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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

OCTOBER 2002

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

Theoretical research at TRIUMF is centred on the TRIUMF Theory group, a group consisting of four permanent members, six to seven research associates, about six graduate students, and many visitors. Its main research interests are physics beyond the standard model, lattice QCD, intermediate energy nuclear physics, and low energy nuclear reactions. In addition to carrying out its own independent research, it provides support for the TRIUMF experimental program and acts as a resource for the experimentalists.

The four permanent members of the Theory group are: Harold W. Fearing (group leader), Byron K. Jennings, John N. Ng and Richard M. Woloshyn. Erich W. Vogt (professor emeritus, UBC) is an associate member. We have had two sabbatical visitors this year, Helmy S. Sherif and Chaoqiang Geng. Our research associates are: W. Chang (since September), A.K. Dutt-Mazumder (since September), J. Escher, S.K. Gosh (until September), C.P. Liu (since September), S. Kondratyuk. X. Kong (until September), A.D. Lahiff, G. Rupak, and W. Schadow (until September). The graduate students associated with the group are: C. Bird, T. Ebertshauser, F. Okiharu, C.C. Liu, E. Ho, I.L. Ho, and T.H. Wu.

The visitors to the Theory group this year include:

K. Abazajian	F. Khanna	S. Reddy
K. Amos	R. Lewis	A. Rinat
A. Arbuzov	H. Lipkin	A.E. Santana
S. Beane	M. Locher	T. Schaefer
B. Campbell	G. McLaughlin	E. Swanson
D. Chang	A. Mekjian	I. Towner
A. Czarnecki	D.-P. Min	W. Wilcox
A. Gal	M. Patel	D. Wilkinson
N. Hambli	D. Phillips	C.E. Wolfe
J. Jose	I. Popescu	S. Wong
C.S. Lam	M. Ramsey-Musolf	L. Zamick
S. Karataglides		

The Theory Research Program

Neutrinos in extra dimensions
(J.N. Ng; C.S. Lam, McGill)

We investigate the possibility that the large mixing of neutrinos is induced by their large coupling to a five-dimensional bulk neutrino. In the strong coupling limit the model is exactly soluble. It gives rise to an oscillation amplitude whose squared-mass difference is independent of the channel, thus making it impossible to explain both the solar and the atmospheric neutrino oscillations simultaneously.

Neutrino mass in the Zee model and muon $g-2$
(J.N. Ng; H.J. He, D. Dicus, Texas)

Existing neutrino oscillation data strongly point to new physics beyond the standard model (SM). We study a minimal modification of the Zee-mechanism with an additional singlet Zee-scalar K^{++} (but the same SM fermion spectrum), which radiatively generates the neutrino Majorana masses from the two-loop. With this scheme, we construct a class of models with minimal U(1) family symmetry (à la Froggatt-Nielsen) to naturally explain the neutrino oscillations and lepton mass spectrum, as well as the BNL muon $g-2$ anomaly. The 3×3 radiative neutrino mass-matrix is found to exhibit nearly bi-maximal mixing, while the K^{++} scalar is shown to be generically light, with essentially flavour non-diagonal Yukawa couplings. Implications for lepton flavour-violation processes are further analyzed.

Testing discrete symmetries with η decays
(C.Q. Geng, Tsing Hua, Taiwan)

The radiative decay $\eta \to \pi\pi\gamma$ can be a probe of new physics that violates charge conjugation (C) and time reversal (T) symmetries. We discuss the measurements required to facilitate such observations. We also show how these studies complement the searches for new physics such as neutron electric dipole moment experiments.

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

The contribution of the strange-quark current to the electromagnetic form factors of the nucleon is being studied using lattice QCD. The strange current matrix elements from our lattice calculation are analyzed in two different ways: the differential method used in an earlier work by Wilcox, and a cumulative method which sums over all current insertion times. The preliminary results of the simulation indicate the importance of high statistics, and that consistent results between the varying analysis methods can be achieved. Several criteria useful in assessing the robustness of a signal extracted from a noisy background have been developed. No signal satisfying these criteria has yet been seen.

