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FOR PARTICLE AND NUCLEAR PHYSICS

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

OCTOBER 2001

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 Theory group at TRIUMF provides a focus for theoretical research at the laboratory and an active group of people doing high quality research in areas which are relevant, in the broadest sense, to the physics program at TRIUMF and to the interests of the subatomic physics community across Canada. The Theory group thus provides support for the TRIUMF experimental program in its many facets. Like the experimental program, the theoretical research program covers a wide range of topics in nuclear and particle physics with relevance to ISAC, to the medium energy program, and to work done by TRIUMF scientists elsewhere. Part of this research involves working directly with the experimentalists in support of particular experiments; part provides a more general background to the experimental program; and an important part deals with fundamental areas not currently directly related to the experimental program.

The Theory group has four permanent staff members: Harold W. Fearing (group leader), Byron K. Jennings, John N. Ng, and Richard M. Woloshyn, plus Erich W. Vogt (professor emeritus, UBC). This year our research associates are: J. Escher (all year), S.K. Ghosh (all year), S. Kondratyuk (since October), X. Kong (all year), A.D. Lahiff (since September), G.C. McLaughlin (until September), T.-S. Park (until September), G. Rupak (since September), and W. Schadow (all year). Long term visitors include K. Maltman (September-December) and T. Schäfer (January-August). Graduate students with the group include: M. Nobes, SFU (until August), supervised by R.M. Woloshyn; and C. Bird, U. Victoria (all year), E. Ho, UBC (all year), T. Ebertshauser, Mainz (May-July), and C. Unkmeir, Mainz (until September) supervised by H.W. Fearing.

Several others participate regularly in Theory group activities including H. Trottier (SFU faculty) and K. Kallio, M. Nobes, N. Shakespeare, K. Wong (SFU students).

The visitors to the Theory group this year include:

L. Abu-Raddad	J. Juge	K. Nollett
A. Arbuzov	K. Langanke	V. Pascalutsa
L. Canton	P. Lee	M. Ramsey-Musolf
C. Cardall	G. Li	A. Rinat
L. Chang	H. Lipkin	N. Shoresh
T. Fujita	M. Locher	R. Springer
H. Hammer	P. Matlock	I. Towner
W. Haxton	T. Mehen	D. Wilkinson
B. Holstein	A. Mekjian	L. Zamick
S. Hong	H. Murayama	

In addition to their research activities, the theorists have taken an active part in the laboratory activities including the Long Range Planning Committee, the Experiments Evaluation Committee, the NSERC 5-Year Plan Committee, computer support, and from time to time have done some teaching at member universities.

As usual the Theory group has been very active and below we briefly describe some of the specific research projects undertaken during the year by members of the group or by longer term visitors while at TRIUMF.

Nuclear Structure and Reactions, Nuclear Astrophysics

The low-energy nuclear density of states and the saddle point approximation
(S.K. Ghosh, B.K. Jennings)

The nuclear density of states plays an important role in nuclear reactions. At high energies, above a few MeV, the nuclear density of states is well described by a formula that depends on the smooth single particle density of states at the Fermi surface, the nuclear shell correction and the pairing energy. We are in the process of analyzing the low energy behaviour of the nuclear density of states using the saddle point approximation and extensions to it. We should be able to develop formulae that work better at low energies.

Nuclear structure and the solar neutrino problem
(J. Escher, B.K. Jennings; S. Karataglidis, LANL)

The ^{7}Be$(p,\gamma)^8$B reaction at solar energies (approximately 20 keV) plays an important role in the "solar neutrino puzzle" since the neutrino event rate in the existing chlorine and water Čerenkov detectors is either dominated by or almost entirely due to the high-energy neutrinos produced in the subsequent beta decay of ^{8}B. The relevant reaction rate has to be deduced by extrapolating the measured absolute (laboratory) cross sections, which diminish exponentially at low energies, from energies above 100 keV to the astrophysically relevant regime. As a result, this reaction rate is the most poorly known quantity in the entire nucleosynthetic chain that leads to ^{8}B. We are using the nuclear shell model to calculate this quantity. Our goal is to provide a better determination of this rate and thus to contribute to a clearer understanding of this rare, but crucial, solar fusion process and to more accurate estimates for the neutrino flux from our sun.

Microscopic substructure effects in potential-model descriptions of the ^{7}Be$(p,\gamma)^8$B reaction
(J. Escher, B.K. Jennings)

Cross sections of external capture reactions, such as ^{7}Be$(p,\gamma)^8$B at low energies, depend primarily on the asymptotic normalization of the bound-state wave function. The asymptotic normalization, however, is in turn connected to the short-distance behaviour of the wave function through the bound-state Lippmann-Schwinger equation. Hence microscopic substructure effects do play a role in the low-energy cross sections, and thus the astrophysical S factors, of such reactions. We investigate the relationship between potential models and the full many-body problem in order to understand how microscopic substructure effects affect the relevant transition matrix elements.

Partial dynamical symmetry in the symplectic shell model
(J. Escher; A. Leviatan, Hebrew Univ.)

In this extension of an earlier work, we present an example of a partial dynamical symmetry (PDS) in an interacting fermion system. We demonstrate the close relationship of the associated Hamiltonians with a realistic quadrupole-quadrupole interaction, thus shedding new light on this important interaction. Specifically, in the framework of the symplectic shell model of nuclei, we prove the existence of a family of fermionic Hamiltonians with partial SU(3) symmetry. We outline the construction process for the PDS eigenstates with good symmetry and give analytic expressions for the energies of these states and E2 transition strengths between them. Characteristics of both pure and mixed-symmetry PDS eigenstates are discussed and the resulting spectra and transition strengths are compared to those of real nuclei. The PDS concept is shown to be relevant to the description of prolate and oblate, as well as triaxially deformed, nuclei. Similarities and differences between the fermion case and the previously established partial SU(3) symmetry in the interacting boson model are considered.

