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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2003

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 PHYSICS

Introduction

The TRIUMF Theory group consists of four staff members, six to seven research associates plus a number of students and visitors. The main research interests are physics beyond the standard model, hadron physics and nuclear physics. In addition to carrying out their own research programs, the members of the Theory group provide support for the TRIUMF experimental program and are available for consultation and collaboration with the experimentalists.

The four permanent staff members of the group are: Harold W. Fearing, Byron K. Jennings (group leader), John N. Ng and Richard M. Woloshyn. Erich W. Vogt (professor emeritus, UBC) is an associate member. During 2002 the Theory group had three sabbatical visitors, Chaoqiang Geng, Colston Chandler and Stephen Godfrey. The research associates are: R. Allahverdi (from September), S. Ando (from November), C. Barbieri (from September), W. Chang, A.K. Dutt-Mazumder, J. Escher (until October), S. Kondratyuk (until October), A.D. Lahiff (until August), C.P. Liu, and J.-M. Sparenberg (from September). The graduate students associated with the group are: C. Bird, F. Okiharu, C.C. Ho, I.L. Ho, and T.H. Wu.

The visitors to the Theory group this year included: J. Al-Khalili, N. Barmbilla, M. Butler, H.C. Chang, M. Chen, H.R. Fiebig, V. Flambaum, S. Godfrey, S. Groot Nibbelink, F. Herwig, S.W. Hong, G. Kribs, H. Lipkin, A. Lisetskiy, M. Locher, I. Low, A. Majumder, K. Maltman, E. Ormand, M. Pospelov, G. Prézeau, M. Ramsey-Musolf, M. Rozali, H. Sherif, A. Vairo, D. Wilkinson, Y.-P. Yan, J. Zanotti.

The Theory Research Program

Neutrino masses in a 5D SU(3)$_W$ TeV unification model

(W.-F. Chang, J.N. Ng; C.-H. Chang, Taiwan Normal Univ.)

We study an SU(3)$_w$ unified theory in the $M_4 \times S_1/(Z_2 \times Z_2')$ orbifold. The theory provides a tree-level mixing angle $\sin^2\theta = 1/4$ at the compactification scale. The SU(3)$_w$ symmetry is broken down to SU(2)×U(1) at one of its two fixed points by choosing adequate boundary conditions. For leptons, e_L, ν_L and e_R^c form an SU(3)$_w$ triplet and are placed at the SU(3)$_w$ invariant fixed point. On the other hand, the quarks can not fit into any SU(3)$_w$ multiplet are to be put at the SU(2)×U(1) fixed point. To give correct fermions masses pattern, the minimum Higgs sector contains a bulk Higgs triplet and a bulk anti-sextet. The tree-level neutrino Majorana masses are forbidden by the orbifold boundary conditions. However, we show that the neutrino Majorana masses can be generated through 1-loop quantum corrections by adding a parity odd bulk Higgs triplet without introducing the right-handed neutrino. Furthermore, the resulting neutrino masses observe the inverted hierarchy and can easily accommodate the bilarge mixing angle solution favoured by the recent neutrino experiments without much fine tuning of parameters. Finally, the $\mu \to 3e$ transition and neutrinoless double β decays were shown to be safely below the current experimental bounds.

Lepton universality, rare decays and split fermions

(W.-F. Chang, I.-L. Ho, J.N. Ng)

Theories with split fermions (SFs) in extra dimension(s) are devised to give an alternative view of fermion masses hierarchy problems. We investigate the constraint on the SFs in extra dimensions by considering the universality of W leptonic decays $W \to l_i\nu_i$, the charged lepton decays $l_i \to l_j\nu_i\bar{\nu}_j$, and the lepton flavour violating process $l_i \to \bar{l}_j l_k l_h$ where $l_i = e, \mu$ or τ. For the standard model (SM) background of $W \to l_i\nu_i$, we extended the one loop quantum correction to include effects of order m_l^2/M_W^2 and the Higgs mass dependence. We find that in general the SF scenarios give rise to a 4D effective Yukawa matrix of the Kaluza-Klein (KK) Higgs bosons which is misaligned with respect to the fermion mass matrix. This holds true for gauge bosons as well. This leads to decays of $l_i \to \bar{l}_j l_k l_h$ at tree level and muonium antimuonium conversion. Interestingly the leptonic universality of W boson decays is not affected at this level.

