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FOR PARTICLE AND NUCLEAR PHYSICS

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2006

The contributions on individual experiments in this report are outlines intended to demonstrate the extent of scientific activity at TRIUMF during the past year. The outlines are not publications and often contain preliminary results not intended, or not yet ready, for publication. Material from these reports should not be reproduced or quoted without permission from the authors.

THEORETICAL PROGRAM

Introduction

The TRIUMF Theory group provides a centre for theoretical research at TRIUMF and a group of active people involved in research in a wide variety of areas. Some of these areas are of direct relevance to the on-site experimental program. Others are more closely related to projects elsewhere involving TRIUMF and other Canadian scientists. Still others are more general, contributing to, and participating in, the efforts of the subatomic physics community both in Canada and elsewhere.

At present the group consists of four permanent staff members, six to seven research associates and a number of students and visitors. Currently the main research interests are nuclear structure and reactions, nuclear astrophysics and cosmology, lattice QCD, effective field theories and chiral perturbation theory, few-body systems, and particle physics beyond the standard model.

The four permanent staff members of the group are: Harold W. Fearing, Byron K. Jennings (group leader), John N. Ng, and Richard M. Woloshyn. A fifth permanent staff member, A. Schwenk, has been hired and will be joining the group in the fall of 2006. Erich W. Vogt (professor emeritus, UBC) is an associate member. Research associates during 2005 were: R. Allahverdi (until November), S. Ando (until October), C. Barbieri (until September), P. Capel, R. Cyburt, W. Liao, S. Nakamura (from July), L. Theussl and J. Wu (from September).

Long term visitors included sabbatical visitors S.W. Hong (Sungkyunkwan University) and H. Trottier (SFU), and visiting graduate student S. Wright.

The graduate students associated with the group during 2005 were: N. Supanam and M. Schindler, supervised by H. Fearing, K.Y. Wong, supervised by R. Woloshyn, and Z. Hao and L. One supervised by H. Trottier.

The short term visitors to the Theory group this year included:
A. Abdel-Rehim
N. Auerbach
C. Bertulani
S. Bilenky
W. Chang
A. Czarnecki
D. Dean
J. de Jesus
H.W. Hammer
J. Heyl
R. Hill
C. Horowitz
W. Hsieh
B. Jones
B. Kayser
C.S. Lam
C. Lee
R. Lewis
L. Loveridge
C. Lunardini
R. Machleidt
E. Ormand
R. Petry
M. Pospelov
I. Sato
J. Schaffner-Bielich
A. Schwenk
S. Tamhankar
E. Tomusiak
R. van de Water
U. van Kolck
M. van Raamsdonk
G. von Hippel
D. Wilkinson

As usual members of the group have been quite active, and below we briefly describe some of the many projects undertaken during the year by members of the group and longer term visitors.

Nuclear Structure and Reactions

Coupling-in-the-continuum effects in Coulomb dissociation of halo nuclei

(P. Capel; D. Baye, Univ. Libre de Bruxelles)

Coulomb dissociation is one of the most widely used tools to study the halo structure. It also provides an indirect method for determining the astrophysical S-factor of radiative capture reactions at stellar energies. In both cases, the experimental data are usually interpreted with a first-order approximation restricted to the E1 multipole with a possible E2 correction. In this perturbative technique, the breakup is assumed to occur in a single-step transition from the initial bound state towards the continuum. However higher-order effects corresponding to multi-step transitions occurring in the continuum may still be non negligible, even at high energies. It is therefore of great importance to assess the validity of the first-order approximation so as to avoid biased analyses of experimental results.

We investigated these higher-order effects by comparing the first-order perturbation theory to the numerical resolution of a time-dependent Schrödinger equation. The calculations have been performed for the breakup on a lead target of ^{11}Be and ^{8}B. The populations of the different partial waves composing the ^{10}Be-neutron or ^{7}Be-proton continuum reveal that couplings in the continuum remain significant even at high impact parameters and high projectile-target relative velocities. Although the total breakup cross section is fairly well described at a first-order approximation, its partial-wave components reached by the first-order transitions are significantly depleted towards other partial waves after the closest approach. The information extracted by assuming the validity of the first-order approximation is affected by an energy distortion. Another distortion is caused by the presence of a resonance as exemplified by the $\frac{5}{2}^{+}$ resonance of ^{11}Be. Such effects may partly explain discrepancies between direct and indirect measurements of the astrophysical S-factor of the $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ reaction at stellar energies.

Influence of the projectile description on breakup calculations

(P. Capel; F.M. Nunes, Michigan State)

Since the early days of radioactive beam experiments, breakup reactions have been an important source of information on the structure of nuclei near the dripline. Usually, the exotic nucleus – the projectile – is simulated by a loosely bound two-body system. The spectroscopic factor of that single-particle wave function is obtained from the comparison of the theoretical predictions with the data. Alternatively, it has been suggested that asymptotic normalization coefficients (ANC) can be obtained from breakup measurements. The basic idea therein is that breakup reactions of loosely bound nuclei are highly peripheral. Since the asymptotic behaviour of the projectile wave function is in general well known, the breakup cross section is proportional to the square of the ANC. In this work, we examine the validity of such procedures. We focus on the dependence of the normalization of the Coulomb induced breakup cross section on the single particle potential used for the description of the ground state, as well as the dependence on other features of the projectile, such as excited or scattering states.

