

Topological Superconductivity

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I. INTRODUCTION

One of the earliest breakthroughs allowed by quantum mechanics is the description of metals and insulators with band theory [1] which saw light in 1930. This theory brought a microscopic understanding of the distinction between these two classes of materials and led to incredible technological advances such as the discovery of the transistor by John Bardeen and Walter Brattain in 1947 [2]. Beyond its incredible success, band theory rapidly came in contact with a myriad of intriguing quantum mechanical effects such as the integer quantum Hall effect discovered in 1980 [3]. In 1982, Thouless et al. [4] figured out the topological nature of the effect and, in term, brought topology closer to band theory. Although the integer quantum Hall effect (QH) requires a strong external magnetic field, it was theorised in 2005 by Charles Kane and Eugene Mele [5] that similar topological properties could be intrinsically realised through the quantum spin Hall effect (QSH) [6]. Experiment then showed in 2007 [7] that HgTe/CdTe quantum wells (mercury telluride heterostructure) could produce a QSH effect. The theory and experiment of QSH effect led to a deeper classification of solids with topological band theory [8]. When applied to insulators, the upgraded band theory creates a separation between the trivial and the *topological insulators* (TI). The latter is generally characterised by a metallic boundary and an insulating bulk [9] as opposed to trivial insulators which are insulating everywhere. The

present review will focus on basic properties of time reversal symmetric topological insulators based on the mercury telluride example. Sec.II presents an overview of important ideas from topological band theory. In sec.III, the main properties of the QSH state are given and compared to the QH effect. Finally, a model of HgTe/CdTe quantum is studied in sec. IV.

II. ELEMENT OF TOPOLOGICAL BAND THEORY

This sections aims to describe the notion of topological invariant and its consequence on the band structure.

A. Topological equivalence of insulators

In a periodic lattice potential, electrons are described by bloch states $|n, \mathbf{k}\rangle$ where n is a discrete quantum number and \mathbf{k} is the crystal momentum in the brillouin zone [10]. Each of those states is associated to an energy $E_{n, \mathbf{k}}$. As it varies with \mathbf{k} , the energy sweeps a continuous range called a band labeled with the number n . Bands are often separated by energy gaps where there are no associated states. Trivial insulators have a gapped ground state meaning that low energy excitations are forbidden by the presence of the gap. On the contrary, topological insulators have metallic (gapless) edge states [11] and different from trivial insulators in a fundamental way.

Small modifications of the hamiltonian of a trivial insulator will change its band structure while leaving it in its ground state. The *deformation* is said to yield equivalent insulators if the gap doesn't close [11]. This equivalence is topological in the same way the continuous deformation from a torus to a coffee mug is. Just like the coffee mug cannot be continuously deformed into a sphere, a trivial insulator cannot be continuously deformed into a topological insulator.

For the coffee mug and the sphere, a number tells if there is topological equivalence or not. This number is called the genus (the number of holes) and it is an analogue for topological insulators [12]. The central property of genus is that it only changes when the torus is broken into a sphere in a necessarily discontinuous way. Therefore, the genus is a topological invariant for the sphere and torus. For the QH effect the topological invariant indicating the persistence of the edge states upon deforming the Hamiltonian is the Chern number. For the QSH effect, a \mathbb{Z}_2 invariant is involved [11]. In the following sec-

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tion, the link between time reversal symmetry and this last invariant is detailed. Mixing symmetry, topological invariants and dimensionality allows for a classification of topological insulators in a form similar to the *periodic table* of elements [13].

