Visualization of Lattice Quantum Chromodynamics (LQCD) Data with varying chemical potential

1. Introduction

Quantum Chromodynamics (QCD) is the theory that defines how physicists view interactions between sub-atomic particles named quarks and gluons. This description of the strong nuclear force shares many similarities to that of the electromagnetic force equivalent, Quantum Electrodynamics (QED), which is propagated by the Photon particle.

However, Quantum Chromodynamics differs in a few important aspects. The force carrying particles of QCD, the gluons, can themselves interact with one another which greatly complicates calculations involving them. Additionally, the QCD equivalent of charge known as colour, has three states: red, green and blue and equivalently anti-red, anti-blue and anti-green. Quarks must exist in colour neutral states with the strength of the interaction between two or more quarks increasing with distance. For these reasons it is considered to be impossible to observe quarks on their own in nature, a principle known as colour confinement.

2. Problem

Due to issues arising because of the strong interaction force, work in QCD is often simulated on a discrete lattice as proposed by Kenneth Wilson [1]. This allows physicists to vary the controlling factors of the simulation. Quarks and gluon fields are represented on a four dimensional Euclidean lattice (3 spatial dimensions and 1 time). Each element is an n x n complex matrix, where n specifies the number of colours. In our work we use two colours, red and blue, therefore n=2. Various calculations can be performed on the lattice to indicate the presence of four dimensional pseudo-particles named instantons.

Simulations are controlled by a number of variables that specify dimensions of the lattice, the lattice resolution and physical factors providing chemical potential (U). It is believed that our simulations are unique in that we vary this value, to our knowledge all other researchers work with a fixed chemical potential of zero (Fig. 1). The outcome of this is that our simulations will resemble varying situations such as the cores of neutron stars and quark matter, in which the balance of quark and anti-quark pairs is skewed away from a neutral value.

3. Related Work

Related work in the field is largely concerned with simulations where the chemical potential is fixed at zero. An early example [2] plotting the position of instantons within a cell structure in order to visualize their location using a number of physical properties. Isosurfaces has also been used to present data as an animated 3D render based upon two attributes; the action density and topological charge density in a project by Derek Leinweber [3].

There are a large quantity of Lattice QCD simulation projects in operation, each with its own methods of storing the data. Work by Massimo Di Pierro et al. [4] attempted to unify this by presenting a number of tools to process the different formats and present the results visually. The end deliverable of the project being a tool that could be accessed using a web interface.

4. Possible Solutions

A number of values can be calculated from the lattice sites such as plaquette values (2D), topological charge density (4D) and Polyakov loops (1D) as is illustrated in Fig. 3. The output from these functions for each simulation is a scalar value that varies over space and time. It is therefore possible to render the image as a three dimensional isosurface, allowing the user to manipulate, rotate and zoom the model.

The parsed data is rendered using the Visit library (Fig. 7). At present the data is far too noisy for use by a physicist. However, an established algorithm known as cooling has been developed which attempts to alleviate as much noise as possible without destroying the intended instanton observables.

Features of the model such as the existence of instantons are able to evolve over time. Therefore, it is expected that a method such as joint contour nets [5] may provide the end user with additional information about how the data set changes whilst also helping to decrease rendering time.

5. Future Work

The complexity of the data means that a large portion of the processing required is spentlooping through sites on the lattice in 4 dimensions. However, with the arrangement of the generated data being static and not having any effect on values within its own local neighbourhood, it should be possible to break down the data set into smaller sections which can then be computed in parallel using GPU processing or cluster computing.

6. References


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Figure 1: Phase diagram of QCD

Figure 2: An early render of the data using Visit. Time dimension is shown by animating the render.

Figure 3: Scalar values that can currently be calculated by the system

Figure 4a: The lattice itself is hypercubic
Figure 4b: Each site has links to neighbours in four dimensions
Figure 4c: Unitary matrix test formula