Calculations of the breakup of ^{8}B and ^{11}Be are performed with the aim of analyzing their sensitivity to the projectile description. Several potentials adjusted on the same experimental data are used for each projectile. The results vary significantly with the potential choice, and this sensitivity differs from one projectile to the other. In the ^{8}B case, the breakup cross section is approximately scaled by the asymptotic normalization coefficient of the initial bound state (ANC). For ^{11}Be, the overall normalization of the breakup cross section is no longer solely determined by the ANC. The partial waves describing the continuum are found to play a significant role in this variation, as the sensitivity of the phase shifts to the projectile description changes with the physical constraints imposed on the potential.

Collisions of halo nuclei within a dynamical eikonal approximation

(D. Baye, G. Goldstein, Univ. Libre de Bruxelles; P. Capel)

Elastic breakup is one of the main tools for determining the properties of weakly bound exotic nuclei. It corresponds to transitions from the ground state into the continuum due to the interaction with a target. A number of theories have been proposed or extended to allow a treatment of this mechanism. Let us mention the continuum discretized coupled-channels method, the adiabatic approximation, the distorted-wave Born approximation, the eikonal approximation, and the time-dependent method.

In the semi-classical approximation, the relative motion between target and projectile is treated in a classical way. When following the trajectory, the two components of the projectile experience Coulomb and nuclear fields from the target that vary in time. This time variation may induce excitation or breakup of the projectile. The semi-classical approximation leads to the resolution of a time-dependent Schrödinger equation. It is a fully dynamical theory where all couplings, not only between the bound states and the continuum but also inside the continuum, are properly taken into account. The semi-classical approach, however, has the drawback of not being a fully quantal approximation.

The eikonal method consists of an approximate calculation of the phase of a three-body wave function describing the relative motion of the target and of the two projectile components. This phase is obtained by integrating the projectile-target interaction along straight lines as if the projectile was feeling the target influence by such trajectories. This approximation has thus a rather simple physical interpretation. To some extent, it takes account in this phase of the few-body degrees of freedom at all orders. However, it is usually derived using an additional adiabatic approximation which neglects dynamical effects inside the projectile. Hence the eikonal approximation is mostly valid for peripheral reactions at rather high energies.

The dynamical eikonal method is a purely quantal method that combines the advantages of both approaches. It improves the eikonal method in the sense that missing dynamical effects are taken into account. It is also an improvement of the semi-classical approach as it takes account of interference effects that were missing with classical trajectories. A good agreement is obtained with experimental differential and integrated cross sections for the elastic scattering and breakup of the ^{11}Be halo nucleus on ^{12}C and ^{208}Pb near 70 MeV/nucleon, without any parameter adjustment. The dynamical approximation is compared with the traditional eikonal method. Differences are analyzed and the respective merits of both methods are discussed.

Separate treatment of short-range and tensor correlations in nuclei
(S. Nakamura; H. Toki, Osaka)

The construction of an effective interaction for describing nuclear structure within a given model-space has been an important subject in nuclear physics. Recently, some authors seriously studied the tensor correlation in nuclei using a configuration mixing. They showed that the tensor force is well handled in an appropriate model-space. Thus, we start with a realistic nuclear force and construct the corresponding effective interaction, eliminating the hard core but keeping the tensor force essentially unchanged. For this purpose, we modify the unitary transformation for deriving a low-momentum interaction as follows. At first, we omit the tensor force and derive the corresponding low-momentum interaction using the unitary transformation. Then we transform the full Hamiltonian, including the tensor force, using the unitary operator determined in the previous step.

Following these steps, we obtain a non-local effective interaction represented in the momentum space. We approximately localize and represent it in the coordinate space for convenience in a practical calculation of nuclear structure. We found that the hardcore is largely reduced and the intermediate attraction becomes shallow as expected. In future, we study the usefulness of the effective interaction in describing the nuclear structure.

Extended optical model analyses of elastic scattering, direct reaction, and fusion cross sections for the ^{9}Be + ^{208}Pb system at near-Coulomb-barrier energies
(W.Y. So, Korea Inst. Radiological and Medical Sciences; S.W. Hong, Sungkyunkwan/TRIUMF; B.T. Kim, Sungkyunkwan; T. Udagawa, Texas Austin)

Based on the extended optical model approach in which the polarization potential is decomposed into direct reaction (DR) and fusion parts, simultaneous χ^2 analyses are performed for elastic scattering, DR, and fusion cross section data for the ^{9}Be + ^{208}Pb system at near-Coulomb-barrier energies. Similar χ^2 analyses are also performed by only taking into account the elastic scattering and fusion data as was previously done by the present authors, and the results are compared with those of the full analysis including the DR cross section data as well. We find that the analyses using only elastic scattering and fusion data can produce very consistent and reliable predictions of cross sections particularly when the DR cross section data are not complete. Discussions are also given on the results obtained from similar analyses made earlier for the ^{9}Be + ^{209}Bi system.

Contribution of multi-phonon states to the ph response of finite nuclei
(C. Barbieri)

Work has been initiated in 2005 to develop a formalism that accounts for the possibility of mixing multi-phonon configurations in the one-body response of finite nuclei. At the two-phonon level, this improves on the second RPA (SRPA) formalism by accounting for the fragmentation of quasiparticles.

