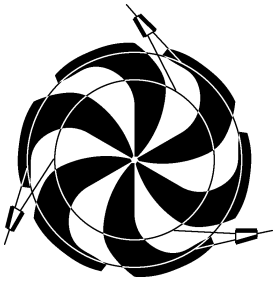
# TRIUMF



# ANNUAL REPORT
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# 1999

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**CANADA'S NATIONAL LABORATORY**
**FOR PARTICLE AND NUCLEAR PHYSICS**

OPERATED AS A JOINT VENTURE

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

JULY 2000

*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. It provides a group of active 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: H.W. Fearing (group leader), B.K. Jennings, J.N. Ng, and R.M. Woloshyn, plus E.W. Vogt (professor emeritus, UBC). This year our research associates are: J. Escher (since October), S.K. Ghosh (since September), H.-W. Hammer (until November), B.D. Jones (until June), S. Karataglidis (until September), X. Kong (since September), G.C. McLaughlin (all year), T.-S. Park (all year), W. Schadow (since September), T. Schäfer (since June), and P.R. Wrean (until September, shared with the DRAGON group). Graduate students with the group include: M. Nobes (SFU), supervised by R.M. Woloshyn; and C. Bird (U. Victoria), E. Ho (UBC) and C. Unkmeir (visiting from Mainz) supervised by H.W. Fearing.

The visitors to the Theory group this year include:

| | | |
|---|---|---|
| R. Allahverdi | J. Hormuzdiar | D.-P. Min |
| B. Allen | N. Ito | A. Rinat |
| N. Auerbach | C. Itoi | S. Scherer |
| M. Bilenky | O. Kong | I. Suh |
| L. Canton | K. Langanke | E. Swanson |
| R. Fiebig | P. Lee | T. Tait |
| J. Gegelia | S. Levit | J. Tandean |
| J. Goity | R. Lewis | I. Towner |
| S. Gurvitz | K. Maltman | G. Valencia |
| W. Haxton | U. Meissner | D. Wilkinson |
| B. Holstein | A. Mekjian | L. Zamick |
| S.W. Hong | T. Melde | |

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 TRIUMF Summer Institute and computer support.

As usual the Theory group has been very active and below we briefly describe some of the specific research projects undertaken by the group during the year.

### Miscellaneous

**Strangelets in terrestrial atmosphere**
*(S.K. Ghosh; S. Banerjee, S. Raha, D. Syam, Calcutta)*

Strangelets are lumps of strange matter consisting of roughly equal numbers of u, d and s quarks. The existence of stable or metastable strangelets would have numerous implications for physics. Most importantly, they can account for the cosmological dark matter problem to a large extent. The unusual binding of the strangelets has been used to propose a dynamical model for the propagation of these strangelets through the earth's atmosphere. It is found that under suitable conditions such strangelets may indeed reach the depths near mountain altitudes with mass number and charges close to the observed values in cosmic ray experiments.

**The Chandrasekhar limit for quark stars**
*(S.K. Ghosh; S. Banerjee, S. Raha, Calcutta)*

The Chandrasekhar limit for quark stars is evaluated from simple energy balance relations, as proposed by Landau for white dwarfs or neutron stars. It has been found that the limit for quark stars depends on, in addition to the fundamental constants, the bag constant.

**The canonical partition function**
*(B.K Jennings; S. Das Gupta, McGill)*

The expansion coefficients, $x_k$, generated by expanding the thermodynamic potential in powers of the fugacity are the same as the cluster functions used in calculating the canonical partition function. Using the well known results for the expansion of the thermodynamic potential symmetrization (or antisymmetrization) effects can be included exactly in calculating with the canonical distribution. We find these effects to be of minor importance. Contributions from bound states and particle-particle interactions can be included in a systematic manner. In particular the effects from the volume excluded by a strong repulsive potential can be approximately included.

**Field transformations and simple models illustrating the impossibility of measuring off-shell effects**
*(H.W. Fearing; S. Scherer, Mainz)*

In the context of simple models illustrating field transformations in Lagrangian field theories, we discuss the impossibility of measuring off-shell effects in

nucleon-nucleon bremsstrahlung, Compton scattering, and related processes. To that end we introduce a simple phenomenological Lagrangian describing nucleon-nucleon bremsstrahlung and perform an appropriate change of variables leading to different off-shell behaviour in the nucleon-nucleon amplitude as well as the photon-nucleon vertex. As a result we obtain a class of equivalent Lagrangians, generating identical $S$-matrix elements, of which the original Lagrangian is but one representative. We make use of this property in order to show that what appears as an off-shell effect in an $S$-matrix element for one Lagrangian may originate in a contact term from an equivalent Lagrangian. By explicit calculation we demonstrate for the case of nucleon-nucleon bremsstrahlung as well as nucleon Compton scattering the equivalence of observables from which we conclude that off-shell effects cannot in any unambiguous way be extracted from an $S$-matrix element. Finally, we also discuss some implications of introducing off-shell effects on a phenomenological basis, resulting from the requirement that the description of one process be consistent with that of other processes described by the same Lagrangian.

