Proposal for realizing Majorana Fermioms in strongly correlated nanowires

E.A. KOCHETOV
BLTP JINR, DUBNA

Introduction

Topological superconductors are quite special: they realize topological phases that support exotic excitations at their boundaries. Most importantly, zero-energy modes localize at the ends of a 1D topological p-wave superconductor. These zero-modes are precisely the condensed matter realization of Majorana fermions that are now being vigorously pursued.

Particularly interesting for the realization of qubits in quantum computing are pairs of localized Majoranas separated from each other by a superconducting region in a topological phase.
Such systems are intrinsically immune to decoherence.

Kitaev's toy model:

$$\hat{H}_{KC} = \sum_i \mu f_i^\dagger f_i + (-t f_{i+1}^\dagger f_i + \Delta f_{i+1}^\dagger f\dagger_i + H.c.)$$

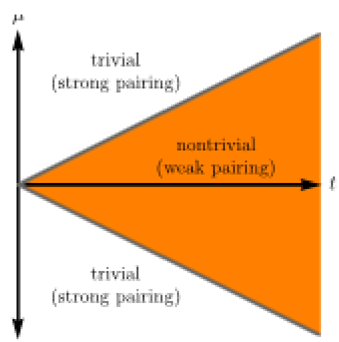
$$f = (\gamma_1 + i\gamma_2)/2$$

$$\gamma_\alpha^\dagger = \gamma_\alpha, \quad \gamma_\alpha^2 = \gamma_\alpha^\dagger \gamma_\alpha = 1, \quad \{\gamma_\alpha, \gamma_\beta\} = 2\delta_{\alpha\beta}.$$

In momentum space

$$\hat{H}_{\mathrm{KC}}^{(k)} = \sum_k (-2t\cos k - \mu)\tilde{f}_k^\dagger \tilde{f}_k - (i\Delta \sin k\, \tilde{f}_k^\dagger f_{-k}^\dagger + \mathrm{H.c.}).$$

The gapless points μ = ±2t separate two qualitatively different regimes, the so-called strong-pairing (|μ| > 2t) and weak- pairing (|μ| < 2t) phase



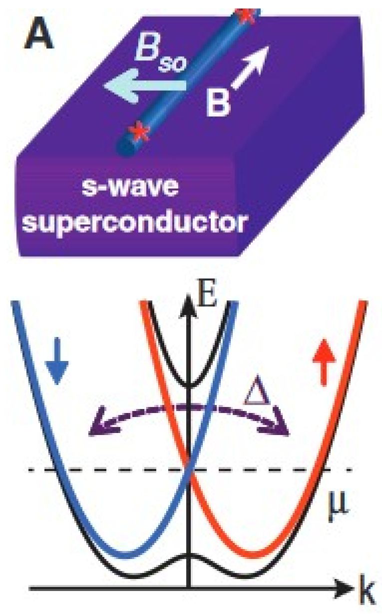
Topological invariant ν

$$(-1)^\nu = \mathrm{sgn}(\mu^2 - 4t^2),$$

which gives ν = 0, 1 respectively for |μ| > 2t and |μ| < 2t, corresponding to the topologically trivial and nontrivial phases

Quantum nanowires & proximity-induced SC:

Three ingredients are required to
obtain a topologically nontrivial superconducting state with Majorana end modes in a realistic 1D condensed matter system: broken time-reversal symmetry (i.e., finite magnetic fields), proximity-induced superconducting pairing, and finite spin-orbit coupling.



$E_Z > (\Delta^2 + \mu^2)^{1/2}$, with the Zeeman energy $E_Z = g\mu_B B/2$ (g is the Landé g factor, μ_B is the Bohr magneton).

Strong correlation

$$H_U = -t \sum_{ij\sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow},$$

$$H_{U=\infty} = -t \sum_{ij,\sigma} \tilde{c}^\dagger_{i\sigma} \tilde{c}_{j\sigma} = -t \sum_{ij,\sigma} X_i^{\sigma 0} X_j^{0\sigma}.$$

$$X^{\sigma 0} = |\sigma\rangle\langle 0|, \quad X^{\sigma\sigma'} = |\sigma\rangle\langle\sigma'|,$$

$$X^{00} + \sum_\sigma X^{\sigma\sigma} = I.$$

Strongly correlated nanowire on a SC substrate

$$H_{\text{eff}} = -\, t \sum_i X_i^{\sigma 0} X_{i+1}^{0\sigma} + X_i^{\sigma' 0} X_{i+1}^{0\sigma'} \; + \Delta \sum_i X_i^{\sigma 0} X_{i+1}^{\sigma' 0} - X_i^{\sigma' 0} X_{i+1}^{\sigma 0} \; + \mu \sum_i X_i^{00}.$$

