TRIUMF

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SCIENTIFIC ACTIVITIES
1998

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

APRIL 1999

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 motivation for a Theory group at TRIUMF has been to assemble a group of active people doing high quality research in areas which are relevant, in the broadest sense, to the physics program at TRIUMF and to the interests of the subatomic physics community across Canada. The Theory group provides a focus for the theoretical research at TRIUMF and support for the TRIUMF experimental program in all its many facets. Complementing the experimental program the theoretical research program also covers a wide range of topics in nuclear and particle physics. Part of this research involves working directly with the experimentalists on particular experiments; part with a more general background to the experimental program; and part with fundamental areas not currently related to the experimental program.

The Theory group has four permanent staff members: H.W. Fearing (group leader), B.K. Jennings, J.N. Ng, and R.M. Woloshyn; plus E.W. Vogt (professor emeritus, UBC). This year our research associates are: H.-W. Hammer, T. Hemmert (until February), B.D. Jones, S. Karataglidis, I. Maksymyk (until September), G.C. McLaughlin (since September) H. Müller (until September), T.S. Park (since September), T. Shoppa (until April) and P.R. Wrean (since September, shared with the DRAGON group). A graduate student, M. Nobes is being supervised by R.M. Woloshyn.

The visitors to the Theory group this year include:

K-L. Chan	J. Juge	A. Rinat
L.N. Chang	F. Khanna	S. Scherer
C. Davies	I.B. Khriplovich	R. Sinha
B. Dutta	V. Kuzmin	Z. Sullivan
A. Gal	C.S. Lam	R. Surman
J. Gasser	K.C. Leung	I. Towner
K. Goeke	H. Lipkin	E. Truhlik
J. Greben	P. Maris	C. Unkmeir
A. Halasz	G.A. Miller	D. Wilkinson
T. Hemmert	A. Misra	C. Wolfe
S.W. Hong	J. Niskanen	L. Zamick
C. Johnson	A. Ramos	

In addition to their research activities the theorists have taken an active part in the laboratory activities including: the Long Range Planning Committee, the Experiments Evaluation Committee, the TRIUMF Summer Institute and computer support.

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

Miscellaneous

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

We study how matter-enhanced active-sterile neutrino transformation in the $\nu_e \rightleftharpoons \nu_s$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ channels could enable the production of the rapid neutron capture (r-process) nuclei in neutrino-heated supernova ejecta. In this scheme the lightest sterile neutrino would be heavier than the ν_e and split from it by a vacuum mass-squared difference of $3\ \mathrm{eV}^2 \lesssim \delta m^2_{es} \lesssim 70\ \mathrm{eV}^2$ with vacuum mixing angle $\sin^2 2\theta_{es} > 10^{-4}$.

Nucleon-nucleon bremsstrahlung: an example of the impossibility of measuring off-shell amplitudes
(H.W. Fearing)

For nearly fifty years theoretical and experimental efforts in nucleon-nucleon bremsstrahlung ($NN\gamma$) have been devoted to measuring off-shell amplitudes and distinguishing among various NN potentials on the basis of their off-shell behaviour. New experiments are under way, designed specifically to attain kinematics further off shell than in the past, and thus to be more sensitive to the off-shell behaviour. We show in a recently published issue of Phys. Rev. Lett. that, contrary to these expectations, and due to the invariance of the S-matrix under transformations of the fields, the off-shell NN amplitude is *as a matter of principle* an unmeasurable quantity in $NN\gamma$.

Nuclear Structure and Reactions

GT strength in mass-6,7 and mass-56
(S. Karataglidis, G.C. McLaughlin)

The Gamow-Teller strength in ^{56}Fe is being calculated within the shell model to determine the usefulness of ^{56}Fe as a target material for a supernova neutrino detector. Such a detector would operate by observing neutrons from neutrino-induced neutron spallation reactions. Since supernovae produce high energy electron, mu and tau neutrinos and antineutrinos, the GT response is being calculated for both the neutral and charged currents. The wave functions for mass-56 have been determined within the fp model space assuming 0p-0h configurations with the addition of 2p-2h excitations in those cases where such is possible.

The GT matrix elements are also being calculated for the β-decays of ^{6}He and ^{7}Be using wave functions determined in a complete $(0+2+4)\hbar\omega$ model space. This “traditional” shell model calculation is being done to compare with the calculations using the exact mass-6 and mass-7 wave functions obtained using the Green's functions Monte Carlo shell model by the Argonne National Laboratory.