Charmed baryons in lattice QCD
(R. Lewis, Regina; N. Mathur, R.M. Woloshyn)

Masses of singly and doubly charmed baryons were calculated in quenched lattice QCD using an improved action of the D234 type on an anisotropic lattice. The mass differences between spin 3/2 and spin 1/2 baryon states were calculated and compared to mass differences between vector and pseudoscalar mesons. The suppression of spin splittings in mesons containing heavy quarks, characteristic of quenched QCD simulations, was not observed in the baryon sector. The mass dependence of colour hyperfine effects is discussed within the context of the quark model and heavy quark effective theory.

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

A project to study quark-quark interactions using the methods of lattice QCD and to compare them to quark-antiquark interactions has been started. This work is motivated in part by empirical evidence which shows a seemingly simple relationship between spin splittings of mesons and baryons. It is also aimed at addressing a recent controversy concerning the nature of gluonic flux distributions within baryons. Initially we will calculate the three-quark potential from baryonic Wilson loops to try to understand the flux distribution. Then the plan is to extend the calculation to the spin dependent parts of the potential and to make a detailed comparison with the quark-antiquark interaction.

Baryon resonance extraction from pion-nucleon 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 from the experimental data in a reliable way. We are developing a relativistic model of pion-nucleon scattering based on the 4-dimensional Bethe-Salpeter equation which, at present, includes the πN, ηN, and an effective $\pi\pi N$ channel. This covariant model will be used to extract resonance masses and partial decay widths from experimental data on the reactions $\pi N \to \pi N$, $\pi N \to \pi\pi N$, and $\pi N \to \eta N$.

Covariant model of anti-kaon nucleon scattering
(A.D. Lahiff)

A covariant meson-exchange model of the $\bar{K}N$ interaction is constructed using the multi-channel Bethe-Salpeter equation, which is solved by means of a Wick rotation. The K^-p, $\bar{K}^0n$, $\pi^0\Lambda$, $\pi^+\Sigma^-$, $\pi^0\Sigma^0$, $\pi^-\Sigma^+$, $\eta\Lambda$, $\eta\Sigma^0$, $K^+\Xi^-$, and $K^0\Xi^0$ channels are taken into account. The interaction kernels are constructed from the s- and u-channel baryon poles and t-channel vector meson pole diagrams obtained from the usual SU(3)-symmetric BBP, BBV, and PPV interaction Lagrangians (here B, P, and V represent the $J^P = 1/2^+$ baryons, the pseudoscalar mesons, and the vector mesons, respectively). All propagators are multiplied by dipole form factors, with the same cutoff mass used everywhere. The basic coupling constants are fixed from other sources, such as decay widths and vector-meson dominance. With just one free parameter (the cutoff mass), a good description of the available $\bar{K}N$ data is obtained from below threshold to 300 MeV laboratory momentum. The $\Lambda(1405)$ and $\Lambda(1670)$ resonances are generated dynamically as $\bar{K}N$ and $K\Xi$ quasi-bound states, respectively.

Unitarity and the Bethe-Salpeter equation
(A.D. Lahiff; I.R. Afnan, Flinders)

We investigate the relationship between different three-dimensional reductions of the Bethe-Salpeter equation and the analytic structure of the resultant amplitudes in the energy plane. This correlation is studied for both the $\phi^2\sigma$ Lagrangian and the πN system with s-, u-, and t-channel pole diagrams as driving terms. We observe that the equal-time (or Klein) equation, which includes some of the three-body unitarity cuts, gives the best agreement with the Bethe-Salpeter result. This is followed by other 3-D approximations that have less of the analytic structure.