B. Time reversal symmetry

In a quantum mechanical setting, an operator U (unitary or anti-unitary) corresponds to a symmetry of a system when $UHU^{-1} = H$ where H is the hamiltonian governing the motion of the system. For a time reversal symmetric (TRS) system this means that evolution follows the same equations of motion as a movie of itself set on rewind [14]. The operator sending a system to its time reverse is an anti-unitary operator noted Θ and TRS corresponds to $\Theta H \Theta^{-1} = H$. In the position representation of the spin, momentum and position observables of an electron, the intuitive effects of this time reversal operator are the following [14] :

$$\begin{aligned}\Theta \mathbf{s} \Theta^{-1} &= -\mathbf{s}, \\ \Theta \mathbf{r} \Theta^{-1} &= \mathbf{r}, \\ \Theta (-i\hbar \nabla) \Theta^{-1} &= +i\hbar \nabla\end{aligned}$$

meaning it sets electrons spinning backwards with a reversed velocity. The operator satisfying all those properties is $\Theta = is_y K$ where K represents complex conjugation and the is_y factor ensures spin is fully reversed [15]. The essential property of the time reversal operator for electrons is that it satisfies $\Theta^2 = -1$. Hence reversing time twice for spin 1/2 particles isn't the identity [13]! This leads to Kramer's theorem which is said to be the most important theorem for time reversal invariant two dimensionnal topological insulators [15]. It states the following:

Kramer's Theorem: For a time reversal invariant system containing an odd number of spin 1/2 particles, there are at least two degenerate energy states [15].

To use this theorem here, it must be applied to the periodic bloch states $|n, \mathbf{k}\rangle$ mentioned before. By bloch's theorem [10], these states can be written as the direct product $|u_n(\mathbf{k})\rangle \otimes |\mathbf{k}\rangle$ where $|\mathbf{k}\rangle$ takes care of the translationnal symmetry of the crystal lattice and $|u_n(\mathbf{k})\rangle$ contains the details of the state over a unit cell. The basic idea of Kramers theorem is that provided a state $|u_n(\mathbf{k})\rangle$, the action of the time reversal on it gives a state $\Theta |u_n(\mathbf{k})\rangle$ which has the same eigen energy as the first (if the hamiltonian is time reversal symmetric). Then, if there is no degeneracy the generated state must be related to the first one with a constant c by $\Theta |u_n(\mathbf{k})\rangle = c |u_n(\mathbf{k})\rangle$ or else two physically different states would have

the same energy [11]. Applying time reversal again yields

$$\begin{aligned}-|u_n(\mathbf{k})\rangle &= \Theta \{ \Theta |u_n(\mathbf{k})\rangle \} \\ &= c^* \Theta |u_n(\mathbf{k})\rangle \\ &= cc^* |u_n(\mathbf{k})\rangle \\ &= |c|^2 |u_n(\mathbf{k})\rangle\end{aligned}$$

where c gets conjugated by K and the property $\Theta^2 = -1$ was used. This series of equalities suggests that, if a state is non degenerate, $|c|^2 = -1$ which is impossible and leads to a contradiction: the states must be twofold degenerate [11]. This can be made more precise by noting that the time reverse of $|u_n(\mathbf{k})\rangle$ is $|u_{n'}(-\mathbf{k})\rangle$ [15] (a state with reversed crystal momentum possibly living on a different band). Furthermore, the time reversed state also has reversed spin [16].

Special points called time reversal invariant momentas (TRIM) lead to a crucial effect of the theorem. They are points in the Brillouin zone that are sent to points with an equivalent cristal momentum by time reversal ($\mathbf{k} \equiv -\mathbf{k}$) [16]. At TRIM points, the Kramer degeneracy can only be satisfied if the states come from 2 different bands having different spins [16]. This forces bands to touch at special points and then split as \mathbf{k} varies through the effect of spin orbit coupling [11]. In two dimensions, if there are edge states locked inside the gap of the bulk of an insulator, Kramer's theorem forces them to have one of two topologies represented on fig. 1 [11]. Consider the points having cristal momentum norm $k = 0$ (Γ_a) and the point $k = \pi/a$ (Γ_b) (with a being the unit cell size in one direction): they are both TRIM points because $\mathbf{0} = -\mathbf{0}$ and $k = \pi/a$ is equivalent to $k = -\pi/a$. The edge states at the TRIM points must connect two bands by Kramer's theorem. They can either do it in a gapped way (see fig. 1 (A)) or in a metallic gapless way (see fig. 1 (B)).