Nucleon-nucleus optical potential in the particle-hole approach
(C. Barbieri, B.K. Jennings)

Feshbach's projection formalism in the particle-hole model space leads to a microscopic description of scattering in terms of the many-body self-energy. To investigate the feasibility of this approach, an optical potential for ^{16}O is constructed starting from two previous calculations of the self-energy for this nucleus. The results reproduce the background phase shifts for positive parity waves and the resonances beyond the mean field. The latter can be computed microscopically for energies of astrophysical interest using Green's function theory.

ANC for the valence neutron in ^{8}Li
(S. Wright, B. Davids; I.J. Thompson, U. Surrey)

Mirror symmetry in the A = 8, T = 1 system implies a strong correlation between the asymptotic normalization coefficients (ANCs) of the valence nucleon in ^{8}B and ^{8}Li. This opens possibilities for determination of the astrophysical factor $S_{17}(0)$, famous for its implications to the solar neutrino problem, from a study of the ^{8}Li system. A theoretical analysis of the one-neutron elastic transfer reaction ^{7}Li(^{8}Li,^{7}Li)^{8}Li using the code FRESCO leads to useful guidance for an experimental set-up to extract the ANC for the valence neutron in ^{8}Li. The experiment will be performed later this year using LEDA.

The nuclear shell model
(B.K. Jennings)

The no-core shell model and the effective interaction $V_{\mathrm{low}\ k}$ can both be derived using the Lee-Suzuki projection operator formalism. The main difference between the two is the choice of basis states that define the model space. The effective interaction $V_{\mathrm{low}\ k}$ can also be derived using the renormalization group. That renormalization group derivation can be extended in a straightforward manner to also include the no-core shell model. In the nuclear matter limit the no-core shell model effective interaction in the two-body approximation reduces identically to $V_{\text{low } k}$. The same considerations apply to the Bloch-Horowitz version of the shell model and the renormalization group treatment of two-body scattering by Birse, McGovern and Richardson.

Projection operator formalisms and the nuclear shell model

(B.K. Jennings)

The shell model solves the nuclear many-body problem in a restricted model space and takes into account the restricted nature of the space by using effective interactions and operators. Two different methods for generating the effective interactions have been considered. One is based on a partial solution of the Schrodinger equation (Bloch-Horowitz or the Feshbach projection formalism) and the other on linear algebra (Lee-Suzuki). The two methods have been derived in a parallel manner so that the difference and similarities become apparent. The Bloch-Horowitz method deals with one state at a time and has energy dependent effective interactions and operators. It can describe any state with a non-zero overlap with the model space. The Lee-Suzuki method deals with a set of wave functions, a set with the same dimension as the model space. It can describe only those states in that set. The effective interactions and operators are energy independent.

Nuclear Astrophysics, Cosmology

The ^{7}Be$(p,\gamma)^8$B reaction and its future

(R.H. Cyburt, B. Davids, B.K. Jennings)

The experimental landscape for the ^{7}Be + p radiative capture reaction is rapidly changing as new high precision data become available. We present an evaluation of existing data, detailing the treatment of systematic errors and discrepancies, and show how they constrain the astrophysical S factor (S_{17}), independent of any nuclear structure model. With theoretical models robustly determining the behaviour of the sub-threshold pole, the extrapolation error can be reduced and a constraint placed on the slope of S_{17}. Using only radiative capture data, we find $S_{17}(0) = 20.7 \pm 0.6(\text{stat}) \pm 1.0(\text{syst})$ eV b if data sets are completely independent, while if data sets are completely correlated we find $S_{17}(0) = 21.4 \pm 0.5(\text{stat}) \pm 1.4(\text{syst})$ eV b. The truth likely lies somewhere in between these two limits. Although we employ a formalism capable of treating discrepant data, we note that the central value of the S factor is dominated by the recent high precision data of Junghans *et al.*, which imply a substantially higher value than other radiative capture and indirect measurements. Therefore we conclude that future progress will require new high precision data with a detailed error budget.

Hadron masses in medium and neutron star properties

(C.Y. Ryu, C.H. Hyun, Sungkyunkwan; S.W. Hong, Sungkyunkwan/TRIUMF; B.K. Jennings)

We investigate the properties of the neutron star with relativistic mean-field models. We incorporate in the quantum hadrodynamics and in the quark-meson coupling models a possible reduction of meson masses in nuclear matter. The equation of state for neutron star matter is obtained and is employed in Oppenheimer-Volkov equation to extract the maximum mass of the stable neutron star. We find that the equation of state, the composition and the properties of the neutron stars are sensitive to the values of the meson masses in medium.