Nuclear rotational motion and multi-$\hbar\omega$ correlations
(J. Escher)

Electron scattering observables for various deformed nuclei are calculated in the framework of the symplectic shell model, an algebraic theory, which treats the nucleus microscopically as a many-fermion system. Since the model takes the collective coherence between the major nuclear shells into full account, it correctly describes the static electromagnetic properties of nuclei without the need for effective charges. It also allows for an investigation of the influence of multi-shell correlations on nuclear charge and current densities. Such studies are important since they allow one to place quantitative limits on the contributions to the nuclear current from meson exchange. Furthermore, since electron scattering observables provide a direct probe of the nuclear current, this study is able to shed light on the dynamical character of nuclear rotational motion and thus it addresses one of the unsolved basic science problems of nuclear structure physics.

Effects of deformation on weak charge transfer transition strengths
(L. Zamick, TRIUMF/Rutgers; S.J.Q. Robinson, A. Mekjian, N. Auerbach, Rutgers)

In this work it is noted that many fundamental experiments are performed on complicated targets, e.g. ^{12}C which is highly deformed. We use sum rule techniques to show that the summed strength for the spin dipole contribution to neutrino capture is independent of deformation but the contributions to individual total angular momenta do depend on the deformation.

Nuclear structure and symmetries
(L. Zamick, TRIUMF/Rutgers)

We consider fermionic symmetries and establish the relationship between spectra of even-even and even-odd nuclei, especially those involving single and double analogue excitations. We have addressed the problem of higher shell admixtures, relativistic effects and self consistency in the nuclear shell model. We have looked at magnetic moments of excited states of nuclei in collaboration with the Rutgers and Bonn experimental groups.

Isospin and nuclear spectroscopy
(L. Zamick, TRIUMF/Rutgers)

We address the problem of what happens in nuclear spectroscopy when we set all isospin two-body matrix elements to zero. Despite the apparent severity of this approximation, we find fairly reasonable spectra with several degeneracies. We are able in part to explain these with some Regge symmetries for 6j symbols. This leads us to suggest that the energy difference of odd J states (not yet well studied experimentally) and the more familiar even J states will teach us about T=0 nucleon nucleon matrix element effects in a nucleus.

Active-sterile neutrino transformation and r-process nucleosynthesis
(G.C. McLaughlin)

The type II supernova is considered as a candidate site for the production of heavy elements. Since the supernova produces an intense neutrino flux, neutrino scattering processes will impact element formation. We examine active-sterile neutrino conversion in this environment and find that it may help to produce the requisite neutron-to-seed ratio for synthesis of the r-process elements.

Few-Body and Medium Energy Processes

The one-pion-exchange three-nucleon force and the A_y puzzle
(W. Schadow; L. Canton, Padova)

We consider a new three-nucleon force generated by the exchange of one pion in the presence of a $2N$ correlation. The underlying irreducible diagram has been recently suggested by the authors as a possible candidate to explain the puzzle of the vector analyzing powers A_y and iT_{11} for nucleon-deuteron scattering. Herein, we have calculated the elastic neutron-deuteron differential cross section, A_y, iT_{11}, T_{20}, T_{21}, and T_{22} below break-up threshold by accurately solving the Alt-Grassberger-Sandhas equations with realistic interactions. The results indicate that this new $3NF$ diagram provides the possible additional contribution, with the correct spin-isospin structure, for the explanation of the origin of this puzzle.

Photonuclear reactions of three-nucleon systems
(W. Schadow; O. Nohadani, W. Sandhas, Bonn)

We discuss the available data for the differential and the total cross section for the photodisintegration of ^{3}He and ^{3}H and the corresponding inverse reactions below $E_\gamma = 100$ MeV by comparing with our calculations using realistic NN interactions. The theoretical results agree within the error bars with the data for the total cross sections. Excellent agreement is achieved for the angular distribution in the case of ^{3}He, whereas for ^{3}H a discrepancy between theory and experiment is found.

Why is the three-nucleon force so odd?
(W. Schadow; L. Canton, Padova)

By considering a class of diagrams which has been overlooked in the most recent literature on three-body forces, we extract a new contribution to the three-nucleon interaction which specifically acts on the triplet odd states of the two nucleon subsystem. In the static approximation, this $3N$-force contribution is fixed by the underlying $2N$ interaction, so in principle there are no free parameters to adjust. The $2N$ amplitude, however, enters in the $3NF$ diagram in a form which cannot be directly accessed or constrained by NN phase-shift analysis. We conclude that this new $3N$-force contribution provides a mechanism which implies that the presence of the third nucleon modifies the p-wave (and possibly the f-wave) components of the $2N$ subsystem in the triplet-isotriplet channels.

Isoscalar off-shell effects in threshold pion production from pd collisions
(W. Schadow; L. Canton, Padova)

We test the presence of pion-nucleon isoscalar off-shell effects in the $pd \to \pi^+ t$ reaction around the threshold region. We find that these effects significantly modify the production cross section and that they may provide the missing strength needed to reproduce the data at threshold.

Comparison of triton bound state properties using different separable representations of realistic potentials
(W. Schadow; W. Sandhas, J. Haidenbauer, A. Nogga, Bonn)

The quality of two different, separable expansion methods (W-matrix and Ernst-Shakin-Thaler) is investigated. We compare the triton binding energies and components of the triton wave functions obtained in this way with the results of a direct two-dimensional treatment. The Paris, Bonn A and Bonn B potentials are employed as underlying two-body interactions, their total angular momenta being incorporated up to $j \leq 2$. It is found that the most accurate results based on the Ernst-Shakin-Thaler method agree within 1.5% or better with the two-dimensional calculations, whereas the results for the W-matrix representation are less accurate.

Three-body scattering below breakup threshold: an approach without using partial waves
(W. Schadow; Ch. Elster, Ohio; W. Glöckle, Bochum)

The Faddeev equation for three-body scattering below the three-body breakup threshold is directly solved without employing a partial wave decomposition. In the simplest form it is a three-dimensional integral equation in four variables. From its solution the scattering amplitude is obtained as a function of vector Jacobi momenta. Based on Malfliet-Tjon type potentials, differential and total cross sections are calculated. The numerical stability of the algorithm is demonstrated and the properties of the scattering amplitude discussed.

