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Job Number: **W22219**

Proposal Abstract In all generality, my goal is to improve hadronic models better fit hadron spectra and to improve models of multi nucleon objects. My proposed method of research is with holographic models. These models have the mysterious fifth dimension, but such a dimension is the geometric realization of the renormalization group (RG) flow of the theory from IR to the UV. The leading holographic model is holographic Sakai-Witten-Sugimoto model that is a bottom-up model with type IIA string theory. The strongly coupled hadron physics is said to be dual to weakly coupled supergravity theory. The model uses topological soliton in the bulk to model baryons (skyrmions) in the boundary with confinement and broken chiral symmetry. I propose to two topics of research: further understanding of the moduli space for the self-dual instantons/dual to skyrmion. I propose two research topics.

One is to extend the moduli analysis currently being done. The instantons in flat space represent the transitions of QCD vaccua. In the holographic, negatively curved space case, the instantons are dual to skyrmions, so the moduli of such holographic solitons are dual to the baryons. Because the holographic solitons are topological, within the Sakai-Witten-Sugimoto number of baryons is a topological invariant. Further, analysis of the moduli space can determine where it is a Riemannian manifold or not. Similar to the flat space case, such understanding of the moduli can help construct multi baryon solutions quantized degrees of freedom.

Another line of research involves the building of nucleon models via holographic methods. The leading model for cold multi baryon holographic QCD model the Sakai-Witten-Sugimoto model. Nevertheless, there are several other models with also have wanted properties bound hadronic states - such as confinement and broken chiral symmetry. Another holographic model one with two-component U(1) complex scalars such that they have a broken chiral symmetry. I would propose such a model since it is known that similar non-holographic models are known to have quasi-topological domain walls. I would claim that such a model represent high spin hadronic spin states.

I believe that the aforementioned research topics would most closely align with Dr. Masaaki Kimura and his group at the Nucleon Many-body Theory laboratory. I also believe that is there is mutual benefit to our collaboration. The majority of my work it more along the lines of finding QCD adjacent theories. The main focus, not to compare with experimental data, but to explore the strongly coupled field theory land-scape. I believe that Dr. Kimura, his group, and I could perform more phenomenological approach to model building with there I would expect a year to find interestingly novel results. After model building, I would expect find analytically or numerical results after one or a few months.

Proposed Method of Research For research involving moduli space of curved space instantons involves more mathematical techniques involving current mathematics high energy physics and mathematics. Essentially, the method of research here would be to conceptually tackle the problem as a simple (but distinct problem first) or to exploit the symmetries of the problem. An important part of such theoretical research is the collaboration and free promulgation of ideas. With this in the context of RIKEN, it's useful to have access to a wide range of researchers and to have the nearby locus of academic institutes, located in Tokyo.

For research pertaining to hadron modeling, first it is important for the research is to construct the model in the terms of a holographic Lagrangian. That is a 5D holography. Immediate candidates would be variations of the Sakai-Witten-Sugimoto. If the model has no known simple homogeneous solutions of the equations of motion, I would first exploring finding such simple solutions. Such solutions are usually thermodynamically the most favorable solution. Saying such thing, I would explore the thermodynamics of such a solution on the boundary. Further, analysis can be done by calculating meson spectra and couplings if admitted by the model. Otherwise, for more non-trival, non-homogeneous solutions, I would numerically solve such solutions as a boundary value problem (BVP). Calculating the spectra and couplings of meson similarly requires one to solve a BVP. The nice property of holographic models the lack of fittable parameters. Thus the statements made by such models carries more power. With the Dr. Kimura and co, I would be of interest to test the predictive power of such holographic models. Thus I would also consult with colleagues there to help guide the creation of models.

Expected Results For model creation and solution solving, I would expect spectra of mesons and thermodynamic properties of holographic models. Such models will have a few parameters to possible fit some nuclear experimental. It is common for such models to fit well for small nucleon cases but the fit worsens for larger body cases. This is goal of this line of research, to improve such results. Further, we expect to find defining features of low temperature QCD, such as chiral symmetry breaking and confinement.

For the moduli space, we would expect to find the dimension of moduli space and information on its geometrical structure. We expect the dimension of the moduli space, $\mathcal{M}$, should take the form $\dim \mathcal{M} = Ak - Bb - C$. A, B, and C are positive integers and $A > B + C$. These coefficients are determined solely by the underlying gauge group of the Yang-Mills theory and the topology of the curved manifold. b is the number of disjoin boundaries. k is the instantons (baryon number). For some b we expect to find, the moduli space is negative. We expect further that these results are conformally invariant, same as the flat case.

Future Work For the moduli space research, I would further develop methods to construct more generic solutions, similar to flat space *ADHM* case. Such solutions would be parametrized by the moduli. These moduli can be quantized with the collective coordinate quantization. It was found in the leading order term in holographic soliton's asymptotic behavior was similar to the massless pion fields and the classical inter-soliton. This structure is similar to the one in Skyrme model. There are a classical multi-soliton bound states do to the known attractive channel. This states can be quantized with the collective coordinate quantization. The multi soliton boundary states would be the holographic. Without a firm understanding of the curved space equivalent of the *ADHM* construction, the construction of holographic nuclei would be challenging [1]. The baryons play a significant role in the QCD phase diagram. Further exploration of such matter in the aforementioned QCD models with significant global rotation would be novel. Within holography, baryons are dual to (topological) solitons Obtaining explicit solutions would be ideals, if where initially numerical solutions were found. Further connections to other works on color superconductivity within other models. The speed of sound reference quantity, often used in holographic QCD. If it is not clear, it would be of interest to further compare such speed of sounds with the conformal speed of sound [2]. Additionally, applications to neutrons stars would be very interesting. At at low densities, first order transitions between the baryon and quark matter phases have been observed in similar holographic QCD models. Such phases possibly can be reached in neutron merger events.

[1] This is because multi-solitons would in general lack $SO(3)$ symmetry.

[2] The conformal speed of sound is $v = 1/\sqrt{3}$ in canonical units.