Lattice QCD

Perturbative results from Monte Carlo simulations

(K.Y. Wong, H.D. Trottier, SFU; R.M. Woloshyn)

Perturbative expansions of several small Wilson loops are computed through next-to-next-to leading order in unquenched lattice QCD, from Monte Carlo simulations at weak couplings. This approach provides a much simpler alternative to conventional diagrammatic perturbation theory, and is applied here for the first time to full QCD. Two different sets of lattice actions are considered: one set uses the unimproved plaquette gluon action together with the unimproved staggered-quark action; the other set uses the one-loop-improved Symanzik gauge-field action together with the so-called asqtad improved-staggered quark action. Simulations are also done with different numbers of dynamical fermions. An extensive study of the systematic uncertainties is presented, which demonstrates that the small third-order perturbative component of the observables can be reliably extracted from simulation data. We also investigate the use of the rational hybrid Monte Carlo algorithm for unquenched simulations with unimproved-staggered fermions. Our results are in excellent agreement with diagrammatic perturbation theory, and provide an important cross-check of the perturbation theory input to a recent determination of the strong coupling by the HPQCD collaboration.

Improved bilinears in lattice QCD with non-degenerate quarks

(J.M.S. Wu; T. Bhattacharya, R. Gupta, LANL; W. Lee, Seoul; S.R. Sharpe, Univ. Washington)

We describe the extension of the improvement program for bilinear operators composed of Wilson fermions to non-degenerate dynamical quarks. We consider two, three and four flavours, and both flavour non-singlet and singlet operators. We find that there are many more improvement coefficients than with degenerate quarks, but that, for three or four flavours, nearly all can be determined by enforcing vector and axial Ward identities. The situation is worse for two flavours, where many more coefficients remain undetermined.

Nucleon and delta masses in twisted mass chiral perturbation theory

(J.M.S. Wu; A. Walker-Loud, Univ. Washington)

We calculate the masses of the nucleons and deltas in twisted mass heavy baryon chiral perturbation theory. We work to quadratic order in a power counting scheme in which we treat the lattice spacing and the quark masses to be of the same order. We give expressions for the mass and the mass splitting of the nucleons and deltas both in and away from the isospin limit. We give an argument using the chiral Lagrangian treatment that, in the strong isospin limit, the nucleons remain degenerate and the delta multiplet breaks into two degenerate pairs to all orders in chiral perturbation theory. We show that the mass splitting between the degenerate pairs of the deltas first appears at quadratic order in the lattice spacing. We discuss the subtleties in the effective chiral theory that arise from the inclusion of isospin breaking.

Twisted mass chiral perturbation theory at next-to-leading order

(J.M.S. Wu; S.R. Sharpe, Univ. Washington)

We study the properties of pions in twisted mass lattice QCD (with two degenerate flavours) using chiral perturbation theory (ChPT). We work to next-to-leading order (NLO) in a power counting scheme in which $m_q \sim a\Lambda^2_{\rm QCD}$, with m_q the physical quark mass and a the lattice spacing. We argue that automatic $O(a)$ improvement of physical quantities at maximal twist, which has been demonstrated in general if $m_q \gg a\Lambda^2_{\rm QCD}$, holds even if $m_q \sim a\Lambda^2_{\rm QCD}$, as long as one uses an appropriate non-perturbative definition of the twist angle. We demonstrate this with explicit calculations, for arbitrary twist angle, of all pionic quantities that involve no more than a single pion in the initial and final states: masses, decay constants, form factors and condensates, as well as the differences between alternate definitions of twist angle. We also calculate the axial and pseudoscalar form factors of the pion, quantities which violate flavour and parity, and which vanish in the continuum limit. These are of interest because they are not automatically $O(a)$ improved at maximal twist. They allow a determination of the unknown low energy constants introduced by discretization errors, and provide tests of the accuracy of ChPT at NLO. We extend our results into the regime where $m_q \sim a2\Lambda^3_{\rm QCD}$, and argue in favor of a recent proposal that automatic $O(a)$ improvement at maximal twist remains valid in this regime.

Applying chiral perturbation to twisted mass lattice QCD

(J.M.S. Wu; S.R. Sharpe, Univ. Washington)

We have explored twisted mass LQCD (tmLQCD) analytically using chiral perturbation theory, including discretization effects up to $O(a2)$, and working at next-to-leading (NLO) order in the chiral expansion. In particular we have studied the vacuum structure, and calculated the dependence of pion masses and decay constants on the quark mass, twisting angle and lattice spacing. We give explicit examples for quantities that both are and are not automatically improved at maximal twisting.

Strange quarks in quenched twisted mass lattice QCD

(A. Abdel-Rehim, R. Lewis, Regina; R.M. Woloshyn, J.M.S. Wu)

We study the issues that arise in twisted mass lattice QCD (tmLQCD), when a second doublet containing the strange quark is included in addition to the light quark ("up-down") doublet. Lattice simulations of strange mesons are performed, and a chiral effective theory for the four-flavoured lattice theory is written down. We calculated the masses and decay constants of pseudoscalar mesons and the masses of vector and axial vector mesons, and we studied the mixing between the third isospin components of scalar and pseudoscalar correlators. Of particular interest are the splittings among the pseudoscalar meson masses, as these provide a measure of the symmetry breakings present in tmLQCD. We also studied the case where the twist angle of the strange quark is set to zero, whereby one is left with a Wilson strange quark and twisted up and down quarks. Simulations in this case are shown to produce clear qualitative differences at non-vanishing lattice spacing to the case where the strange quark is twisted.

Two-loop matching of lattice and continuum heavy-light axial vector current in NRQCD

(J.M.S. Wu; H. Trottier, SFU)

We calculate matching factors to two-loop order in lattice perturbation theory for constructing heavy-light axial vector current in lattice NRQCD necessary for high precision study of charmed systems.