Few-body states in Fermi systems and condensation phenomena
(W. Schadow; P. Schuck, Grenoble; M. Beyer, G. Röpke, A. Schnell, Rostok)

Residual interactions in many particle systems lead to strong correlations. A multitude of spectacular phenomena in many particle systems are connected to correlation effects in such systems, e.g. pairing, superconductivity, superfluidity, Bose-Einstein condensation, etc. Here we focus on few-body bound states in a many-body surrounding.

Three-nucleon portrait with pion

(W. Schadow; L. Canton, G. Pisent, Padova; T. Melde, J.P. Svenne, Manitoba)

We report on recent results obtained by the above collaboration on the collision processes involving three nucleons, where we pay particular attention to the dynamical role of the pion. After discussing the case at intermediate energies, where real pions can be produced and detected, we have considered the case at lower energies where the pions being exchanged are virtual. The study has revealed the presence of some new pion-exchange mechanisms, which leads to a new three-nucleon force of tensor structure. Recently, the effect of this tensor three-nucleon force on the spin observables for neutron-deuteron scattering at low energy has been analyzed, and will be briefly reviewed.

Spin observables for pion production from *pd* collisions

(W. Schadow; L. Canton, G. Pisent, Padova; J.P. Svenne, Manitoba)

We have calculated the proton analyzing power A_{y0} of the pion-production reaction from pd collisions for one energy close to threshold and for another in the region of the Δ-resonance. A fair reproduction of the experimental data could be obtained in both cases with a model which includes isoscalar and isovector πN rescatterings in s-waves, as well as the p-wave rescattering mechanisms mediated by the πNN and $\pi N\Delta$ vertices. For the analyzing power at threshold we found that the initial-state interaction (ISI) is also quite important.

Dressing the nucleon in a dispersion approach

(S. Kondratyuk; O. Scholten, Groningen)

We present a model for dressing the nucleon propagator and vertices. In the model the use of a K-matrix approach (unitarity) and dispersion relations (analyticity) are combined. The principal application of the model lies in pion-nucleon scattering where we find that effects of the dressing on the phase shifts can be significant. In addition to the nucleon and pion, we include other low-lying meson and baryon degrees of freedom, in particular the ρ and σ mesons and the Δ resonance. A good quantitative description of phase shifts can be achieved at the energies exceeding the scale due to the degrees of freedom explicit in the model.

Taking advantage of the known ambiguity in the choice of the interacting fields, we transform away the nucleon self-energy, which allows us to interpret effects of the dressing in terms of the πNN form factors. At large momenta squared of the off-shell nucleon, the dressed form factors decrease faster than the bare form factors. We find a large contribution of multiple meson loops.

Compton scattering in a unitary approach with causality constraints

(S. Kondratyuk; O. Scholten, Groningen)

Pion-loop corrections for Compton scattering are calculated in an approach based on the use of dispersion relations in a formalism obeying unitarity. The basic framework is developed, including an application to Compton scattering. In the approach, the effects of the non-pole contribution arising from pion dressing are expressed in terms of (half-off-shell) form factors and the nucleon self-energy. These quantities are constructed through the application of dispersion integrals to the pole contribution of loop diagrams, the same as those included in the calculation of the amplitudes through a K-matrix formalism. The resulting relativistic-covariant model combines constraints from unitarity, causality, and crossing symmetry. The prescription of minimal substitution is used to build a contact $\gamma\pi NN$ term and thereby to restore gauge invariance. We investigate the influence of the transverse part of the contact term on the γNN form factors.

We have found that the dependence of the form factors on the momentum squared of the off-shell nucleon deviates from a monopole- (or dipole-) like shape often adopted in phenomenological applications. In particular, a characteristic feature of our results is a cusp structure of the form factors in the vicinity of the pion production threshold, showing most clearly in the magnetic form factors corresponding to negative-energy states of the off-shell nucleon.

We discuss effects of the dressing on the f_{EE}^{1-} partial amplitude for Compton scattering on the proton, emphasizing the importance of the analyticity and unitarity constraints for understanding of the specific behaviour of the amplitude at the pion threshold.

Compton scattering on the nucleon at intermediate energies and polarizabilities in a microscopic model

(S. Kondratyuk; O. Scholten, Groningen)

A microscopic model is presented in which both polarizabilities of the nucleon as well as Compton scattering up to energies in the second resonance region can be calculated. To achieve a description over such a wide range of energies the model should obey the symmetries that are important in the different energy regimes. At the lowest energies, gauge invariance, CPT invariance and crossing symmetry are important for the model to obey low-energy theorems. At energies near the pion production threshold, unitarity and analyticity put strong constraints on the amplitude. Since a wide energy span needs to be described, it is most efficient to use a relativistic covariant model.

We have developed the approach called the "dressed K-matrix model". Since this model is based on a K-matrix formulation, unitarity (in the coupled channel space) and crossing symmetry are easily implemented. The kernel is formulated with dressed vertices and propagators such that certain analyticity constraints are incorporated. At the level of one-particle reducible diagrams, analyticity constraints are obeyed with small violations due to ignoring singularities of the regularization form factor, which are chosen far away from the regime of interest. On the other hand, analyticity is satisfied only approximately for one-particle irreducible diagrams. Gauge invariance is exact through the introduction of contact terms obtained by minimal substitution.

The parameters in the model Lagrangian are fixed from pion-nucleon scattering, pion photoproduction and Compton scattering. The requirement of convergence of the dressing procedure limits the allowed range of the parameters. We compare the results of the full calculation, utilizing the dressed vertices and propagators, with that in which these quantities are bare (the latter case corresponds to the conventional K-matrix approach). In general, the full calculation gives a considerable improvement in the description of the data. We also find that the dressing is important for reproducing both scalar and vector polarizabilities of the proton and neutron.

