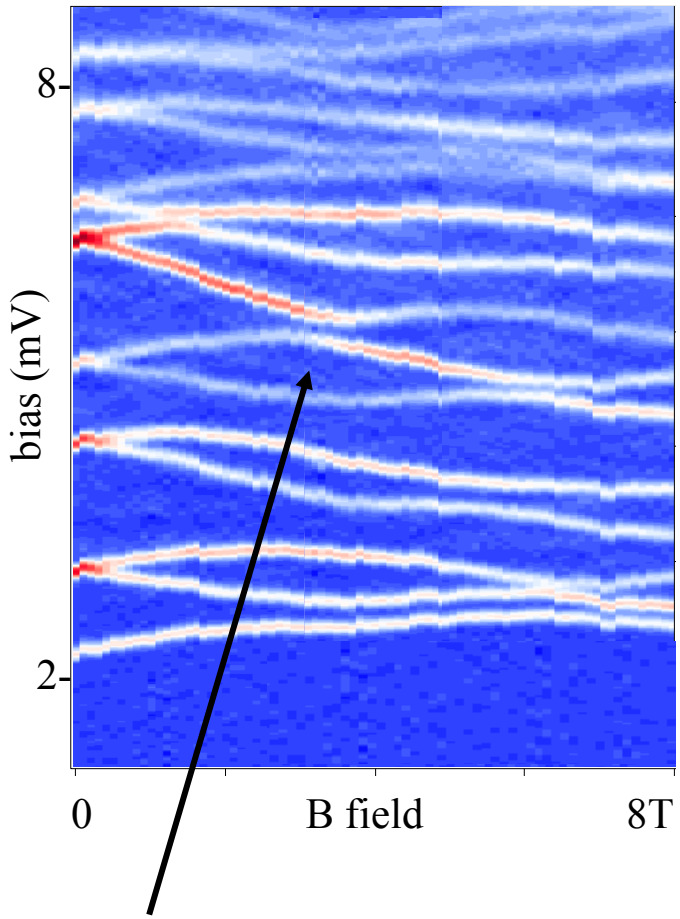




large magnetic field: mixing of orbits, level crossing



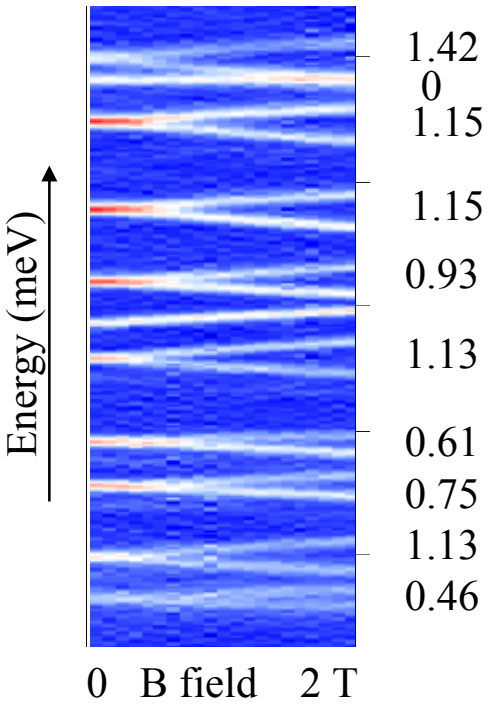
avoided level crossing

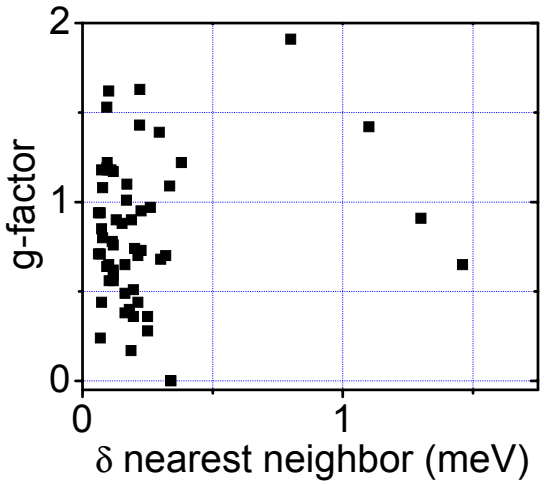


mixing of orbits

small field splitting: g-factors ~ 1

g-factors ($\delta = 0.26$ meV):





S. Adam et al
Phys. Rev. B ***66****, 195412 (2002)*

$$\langle g^2 \rangle = \underbrace{\frac{3}{\pi\hbar}\tau_{so}\delta}_{\text{spin}} + \underbrace{\alpha\frac{l}{L}}_{\text{orbit}}$$

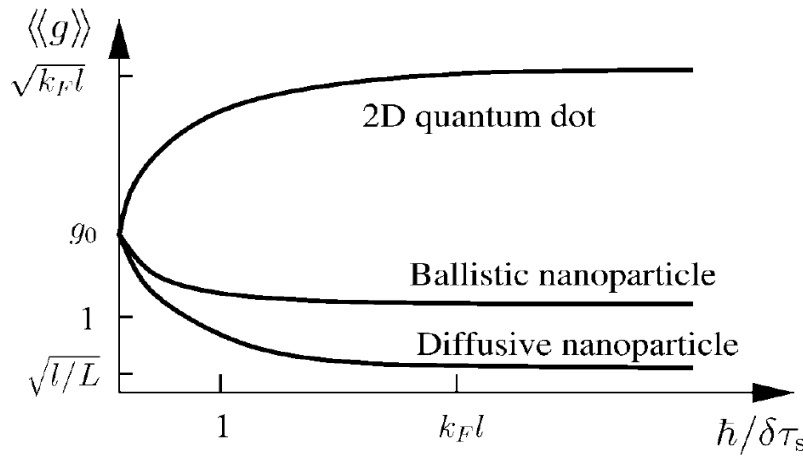
for all particles we measured, only a few levels show g < 0.5

→ agrees with theoretical predictions for ballistic particles with strong SO-scattering

K.A. Matveev et al, PRL 85, 2789 (2000)

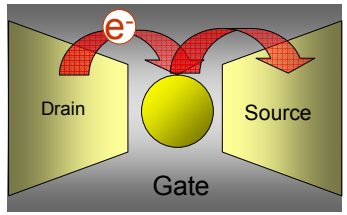
J. Petta et al,
Phys. Rev. Lett. ***87****, 266801 (2001)*

	g-factor	δ [meV]
Au#1	0.12	0.10
Au#2	0.17	0.12
Au#3	0.45	0.27



conclusions

- new fabrication method for single electron transistors
  employs chemical tools for particle synthesis,
  size control, self assembly and tunnel barrier



- in dilution refrigerator: can resolve discrete energy spectrum of individual gold nanoparticles of various sizes

- g-factors are different for each quantum level, with $\bar{g} \sim 1$ for all gold particles 5 - 15 nm
  in agreement with theory for ballistic particle and strong SO-coupling

future

- take advantage of chemical control over size, shape and composition of particles. e-e-interactions, magnetism, high-spin ground states