Effects of meson loops on the interaction of the Δ resonance
(S. Kondratyuk)

The dressed Δ propagator and $\pi N\Delta$ vertex are calculated including meson loop corrections up to infinite order. Thus a self-consistent procedure is developed in which the nucleon and Δ propagators and vertices are treated on the same footing. The dressing procedure is part of a K-matrix approach to the pion-nucleon scattering, pion photoproduction and Compton scattering. The central ingredient of the method is a system of coupled integral equations which is solved by iteration, including the loop corrections with the π, ρ and σ mesons. The obtained propagators and vertices are consistent with the important constraints of unitarity, analyticity and crossing symmetry for the scattering amplitude. The effects of the meson loop corrections on the πNN and $\pi N\Delta$ form factors are qualitatively similar. A good description of the pion-nucleon phase shifts is obtained even though the few input parameters are tightly constrained due to the nonperturbative nature of the procedure. The description of the P33 phase shift is improved by the dressing of the Δ resonance.

The equivalence theorem and the Bethe-Salpeter equation
(S. Kondratyuk, A.D. Lahiff, H.W. Fearing)

The independence of the scattering matrix on the choice of interpolating fields is known as the equivalence theorem. To examine the validity of the equivalence theorem in typical non-perturbative approaches to hadronic processes, we solve the Bethe-Salpeter equation for two-particle scattering in a field-theoretical model using two Lagrangians related by a field transformation. The kernel of the equation consists of the sum of all tree-level diagrams for each Lagrangian. The solutions differ even if all four external particles are put on the mass shell, which implies that observables calculated by solving the Bethe-Salpeter equation depend on the representation of the theory. We argue that the principal origin of this representation-dependence is the well-known fact that certain classes of loop graphs are not generated by the equation with a tree-level kernel. An important implication of our result is that the choice of a convenient representation is an additional model assumption in traditional dynamical approaches based on the Bethe-Salpeter equation.

Irreducible pionic effects in nucleon-deuteron scattering below 20 MeV

(L. Canton, INFN, Padova; W. Schadow; J. Haidenbauer, IKP-Jülich)

The consequences of a recently introduced irreducible pionic effect in low energy nucleon-deuteron scattering are analyzed. Differential cross sections, nucleon (vector) and deuteron (vector and tensor) analyzing powers, and four different polarization transfer coefficients have been considered. This $3NF$-like effect is generated by the pion-exchange diagram in the presence of a two-nucleon correlation, and is partially cancelled by meson-retardation contributions. Indications are provided that such types of effects are capable of selectively increasing the vector (nucleon and deuteron) analyzing powers, while in the considered energy range they are almost negligible on the differential cross sections. These indications, observed with different realistic nucleon-nucleon interactions, provide additional evidence that such $3NF$-like effects indeed have the potential to solve the puzzle of the vector analyzing powers. Smaller but non-negligible effects are observed for the other spin observables. In some cases, we find that the modifications introduced by such pionic effects on these spin observables (other than the vector analyzing powers) are significant and interesting and could be observed by experiments.

The one-pion-exchange three-nucleon force and the A_y puzzle

(L. Canton, INFN, Padova; W. Schadow)

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

Photonuclear reactions of three-nucleon systems

(W. Schadow; O. Nohadani, W. Sandhas, Bonn)

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

Few-body states in Fermi systems and condensation phenomena

(P. Schuck, ISN Grenoble; M. Beyer, G. Röpke, Rostock; W. Schadow; A. Schnell, Washington)

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

Three-nucleon portrait with pion

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

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

Spin observables for pion production from *pd* collisions

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

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

Sigma-term and pion-nucleon amplitude near threshold: beyond few pion-loop corrections

(S. Kondratyuk)