## Few-Body and Medium Energy Processes

### Spectral content of isoscalar nucleon form factors

*(H.-W. Hammer; M.J. Ramsey-Musolf, Connecticut)*

The nucleon strange vector and isoscalar electromagnetic form factors are studied using a spectral decomposition. The $K\bar{K}$ contribution to the electric and magnetic radii as well as the magnetic moment is evaluated to all orders in the strong interaction using an analytic continuation of experimental $KN$ scattering amplitudes and bounds from unitarity. The relationship between non-resonant and resonant $K\bar{K}$ contributions to the form factors is demonstrated, and values for the vector and tensor $\phi N\bar{N}$ couplings are derived. The $K\bar{K}$ spectral functions are used to evaluate the credibility of model calculations for the strange quark vector current form factors.

### $K\bar{K}$-continuum and isoscalar nucleon form factors

*(H.-W. Hammer; M.J. Ramsey-Musolf, Connecticut)*

We analyze the isoscalar vector current form factors of the nucleon using dispersion relations. In addition to the usual vector meson poles, we account for the $K\bar{K}$-continuum contribution by drawing upon a recent analytic continuation of $KN$ scattering amplitudes. For the Pauli form factor all strength in the $\phi$ region is already given by the continuum contribution, whereas for the Dirac form factor additional strength in the $\phi$ region is required. The pertinent implications for the leading strangeness moments are demonstrated as well. We derive a reasonable range for the leading moments which is free of assumptions about the asymptotic behaviour of the form factors. We also determine the $\phi NN$ coupling constants from the form factor fits and directly from the $K\bar{K} \to N\bar{N}$ partial waves and compare the resulting values.

### Rare pionium decays and pion polarizability

*(H.-W. Hammer, J.N. Ng)*

We calculate the decay of pionium atoms into two photons. The pion polarizabilities give rise to a 10% correction to the corresponding decay width for point-like pions. This opens the possibility to obtain the difference between the electric and magnetic polarizability of the charged pion from a future measurement of the branching fraction of pionium into two photons. For such an experiment the $\pi\pi$-scattering lengths would have to be known to better than 5% precision. We also comment on the contribution of the axial anomaly to the decay of pionium into $\gamma\pi^0$.

### Isoscalar off-shell effects in threshold pion production from *pd* collision

*(W. Schadow; L. Canton, Padua)*

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.

### 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.

### Three-body properties in hot and dense nuclear matter

*(W. Schadow; M. Beyer, C. Kuhrts, G. Röpke, Rostock)*

We derive three-body equations valid at finite densities and temperatures. These are based on the cluster mean field approach consistently including proper self

energy corrections and Pauli blocking. As an application we investigate the binding energies of the triton and determine the Mott densities and momenta relevant for a many particle description of nuclear matter in a generalized Beth-Uhlenbeck approach. The method, however, is not restricted to nuclear physics problems but may also be relevant, e.g., to treat three-particle correlations in weakly doped semiconductors or strongly coupled dense plasmas.

**Three-body bound state calculations without angular momentum decomposition**
*(W. Schadow; Ch. Elster, Ohio; A. Nogga, W. Glöckle, Bochum)*

The Faddeev equations for the three-body bound state are solved directly as three dimensional integral equations without employing partial wave decomposition. The numerical stability of the algorithm is demonstrated. The three-body binding energy is calculated for Malfliet-Tjon type potentials and compared with results obtained from calculations based on partial wave decomposition. The full three-body wave function is calculated as a function of the vector Jacobi momenta. It is shown that it satisfies the Schrödinger equation with high accuracy. The properties of the full wave function are displayed and compared to the ones of the corresponding wave functions obtained as a finite sum of partial wave components. The agreement between the two approaches is essentially perfect in all respects.

**Radiative capture of protons by deuterons**
*(W. Schadow; W. Sandhas, Bonn)*

The differential cross section for radiative capture of protons by deuterons is calculated using different realistic $NN$ interactions. We compare our results with the available experimental data below $E_x = 20$ MeV. Excellent agreement is found when taking into account meson exchange currents, dipole and quadrupole contributions, and the full initial state interaction. There is only a small difference between the magnitudes of the cross sections for the different potentials considered. The angular distributions, however, are practically potential independent.

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

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.

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

There is a TRIUMF experiment on radiative muon capture in $^3$He currently going on with the aim of measuring the pseudoscalar form factor $g_P(q^2)$ over the range of four momentum transfer $q^2$ for the above mentioned process.