Approximations to the Bethe-Salpeter equation for pion-nucleon scattering
(A.D. Lahiff; I.R. Afnan, Flinders)

Over the past decade a number of meson-exchange models of pion-nucleon scattering have been developed. These models have all relied upon the K-matrix approximation, or approximated the 4-dimensional Bethe-Salpeter equation with a 3-dimensional quasipotential equation. Recently we have constructed a realistic model of pion-nucleon scattering based on the Bethe-Salpeter equation. In this work we compare the K-matrix approximation and several quasipotential equations to the Bethe-Salpeter equation. In particular, we consider the 3-dimensional Klein equation, which differs from other quasipotential equations in that the relative energy is integrated out, rather than being fixed by a δ-function.

A covariant model of pion photoproduction including final-state interactions
(A.D. Lahiff, S. Kondratyuk; V. Pascalutsa, Flinders)

We are constructing a microscopic model for pion photoproduction off the proton which should be applicable at photon energies up to around 1 GeV. The model is based on the 4-dimensional Bethe-Salpeter equation and fully takes into account final-state interactions. The approach should obey constraints from both unitarity and gauge invariance. We are studying the question of whether the various methods of imposing gauge invariance are applicable in the 4-dimensional unitary framework.

Quark-meson coupling model for a nucleon by using a density-dependent bag constant
(B.K. Jennings; S.W. Hong, Sungkyunkwan Univ.)

We considered the quark-meson coupling model for a nucleon. The model describes a nucleon as an MIT bag, in which quarks are coupled to the scalar and the vector mesons. A set of coupled equations for the quark and the meson fields are obtained and are solved in a self-consistent manner. We show that the mass of a dressed MIT bag interacting with σ- and ω-meson fields differs considerably from the mass of the free MIT bag. The effects of the density-dependent bag constant are investigated. We showed that including the density-dependent bag constant induces attraction and lowers the bag mass. The results of our calculations imply that the self-energy of the bag in the quark-meson coupling model is significant and needs to be considered in doing the calculations for nuclear matter or finite nuclei.

Radiative muon capture on ^{3}He
(E. Ho, H.W. Fearing)

A recent TRIUMF experiment has measured radiative muon capture in ^{3}He. The aim has been to measure the induced pseudoscalar form factor $g_P(q^2)$ over the range of four momentum transfer q^2 of the process and to test the Goldberger-Treiman relation which relates this form factor to the axial form factor g_A by the relation

$$g_P(q^2) = \frac{2m_N m_\mu g_A(0)}{m_\pi^2 - q^2}$$

where m_N, m_μ and m_π are respectively the masses of the nucleon, muon and pion.

We have used two approaches to analyze this process. One is the so-called "elementary particle method" which treats the helion, triton, muon, photon and neutrino as "elementary particles". This approach is easy but requires the *nuclear* form factors, which must be obtained from phenomenological form factors of both the helion and triton measured in other experiments or inferred using the conserved vector current hypothesis. The second method is the "impulse approximation" method. In this method the helion and triton are regarded as composed of 3 nucleons, and then a wave function for the three nucleons is derived for the nucleus. One then uses the wave function to calculate various observables. The input here comes from the *nucleon* form factors (at low momentum transfer) which have been known quite accurately for a long time, but the approach is much more technically involved. The main new feature of our use of the impulse approximation is the evaluation of the wave functions and matrix elements in momentum space, in contrast to coordinate space which has normally been used.

Calculations for both ordinary and radiative muon capture have been performed, and a number of small improvements over existing calculations have been made. In general the results agree, to within a few per cent with previous calculations, given the same input. A variety of trinucleon wave functions (provided by W. Schadow) have been used. Both the IA RMC and OMC rates exhibit a slight model dependence (about 5%), arising from different binding energies and possibly different compositions of angular momentum eigenstates of the wave functions.

Effective Field Theories and Chiral Perturbation Theory

Contributions of the $\boldsymbol{\Delta}$ resonance and the $\boldsymbol{\sigma}$ meson to low-energy constants of the fourth-order Lagrangian of HBChPT

(S. Kondratyuk, H.W. Fearing)

The resonance saturation hypothesis has been the principal method used to estimate values of the low-energy constants of the Lagrangian of heavy baryon chiral perturbation theory (HBChPT). Unfortunately, this approach yields rather large error bars for some of the fourth-order constants, which is mainly related to uncertainties in treating the Δ resonance contribution. In this study, a relativistic microscopic model is employed in order to extract values of fourth-order low-energy constants which are important for the description of low-energy Compton scattering. The model is based on the K-matrix formalism and obeys unitarity, crossing symmetry and gauge invariance. Also, certain analyticity constraints are incorporated through the use of dressed vertices and propagators in the K-matrix. The model yields a good quantitative description of pion photoproduction and Compton scattering at both intermediate and low energies.

The low-energy constants are estimated by comparing the predictions of the HBChPT for the nucleon polarizabilities with the values obtained from the model. The main source of errors in this procedure stems from the sensitivity of observables for photoproduction and Compton scattering to the coupling parameters in the $\Delta N\gamma$ and $\sigma\gamma\gamma$ vertices. We investigate effects of the Δ and σ couplings on the low-energy constants. While the values of the extracted low-energy constants are consistent with those obtained from the resonance saturation hypothesis, the present method yields smaller errors. This is due to the tight constraints imposed on the parameters of the model by the requirement of simultaneous description of pion photoproduction and Compton scattering in the extended energy range.

