RECENT PROGRESS OF LATTICE QCD IN CHINA

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Lattice QCD is the most reliable non-perturbative method in quantum field theory. In the last few years, some problems crucial to high energy experiments have been solved. We review some recent work done by the Chinese lattice community.

1 Introduction

Particle physics and gauge field theories are frontiers of fundamental sciences of matter. According to Yang and Mills, any basic theory of interacting matter should satisfy gauge invariance. QCD has been accepted to be the most successful gauge theory of strongly interacting particles. In QCD, hadronic matter is composed of quarks, and interactions between them are mediated by eight massless gluons generated by the SU(3) gauge group. Asymptotic freedom of QCD at short distances makes the perturbative calculations of high-energy processes possible. At low energy scales, however, QCD has many important properties which can not be studied perturbatively, like confinement of quarks and gluons, vacuum structure, chiral-symmetry breaking, glueball masses, hadronic spectrum and weak interaction processes, and behaviors of hadronic matters at high temperature or high density.

Lattice gauge theory (LGT) has developed into a promising first principle non-perturbative approach to these phenomena. The basic idea, as proposed by K. Wilson in 1974, is to replace the continuous space and time by a discrete grid:

Gluons live on links $U(x, \mu) = e^{ig \int^{x+\alpha \mu} dx' A_{\mu}(x')}$, and quarks live on sites. The continuum Yang-Mills action $S_y = \int d^4x \text{Tr} F_{\mu\nu}(x) F_{\mu\nu}(x) / 2$ is replaced by

$$S_y = \frac{1}{g^2} \sum_p \text{Tr}(U_p + U_p^\dagger - 2),$$

where $U_p$ is the ordered product of link variables $U$ around an elementary plaquette. The continuum quark action $S_q = \int d^4x \bar{\psi}(x)(\gamma_{\mu}D_{\mu} + m)\psi(x)$ is replaced by

$$S_q = a^4 \sum_x m\bar{\psi}(x)\psi(x) + \frac{a^2}{2} \sum_x \sum_{k=\pm1} \bar{\psi}(x)\gamma_k U(x, k)\psi(x + ka) + \frac{r}{2a} \sum_x \sum_{k=\pm1} \bar{\psi}(x)U(x, k)\psi(x + ka),$$

where $\gamma_{-k} = -\gamma_k$ and the last term is added to avoid species doubling. Then all the physical quantities are calculable through Monte Carlo (MC) simulations with importance sampling:

$$\langle O \rangle = \frac{\int [dU_i] \bar{\psi}(x,\mu) O[U_i] e^{-S_{\text{eff}}(U_i)}}{\int [dU_i] e^{-S_{\text{eff}}(U_i)}} \approx \frac{1}{N_{\text{config}}} \sum_C \bar{O}[C],$$

Here $C$ stands for a gluonic configuration drawn from the Boltzmann distribution. Fermion fields must be integrated out before the simulations, which leads to $\bar{O}$ and $S_{\text{eff}}$. Since the derivatives are approximated by finite differences, the gluonic action in Eq. (1) has lattice spacing error of order $a^2$, and quark action Eq. (2) has error of order $a$. To compare with the real world, the continuum limit $a \to 0$ should be eventually taken. On the other hand, to keep the physical volume $L^4$ unchanged, the number of lattice sites should be very large. Therefore, the computational task will then be tremendously increased.

Chinese physicists have been involved in this field since early 80’s. Although some very interesting results were obtained, most of them were analytical investigations (for review, see [6]), due to limited computational facilities. Thanks to the rapid development of high performance supercomputers in China in late 90’s and Symanzik improvement of LGT, this situation has changed. Today Chinese physicists play an active role in the lattice community. Here we would like to give an overview of the relevant developments in recent years.
2 Status

2.1 Zhongshan University

The interests of our group cover glueballs, QCD at finite density, supersymmetry, new Monte Carlo algorithms, and construction of parallel computers.

(a) Glueball spectrum. The spectroscopy of QCD in the pure gauge sector, i.e., the glueball masses attract considerable attention. In the quenched approximation, these glueball are non q\bar{q} gluonic bound states formed by strong self-interactions of the gluons, and their masses vary from about 1.4 GeV to 2.5 GeV. A lot of glueball candidates observed in BES experiments such as \( \epsilon(1440) \), \( f_0(1520) \), \( \theta/f_1(1720) \) and \( \xi(2230) \), produced in the \( J/\psi \) radiative decays are within this range. The difficulty in experimental identification of a glueball comes from the complexity in determining the quantum numbers \( J^{PC} \) of these particles. The lattice QCD prediction for the glueball spectrum will help the experimental physicists in their search for glueballs. Concerning the lightest glueball \( 0^{++} \), more accurate MC calculations by the IBM group on much larger lattices, higher statistics and better algorithm gave \( M(0^{++}) \approx 1.740 \pm 0.071 \) GeV, where the infinite volume extrapolation has been made. Active investigation on the improvement of the lattice techniques are still being carried out so that the errors due to various approximations are reduced and the glueball masses are more accurately estimated. We proposed an alternative way to extract the glueball masses by solving the lattice QCD Schrödinger equation. We obtained \( M(0^{++}) = 1.71 \pm 0.05 \) GeV, in nice agreement with the IBM data. The advantage of this method, is its potential to extract the wavefunction of a glueball. To reduce the lattice spacing errors in Eq. (1) and Eq. (2), we also carried out the Symanzik improvement which allows us to increase the precision and perform the calculation on smaller computers.