Since it is believed that this form factor is related to the axial form factor $g_A$ by the relation

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

where $m$ is the mass of the muon and $m_\pi$ is the mass of the pion (the partially conserved axial current hypothesis, PCAC), we have decided to perform a theoretical analysis of this process using modern wave functions and form factors. One way is to use the so-called "elementary particle method" which treats the helion, triton, muon, photon and neutrino as "elementary particles" and the amplitude of the process is then calculated. The advantage of this method is its ease of calculation, but the drawback is that both the $g_V$ and $g_A$ (i.e. the *nuclear* vector and axial vector form factors respectively) have to be obtained (via the conserved vector current hypothesis, CVC) from the phenomenological electromagnetic form factors of both helion and triton. In this context, $M$ of the above equation is the mass of the helion (or triton) and all form factors are *nuclear* form factors.

The second method is the "impulse approximation" method. This method is to regard both the helion and triton as composed of 3 nucleons, then a wave function for the three nucleons is derived for the nucleus. One then uses the wave function to calculate various observables. Since the *nucleon* electromagnetic form factors (at low momentum transfer) have been known quite accurately for a long time, this method does not rely on the phenomenological electromagnetic nuclear form factors but it is more technically involved. In this context, $M$ is the mass of the proton (or neutron) and all form factors are *nucleon* form factors.

Our aim is to determine the sensitivity of $g_P$ for the above process in a precise manner.

## Nuclear Structure and Reactions, Nuclear Astrophysics

**Effects of in-medium meson masses on nuclear matter properties**
*(S.K. Ghosh; A. Bhattacharyya, S.C. Phatak, S. Raha, Calcutta)*

Masses of hadrons (baryons as well as mesons) are modified in the nuclear medium because of their in-

teractions. In this work we investigate the effect of in-medium meson masses on the properties of nuclear matter. The calculations are performed in the Walecka model. We find that with the inclusion of meson mass modification, the computed equation of state becomes softer.

**Rho mass modification in $^3$He: a signal of restoration of chiral symmetry or a test for nuclear matter models**
*(S.K. Ghosh; A. Bhattacharyya, S. Raha, Calcutta)*

Two recent experiments have demonstrated that the effective $\rho$ mass in a nuclear medium, as extracted from the $^3\mathrm{He}(\gamma, \pi^+\pi^-)$ reaction, is substantially reduced. This has been advocated as an indication of partial restoration of chiral symmetry in nuclear matter. In this work we have shown that, even in the absence of chiral symmetry, effective mean field nuclear matter models can explain these findings qualitatively.

**Rho-nucleus bound states**
*(S.K. Ghosh, B.K. Jennings)*

Using the Walecka model we investigate the possibility of a $\rho$-nucleus bound state for different nuclei. Our study shows the existence of such bound states for nuclei ranging from $^3$He to $^{208}$Pb. Currently we are investigating the effect of these bound states on the photoproduction of $\rho$ mesons from nucleons. This may help us to shed new light on the recent experimental results.

**Active-sterile neutrino transformation solution for *r*-process nucleosynthesis**
*(G.C. McLaughlin; A.B. Balantekin, J.M. Fetter, Wisconsin; G.M. Fuller, San Diego)*

We study how matter-enhanced active-sterile neutrino transformation in the $\nu_e \rightleftharpoons \nu_s$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ channels could enable the production of the rapid neutron capture ($r$-process) nuclei in neutrino-heated supernova ejecta. In this scheme the lightest sterile neutrino would be heavier than the $\nu_e$ and split from it by a vacuum mass-squared difference of $3\ \mathrm{eV}^2 \lesssim \delta m^2_{es} \lesssim 70\ \mathrm{eV}^2$ with vacuum mixing angle $\sin^2 2\theta_{es} > 10^{-4}$. In particular, we are now studying the possibility of detecting such a signal in SNO. In addition we evaluate the neutrino-neutrino scattering background contribution to the MSW potential and the consequences for this solution.

**Electron scattering and multi-$\hbar\omega$ correlations**
*(J. Escher; J.P. Draayer, Louisiana State)*

We employed the symplectic shell model (SSM) to investigate the relevance of multi-$\hbar\omega$ correlations for electron scattering form factors of strongly-deformed light nuclei. The SSM, an algebraic theory which treats the nucleus microscopically as a many-fermion system, classifies and truncates the enormous shell model space (typical dimensions: 93,710 for $^{28}$Si, $2.5 \times 10^9$ for $^{60}$Zn, and $4.1 \times 10^{11}$ for $^{154}$Sm) while retaining the multi-shell quadrupole correlations which lead to deformation. Since the model takes the collective coherence between the major oscillator shells into full account, it correctly describes the static electromagnetic properties of nuclei without the need for effective charges. We found that multi-shell correlations contribute in a complex manner to nuclear charge and current densities. Our study demonstrated that most of the discrepancies between data and predictions based on $0\hbar\omega$ model wave functions can be attributed to correlations between different major shells; in lowest order, meson exchange effects are not required. These findings imply that calculations which explicitly include multi-$\hbar\omega$ correlations will play a crucial role in the process of placing quantitative limits on the contributions to the nuclear current from meson exchange.

