TRIUMF

ANNUAL REPORT
SCIENTIFIC ACTIVITIES
2003

ISSN 1492-417X

CANADA'S NATIONAL LABORATORY
FOR PARTICLE AND NUCLEAR PHYSICS

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2004

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

THEORETICAL PROGRAM

Introduction

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

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

The four permanent staff members of the group are: Harold W. Fearing, Byron K. Jennings (group leader), John N. Ng, and Richard M. Woloshyn. Erich W. Vogt (professor emeritus, UBC) is an associate member.

Research associates during 2003 were: R. Allahverdi, S. Ando, C. Barbieri, W. Chang, R. Cyburt (from September), A.K. Dutt-Mazumder (until December), C.P. Liu (until October), J.-M. Sparenberg, and L. Theussl (from September).

The graduate students associated with the group during 2003 were: F. Okiharu and K. Wong, both supervised by R. Woloshyn.

The visitors to the Theory group this year included: J. Al-Khalili, D. Atwood, B. Balantekin, T. Becher, S. Bilenky, C.W. Chiang, G. Carter, A. Datta, W. Detmold, W. Dickhoff, G. Drake, A. El-Khadra, V. Flambaum, C.Q. Geng, S. Godfrey, S. Groot Nibbelink, T. Hemmert, F. Herwig, K. Hornbostel, K. Langanke, M. Locher, K. Maltman, B. McElrath, R. Myers, A. Nogga, K. Nollett, M. Pospelov, A. Rinat, S. Scherer, I. Stetcu, T. Tait, M. Voloshin, N. Weiner, D. Wilkinson, M. Wingate and J. Yoo.

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

Nuclear Structure and Reactions

Potential-model and R-matrix analyses of ^{12}C + α elastic scattering phase shifts

(J.-M. Sparenberg)

Using general results from the inverse problem in quantum scattering theory, it has been argued that, for a given partial wave, bound-state properties (number of bound states, energies, asymptotic normalization constants) are independent of one another and of the corresponding scattering phase shifts. This has been illustrated on the $\ell = 2$ partial wave of the ^{12}C + α system in a simplified potential model: with the help of an inversion method based on supersymmetric quantum mechanics, potentials have been constructed, that reproduce the $\ell = 2$ phase shifts deduced from a recent re-measurement of the elastic-scattering cross sections. By construction, these *phase-equivalent* potentials (identical phase shifts) have a bound state at -245 keV describing the 2^+ subthreshold state of ^{16}O, which is known to have a strong influence on the ^{12}C $(\alpha,\gamma)^{16}$O capture reaction at astrophysical energies. However, the asymptotic normalization constant of this state, C_{12}, which is the key quantity for the capture reaction, is arbitrarily different from one potential to the other, despite their identical phase shifts and bound-state energy. This contradicts two recent R-matrix analyses of the ^{12}C + α system, aiming at extracting C_{12} from the $\ell = 2$ phase shifts and the bound-state energy: both analyses have been shown to be unreliable, which explains the inconsistency between their results. In contrast, it has been shown that if the inversion potential is used to reproduce not only the $\ell = 2$ data but the whole $\ell = 0, 2, 4, 6$ rotational band, C_{12} is strongly constrained. Combining this result with other potentials from the literature has led to $C_{12} = 144.5 \pm 8.5 \times 10^3$ fm$^{-1/2}$. This value is consistent with a theoretical estimate from the microscopic cluster model and with transfer-reaction data, provided small many-body effects are taken into account. On the other hand, it disagrees with cascade-transition data, a new measurement of which is foreseen at TRIUMF.

Construction of a Λ-Λ effective interaction for the calculation of hypernuclei

(J.-M. Sparenberg; Y. Fujiwara, Kyoto; K. Miyagawa, Okayama Science Univ.; M. Kohno, Kyushu Dental College; Y. Suzuki, Niigata; D. Baye, Brussels Free Univ.)

The $^1S_0$ Λ-Λ phase shifts generated by a QCD-inspired spin-flavour SU_6 quark model have been analyzed by a supersymmetric inversion method. This leads to a local potential which has been approximated by the sum of two Gaussian functions. This effective potential, together with Λ-N effective interactions obtained in the same way, has been used in microscopic calculations of the ${}^{6}_{\Lambda\Lambda}$He and ${}^{9}_{\Lambda}$Be hypernuclei with a new three-cluster Faddeev formalism based on the two-cluster resonating-group-method kernel.