Proton-proton fusion in effective field theory

(X. Kong; F. Ravndal, Oslo)

The rate for the fusion process $p + p \rightarrow d + e^{+} + \nu_e$ is calculated using non-relativistic effective field theory. Including the four-nucleon derivative interaction, results are obtained in next-to-leading order in the momentum expansion. This reproduces the effects of the effective range parameter. Coulomb interactions between the incoming protons are included non-perturbatively in a systematic way. The resulting fusion rate is independent of specific models and wave functions for the interacting nucleons. At this order in the effective Lagrangian there is an unknown counter term which limits the numerical accuracy of the calculated rate given by the squared reduced matrix element $\Lambda^2(0) = 7.37$. Assuming the counter term to have a natural magnitude, we estimate the accuracy of this result to be 6-8%. This is consistent with previous nuclear physics calculations based on effective range theory and inclusion of axial two-body weak currents. The true magnitude of the counter term can be determined from a precise measurement of the cross section for low-energy neutrino scattering on deuterons.

Neutrino deuteron scattering in effective field theory at next-to-next-to-leading order

(X. Kong; M. Butler, St. Mary's; J.-W. Chen, Maryland)

We study the four channels associated with neutrino-deuteron breakup reactions at next-to-next-to-leading order in effective field theory. We find that the total cross section is indeed converging for neutrino energies up to 20 MeV, and thus our calculations can provide constraints on theoretical uncertainties for the Sudbury Neutrino Observatory. We stress the importance of a direct experimental measurement to high precision in at least one channel, in order to fix an axial two-body counter term.

Proton-deuteron scattering in effective field theory

(X. Kong, G. Rupak)

Compared to the neutron-deuteron scattering calculation, the only difference in proton-deuteron scattering is the Coulomb effect. A formalism to treat the Coulomb effect in KSW counting has been introduced by Kong and Ravndal, and applied to proton-proton scattering and proton-proton fusion. Currently we are applying the formalism to include Coulomb effects in quartet S-wave proton-deuteron scattering.

Nucleon polarizabilities from Compton scattering on the deuteron
(G. Rupak; H.W. Griesshammer, TU München)

An analytic calculation of the differential cross section for elastic Compton scattering on the deuteron at photon energies ω in the range of 25–50 MeV is presented to next-to-next-to-leading order, i.e. to an accuracy of $\sim$3%. The calculation is model independent and performed in the low energy nuclear effective field theory without dynamical pions. The isoscalar, scalar electric and magnetic nucleon polarizabilities α_0 and β_0 enter as free parameters with a theoretical uncertainty of about 20%. Using data at $\omega_{\rm Lab} =$ 49 MeV we find $\alpha_0 = 8.4 \pm 3.0(\rm exp) \pm 1.7(\rm theor)$, $\beta_0 = 8.9 \pm 3.9(\rm exp) \pm 1.8(\rm theor)$, each in units of 10^{-4} fm^3. With the experimental constraint for the isoscalar Baldin sum rule, $\alpha_0 = 7.2 \pm 2.1(\rm exp) \pm 1.6(\rm theor)$, $\beta_0 = 6.9 \mp 2.1(\rm exp) \mp 1.6(\rm theor)$. A more accurate result can be achieved by: (i) better experimental data, and (ii) a higher order theoretical calculation including contributions from a couple of so far undetermined four-nucleon-two-photon operators.

Threshold $pp \to pp\pi^0$ up to one-loop accuracy
(T.-S. Park; S.-I. Ando, South Carolina; D.-P. Min, SNU)

The $pp \to pp\pi^0$ cross section near threshold is computed up to one-loop order including the initial and final state interactions using the hybrid heavy baryon chiral perturbation theory. With the counter terms whose coefficients are fixed by the resonance-saturation assumption, we find that the one-loop contributions are quite important and bring our theoretical value of the cross section closer to the experimental data. The short-range contributions are treated by means of a cutoff, and only a mild cutoff dependence is observed when all diagrams of the given chiral order are summed. To the order treated, however, heavy baryon chiral perturbation theory converges rather slowly, calling for further studies of the process including going to higher orders.

Effective field theory for nuclei: confronting fundamental questions in astrophysics
(T.-S. Park; K. Kubodera, USC; D.-P. Min, SNU; M. Rho, Saclay)

Fundamental issues involving nuclei in the celebrated solar neutrino problem are discussed in terms of an effective field theory adapted to nuclear few-body systems, with a focus on the proton fusion process and the hep process. Our strategy in addressing these questions is to combine chiral perturbation theory – an effective field theory of QCD – with an accurate nuclear physics approach to arrive at a superior effective field theory that reveals and exploits a subtle role of the chiral-symmetry scale in short-distance effects encoded in short-range nuclear correlations. Our key argument is drawn from the close analogy of the principal weak matrix element figuring in the hep process to the suppressed matrix elements in polarized neutron-proton capture at threshold currently being measured in the laboratories.

Asymmetry in $\vec{n} + p \to d + \gamma$
(T.-S. Park; C.H. Hyun, D.-P. Min, SNU)

Heavy baryon chiral perturbation theory (HBChPT) is applied to the asymmetry A_γ in $\vec{n} + p \to d + \gamma$ at threshold, which arises due to the weak parity non-conserving interactions. Instead of appealing to Siegert's theorem, transition operators up to next-to-leading chiral order are derived and the corresponding amplitudes are evaluated with the Argonne v_{18} wave functions. In addition to the impulse contribution, both parity-conserving and parity-non-conserving two-body one-pion-exchange diagrams appear up to this order. Our prediction for the asymmetry is $A_\gamma = -0.10 h^{(1)}_{\pi NN}$, which is close to the Siegert's theorem based result, $A_\gamma \simeq -0.11 h^{(1)}_{\pi NN}$. This illustrates that HBChPT is effective in parity-non-conserving physics.

In-medium effective pion mass from heavy-baryon chiral perturbation theory
(T.-S. Park; H. Jung, Sookmyung Women's Univ.; D.-P. Min, SNU)

Using heavy-baryon chiral perturbation theory, we have calculated all the diagrams up to two-loop order which contribute to the S-wave pion self-energy in symmetric nuclear matter. Some subtleties related to the definition of pion fields are discussed. The in-medium pion mass turns out to be increased by only 6$\sim$7 per cent in normal nuclear matter density, without any off-shell ambiguity.