**Rotational motion of deformed nuclei**
*(J. Escher)*

Measurements of the transverse nuclear form factor provide a direct probe of the nuclear current. In this study, transverse form factors are calculated for a series of rotational nuclei. A careful comparison of the theoretical predictions with experimental results will yield the nuclear rigidity, a quantity which indexes nuclear rotational motion between the limits of rigid rotation and irrotational flow. This study promises to shed light on the dynamical character of nuclear rotational motion and thus addresses one of the unsolved basic science problems of nuclear structure physics.

**A new symmetry concept in many-body systems**
*(J. Escher; A. Leviatan, Hebrew Univ.)*

The application of exact or dynamical symmetries to realistic Hamiltonian systems has its limitations: Usually the assumed symmetry is only approximately fulfilled, and imposing certain symmetry requirements on the Hamiltonian might result in constraints which are too severe and incompatible with experimentally observed features of the system. Alternatively, one can consider breaking the symmetry of a system in a specific way which might result in mixing of representations for some of the states, while retaining good symmetry for a subset of eigenstates. This intermediate symmetry structure is referred to as a 'partial dynamical symmetry' (PDS).

We have studied partial dynamical symmetries in fermionic models of the nucleus. In a recently submitted letter, we introduced a family of Hamiltonians

with partial SU(3) symmetry and showed that these Hamiltonians are closely related to the quadrupole-quadrupole interaction, an important ingredient in models that aim at reproducing quadrupole collective properties of nuclei. The new scheme was employed to describe spectra and electromagnetic transition rates of light nuclei, and to study the structure of the associated eigenstates.

**A review of the current status of nucleon-nucleus effective interactions**
*(S. Karataglidis)*

A review of the current status of nucleon-nucleus effective interactions and their use in optical model analyses of elastic and inelastic proton scattering data has been undertaken. The field has seen a resurgence in light of the growing number of experiments on the scattering of light radioactive nuclei from hydrogen which, in the inverse kinematics, elicits proton scattering data from those nuclei. Such experiments are the only current means of gaining information on the microscopic structures of such systems, particularly those involving densities extending to large radii (halos, for example). The success of current microscopic models in predicting differential cross sections and spin observables makes such a review an important resource for future experiments and analyses.

**A signature for a halo in $^6$He from the reaction $p(^6\mathrm{He},^6\mathrm{He}^*)p'$**
*(S. Karataglidis)*

There has been a question on the nature of $^6$He: how does the neutron density behave at large radii? Breakup experiments have suggested either a neutron halo or a neutron skin, but have not been conclusive either way. The large two-neutron separation energy is suggestive of a halo, but the width of the momentum distribution is twice as large as that for $^{11}$Li. An alternative means by which to gauge the behaviour has been to scatter $^6$He from hydrogen and use the proton scattering data from $^6$He obtained in the inverse kinematics to obtain information on the matter density within a microscopic framework. New elastic and inelastic data from GANIL at 41 MeV have been obtained and analyzed within a fully microscopic model using a large space ($4\hbar\omega$ or $8\hbar\omega$) shell model description for $^6$He. The model of scattering is based on an effective interaction based on the g matrix (the solution of the Bruckner-Bethe-Goldstone equation) which incorporates Pauli blocking and mean field effects, and is dependent on the density obtained from the shell model calculations. The data are well predicted when using single particle wave functions that take into account the extension of the neutron density which is consistent with the single neutron separation energy to the lowest $p$-wave resonance in $^5$He. This is the first unambiguous signature of a halo for $^6$He.

**Low energy behaviour of the $^7$Be $(p,\gamma)^8$B reaction**
*(B.K. Jennings, S. Karataglidis)*

Three related features of the astrophysical S-factor, $S_{17}$, for low energies are an upturn as the energy of the proton goes to zero, a pole at the proton separation energy and a long ranged radial integral peaking at approximately 40 fm. These features, particularly the last, mean $S_{17}$ at threshold is largely determined by the asymptotic normalization of the proton bound-state wave function. We have recently derived expressions for the pole contribution that do not explicitly consider the asymptotic behaviour of the bound state wave function. This allows us to calculate $S_{17}$ in terms of purely short range integrals involving the two-body potential. Much of the derivation is relevant to other radiative capture processes especially those with weakly bound final states. Work is in progress to use shell model wave functions to derive the asymptotic normalization for $^8$B.

**The low energy nuclear density of states and the saddle point approximation**
*(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. In this paper we analyze the low energy behaviour of the nuclear density of states using the saddle point approximation and extensions to it.