Comparison of one-body functions deduced from microscopic models of the ^{8}B and ^{17}F nuclei

(J.-M. Sparenberg, C. Barbieri, B. Jennings; P. Descouvemont, Brussels Free Univ.)

Different ways of reducing a many-body problem to a two-body problem have been proposed in the literature, depending on the type of one-body function used. We have compared the approach based on the one-body overlap function to that based on an auxiliary function used in the microscopic cluster model. For the ^{17}F nucleus, as calculated by a microscopic Green's function-Faddeev equation method, both functions are very close to one another for states that have a strong ^{16}O + p structure, and appreciably different from one another for states that have a more complicated structure. For the ^{8}B ground state, as calculated by a microscopic generator-coordinate cluster model, an appreciable difference between both functions is also seen, despite the fact that this state seems to have a ^{7}Be + p structure with a good approximation. Only the one-body overlap function is close to the phenomenological ^{7}Be + p potential-model wave function, which tends to indicate that it has a stronger physical meaning than the auxiliary function.

Proton emission

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

We have embedded the elegant Gurvitz-Kalbermann approach to proton emission [Gurvitz and Kalbermann, Phys. Rev. Lett. **59**, 262 (1987)] in a full many-body picture. We reduced the formalism to an effective one-body problem and demonstrated that the decay width can be expressed in terms of a one-body matrix element multiplied by a normalization factor. At first sight, this result agrees with the standard procedure for extracting spectroscopic factors from measurements via dividing an experimental width by a calculated single-particle width. The present work, however, clearly demonstrates that this procedure for determining spectroscopic factors is only valid if the phenomenological potential used to generate the single-particle width corresponds to the mass operator in the particle-hole Green's function. It is not *a priori* clear that this is actually the case. In fact, it has been strongly suggested [see Varga and Lovas, Phys. Rev. **C43**, 1201 (1991); Lovas *et al.*, Phys. Rep. **294**, 265 (1998) and references therein] this is not the case. While that study was carried out for alpha decay, the arguments given there can be carried over to a description of the proton emission process. Furthermore, the present work suggests that $\int_0^{r_t} dr\phi_{\rm r}^*(r)\left[1-\frac{\partial H_{\rm r}(E)}{\partial E}\right]\phi_{\rm r}(r)$ is the appropriate observable that can be extracted from proton emission experiments.

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 ^{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 tend to reduce the disagreement with the experimental data and suggest that further improvement should come from better treatment of long-range correlations. The latter need to be described in terms of low energy collective excitations, including the effects of fragmentation. For the particular case of ^{16}O it appears that the coupling of up to four-phonon states is required. Encouraging results have been obtained by considering the coupling of two phonons and the extension of our calculation to the full four-phonon case is under way.

The present calculations on ^{16}O are also meant to serve as a test ground for calculations with the above formalism, in view of possible application to other medium and heavy nuclei.

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. In collaboration with the Pavia group, 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.

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 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 couplings between the nucleon and the surface vibrations of the target. Such low-energy modes have been considered for ^{16}O in earlier works. There, the nuclear self-energy was obtained using self-consistent Green's function theory.

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. Work is in progress to employ the above calculated self-energy as an optical potential to analyze the scattering and capture of nucleons at low energy.

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

(C. Barbieri; L. Lapikás, NIKHEF; D. Rohe, Basel, for the E97-006 collaboration)

The contribution of rescattering to final state interactions in the $(e, e'p)$ cross section is studied using a semiclassical model. This approach considers a two-step process with the propagation of an intermediate nucleon and uses Glauber theory to account for the reduction of the experimental yield due to $N - N$ scattering. This calculation has relevance for the analysis of data at high missing energies and in particular at the kinematics of the E97-006 experiment done at JLab. It is found that rescattering is strongly reduced in parallel kinematics and that the excitation of nucleon resonances is likely to give important contributions to the final state interactions in the correlated region. For heavy nuclei, further enhancement to the rescattering is expected to be generated from the strength in the mean field region.