The KN sigma term
(T.-S. Park, A. Olin; F. Myhrer, USC)

The experimental data for the differential cross section of K^+p elastic scattering has been re-analyzed and compared to the NLO HBChPT calculation, which gives us the opportunity to extract the KN sigma term directly from the data.

Further analysis of the chiral perturbation theory meson Lagrangian to order p^6
(H.W. Fearing; T. Ebertshäuser, S. Scherer, Mainz)

Some time ago Fearing and Scherer wrote down systematically the most general Lagrangian density for mesonic ChPT of chiral order $\mathcal{O}(p^6)$, both for the normal (non-epsilon) and anomalous (epsilon) sector.

By setting up a somewhat different (and extended) approach, which is based on the use of different basic building blocks, and implementing the so-called Bianchi identities for field strength tensors, and additional trace relations, we derived a modified list containing slightly fewer independent $SU(n)$ terms than originally obtained. We also obtained explicitly its reduction to $SU(2)$ and $SU(3)$.

By rewriting (expanding) the compact structures in terms of conventional Goldstone boson and external fields, we were able to assign (at least half of) the anomalous $SU(3)$ low-energy constants to measurable physical processes and provide the respective Lagrangian densities.

Radiative pion capture by a nucleon
(H.W. Fearing; T.R. Hemmert, Jülich; R. Lewis, Regina; C. Unkmeir, Mainz)

We have calculated in heavy baryon chiral perturbation theory (HBChPT) the differential cross sections for $\pi^- p \to \gamma n$ and $\pi^+ n \to \gamma p$ up to $\mathcal{O}(p^3)$. The results at $\mathcal{O}(p)$ and $\mathcal{O}(p^2)$ have no free parameters. There are three unknown parameters at $\mathcal{O}(p^3)$, low energy constants of the HBChPT Lagrangian, which are determined by fitting to experimental data. Two acceptable fits are obtained, which can be separated by comparing with earlier dispersion relation calculations of the inverse process. Expressions for the multipoles, with emphasis on the p-wave multipoles, are obtained and evaluated at threshold. Generally the results obtained from the best of the two fits are in good agreement with the dispersion relation predictions.

Pion doubly radiative processes in heavy baryon chiral perturbation theory
(H.W. Fearing; C. Unkmeir, S. Scherer, Mainz)

We are calculating the processes $\pi + p \to n + \gamma + \gamma$ and $\gamma + p \to n + \pi + \gamma$ in heavy baryon chiral perturbation theory. Both processes contain as subdiagrams the reaction $\gamma + \pi \to \gamma + \pi$, i.e. pion Compton scattering. Thus in principle they may give some of the same information, such as pion polarizabilities, as would be obtained by a direct measurement, which is not really possible to do. The calculations are of interest also as the capture reaction has been measured at TRIUMF and the scattering reaction is under investigation at Mainz. We are calculating to $\mathcal{O}(p^3)$, that is to one loop order, in a way which allows us to check gauge invariance explicitly. The amplitude to $\mathcal{O}(p^2)$ has been obtained, most of the subsidiary processes necessary to evaluate the low energy constants have been completed, and efforts are now directed to completing the $\mathcal{O}(p^3)$ pieces.

Infrared regularization in ChPT
(C. Bird, H.W. Fearing)

When chiral perturbation theory is used to study reactions involving massive particles, the standard power counting is not valid. As a result other methods were developed, such as heavy baryon chiral perturbation theory (HBChPT). However HBChPT involves an additional series expansion of each term in the original Lagrangian and the complexity of the calculations has limited most prior work in this field to $\mathcal{O}(p^3)$.

We have been studying an alternative method, infrared regularization (IR), in which the original relativistic chiral Lagrangian is used and the loop integrals are divided into high energy and low energy components. The high energy loop integrals are absorbed into the low energy constants, while the low energy loop integrals are calculated explicitly. Using this new regularization, power counting can be recovered while maintaining the simplicity of the relativistic Lagrangian. In order to study IR and compare the results with HBChPT, we are also using IR to calculate several simple reactions at $\mathcal{O}(p^4)$ including pion photoproduction and radiative pion capture.

Hadronic Structure and QCD

Masses of heavy baryons
(N. Mathur, R.M. Woloshyn; R. Lewis, Regina)

The spectrum of baryons containing one or two heavy (b or c) quarks is calculated using improved lattice QCD in the quenched approximation. The calculations are being done in two different ways. In one approach, a relativistic action of the D234 type is used for light (up, down, strange) and charm quarks. A second calculation uses lattice NRQCD for charm and bottom quarks. One of the goals is to compare relativistic and non-relativistic treatments in the charm sector where the spectrum of charmonium, for example, has been found to be quite sensitive to higher order terms in the lattice NRQCD expansion.

***S*- and *P*-wave heavy-light mesons**
(R.M. Woloshyn; R. Lewis, Regina)

The mass spectrum of S- and P-wave mesons containing a single heavy quark was computed in the quenched approximation, using NRQCD up to third order in the inverse heavy quark mass expansion. Previous results found third order contributions which were as large in magnitude as the total second order contribution for the charmed S-wave spin splitting. We have considered variations such as anisotropic lattices, Landau link tadpole improvement, and a highly-improved light quark action, and find that the second order correction to the charmed S-wave spin splitting is about 20% of the leading order contribution, while the third order correction is about 20%(10%) for $D^*-D(D_s^*-D_s)$. Nonleading corrections are very small for the bottom meson spectrum, and are statistically insignificant for the P-wave charmed masses.