The nucleon sigma-term describes how the nucleon mass changes with varying quark mass and as such is an important link between fundamental degrees of freedom of QCD and properties of hadrons. In particular, it serves as a measure of the explicit chiral symmetry breaking. The sigma-term can be calculated from the pion-nucleon scattering amplitude in the sub-threshold region, where it is constrained by chiral low-energy theorems. In this work the nucleon sigma-term is computed using a dynamical relativistic-invariant, unitary and crossing symmetric model in which certain analyticity constraints are also implemented. The most important hadronic degrees of freedom are included in the model: the nucleon, the Δ resonance, the π, ρ and σ mesons. The interactions of the nucleon and the Δ with the pion are calculated in a self-consistent dressing procedure through solving a system of coupled integral equations for the corresponding Green's functions. Compared to existing effective perturbative approaches, the present calculation allows one to study effects of multiple meson loops on the sub- and near-threshold amplitude. In particular, we find that these effects are rather important for the sigma-term. The calculated amplitude at the sub-threshold Cheng-Dashen point threshold is compatible with the values extracted from dispersion data analysis. The calculated pion-nucleon scattering lengths are also consistent with experiment, as well as the phase shifts up to pion energies of 800 MeV. The good description of the amplitude both below and above the threshold region is achieved because the essential analyticity and unitarity structure of the calculated Green's functions is correctly reproduced. This in turn is effected by utilizing dispersion techniques in solving the dressing equations.

Vector mesons in the nuclear medium

(A.K. Dutt-Mazumder)

One of the contemporary issues of high energy nuclear physics has been to study the in-medium properties of hadrons. In particular, the behaviour of vector mesons in a thermal bath has become a cardinal focus for quite some time. This is because of two reasons. Firstly, they can decay into a photon and dileptons and provide a penetrating probe to the hot and dense nuclear system temporarily produced in high energy heavy ion collisions. Secondly, there has been a prediction that in hot and/or dense matter their masses might undergo a reduction indicating partial restoration of chiral symmetry.

We have studied the properties of light vector mesons, viz. ρ, ω and ϕ in various phenomenological models including QCD sum rule. We have shown that the ρ meson spectral function undergoes dramatic changes in the nuclear medium and could hardly be interpreted as quasiparticle excitation anymore. Furthermore, we also have discussed various symmetry breaking effects viz. the Lorentz symmetry breaking and the violation of charge conjugation symmetry in hot and dense nuclear matter, which, unlike vacuum, might lead to a mixing of different quantum states resulting in a different dilepton spectra than what one expects without taking these additional effects into account. Presently we are focusing on the possibilities of delineating such signals in the experiments to be performed at GSI, CERN and RHIC.

Consistency between the low-energy nucleon Compton scattering and sum rules

(S. Kondratyuk; O. Scholten, Groningen)

The purpose of this work is to focus attention on the general question of agreement between the polarizabilities extracted from the low-energy expansion of the amplitude and those obtained from the sum rules. The Gerasimov-Drell-Hearn and Baldin-Lapidus sum rules are evaluated in the dressed K-matrix model for photon-induced reactions on the nucleon. For the first time the sum $\alpha+\beta$ of the electric and magnetic polarizabilities and the forward spin polarizability γ_0 are explicitly calculated in two alternative ways – from the sum rules and from the low-energy expansion of the real Compton scattering amplitude – within the *same* framework. We find agreement between the two methods in the leading order terms related to the anomalous magnetic moment (the Gerasimov-Drell-Hearn sum rule) and $\alpha+\beta$ (the Baldin-Lapidus sum rule), but some violation in the next order related to γ_0. This discrepancy at third order can be understood on the basis of model approximations in the treatment of the self-energy and vertex corrections of the Δ resonance. Consistency between the two ways of determining the polarizabilities is a measure of the extent to which basic symmetries of the model are obeyed. In particular, the agreement found at the leading orders shows that the model obeys the essential causality constraints.

Polarized photons in radiative muon capture
(S.-I. Ando, South Carolina; D.-P. Min, Seoul; H.W. Fearing)

We discuss the measurement of polarized photons arising from radiative muon capture. The spectrum of left circularly polarized photons, or equivalently the circular polarization of the photons emitted in radiative muon capture on hydrogen, is quite sensitive to the strength of the induced pseudoscalar coupling constant g_P. A measurement of either of these quantities, although very difficult, might be sufficient to resolve the present puzzle resulting from the disagreement between the theoretical prediction for g_P and the results of a recent experiment. This sensitivity results from the absence of left-handed radiation from the muon line and from the fact that the leading parts of the radiation from the hadronic lines, as determined from the chiral power counting rules of heavy-baryon chiral perturbation theory, all contain pion poles.

