

Project Title:

Nucleon Structure from Lattice QCD with Domain Wall Fermions

Name : ○Tom Blum, Chris Dawson, Chulwoo Jung, Meifeng Lin,
Shigemi Ohta, Shoichi Sasaki, Takeshi Yamazaki

Affiliation : Riken BNL Research Center,
Riken Nishina Center for Accelerator-Based Science, Wako Institute

1. Background and purpose of the project, relationship of the project with other projects

1.1 Background

Protons and neutrons (collectively called nucleons) compose the major part of atoms, and are fundamental building blocks of matter. Understanding their internal structure advances our fundamental knowledge about the composition of the universe, and is a top-priority topic of the US Department of Energy (DOE) nuclear physics long-range plan. Many particle and nuclear experiments worldwide are actively probing the charge, current, magnetization and other fundamental properties of protons and neutrons, such as Mainz in Germany and the Jefferson Lab in the US. In particular, the RIKEN sponsored RHIC-Spin experiment at Brookhaven National Laboratory in the US probes the spin structure of the nucleon. From a theorist's point of view, being able to interpret the observed experimental data and predict new properties of the nucleons from first-principles theories enhances our fundamental understanding of the underlying interactions and is the ultimate goal of our proposed research topic.

The theory that describes the interactions inside a proton is the so-called Standard Model of particle physics. In particular, we will be interested in the component of the Standard Model known as Quantum Chromo-dynamics (QCD). In this theory, a proton consists of quarks which are fermions with fractional charges, and gluons which mediate the strong interactions among quarks. Because of the nature of the strong interactions, traditional perturbative theoretical calculations (which assume

that fermions receive only small corrections to their behavior from the force carrying bosons) fail to work. In the 1970s Kenneth Wilson (later to win the Nobel Prize for his work on the Renormalization Group and Critical Phenomena) formulated Lattice QCD. This did two things: firstly, it provided a rigorous definition of the meaning of QCD beyond perturbation theory, and secondly it provided a way to perform first-principles calculations numerically. While it has taken several decades of improvements in computing power and algorithmic developments, recently the latter has been very successful in reproducing observed experimental data, such as the particle spectrum and decay properties. In lattice QCD calculations, the four-dimensional space-time is discretized into a box with discrete grid points, and Monte Carlo simulations based on the Standard Model are carried out on computers. Since lattice QCD simulations are carried out in a finite box, at finite quark masses and at a finite lattice spacing, before we can reliably interpret our results, we need to have the associated systematic errors under control.

The two most prominent systematic errors may be the errors associate with the finite volume and finite quark masses in the lattice calculations. In order to relate the results from lattice simulations to the real world, extrapolations are required to obtain results at the physical point which can then be compared to known experimental values or as predictions for future experiments. Chiral perturbation theory (ChPT), a low-energy effective theory, is often used to guide the extrapolation. However, at the order practical for our calculation, chiral perturbation

theory is only applicable at small quark masses (or equivalently, small pion masses). Existing lattice calculations of nucleon structure have pion masses only as low as 300 MeV (while the physical pion mass is about 140 MeV), which are at the edge of the applicability of chiral perturbation theory of the appropriate order. It has been found that lattice results at these pion masses are not consistent with the predictions of chiral perturbation theory, and the extrapolated values using ChPT deviate from the experimental values, indicating the systematic errors from chiral extrapolations are large. Doing lattice calculations at lighter pion masses will greatly reduce the uncertainty associated with the chiral extrapolation and has the potential of producing high-precision results valuable to both the theory and experiment communities.

As the pion mass gets lighter, the pion Compton wavelength gets larger, and the size of the lattice volume needs to be larger to accommodate the pions. As the pion mass gets lighter and the volume gets larger, the numerical cost of the lattice calculations increases dramatically. Due to the complexity, and expense, of such calculations, there are naturally large research collaborations to facilitate the research efforts.

