Sunethra Ramanan - Research Statement

My research work has applied Renormalization Group theory to the nucleon-nucleon interaction in order to simplify the nuclear many-body problem. Conventional nuclear many-body calculations are strongly non-perturbative in the inter-nucleon interactions. This non-perturbative behavior arises from several sources: 1. a strongly repulsive short-range interaction, 2. a tensor force, e.g. from pion exchange, which is highly singular at short-distances, 3. the presence of low-energy bound states or nearly bound states (in the S waves).

There are several high-precision potentials which model the nucleon-nucleon interaction. These models use one pion-exchange physics for the long-range part of the interaction, but the intermediate and short distances use different phenomenological representations. Yet all these models reproduce nucleon-nucleon phase shifts to high accuracy ($\frac{\chi^2}{d.o.f} \approx 1$). Therefore we can conclude that the long-distance physics is insensitive to the *details* of the short-distance physics. This fact is exploited by the Renormalization Group based approach to effective potentials. In this approach, one of these high-precision potentials is used as the starting point. The momentum of the intermediate states of the Lippmann-Schwinger equation for the T matrix for a particular partial wave is cut-off at Λ, which is the scale up to which the details of the physics is resolved and the details of the physics beyond this limit of resolution are integrated out and included in the potential. The cut-off is then subsequently lowered to smaller values while preserving physical observables. This results in a cut-off dependent potential which is valid for low-energy regime, while the physical observables are independent of this cut-off.

When these renormalization group based effective potentials are used in nuclear many-body calculations, it has been observed that the first two sources of non-perturbative behavior are greatly dampened as the cut-off is lowered and therefore are scale-dependent sources. In free space, the third source of non-perturbative behavior (low-energy bound states or nearly bound states) persists, as this is a physical property, but it is eliminated in medium at intermediate-densities due to Pauli blocking. As a result, while calculating bulk properties of nuclear matter using these low-momentum effective potentials, all the three sources of non-perturbative behavior are removed. This results in a perturbative nuclear matter calculation in at least the particle-particle channel, contrary to conventional wisdom.

A useful tool to observe and monitor sources of non-perturbative behavior is the method introduced by Weinberg, which focuses on the complex eigenvalues of the operator $G_0(z)V$ which appears in the Lippmann-Schwinger equation, $T(z) = V + VG_0(z)T(z)$. When the magnitude of the largest eigenvalue is < 1, the Born-series expansion of the scattering T matrix equation converges. In a recent paper (nucl-th/0602060), my collaborators and I have investigated Weinberg eigenvalues of the renormalization group based effective potentials, including chiral effective theory potentials, as a function of cut-off. The studies have shown that the Weinberg eigenvalues are a useful diagnostic for non-perturbative physics in many-body calculations.

Another interesting direction that my collaborators and I are investigating is the choice of the regulator which cuts off high momenta in the intermediate states. A simple choice originally used is a sharp cut-off. While this choice leads to relatively simple renormalization group equations for calculating effective potentials, manifestations of the sharp cut-off are observed in calculated quantities, such as cusp-like behavior for the potential in some channels and also for the deuteron wave function, which is increasingly evident as the cut-off is lowered. These lead to convergence issues in few-body calculations. My collaborators and I are exploring in detail the construction of these effective potentials using a smooth regulator to cut-off the intermediate state momenta (work in progress). This complicates the renormalization group equation, but variational calculations improve and the wave function artifacts at lower cut-offs are eliminated.

In an effective field theory approach, many-body forces are inevitable and a pertinent question is to estimate how large these forces should be. It has been well established that for all realistic potentials, three-body forces are essential to describe light nuclei. A full renomalization group running starting with two and three-body bare potentials is not yet available. So far the three-body potential has been fitted at a particular cut-off to the leading order $3N$ force from chiral EFT. In these studies, it has been shown that the leading three body components of $3N$ force become perturbative as the cut-off is lowered. One of the immediate steps I would like to address is to extend the renormalization group approach to three-nucleon interactions, where the starting point would be the chiral three-body potential. Another important direction for my future work is to investigate the generality of the renormalization group approach and the possible application of this formalism to other systems which have similar scale separation. I would like to explore whether similar simplification in many-body calculations are found elsewhere, using the above formalism and tools. I am also very open to collaborating with on going projects in your institution and broaden my horizons.