CP violation in 5D split fermion models

(W.-F. Chang, J.N. Ng)

We give a new configuration of SF positions in one extra dimension with two different Yukawa coupling strengths for up-type, h_u, and down-type, h_d, quarks at $\frac{h_u}{h_d} = 36.0$. The new configurations can give enough CP violating (CPV) phase to accommodate all currently observed CPV processes. Therefore, a 5D SM with SFs is viable. In addition to the standard CKM phase, new CPV sources involving KK gauge bosons coupling which arise from the fact that unitary rotation which transforms weak eigenstates into their mass eigenstates only holds for the zero modes which are the SM fields and not for the KK excitations. We have examined the physics of kaon, neutron, and B/D mesons and found the most stringent bound on the size R of the extra dimensions comes from $|\epsilon_K|$. Moreover, it depends sensitively on the width, σ, of the Gaussian wavefunction in the extra dimension used to describe the fermions. When $\sigma/R \ll 1$, the constraint will be lifted due to GIM suppression on the flavour changing neutral current and CPV couplings.

Constraint on the MSSM baryogenesis scenario from electric dipole moment

(W.-F. Chang; D. Chang, W.Y. Keung, CTS, Taiwan)

A commonly accepted mechanism of generating baryon asymmetry in the minimal supersymmetric standard model (MSSM) uses the CPV relative phase between the gaugino mass and the Higgsino μ term. The most severe constraint on this phase is from the limit on electric dipole moments of various light fermions. To avoid such constraint, a popular scheme with the first two generation sfermions naturally heavy is always used to suppress the one-loop level contributions. We point out that under such a scheme the most severe constraint may come from a new (two-loop level) contribution to the electric dipole moments of the electron, the neutron or atoms via the chargino sector in MSSM. As a result, the allowed parameter space of MSSM is severely constrained independent of the masses of the first two generation sfermions for baryogenesis.

Leptogenesis with superheavy Majorana neutrinos

(R. Allahverdi; A. Mazumdar, McGill)

Leptogenesis is an elegant mechanism which connects the observed baryon asymmetry of the universe to tiny masses of the light neutrinos. In the standard scenarios of leptogenesis the out-of-equilibrium decay of heavy Majorana neutrinos into the standard model Higgs and leptons generates a lepton asymmetry which is partially converted to baryon asymmetry through non-perturbative electroweak processes. We showed that successful leptogenesis is possible even if Majorana neutrinos are too heavy to be excited in the early universe, e.g. for Majorana masses as high as 10^{16} GeV. In our proposed model, the lepton asymmetry is directly produced from decay of the inflaton, the scalar field which drives cosmic inflation, into the standard model Higgs and leptons occuring via superheavy off-shell Majorana neutrinos. This model also naturally satisifies the bounds on the highest temperature in the early universe allowed in supersymmetric models.

Sleptogenesis

(R. Allahverdi; B. Dutta, Regina; A. Mazumdar, McGill)

As another alternative to standard leptogenesis, we propose that the lepton asymmetry can be created in inflaton decay to supersymmetric partners of Majorana neutrinos. The main feature of this scenario is decoupling of the generated asymmetry from the neutrino Yukawa sector. As a consequence, it can accommodate leptogenesis for Majorana masses as low as 10 TeV, without unnatural assumptions, fine-tuning or complications which arise otherwise. Our scenario can be naturally embedded within models which seek the origin of a tiny mass for the light neutrinos, e.g. models with a left-right symmetry.

Non-thermal dark matter

(R. Allahverdi; M. Drees, Munich)

The parameter space of various supersymmetric extensions of the standard model has been explored extensively, and regions which allow the lightest supersymmetric particle to be a viable thermal dark matter candidate are identified. New possibilties will arise by invoking non-thermal dark matter. On the one hand, some of the regions ruled out from thermal dark matter considerations can still be allowed. More generally, weakly interacting particles heavier than 100 TeV, ruled out as thermal dark matter by the unitarity bound, can be viable candidates. The important question is how to produce such particles abundantly. We considered various processes occuring in inflaton decay and thermalization of decay products. It was shown that stable (or long-lived) particles within a wide mass range, as heavy as 10^{12} GeV, can be copiously produced from reactions not considered before, without requiring non-perturbative processes. Therefore cosmological constraints on models containing such particles are (much) more severe than had previously been thought.

Cosmological bounds on large extra dimension models

(R. Allahverdi; C. Bird, S. Groot Nibbelink, M. Pospelov, Victoria)

Models with large extra spatial dimensions can solve the gauge hierarchy problem by bringing down the quantum gravity scale close to the electroweak scale. In these models, matter and gauge fields live on a 3-brane while gravity propagates in the bulk of the space, and hence a tower of Kaluza-Klein modes appears for the graviton. This leads to constraints on the fundamental scale from collider experiments and, more tightly, cosmology. So far, on the cosmology side, all studied processes only result in significant production of Kaluza-Klein gravitons which are lighter than 50 MeV, from the primordial bath. The current limits on the diffuse photon background from the late decay of such modes then translates into a bound on the fundamental scale. We show that much heavier Kaluza-Klein gravitons, with a mass of order TeV, can be efficiently produced directly from inflaton decay. These modes decay rather early which can lead to dissociation of the light elements from big bang nucleosynthesis. In this case, the requirement for successful nucleosynthesis constrains the abundance of Kaluza-Klein gravitons and, consequently, sharpens the cosmological bounds on large extra dimension models.