Alternative evaluations of halos in nuclei

(S. Karataglidis; K. Amos, P.J. Dortmans, Melbourne; C. Bennhold, George Washington Univ.)

Data for the scattering of ^{6}He, ^{8}He, ^{9}Li, and ^{11}Li from hydrogen have been analyzed within a fully microscopic folding model of proton-nucleus scattering. The model is based on the shell model and the g matrix constructed from the bare NN potential. The nuclear states were calculated in complete multi-$\hbar\omega$ spaces. Current data suggest that of these only ^{11}Li has a noticeable halo, although no definitive conclusion may be reached for ^{6}He. For that nucleus, one may look to the alternative reaction, $^6\mathrm{Li}(\gamma,\pi^+)^6\mathrm{He}_{gs}$, the data for which support the assertion that ^{6}He is not a halo system. However, more data for both the proton scattering and (γ,π^+) reaction are needed before such a conclusion may be reached.

S_{eff} and the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction

(B.K. Jennings, S. Karataglidis)

We explore approximations to the effective S factor for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction using different approximation for the integral over the Gamow peak. In the temperature range of interest for solar neutrino production, S_{eff} may be determined to within 0.5% from $S(20)$ with no direct information on the derivatives of $S(E)$.

Extrapolation of the astrophysical S factor for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ to solar energies

(B.K. Jennings, S. Karataglidis, T.D. Shoppa)

We investigate the energy dependence of the astrophysical S factor for the reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$, the primary source of high energy solar neutrinos in the solar pp chain. Using simple models we explore the model dependence in the extrapolation of the experimental data to the region of astrophysical interest near 20 keV. We find that below approximately 400 keV the energy dependence is very well understood and constrained by the data for the elastic scattering of low energy neutrons from ^{7}Li. Above 400 keV nuclear distortion of the wave function of the incident proton introduces a significant model dependence. This is particularly important for the s-wave contribution to the S factor. The extracted value of $S(0)$ is $19.0 \pm 1.0 \pm 0.2$ eVb. The first error is experimental while the second is an estimate of the theoretical error in the extrapolation.

On the equivalence of the impulse approximation and the Gersch-Rodriguez-Smith series for structure functions

(A.S. Rinat, Weizmann; B.K. Jennings)

For a non-relativistic system we compare the Gersch-Rodriguez-Smith and the IA approaches to the structure function. The first of these two approaches generates a series in $1/q$, whereas the second treats the interaction between the struck and core nucleons perturbatively. Instead of the IA series we derive a DWIA representation and prove that, up to and including terms of order $\mathcal{O}(1/q^2)$, it is contained in the GRS series of the same order. This clarifies the relation between the two approaches and suggests that the two approaches, when treated exactly, produce identical structure function to arbitrary order in $1/q$.

Quark-meson coupling models for nuclear matter and finite nuclei

(H. Müller and B.K. Jennings)

The basic motivation of applying quark models to nuclear structure is the hope to reveal medium modifications of the internal structure of the nucleon. The idea that nucleons might undergo considerable change of their internal structure in a baryon-rich environment is supported by our understanding of asymptotic freedom in QCD. At sufficiently high densities one expects a transition to a new phase of matter with deconfined quarks and gluons. Quark-meson coupling (QMC) models are designed to explore indications of this phenomena at normal nuclear densities. However, it is important that these models which connect observed nuclear phenomena and the underlying physics of strong interactions respect established results.

In the original version of the QMC model proposed by Guichon [Phys. Lett. **B200**, 235 (1988)] nucleons arise as non-overlapping MIT bags interacting through meson mean fields. Although it provides a simple and intuitive framework to incorporate quark degrees of freedom in the study of nuclear many-body systems, the QMC model has a serious shortcoming. The predicted nucleon mass is too high and, as a consequence, the spin-orbit force is too weak to explain spin-orbit splittings in finite nuclei. The QMC model can be significantly improved by introducing the concept of a density dependent bag constant. In our work we have demonstrated that such a modified quark-meson coupling (MQMC) model can be accurately calibrated to produce the empirical saturation properties of nuclear matter and that it provides a good description of the bulk properties of finite nuclei. By analyzing binding energies, charge radii, nuclear shapes and single-particle spectra of spherical nuclei we find that the MQMC model leads to results of the same quality as in established hadronic models. Most importantly, the accurate reproduction of the effective nucleon mass leads to a realistic description of spin-orbit splittings. Furthermore, unrealistic features of the nuclear shapes which arise in the original version of the QMC model are significantly corrected.