Strange magnetic moment of the nucleon
(N. Mathur; S.-J. Dong, K.-F. Liu, Kentucky)

Recently there has been considerable interest in the strange magnetic moment of the nucleon ($G_M^s(0)$) as it can provide important information about the internal quark structure of the nucleon. There are numerous theoretical predictions over a wide range, –0.75 to +0.30 μ_N. Most of them are negative and are in the range -0.45 to -0.25. On the other hand, recent experiments of the SAMPLE collaboration on parity violating electron scattering suggest that the strange magnetic moment of the nucleon could be positive. Two of their recent results are $G_M^s(Q^2 = 0.1\,\mathrm{GeV}^2) = +0.23 \pm 0.37 \pm 0.15 \pm 0.19\,\mu_N$ and $+0.61 \pm 0.17 \pm 0.21 \pm 0.19\,\mu_N$. However, combined with data from the deuteron, the new result is closer to zero with a relatively larger error. To get the lattice QCD input on this yet unsettled problem of strange magnetic moment content of the nucleon, we extend our previous lattice calculation. We calculate the strange magnetic moment of the nucleon on a quenched $16^3 \times 24$ lattice at $\beta = 6.0$, and with Wilson fermions at $\kappa = 0.148$, 0.152 and 0.154. The strange quark contribution from the disconnected insertion is estimated stochastically by employing the Z_2 noise method. Using an unbiased subtraction along with the help of charge conjugation and hermiticity, we reduce the error by a factor of 2 with negligible overhead. Our result is $G_M^s = -0.28 \pm 0.10\ \mu_N$.

Perfect lattice action for $SO(N)$ spin model
(N. Mathur)

Non-linear sigma models are particularly interesting as they can provide important information about asymptotically free theories, like QCD. A perfect lattice action for $O(3)$ non-linear sigma model was studied sometime earlier by Hasenfratz and Niedermayer. Following their track, we investigate a perfect lattice action for the $SO(N)$ non-linear sigma model (with $N = 3$) which is asymptotically free in $1 + 1$ dimensions. We observe that along with two-point couplings, four-point couplings of the $SO(N)$ matrix spin model are equal to those of the $O(N)$ vector spin model. With a few couplings, rotational invariance is seen to be fully restored even on a small lattice. By calculating the Lüscher step scaling function, we also investigate the degree of perfection for the fixed-point action of this model.

Status report on lattice QCD and QCD sum rule determinations of the light quark masses
(K. Maltman, TRIUMF/York; R. Gupta, LANL)

At present, the light quark masses are among the least well known of the fundamental parameters of the standard model. Very recent work, from both the QCD sum rule and lattice QCD perspective, has produced significant improvement in this situation. We have performed a number of new sum rule calculations to elucidate the role of direct instanton effects, previously neglected in pseudoscalar sum rule treatments, and updated previous sum rule analyses to correspond to the latest data sets in the case of analyses based on flavour breaking in hadronic tau decay. These are combined with existing work to form an extensive review of the current situation. We find that, not only are all QCD sum rule analyses consistent within errors, and all lattice QCD analyses consistent within errors, but the two approaches are now also highly consistent. The result is a determination of m_u, m_d, and m_s with errors more than a factor of 2 smaller than those of PDG2000. We also show how the errors can be further reduced in the near future.

Vacuum condensates and finite energy sum rules
(K. Maltman, TRIUMF/York; G. Golowich, Massachussetts)

Using soft pion techniques, valid in the chiral limit, it was recently shown that the chiral limit value of the matrix element of the electroweak penguin operator, which plays an important role in determining the standard model contribution to ϵ'/ϵ, is related to dimension 6 vacuum condensates which appear in the OPE representation of the light quark isovector V-A correlator difference. The extraction of these condensate values from experimental data can, in principle, allow a significant improvement in the situation of the understanding of the value of this matrix element. Finite energy sum rule (FESR) techniques are being employed to make this extraction, the freedom in the choice of weight function being crucial to making a reliable extraction in which possible contributions from yet higher dimension operators are brought under control.

Extraction of r_s
(K. Maltman, TRIUMF/York; J. Kambor, Zurich)

The ratio, r_s, of the s and u (or d) quark condensates is a dynamical quantity in QCD which cannot be predicted beyond leading order in chiral perturbation theory (ChPT) since it involves the chiral low energy constant, H_2, which depends on the conventions employed to regularize the quark condensate in the underlying theory (QCD), and hence cannot be determined experimentally. Once one determines this ratio, however, the isospin-breaking deviation of the ratio of u and d condensates from 1, which enters sum rule treatments of various isospin-breaking observables, is uniquely determined by ChPT. In some models, such as the extended NJL model, used extensively to estimate matrix elements of the operators of the effective strangeness-changing weak Hamiltonian, r_s is, in fact, significantly greater than 1. Thus, there are a number of phenomenologically important reasons for wishing to have a good determination of r_s. We have studied sum rules involving the difference of the transverse part of the flavour ud and us vector-plus-axial-vector correlator sum, with an aim to constructing FESRs which allow a theoretically optimal extraction of the product of the strange quark mass and strange condensate. Although the rather large ($\sim$20–30%) errors on the strange spectral distribution measured in hadronic tau decay above $\sim$1 GeV limit the accuracy of this extraction at present, the increase of nearly two orders of magnitude in the usable tau sample which should become available over the lifetime of an experiment like BaBar will make this a very useful method for determining r_s in the future.

Finite energy sum rule extraction of the decay constants of pseudoscalar mesons
(K. Maltman, TRIUMF/York; J. Kambor, Zurich)

The relative strengths of the couplings of hadronic states to different probes (currents or densities) can provide very useful information on spectroscopic classification. We are in the process of studying the FESR extraction of the decay constants describing the coupling of the excited strange and non-strange pseudoscalar mesons (the $\pi(1300)$, $\pi(1800)$, $K(1460)$, and $K(1830)$) to the vacuum through the relevant pseudoscalar densities. This will play a role in improving the reliability of the determination of the light quark masses from hadronic τ decay data (this is a rather technical point, and cannot be easily elaborated on in this short space), and also help to shed light on the excited η sector, whose couplings to the 8th member of the pseudoscalar density will be similarly computed, using also ChPT input, in the future.

