Summary of scientific contributions

I have contributions in high energy theory and phenomenology as well as in condensed-matter physics, although I have mainly worked in condensed matter physics after joining the Harish-chandra Research Institute in 1995.

One of my most important results involves non-abelian topologically massive theories in 2+1 dimensions. We obtained a new topological Ward identity which showed that the coefficient of the non-abelian Chern-Simons term, which has to be quantised as an integer for topological reasons, gets renormalised by an integer at the one-loop level, and gets no further corrections at higher orders. (A non-perturbative proof of this result was later given by Witten, who also showed the connection between this renormalisation and the renormalisation of the parameter k in Wess-Zumino-Witten models). In another important paper, we obtained a prediction of the Higgs mass as a function of the top quark mass (which was undiscovered then) in a simple two-Higgs extension of the standard model using renormalisation group methods. In a third important paper, we classified all dimension six operators which could contribute to new physics at significant levels if there are intermediate energy scales. This work continues to be used till today as the basis for many phenomenological analyses. My thesis research was on $n - \bar{n}$ oscillations and $(B - L)$ violation in grand unified theories, where I calculated matrix elements of the $n - \bar{n}$ transition operators in the MIT bag model. We have also clarified subtleties involved in showing that there is no parity anomaly in QED_3, but that there exists a non-perturbative parity anomaly in QCD_3. My work on dynamical breaking of chiral symmetry in 2+1 dimensional models and on the question of topological mass for the graviton are also well-recognised.

In condensed-matter physics, I have worked in the areas of anyons, fractional quantum Hall effect, spin systems and, later, in quantum systems in low dimensions, such as quantum wires and dots, and the physics of Luttinger liquids and edge states of quantum Hall samples. Most recently, I have been working on graphene and related materials like silicene and on topological insulators and related topological systems like Weyl semi-metals.

In the last decade or so, my work has focussed mainly on electronic transport in low dimensional mesoscopic systems such as quantum wires, quantum dots and edge or surface physics. My main emphasis has been on the effects of electron-electron correlations on electronic conductances. The idea is that in low dimensional systems, interaction effects are important and can lead to qualitatively new physics, rather than merely leading to quantitative corrections. For instance, in one-dimensional wires, interacting electrons necessarily form a Luttinger liquid, rather than a Fermi liquid. We have studied the effects of interactions on electronic conductances, focussing on the effects of the contacts between the leads and the wire, junctions between several wires, and correlated transport through coupled quantum dots. We have also studied time dependent transport in mesoscopic systems, particularly on the idea of charge pumping through quantum dots and through junctions of quantum wires. Most recently, my work has focussed on new materials like graphene, silicene, topological insulators and Weyl semi-metals where the topology of the band-structure has led to unexpected effects. Here too, I have mainly focussed on transport through junctionss and in different geometries. The work in this field has considerable scope for applications in the near future. Below, we describe some of the work in the last ten years in more detail.

We pioneered the work on junctions of three or more quantum wires meeting at a point and showed how the S-matrix at the junction changes as a function of the energy scale due to interactions. For scalar junctions, the only fully stable fixed point is when all the wires are decoupled from one another. We also found several other interesting fixed points, including chiral fixed points, along with their domains of stability. Away from the fixed point, we showed the renormalisation group flow of the couplings, and computed length and temperature dependences of conductances. Essentially, this is a multi-terminal generalisation of the two-terminal results on quantum wires. Using this generalisation, we studied conductances in different geometries of quantum wires including rings with Aharanov-Bohm fluxes and t-stubs and obtained results for different temperatures, lengths of wires and magnetic fluxes. Surprisingly, in some geometries, we found that the back-scattering decreases and conductance increases due to interactions, contrary to the experience of two-terminal junctions. Also by studying coherent and incoherent transport in these systems, we have presented a phenomenologically motivated formalism for studying conductances in an intermediate partially coherent regime. We also found that there are fixed points for the three-wire junction, which allow for an enhancement of the tunneling density of states close to the junction, in contrast to the two terminal junction where the tunneling density of states is always suppressed. Furthermore, when an impurity spin was coupled to a junction, we found that, if the electron-electron interactions are sufficiently strong, the system flows to the multichannel fixed point (the two-channel Kondo fixed point for two wires) and we computed the associated power law behaviour including the interaction logarithms as well as the Kondo logarithms.