The corresponding imaginary time phase-space action takes on the form,

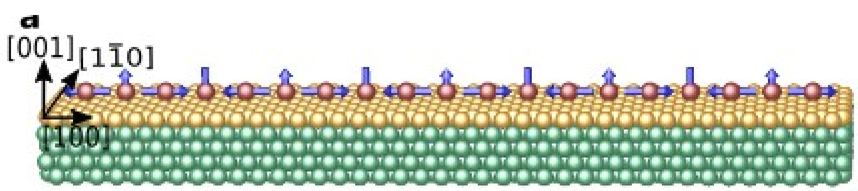
$$\mathcal{S}_{su(2|1)} = -\int_0^\beta \langle z, \xi | \frac{d}{dt} + H(X) | z, \xi \rangle dt,$$

<u>*Example:*</u> $X_{cs}^{\uparrow 0} = -\frac{\xi}{1+|z|^2},$

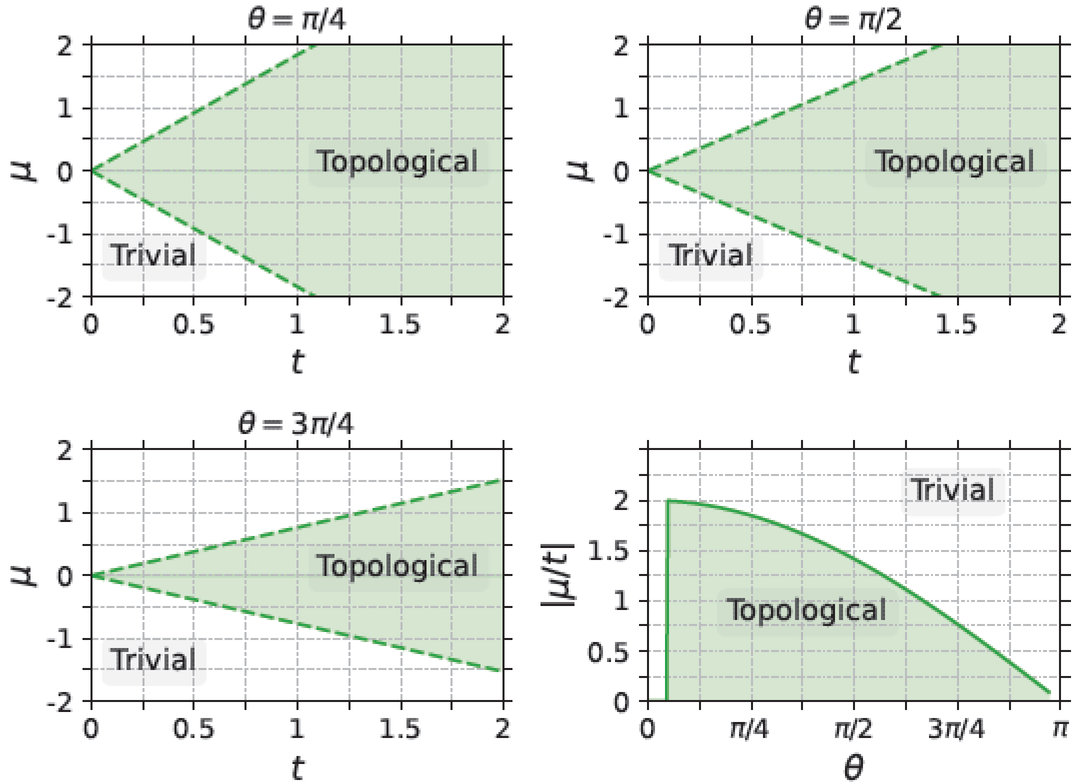
Spiral-spin profile: $\vec{S}_i = \left(S_i^x, S_i^y, S_i^z\right) = \frac{1}{2}\left(\cos\theta_i, \sin\theta_i, 0\right).$

<u>*Example:*</u> *Neel spin spiral:*

$$\theta_{i+1} - \theta_i \equiv \theta = \pi$$



θ is a rotation rate between the adjacent magnetic moments.



$$H_{\text{eff}} = -t\sum_i (f_i^\dagger f_{i+1}\cos\frac{\theta}{2} + H.c.) + \mu\sum_i f_i^\dagger f_i + i\Delta_0\sum_i (f_{i+1}^\dagger f_i^\dagger - f_i f_{i+1})\sin\frac{\theta}{2}.$$

This is an emergent topological Kitaev model in a strongly correlated electronic system (Ferraz&Kochetov Ann. Phys. v.456, 169234 (2023)).

Thank you for attention!