Separating Spins in a One-Dimensional Metal

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Nondegenerate Metallic States on Bi(114): A One-Dimensional Topological Metal.

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The manipulation and effective transport of the electron spin without the use of magnetic fields lies at the heart of the developing field of spintronics. One of the advantages of spintronics compared to conventional electronics, which is based on the charge of the electron, is that much less energy is needed to process the same amount of information. The most promising candidate mechanism to control the electron spin without magnetic fields is provided by the Rashba-Bychkov effect. This relativistic effect is caused by spin-orbit coupling and the symmetry breaking at surfaces or interfaces. It is currently under intense investigation at the Swiss Light Source [1, 2].

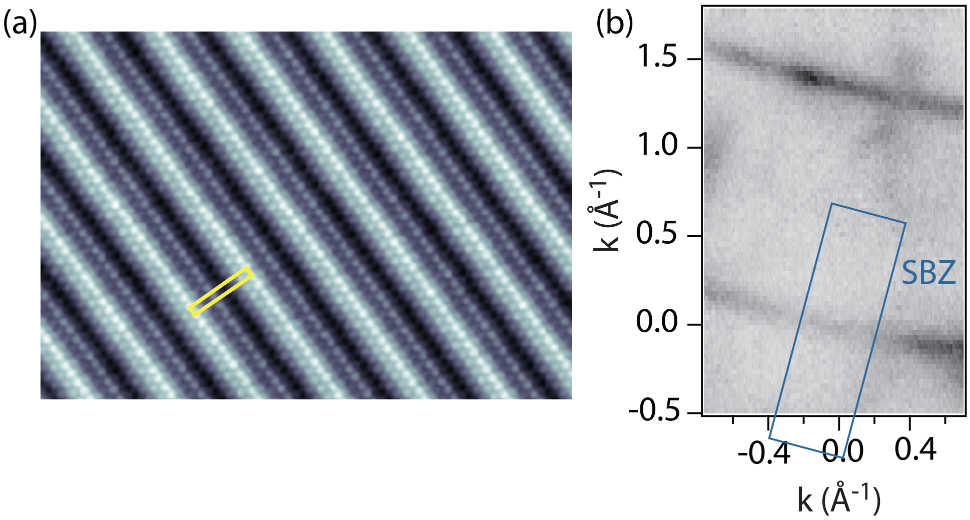

FIG. 1: *(a) Scanning tunneling microscopy image of Bi(114) (36 nm × 25 nm sample bias: -150 mV). (b) Photoemission intensity at the Fermi energy (taken at a photon energy of* $h\nu = 70$ *eV at the synchrotron radiation source ASTRID in Aarhus), revealing the existence of a quasi-one-dimensional Fermi line, passing through the origin. Also indicated is the surface Brillouin zone (SBZ) for the truncated bulk surface.*

The second important ingredient is the transport of the spin over macroscopic distances with low resistance and without the loss of information, implying macroscopic spin coherence lengths. Here the necessary prerequisites are met by the quantum spin Hall effect (QSHE) which is the fourth type of Hall effect and has been predicted only very recently [3]. In the quantum Hall effect, spin degenerate edge states are formed under the application of (strong) magnetic fields. In the QSHE on the other hand, spin polarized edge states form without the application of magnetic fields. Furthermore, the topology of the states is such that their spin split Fermi level crossings can't be removed by a non-magnetic perturbation. In practice this means that the number of Fermi level crossings on a straight line connecting one centre of the surface Brillouin zone (SBZ) with the next time-reversal protected point should be odd (for example between $\bar{\Gamma}$ and $\bar{X}$ in Fig. 2 (d)). In this counting scheme, degenerate bands are of course counted twice. As a result one is always left with one band for which there is no counterpart with opposite spin and the same sign of momentum. Therefore the electrons in this band can't continue moving in the same direction after a spin flip, and more importantly they can't change their direction without changing spin. In the absence of magnetic impurities or magnetic fields the probability of such a spontaneous spin flip is extremely low, and the electron can thus not change its direction. Consequently, the spin information can be transported with very low resistance over large distances in such systems.

The first direct observation of a Fermi surface topology which fulfills the requirements for a quantum spin Hall phase was performed at the Surface and Interface Spectroscopy beamline at the SLS on a bismuth and antimony alloy ($\mathrm{Bi}_{0.9}\mathrm{Sb}_{0.1}$) [4]. In this system the relevant states form a two-dimensional electron gas on the surface of the crystal and the electrons can, depending on their spin, move in all directions in this plane. The next step is now to restrict the motion of the electrons even further, so that they can move only in one dimension. This means that one would obtain something like an atomic wire. In experiments performed in a collaboration of the SLS and the Universities of Zurich, Aarhus, Trondheim and Berlin, it was explicitly demonstrated that this situation can be obtained by creating a densely stepped bismuth surface [5]. Fig. 1 (a) shows scanning tunneling microscopy (STM) images of this Bi(114) surface with atomic resolution, where one can directly identify the parallel chains of atoms. Due to the global miscut of the surface these lines run parallel over the whole macroscopic surface.