We also showed that many of the novel fixed points in junctions can be accessed in a system which contains a junction of three quantum Hall line junctions of fractional quantum Hall edge states. We showed that it is possible to tune through the intermediate (unstable) fixed point between the flower (single droplet) and islands (three droplets) configurations by varying the width of the line junction. A measurement of the tunneling conductance as a function of the gate voltage controlling inter-edge repulsions can thus give a clear experimental signal of some of the junction fixed points. More recently, she has found a stable fixed point in the edge state system of the recently discovered $\nu = 5/2$ system where the half-filled level is completely transmitting and the two other filled levels are back-scattered, thus isolating the edge that hosts the non-abelian quasiparticles.

In graphene, we studied resonant tunneling through a superconducting double barrier structure as a function of the system parameters and showed that in this geometry, in the subgap regime, there is resonant suppression of Andreev reflection at certain energies, due to the formation of Andreev bound levels between the two superconducting barriers, where the transmission probability T for electrons incident on the double barrier structure becomes unity. The evolution of the transport through the superconducting double barrier geometry as a function of the incident energy for various angles of incidence shows the damping of the resonance as normal reflection between the barriers increases. We also considered the phenomenon of quantum charge pumping of electrons across a superconducting double barrier structure in graphene in the adiabatic limit. In this geometry, quantum charge pumping can be achieved by modulating the amplitudes (Δ_1 and Δ_2) of the gaps associated with the two superconducting strips. We showed that the superconducting gaps give rise to a transmission resonance in the Δ_1-Δ_2 plane, resulting in a large value of pumped charge, when the pumping contour encloses the resonance. This is in sharp contrast to the case of charge pumping in a normal double barrier structure in graphene, where the pumped charge is very small, due to the phenomenon of Klein tunneling.

In the field of topological insulators, we proposed a three terminal spin polarized scanning tunneling microscope setup for probing the helical nature of the Luttinger liquid edge state that appears in the quantum spin Hall system. We showed that the three-terminal tunneling conductance strongly depends on the angle (θ) between the magnetization direction of the tip and the local orientation of the electron spin on the edge while the two terminal conductance is independent of this angle. We demonstrated that chiral injection of an electron into the helical Luttinger liquid (which occurs when θ is zero or π) is associated with fractionalization of the spin of the injected electron in addition to the fractionalization of its charge. We also studied the Fabry-Perot type resonances which appear in the transport characteristics of a helical edge state exposed to a uniform magnetic field over a finite length. The intrinsic spin anisotropy of the edge state allows us to tune the resonances as a function of the direction of the magnetic field keeping its magnitude fixed. These resonances provide a unique way of identifying the helical nature of the edge states.

Most recently, we have been studying the surface states that appear at the surfaces of three dimensional topological insulators. In particular, we have focussed on effects on the spin and charge transport due to the curvature of the surfaces. We have also worked on a metallic variant called Weyl semi-metals and the proximity induced superconductivity in such Weyl semi-metals. We studied the various induced pairings in the Weyl semi-metal due to the proximity of the superconductor and showed that although no true gap develops, the coherence peaks do not penetrate into the bulk and all the pairings decay exponentially in the bulk. We are currently studying the Josephson effect in Weyl semi-metals as well as through silicene.

Although the kind of work that I am doing does not have any direct practical implications, because it is purely theoretical and focusses more on possibilities than on any particular materials, the field itself has a lot of scope for practical applications in the future, because of the possibility of using these materials, graphene, silicene, topological insulators and other Dirac materials for quantum computation.