Effective field theory for $\Lambda - \Sigma^0$ mixing in nuclear matter
(H. Müller)

Strangeness adds another, still largely unexplored, dimension to nuclear structure. On the experimental side, physics of hypernuclei is approaching a phase in which not only ground state energies but also excitation spectra and electromagnetic properties are being measured. To explain properties of hypernuclei, detailed information on the elementary nucleon-hyperon and hyperon-hyperon interaction is needed which, at present, is scarce and incomplete.

We extend the effective field theory approach which successfully describes ordinary nuclei and nuclear matter to incorporate strangeness in nuclear structure. The central object is a chiral effective Lagrangian involving the baryon octet, the Goldstone boson octet, the vector meson octet and a light scalar singlet. According to the rules of effective field theory, we include all interaction terms (up to a given order of truncation) that are consistent with the underlying symmetries of QCD.

We develop a mean-field approximation and study nuclear matter as a simple model for multi-strange systems. A D-type Yukawa coupling between baryons and vector mesons leads to $\Lambda - \Sigma^0$ flavour mixing in the nuclear medium. The primary result is that nuclear matter is generally in a state of mixed flavour rather than in a state with distinct Λ and Σ^0 particles. As a consequence, systems which contain Λ hyperons always have a small admixture of Σ^0 hyperons. Disturbing the time independent nuclear matter ground state leads to flavour oscillations characterized by distinct frequencies. This effect is closely related to the phenomenon of neutrino oscillations.

Effective Field Theories and Chiral Perturbation Theory

The power of effective field theories in nuclei: the deuteron, NN scattering and electroweak processes
(T.-S. Park; K. Kubodera, USC; D.-P. Min, SNU; M. Rho, Saclay)

We show how *effectively* effective quantum field theories work in nuclear physics. Using the physically transparent cut-off regularization, we study the simplest nuclear systems of two nucleons for both bound and scattering states at a momentum scale much less than the pion mass. We consider all the static properties of the deuteron, the two-nucleon scattering phase-shifts, the $n+p \to d+\gamma$ process at thermal energy and the solar proton fusion process $p+p \to d+e^+ + \nu_e$, and we demonstrate that these are all described with great accuracy in the expansion to the next-to-leading order. We explore how a “new” degree of freedom enters in an effective theory by turning on and off the role of the pion in the Lagrangian.

The solar proton burning process: revisited in chiral perturbation theory
(T.-S. Park; K. Kubodera, USC; D.-P. Min, SNU; M. Rho, Saclay)

The proton burning process $p + p \to d + e^+ + \nu_e$, important for the stellar evolution of main-sequence stars of mass equal to or less than that of the Sun, is computed in effective field theory using chiral perturbation expansion to the next-to-next-to-leading chiral order. This represents a model-independent calculation consistent with low energy effective theory of QCD comparable in accuracy to the radiative np capture at thermal energy previously calculated by first using very accurate two-nucleon wave functions backed up by an effective field theory technique with a finite cut-off. The result obtained thereby is found to support within theoretical uncertainties the previous calculation of the same process by Bahcall and his co-workers.

Effective field theory for low energy two-nucleon systems
(T.-S. Park; K. Kubodera, USC; D.-P. Min, SNU; M. Rho, Saclay)

We illustrate how effective field theories work in nuclear physics by using an effective Lagrangian in which all other degrees of freedom than the nucleonic one have been integrated out to calculate the low energy properties of two-nucleon systems, viz, the deuteron properties, the np $^1S_0$ scattering amplitude and the $M1$ transition amplitude entering into the radiative np capture process. Exploiting a finite cut-off regularization procedure, we find all the two-nucleon low energy properties to be *accurately* described with little cut-off dependence, in consistency with the general philosophy of effective field theories.