The RIKEN-BNL-Columbia (RBC) collaboration started around the same time as the RIKEN-BNL Research Center (RBRC) was founded in 1997. RIKEN and Columbia jointly built the 600-GFlops QCDSF (Quantum Chromodynamics on Digital Signal Processors) computer dedicated for lattice-QCD numerical research at RBRC. The RBC also pioneered the use of a particular formulation of lattice QCD known as Domain Wall Fermions (DWF). Traditional lattice discretizations break many of the symmetries of the continuum theory. Perhaps the most important of these is chiral symmetry which says that left-handed and right-handed quarks are only coupled due to the small mass terms of the

quarks. Naive lattice QCD formulations lead to couplings which are orders of magnitude too large. In DWF an additional fifth dimension is introduced to the space-time, with the left- and right-handed fermions living on opposite four-dimensional boundaries of the five-dimensional space, which greatly improves chiral symmetry. This formulation revolutionized the way numerical lattice QCD research is conducted. An important outcome was that the so-called non-perturbative renormalization method became practical, and made possible, for the first time in history, accurate calculations of quantum transitions between hadronic states.

1.2 Purpose of the Project

The purpose of this proposal is to calculate the structure of nucleons using lattice QCD techniques. The primary focus of this research is to calculate all the isovector vector- and axial-vector form factors and some low moments of isovector structure functions of nucleon using a new set of lattice QCD numerical ensembles at larger than ever spatial volume of about 5 fm across and pion masses as low as 180 MeV. An exploratory study of the nucleon strangeness content will also be pursued. We also propose to use a small fraction of the time for algorithmic developments. Detailed descriptions of each topic are given below.

(1) Precision lattice determination of nucleon mass.

Being able to reproduce the experimentally well-known nucleon mass from the first-principles lattice calculations is a great step in establishing the precision test of lattice QCD. Previously, the heavy pion masses in the calculations make it hard to perform chiral extrapolations. With nearly physical pion mass in our calculations, we will be able to obtain a nucleon mass which is free of large systematic errors coming from chiral extrapolations. We will also be able to investigate the validity of chiral perturbation theory in these small pion mass ranges. Such calculations will be a great milestone

towards high-precision lattice calculations.

(2) Nucleon vector form factors. Nucleon isovector vector form factors are part of the electromagnetic form factors and thus studied mainly by elastic electromagnetic processes such as electron scattering off nucleons or nuclei. They provide information of such important properties as mean-squared charge radii or anomalous magnetic moments which determine electromagnetic interactions of nuclei with other electromagnetic entities such as photon and electron. Thus these form factors ultimately determine electromagnetic properties of atoms which in turn govern properties of chemistry and biology.

Because the quark masses in lattice calculations are heavier than reality extrapolations that utilize the formula given by chiral perturbation theory are needed. In order to be able to reliably apply the chiral formula, the quark masses in the simulations need to be small enough. Existing lattice calculations have pion masses usually larger than 300 MeV, while a physical pion mass is about 140 MeV, which requires a long extrapolation from the simulated data to the physical point. Performing lattice calculations on the new DWF ensembles at pion masses of 250 MeV and 180 MeV will significantly reduce the systematic errors coming from chiral extrapolations. In addition, the large volume of the new ensembles will make the calculations less susceptible to finite volume effects and have the potential of achieving unprecedented statistical and systematic precisions.

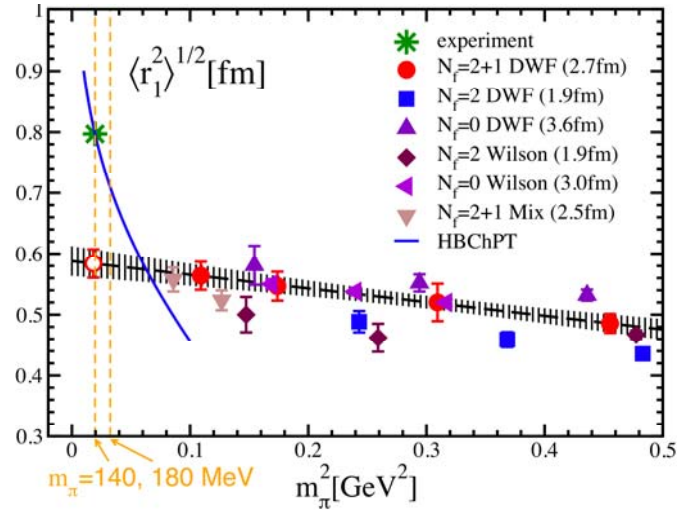


Figure 1: Nucleon isovector charge radii from previous lattice calculations. The green star is the experimental point, and the blue curve is prediction from chiral perturbation theory.