**Effective Field Theories and Chiral Perturbation Theory**

**Pion-deuteron scattering length from effective field theory**
*(X. Kong)*

An effective Lagrangian is constructed for pion-nucleon scattering at non-relativistic energies. The coupling constants can be expressed in terms of scattering lengths. When used in the calculation of the pion-deuteron scattering length, the standard result is reproduced for the dominant contribution. An new correction term generated by the momentum of nucleons is found to be large. Both Hulthen and Pieper-Reid's wave functions of the deuteron are used, in order to check the dependence on different deuteron wave functions. In this formalism, Coulomb corrections can be calculated with no ambiguities. The energy level shift of pionic deuterium is also easy to obtain.

**$\nu d \to e^- pp$ in effective field theory**
*(X. Kong; M. Butler, St. Mary's; J. Chen, Washington)*

The differential cross sections for the reaction $\nu d \to e^- pp$ are calculated analytically using nucleon-nucleon effective field theory. The result is useful for the Sudbury Neutrino Observatory.

**Non-relativistic pion interactions and the pionium lifetime**
*(X. Kong; F. Ravndal, Oslo)*

We construct an effective Lagrangian for interacting pions with non-relativistic energies. The coupling constants can be expressed in terms of the different scattering lengths and slopes. Corrections to the pionium decay rate are calculated by using the effective Lagrangian.

**Relativistic corrections to the pionium lifetime**
*(X. Kong; F. Ranvdal, Oslo)*

Next-to-leading-order contributions to the pionium lifetime are considered within non-relativistic effective field theory. A more precise determination of the coupling constants is then needed in order to be consistent with the relativistic pion-pion scattering amplitude which can be obtained from chiral perturbation theory. The relativistic correction is found to be 4.1% and corresponds simply to a more accurate value for the non-relativistic decay momentum.

**Proton-proton scattering lengths from effective field theory**
*(X. Kong; F. Ravndal, Oslo)*

Using a recently developed effective field theory for the interactions of nucleons at non-relativistic energies, we calculate the Coulomb corrections to proton-proton scattering. Including the dimension-eight derivative interaction in the PDS regularization scheme, we obtain a modified Jackson-Blatt relation for the scattering lengths which is found to be phenomenologically satisfactory. The effective range is not modified by Coulomb effects to this order in the calculation.

**Coulomb effects in low energy proton-proton scattering**
*(X. Kong; F. Ravndal, Oslo)*

We calculate non-perturbatively Coulomb corrections to proton-proton scattering. Including the dimension-eight derivative interaction in the PDS regularization scheme, we recover a modified form of the Blatt-Jackson relation between the scattering lengths. The effective range receives no corrections from the Coulomb interactions to this order. Also the case of scattering in channels where the Coulomb force is attractive, is considered. This is of importance for hadronic atoms.

**Proton-proton fusion in leading order of effective field theory**
*(X. Kong; F. Ravndal, Oslo)*

Using a recently developed effective field theory for the interactions of nucleons at non-relativistic energies, we calculate the rate for the fusion process $p + p \to d + e^+ + \nu_e$ to leading order in the momentum expansion. Coulomb effects are included non-perturbatively in a systematic way. The resulting rate is independent of specific models for the strong interactions at short distances and is in agreement with the standard result in the zero-range approximation.

**Effective-range corrections to the proton-proton fusion rate**
*(X. Kong; F. Ravndal, Oslo)*

Proton-proton fusion is considered in the effective field theory of Kaplan, Savage and Wise. Coulomb effects are included systematically in a non-perturbative way. Including the dimension-eight derivative coupling which determines the effective ranges of the scattering amplitudes, next-to-leading order corrections to the fusion rate are calculated. When the renormalization mass is well above the characteristic energies of the system, this contribution gives a rate which is eight per cent below the standard value. The difference can be due to an unknown counterterm which comes in at this order.

**The three-boson system with short-range interactions**
*(H.-W. Hammer; P.F. Bedaque, INT; U. van Kolck, Caltech)*

We discuss renormalization of the non-relativistic three-body problem with short-range forces. The problem is non-perturbative at momenta of the order of the inverse of the two-body scattering length. An infinite number of graphs must be summed, which leads to a cut-off dependence that does not appear in any order in perturbation theory. We argue that this cut-off dependence can be absorbed in one local three-body force counterterm and compute the running of the three-body force with the cut-off. This allows a calculation of the scattering of a particle and the two-particle bound state if the corresponding scattering length is used as input. We also obtain a model-independent relation between binding energy of a shallow three-body bound state and this scattering length. We comment on the power counting that organizes higher-order corrections and on the relevance of this result for the effective field theory program in nuclear and molecular physics.