The analysis of data from the E97-006 collaboration is expected to yield, for the first time, experimental information on the spectral distribution of short-range correlated nucleons in finite nuclei.

Nuclear Astrophysics, Cosmology

Solar neutrino constraints on the BBN production of Li

(R.H. Cyburt; B.D. Fields, Illinois; K.A. Olive, Minnesota)

Using the recent WMAP determination of the baryon-to-photon ratio, $10^{10}\eta = 6.14$ to within a few per cent, big bang nucleosynthesis (BBN) calculations can make relatively accurate predictions of the abundances of the light element isotopes which can be tested against observational abundance determinations. At this value of η, the ^{7}Li abundance is predicted to be significantly higher than that observed in low metallicity halo dwarf stars. Among the possible resolutions to this discrepancy are 1) ^{7}Li depletion in the atmosphere of stars; 2) systematic errors originating from the choice of stellar parameters – most notably the surface temperature; and 3) systematic errors in the nuclear cross sections used in the nucleosynthesis calculations. Here, we explore the last possibility, and focus on possible systematic errors in the ^{3}He$(\alpha,\gamma)^7$Be reaction, which is the only important ^{7}Li production channel in BBN. The absolute value of the cross section for this key reaction is known relatively poorly both experimentally and theoretically. The agreement between the standard solar model and solar neutrino data thus provides additional constraints on variations in the cross section (S_{34}). Using the standard solar model of Bahcall, and recent solar neutrino data, we can exclude systematic S_{34} variations of the magnitude needed to resolve the BBN ^{7}Li problem at $> 95\%$ CL. Additional laboratory data on ^{3}He$(\alpha,\gamma)^7$Be will sharpen our understanding of both BBN and solar neutrinos, particularly if care is taken in determining the absolute cross section and its uncertainties. Nevertheless, since it already seems that this "nuclear fix" to the ^{7}Li BBN problem is unlikely, other possible solutions are briefly discussed.

Primordial nucleosynthesis for the new cosmology: determining uncertainties and examining concordance

(R.H. Cyburt)

Big bang nucleosynthesis (BBN) and the cosmic microwave background (CMB) have a long history together in the standard cosmology. BBN accurately predicts the primordial light element abundances of deuterium, helium and lithium. The general concordance between the predicted and observed light element abundances provides a direct probe of the universal baryon density. Recent CMB anisotropy measurements, particularly the observations performed by the WMAP satellite, examine this concordance by independently measuring the cosmic baryon density. Key to this test of concordance is a quantitative understanding of the uncertainties in the BBN light element abundance predictions. These uncertainties are dominated by systematic errors in nuclear cross sections. We critically analyze the cross section data, producing representations that describe this data and its uncertainties, taking into account the correlations among data, and explicitly treating the systematic errors between data sets. The procedure transforming these representations into thermal rates and errors is discussed. Using these updated nuclear inputs, we compute the new BBN abundance predictions, and quantitatively examine their concordance with observations. Depending on what deuterium observations are adopted, one gets the following constraints on the baryon density:

$\Omega_B h^2 = 0.0229 \pm 0.0013$ or $\Omega_B h^2 = 0.0216^{+0.0020}_{-0.0021}$ at 68% confidence, fixing $N_{\nu,\mathrm{eff}} = 3.0$. If we instead adopt the WMAP baryon density, we find the following deuterium-based constraints on the effective number of neutrinos during BBN: $N_{\nu,\mathrm{eff}} = 2.70^{+0.84}_{-0.90}$ or $N_{\nu,\mathrm{eff}} = 3.50^{+1.39}_{-1.35}$ at 68% confidence. Concerns over systematics in helium and lithium observations limit the confidence constraints based on this data. BBN theory uncertainties are dominated by the following nuclear reactions: $d(d,n)^3\mathrm{He}$, $d(d,p)t$, $d(p,\gamma)^3\mathrm{He}$, $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^3\mathrm{He}(d,p)^4\mathrm{He}$. With new nuclear cross section data, light element abundance observations and the ever increasing resolution of the CMB anisotropy, tighter constraints can be placed on nuclear and particle astrophysics.