Given in Fig.1 are the results from previous lattice calculations for the nucleon isovector Dirac radii as a function of the pion mass squared, where the lattice results are systematically lower than the experimental point and are not consistent with the prediction from chiral perturbation theory. A naive linear extrapolation to the lattice data gives a value at the physical point which is much smaller than expected. Having lattice results at lower pion masses will undoubtedly improve our ability to perform a more reliable chiral extrapolation.

(3) Nucleon axial form factors. Nucleon axial and induced pseudoscalar form factors probe the weak structure of the nucleon, and are also actively pursued experimentally, for example by using muon instead of electron: muon capture process is sensitive to a part of these form factors, g_P , for example.

The nucleon axial charge g_A is defined as the zero momentum-transfer limit of the axial form factor, and determines the neutron lifetime. It is indeed best measured in neutron beta decay, in which a neutron decays into a proton via weak interaction and emits an electron and anti-neutrino. It also controls the interaction of pion and nucleon through

the Goldberger-Treiman relation. Thus it is the single most important nucleon property in determining the abundance of elements that are formed in primordial and stellar nucleosynthesis. In contrast to the corresponding vector charge, g_V , which is not affected by the strong interaction, it receives corrections from the strong interaction and deviates from unity in units of g_V , $g_A = 1.2694(28) g_V$. We recently discovered this strong correction is strongly dependent on the pion mass and the volume in which the lattice calculation is conducted. This is shown in Fig. 2, where lattice results from different lattice volumes and different lattice formulations depend not only on the pion masses, but also the volumes. This discovery provides the first concrete evidence that a significant portion of the charge is carried by the virtual pion cloud surrounding nucleon that extend as far away as about 10 fm in radius. A better understanding of this phenomenon will provide the basis for the ultimate understanding of the stability of baryonic matter, and hence of our own existence.

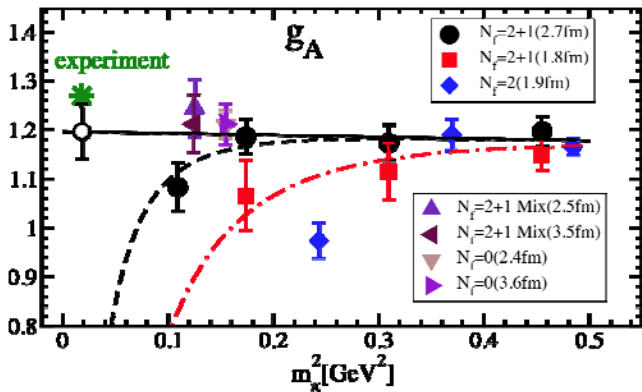


Figure 2: g_A calculated in different volumes. The dashed and solid lines denote fit results and linear chiral extrapolation in infinite volume, respectively. The open circle is extrapolated result at the physical pion mass of around 140 MeV.

(4) Nucleon structure functions. Studied mainly by lepton deep inelastic scattering and Drell-Yan experiments off nucleon and nuclei, these reveal

deeper structures of nucleon and led to discovery of quarks and QCD. RIKEN experimenters are trying to resolve a puzzle in spin-dependent structure functions of nucleon through the RHIC-Spin experiments now conducted at RIKEN-BNL Research Center. Of particular interest are the quark momentum fraction, helicity fraction, and tensor charge, all in isovector combinations.

For the first two quantities conventional lattice-QCD numerical calculations significantly over estimate the experimental values. A recent joint study by RBC and UKQCD collaborations found that at the lightest quark mass value that corresponds to 330 MeV pion mass these values trend down to the experiment. By comparing the two different volumes, it is suggested the finite-size effects in these quantities seem absent, in contrast to the situation for the axial form factors discussed in the above. It is thus interesting to see if the trend toward experiment and apparent absence of the finite-size effect hold at the lighter quark masses that correspond to 250 MeV and 180 MeV pions.

For tensor charge the same joint RBC/UKQCD study have a crude prediction. As this quantity will soon be experimentally measured, it is obviously important to refine this prediction at lighter quark mass values.

(5) Strangeness content of the nucleon. There has been much interest in a more accurate evaluation of scalar matrix elements of nucleons, in particular due to its connection to the coupling of nucleons to MSSM (Minimal Supersymmetric Standard Model) dark matter candidates via Higgs boson. However, lattice calculation of this quantity has been a challenge, due to the fact that the traditional method of calculating such quantities involves evaluation of what is known as disconnected diagrams, which are intrinsically noisy and so, when using standard techniques, require a large number of measurements.

