

INT Program INT-12-2b  
Lattice QCD studies of excited resonances and multi-hadron systems  
July 30 – August 31, 2012  
SEMINAR SCHEDULES

**Week 1**  
**July 30 – August 3, 2012**  
**All talks in room C421, Physics/Astronomy Building**

**Monday, July 30**

11:30 am: Sinead Ryan, Trinity College

*"The excitation spectrum of charmonium from lattice QCD"*

Abstract: Experimental studies of charmonium over the past decade have observed many new resonances above the open-charm threshold but no clear theoretical understanding has emerged. Lattice QCD calculations of these highly excited states and resonances remain very challenging. In this talk, I will review recent progress on studying these states on the lattice and describe the remaining problem.

**Tuesday, July 31**

11:30 am: Zohreh Davoudi, University of Washington

*"Restoration of rotational symmetry in the continuum limit of lattice field theories"*

Abstract: Due to the reduced symmetry of hyper-cubic lattices compared to the space-time continuum, Lattice QCD calculations of higher angular momentum states as well as the high moments of hadron structure functions currently suffer from overwhelming uncertainties due to power-divergent mixing between operators that have different angular momentum in the continuum limit. I will show how rotational invariance is systematically recovered from calculations on hyper-cubic lattices through the use of lattice operators that smoothly evolve into continuum operators with definite angular momentum as the lattice spacing is reduced, and that are smeared throughout a spatial volume with dimensions that are large compared to the lattice spacing, but small compared to the hadronic scale; as a result no power divergence of lower dimensional operators survives.

**Wednesday, August 1**

11:30 am: Raúl Briceño, University of Washington

*"Moving Multi-Channel Systems in a Finite Volume"*

Abstract: The spectrum of a system with multiple channels composed of two hadrons with nonzero total momentum is determined in a finite volume with periodic boundary conditions using effective field theory methods. The results presented are accurate up to exponentially suppressed corrections in the volume. The formalism allows one to determine the phase shifts and mixing parameters of  $\pi\pi$ - $KK$  isosinglet coupled channels directly from Lattice Quantum Chromodynamics. We show that the extension to more than two channels is straightforward. From the energy quantization condition, the volume dependence of electroweak matrix elements of two-hadron processes is extracted, for both relativistic and non-relativistic systems. In the non-relativistic case, we pay close attention to processes that mix the isosinglet-isotriplet two-nucleon states, e.g. proton-proton fusion ( $pp \rightarrow d + \nu_e + e^+$ ), and show how to determine the transition amplitude of such processes directly from lattice QCD.

**Thursday, August 2**

11:30 am: Keh-Fei Liu, University of Kentucky

“Roper Resonance and  $1^{-+}$  Meson”

Abstract: The Roper resonance from the overlap fermion on 2+1 flavor DWF configurations is compared with those from other calculations. Attempt is made to understand the nature of Roper resonance from its radial Bethe-Salpeter wavefunction.

**Friday, August 3**

11:30 am: Saul Cohen, University of Washington

“Multigrid Algorithms for Fermion Inversion”

**Week 2**  
**August 6 - 10, 2012**

**Monday, August 6**

11:35 am: Sinya Aoki, University of Tsukuba  
Room A114, Physics/Astronomy Auditorium

*"Hadron interactions from lattice QCD"*

Abstract: Progress on the potential method, recently proposed to investigate hadron interactions in lattice QCD, is introduced. The strategy to extract the potential in lattice QCD is explained in detail. The method is applied to extract NN potentials, hyperon potentials and the meson-baryon potentials. A theoretical investigation is made to understand the origin of the repulsive core using the operator product expansion. Some recent extensions of the method are also discussed.