Effective theory for the non-relativistic three-body system
(H.-W. Hammer; P.F. Bedaque, INT; U. van Kolck, Caltech)

Following a proposal by Weinberg, there has been much interest recently in applying the successful concept of effective field theory (EFT) to nuclear physics. However, the presence of shallow bound states and the associated unnaturally large scattering length in nuclear systems complicate the problem as the EFT resembles a condensed matter system near a phase transition. During the last year a consistent power counting scheme, the basis of an EFT, has been established for the two-body system. We have applied the EFT ideas to the three-body system and neutron-deuteron scattering in particular. While precise predictions are straightforwardly obtained for neutron-deuteron scattering in the spin-3/2 channel, additional complications due to a nonperturbative renormalization arise in the spin-1/2 channel and the bosonic system. These complications are related to the well known Thomas and Efimov instabilities. The problem can be solved by introducing a one-parameter three-body force at leading order. Although one additional parameter appears, the EFT still retains its predictive power. We have successfully applied this idea to the bosonic system of ^{4}He-atoms and neutron-deuteron scattering in the spin-1/2 channel and the triton.

Bianchi identities and the extension of the chiral perturbation theory meson Lagrangian to order p^6

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

We discuss the application of Bianchi identities in the construction of the chiral perturbation theory meson Lagrangian to order p^6. We propose a strategy to implement the constraints due to the Bianchi identities in combination with the trace and epsilon relations previously derived and explicitly identify terms of our original Lagrangian which are related by these identities and thus not independent. We find a reduction by 4 and 7 terms in the even and odd intrinsic parity sectors, respectively, resulting in 107 and 25 independent structures for SU(3).

Few-body processes in heavy baryon chiral perturbation theory

(H.W. Fearing; T. Hemmert, Julich; R. Lewis, N. Mobed, Regina; S. Scherer, C. Unkmeir, Mainz)

We have begun a series of calculations of few-body processes involving pions, photons, and a single nucleon in the framework of heavy baryon chiral perturbation theory. The approach follows that of our recently published calculation of ordinary muon capture, $\mu + p \to n + \nu$. The reactions of interest include radiative muon capture, $\mu + p \to n + \nu + \gamma$, radiative pion capture, $\pi + p \to n + \gamma$ and the associated electron processes, $\pi + p \to n + e^+ + e^-$ and $e + p \to e + n + \pi$, and doubly radiative pion capture $\pi + p \to n + \gamma + \gamma$ and its associated process $e + p \to e + n + \pi + \gamma$.

Comment on 'Induced pseudoscalar coupling constant' by I-T. Cheon and M.K. Cheoun

(H.W. Fearing)

In a recent preprint Cheon and Cheoun have derived from a chiral model an additional term, not usually appearing in the standard matrix element for radiative muon capture. Using that term they generate a large correction to the RMC spectrum which tends to resolve the problem caused by the too large value of g_P found in the TRIUMF RMC experiment. In this comment we observe first that their extra term leads to an amplitude which is not gauge invariant and second that such a term should be present, in a gauge invariant way, in an earlier full chiral perturbation theory calculation, which, however, found negligible differences from the standard approach.

Hadronic Structure

Spectral content of isoscalar nucleon form factors

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

The low energy structure of the nucleon's $s\bar{s}$ sea has become a topic of intense studies in the hadron physics community. In particular, the contribution of strange quarks to the spatial distribution of the nucleon's charge and magnetic moment is interesting, since it can be measured directly in parity violating electron scattering. On the theoretical side a plethora of calculations is available, each having its particular merits and limitations. Our alternative approach is to start from a spectral decomposition of the strange vector form factors and to evaluate the obtained imaginary parts using dispersion relations and experimental data. Some previous model calculations are recovered as certain approximations in this framework. Most model calculations base on the so called "kaon cloud dominance" assumption, i.e. the strange sea in the nucleon is generated by virtual transitions of the nucleon to a kaon and a hyperon (e.g. $p \to K^+\Lambda \to p$). Using dispersion relations, we study the lightest such contribution stemming from the $K\overline{K}$-intermediate state. Based on an analytic continuation of experimental KN scattering amplitudes and bounds from unitarity, we evaluate the $K\overline{K}$ contribution to the electric and magnetic radii as well as the magnetic moment to all orders in the strong interaction. We also demonstrate the relationship between non-resonant and resonant $K\overline{K}$ contributions to the form factors and derive values for the vector and tensor $\phi N\overline{N}$ couplings. The $K\overline{K}$ spectral functions are used to evaluate the credibility of model calculations for the strange quark vector current form factors.