RICC Usage Report for Fiscal Year 2010

Recent studies with a formulation of lattice QCD known as Overlap fermions suggest the preservation of chiral symmetry is crucial in controlling systematic errors, suggesting a DWF calculation would be advantageous.

Recently there have been lattice studies using Feynman-Hellman theorem, which showed promise in calculating the scalar matrix element without expensive evaluation of disconnected diagrams, but rather via a calculation of the derivative of much less expensive observables with respect to the strange quark mass. Here we propose to evaluate the nucleon scalar matrix element by taking such a numerical derivative of the nucleon mass via what is known as a reweighting; a technique we have recently successfully applied to modifying the strange quark mass of our lattice gauge configurations.

(6) Algorithmic development. The choice of which problems to address using lattice techniques is constrained by the algorithms available to both generate the lattice gauge field configurations, and calculate quantities using them. While the increase in available computer power over the past few years has played a vital role in making Lattice QCD a realistic tool for studying QCD, algorithmic improvements have played a role at least as important, and we propose to use a small portion of the computer time covered by this proposal to continue such developments.

When calculating observables on a given gauge field configuration, the basic problem is to sum over all possible paths that the quarks may take between any two points. Lattice QCD is formulated in such a way that this problem is equivalent to inverting a large, sparse matrix. For the size of matrices involved (~100 million x 100 million), this problem is challenging even using modern super-computers, and so the computationally less intensive problem of

calculating the product of the inverse and a fixed vector (equivalent to summing over all paths the quark may take from a fixed starting point to all others), is usually taken. However, this puts an artificial constraint on the physics topics than can be addressed, as it forces so-called "disconnected contributions" to be left out.

A common technique for speeding up both of these inversion problems is to first find a solution to the problem on some small -- and so computationally inexpensive -- subspace, then approximately solve for the difference between this and the full solution. For a well-chosen sub-space, this can lead to a large speed-up. In the past few years, several inversion algorithms have been developed which make use of the low-lying eigenvectors as a subspace to improve subsequent inversions. The only problem with this approach is how practical it is to store enough eigenvectors. This is particularly a problem for DWF, as the required storage for a single eigenvector is much larger due to the fifth dimension, but becomes a problem for any formulation as the volume of the lattice is increased.

This volume scaling problem has been addressed by Luscher, who noted that it is not necessary to use exact eigenvectors, and demonstrated that, in fact, a basis could be constructed by taking a basis of rough eigenvector estimates and making a much larger basis by blocking these vectors (i.e. zeroing out the elements of the vectors for all but a given hypercube, repeated for all possible non-overlapping hypercubes). Remarkably, this basis was found to overlap well with the important degrees of freedom for lattice QCD (a quality named local coherence by Luscher), and using an optimal solution on this basis as an initial guess for the inversion algorithms gave a large speed-up.

We intend to investigate applying similar subspace/blocking techniques to the Domain Wall

Fermion approach with the initial aim of speeding up the calculations covered in the rest of the proposal, but with the long term goal of making it possible to perform accurate calculations which include disconnected contributions. While there are many observables in Nuclear Physics which require the calculation of disconnected contributions, an interesting initial goal would be to directly calculate the strangeness content of the Nucleon to provide a cross-check of the indirect extraction mentioned earlier.

2. Specific usage status of the system and calculation method

2.1 Computational Methods

We perform our calculations with domain wall fermions on the existing gauge backgrounds generated by the RBC and UKQCD collaborations. These gauge backgrounds encode a particular configuration of the gluon fields. For each such configuration we need to calculate the sum of all possible paths a quark can take between a given set of starting positions (sources) and all points on the lattice. While other calculations will be involved, this will be the dominant calculation in terms of computer time. The natural unit in which to measure such things is a single starting position. A single starting position leads to the calculation of a single quark propagator. To make the best use of the available gauge backgrounds, we plan to calculate quark propagators at four independent starting positions. From each propagator four so-called sequential propagators will be needed to perform the proposed calculations. The sequential propagators will then multiply the forward propagator from the source with appropriate operators and momentum of interest. Thus on each gauge background, 20 propagators are needed.