**Tuesday, August 7**

11:35 am: Murray Moinester, Tel Aviv University  
Room A114, Physics/Astronomy Auditorium

*"Exotic mesons at CERN COMPASS"*

Abstract: COMPASS is a multi-purpose fixed-target experiment at the CERN Super Proton Synchrotron aimed at studying the structure and spectrum of mesons and baryons. The experiment features charged particle tracking as well as good coverage by electromagnetic calorimetry. One primary goal is the search for exotic hadronic states, in particular spin-exotic (hybrid quark-gluon) mesons and glueballs. Our data provide an excellent opportunity for simultaneous observation of such states in different decay modes by the same experiment. Results are presented of recent partial-wave analyses of various final states observed via diffractive dissociation of a 190 GeV/c pion beam on a proton target. We describe also the COMPASS potential and data for hybrid meson production in photon-pion interactions via Primakoff scattering of high energy pions from virtual photons in the Coulomb field of High-Z targets. A status report on various claimed hybrid meson resonances is given.

**3:00 pm: David Kaplan, INT**

Room C520, Physics/Astronomy Building

*"Noise, sign problems and chiral symmetry breaking"*

**Wednesday, August 8**

11:35 am: Christian Lang, University of Graz  
Room A114, Physics/Astronomy Auditorium

*"Hadron excitations and decays from lattice QCD"*

Abstract: Methods to determine masses and, more generally, energy levels of hadron correlators are discussed; I present recent results on excited states of baryons and mesons. For resonances it is important to extend the basis of interpolators to two-hadron states. From the energy values one can determine the scattering phase shifts. The efficiency of the used tools is demonstrated for the case of meson decays.

**Thursday, August 9**

11:35 am: Steve Sharpe, University of Washington  
Room A114, Physics/Astronomy Auditorium

*"Multiple-channel generalization of the Lellouch-Luscher formula"*

Abstract: The Lellouch-Luscher formula allows one to determine infinite volume weak decay matrix elements given the corresponding results in finite volume. It is valid in the elastic regime for the two-pion state, and has been successfully applied to the two pion decay of the kaon. In many weak decays of interest (e.g. those of D mesons) the final state is not in the elastic regime, and involves multiple two-particle

channels (two pions, K and K-bar, two etas, etc.) as well as channels containing four or more pions. As a step on the way to a complete analysis of such decays, we consider the case with multiple two-particle channels, and show how the Lellouch-Luscher formula can be generalized. This also requires a generalization of Luscher's finite-volume quantization results, which have been given previously for vanishing total momentum, and which we generalize to arbitrary total momentum.

**Friday, August 10**

11:35 am: Sasa Prelovsek, Jozef Stefan Institute

Room A114, Physics/Astronomy Auditorium

*"Resonances in D pi and K pi scattering"*

Abstract: I will present the simulation of the D pi and D\* pi scattering in s-wave. The masses and the widths of the open-charm resonances in these channels are extracted from the corresponding phase shifts. K pi scattering in s-wave and p-wave will also be discussed. The total momentum of the system is zero in this simulation. In the second part of the talk I will focus on the scattering of two non-degenerate particles with non-zero total momenta. Sample interpolators and the Luscher-type relations will be presented. I will pay particular attention to the difficulties that such simulations will be facing.

**Week 3**  
**August 13 - 17, 2012**

**Monday, August 13**

11:35 am: Leonid Glozman, University of Graz  
Room A114, Physics/Astronomy Auditorium

*"Symmetries of hadrons after unbreaking the chiral symmetry"*

Abstract: We study hadron correlators upon artificial restoration of the spontaneously broken chiral symmetry. In a dynamical lattice simulation we remove the lowest lying eigenmodes of the Dirac operator from the valence quark propagators and study evolution of the hadron masses obtained. All mesons and baryons in our study, except for a pion, survive unbreaking the chiral symmetry and their exponential decay signals become essentially better. From the analysis of the observed spectroscopic patterns we conclude that confinement still persists while the chiral symmetry is restored. All hadrons fall into different chiral multiplets. The broken  $U(1)_A$  symmetry does not get restored upon unbreaking the chiral symmetry. We also observe signals of some higher symmetry that includes chiral symmetry as a subgroup. Finally, from comparison of the Delta - N splitting before and after unbreaking of the chiral symmetry we conclude that both the color-magnetic and the flavor-spin quark-quark interactions are of equal importance.