The anomalous chiral perturbation theory meson Lagrangian to order p^6 revisited
(T. Ebertshäuser, S. Scherer, Mainz; H.W. Fearing)

We present a revised and extended construction of the mesonic Lagrangian density in chiral perturbation theory (ChPT) at order p^6 in the anomalous (or epsilon) sector, $\mathcal{L}_{6,\epsilon}$. After improving several aspects of the strategy we used originally, i.e., a more efficient application of partial integration, the implementation of so-called Bianchi identities, and additional trace relations, we find the new monomial sets to include 24 SU(N_f), 23 SU(3), and 5 SU(2) elements. Furthermore, we introduce 8 supplementary terms due to the extension of the chiral group to $\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R \times \mathrm{U}(1)_V$.

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

The rate of the nuclear reaction $^3\mathrm{He} + \mu^- \rightarrow {}^3\mathrm{H} + \gamma + \nu_\mu$ has been calculated using both the elementary particle model (EPM) approach and the impulse approximation (IA) approach. Using the EPM approach, the exclusive statistical radiative muon capture (RMC) rate for photon energy greater than 57 MeV is found to be 0.245 s^{-1} and the ordinary muon capture (OMC) rate to be 1503 s^{-1}. The IA calculation exhibits a slight dependence on the type of trinucleon wave function used. The difference between the IA and EPM calculation is larger for RMC than for OMC. To resolve the difference between the two approaches a more detailed investigation including meson exchange corrections will be required.

Infrared regularization in relativistic chiral perturbation theory
(C. Bird, H.W. Fearing)

Chiral perturbation theory is a useful tool in the study of low energy reactions involving light particles. However, the inclusion of heavy particles in chiral perturbation theory results in large contributions from loop diagrams which violate the standard power counting scheme. We review two methods, referred to as heavy baryon chiral perturbation theory and infrared regularization, which remove the high energy effects of the heavy particles and which therefore do not violate the power counting scheme. We then use these two methods to calculate the amplitude for pion photoproduction to fourth order and prove that the two amplitudes are equivalent.

Double radiative pion capture in heavy baryon chiral perturbation theory
(H.W. Fearing; C. Unkmeir, S. Scherer, Mainz)

The process $\pi + p \rightarrow n + \gamma + \gamma$, or equivalently $\gamma + p \rightarrow n + \pi + \gamma$, is of interest because one of the contributing sub-diagrams contains the pion Compton scattering reaction and the question arises whether or not a measurement of these processes would give somewhat the same information as could be obtained from pion Compton scattering, were it possible to do that experiment directly. Experiments are under way both at TRIUMF and Mainz to investigate these processes. We have calculated the amplitude for the doubly radiative capture process in heavy baryon chiral perturbation theory to one loop order, that is, to $\mathcal{O}(p^3)$. The low energy constants involved are the same as those we evaluated earlier in calculations of muon capture and singly radiative pion capture. The amplitude is, however, extremely complicated and efforts are under way to simplify our result enough to make it possible to easily compare with experiment.

The induced pseudoscalar coupling of the proton weak interaction
(T. Gorringe, Kentucky; H.W. Fearing)

Of the fundamental couplings which contribute to the weak interaction of nucleons, the induced pseudoscalar g_P is least well known. There is a well known theoretical prediction, the Goldberger-Treiman relation, coming from PCAC, which can be strengthened using the techniques of chiral perturbation theory. Empirical information comes primarily from both ordinary and radiative muon capture. We are preparing a review summarizing what is known theoretically about g_P and what can be extracted from data on muon capture in nuclei and on the proton.