Effective Field Theories and Chiral Perturbation Theory

Neutron-neutron fusion

(S. Ando; K. Kubodera, South Carolina)

The neutron-neutron fusion process, $nn \to de\nu$, at very low neutron energies is studied in the framework of pionless effective field theory that incorporates dibaryon fields. The cross section and electron energy spectrum for this process are calculated up to next-to-leading order. We include the radiative corrections of $\mathcal{O}(\alpha)$ calculated for the one-body transition amplitude. The precision of our theoretical estimates is found to be governed essentially by the accuracy with which the empirical values of the neutron-neutron scattering length and effective range are currently known. Also discussed is the precision of theoretical estimates of the transition rates of related electroweak processes in few-nucleon systems.

The $np \to d\gamma$ cross sections at the BBN energies

(S. Ando, R.H. Cyburt; S.W. Hong, Sungkyunkwan; C.H. Hyun, Seoul/Sungkyunkwan)

The total cross section for radiative neutron capture on a proton, $np \to d\gamma$, is evaluated at big bang nucleosynthesis (BBN) energies. The electromagnetic transition amplitudes are calculated up to next-to leading order within the framework of pionless effective field theory with dibaryon fields. We also calculate the $d\gamma \to np$ cross section and the photon analyzing power for the $d\vec{\gamma} \to np$ process from the amplitudes. The values of low energy constants that appear in the amplitudes are estimated by a Markov Chain Monte Carlo analysis using the relevant low energy experimental data. Our result agrees well with those of other theoretical calculations except for the $np \to d\gamma$ cross section at some energies estimated by an R-matrix analysis. We also study the uncertainties in our estimation of the $np \to d\gamma$ cross section at relevant BBN energies and find that the estimated cross section is reliable to within ∼1% error.

Effective field theory of the deuteron with dibaryon fields

(S. Ando; C.H. Hyun, Seoul/Sungkyunkwan)

Pionless effective field theory with dibaryon fields is reexamined for observables involving the deuteron. The electromagnetic form factors of the deuteron and the total cross section of radiative neutron capture on the proton, $np \to d\gamma$, are calculated. The low energy constants of vector(photon)-dibaryon-dibaryon vertices in the effective Lagrangian are fixed primarily by the one-body vector(photon)-nucleon-nucleon interactions. This scheme for fixing the values of the low energy constants satisfactorily reproduces the results of the effective range theory. We also show that, by including higher order corrections, one can obtain results that are close to those of the Argonne v18 potential model.

Ordinary muon capture on a proton in manifestly Lorentz invariant baryon chiral perturbation theory

(S. Ando, H.W. Fearing)

The amplitude for ordinary muon capture on the proton is evaluated, through the first four orders in the expansion parameter, in a manifestly Lorentz invariant form of baryon chiral perturbation theory. We obtain expressions for the low energy constants in terms of physical quantities. We compare and contrast the several regularization proposals for forcing the relativistic approach to obey the same counting rules as obtained in heavy baryon chiral perturbation theory.

Baryon chiral perturbation theory with virtual photons and leptons

(N. Supanam, H.W. Fearing)

Chiral perturbation theory is the effective field theory of the standard model at low energies in the hadronic sector. Nowadays, it has become a precision tool to investigate a variety of processes in the pion-nucleon system. In the last few years, baryon chiral perturbation theory in the presence of virtual photons has been considered. In our project, we enlarge the baryon chiral perturbation theory with virtual photons by including the light leptons as dynamical degrees of freedom. We construct the general effective chiral pion-nucleon SU(2) Lagrangian with virtual photons and leptons at third order in the chiral expansion. In what follows, we will apply our Lagrangian to radiative corrections, to weak processes, and to processes like radiative muon capture.

Axial form factors of the nucleon in ChPT including axial vector mesons
(M.R. Schindler, H. Fearing; S. Scherer, Mainz)

The development of new renormalization schemes has allowed for the inclusion of additional degrees of freedom, such as vector mesons or axial-vector mesons, in chiral perturbation theory (ChPT). These new renormalization schemes have been used to calculate the electromagnetic form factors of the nucleon under the inclusion of vector mesons, resulting in an improved description of the data. The aim of the current project is the calculation of the axial form factors of the nucleon in manifestly Lorentz-invariant ChPT under the inclusion of axial-vector mesons. From the axial form factors one can infer information about the induced pseudoscalar coupling of the proton, g_p, for which the theoretical predictions so far do not agree with the experimental data as obtained from muon capture experiments at TRIUMF and Saclay.

Few-Body and Medium Energy Processes

Renormalization group analysis of nuclear current operators
(S. Nakamura, S. Ando)

Electroweak processes in few and many nucleon systems have been of interest in nuclear physics. Nuclear current operators for those processes are from, e.g., either phenomenological models or nuclear effective field theory (NEFT). Though detailed expressions and behaviours of the current operators for these two cases are in general different from each other, it has been reported that the two approaches give essentially the same reaction rates for several low-energy electroweak processes in few-nucleon systems. This implies equivalence between the two approaches in describing the low-energy electroweak processes. We study the relation between them employing a renormalization group analysis. By reducing the model space of the current operators of νd reactions in using the Wilsonian renormalization group equation, we essentially obtain single effective operators in a certain small model space that is relevant to pionless theory. Therefore, we conclude that as long as reactions with the kinematics included in the small model space are concerned, the reactions hardly probe details of small scale physics which appear as the differences among the nuclear operators.