Parity violation in deuteron electrodisintegration
(C.P. Liu; G. Prézeau, Caltech; M.J. Ramsey-Musolf, Caltech/Connecticut)

Parity violating (PV) electron-nucleus scattering provides more observables, normally not accessible by parity conserving (PC) scattering experiments, to study the structure of a nucleon. By measuring the asymmetry factors in elastic electron-proton and quasielastic (QE) electron-deuteron scattering at backward angles, one can determine the strange magnetic form factor G_M^s, and the isovector axial form factor (seen by the electron), $G_A^e(T = 1)$. The former provides a way to explore the strangeness content of a nucleon, which is a result anticipated by QCD, while the latter could be used to constrain the anapole form factor of a nucleon, which could be understood as a radiative correction in the unified electroweak theory. The surprising result published by the SAMPLE collaboration which gave a much larger $G_A^e(T = 1)$ than the theoretical prediction, has already caught a lot of attention. One possibility for this huge discrepancy is ignorance of the contribution from the PV NN interaction. However, our calculation – using AV_{18} as the PC interaction, and DDH potential (a $\pi^{\pm}$-, ρ-, and ω-meson exchange potential formulated by Desplanques, Donoghue, and Holstein) as the PV interaction – showed that while the effect of hadronic PV dominates in the threshold region, it is negligible at the QE kinematics relevant to SAMPLE experiments. In other words, quasi-elastic PV electron-deuteron scattering is indeed a clean probe of nucleon structure. The discrepancy still persists at the current stage.

Deuteron photodisintegration
(C.P. Liu; B. Desplanques, Grenoble; C.H. Hyun, Sungkyunkwan)

Threshold deuteron photodisintegration is another possible way to examine nuclear PV besides the radiative neutron capture and deuteron electrodisintegration. The existing analysis, using basically the zero-range approximation for the strong interaction, is being updated by modern high-quality NN potentials, given the fact that several groups are planning to do the experiments.

Deuteron anapole moment
(C.P. Liu; B. Desplanques, Grenoble; C.H. Hyun, Sungkyunkwan)

A previous work by B. Desplanques and C.H. Hyun was done in the model only with pion exchanges. Though the pion sector is the dominant subset in the DDH potential, as our work on deuteron electrodisintegration showed, the ρ and ω sectors give negligible contributions to the parity admixtures in the deuteron wave function, thus to the deuteron anapole. We are doing a complete calculation by including everything allowed by the DDH model.

Parity violating electromagnetic meson exchange currents
(C.P. Liu; B. Desplanques, Grenoble; C.H. Hyun, Sungkyunkwan)

The existence of meson exchange currents (MECs) has been acknowledged for quite a long time, and the inclusion of these currents is essential to guarantee the gauge invariance of any related calculation. Though the PV EM MECs in the framework of DDH scheme have been derived, it was pointed out by B. Desplanques that there might be some problems involved in the derivation of the heavy meson sectors, i.e., ρ and ω exchanges, so that they are not fully conserved. This new work aims to check the original derivation, fix the mistake if any, and get the correct result by explicitly showing the continuity equation is satisfied.

Reanalysis of nuclear parity violating observables in the framework of effective field theory
(C.P. Liu; M.J. Ramsey-Musolf, Caltech/Connecticut; B.R. Holstein, Massachusetts)

Traditional analyses of nuclear PV observables are done by using the DDH potential and then the experimental results are used to constrain the six PV meson-nucleon coupling constants, h_π^1, $h_\rho^{0,1,2}$, and $h_\omega^{0,1}$. However, one big puzzle in this field is that the current constraints on h_π^1, obtained from various nuclear PV observables, have not been very consistent, and they also do not agree well with the theoretical predictions, e.g., the DDH "best" value. One possible source of this inconsistency might be due to the fact that this widely-adopted potential is model-dependent. A new development by M.J. Ramsey-Musolf *et al.* of formulating a model-independent PV potential within the framework of effective field theory has been in progress. Our goal here is using this new potential – parametrized by various low energy constants (LECs) – to reanalyze nuclear PV observables and see if one can get a more consistent results in this framework.

Induced pseudoscalar coupling of the proton weak interaction

(T. Gorringe, Kentucky; H.W. Fearing)

The induced pseudoscalar coupling g_p is the least well known of the weak coupling constants of the proton's charged-current interaction. Its size is dictated by chiral symmetry arguments, and its measurement represents an important test of quantum chromodynamics at low energies. During the past decade a large body of new data relevant to the coupling g_p has been accumulated. This data includes measurements of radiative and non radiative muon capture on targets ranging from hydrogen and few-nucleon systems to complex nuclei. We have reviewed the theoretical underpinnings of g_p, the experimental studies of g_p, and the procedures and uncertainties in extracting the coupling from data. Current puzzles are highlighted and future opportunities are discussed. The review has been prepared for and submitted to Reviews of Modern Physics.