Once the forward propagators and the sequential

propagators are calculated, we construct two and three-point functions of the nucleon. The two-point nucleon correlation functions are traces of the products of the forward propagators, and the three-point functions are traces of the products of the forward propagators and sequential propagators. A graphical representation of the so-called connected diagram of the three-point function is shown in Fig.3.

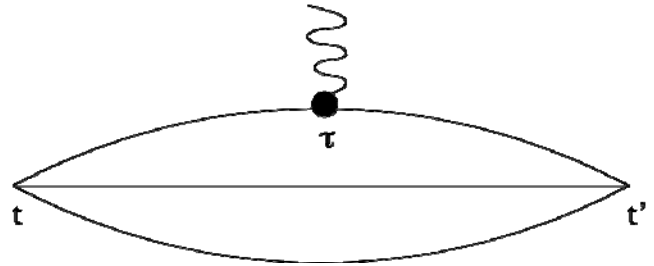


Figure 3: An illustration of the connected contribution to the nucleon three-point function which enters the nucleon structure calculations. t and t' are the locations of the nucleon source and sink, respectively. τ is the location of the operator of interest.

In addition to the connected contribution, another type of diagram also exists except in the isovector limit. This type of diagram is shown in Fig. 4, and is called the disconnected diagram. We are not considering this in most of our calculations, and only investigate it in our algorithmic development phase.

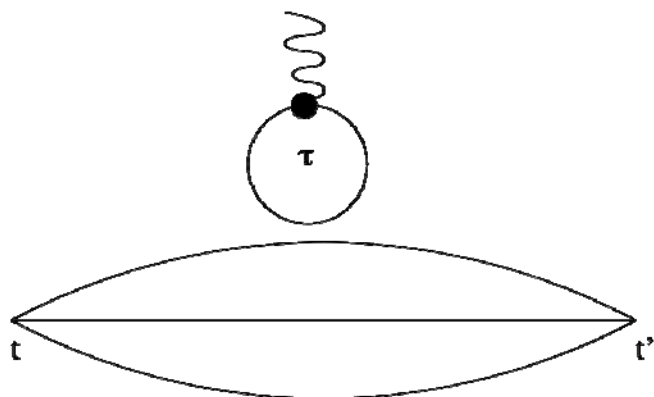


Figure 4: An illustration of the disconnected contribution to the nucleon three-point function which enters the nucleon structure calculations. t

and t' are the locations of the nucleon source and sink, respectively. t is the location of the operator of interest.

Since we perform Monte Carlo simulations, we will need to do the calculations on multiple gauge backgrounds so that statistical averages and errors can be calculated. We perform the calculations on the gauge backgrounds separated by 8 time units to reduce the autocorrelations between measurements. On each gauge background, we will also use 4 different source locations separated by 16 lattice sites in the time direction to take advantage of the large size of the lattice.

As we are interested in the properties of the nucleon ground state, we need to make sure that the operator insertion τ is within the asymptotic region where the nucleon ground state dominates. Hence we need to choose the source-sink separation $t' - t$ such that it is large enough to eliminate the excited state contaminations which are exponentially decaying with the distance from the source. However, as the source-sink separation $t' - t$ gets larger, gauge fluctuations generate more noise, which makes the already-difficult-to-get signal worse. Thus the first step is to choose an optimal source which has a good overlap with the nucleon ground state, so that we do not have to have a very large source-sink separation to be able to do nucleon ground state physics. This is the source-tuning process which is done before production runs begin.

2.2 Usage Status

Our usage of the system can be divided into three different periods: (1) the initial period from April 1, 2010 to June 30, 2010 for our provisional allocation of 2.6 million core*hours, (2) the period from July 1, 2010 to September 30, 2010 with low priority and (3) the period from October 1, 2010 to

present when the priority of our project is higher.

(1) From April 1, 2010 to June 30, 2010. Since we were all new users of the RICC system, we spent two weeks setting up the accounts and doing necessary code testing. We did not start production job running until April 18, 2010. Since then we were running continuously, but due to the low priority of our project (rank 2), we were only able to use 33.2% of the allocated time by June 30, 2010. During this period, we also found that the performance of the machine was lower than expected. For example, the average time it took to calculate a quark propagator on the 250 MeV ensemble was 28.6 hours, compared to 20 hours we are observing now, which inevitably slowed down the progress of our calculation. Nevertheless, we were able to obtain some initial results for the source tuning mentioned previously.