Neutrino-deuteron reaction beyond solar neutrino regime
(S. Nakamura; T. Sato, Osaka; K. Kubodera, South Carolina)

The SNO experiment has been interested in measuring the solar neutrino flux, and found a strong evidence of the neutrino oscillation. In order to extract meaningful information from the data, accurate theoretical values of cross sections for the neutrino-induced deuteron disintegration is prerequisite. Our group contributed to the experiment by presenting the theoretical cross sections for the solar neutrino energy regime ($E_\nu \leq 20$ MeV, E_ν: the neutrino energy in the laboratory frame). Now the SNO group is concerned with the neutrinos from supernovae. The supernova neutrino is more energetic than the solar neutrino and, for a good analysis of the data, theoretical cross sections are required up to $E_\nu \sim 150$ MeV. We extended our previous calculation to present the cross sections in this energy region.

Kaon optical potential in nuclei and kaon condensation in neutron star
(C.Y. Ryu, C.H. Hyun, B.T. Kim, Sungkyunkwan; S.W. Hong, Sungkyunkwan/TRIUMF)

Recent experiments at KEK, BNL, and DAΦNE revealed very interesting peaks that might be interpreted as deeply bound kaonic nuclear systems, which were predicted by Akaishi and Yamazaki. If those peaks are indeed deeply bound kaonic nuclear states, it implies that the real part of the kaon optical potential is very large. We consider this possibility and try to fix the coupling constants for strange quarks within the framework of a modified quark-meson coupling model. We then apply the modified quark-meson coupling model to the neutron star matter and obtain the equation of state and the maximum mass of a neutron star. It is found that the equation of state, composition of matter and properties of a neutron star are very sensitive to the interaction strength of a kaon in matter. We find interesting critical phenomena when the magnitude of the real part of the kaon optical potential in matter at the saturation density becomes as large as 140 MeV.

Effective mass and decay of Θ^+ in nuclear matter in the quark-meson coupling models
(C.Y. Ryu, C.H. Hyun, Sungkyunkwan; S.W. Hong, Sungkyunkwan/TRIUMF; J.Y. Lee, Sejong)

The in-medium mass of a Θ^+, $m^*_{\Theta^+}$, in cold symmetric nuclear matter is calculated by using the quark-meson coupling model. The Θ^+ is treated as an MIT bag with a quark content $uudd\bar{s}$. The bag parameters for a free Θ^+ are fixed to reproduce the observed mass of the Θ^+. In doing so, we use three different values of the s-quark mass since the mass of the s-quark is not well known. As usual, the strengths of the u and d quark couplings to σ- and ω-meson fields are determined to fit the nuclear saturation properties. However, the coupling constant g^s_σ between the s-quark and the σ-meson cannot be fixed from the saturation properties, and thus we treat g^s_σ as a free parameter and investigate how $m^*_{\Theta^+}$ depends on g^s_σ. We find that

$m^*_{\Theta^+}$ depends significantly on the value of g^s_σ but not on the mass of the s-quark. Chemical potentials of the Θ^+ and the $K+N$ system are calculated to discuss the decay of a Θ^+ in nuclear matter. We calculate the effective mass of a kaon in nuclear matter in two ways; using the optical potential of K^- in matter and using a quark model. By comparing the effective masses of K calculated from these two methods, we find the magnitude of the real part of the optical potential that is consistent with the quark model is about 100 MeV. In that case, we find $g_{\sigma K} \approx 2$.

Parity-nonconserving observables in thermal neutron capture on a proton
(C.H. Hyun, S.J. Lee, S.W. Hong, Sungkyunkwan; J. Haidenbauer, Forschungszentrum Jülich)

We calculate parity-nonconserving observables in the processes where a neutron is captured on a proton at the threshold energy radiating a photon. Various potential models such as Paris, Bonn and Argonne v18 are used for the strong interactions, and the meson exchange description is employed for the weak interactions between hadrons. The photon polarization P_γ in the unpolarized-neutron capture process and photon asymmetry A_γ in the polarized-neutron capture process are obtained in terms of the weak meson-nucleon coupling constants. A_γ turns out to be basically insensitive to the employed strong interaction models and thus can be uniquely determined in terms of the weak coupling constants, but P_γ depends significantly on the strong interaction models.

Generalized parton distributions of the pion in a Bethe-Salpeter approach
(L. Theussl; S. Noguera, V. Vento, Valencia)

Generalized parton distribution functions are calculated in a field theoretic formalism using a covariant Bethe-Salpeter approach for the determination of the bound-state wave function. The procedure is described in an exact calculation in scalar electrodynamics, proving that the first higher order corrections vanish. The formalism is extended to the Nambu-Jona-Lasinio model, a realistic theory of the pion. It is found that in both cases all important features required by general physical considerations, like symmetry properties, sum rules and the polynomiality condition, are explicitly verified.