**Effective theory of the triton**
*(H.-W. Hammer; P.F. Bedaque, INT; U. van Kolck, Caltech)*

We apply the effective field theory approach to the three-nucleon system. In particular, we consider $S = 1/2$ neutron-deuteron scattering and the triton. We show that in this channel a unique nonperturbative renormalization takes place which requires the introduction of a single three-body force at leading order. With one fitted parameter we find a good description of low energy data. Invariance under the renormalization group explains some universal features of the three-nucleon system – such as the Thomas and Efimov effects and the Phillips line – and the origin of SU(4) symmetry in nuclei.

**Effective field theory approach to $\vec{n}+\vec{p} \to d+\gamma$ at threshold**
*(T.-S. Park; K. Kubodera, South Carolina; D.-P. Min, Seoul; M. Rho, Saclay)*

Previously, in an effective field theory formulated by us, we have carried out parameter-free calculations of a large number of low energy two-nucleon properties. An experiment at the Institut Laue-Langevin is currently measuring spin-dependent effects in the polarized $np$ capture process $\vec{n} + \vec{p} \to d + \gamma$ at threshold. Noting that spin-dependent observables for this reaction are sensitive to terms of chiral orders higher than hitherto studied, we extend our effective theory approach to this process and make parameter-free predictions on the spin-dependent observables.

**A higher-order calculation of $np$ scattering in cut-off effective field theory**
*(T.-S. Park; C.H. Hyun, D.-P. Min, Seoul)*

We report a next-to-leading-order (NLO) chiral perturbation theory calculation of the neutron-proton scattering cross section in the ${}^1S_0$ channel using a cut-off regularization. The inclusion of two-pion exchanges in the irreducible diagrams – or potential – figuring at NLO is found to be important in enlarging the domain of validity of the effective field theory. We are able to reproduce the *empirical* scattering phase shift up to $p$ = 300 MeV – which is comparable to the cut-off scale involved – with an agreement which is superior to results of other effective field theory approaches. We also discuss the role of the cut-off as a renormalization prescription and the importance of the explicit pion degree of freedom in scattering processes.

**The hep process in the sun in chiral perturbation theory**
*(T.-S. Park; K. Kubodera, South Carolina; D.-P. Min, Seoul; M. Rho, Saclay)*

We have obtained all the Gamow-Teller (GT) operators up to $\mathcal{O}(Q^4)$ that figure in the "hep" process using chiral perturbation theory. What makes our calculation truly meaningful is that there is effectively only one parameter in the theory up to $\mathcal{O}(Q^4)$ which can be fixed from triton beta decay, thereby freeing us from dependence on unknown parameters. A detailed comparison of the GT operator with the work by Carlson *et al.* has been made, which shows a substantial difference in the long-range part and marked difference in the short-range part. The matrix element of the GT operators is being calculated by the variational Monte Carlo (VMC), with the metropolis random walk sampling. The computational work is almost done, and we are about to get the final results. Its implication on the recent measurement at SuperKamiokande will be discussed.

**In-medium pion mass from chiral perturbation theory**
*(T.-S. Park; H. Jung, D.-P. Min, Seoul)*

Using chiral perturbation theory, we have calculated all the diagrams up to two-loop order which contribute to the $S$-wave pion's self energy. The in-medium pion mass turned out to be increased by a few per cent in normal nuclear matter density. Some subtleties related to the definition of pion fields are discussed. A draft of this project is being written.

**$pp \to pp\pi^0$ near threshold up to one-loop**
*(T.-S. Park; S. Ando, South Carolina; D.-P. Min, Seoul)*

The $pp \to pp\pi^0$ process near threshold has been studied up to one-loop order using heavy baryon chiral perturbation theory. The one-loop contributions are found to play quite an important role. With a non-trivial cut-off dependence, we could reproduce the experimental cross section with good agreement. A draft of this project is being written.

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

As part of our program of evaluating a number of simple few-body radiative processes in heavy baryon chiral perturbation theory we are calculating the processes $\pi + p \to n + \gamma + \gamma$ and $\gamma + p \to n + \pi + \gamma$. The former reaction is the subject of an experiment at TRIUMF and the latter, which involves the same matrix element, is under investigation at Mainz. The

calculation is being carried out to $O(p^3)$, that is to one-loop order. The aim is to explore the sensitivity of both processes to the low energy constants of the chiral Lagrangian. In principle, since virtual Compton scattering on a pion is a subprocess of both these reactions, one should get similar information, e.g. pion polarizabilities, to that which would be obtained by a direct measurement of that process, which is extremely difficult to do. One aim of the calculation is to see if there is enough sensitivity in either process to get such information.