New nucleosynthesis constraints on hadronic decaying relic particles
(R.H. Cyburt; J. Ellis, CERN; B.D. Fields, Illinois; K.A. Olive, Minnesota)

We are exploring the constraints placed on the abundance of an unstable relic particle with lifetimes between 10^{-2} and 10^4 sec. We consider decays which produce hadronic showers, and constrain them through their effects on primordial nucleosynthesis. Hadronic showers change the light element predications in two ways, through hadronic induced pn-interconversion and nuclide disintegration. This project requires an intimate knowledge of hadronic thermalization processes and hadron-nuclide scattering and break-up cross sections.

Model independent $S_{17}(0)$ and error budget accounting
(R.H. Cyburt, B. Davids)

In an effort to combine all existing data, we use the data analysis formalism developed by Cyburt [astro-ph/0401091] and apply the methods to the specific case of $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$. Also, we detail all contributing sources of uncertainty, both statistical and systematic. We also show how inclusion of various theories can be used to reduce extrapolation errors, but we highlight that theory systematics must be taken into account in the error budget. In most cases, previous determinations of $S_{17}(0)$ have underestimated the true systematic uncertainty.

The cosmological concordance project
(G. Huey, B.D. Wandelt, Illinois; R.H. Cyburt)

This is an ongoing project that makes cosmological parameter extraction accessible to the general scientific community. The project Web page (http://galadriel.astro.uiuc.edu/ccp/) allows users to choose from a variety of observational data sets and theoretical constraints. The main motivation for the work is to make it easy for experimentalists and theorists alike to explore and interpret the current state of cosmological knowledge.

Quick CMB parameter estimation
(R.H. Cyburt; G. Huey, B.D. Wandelt, Illinois)

With the growing precision and number of cosmological data sets, ever more complex and detailed cosmological models can be explored and constrained. With this added complexity, the field becomes computationally overtaxed and an exhaustive treatment becomes prohibitive. We outline a method for quick parameter estimation, detailing its advantages and range of applicability. Of particular usefulness are the theory sensitivities to these parameters, which will help limit the level of complexity a particular cosmological model can have. Another advantage of this method is that it allows a clear separation of individual data sets, allowing exploration of systematics. We use this method for parameter estimation including the second year WMAP data release.

Lattice QCD

Colour field distributions in the baryon
(F. Okiharu, Nihon Univ.; R.M. Woloshyn)

Chromo-electric and chromo-magnetic field distributions in mesons have been extensively studied but for baryons it is much more difficult to map the colour fields. Some special technique, such as using Abelian projected fields, to reduce statistical fluctuations needs to be applied. Once statistical fluctuations are under control the question of systematic errors has to be studied. We investigated the sensitivity of baryonic observables to the choice of the three-quark interpolating operator. It was found that consistent values for the static three-quark potential could be obtained in lattice QCD simulations for different (static) baryon interpolating operators. However, operator independence for the colour field distribution is more difficult and could not be achieved in present simulations. New techniques for reducing statistical fluctuations, which will allow for simulations with larger Wilson loops, are being investigated. Unitarized fat7 smearing, which was developed to suppress hard gluon interactions in hadrons made from staggered quarks, may be promising.

Lattice QCD simulations with dynamical improved staggered quarks
(K.Y. Wong, SFU; R.M. Woloshyn)

A major challenge for lattice QCD simulations is to include the effects of quark loops in the vacuum, so-called dynamical fermion effects. The most cost effective way of doing this is using staggered quarks. However, staggered quarks have species doubling and "taste symmetry" among different species is broken by hard gluonic interactions. Recently a new class of improved staggered fermion actions has been proposed [Follana *et al.*, hep-lat/031104] in which the taste symmetry breaking effects are suppressed by unitarized fat7 smearing of the gauge field links. We have developed and tested computer programs, utilizing the hybrid molecular dynamics (HMD) algorithm, for these new actions. Parallelized versions of the programs (using MPI) have been developed for use at WestGrid and other large scale computing facilities.