Is there a three-body force?
(R. Cyburt, L. Theussl)

Realistic calculations of the triton binding energy with modern nucleon-nucleon potentials (excluding three-body forces) result in a discrepancy of $\sim$1 MeV as compared to the experimentally observed value of -8.48 MeV. This is often considered an empirical proof for the existence of a three-body force. We attempt a critical review of this notion by considering a simple model that illustrates the different effect of the renormalization-scheme dependent cut-off parameter in the two- and three-body sectors, as well as the parameter space that is used to fit the empirical data. We also investigate the same kind of effects in a fully relativistic calculation.

2- and 3-body forces and effective interactions
(R.H. Cyburt, L. Theussl)

We examine methods used in extracting an effective interaction from 2- and 3-body data, exploring both phenomenological and field theoretic techniques. We discuss how integrating out high momentum components of a “bare” potential is advantageous. However, failure to add an effective high momentum interaction to this regulated potential can lead to misleading conclusions, such as the necessity and/or strength of a 3-body interaction. Concern remains over choosing an appropriate regulating scale, for which field theory can approximate. We discuss more rigorous definitions of this scale.

Exact numerical solution of a 3-body Bethe-Salpeter equation
(L. Theussl)

We present a benchmark calculation of binding energies and wave functions of a bound state composed of three equal-mass scalar particles in the Bethe-Salpeter framework. Ground and excited states, including different orbital angular momenta, as well as different masses of the exchanged particle are considered.

Bethe-Salpeter equation with non-planar diagrams
(L. Theussl)

We present a formalism that allows the inclusion of an infinite number of crossed diagrams in a Bethe-Salpeter equation. The method is illustrated and numerical benchmark results are presented for a simple two-body system of scalar particles.

Final state interactions in electron scattering at high missing energies and momenta
(C. Barbieri; L. Lapikás, NIKHEF; D. Rohe, Basel, for the E97-006 collaboration)

Calculations of two-step rescattering and pion emission for the $^{12}\mathrm{C}(e,e'p)$ reaction at very large missing energies and momenta are compared with recent data from TJNAF. For parallel kinematics, final state interactions are strongly reduced by kinematical constraints. A good agreement between calculation and experiment is found for this kinematics when one admits the presence of high momentum components in the nuclear wave function.

Quantum opacity, the RHIC HBT puzzle, and the chiral phase transition

(J.M.S. Wu; J.G. Cramer, G.A. Miller, J.H.S. Yoon, Univ. Washington)

We present a relativistic quantum mechanical treatment of opacity and refractive effects that allows reproduction of observables measured in two-pion (HBT) interferometry and pion spectra at RHIC. The inferred emission duration is substantial. The results are consistent with the emission of pions from a system that has a restored chiral symmetry.

Particle Physics

Supermassive gravitinos, dark matter, leptogenesis and flat direction baryogenesis

(R. Allahverdi; S. Hannestad, Arhus; A. Jokinen, A. Mazumdar, NORDITA; S. Pascoli, CERN)

In general the gravitino mass and/or the soft supersymmetry breaking masses in the observable sector can be much larger than the TeV scale. Depending on the relation between the masses, new important channels for gravitino production in the early universe can arise. Gravitinos with a mass above 50 TeV decay before big bang nucleosynthesis, which leads to relaxation of the well known bound on the reheating temperature $T_{\rm R} \leq 10^{10}$ GeV. However, if the heavy gravitinos are produced abundantly in the early universe, their decay can alter the abundance of the lightest supersymmetric particle. Moreover, they may dominate the energy density of the universe. Their decay will, in this case, increase entropy and dilute already created baryon asymmetry and dark matter. Such considerations put new constraints on gravitino and sfermion masses, and the reheating temperature. In this paper we examine various cosmological consequences of supermassive gravitinos. We discuss advantages and disadvantages of a large reheating temperature in connection with thermal leptogenesis, and find that large parts of the parameter space are opened up for the lightest right-handed (s)neutrino mass. We also discuss the viability of Affleck-Dine baryogenesis under the constraints from gravitino decay, and gravitino production from the decay of Q-balls.

Quasi-thermal universe and its implications for gravitino production, baryogenesis and dark matter

(R. Allahverdi; A. Mazumdar, NORDITA)

Under general circumstances full thermal equilibrium may not be established for a long period after perturbative or non-perturbative decay of the inflaton has completed. One can instead have a distribution of particles which is in kinetic equilibrium and evolves adiabatically during this period. Number-violating reactions which are required to establish chemical equilibrium can become efficient only at much later times. We highlight some of the striking consequences of such a quasi-thermal universe. In particular, thermal gravitino production yields no bound on the maximum temperature of the primordial thermal bath alone. As another consequence, the lower bound on the mass of the lightest right-handed (s)neutrino from thermal leptogenesis can be $\gg 10^9$ GeV. Depending on the phase, a Wino or Higgsino considerably lighter than a TeV, or a Bino in the bulk region, can be a viable thermal dark matter candidate. Finally the electroweak symmetry may never be restored in the early universe, therefore weakening any hopes of realizing a successful electroweak baryogenesis.