Solar-neutrino reactions on deuteron in effective field theory

(S. Ando; Y.H. Song, Seoul National Univ.; H.W. Fearing; T.-S. Park, K. Kubodera, South Carolina)

The cross sections for low-energy neutrino-deuteron reactions are calculated within heavy-baryon chiral perturbation theory employing the cut-off regularization scheme. The transition operators are derived up to next-to-next-to-next-to-leading order in the Weinberg counting rules, while the nuclear matrix elements are evaluated using the wave functions generated by a high-quality phenomenological NN potential. With the adoption of the axial-current-four-nucleon coupling constant fixed from the tritium beta decay data, our calculation is free from unknown low-energy constants. Our results exhibit a high degree of stability against different choices of the cutoff parameter, a feature which indicates that, apart from radiative corrections, the uncertainties in the calculated cross sections are less than 1%.

Radiative corrections for neutron β-decay revisited

(S. Ando; V. Gudkov, K. Kubodera, F. Myhrer, South Carolina; S. Nakamura, T. Sato, Osaka)

The recent very accurate measurements of the lifetime and the correlation coefficients of neutron β-decay play a key role in deducing precise values of physical constants, e.g., a K-M matrix element V_{ud} and axial vector coupling constant g_A. Furthermore, they probe for new physics beyond the standard model. The radiative corrections in $\mathcal{O}(\alpha)$ have been well established by Sirlin, where α is the fine structure constant. On the other hand, since the energy scale of the reaction is very small (about the electron mass), we can employ an effective Lagrangian in which the nucleon is treated as a heavy-baryon field and pions are integrated out. We re-examine the life time and correlation coefficients of neutron β-decay up to $\mathcal{O}(\alpha)$ and including the $1/m_N$ correction (where m_N is the nucleon mass) within this formalism.

Radiative corrections for solar-neutrino reactions on deuteron in effective field theory

(S. Ando;V. Gudkov, K. Kubodera, F. Myhrer, South Carolina; S. Nakamura, T. Sato, Osaka)

The recent experimental results at SNO show that the flavour of solar-neutrino changes while it flies to the Earth. This provides strong evidence that the neutrino has a mass. The neutrino reactions on deuteron are the detecting reactions of solar-neutrinos and, therefore, it is essential to provide the cross sections of the reactions as accurately as possible by theory, to deduce the mass and the mixing angle of neutrinos from the data. Moreover, it is known that radiative corrections of the reactions are significant, leading to a few percent corrections to the cross sections, which is comparable to an unknown constant in the hadronic sector in effective theory calculations. In this work, we incorporate the photon degree of freedom into an effective Lagrangian to study the radiative corrections of the reactions within the frame work of effective field theory.

The process $\pi p \to n e^+ e^-$ in heavy baryon chiral perturbation theory

(H.W. Fearing)

Heavy baryon chiral perturbation theory is an effective field theory approach which allows one to evaluate low energy processes using a Lagrangian which has the same symmetries as the underlying QCD, but which however contains some parameters, the so called low energy constants (LECs) which must be evaluated by fits to experiment. Earlier we looked at the process $\pi p \to n\gamma$ and used data from TRIUMF and Saskatoon to fit the S and P wave amplitudes and thus evaluate the appropriate LECs. [Fearing *et al.*, Phys. Rev. **C62**, 054006 (2000)]. We have now extended this calculation to the process $\pi p \to n e^+ e^-$. This latter process is of particular interest because it in principle provides information about the axial form factors in the time-like momentum transfer region. To extend the original calculation one has to allow for off shell photons, attach the e^+e^- pair, and evaluate a more complicated phase space. The required LECs are all known from the earlier calculation, and so the result here becomes a prediction for the rate, or alternatively a consistency check on the LECs previously evaluated. The ne^+e^- final state has been measured in a TRIUMF experiment and we expect to be able to compare our theoretical results with the data, once the experimental analysis is complete.

Low-energy pion-nucleon scattering and the Adler-Weisberger sum rule in a unified dynamical description
(S. Kondratyuk)

An effective Lagrangian model for pion-nucleon scattering is utilized to address the following problem: "What can one learn from a comparison of the isospin-odd amplitude obtained in the low-energy limit with the value of the calculated Adler-Weisberger sum rule?". It is essential that the two methods of evaluation are done within the same dynamical approach. Since the model used – the dressed K-matrix approach – includes dressing of the nucleon two- and three-point Green's functions up to infinite order and successfully describes pion-nucleon scattering at low as well as intermediate energies, it is uniquely suited to study the above question. The basic assumptions on which the Adler-Weisberger sum rule rests are chiral symmetry and causality, both of which are, in principle, satisfied only approximately. The difference between the low-energy and sum-rule evaluations of the isospin-odd amplitude can be related to the degree to which these physical properties are violated. In the dressed K-matrix approach, a satisfactory agreement is found between the low-energy and sum-rule calculations. The remaining small discrepancy is in part due to omitted ingredients in the procedure for dressing the four-point $\pi\pi NN$ Green's functions, which causes only partial fulfilment of analyticity constraints.