The asymmetry in quasielastic electron-deuteron scattering due to the parity-nonconserving nucleon-nucleon interaction
(C.P. Liu, W. Haxton, INT/Washington; M. Ramsey-Musolf, Connecticut; G. Prézeau, Caltech)

By measuring the asymmetry factors in elastic electron-proton and quasielastic electron-deuteron scattering, one can determine the strange magnetic form factor, G_M^s, and the isovector axial form factor (seen by the electron), $G_A^e(T=1)$, at a certain Q^2 set up by the experiment. 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. According to the results published by the SAMPLE collaboration, the experimental value for $G_A^e(T=1)$ is much larger than the theoretical prediction, and this puzzle has already caught a lot of attention. One key assumption made when interpreting the measured asymmetry is the static approximation, which pictures proton and neutron as independent particles. Although it seems reasonable at the quasielastic limit, however, it needs to be further confirmed given such a big theory–vs.–experiment discrepancy. As the parity-nonconserving nucleon-nucleon interaction also contributes to the asymmetry in the deuteron case, we would like to clarify the role it plays in the SAMPLE experiment and see if it helps to resolve the puzzle.

Radiative corrections in the superallowed Fermi β decay
(C.P. Liu, W. Haxton, INT/Washington; M. Ramsey-Musolf, Connecticut)

The unitarity of the Cabbibo-Kobayashi-Maskawa matrix is extremely important for the test of the standard model and the constraint of physics beyond. In the unitarity relation of the first row, i.e. $\sum_i |V_{ui}|^2 = 1$, the element V_{ud} is the dominant one. Currently the most precise value for V_{ud} comes from the superallowed Fermi β decay (the precision is about two times better than what is achieved in free neutron decay), which gives $|V_{ud}| = 0.9740 \pm 0.0005$. Combined with the values of V_{us} and V_{ub}, the unitarity has failed by 2σ. One uncertainty in the extraction of V_{ud} comes from the estimation of the radiative corrections. Since the nuclei are many-body systems, how the radiative corrections are modified by the nuclear correlation, and how the nuclear Green's function is different from the free particle propagator are what we are trying to figure out and we hope to improve previous work on this subject.

Nuclear structure effects in nucleon capture reactions
(J. Escher, B.K. Jennings, H.S. Sherif)

Nucleon capture reactions play an important role in our understanding of astrophysical phenomena. For example, exact knowledge of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section is necessary for calculating the neutrino flux generated in the sun, the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ process plays an important role in the hot CNO cycle, and the $^7\mathrm{Li}(n,\gamma)^8\mathrm{Li}$ reaction is a key element of primordial nucleosynthesis in inhomogeneous big bang scenarios. We have been studying spectroscopic amplitudes, spectroscopic factors, and their significance for the description of single-particle transfer reactions such as nucleon capture. We demonstrated that spectroscopic amplitudes (overlap functions) contain both single-particle and many-nucleon aspects of the nuclear many-body problem. In principle, the amplitudes can be obtained from a fully microscopic model. We presented two alternative approaches, each based on a set of exact coupled-channels equations, from which we derived several well-known approximation schemes, such as Hartree, Hartree-Fock and two distinct single-particle models. We considered the implications of our results for the calculation of reaction cross sections in potential-model approaches and illustrated how microscopic structure effects arise naturally in the relevant transition matrix elements and can be (in part) accounted for via spectroscopic factors.

Spectroscopic amplitudes from shell model and cluster model approaches
(J. Escher, B.K. Jennings)

A reliable calculation of nuclear reaction cross sections must include both one-body and many-body effects. For single-particle transfer reactions this can be accomplished through the use of spectroscopic amplitudes (overlap functions). Obtaining these amplitudes, however, requires solving a set of complicated coupled differential equations or a fully microscopic model. Recent advances in nuclear many-body theory have resulted in highly accurate microscopic treatments for very light nuclei. For heavier systems one has more traditional approaches available such as the shell model or the cluster model, both of which include some many-nucleon correlations and provide reasonable approximations to the full problem. Currently, we are exploring possibilities for obtaining realistic spectroscopic amplitudes from shell model and cluster model approaches.