Supersymmetric thermalization and quasi-thermal universe: vonsequences for gravitinos and leptogenesis

(R. Allahverdi; A. Mazumdar, NORDITA)

Motivated by our earlier paper, we discuss how the infamous gravitino problem has a natural built in solution within supersymmetry. Supersymmetry allows a large number of flat directions made up of gauge invariant combinations of squarks and sleptons. Out of many at least one generically obtains a large vacuum expectation value during inflation. Gauge bosons and Gauginos then obtain large masses by virtue of the Higgs mechanism. This makes the rate of thermalization after the end of inflation very small and as a result the universe enters a quasi-thermal phase after the inflaton has completely decayed. A full thermal equilibrium is generically established much later on when the flat direction expectation value has substantially decreased. This results in low reheat temperatures, i.e. $T_{\rm R} \sim \mathcal{O}(\rm TeV)$, which are compatible with the stringent bounds arising from the big bang nucleosynthesis. There are two very important implications: the production of gravitinos and generation of a baryonic asymmetry via leptogenesis during the quasi-thermal phase. In both cases the abundances depend not only on an effective temperature of the quasi-thermal phase (which could be higher, i.e. $T \gg T_{\rm R}$), but also on the state of equilibrium in the reheat plasma. We show that there is no "thermal gravitino problem" at all within supersymmetry and we stress the need of a new paradigm based on a "quasi-thermal leptogenesis", because in the bulk of the parameter space the old thermal leptogenesis cannot account for the observed baryon asymmetry.

CP violation in orbifold gauge-Higgs unification models
(W.F. Chang, Academia Sinica; W. Liao, J.N. Ng)

An important problem in the approach of gauge-Higgs unification is whether CP violation can be accommodated. In the standard model CP violation is given in the complex Yukawa couplings of two fermions with one scalar. Since there is no extra scalar in the gauge-Higgs unification, it is not clear whether CP violation can be achieved. Analogous to the spontaneous CP violation, the extra dimensional component of the gauge fields can have vacuum expectation values and may trigger CP violation. We show that in 5-D models it is however impossible to achieve CP violation. It is possible in 6D models.

Toward precision measurement in solar neutrinos
(W. Liao)

Solar neutrino physics is, at present, in a position to enter the stage of precision measurements. In this report I will review the so-called solar neutrino problem. This problem in physics is established by the efforts of solar physicists and a number of solar neutrino experiments dated back to 1969. Major theoretical works toward solving the problem appeared in 1970s and 1980s. Just in recent years, the large mixing angle(LMA) Mikheyev-Smirnov-Wolfenstein(MSW) solution hass finally been established as the solution to the solar neutrino problem. There are, however, theoretical problems, e.g. the complex arising from the Earth density profile and the effect of averaging over neutrino energy, to further test the LMA MSW solution in view of the precision to be achieved in future experiments. As will be shown, these problems are solved by using the adiabatic perturbation theory to derive a precise analytic description of the neutrino conversion in the context of the LMA MSW solution.

An effective operator analysis of leptonic CP violation: bridging high and low energy processes
(W.F. Chang, J.N. Ng)

We study the leptonic CP violation by employing the complete set of dimension-six pure leptonic effective operators. Connection among the observable at different energy scales can be made by the running of the renormalization group equations. Explicitly, we study the charged lepton electric dipole moment, muon Michel decay, and the triple product correlations at the linear colliders. We found the electron electric dipole moment, which starts at 2-loop level, severely constrains the possibilities to detect the CP violating signatures in muon decay and at the linear colliders.

An effective operator analysis of CP violation: the semileptonic case
(W.F. Chang, J.N. Ng)

Aiming at a model-independent analysis of possible new physics effects in semileptonic processes at various energy scales, we list and study a complete set of $SU(3)_c\times$ $SU(2)_L\times$ $U(1)_Y$ invariant 4-Fermi operators which consist of a pair of quarks and a pair of leptons above the electroweak symmetry breaking. We give a full 1-loop renormalization group treatment of the evolution of the Wilson coefficients associated with these 4-Fermi operators between low energy ($\sim$ meson masses) and the cutoff scale Λ, $\sim$1–10 TeV, where we assume a new degree of freedom beyond standard model will begin to appear and an ultra-violet completion of our effective theory will take place.

Motivated by the existing phenomenological bounds, we argue that the new CP violation can only stem from the scalar and tensor types of 4-Fermi interaction. Some interesting constraints are obtained by studying the universality of kaon and pion leptonic decays, CP violating polarization of $K^+_{\mu 3}$, charged lepton anomalous magnetic moments, and ($\mu \to e\gamma$) like rare decays. In particular, we can use the limit of electron dipole moment to constrain the size of the CP violating triplet correlation in the $e^+e^- \to t\bar{t}$ process.

Miscellaneous

Scientific and technical computing: the Colt Project
(L. Theussl)

Scientific and technical computing, as, for example, carried out at CERN, is characterized by demanding problem sizes and a need for high performance at reasonably small memory footprint. There is a perception by many that the JAVA language is unsuited for such work. However, recent trends in its evolution suggest that it may soon be a major player in performance sensitive scientific and technical computing and JAVA is finding increased adoption in the field. The reasons include ease of use, cross-platform nature, built-in support for multi-threading, network friendly APIs and a healthy pool of available developers. The Colt library (http://dsd.lbl.gov/ hoschek/colt/) provides fundamental general-purpose data structures optimized for numerical data, such as resizable arrays, dense and sparse matrices (multi-dimensional arrays), linear algebra, associative containers and buffer management.