Cutoff as an energy scale in pion-nucleon scattering
(S. Kondratyuk, B.K. Jennings)

Realistic dynamical models describing hadronic interactions from low to resonance energies typically rely on the usage of an energy-momentum cutoff. For theories applicable in a very wide energy span, such as quantum electrodynamics, the Wilson renormalization techniques offer a useful interpretation of a cutoff as a "floating" energy scale. By imposing the condition that the cutoff should not affect quantities observable at much lower energies, one calculates a beta-function whose properties can be used to describe dynamics of the system at various energy regimes. The main purpose of the present study is to apply Wilsonian methods to the pion-nucleon interaction at low and intermediate energies. The dynamics of this system are quite distinct in that they are essentially nonperturbative and typical cutoffs are not much larger than the nucleon mass. Therefore we use a nonperturbative dynamical model to compute beta-functions by sliding the cutoff in the pion-nucleon vertex while keeping low-energy observables, such as scattering lengths, fixed. A possible application for the obtained beta-functions could be to gain insight into the problem of connecting the low- and intermediate-energy regimes of pion-nucleon dynamics.

The Bethe-Salpeter equation and the low energy theorems for pion-nucleon scattering
(A.D. Lahiff; I.R. Afnan, Flinders)

The Bethe-Salpeter amplitude for πN scattering is evaluated at the off-mass-shell points corresponding to the low energy theorems based on PCAC and current algebra. We find that chiral symmetry is broken via the higher-order multiple scattering of t-channel ρ exchange. The results suggest a way of maintaining consistency between the Bethe-Salpeter amplitude and the low energy theorems.

Baryon resonance extraction from pion-nucleon scattering data in a covariant approach
(A.D. Lahiff; C. Bennhold, George Washington Univ.)

There are a large number of baryon resonances observed experimentally in meson-baryon scattering processes. It is important to be able to extract the properties of these resonances in a reliable way. We are developing a relativistic model of pion-nucleon scattering based on the 4-dimensional Bethe-Salpeter equation including the πN, ηN, $K\Lambda$, and $K\Sigma$ channels, as well as an effective $\pi\pi N$ channel. This covariant model is intended to be used for extracting resonance masses and partial decay widths from experimental data.

Heavy baryons in lattice NRQCD
(N. Mathur, R.M. Woloshyn; R. Lewis, Regina)

The mass spectrum of charmed and bottom baryons was calculated using quenched lattice nonrelativistic QCD. The mass splittings between spin 3/2 and spin 1/2 baryons were calculated and no evidence was found to suggest that there is a suppression of the colour hyperfine effects in baryons as is seen in quenched lattice simulations of the meson sector. In the charm sector the results using NRQCD are compatible with those obtained earlier using a Dirac-Wilson action of the D234 type for the charm quarks.

Strangeness matrix elements in the nucleon
(R. Lewis, Regina; W. Wilcox, Baylor; R.M. Woloshyn)

Quenched lattice QCD simulations and quenched chiral perturbation theory were used together to study matrix elements of strange quark currents in the nucleon. Dependences of the matrix elements on strange quark mass, valence quark mass and momentum transfer calculated in the chiral framework were used to extrapolate lattice QCD results to the physical region.

The main conclusions of this work are that the lattice QCD results for the strange-quark vector current matrix elements in the nucleon are very small in the quark mass range of the simulations and remain small when extrapolated to the physical region. The results of this analysis are consistent with existing experimental results.

Quark interactions in baryons
(F. Okiharu, Nihon Univ.; R.M. Woloshyn)

The interactions of static quarks within baryons is being studied using the methods of lattice QCD. The three quark potential has been calulated and it has been confirmed that the spatial dependence is not that given by either the simplest Y-shaped or triangluar-shaped flux tube models. For large quark separations the Y-shaped flux tube potential seems to be slightly favoured. The distribution of chromo-electric and chromo-magnetic field within the static baryon are being calulated directly to see if this can distingush between the different flux tube configurations. The results of this simulation have large statistical errors and techniques to improve the signals are being studied.