**Tuesday, August 14**

11:35 am: Gerrit Schierholz, DESY  
Room A114, Physics/Astronomy Auditorium

*"On the art of computing resonances"*

Abstract: Most hadrons are resonances. Extracting masses and widths of unstable particles from the lattice is made difficult by the fact that resonances cannot be identified directly with the energy levels of the lattice Hamiltonian. For elastic two-body resonances the method of choice, originally proposed by Lüscher and Wiese, is to compute the phase shift in the infinite volume from the volume dependence of the energy spectrum. In this talk I will explain the problems that this involves with applications to the Delta(1232) resonance.

**Wednesday, August 15**

11:35 am: Philippe de Forcrand, ETH Zurich  
Room A114, Physics/Astronomy Auditorium

*"Conformality in many-flavor strongly coupled lattice QCD"*

Abstract: It is widely believed that chiral symmetry is spontaneously broken at zero temperature in the strong coupling limit of staggered fermions, for any number of colors and flavors. Using Monte Carlo simulations, we show that this conventional wisdom, based on a mean-field analysis, is wrong. For sufficiently many fundamental flavors, chiral symmetry is restored via a bulk, first-order transition. This chirally symmetric phase appears to be analytically connected with the expected conformal window of many-flavor continuum QCD. We perform simulations in the chirally symmetric phase at zero quark mass for various system sizes  $L$ , and measure the torelon mass, the Dirac spectrum and the hadron spectrum. All masses go to zero with  $1/L$ .  $L$  is hence the only infrared length scale. Thus, the strong-coupling chirally restored phase appears as a convenient laboratory to study IR-conformality. Finally, we present a conjecture for the phase diagram of lattice QCD as a function of the bare coupling and the number of quark flavors.

**Thursday, August 16**

11:35 am: Akaki Rusetski, University of Bonn

Room A114, Physics/Astronomy Auditorium

*"Non-relativistic field theories in a finite volume"*

Abstract: I review different applications of the non-relativistic effective field theory methods in a finite volume to study the properties of unstable states on the lattice. In particular, I address the following issues:  
1. Evaluation of the form factors of unstable states (e.g., the electromagnetic form factor of the Delta-resonance, or the transition form factor Delta-N-gamma) in lattice QCD. 2. Generalization of the Luescher approach to the case of inelastic resonances, which decay into the two- as well as tree-particle final states.

3:00 pm: Martin Savage, University of Washington

Room C520, Physics/Astronomy Tower

*"Nuclei"*

Abstract : I will discuss the current status of lattice QCD calculations of nuclei. This will include both formal and numerical aspects of the program.

**Friday, August 17**

11:35 am: Michael Doring, Helmholtz-Inst Strahlen- Kernphysik

Room A114, Physics/Astronomy Auditorium

*"Finite volume methods to extract resonances"*

Abstract: Lattice gauge simulations allow for the ab-initio approach to hadronic resonances. To connect lattice results to the physical limit, chiral effective field theory serves to take account of finite volume effects as will be discussed in this talk. Varying the volume, applying hybrid boundary conditions, or working in moving frames promises to extract a maximum of information from lattice data. Such approaches are applied to coupled-channel pion-kaon and pion-pion scattering for which the required precision on lattice data are determined to access the broad scalar resonances. Also, coupled-channel meson-baryon scattering will be discussed including partial wave mixing and the important contributions from the two-meson-baryon channels.