While the band configuration in fig. 1 (A) can be gapped out by the addition of disorder (time reversal symmetric impurities [17]), configuration (B) always remain gapless and its metallic behavior is robust to deformations of the system (and of its Hamiltonian) [4]. This is where the word *topological* insulator gets its meaning. To be more precise, disforming the band structure from (A) to (B) would require closing the bulk gap or breaking TRS which would indicate a topological phase transition [4]. Just like it was mentioned in sec. IIA, there is a number distinguishing between configuration (A) and (B) referred to as the \mathbb{Z}_2 topological invariant.

Since there are *two* different ways to connect TRIM points, the invariant used to qualify the topology of a 2D TRS topological insulators is an integer ν taking values 0 or 1 [15]. If $\nu = 0$ then the band insulator is trivial and, if $\nu = 1$, it is topological [4]. To give precise meaning to this number, it suffice to use the notion of a *Kramer*

pair. Two states related to each other by the application of Θ are called a Kramer pair [17]. In fig. 1, only one member of each Kramer pair is shown so it is important to keep in mind that all points show effectively count for one pair. The ν invariant corresponds to the parity of the number of kramer pairs at a fixed energy [17]. If the number of pairs is even (A) then $\nu = 0$, the insulator is gapped and trivial. Otherwise the number of pairs is always odd (B) and the insulator is topological.

III. HALL EFFECTS

One of the defining properties of topological insulators is the presence of conducting edge states with an insulating bulk. The example considered here in sec. IV is a two dimensionnal material and its edge is therefore one-dimensionnal. The QH and QSH effects both involve one-dimensionnal conduction. In one dimension, electrons can either move forward or backward on the edge of the sample and this restriction is central for Hall effects. [6].

A. QH

B. QSH

IV. HGTE/CDTE HETEROSTRUCTURE

The first observed topological insulator is a mercury telluride heterostructure consisting of a stacking of thin HgTe layers between $\text{Hg}_x\text{Cd}_{1-x}\text{Te}$ [18]. If the thickness of the HgTe layers is right, a spin Hall effect arises. To model this system, the

V. CONCLUSION

1. Opening on other topological systems (topological Superconductivity and charge pumps)

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- [1] Lillian Hoddeson, Gordon Baym, and Michael Eckert. The development of the quantum-mechanical electron theory of metals: 1928—1933. *Reviews of Modern Physics*, 59(1):287–327, January 1987.
 - [2] W.F. Brinkman, D.E. Haggan, and W.W. Troutman. A history of the invention of the transistor and where it will lead us. *IEEE Journal of Solid-State Circuits*, 32(12):1858–1865, December 1997. Conference Name: IEEE Journal of Solid-State Circuits.
 - [3] K. v. Klitzing, G. Dorda, and M. Pepper. New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance. *Physical Review Letters*, 45(6):494–497, August 1980.
 - [4] J Cayssol and J N Fuchs. Topological and geometrical aspects of band theory. *Journal of Physics: Materials*, 4(3):034007, July 2021.
 - [5] C. L. Kane and E. J. Mele. Quantum Spin Hall Effect in Graphene. *Physical Review Letters*, 95(22):226801, November 2005. arXiv: cond-mat/0411737.
 - [6] Xiao-Liang Qi and Shou-Cheng Zhang. The quantum spin Hall effect and topological insulators. *Physics Today*, 63(1):33–38, January 2010.
 - [7] Markus Koenig, Steffen Wiedmann, Christoph Bruene, Andreas Roth, Hartmut Buhmann, Laurens W. Molenkamp, Xiao-Liang Qi, and Shou-Cheng Zhang. Quantum Spin Hall Insulator State in HgTe Quantum Wells. *Science*, 318(5851):766–770, November 2007. arXiv: 0710.0582.
 - [8] Alexey A Soluyanov. TOPOLOGICAL ASPECTS OF BAND THEORY. page 174.
 - [9] Joel E. Moore. The birth of topological insulators. *Nature*, 464(7286):194–198, March 2010.
 - [10] Steven M. Girvin and Kun Yang. *Modern Condensed Matter Physics*. Cambridge University Press, February 2019. Google-Books-ID: ymYNuQEACAAJ.
 - [11] C.L. Kane. Topological Band Theory and the \mathbb{Z}_2 Invariant. In *Contemporary Concepts of Condensed Matter Science*, volume 6, pages 3–34. Elsevier, 2013.
 - [12] Navketan Batra and Goutam Sheet. Physics with Coffee and Doughnuts: Understanding the Physics Behind Topological Insulators Through Su-Schrieffer-Heeger Model. *Resonance*, 25(6):765–786, June 2020.
 - [13] M. Z. Hasan and C. L. Kane. Topological Insulators. *Reviews of Modern Physics*, 82(4):3045–3067, November 2010. arXiv: 1002.3895.
 - [14] R. Shankar. Topological Insulators – A review. *arXiv:1804.06471 [cond-mat]*, April 2018. arXiv: 1804.06471.
 - [15] B. Andrei Bernevig and Taylor L. Hughes. *Topological Insulators and Topological Superconductors*. Princeton University Press, April 2013.
 - [16] Jorrit Kruthoff, Jan de Boer, and Jasper van Wezel. Topology in time-reversal symmetric crystals. *Physical Review B*, 100(7):075116, August 2019. arXiv: 1711.04769.
 - [17] János K. Asbóth, László Oroszlány, and András Pályi. *A Short Course on Topological Insulators*, volume 919 of *Lecture Notes in Physics*. Springer International Publishing, Cham, 2016.
 - [18] Charles Kane. This newly discovered phase of matter has become one of the hottest topics in condensed-matter physics. It is hard to understand – there is no denying it – but take a deep breath, as Charles Kane and Joel Moore are here to explain what all the fuss is about. *Topological insulators*, page 5, 2011.

