# Topological insulator particles as optically induced oscillators: Towards dynamical force measurements and optical rheology

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**TOPOLOGICAL STATES OF MATTER - IIP/NATAL/BRAZIL**

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V.E. Carvalho - DPF/UFMG

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# 3D Topological Insulators

- Theoretically predicted in 2007

PRL **98,** 106803 (2007) PHYSICAL REVIEW LETTERS week ending 9 MARCH 2007

**Topological Insulators in Three Dimensions**

Liang Fu, C. L. Kane, and E. J. Mele
*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
(Received 26 July 2006; published 7 March 2007)

- Experimentally observed in 2008

nature Vol 452|24 April 2008|**doi:10.1038/nature06843**

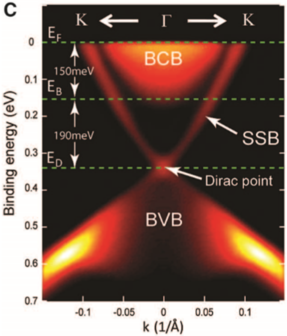
LETTERS

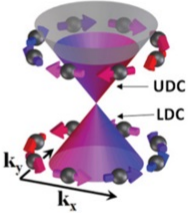
**A topological Dirac insulator in a quantum spin Hall phase**

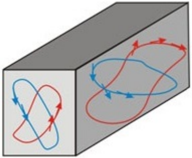
D. Hsieh[1], D. Qian[1], L. Wray[1], Y. Xia[1], Y. S. Hor[2], R. J. Cava[2] & M. Z. Hasan[1,3]

# Topological insulators properties

- Strong spin-orbit coupling
- Gapped bulk band structure; metallic surface states protected by time reversal symmetry
- Spin-momentum locking
- Dissipationless propagation of electrons



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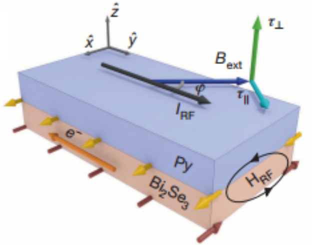
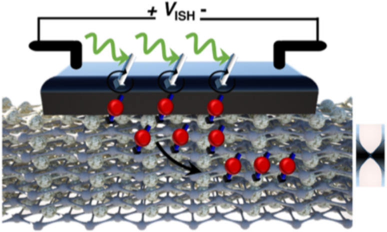
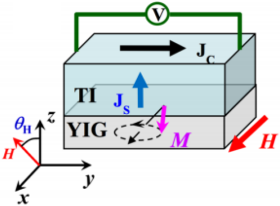
# Application prospects

- Topological quantum computing
- Electronic devices with low dissipation
- Spintronics

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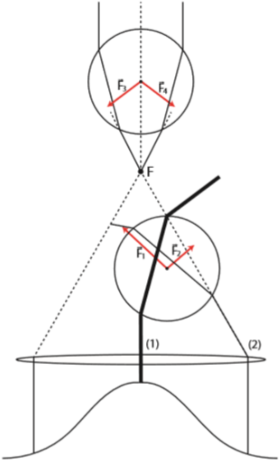
# Optical tweezers technique

- $\lambda \sim$ 1064 nm ytterbium-doped fiber laser
- Laser power $\sim$ 25 mW

# Optical tweezers technique




Ray optics regime (*radius* $>> \lambda$)

- Highly focused Gaussian light beam:

$$I = I_0 e^{-Ar^2}$$

- Conservation of linear momentum
- Snell law: $n_p \sin\theta_p = n_{med} \sin\theta_{med}$

$$n_{particle} > n_{medium}$$

- Refraction in the bulk leads to **gradient force**:

$$\vec{F}_g \sim \vec{\nabla} I$$

Rocha, M. S. *Am. J. Phys.* **77**, (2009): 704.

# Optical tweezers technique

- Absorption and reflection leads to **radiation pressure**:

$$F_{rp} \sim I$$

- Radiation pressure deflects the particle from the focus
- There is also a viscous (Stokes) force exerted by the surrounding medium:

$$\vec{F}_s \sim -\vec{v}$$

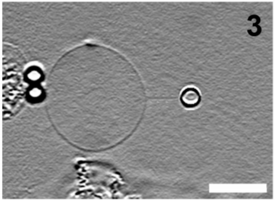
Dielectric particle → gradient force dominates → stable trap

Metallic particle → radiation pressure dominates → deflection

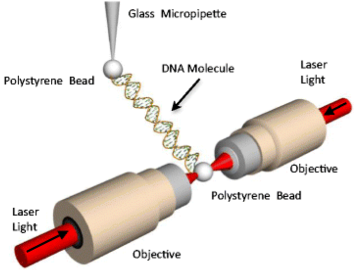
Rocha, M. S. *Am. J. Phys.* **77**, (2009): 704.