(b) QCD at finite density. This investigation is relevant for cosmology and neutron star phenomenology. When temperature or density is sufficiently high, a new state of matter called quark-gluon plasma (QGP) is expected to form. The goal of Relativistic Heavy Ion Collider (RHIC) at BNL and Large Hadron Collider (LHC) at CERN is to create the QGP phase, and replay the evolution of the universe. Although the standard lattice Lagrangian Monte Carlo method works very well for QCD at finite temperature, it unfortunately breaks down at finite density (chemical potential), because of the complexity. For \( SU(3) \) gauge theory with quarks, the Lagrangian MC methods always lead to an unphysical critical chemical potential \( \mu_c = 0 \) in the chiral limit. The Hamiltonian formulation does not have such a problem and is therefore a promising alternative. Recently, we have developed a Hamiltonian approach to lattice QCD at finite density. It avoids the usual problem in the Lagrangian Monte Carlo method of either an incorrect continuum limit or a premature onset of the transition to nonzero quark density as \( \mu \) is raised. We solved it in the case of free quarks and in the strong coupling limit. At zero temperature, we calculated the vacuum energy, chiral condensate, quark number density and its susceptibility, as well as mass of the pseudoscalar, vector mesons and nucleons. We found that the chiral phase transition is of first order, and the critical chemical potential is \( \mu_c = m_{dyn}(0) \) (dynamical quark mass at \( \mu = 0 \)). This is consistent with \( \mu_c \approx M_N^{(0)} / 3 \) (where \( M_N^{(0)} \) is the nucleon mass at \( \mu = 0 \)).

(c) Dynamical quarks. Most conventional full QCD algorithms are expensive and do not work in the chiral limit. The microcanonical fermionic average (MFA) method works not only on smaller computers, but also in the chiral limit, which is very useful for studying spontaneous chiral symmetry breaking and chiral phase transition. We generalized the MFA method to QCD.

(d) Monte Carlo Hamiltonian. In Lagrangian formulation, only the lowest-lying state can be extracted from the correlation function. It is extremely difficult to compute the excited states. We proposed a different approach: the Monte Carlo Hamiltonian method, designed to overcome the difficulties of the conventional approach. The method has been well tested in quantum mechanics using a regular basis in Hilbert space. To apply the method to many body systems and quantum field theory, stochastic basis has to be used.

(e) SUSY. Supersymmetry is a promising fundamental theory of elementary particles that describes a mapping between bosons and fermions. It underlies many modern theories of strings and quantum gravity. Lattice investigations of supersymmetry may provide some new non-perturbative physics beyond the standard model. Some numerical simulations have been done.

(f) Parallel computation. The tremendous advance in computer technology in the past decade has made it possible to achieve the performance of a supercomputer on a very small budget. We have built a multi-CPU cluster of Pentium PC's capable of high performance parallel computations at a very good price/performance rate (US$7/MFlops). We believe this is the first such a machine constructed in academic institutions in China. QCD code with an improved action has been implemented on the machine.

2.2 Beijing University

Although Kogut-Susskind fermions and Wilson fermions have been extensively used in numerical simulations, they
are not free of problems. There has been evidence showing that those two approaches may give the topological charge or anomaly incorrectly on a finite lattice. Kaplan’s domain wall fermions and Neuberger’s overlap fermion formulation have attracted much attention, because they satisfy the Ginsparg-Wilson relations, they also produce the correct chiral modes, anomaly and topological charge. For domain wall fermions there is an extra logical charge. For domain wall fermions there is an extra logical charge or anomaly incorrectly on a finite lattice.

2.3 Institute of High Energy Physics

In quantum theory, instantons are known to be a classical solution to the vacuum. They might play an important role in confinement and chiral symmetry breaking. Chen, Wu and He calculated the glueball masses using classical SU(2) gauge configurations and found that the instantons might also give important contributions to the glueball spectrum. Wu is well known for his original work with Hamber on improved fermionic actions in early 80’s.

2.4 Institute of Theoretical Physics

Ma investigated the behavior of the gluon propagator in lattice QCD with an improved gauge action. He also used an improved fermionic action to calculate the spectrum of light and heavy hadrons.

2.5 Zhejiang University

Ji, Li, Ying, and Zhang began numerical simulations of LGT in early 80’s. Due to limited computing facilities, they changed their interest to statistical physics. The success of Symanzik improvement retrieves their interest in LGT. They recently did glueball spectrum calculations on a smaller computer.

2.6 Beijing, Nankai and Sichuan Universities

Chen, and Zheng and Zhu are the leading experts on cumulant expansion of LGT and continue their efforts in this direction. Recently, Ren, Zhu and Chen successfully used symbolic language to do higher order cumulant expansion systematically.

3 Outlooks

These years have seen increasing contributions by the Chinese lattice community. We believe they will play more active role in the near future.

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