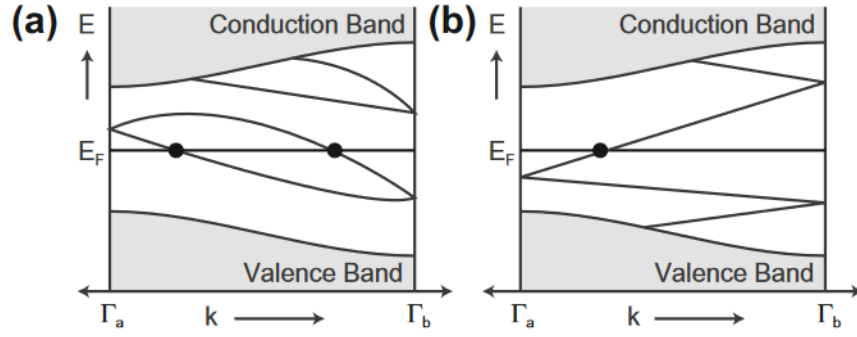


FIG. 1. Schematic representation of the two typical ways Kramer's theorem can be satisfied between TRIM points. (A) Shows a way to connect TRIM points without closing the gap. In this case there is an even amount of intersection points with the Fermi level. (B) Shows second way to connect TRIM points that closes the gap and has an odd number of intersections with the Fermi level [11]. To get a complete picture, one must keep in mind that the energies at $-\mathbf{k}$ are the same as the represented ones along the k values of interest (they are Kramer degenerate).

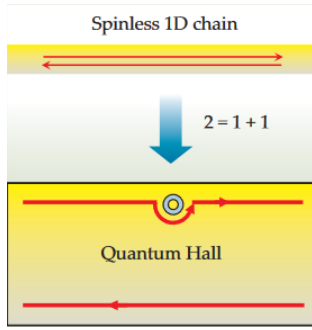


FIG. 2. Schematic representation of the conduction channels in a spinless quantum Hall system.[6]

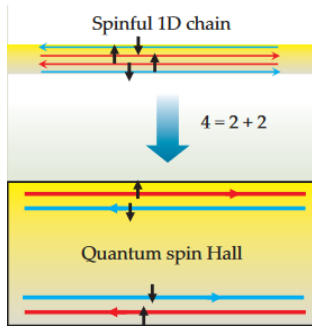


FIG. 3. Schematic representation of the conduction channels in a spinful quantum Hall system.