Effective Field Theories and Chiral Perturbation Theory

Neutron beta decay in effective field theory

(S. Ando, H.W. Fearing; V. Gudkov, K. Kubodera, F. Myhrer, USC; S. Nakamura, T. Sato, Osaka)

Radiative corrections to the lifetime and angular correlation coefficients of neutron beta decay are evaluated in effective field theory. We also evaluate the lowest order nucleon recoil corrections, including weak-magnetism. Our results agree with those of the long-range and model-independent part of previous calculations. In an effective theory the model dependent radiative corrections are replaced by a well-defined low energy constant. The effective field theory allows a systematic evaluation of higher order corrections to our results to the extent that the relevant low-energy constants are known. We estimate the accuracy of our calculated observables to be of the order of 10^{-3}.

Effective field theory on the deuteron revisited

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

Pion-less dibaryon effective field theory for the deuteron is studied. The electromagnetic form factors of the deuteron and the cross section of radiative neutron capture on a proton, $np \to d\gamma$, are calculated within the theory. In accordance with the counting rule of the theory, we have the low-energy constants (LECs) in the higher order diagrams, which stem from integrating out high energy degrees of freedom from the effective Lagrangians, such as the meson exchange currents, and the values of the LECs should be fixed by experiments. We find that the contributions of the LECs of vector-two-dibaryon interactions turn out to be large, comparable to those of leading two-nucleon loop diagrams. We discuss the duality of two-nucleon and dibaryon field in the description of the deuteron, that is, those two kinds of diagrams are of leading order and the LECs can be fixed by the one-body interaction with an external probe. We find that this assumption reproduces well the results of effective range theory.

Second-class current on the nucleon in chiral perturbation theory

(S. Ando)

Experiments for investigation of the second-class current have been conducted at TRIUMF by a group from Osaka University for a long time. It was a challenge to detect this tiny quantity, since it is predicted theoretically that the magnitude of the second-class current (the axial tensor coupling constant g_T) is proportional to the mass difference between u- and d-quark, based on an estimate using QCD sum rules. Chiral perturbation theory (χPT) provides the other systematic framework to incorporate the symmetry breaking patterns of QCD induced by the quark masses into the calculations. Though the isospin symmetry breaking terms have usually been neglected in the former calculations, the inclusion of the mass difference between the light quarks is straightforward except for the inclusion of the other isospin breaking effect, that is, the electromagnetic interactions. It would be interesting to estimate the coupling constant g_T by employing the χPT.

Solar-neutrino reactions on the deuteron in dibaryon effective field theory

(S. Ando)

The recent experimental results at SNO show that the flavour of the solar-neutrino changes while it flies to the earth. This strongly indicates that the neutrino has a mass. The neutrino reactions on deuteron are the detecting reactions of solar-neutrinos at SNO and therefore it is essential to provide the theoretical cross sections for the reactions as accurately as possible to deduce the mass and the mixing angle of neutrinos from the data.

The cross sections have been estimated by using several different theoretical approaches so far: 1) standard nuclear physics calculations employing model Lagrangians to construct the exchange currents, 2) effective field theoretical (EFT) calculations employing the Weinberg's counting scheme, and 3) EFT calculations employing the power divergence subtraction scheme. The results of those calculations turn out to agree well with each other. However, interrelations between these three approaches have not been well studied yet. We calculate the cross sections of the reactions employing dibaryon EFT without pions, which can correctly reproduce the results of the effective range theory, and compare the results with those of the former calculations.

Regularization procedures in relativistic chiral perturbation theory

(S. Ando, H.W. Fearing)

Relativistic chiral perturbation theory presents some problems not present in non-relativistic approaches because of the non-zero baryon masses in the chiral limit. In particular it is hard to obtain a systematic expansion scheme in the relativistic theory. A new renormalization scheme for relativistic ChPT with nucleons was proposed by Becher and Leutwyler and modifications of the approach have been intensively studied by Fuchs *et al.* These approaches seemingly correct the analytic structure of the amplitudes, and in the case of Fuchs *et al.* generate a systematic counting procedure which reproduces the results of heavy baryon chiral perturbation theory. We have been looking at these new approaches, examining the pros and cons, and trying to understand how they can best be applied to practical calculations.