Nuclear structure and solar neutrinos
(B.K. Jennings, J. Escher)

The $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction at solar energies ($E_{cm} \leq$ 20 keV) is relevant to neutrino physics since the neutrino event rate in the existing chlorine and water Čerenkov detectors is dominated by the high-energy neutrinos produced in the subsequent β decay of ^{8}B. Precise knowledge of the neutrino flux generated in the sun will help to place constraints on possible "new physics" scenarios such as neutrino flavour oscillations. Direct measurements of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction at energies corresponding to astrophysically relevant temperatures are very difficult, since the cross section diminishes exponentially at low energies. The reaction rate has to be deduced by extrapolating the measured absolute (laboratory) cross section from energies above 100 keV to the astrophysically relevant regime. While theoretical considerations have established the energy dependence of the cross section for energies below about 400 keV, the overall normalization of the cross section is more difficult to obtain. We are currently exploring several options for improving the theoretical predictions for this quantity. The goal of this project is to provide a better determination of the reaction rate and thus to contribute to a clearer understanding of this rare, but crucial, solar fusion process, as well as to achieve more accurate estimates of the neutrino flux from our sun.

Partial dynamical symmetry in an interacting fermion system
(J. Escher; A. Leviatan, Hebrew Univ.)

Symmetries play an important role in dynamical systems. They provide labels for the classification of states, determine selection rules, and simplify the relevant Hamiltonian matrices. Algebraic, symmetry-based models offer significant simplifications when the Hamiltonian under consideration commutes with all the generators of a particular group ("exact symmetry") or when it is written in terms of the Casimir operators of a chain of nested groups ("dynamical symmetry"). However, 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 are 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 (i.e. quantum labels) 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). Partial symmetries have been investigated in both bosonic and fermionic descriptions of nuclei, in the context of supersymmetry, as well as in molecular physics. We have studied PDS in fermionic models of the nucleus, introduced a family of Hamiltonians with partial SU(3) symmetry, and shown 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 prolate, oblate, and triaxially deformed nuclei, and to study the structure of the associated eigenstates.

Symplectic shell model and multi-$\hbar\omega$ correlations in electron scattering observables
(J. Escher)

A microscopic theory for deformed nuclei, which takes proper account of the Exclusion Principle and of inter-shell couplings, is given by the Symplectic Shell Model. The model uses symmetries of the nuclear many-body system to classify and truncate the enormous shell model space while retaining the multi-shell quadrupole correlations which lead to deformation. It is able to reproduce intra-band and inter-band E2 transition strengths between low-lying, as well as giant, resonance states without introducing proton and neutron effective charges, and its observables are expressible in microscopic shell-model terms. We apply the symplectic model to light (p-shell and sd-shell) nuclei and investigate the influence of multi-shell correlations on nuclear charge and current densities. Such studies are important since they allow one to place quantitative limits on the contributions to the nuclear current from meson exchange. Furthermore, since electron scattering observables provide a direct probe of the nuclear current, this study is able to shed light on the dynamical character of nuclear rotational motion and thus it addresses one of the unsolved fundamental questions of nuclear structure physics.

Shell closures in nuclei far off stability
(J. Escher, B.K. Jennings)

Whereas the magic numbers are very well established for stable nuclear species, little is known about the shell structure of nuclei far off the line of stability. This information, however, is very valuable, not only for achieving simplifications in the descriptions of these nuclei, but also in the context of astrophysics. Nuclear abundances from the astrophysical r-process, for example, depend on the shell closures in neutron-rich nuclei beyond the iron region. Traditional experimental signatures for magic numbers involve primarily systematic features, such as the energies and electromagnetic transition strengths of the first excited states in even-even nuclei or nucleon separation energies of odd-A chains. Our recent work suggests that a new measure for shell closures in a given even-even nucleus can be found in the adjacent A±1 nucleon systems. Since the proposed new signature involves spectroscopic information on very specific excited states of the immediate neighbours only, it is different from and complementary to traditional approaches. Furthermore, the new signature provides some quantitative measure for the goodness of shell closures in the region considered. We have been testing this new signature for stable nuclei, for which there is much spectroscopic information available, and are now working on applications to the oxygen isotopes near the neutron drip line.