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

The differential cross sections for $\pi^- p \to \gamma n$ and $\pi^+ n \to \gamma p$ are computed up to $O(p^3)$ in heavy baryon chiral perturbation theory (HBChPT). The expressions at $O(p)$ and $O(p^2)$ have no free parameters. There are three unknown parameters at $O(p^3)$ which are determined by fitting to experimental data. Although this fit has an acceptable $\chi^2$, it is noted that one of the HBChPT parameters acquires a rather large value, thus raising concerns about the rate of convergence of the chiral expansion for these reactions. Finally, the $s$- and $p$-wave multipoles are determined by evaluating the HBChPT expressions at threshold, and are compared to other theoretical predictions.

## Hadronic Structure and QCD

**Quark description of hadronic phases**
*(T. Schäfer; F. Wilczek, IAS, Princeton)*

We extend our proposal that major universality classes of hadronic matter can be understood, and in favourable cases calculated, directly in the microscopic quark variables, to allow for splitting between strange and light quark masses. A surprisingly simple but apparently viable picture emerges, featuring essentially three phases, distinguished by whether strangeness is conserved (standard nuclear matter), conserved modulo two (hypernuclear matter), or locked to colour (colour flavour locking). These are separated by sharp phase transitions. There is also, potentially, a quark phase matching hadronic K-condensation. The smallness of the secondary gap in two-flavour colour superconductivity corresponds to the disparity between the primary dynamical energy scales of QCD and the much smaller energy scales of nuclear physics.

**High density QCD and instantons**
*(T. Schäfer; R. Rapp, E.V. Shuryak, Stony Brook; M. Velkovsky, BNL)*

Instantons generate strong non-perturbative interactions between quarks. In the vacuum, these interactions lead to chiral symmetry breaking and generate constituent quark masses on the order of 300–400 MeV. The observation that the same forces also provide attraction in the scalar diquark channel leads to the prediction that cold quark matter is a colour superconductor, with gaps as large as ∼100 MeV. We provide a systematic treatment of colour superconductivity in the instanton model. We show that the structure of the superconductor depends on the number of flavours. In the case of two flavours, we verify the standard scenario and provide an improved calculation of the mass gap. For three flavours, we show that the ground state is colour-flavour locked and calculate the chiral condensate in the high density phase. We show that as a function of the strange quark mass, there is a sharp transition between the two phases. Finally, we go beyond the mean field approximation and investigate the role of instanton-anti-instanton molecules, which – besides superconducting gap formation – provide a competitive mechanism for chiral restoration at finite density.

**Superconductivity from perturbative one-gluon exchange in high density quark matter**
*(T. Schäfer; F. Wilczek, IAS, Princeton)*

We study colour superconductivity in QCD at asymptotically large chemical potential. In this limit, pairing is dominated by perturbative one-gluon exchange. We derive the Eliashberg equation for the pairing gap and solve this equation numerically. Taking into account both magnetic and electric gluon exchanges, we find $\Delta \sim g^{-5} \exp(-c/g)$ with $c = 3\pi^2/\sqrt{2}$, verifying a recent result by Son. For chemical potentials that are of physical interest, $\mu < 1$ GeV, the calculation ceases to be reliable quantitatively, but our results suggest that the gap can be as large as 100 MeV.

**Patterns of symmetry breaking in QCD at high baryon density**
*(T. Schäfer)*

We study the structure of QCD at very large baryon density for an arbitrary number of flavours $N_f$. We provide evidence that for any number of flavours larger than $N_f = 2$, chiral symmetry remains broken at asymptotically large chemical potential. For $N_c = N_f = 3$, chiral symmetry breaking follows the standard pattern $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \to \mathrm{SU}(3)$, but for $N_f > 3$ unusual patterns emerge. We study the case $N_f = 3$ in more detail and calculate the magnitude of the chiral order parameters $< \bar{\psi}\psi >$ and $< (\bar{\psi}\psi)^2 >$ in perturbative QCD. We show that, asymptotically, $< \bar{\psi}\psi >^{1/3}$ is much smaller than $< (\bar{\psi}\psi)^2 >^{1/6}$. The result can be understood in terms of an approximate discrete symmetry.

**Towards an instanton liquid calculation in supersymmetric QCD**
*(T. Schäfer)*

We study chiral symmetry breaking and the spectrum of the Dirac operator in the semi-classical approximation in theories with adjoint fermions. The Dirac operator in the adjoint representation has $2N_c$ zero modes in the background field of an instanton. We have calculated overlap matrix elements of the Dirac operator between individual instanton and anti-instanton zero modes. This is the first step in performing an interacting instanton calculation. The goal of this study is to compare the mechanism for chiral symmetry breaking in theories with fundamental and adjoint fermions, and to compare with some known exact results in SUSY QCD.

**Decays of $B_c$ mesons**
*(M.A. Nobes, R.M. Woloshyn)*

The semileptonic decay form factors of the double heavy $B_c$ meson provide a unique opportunity to study the strong interactions between two heavy quarks. A fully relativistic quark-meson effective theory, with non-local interactions, is used to compute semileptonic decay form factors, for both the $B_c$ and a wide range of other heavy-light mesons. Using these form factors, predictions for decay rates and branching ratios are obtained. The results are compared to other theoretical approaches and, where available, to experimental results. In addition the radiative decay rate of $B_c^*$ is calculated in the same model.