(2) From July 1, 2010 to September 30, 2010. We continued to run in the "rank 2" priority, and were able to use 13.4% of the 7.8 million core*hours allocated to us for nine months. During this time it appeared that the performance of the machine was improved. It took on average 20 hours to invert one quark propagator on the 250 MeV ensemble, in comparison to 28.6 hours previously.

(3) From October 1, 2010 to present. The priority of our project was upgraded from Rank 2 to Rank 1 on October 1, 2010, which greatly improved the execution of our queued jobs. By March 1, 2011, we have already used 63.1% of the 7.8 million core*hours. That is, during the five months from October 1, 2010 to March 1, 2011, we have used 50% of the allocation. The projected usage by March 30, 2011 would be 75% of the allocation. If we had been given the same Rank 1 priority from the beginning, we would be able to use 90% of the allocation by the end of the fiscal year assuming the same throughput of the system.

RICC Usage Report for Fiscal Year 2010

The usage status up to March 1, 2011 is thus summarized in Table 1.

Period	Allocated [core*hour]	Used [core*hour]	Percent [%]
04/01/2010 -06/30/2010	2,602,987	863,873	33.2
07/01/2010 -03/01/2011	7,808,961	4,930,310	63.1

Table 1: Usage status from April 1, 2010 to March 1, 2011.

The resources we have used so far enable us to finish the source tuning for our calculation. Specifically, we initially did the calculation using two values for the width of the so-called Gaussian source: 4.0 and 6.0. By comparing the nucleon effective masses obtained using the two different values, we were able to identify the better choice among these two, which is 6.0. Thus width 6.0 is our final choice for the source width, and has been used in the forward quark propagators necessary for our nucleon structure calculations. The number of quark propagators we have calculated so far for each choice of the source width on each ensemble is summarized in Table 2.

Pion Mass	Source Width	N. Sources	N. Cfgs.	N. Props
180 MeV	4.0	2	29	58
	6.0	4	95	380
250 MeV	4.0	2	56	112
	6.0	4	165	660

Table 2: The numbers of forward quark propagators calculated so far (dated: March 1, 2011). “N. Sources” – Number of nucleon sources on each gauge configuration. “N. Cfgs.” – Number of gauge configurations calculated. “N. Props” – Number of quark propagators calculated. Note: N.

$$\text{Props} = \text{N. Sources} \times \text{N. Cfgs.}$$

In addition to the forward propagators, we have also started to calculate the sequential propagators needed for the nucleon three-point functions on the 250 MeV ensemble, with a source-sink separation, $t-t'$, of 9 lattice sites. For each forward propagator, we will need to calculate four sequential propagators. The number of sequential propagators we have calculated so far is summarized in Table 3, from which we have constructed 67 three-point functions (It takes two sequential propagators to get one three-point function.)

Pion Mass	Source Width	$t-t'$	N. Seq.Props.
250 MeV	6.0	9	134

Table 3: The numbers of sequential quark propagators calculated so far (dated: March 1, 2011).

We have also used a small fraction of the time to do algorithm and code improvement. The total percentage of time used for this purpose is estimated to be less than 5%.

3. Result

As mentioned previously, the first part of our calculation was to find a nucleon source which has a better overlap with the nucleon ground state. One way to look at such overlap is to calculate the nucleon effective mass for the different choices of the source parameter, and see which one reaches a plateau region sooner. Shown in Fig. 5 and Fig. 6 are such nucleon effective mass plots for the 180 MeV and 250 MeV ensembles, respectively. From these plots, we conclude that a width of 6.0 is better for our calculation.

Fitting the plateau regions of the effective masses

gives us the nucleon mass at the given pion mass (the horizontal lines in Fig. 5 and Fig. 6). The nucleon masses so determined are plotted with results from our earlier calculations as well as the experimental value in Fig. 7. From Fig. 7 we can see that our results for the nucleon mass are approaching the physical value monotonically. An accurate determination of the nucleon mass would be an important first step to precise determinations of other more involved quantities in nucleon physics. And our results seem very encouraging.

denote different values (6.0 and 4.0, respectively) for the nucleon source. "point" and "unitary" denote different nucleon sinks.