The Standard Model and Beyond

Constraints on *T*-odd, *P*-even interactions from electric dipole moments
(G.C. McLaughlin; A. Kurylov, M.J. Ramsey-Musolf, Connecticut)

We construct the relationship between non-renormalizable, effective, time-reversal violating (TV) parity-conserving (PC) interactions of quarks and gauge bosons and various low-energy TVPC and TV parity-violating (PV) observables. Using effective field theory methods, we delineate the scenarios under which experimental limits on permanent electric dipole moments (EDMs) of the electron, neutron, and neutral atoms, as well as limits on TVPC observables, provide the most stringent bounds on new TVPC interactions. Under scenarios in which parity invariance is restored at short distances, the one-loop EDM of elementary fermions generate the most severe constraints. The limits derived from the atomic EDM of ^{199}Hg are considerably weaker. When parity symmetry remains broken at short distances, direct TVPC search limits provide the least ambiguous bounds. The direct limits follow from TVPC interactions between two quarks.

Neutrinos in extra dimensions and the anomalous magnetic moments of leptons
(G.C. McLaughlin, J.N. Ng)

The use of extra dimensional scenarios as models for neutrino mass affects many low energy observables. We consider the implications of virtual bulk neutrinos in precision experiments of the anomalous magnetic moments of the muon and the electron. We consider neutrino models in factorizable geometry of the type $M_4\times$ T as well as the sliced AdS_5 non-factorizable geometry. In both geometries we find finite contributions to g-2 after summing over the KK excitations of the bulk neutrinos. In the case of Randall-Sundrum geometry, we find that the muon experiment is approaching the precision necessary to probe these models.

The use of nuclear beta decay as a test of bulk neutrinos in extra dimensions
(G.C. McLaughlin, J.N. Ng)

Theories which include neutrinos in large extra dimensions can be constrained by nuclear beta decay experiments. We examine universality of beta decay strengths of Fermi transitions. From this we find that the extra dimensional Yukawa coupling for a higher dimensional scale of 10 TeV and two extra dimensions can be constrained to y $<$ 1. Kinematic implications are also discussed. In particular, an extra dimensional scenario will produce a tritium decay endpoint spectrum with a different shape than that for just one massive state.

Higgs physics and extra dimensions
(J.N. Ng; V. Chang, Normal Univ., Taiwan)

We embed the standard model in the Randall-Sundrum model of 5 dimensional brane localized gravity. The SM gauge and chiral fermion fields are restricted on the 4D visible brane, whereas the Higgs and the right-handed neutrino are assumed to be 5D bulk fields. We calculate the effective couplings of the lowest mass Higgs field to the SM fermions and to the gauge bosons and find that the couplings are enhanced. Furthermore, the invisible decay width of a bulk Higgs of mass 150 GeV is shown to be large.

CP violation and B physics

(J.N. Ng; Y. Zhou, Y.L. Wu, C.Q. Geng, ITP Beijing)

We present a general analysis on charmless B-meson decays $B \to \pi\pi$ and πK. It is noticed that the final state interactions and inelastic rescattering effects must be significant in order to understand the consistency of the current data. As a consequence, the isospin amplitude $a^c_{3/2}$ and the strong phase δ are found to be unexpectedly large: $a^c_{3/2} \simeq -(40 \sim 100)$, $\delta \simeq \pm(93^\circ \pm 6^\circ)$. With such a large value, it is shown that the weak phase γ is allowed to be smaller so as to be consistent with the other constraint from the standard model. While in the standard model it seems difficult to enhance $a^c_{3/2}$ by an order of magnitude. If the usual assumption on relations for strong phases is reliable, our analysis indicates that either the current measured central values of the branching ratios of decay modes $B \to \pi^0 K$ are larger than the actual values, or new physics may be necessary to provide large contributions which effectively enhance the electroweak penguins. Using current data, the branching ratio for $B \to \pi^0\pi^0$ is found to be larger by an order of magnitude compared to the one calculated based on the factorization approach. We also present the direct CP violating asymmetries in all the decay modes and find them to be close to the sensitivity of the present experiments.

Miscellaneous

Strangelets in the cosmic ray flux

(S.K. Ghosh; S. Banerjee, S. Raha, D. Syam, Calcutta)

We have shown that our proposed mechanism for strangelet propagation through the earth's atmosphere, together with a proper account of charge capture and ionization loss, would solve the problem of the requirement of unusually high penetrability of strangelets through the terrestrial atmosphere. Furthermore, this could lead to viable strategies for definitive detection of strange quark matter in the cosmic ray flux using a ground based, large area array of passive detectors.

Cosmological quark-hadron transition and massive compact halo objects

(S.K. Ghosh; A. Bhattacharyya, S. Banerjee, S. Raha, B. Sinha, Calcutta)

One of the abiding mysteries in the so-called standard cosmological model is the nature of the dark matter. It is universally accepted that there is an abundance of matter in the universe which is non-luminous due to its very weak interaction, if at all, with the other forms of matter, excepting of course the gravitational attraction. Speculations as to the nature of dark matter are numerous, often bordering on the exotic, and searches for such exotic matter is a very active field of astroparticle physics. Nevertheless, in recent years, there has been experimental evidence for at least one form of dark matter – the massive compact halo objects detected through gravitational microlensing effects proposed by Paczynski some years ago. To date, there is no clear consensus as to what these objects are. They are referred to in the literature by the acronym MACHO. In our work, we show that these objects may find a natural explanation as leftover relics from the putative first order cosmic quark-hadron phase transition that is predicted by the standard model of particle interactions to have occurred during the microsecond epoch of the early universe.

Bosonic symmetries and pionic fluctuations and correlations

(A.Z. Mekjian, TRIUMF/Rutgers)

Pionic yields, fluctuations and correlations are studied in a general framework based on a cycle class picture associated with bosonic symmetries. Various models such as the disoriented chiral condensate, the negative binomial distribution, partially coherent state emission and field emission from Lorentzian line shapes are discussed. Generalizations based on these important specific cases are developed. Connections of the cycle class picture developed from a path integral approach with other approaches based on combinants, cumulants, hierarchical models and clan variables are presented for the specific and general cases.