# Dynamic RKKY interaction in graphene

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# Mauro Ferreira

School of Physics Trinity College Dublin Ireland



**<u><b>RKKY**</u> interaction: Interaction between localized magnetic moments mediated by the surrounding conduction electrons.



Two localized magnetic moments a distance D apart :



$$J(D) \sim \frac{\cos(2k_F D)}{D^{\alpha}}$$
 where  $\alpha = 1$ 

Long ranged interaction in nanotubes

## Two localized magnetic moments a distance D apart :



Static spin susceptibility  $\chi(D) \sim 1/D^{\alpha}$  ( $\alpha = 2, 3 \text{ or } 7$ )



### What if the moments are set in motion?

Dynamic spin susceptibility  $\chi(\omega, D) \sim 1/D^{\beta}$  ( $\beta = ?$ )

## THEORY - DYNAMIC SPIN SUSCEPTIBILITY

 $\bullet$  We consider a small time-dependent transverse magnetic field that drives the precession with a frequency  $\,\omega$ 



• The unperturbed system is described by

$$\hat{H} = \sum_{ij\sigma} t_{ij} \hat{c}_{i\sigma}^{\dagger} \hat{c}_{j\sigma} + \frac{1}{2} \sum_{i\sigma} U_i \hat{n}_{i\sigma} \hat{n}_{i\overline{\sigma}} + g\mu_B H_0 \sum_i \hat{S}_i^z$$



• Within the Random Phase Approximation (RPA)

$$\chi(\omega) = [1 + \chi^0(\omega) U]^{-1} \chi^0(\omega)$$





How come?





Spin current (with no charge current) is responsible for the dynamic coupling that arises between precessing moments

#### PHYSICAL REVIEW LETTERS PRL 106, 037205 (2011)

#### **Itinerant Nature of Atom-Magnetization Excitation by Tunneling Electrons**

A. A. Khajetoorians,<sup>1,\*</sup> S. Lounis,<sup>2,†</sup> B. Chilian,<sup>1</sup> A. T. Costa,<sup>2,3</sup> L. Zhou,<sup>1</sup> D. L. Mills,<sup>2</sup> J. Wiebe,<sup>1,‡</sup> and R. Wiesendanger<sup>1</sup>

<sup>1</sup>Institute of Applied Physics, Hamburg University, Jungiusstrasse 11, D-20355 Hamburg, Germany

<sup>2</sup>Department of Physics and Astronomy, University of California Irvine, Irvine, California, 92697 USA

<sup>3</sup>Instituto de Física, Universidade Federal Fluminense, 24210-340 Niterói, RJ, Brazil

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We have performed single-atom magnetization curve (SAMC) measurements and inelastic scanning tunneling spectroscopy (ISTS) on individual Fe atoms on a Cu(111) surface. The SAMCs show a broad distribution of magnetic moments with 3.5  $\mu_B$  being the mean value. ISTS reveals a magnetization excitation with a lifetime of 200 fsec which decreases by a factor of 2 upon application of a magnetic field of 12 T. The experimental observations are quantitatively explained by the decay of the magnetization excitation into Stoner modes of the itinerant electron system as shown by newly developed theoretical modeling.

> fcc Fe atom = 3.38

> > 1.5

7

m

0.5

5

6

0

B (T)

4







## **Experimental feasibility**



## Nature **448**, 571 (2007) PRB **83**, 115410 (2011)

- The RKKY interaction in graphene becomes far more long ranged when the magnetic moments are set in motion
- This interaction can be probed with currently available experimental methods.

## in collaboration with

Stephen Power (TCD, Ireland)

Filipe Guimarães (UCI, USA)

Antonio Costa (UFF, Brazil)

Roberto B. Muniz (UFF, Brazil)

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