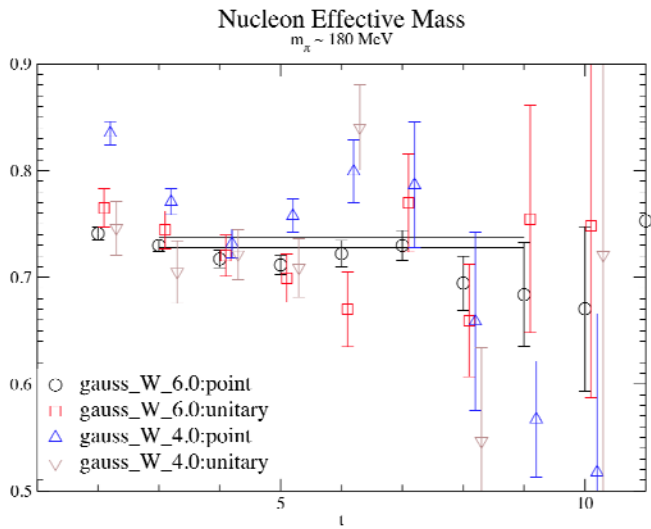


Figure 5: Nucleon effective mass on the $m_\pi \sim 180$ MeV ensemble. "gauss_W_6.0" and "gauss_W_4.0" denote different values (6.0 and 4.0, respectively) for the nucleon source. "point" and "unitary" denote different nucleon sinks.

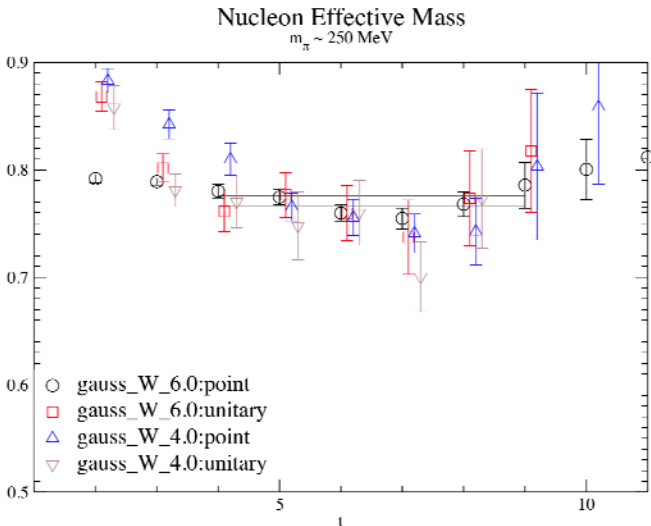


Figure 6: Nucleon effective mass on the $m_\pi \sim 250$ MeV ensemble. "gauss_W_6.0" and "gauss_W_4.0"

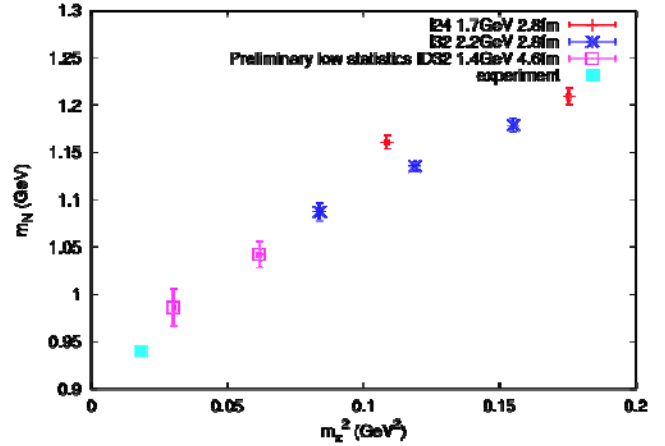


Figure 7: Nucleon mass from this calculation and previous lattice calculations. Our new results will reduce the systematic errors associated with extrapolations towards the physical pion mass.

With the limited data for the nucleon three-point functions, we have only done preliminary analysis for quantities not involving any finite momenta. The simplest quantities to look at are the nucleon vector and axial charges, g_V and g_A . The inverse of g_V can be used to set the normalization for the vector current in our calculation, and can be cross-checked with other calculations on the lattice. Our preliminary analysis showed $1/g_V \sim 0.7$, which is consistent with an independent calculation. We are still in the process of getting the preliminary results for g_A and other quantities.

