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  
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\[ g \approx 0.15 \quad (\delta \approx 0.2 \text{ meV}) \]

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\[ g \approx 1.3 \quad (\delta \approx 1.0 \text{ meV}) \]

\[ \Delta E_n = g_n \mu_B H \]

**perturbation theory**  

\[ g_n = 2 - 4 \sum_{m \neq n} \left| \left\langle \Psi_m \left| H_{SO} \right| \Psi_n \right\rangle \right|^2 \frac{1}{(E_n - E_m)^2} \]

**Eliot-Yafet mechanism**

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

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

\[ \tau_{SO} = \tau / \alpha \]

spin-flips via lots of momentum scattering events

SO-interaction level spacing  
\(~ 1 \text{ for } 10 \text{ nm gold particle}\)
chemical control over size, density, tunnel barrier

\begin{align*}
\text{Pt} & \quad 10\text{nm} \\
\text{Pd} & \quad 10\text{nm} \\
\text{CdSe} & \quad 10\text{nm} \\
15\text{nm Au} & \quad \delta \sim 0.07 \text{ meV} \\
10\text{nm Au} & \quad \delta \sim 0.25 \text{ meV} \\
5\text{nm Au} & \quad \delta \sim 2 \text{ meV}
\end{align*}
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)

Bias voltage $V_{\text{Gate}}$ and gate voltage $V_{\text{Gate}}$ are shown. The figure illustrates the relationship between gate voltage and bias voltage, with $e/C_{\text{gate}}$ and $4E_c/e$ highlighted. The model includes:

- $E_{\text{charging}} \approx 30 \text{ meV}$
- $C_{\text{gate}} \approx 0.03 \text{ aF}$
- $C_{\text{source,drain}} \approx 1.3 \text{ aF}$

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)

Surface roughness >> $\lambda_{\text{Fermi}}$

Electron diffraction →

Nanoparticles are not single crystal
level spacing statistics

$B=0$
$\delta \sim 0.26 \text{ meV}$

level spacing distribution  $\text{GSE} \rightarrow \text{GUE}$

integrated occurrence

weak B field
strong B field
symplectic
unitary

$\delta / \langle \delta \rangle$
large magnetic field: mixing of orbits, level crossing

avoided level crossing

mixing of orbits
small field splitting: g-factors $\sim 1$

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

\[ \langle g^2 \rangle = \frac{3}{\hbar} \tau_{so} \delta + \alpha \frac{l}{L} \]

\[ \langle g \rangle = \frac{\langle g^2 \rangle}{\sqrt{\kappa F l}} \]

$\delta$ nearest neighbor (meV)

\begin{align*}
\text{Energy (meV)} & \quad 0 \quad 0.46 \quad 0.61 \quad 0.75 \quad 1.13 \quad 1.15 \\
\text{g-factors (}\delta = 0.26 \text{ meV):} & \quad 2 \\
\end{align*}

\begin{tabular}{|c|c|c|}
\hline
Au#1 & 0.12 & 0.10 \\
Au#2 & 0.17 & 0.12 \\
Au#3 & 0.45 & 0.27 \\
\hline
\end{tabular}

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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