**Spectroscopy of charmed baryons**
*(R.M. Woloshyn)*

The spectrum of baryons containing one or two charmed quarks is calculated using improved lattice QCD in quenched approximation. A recent calculation by the UKQCD collaboration found for singly-charmed baryons that spin 3/2 states were less massive than their spin 1/2 partners. This ordering is opposite to what is expected in quark models. Our calculations indicate that the projection technique used by the UKQCD group to construct the correlation functions for the spin 1/2 states picks out states with very poor overlap with the ground state. Using a more direct method to determine masses of spin 1/2 states results in mass splittings that have the expected sign and which are larger in magnitude than experimental values as is common for quenched QCD simulations.

**Spectroscopy of heavy-light mesons**
*(R.M. Woloshyn; R. Lewis, Regina)*

The masses of $S$- and $P$-wave heavy-light mesons are computed in quenched QCD using a classically and tadpole improved action on ansiotropic lattices. Of particular interest are the splittings among the $P$-wave states. It has been suggested that the ordering of these states is inverted from the natural ordering in heavy-light mesons due to an interplay of spin-orbit and relativistic effects. Our simulation does not provide any evidence for such an inverted spectrum. However, our bound on the ${}^3P_2 - {}^3P_0$ splitting of about 100 MeV for $B$ mesons is somewhat lower than previous calculations of this quantity.

**The Standard Model and Beyond**

**A study of the charged scalar in the Zee model**
*(G.C. McLaughlin, J.N. Ng)*

An extension of the Zee model involving a light right-handed neutrino, $\nu_R$, is considered. We update constraints on couplings between the bilepton scalar, the active neutrinos, $\nu_R$ and the charged leptons. We find that the most stringent constraint currently comes from measurements limiting the width of the decay $\mu \to e\,\gamma$. These are used to predict the upper bound on violation of lepton universality in $W$ boson decays.

**Singlet interacting neutrinos in the extended Zee model and solar neutrino transformation**
*(G.C. McLaughlin, J.N. Ng)*

We study the impact of standard model singlet neutrinos on neutrino flavour transformation. We focus on an extension of the Zee model which includes singlet neutrinos, and find that the best limits on the interactions of the singlet neutrinos come from astrophysical phenomena. Singlet neutrino-electron scattering will impact both the matter enhanced flavour transformation potential as well as detector cross sections. If electron neutrino – singlet neutrino oscillations are responsible for the solar neutrino anomaly, then the limit on the singlet neutrino interaction strength is of order of the weak interaction scale. Zee model modification of $\nu_\tau - e$ scattering also impacts solar neutrino transformation, although this interaction is more tightly constrained.

**Astrophysical implications of the induced neutrino magnetic moment from large extra dimensions**
*(G.C. McLaughlin, J.N. Ng)*

Theories involving extra dimensions, a low ($\sim$ TeV) string scale and bulk singlet neutrinos will produce an effective neutrino magnetic moment which may be large ($< 10^{-11}\mu_B$). The effective magnetic moment increases with neutrino energy, and therefore high energy reactions are most useful for limiting the allowed number of extra dimensions. We examine constraints from both neutrino-electron scattering and also astrophysical environments. We find that supernova energy loss

considerations require a number of extra dimensions, $n \geq 2$, for an electron neutrino-bulk neutrino Yukawa coupling of order 1.

**$\beta$-decay universality tests of bulk neutrinos in extra dimensions**

*(G.C. McLaughlin, J.N. Ng)*

We study constraints on theories involving extra dimensions and bulk singlet neutrinos using $\beta$-decay universality tests. We also examine the potential signature of these neutrinos in both Kurie plots and nuclear recoil momentum measurements.

**Constraints on T-odd, P-even interactions from electric dipole moments, revisited**

*(G.C. McLaughlin; M.J. Ramsey-Musolf, A. Kuriliov, Connecticut)*

One manifestation of possible physics beyond the standard model (SM) may be the existence of new low energy interactions which violate time-reversal invariance (T) but conserve parity invariance (P). On general grounds, one expects the most important low energy effects to arise from the lowest-dimension effective operators, since their effects scale as $(\frac{p}{M_x})^{d-4}$, with $p$ being a typical momentum associated with the low energy process of interest, $d$ the operator dimension, and $M_x$ being the low mass scale associated with the new physics. We derive the bounds on these operators from experiment. We are computing the effective T-odd P-odd dimension seven operators generated by parity violating weak radiative corrections. We are relating this TOPO operator and the original TOPE operator to $\bar{g}_\pi$ and $\bar{g}_\rho$.