**Week 4**  
**August 20 - 24, 2012**

**Monday, August 20**

11:35 am: Murray Moinester, Tel Aviv University  
Room A114, Physics/Astronomy Auditorium

*"Pion Polarizability at CERN COMPASS and Doubly Charmed Baryons at Fermilab SELEX"*

Abstract: 1) CERN COMPASS uses a 180 GeV pion beam and a virtual photon (Primakoff) target to study gamma-pion Compton scattering and the pion polarizability. Data and analysis and comparisons with theory are described. 2) The existence of baryons with two charm quarks is expected from our present understanding of hadronic structure. Fermilab SELEX has data for doubly charmed baryon  $\Xi_{cc}^+$  ( $ccu$ ) and  $\Xi_{cc}^0$  ( $ccu$ ) charged decay modes  $\Xi_{cc}^+ \rightarrow \Lambda^0 c + K^+ \pi^+$  and  $\Xi_{cc}^0 \rightarrow p D^0 + K^-$  and  $\Xi_{cc}^{++} \rightarrow \Lambda^0 c + K^- \pi^+ \pi^+$ . The masses of doubly charmed baryon candidates are consistent with theoretical considerations, but the spectroscopy is surprising. Data and analysis and comparisons with theory are described.

**Tuesday, August 21**

11:35 am: Assumpta Parreno, University of Barcelona  
Room A114, Physics/Astronomy Auditorium

*"Lattice QCD calculations for hypernuclear physics"*

Abstract: I will overview the Lattice QCD results generated by the NPLQCD Collaboration for the interaction among baryons. I will concentrate in the strange two-baryon sector, where the lack of precise experimental data makes LQCD calculations particularly relevant in our way to constrain the YN interactions.

**Wednesday, August 22**

11:35 am: Brian Tiburzi, City College of New York  
Room A114, Physics/Astronomy Auditorium

*"Anatomy of Hadronic Parity Violation on the Lattice"*

**Thursday, August 23**

11:35 am: Shin-Nan Yang, National Taiwan University  
Room A114, Physics/Astronomy Auditorium

*"Study of resonance properties with Dubna-Mainz-Taipei dynamical model"*

Abstract: The resonance properties extracted from pion-nucleon scattering and pion electromagnetic production with the Dubna-Mainz-Taipei (DMT) meson-exchange model will be summarized. The data analyzed cover from threshold up to c.m. energies  $W \leq 2$  GeV. The properties extracted include masses, widths, pole positions, as well as the deformation of  $\Delta(1232)$ . We will also discuss the multiple poles structure of the Roper resonance and argue that it is a general mathematical consequence when additional Riemann surface is included in the study.

**Friday, August 24**

11:35 am: Christopher Thomas, Trinity College Dublin

Room A114, Physics/Astronomy Auditorium

*"General multi-hadron operator constructions and application to  $\pi\pi$   $l=2$  scattering"*

Abstract: I present general operator constructions which respect the symmetries of a multi-hadron system at zero and non-zero momentum in a finite volume. The efficacy of these constructions is demonstrated in an application to isospin-2  $\pi\pi$  at a pion mass of 396 MeV which provides a useful testing ground. I show how, in combination with a range of other techniques, this methodology enables the reliable determination of the excited state spectrum from variational analyses using large bases of operators. The S and D-wave scattering phase-shifts are then determined at a large number of kinematic points within the elastic region; these are found to be well described by a scattering length parameterisation. I comment on further applications to more physically interesting scattering channels.



**Week 5**  
**August 27- 31, 2012**

**Monday, August 27**

11:15 am: Carsten Urbach, Bonn University  
Room C421, Physics/Astronomy Building  
*"eta and eta' mesons from  $N_f=2+1+1$  flavour lattice QCD"*

Abstract: We determine mass and mixing angles of eta and eta' states using  $N_f=2+1+1$  Wilson twisted mass lattice QCD. We describe how those flavour singlet states need to be treated in this lattice formulation. Results are presented for three values of the lattice spacing,  $a=0.061$  fm,  $a=0.078$  fm and  $a=0.086$  fm, with light quark masses corresponding to values of the charged pion mass in a range of 230 to 500 MeV and fixed bare strange and charm quark mass values. In addition to the unitary approach we will also use a mixed action ansatz and discuss its features.

