

DHIRANI GROUP

Leveraging a recently discovered quantum phenomenon

When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. ... We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc....

R. Feynman, APS 1959, "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics."

What are nanostructures?

Nanostructures are ~ 1 + nm or ~ 10 + Å or ~ 10 + atoms in size. At the nanometer scale, there a strong link between structure and quantum behaviour. As a result, nanostructures have a "designer" nature. A well-known example is the semi-conductor nanoparticle which exhibit strongly size-dependent optical properties; their discovery and development garnered a 2023 Nobel prize.

Why is the Dhirani group interested in them?

A theme of the Dhirani group's research is to use nanostructures as building blocks to fabricate "tailored" quantum materials or quantum "nanoengineered" materials (q-NEMS). q-NEMs properties can be controlled from the bottom-up through choice of nano-building block and material architecture. This approach uses the wide variety of nanostructures with controlled structure described in the literature as building blocks. The aim is that fabricate q-NEMs with controlled structure – property behaviour to shed light on previously observed but not well understood quantum phenomena, e.g., strongly correlated (localized vs delocalized) electron interaction, which are at the heart of exotic quantum phenomena such as high Tc superconductivity and heavy Fermions. In addition, new combinations of nanobuilding blocks can lead to observation of new phenomena and devices.

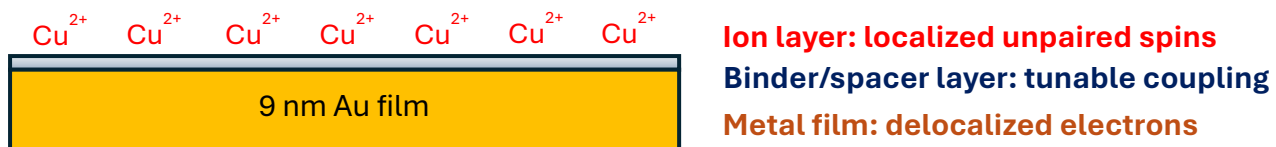


Figure 1: Device geometry exhibiting the "proximity Kondo effect"

Fig 1 shows an example of a quantum nanostructured architecture recently developed by the Dhirani group following this bottom-up approach. This example of a q-NEMs has 1) a bottom metal Au film which serves as a source of delocalized electrons; 2) a top ion layer which serves as a source of localized, unpaired electrons; and 3) a middle binder/spacer layer that tunably couples the two types of electrons. Resistance vs temperature measurements of the Au film exhibit an upturn below 10 K. This is a hallmark signature of the quantum Kondo scattering of the delocalized electrons from the localized electrons – even though the Cu²⁺ ions are outside the Au film! Hence, we attribute this phenomenon to a "proximity Kondo effect". Studies of these and other new materials and devices are ongoing in the Dhirani group.

Building on these results and depending on student interest, students have an opportunity to:

- Combine metal nanostructures and study the range of resulting quantum behaviours exhibited by such materials; e.g. strongly correlated electrons; or
- develop their potential device applications such as charge exchange transistors, a field the Dhirani group is pioneering, and
- nanostructured direct solar-to-hydrogen energy conversion devices.

DESCRIPTION OF STUDENT PARTICIPATION:

Students will begin by performing a literature review. In the first phase of an experiment, they will fabricate and characterize nanostructured materials/devices. In the second phase of the experiment, students will help take measurements of and/or apply material properties (electrical, magnetic, optical).

[1] Zabet-Khosousi, A. and **Dhirani, A.A.**, 2008. Charge transport in nanoparticle assemblies. *Chemical reviews*, 108(10), pp.4072-4124.

[2] M. Tie and **A.-A. Dhirani**. "Coulomb effects and exotic charge transport in nanostructured materials." *21st Century Nanoscience – A Handbook*. Ed. K. Sattler. Milton Park: Taylor and Francis (CRC Press), 2018.

[3] Gravelsins, S., Park, M.J., Niewczas, M., Hyeong, S.K., Lee, S.K., Ahmed, A. and **Dhirani, A.A.**, 2022. Large emergent optoelectronic enhancement in molecularly cross-linked gold nanoparticle nanosheets. *Communications Chemistry*, 5(1), p.103.