Omega meson propagation in dense nuclear matter and collective excitations
(A.K. Dutt-Mazumder)

The bosonic excitations induced by omega meson propagation in dense nuclear matter are studied within the framework of random phase approximation. The collective modes are then analyzed by finding the zeros of the relevant dielectric functions. Subsequently we present closed form analytical expressions for the dispersion relations in different kinematical regime. Next, the analytical behaviour of the in-medium effective propagator for the omega meson is examined. This is exploited to calculate the full spectral function for the transverse (T) and longitudinal (L) mode of the omega meson. In addition, various sum rules are constructed for the omega meson spectral density in nuclear medium. Results are then discussed by calculating residues at the poles and discontinuities across the cuts.

Aspects of meson properties in dense nuclear matter
(O. Teodorescu, C. Gale, McGill; A.K. Dutt-Mazumder)

We investigate the modification of meson spectral densities in dense nuclear matter at zero temperature. These effects are studied in a fully relativistic mean field model which goes beyond the linear density approximation and also includes baryon resonances. In particular, the role of $N^*(1520)$ and $N^*(1720)$ on the rho meson spectral density is highlighted. Even though the nucleon-nucleon loop and the nucleon-resonance loop contribute with the opposite sign, an overall reduction of rho meson mass is still observed at high density. Importantly, it is shown that the resonances cause substantial broadening of the rho meson spectral density in matter and also induce non-trivial momentum dependence. The spectral density of the a_0 meson is also shown. We study the dispersion relations and collective oscillations induced by the rho meson propagation in nuclear matter together with the influence of the mixing of rho with the a_0 meson. The relevant expression for the plasma frequency is also recovered analytically in the appropriate limit.

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

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 have presented an analysis of the low energy behaviour of the nuclear density of states using the saddle point approximation and extensions to it. Furthermore, we prescribe a simple parabolic form for excitation energy, in the low energy limit, which may facilitate an easy computation of level densities.

Signatures of broken symmetry at GSI
(O. Teodorescu, C. Gale, McGill; A.K. Dutt-Mazumder)

The possibility of observing exclusive matter induced processes in high energy heavy ion collision is discussed. This involves mixing of different quantum states in nuclear matter as a result of broken symmetry in a thermal bath. It is argued that such processes could be observed in the dilepton spectra at GSI energy. Results are compared with CERN dilepton data. We highlight the qualitative difference that one might expect to observe at GSI energies stemming from the matter induced processes with that of CERN/SPS. The most dramatic effect is the clear appearance of an additional peak caused by the matter driven process like π-η annihilation which essentially is related with the broken symmetry in nuclear matter. The whole analysis is performed with the equation state determined from a interacting nuclear matter within the scope of a mean field model.

Low-energy nuclear structure and one-hole spectral function of ^{16}O

(C. Barbieri; W.H. Dickhoff, Washington Univ. (St. Louis))

The best theoretical calculations presently available for the nucleus of ^{16}O are still in disagreement with the experimental data obtained from $(e, e'p)$ reactions. In particular, the theory predicts too high values of the spectroscopic factors at small missing energies. In order to approach this problem we developed a formalism based on Green's function theory and the Faddeev equations technique. Results from such calculations have eventually been obtained during the last year. While discrepancies with the experiment still persist, the new results tend to reduce the disagreement with data and suggest that further improvement should come from better treatment of long-range correlations. In particular, it appears that a better description of the lowest positive parity excited state of the ^{16}O core is required to solve the problem. As a first step in this direction, we have studied the low-energy spectrum of ^{16}O by including the effects of the mixing of two-phonon states. This was done by means of an extension of the random phase approximation equations.

Study of short-range correlation by means of the $(e, e'pN)$ reactions

(C. Barbieri; W.H. Dickhoff, Washington Univ. (St. Louis); C. Giusti, F.D. Pacati, Pavia)

Two-nucleon emission reactions have recently proved to be a powerful tool to study two-body short-range and tensor correlations in nuclei. In these studies, the effects of long-range motion are also important and need to be properly accounted for. The recent Faddeev studies of low-energy structure of ^{16}O (described above) have also produced improved results for the two-hole spectral function. These include the effects of self-consistency and of ground state correlation in the target nucleus. We are now employing these two-hole spectral functions to study the two-proton and the proton-neutron emission from the nucleus of ^{16}O.

Rescattering contribution to $(e, e'p)$ cross section at high missing energy and momenta

(C. Barbieri; W.H. Dickhoff, Washington Univ. (St. Louis); L. Lapikás, NIKHEF; D. Rohe, Basel)

The one-hole spectroscopic function has been measured at Jefferson Laboratory for different nuclei, by the E97-006 collaboration. This experiment focused on the region at high missing energy and missing momenta, where the effects of short-range and tensor correlations are predominant. The data obtained show that a sizable contribution to the experimental cross section comes from processes involving the rescattering of the detected proton against other nucleons in the target. These effects are to be subtracted from the data in order to obtain meaningful results. The contribution of rescattering processes is presently being computed by applying a semiclassical model. This takes into account both the effects of nuclear transparency and the in-medium dependence of the proton-nucleon rescattering rate.