# Some applications of optical tweezers

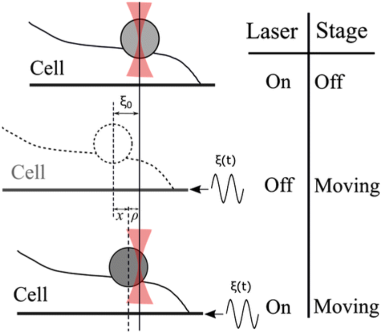
- Membrane elastic properties




- DNA studies




- Micro-rheology

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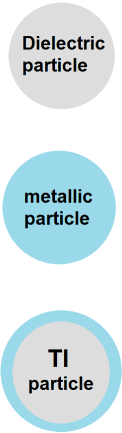
# Topological insulator bead in optical tweezers



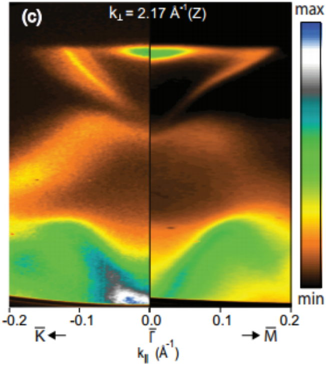

**Gradient force dominates "particle trapping"**

**Radiation pressure dominates "particle deflection"**

**Gradient force and radiation pressure compete "oscillatory motion"**

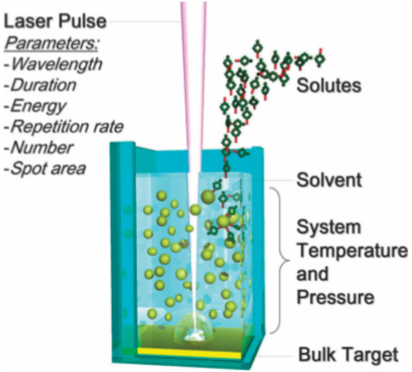
# Syntesis of TI-particles

- ARPES measurements for $Bi_2Te_3$:




Michiardi, M. et al. *Phys. Rev. B* **90** (2014): 075105

- Laser ablation technique in liquid solution:

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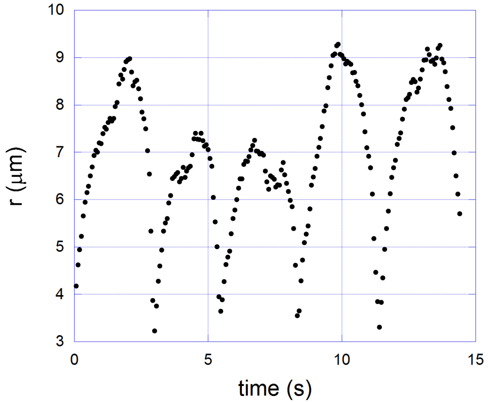
# Oscillatory motion

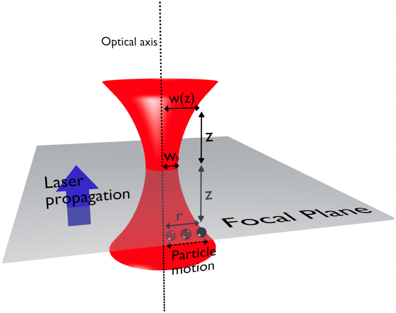


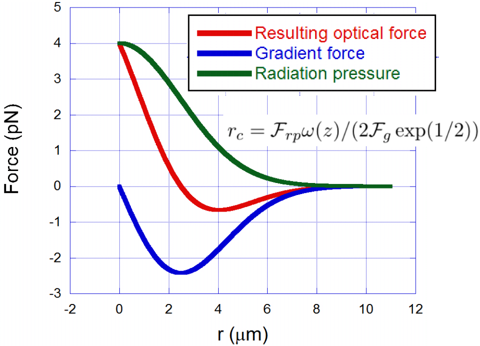

- Particles diameter between $\sim 3\mu$m and $7\mu$m
- Oscillation parallel to the focal plane

For a particle with diameter $\sim 4.2\mu$m:

- Amplitudes vary between $\sim 7\mu$m$-9\mu$m
- Closest approximation $\sim 3.2\mu$m
- Well-defined period: $T = (3.52 \pm 0.32)$s

