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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Topological Insulator particles as optically induced oscillators
Topological Insulators
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Topological Insulator particles as optically induced oscillators

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3D Topological Insulators

- Theoretically predicted in 2007

**Topological Insulators in Three Dimensions**

Liang Fu, C.L. Kane, and E.J. Mele

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(Received 26 July 2006; published 7 March 2007)

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

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Week ending 9 March 2007

PRL 98, 106803 (2007)
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

Chen, Y. L., et al. Science 329, 5992, (2010): 659.
Hasan, M. Z. and Kane, C. L. Rev. Mod. Phys. 82, (2010): 3045.
Qi, X.-L. and Zhang, S.-C. Rev. Mod. Phys. 83, (2011): 1057.
Application prospects

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

Mellnik, A. R. et al. *Nature* **511**, (2014): 449.
Jamali, M. et al. *Nano Lett.*, **15**, (2015): 7126.
Wang, H. et al. *Phys. Rev. Let.*, **117**, (2016): 076601.
Optical tweezers technique

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

Ray optics regime \((radius \gg \lambda)\)

- Highly focused Gaussian light beam:
  \[ I = I_0 e^{-A r^2} \]
- 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 $\rightarrow$ gradient force dominates $\rightarrow$ stable trap

Metallic particle $\rightarrow$ radiation pressure dominates $\rightarrow$ deflection

Rocha, M. S. Am. J. Phys. 77, (2009): 704.
Some applications of optical tweezers

- Membrane elastic properties

![Image of membrane elastic properties](image)

- DNA studies

![Image of DNA studies](image)

- Micro-rheology

![Diagram of micro-rheology](image)

Pontes, B. et al. *PLoS One* **8.7**, (2013): e67708.
Murugesapillai, D. et al. *Biophys. Rev.* **9**, (2016): 17.
Ayala, Y. A. et al. *BMC biophysics* **9.1**, (2016): 5.
Alemany, A. et al. *Biophys. J.* **110.1**, (2016): 63.
Naufer, M. et al. *Protein Science*, (2017): Early View.
Topological insulator bead in optical tweezers

- **Dielectric particle**
  - Gradient force dominates "particle trapping"

- **Metallic particle**
  - Radiation pressure dominates "particle deflection"

- **TI particle**
  - Gradient force and radiation pressure compete "oscillatory motion"
Syntesis of TI-particles

- ARPES measurements for Bi$_2$Te$_3$:

- Laser ablation technique in liquid solution:

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

Amendola, V. and Meneghetti, M. *Phys. Chem. Chem. Phys.* **15** (2013): 3027.
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

\[ I_N = \exp \left( \frac{-2r^2}{\omega(z)^2} \right) \]

\[ \omega(z) = \omega_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2} \]

\[ z_R = \frac{\pi \omega_0^2}{\lambda} \]

\[ F_{rp} = F_{rp} \exp \left( \frac{-2r^2}{\omega(z)^2} \right) \]

\[ F_g = -\frac{2rF_g \exp(1/2)}{\omega(z)} \exp \left( \frac{-2r^2}{\omega(z)^2} \right) \]

\[ F = \left( F_{rp} - \frac{2rF_g \exp(1/2)}{\omega(z)} \right) \exp \left( \frac{-2r^2}{\omega(z)^2} \right) \]
Physical parameters:

- $\omega(z) = (5.55 \pm 0.15) \mu m$
- $F_{rp} = (4.1 \pm 0.6) pN$
- $F_g = (2.1 \pm 0.2) pN$
- $\langle \omega(z) \rangle_{cicles} = (5.7 \pm 0.3) \mu m$
- $\omega_{0\ exp} = (0.45 \pm 0.02) \mu m$
- $\omega_{0\ pred} = \frac{2\lambda}{\pi N.A.} \sim 0.36 \mu m$
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
- $F_g \sim Aa^3$  
  $F_{rp} \sim Ba^2$
- $F_S \sim Ca$

Harmonic description:

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

- **Dynamic force measurements**

  Wang, M.D. et al. *Biophys. Journal* **72**, (1997): 1335-1346

- **Microrheology**

  Preece, D. et. al. *J. Opt.*** **13**, (2011): 044022
Conclusions and Prospects

- Microsized TI Bi$_2$Te$_3$ 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.
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Thank you!