For states located on these chains, one would expect a one-dimensional behaviour also in the electronic structure. That this is the case can be verified from the surface Fermi surface shown in Fig. 1 (b) where the electronic structure primarily consists of straight parallel lines. In conformance with expectations for a truly one-dimensional system, these lines run in the direction perpendicular to the steps. For other surfaces of bismuth a strong spin splitting of the states located at the surface has been observed [6] and it was surprising that no such splitting is evident in the high resolution ARPES data of Fig. 1 (b).

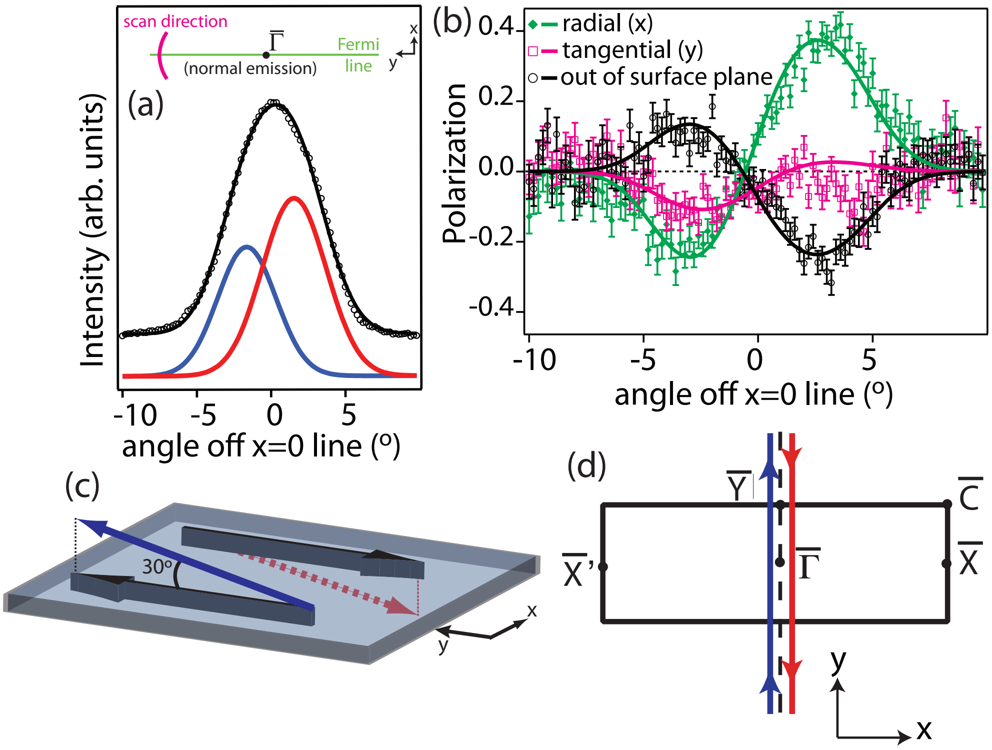

FIG. 2: *Black open markers: spin-integrated photoemission intensity for an azimuthal angle scan through the surface Fermi line, taken at a polar off-normal emission angle of 35° . Two Gaussian components [red and blue] are fitted to the data to represent the two spin-split components. The black line is the result of the fit. (inset) Sketch of the scan geometry. (b) Measured (markers) and fitted (lines) spin polarization data along the scan, split up into three mutually perpendicular components: x, y, and out of the surface plane (z). (c) The directions of the experimentally determined spin polarization vectors relative to the surface plane. (d) Schematic spin resolved Fermi surface of Bi(114).*

Further investigation of the electronic structure using spin resolved ARPES at the SLS yields a more complete picture of the electronic structure of Bi(1114). In the total intensity of all spin channels as displayed in Fig. 2 (a) by the black symbols it is not possible to distinguish two bands. On the other hand, the three spatial components of the measured spin polarization (symbols in Fig. 2 (b)) can only be interpreted by assuming two bands with opposite spin polarization. Using a two-step fitting routine as described in Ref. [1] it is now possible to fit the spin resolved data set and obtain the spin polarization vectors of the two bands in 3D. The obtained vectors are displayed in Fig. 2 (c) and one can directly see that they have opposite directions and lie along the Fermi surface lines with a small out-of-plane component. Cuts along different segments of the Fermi surface lines show exactly the same result, which means that the single lines in Fig. 1 (b) actually consist of two parallel bands with opposites spin direction.

Within the surface Brillouin zone there are no other surface derived bands, which means that there is only one spin polarized Fermi crossing between the centre and the edge of the SBZ. Therefore all electrons located at the surface that move to the right (left) have spin up (down) and they can't change their propagation direction without changing their spin. This is exactly the Fermi surface topology one would expect for a one-dimensional version of the quantum spin Hall effect. It has to be noted that although the bulk conductivity of bismuth is relatively low, it will still strongly influence the electron transport on the surface. In order to avoid this, one would have to open up a band gap in the bulk band structure around the Fermi level, like in the two-dimensional case of $Bi_{0.9}Sb_{0.1}$.

To summarize, using the unique capabilities of the COPHEE end station at the SIS beamline at the SLS, combined with a powerful two-step analysis routine, we have been able to identify a one-dimensional non-degenerate surface state on Bi(114). Given the spin resolved Fermi surface topology this system can be viewed as a parent compound for a one-dimensional version of the quantum spin Hall effect.

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