K^* mesons and nucleon strangeness

(H.-W. Hammer; L.L. Barz, F.S. Navarra, M. Nielsen, Sao Paulo; H. Forkel, Heidelberg; M.J. Ramsey-Musolf, Connecticut)

We study contributions to the nucleon strange quark vector current form factors from intermediate states containing K^* mesons. We show how these contributions may be comparable in magnitude to those made by K mesons, using methods complementary to those employed in quark model studies. We also analyze the degree of theoretical uncertainty associated with K^* contributions.

Parity violating excitation of the $\Delta(1232)$: hadron structure and new physics

(H.-W. Hammer; J. Líu, N.C. Mukhopadhyay, RPI; S.J. Pollock, Colorado; M.J. Ramsey-Musolf, Connecticut)

We consider the prospects for studying the parity violating (PV) electroweak excitation of the $\Delta\,(1232)$ resonance with polarized electron scattering. Given present knowledge of standard model parameters, such PV experiments could allow a determination of the $N \rightarrow \Delta$ electroweak helicity amplitudes. We discuss the experimental feasibility and theoretical interpretability of such a determination as well as the prospective implications for hadron structure theory. We also analyze the extent to which a PV $N \rightarrow \Delta$ measurement could constrain various extensions of the standard model.

Phenomenology of B_c mesons

(M. Nobes, SFU; R.M. Woloshyn)

The leptonic and semi-leptonic decays of B_c mesons are calculated in an extended NJL model which has been extended further for use with heavy quarks. A shortcoming of this approach is the lack of confinement which prevents the application of this model to the description of certain light vector mesons. To overcome this limitation, calculations are also being done using the quark confinement model. Lepton spectra as well as total decay rates for all semi-leptonic decay modes of B_c are being calculated and will be compared with other kinds of model calculations. Leptonic and semi-leptonic decays of D D_s B and B_s mesons are being studied as well to determine the parameters in the calculation.

Mesonic decay constants in lattice NRQCD

(B.D. Jones, R.M. Woloshyn)

Lattice NRQCD with leading finite lattice spacing errors removed is used to calculate decay constants of mesons made up of heavy quarks. Quenched simulations are done with a tadpole improved gauge action containing plaquette and six-link rectangular terms. The tadpole factor is estimated using the Landau link. For each of the three values of the coupling constant considered, quarkonia are calculated for five masses spanning the range from charmonium through bottomonium, and one set of quark masses is tuned to the $B(c)$. "Perturbative" and non-perturbative meson masses are compared. One-loop perturbative matching of lattice NRQCD with continuum QCD for the heavy-heavy vector and axial vector currents is performed. The data are consistent with the vector meson decay constants of quarkonia being proportional to the square root of their mass and the $B(c)$ decay constant being equal to 420(13) MeV.

Valence QCD

(K.F. Liu, S.J. Dong, T. Draper, J. Sloan, Kentucky; D.B. Leinweber, Adelaide; W. Wilcox, Baylor; R.M. Woloshyn)

A valence QCD theory was developed to study the valence quark properties of hadrons. To keep only the valence degrees of freedom, the pair creation through the Z graphs was deleted in the connected insertions, whereas the sea quarks were eliminated in the disconnected insertions. This was achieved with a new "valence QCD" Lagrangian where the action in the time direction was modified so that the particle and antiparticle decouple.

It was shown in this valence version of QCD that the ratios of isovector to isoscalar matrix elements (e.g. F_A/D_A and F_S/D_S ratios) in the nucleon reproduce the SU(6) quark model predictions in a lattice QCD calculation.

In addition, it was found that the masses of N, Δ, ρ, π, a_1, and a_0 all drop precipitously compared to their counterparts in the quenched QCD calculation. This was interpreted as due to the disappearance of the 'constituent' quark mass which is dynamically generated through tadpole diagrams. The origin of the hyper-fine splitting in the baryon was largely attributed to the Goldstone boson exchanges between the quarks. Both of these are the consequences of the lack of chiral symmetry in valence QCD.

The Standard Model and Beyond

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

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

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

Invisible decays of quarkonium states
(L.N. Chang, O. Lebedev, VPISU; J. Ng)

We estimated the most important corrections to the branching ratios for the invisible decays of quarkonium states, arising from possible extensions of the standard model. Among the possibilities considered are the presence of extra Z-bosons, minimal supersymetric extensions of the standard model with R-parity violation and decays into Goldstinos. Prospects of detecting these corrections at existing and future B-factories and τ-charm factories are discussed.