Muon capture on a proton in relativistic chiral perturbation theory

(S. Ando, H.W. Fearing; S. Scherer, Mainz)

As an application of the new approaches to relativistic chiral perturbation theory which have been proposed, we have begun a calculation of ordinary, non-radiative, muon capture on the nucleon using the infrared regularization scheme of Becher and Leutwyler and the power counting proposals of Fuchs *et al.* The calculation will be compared to the non-relativistic heavy baryon ChPT approach used earlier [Nucl. Phys. **A631**, 735 (1998)]. This process primarily fixes the low energy constants needed for vector and axial vector interactions, and thus is a necessary first step for future applications to radiative muon capture, radiative pion capture and similar processes.

Reanalysis of nuclear PNC observables in the framework of effective field theory

(C.-P. Liu; M.J. Ramsey-Musolf, Caltech/Connecticut; B.R. Holstein, Massachusetts)

Traditional analysis of nuclear PNC observables is done by using the DDH potential. However, one big puzzle in this field is that the current constraints on PNC πNN coupling, obtained from various nuclear PNC 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.R.-M. *et al.* of formulating a model-independent PNC potential within the framework of effective field theory is in progress. Our goal here is using this new potential – parametrized by various low energy constants (LECs) – to reanalyze nuclear PNC observables and see if one can get a more consistent result in this framework. This work is still ongoing.

Few-Body and Medium Energy Processes

Induced pseudoscalar coupling of the proton weak interaction

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

An extensive review of what is known, both theoretically and experimentally, about the induced pseudoscalar coupling g_P appearing in the weak nucleon current was revised and extended during the year. Most information comes from muon capture and radiative muon capture, and so these processes were extensively reviewed. The review has now been published in Reviews of Modern Physics. The most interesting new result to come from this work was the suggestion that, based on an updated analysis, the older measurements of muon capture on the proton may not be in as good agreement with the predictions of chiral symmetry as previously supposed. This enhances the importance of new experiments on this process which are now in progress.

Parity-nonconserving 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. A set of fully conserved parity-nonconserving (PNC) MECs is constructed within the framework of the DDH potential, the most widely-used model for the PNC nucleon-nucleon interaction, which consists of π-, ρ-, and ω-exchanges. This work has been done with the choice of the Feynman gauge for vector mesons. A further study will be using some other gauge, e.g., the unitary gauge, for vector mesons to insure the invariance property.

Deuteron anapole moment with heavy mesons

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

Though the detection of nuclear anapole moment, a P-odd T-even electromagnetic moment, in light systems is still out of reach, there have been quite some theoretical works on the deuteron as it is one of the simplest systems to test nuclear parity nonconservation. We extended the earlier work by B.D. and C.H.H., which only included pion-exchange, to the full DDH model. It was found that the vector-meson exchange has little correction at the two-body level either through the polarization effect or MECs. However, its contribution at the single-nucleon level (via loop diagrams) which produces the nucleonic anapole moment, is important, but still with a large theoretical uncertainty.

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

While the asymmetry in polarized thermal neutron capture by hydrogen, which LANSCE plans to measure, provides information about the PNC πNN coupling constant, the asymmetry in its inverse process, i.e. deuteron photodisintegration by circularly-polarized light, is mostly sensitive to the isoscalar and isotensor parts of PNC heavy-meson-nucleon coupling constants. Therefore, these two experiments combined would provide valuable information about nuclear parity-nonconservation. Furthermore, some exciting calculations even suggested that at higher energies, the pion exchange dominates the deuteron photodisintegration asymmetry. Were this true, it could be an independent check on the LANSCE result.

With the advent of high-quality polarized photon beam, there is interest in doing this experiment at several places, which justifies an updated, more modern calculation. Within the framework of the DDH model and for photon energy up to 10 MeV above the threshold, we found that: i) near the threshold region, our results are consistent with the literature, and the asymmetry is of the order 10^{-8}, and ii) as the photon energy reaches 1 MeV above the threshold, the asymmetry drops to the order of 10^{-9}, and we did not see the great sensitivity to pion-exchange reported before. Therefore, our suggestions for such an experiment would be i) near the threshold, and ii) keeping away from the energy region about 4–6 MeV above the threshold, as a sign change in the asymmetry implies a great possibility of a null result.