Nucleon-nucleus optical potential at low energy and proton capture

(C. Barbieri, B.K. Jennings)

The proton capture reactions ^{7}Be$(p, \gamma)^{8}$B and ^{16}O$(p, \gamma)^{17}$F at low energy play an important role in the understanding of stellar evolution. In this regime, the nuclear optical potential that describes the nucleon-nucleus interaction can present substantial energy dependence and is expected to be sensitive to the surface of the target nucleus. Such low-energy correlations have been considered for ^{16}O in earlier works, based on the self-consistent Green's function theory. The nuclear self-energy obtained in the latter works is expected to account for the most relevant features of the collective motion on the target nucleus. In general, the nuclear self-energy at positive energies is a realization of the optical potential for the nucleon-nucleus scattering, while at negative energies it gives information on the binding of the final A+1 body system. We are beginning to employ the above self-energy as an optical potential to analyze the scattering of protons by a finite nucleus. The final goal is to eventually reach a reliable theory of proton capture processes and to apply it to the reactions mentioned above.

Numerical calculation of the phase shift with an integral formula

(J.-M. Sparenberg)

A new integral formula for the scattering phase shift has been recently established by Chadan *et* al. [J. Math. Phys. **42**, 4031 (2001)]. Contrary to previous ones, this formula provides the absolute phase shift (no π ambiguity) and does not require a particular normalization of the scattering wave function. It seems thus particularly well suited for numerical calculations. Indeed, both finite-difference and Lagrange-mesh implementations of this formula have revealed several advantages: (i) easy calculation of narrow resonances, (ii) wave function needed on a limited interval only (potential range), (iii) good robustness with respect to imprecise wave functions, (iv) validity in presence of a Coulomb potential. The only drawback appearing up to now is the behaviour of this formula at very low energies in the presence of bound states or narrow resonances. The integrand then presents quasi-singularities that are difficult to handle numerically. A theoretical study of the position of these singularities has been performed and has been able to relate them to the zero-energy wave function. Numerically, the use of an adaptive-step integration method makes things better without totally solving them (increase of computing time).

Study of the nucleon-hyperon interaction by the supersymmetric inversion method
(J.-M. Sparenberg; D. Baye, Free University of Brussels; Y. Fujiwara, Kyoto)

The construction of nucleon-hyperon interaction potentials is interesting for structure studies of hypernuclei, i.e. of nuclei containing one or several hyperons. Since experimental data are rather scarce for these systems, an interesting alternative is to estimate these potentials from theoretical models. For instance, by applying the resonating group method to a constituent quark model, one can get nucleon-hyperon elastic-scattering phase shifts, which can then be turned into potentials through the use of inversion techniques. We have applied an inversion method based on the algebraic formalism of supersymmetric quantum mechanics to analyze the $^1S_0$ and $^3S_1$ $\Lambda - N$ phase shifts. The corresponding potentials are smooth as long as the inverted data lie below the first inelastic threshold. The $^1S_0$ potential is not deeper than the $^3S_1$ one but has a longer range.

Analysis of the ^{12}C + α elastic scattering data by the supersymmetric inversion method
(J.-M. Sparenberg, L. Buchmann)

The ^{12}C (α, γ) ^{16}O radiative capture reaction plays an important role in nuclear astrophysics during the helium combustion phase in stars. Unfortunately, for the very weak energies of astrophysical interest (typically 300 keV in the centre-of-mass frame), this reaction cannot be measured directly in the laboratory (minimal energy: 1 MeV). A theoretical model is thus generally adjusted to available experimental data (radiative capture, α emission of ^{16}O excited states and ^{12}C + α elastic scattering data) to extrapolate them to low energies. The most commonly used model is the R matrix. In principle, an interesting alternative to the R matrix is the potential model; however, no satisfactory potential has been found up to now to describe the ^{12}C + α system. Since the ^{12}C + α elastic scattering has been recently remeasured with a very high precision, inversion techniques can now be used to construct such a potential. We have applied an inversion method based on supersymmetric transformations of the radial Schrödinger equation to construct a potential which reproduces the $l = 0$ phase shifts and which has no bound state. It presents a rather long range, which suggests a polarization phenomenon. Phase-equivalent addition of bound states to this potential as well as inversion of other partial waves are currently under study.