# Theoretical model




$$I_N = \exp\left(\frac{-2r^2}{\omega(z)^2}\right) \qquad \omega(z) = \omega_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

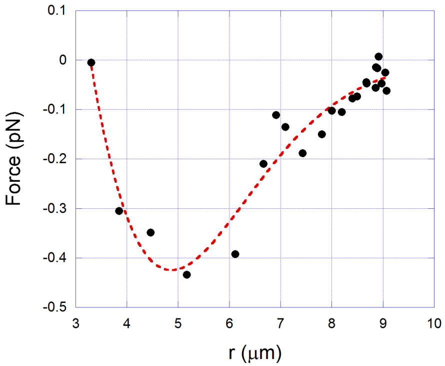
$$z_R = \frac{\pi\omega_0^2}{\lambda}$$

$$F_{rp} = \mathcal{F}_{rp}\exp\left(\frac{-2r^2}{\omega(z)^2}\right)$$

$$F_g = -\frac{2r\mathcal{F}_g\exp(1/2)}{\omega(z)}\exp\left(\frac{-2r^2}{\omega(z)^2}\right)$$

$$\boxed{F = \left(\mathcal{F}_{rp} - \frac{2r\mathcal{F}_g\exp(1/2)}{\omega(z)}\right)\exp\left(\frac{-2r^2}{\omega(z)^2}\right)}$$

# Optical force

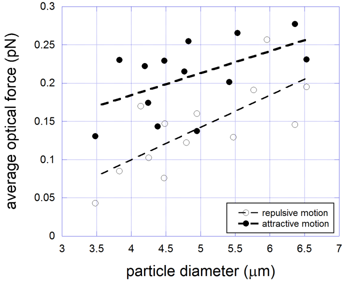


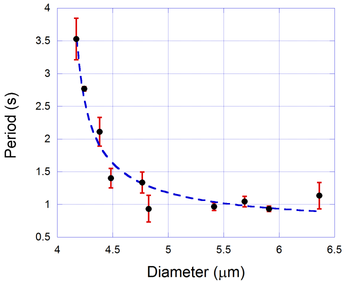

Physical parameters:

- $\omega(z) = (5.55 \pm 0.15)\mu$m
- $\mathcal{F}_{rp} = (4.1 \pm 0.6)$pN
- $\mathcal{F}_{g} = (2.1 \pm 0.2)$pN

- $\langle\omega(z)\rangle_{cicles} = (5.7 \pm 0.3)\mu$m
- $\omega_{0_{exp}} = (0.45 \pm 0.02)\mu$m
- $\omega_{0_{pred}} = \frac{2\lambda}{\pi N.A.} \sim 0.36\mu$m

# Averages: Dependence with diameter




In the range analysed (diameter $\sim 3.5 - 6.5\mu$m) :

- Optical forces increase with the particle size
- Frequency increases with particle size
- $F_g \sim Aa^3 \qquad F_{rp} \sim Ba^2$

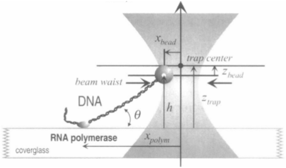
$$F_S \sim Ca$$

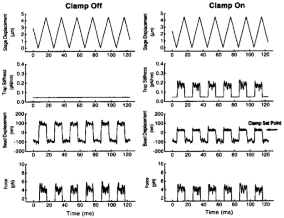
Harmonic description:

- $T = 2\pi\sqrt{\frac{m}{k}} \sim \sqrt{\frac{a^3}{Aa^3+Ba^2+Ca}}$
- $A \sim 1.81\text{s}^{-2} \qquad B \sim 3.89\mu\text{ms}^{-2}$
  $C \sim -46.50\mu\text{m}^2\text{s}^{-2}$

# Some potential applications

- Dynamic force measurements

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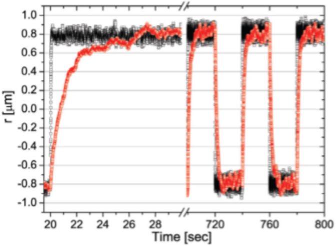
- Microrheology

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# Conclusions and Prospects

- Microsized TI $Bi_2Te_3$ particles oscillate perpendicularly to the optical axis when subject to a highly focused light beam
- Frequency remains practically constant during a number of cycles
- For practical purposes, frequency can be controlled by changing the power of the light beam and diameter of the particles
- Regular spherical shape is crucial for highly precise applications
- Other TI composites may have more intense manifestation of these properties
- Functionalize the TI particles
- Work available in **arXiv:1703.04556**

# Acknowledgements

Thank you!

CAPES

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