Form factors in the point form of relativistic quantum mechanics
(A. Amghar, Boumerdes, Algeria; B. Desplanques, LPSC, Grenoble; L. Theussl)

Among the three forms of relativistic quantum mechanics proposed by Dirac (instant form, front form and point form), only the former two have been extensively used for describing few-body systems in the past. We consider the calculation of the electromagnetic form factor of the pion, but also electromagnetic and Lorentz-scalar form factors of scalar two-body bound states, in point form. In all cases, the comparison with results from an explicitly covariant Bethe-Salpeter approach evidences sizable discrepancies, pointing to large contributions from two-body currents in point form. The latter ones are constructed using two constraints: ensuring current conservation and reproducing the Born amplitude. The two-body currents so obtained are qualitatively very different from standard ones. Quantitatively, they turn out not to be sufficient to remedy all the shortcomings of the form factors in point form evidenced in impulse approximation. These results call for major improvements in the implementation of the point-form approach.

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

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

Z^* resonances: phenomenology and models
(B. Jennings; K. Maltman, York)

We explore the phenomenology of, and models for, the Z^* resonances, the lowest of which is now well established and called the Theta. We provide an overview of three models which have been proposed to explain its existence and/or its small width, and point out other relevant predictions, and potential problems, for each. The relation to what is known about KN scattering, including possible resonance signals in other channels, is also discussed.

Particle Physics

Rare tau decays in extra dimension models
(W.-F. Chang, J.N. Ng)

The recent neutrino experiment data show strong evidence that neutrinos have non-zero masses and mixings. This clearly indicates new physics beyond the SM in the neutrino sector and certainly implies the existence of lepton flavour violation (LFV) in the charged lepton sector. These LFV processes are either related or unrelated to the neutrino masses. They can also be used to discriminate different models. We discuss few examples of extra dimension models which give potentially testable LFV signatures. We compare the LFV processes in five dimension $SU(3)_W$ and SU(5) GUT models where neutrino Majorana masses are generated radiatively without a right-handed neutrino. Also, we discuss the split fermion or multi-brane scenario where LFV coupling is generated geometrically.

Phenomenology of a 5D orbifold SU(3)$_W$ unification model

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

We study the phenomenology of a 5D SU(3)$_W$ model on a $S_1/(Z_2 \times Z_2')$ orbifold in which the minimal scalar sector plays an essential role of radiatively generating neutrino Majorana masses without the benefits of right-handed singlets. We carefully examine how the exotic scalars affect the renormalization group (RG) equations for the gauge couplings and the 5D SU(3)$_W$ unification. We found that the compactification scale of extra dimension is in the range of $1/R \sim 1.5-5$ TeV. The possibility of the existence of relatively low mass Kaluza-Klein excitations makes the phenomenology of near term interest. Some possible bilepton signatures can be searched for in future colliders and in neutrino scattering experiments with intense neutrino beams. The low energy constraints from muon physics and lepton number violating decay process induced by bilepton are also discussed. These constraints can provide new information on the structure of Yukawa couplings which might be useful for future model building.

Neutrino masses in 5D orbifold SU(5) unification models without right-handed singlets

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

We explore a mechanism for radiatively generating neutrino Majorana masses in a 5 dimensional orbifold SU(5) unification model without introducing right-handed singlets. The model is non-supersymmetric and the extra dimension is compactified via a $s_1/(Z_2 \times Z_2')$ orbifold geometry. The necessary lepton number violating interaction arises from the Yukawa interactions either between a 10-plet or a 15-plet bulk scalar field and the fermion quintuplets which are residents on the SU(5) symmetrical brane located at one of the orbifold fixed points. The model is engineered to give realistic charged fermion masses and mixing and at the same time to avoid the rapid proton and neutron decays by geometric construction. The gauge unification can be maintained by adding extra fermion or scalar fields. The unification scale is found to be larger than 10^{15} GeV by adding a bulk vector decuplet pair whose zero mode has masses around the $10 \sim 100$ TeV range. We found that neutrino mass matrix of the normal hierarchy type is favoured by using 15-plet scalar. We give a solution of this type which has detectable $\mu \to 3e$ transition. On the other hand, by introducing 10-plet scalar, the leading neutrino mass matrix can only be inverted hierarchical and gives at most bi-maximal mixing.