Comparison of calculation methods for resonance widths
(B.K. Jennings, J.-M. Sparenberg)

The calculation of resonance widths is an important issue in nuclear physics, e.g. for the calculation of proton or α decays (see below). The most common method to do so is probably the R matrix, in which the width is expressed in terms of the wave function calculated at some sufficiently large radius (outside the range of nuclear forces). An alternative and elegant method has been proposed by Gurwitz and Kalbermann for the two-body case in which the width is expressed in terms of the Wronskian of the wave function and of a modified Coulomb regular solution, calculated at a particular radius (the top of the potential barrier). This method has been extended to the many-body case and the limitation to a particular radius has been shown to be unnecessary. We have compared these two formalisms in the two-body case, both from the theoretical and numerical point of view. From the theoretical point of view, the equivalence between both methods can be established for narrow resonances without background, provided the radius is chosen inside the barrier and sufficiently far from the classical turning points. The comparison has also revealed the interest of an integral formula for the resonance width. The two methods have been compared numerically for a narrow resonance of a Coulomb + square well potential. Well inside the barrier, both methods provide similar results, as expected from the theoretical analysis. In the vicinity of the turning points, Gurwitz' method provides much better results than the R-matrix without surface correction. Applying the surface correction to the R matrix makes it very precise (much more precise than Gurwitz' formula) in the vicinity of the internal turning point. The comparison in the case of wider resonances and of continuous potentials is in progress.

One-body overlap functions, equations of motion and phenomenological potentials
(J. Escher, B.K. Jennings)

One-body overlap functions play an important role for the description of nuclear structure and nuclear reactions. Equations of motion for the one-body overlaps, based on particle-only, hole-only, and particle-hole approaches, are studied. A given overlap function is shown to satisfy four different Schrödinger-like equations, all of which can be derived in the framework of the Feshbach projection operator formalism. Approximating the relevant potential by a local potential is only valid in the particle-hole approach. Previously proposed one-body functions, which can be derived from the overlap functions, are also considered. It is argued that the latter do not satisfy a Schrödinger-like equation with an approximately local potential.

Contemplating a new measure for nuclear shell closures

(J. Escher, B.K. Jennings)

A special class of low-energy states has been identified for $(A \pm 1)$-body nuclei adjacent to even-even systems for which the independent-particle model (IPM) predicts closed (sub)shells. The states are characterized by spin-parity quantum numbers which match the quantum labels of the associated $(A \mp 1)$-body ground states and by small spectroscopic factors for one-nucleon transfers to/from the ground states of the even-even nuclei. A study of the associated Fliessbach functions shows that these states are structurally correlated with A-body g.s. components other than closed (sub)shell configurations. Under these circumstances, the spectroscopic factors provide a measure of the softness of the Fermi surface in the A-body nucleus. This measure, which is complementary to the systematic features usually employed to study shell closures, was tested for various well-studied nuclei and found to be very reasonable. An application to the ^{22}O region indicates that measuring the spectroscopic factors for the one-body transitions between the ^{22}O ground state and the low-lying $(1/2)^+$ and $(3/2)^+$ states of ^{21}O as well as the low-energy $(5/2)^+$ states of ^{23}O will provide valuable information about the shell structure of ^{22}O.

Proton emission and spectroscopic factors

(J. Al-Khalili, Surrey; J. Escher, B.K. Jennings, J.-M. Sparenberg)

We have shown how to embed the elegant results for proton emission [Gurvitz, Phys. Rev. **A38**, 1747 (1987)] into the full many-body problem. At first sight the results are very encouraging. We have seen that it is possible to express the decay width as the single particle result times the spectroscopic factor. This reinforces the procedure of S. Åberg *et al.* [Phys. Rev. **C56**, 1762 (1997)] where the spectroscopic factor was obtained by dividing a single particle calculation by the experimental lifetime. The decay width is proportional to the square of the matrix element $\langle\psi_0|HQ|\zeta_{E'}\rangle$ (the Q is optional). We now understand how this expression arises and why it is not zero. Neither $|\psi_0\rangle$ nor $|\zeta_{E'}\rangle$ is an eigenfunction of H but both are well defined. If either were eigenfunctions then the matrix element would be zero because $|\psi_0\rangle$ and $|\zeta_{E'}\rangle$ are orthogonal. This should resolve an old dispute.

Unfortunately there is a serious problem: the spectroscopic factor is not actually an observable in proton emission but rather $\int^{r_t} dr\phi_R^*(r)\left(1-\frac{\partial H_R(E)}{\partial E}\right)\phi_R(r)$ is the observable. The optical potential dependence noted in calculations is not just a practical detail but an important matter of principle. If the phenomenological potential does not correspond to the potential in the Hamiltonian for the spectroscopic factor but rather a different Hamiltonian then S_0 does not occur, but rather a different normalization constant. Indeed, K. Varga and R.G. Lovas [Phys. Rev. **C43**, 1201 (1991)] argue strongly that it is $\bar{\phi}(r)$ that corresponds to the phenomenological potential. There the argument is applied to alpha emission but a similar analysis will carry over for proton emission.

Partial dynamical symmetry in an interacting fermion system

(J. Escher; A. Leviatan, Hebrew Univ.)

We present an example of a partial dynamical symmetry (PDS) in an interacting fermion system and 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, 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.