4. Conclusion

Thanks to the computing power on RICC, we have been able to tune the nucleon source to meet the requirements of our calculations. We have obtained some preliminary results for the nucleon mass at the two pion masses, which falls on the expected path towards the physical limit. Our calculations of the nucleon three-point functions, and eventually the nucleon form factors are still ongoing. But the

RICC Usage Report for Fiscal Year 2010

preliminary analysis seems quite encouraging. We will still need more statistics to be able to draw a definitive conclusion.

5. Schedule and prospect for the future

We plan to finish the sequential propagator calculations on the existing forward propagators within a year. We also plan to extend our calculation for the light, 180 MeV, ensemble, on about 100 new gauge configurations.

While the number of sequential propagators we need to calculate is four times more than that of the forward propagators, we have made significant improvements in the code we will be using, which would result in a factor of 2 speedup. We have also been looking into a new way of calculating the sequential propagators, which would further reduce the amount of time required to calculate these expensive propagators if it should turn out to be working as expected. Such improvements would make our calculations feasible within the time scale we are aiming for.

We think our calculation, once completed, will be the state-of-the-art calculation of nucleon structure and will have a great impact on nucleon physics on the lattice.

6. If you wish to extend your account, provide usage situation (how far you have achieved, what calculation you have completed and what is yet to be done) and what you will do specifically in the next usage term.

We have completed all the required forward propagator calculations for the heavy, 250 MeV, ensemble, and have started the sequential propagator calculations. The calculations we have

completed so far are shown in Table 2 and 3. We are yet to finish the forward propagator calculations on the 180 MeV ensemble, as well as all the remaining sequential propagators. The numbers of propagators we will need to complete are tabulated in Table 4.

Pion Mass	# f.p.	# s.p.	Total
180 MeV	400	3120(*)	3520
250 MeV	0	2640(*)	2640

Table 4: Numbers of propagators to be calculated. # f.p. stands for the number of forward propagators. # s.p. stands for the number of sequential propagators. (*) The number of sequential propagators we need may be reduced by a factor of 2 to 4 if our new implementation of the calculation works.

We will also look into the source-sink separation dependence of the calculation, which may require an extra 20% of the total time needed above.

7. If you have a "General User" account and could not complete your allocated computation time, specify the reason.

As mentioned in Section 2, the priority of our project was lower at the beginning of the allocation cycle, and our queued jobs were not run as fast as it would require to use up our allocation. Once the priority was promoted, our usage of the system has been quite good, and would be very close to completing the allocated computation time if the priority had stayed high throughout the year. In addition, there were some interruptions of our running when we were tuning the code and implementing new algorithms, which could also result in under-usage of our allocation.

Fiscal Year 2010 List of Publications Resulting from the Use of RICC

[Publication]

We are yet to publish our RICC results in a refereed journal.

[Proceedings, etc.]

- 1) Nucleon structure from RBC/UKQCD 2+1 flavor DWF dynamical ensembles at a nearly physical pion mass. Proceedings of Science (Lattice 2010), 152 (2010).
- 2) Nucleon structure from 2+1 flavor domain wall QCD at nearly physical pion mass. To appear in Proceedings of Tropical QCD (2010).

[Oral presentation at an international symposium]

- 1) Nucleon structure from RBC/UKQCD 2+1 flavor DWF dynamical ensembles at a nearly physical pion mass. Presented by Shigemi Ohta at the 28th International Symposium on Lattice Field Theory, Sardinia, Italy, June 14-19, 2010.
- 2) Nucleon structure from 2+1 flavor domain wall QCD at nearly physical pion mass. Presented by Shigemi Ohta at Tropical QCD 2010, Cairns, QLD, September 27-October 1, 2010.
- 3) "Nucleon structure from 2+1 flavor domain wall QCD at a nearly physical pion mass," JPS biannual meeting in at Kyushu Institute of Technology, Kitakyushu, Fukuoka, Japan, September 11-14, 2010.

[Others]

- 1) Presentation: "Nucleon Physics on the Lattice", Meifeng Lin, Joint High Energy Theory/RIKEN Seminar, Brookhaven National Laboratory, August 19, 2010.
- 2) Presentation: "QCD and Beyond on the Lattice", Meifeng Lin, Particle, Astrophysics and Nuclear Physics Seminar, University of Connecticut, February 25, 2011.