Sleptogenesis

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

We propose that the observed baryon asymmetry of the universe can naturally arise from a net asymmetry generated in the right-handed sneutrino sector at fairly low reheat temperatures. The initial asymmetry in the sneutrino sector is produced from the decay of the inflaton, and is subsequently transferred into the standard model (s)lepton doublet via three-body decay of the sneutrino. Our scenario relies on two main assumptions: a considerable branching ratio for the inflaton decay to the right-handed (s)neutrinos, and Majorana masses which are generated by the Higgs mechanism. The marked feature of this scenario is that the lepton asymmetry is decoupled from the neutrino Dirac Yukawa couplings. We exhibit that our scenario can be embedded within minimal models which seek the origin of a tiny mass for neutrinos.

Cosmological bounds on large extra dimension models

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

The existing cosmological constraints on theories with large extra dimensions rely on the thermal production of the Kaluza-Klein modes of gravitons and radions in the early universe. Successful inflation and reheating, as well as baryogenesis, typically requires the existence of a TeV-scale field in the bulk, most notably the inflaton. The non-thermal production of KK modes with masses of order 100 GeV accompanying the inflaton decay sets the lower bounds on the fundamental scale M_*. For a 1 TeV inflaton, the late decay of these modes distorts the successful predictions of Big Bang Nucleosynthesis unless $M_* > 35,\ 13,\ 7,\ 5$ and 3 TeV for 2, 3, 4, 5 and 6 extra dimensions, respectively. This improves the existing bounds from cosmology on M_* for 4, 5 and 6 extra dimensions. Even more stringent bounds are derived for a heavier inflaton.

Leptogenesis from a sneutrino condensate

(R. Allahverdi; M. Drees, Munich)

We re-examine leptogenesis from a right-handed sneutrino condensate, paying special attention to the B-term associated with the see-saw Majorana mass. This term generates a lepton asymmetry in the condensate whose time average vanishes. However, a net asymmetry will result if the sneutrino lifetime is not much longer than the period of oscillations. Supersymmetry breaking by thermal effects then yields a lepton asymmetry in the standard model sector after the condensate decays. We explore different possibilities by taking account of both the low-energy and Hubble B-

terms. It will be shown that the desired baryon asymmetry of the Universe can be obtained for a wide range of Majorana mass.

Modulated cosmological perturbations
(R. Allahverdi; L. Kofman, M. Peloso, CITA)

In an alternative mechanism recently proposed, adiabatic cosmological perturbations are generated at the decay of the inflaton field due to small fluctuations of its coupling to matter. This happens whenever the coupling is governed by the vacuum expectation value of another field, which acquires classical fluctuations during inflation. We discuss generalizations and various possible implementations of this mechanism. In many cases the second field can start oscillating before perturbations are imprinted, or survive long enough so as to dominate over the decay products of the inflaton. The primordial perturbations are then modified accordingly in such cases.

Leptogenesis in extra dimensions without a right-handed neutrino
(R. Allahverdi, W.-F. Chang)

As originally proposed by Zee, light neutrino masses can be generated by adding new Higgs fields (instead of a right-handed neutrino as in the see-saw mechanism) to the standard model. It is also possible to produce a lepton asymmetry in these models from the decay of a heavy Higgs field with lepton number violating interactions. This, however, requires that at least two copies of that field be introduced. Recently, Zee-like models have been constructed in five dimensions which generate preferred neutrino masses and mixings. We show that leptogenesis with only one copy of Higgs is possible in these models, provided that it is a bulk field and fermions are localized in different positions along the fifth dimension.

Miscellaneous

JaxoDraw: a graphical user interface for drawing Feynman diagrams
(D. Binosi, Trento; L. Theussl)

JaxoDraw is a Feynman graph plotting tool written in Java. It has a complete graphical user interface that allows all actions to be carried out via mouse click-and-drag operations in a WYSIWYG fashion. Graphs may be exported to postscript/EPS format and can be saved in XML files to be used in later sessions. One of the main features of JaxoDraw is the possibility to produce LaTeX code that may be used to generate graphics output, thus combining the powers of TeX/LaTeX with those of a modern day drawing program. With JaxoDraw it becomes possible to draw even complicated Feynman diagrams with just a few mouse clicks, without the knowledge of any programming language.