**Tuesday, August 28**

11:15 am: Michael Buchoff, Lawrence Livermore National Laboratory  
Room C421, Physics/Astronomy Building  
*"Neutron-Antineutron Oscillations on the Lattice"*

Abstract: One possible low energy process due to beyond the Standard Model (BSM) physics is the neutron-antineutron transition, where baryon number changes by two units. In addition to providing a source of baryon number violation in the early universe, interactions of this kind are natural in grand unified theories (GUTs) with Majorana neutrinos that violate lepton number. Bounds on these oscillations can greatly restrict a variety of GUTs, while a non-zero signal would be a "smoking gun" for new physics. However, to make a reliable prediction, the six-quark neutron-antineutron matrix elements must first be calculated non-perturbatively via lattice QCD. In this talk, I review the current understanding of this quantity, describe the lattice formalism for the three-point function of interest, and present preliminary results from  $32^3 \times 256$  clover-Wilson lattices with a pion mass of 390 MeV. Additionally, since all contractions occur at the operator insertion with the absence of disconnected diagrams, the lattice calculation of this matrix element is an ideal testing ground for excited state contamination in nucleon three-point functions. Multiple analysis methods will be explored to quantify this systematic.

**Particle Theory Seminar**

Room C421, Physics/Astronomy Tower  
2:30 pm: Andre Walker-Loud, Lawrence Berkeley National Laboratory  
*"The Cottingham formula for  $M_p - M_n$ "*

**Wednesday, August 29**

11:15 am: Emmanuel Chang, University of Barcelona  
Room C421, Physics/Astronomy Building  
*"Pionic couplings to the lowest heavy-light mesons of positive and negative parity"*

Abstract: We present the method and compute the strong couplings of the lowest and first orbitally excited heavy-light mesons to a soft pion in the static heavy quark limit on the lattice. Besides the usual  $\hat{g}$  and  $\tilde{g}$  couplings, we were able to make the first computation of the coupling  $h$  using the relevant radial distributions. Our results are obtained from the simulations of QCD with  $N_f = 2$  light Wilson-Clover quarks, combined with the improved static quark action. The hierarchy among couplings that emerges from our study is  $\tilde{g} < \hat{g} < h$ .

**Thursday, August 30**

11:15 am: Joe Wasem, Lawrence Livermore National Laboratory

Room C421, Physics/Astronomy Building

*"Omega Baryon Interactions with Lattice QCD"*

Abstract: I discuss the interactions of the two-Omega baryon system in multiple spin channels with lattice QCD. In addition to being an interesting hyperonic system in its own right, the two-Omega system also provides an ideal laboratory for exploring the interactions of multi-baryon systems with minimal dependence on light quark masses. Previous model calculations of the two-Omega system have obtained conflicting results, which can be resolved by lattice QCD. The lattice calculations are performed using two different volumes with  $L \sim 2.5$  and  $3.9$  fm at  $m_\pi \sim 390$  MeV with a lattice spacing of  $a \sim 0.123$  fm. Using multiple interpolating operators from a non-displaced source, we present scattering information for two ground state Omega baryons in both the  $S=0$  and  $S=2$  channels. For  $S=0$ ,  $k \cot(\delta)$  is extracted at two volumes, which leads to an extrapolated scattering length of  $0.16 \pm 0.22$  fm, indicating a weakly repulsive interaction. Additionally, for  $S=2$ , two separate highly repulsive states are observed.

**Friday, August 31**

11:15 am: Andre Walker-Loud, Lawrence Berkeley National Laboratory

Room C421, Physics/Astronomy Building

*"The light quark mass dependence of QCD: myths and facts"*