THEORETICAL PROGRAM

Introduction

The TRIUMF Theory group provides a focus 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 onsite 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 five permanent staff members, six to seven research associates and a number of students and visitors. Currently the main research interests are nuclear few- and many-body physics, astrophysics and cosmology, lattice QCD, effective field theories and chiral perturbation theory, and particle physics beyond the standard model.

The five permanent staff members of the group are: Harold W. Fearing, Byron K. Jennings (group leader), John N. Ng, Achim Schwenk (from August) and Richard M. Woloshyn. Erich W. Vogt (professor emeritus, UBC) is an associate member. Research associates during 2006 were: I. Allison, P. Capel (until September), R. Cyburt (until September), J. Holt (from September), W. Liao, S. Nakamura, P. Reuter (from July), L. Theussl (until October) and J.M.S. Wu.

The students associated with the group during 2006 were: S.-H. Ho (National Tsing Hua University), supervised by C.Q. Geng, E. O'Connor (University of Prince Edward Island), supervised by A. Schwenk, and N. Supanam (Suranee University of Technology), supervised by H. Fearing.

Long term visitors included E. Dalgic (SFU), C.Q. Geng (National Tsing Hua University), S.W. Hong (Sungkyunkwan University), Y.K. Hsiao (National Tsing Hua University) and J. Shigemitsu (Ohio State University).

The short term visitors to the Theory group this year included:
B. Barrett
J. Braun
D. Cardamone
E.D. Cooper
A. Czernecki
M. Forbes
A. Frolov
C. Gale
C.J. Horowitz
M. Kennett
A.N. Kvinikhidze
C. Lunardini
M. Metlitski
N. Michel
A. Mukhamedzhanov
A. Nogga
F. Nunes
T. Papenbrock
Y. Qian
S. Quaglioni
G. Rupak
M. Savage
S. Scherer
I. Stetcu
D. Wilkinson
M. Wingate
F. Zhou
K. Zurek.

As usual members of the group have been very 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 Few- and Many-body Physics

Peripherality of breakup reactions

(P. Capel; F.M. Nunes, NSCL/MSU)

Recent theoretical papers show that breakup amplitudes are sensitive mainly to asymptotic properties of projectile wavefunction. To study this, breakup calculations of loosely bound nuclei (^{8}B and ^{11}Be) were performed with two different descriptions of the projectile. The descriptions differ strongly in the interior of the wave function, but exhibit identical asymptotic properties (ANC, and phase shifts). Calculations were performed for both nuclei at intermediate (4070 MeV/nucleon) and low (26 MeV) energies with heavy and light targets. No dependence on the projectile description is observed. This result confirms that breakup reactions probe only the external part of the wave function. The extraction of spectroscopic factors from these measurements is therefore meaningless.

Influence of the projectile description on breakup calculations

(P. Capel; F.M. Nunes, NSCL/MSU)

Calculations of the breakup of ^{8}B and ^{11}Be were performed with the aim of analyzing their sensitivity to the projectile description. Several potentials adjusted on the same experimental data were used for each projectile. The results vary significantly with the potential choice, and this sensitivity differs from one projectile to the other. In the ^{8}B case, the breakup cross section is approximately scaled by the asymptotic normalization coeffcient of the initial bound state (ANC). For ^{11}Be, the overall normalization of the breakup cross section is no longer solely determined by the ANC. The partial waves describing the continuum are found to play a significant role in this variation, as the sensitivity of the phase shifts to the projectile description changes with the physical constraints imposed to the potential.

Extended optical model analyses of elastic scattering

(S.W. Hong, Sungkyunkwan/TRIUMF; B.T. Kim, Sungkyunkwan; W.Y. So, T. Udagawa, Texas at Austin; K.S. Kim, Hankuk Aviation Univ.)

Based on the extended optical model approach in which the polarization potential is decomposed into direct reaction (DR) and fusion parts, simultaneous χ^2 analyses are performed for elastic scattering and fusion cross section data for the ^{6}Li+^{208}Pb system at near-Coulomb-barrier energies. A folding potential is used as the bare potential. It is found that the real part of the resultant DR part of the polarization potential is repulsive, which is consistent with the results from the continuum discretized coupled channel (CDCC) calculations and the normalization factors needed for the folding potentials. Further, it is found that both DR and fusion parts of the polarization potential satisfy separately the dispersion relation.

Microscopic restoration of proton-neutron mixed symmetry in weakly-collective nuclei

(J.D. Holt; N. Pietralla, Darmstadt; J.W. Holt, T.T.S. Kuo, Stony Brook)

Starting from microscopic lowmomentum nucleon-nucleon interactions $V_{\mathrm{low}\,k}$, we presented the first systematic shell model study of magnetic moments and magnetic dipole transition strengths of the basic lowenergy one-quadrupole phonon excitations in nearly-spherical nuclei. Studying in particular the eveneven N = 52 isotones from ^{92}Zr to ^{10}Cd, we predicted the evolution of two important observables in mixedsymmetry studies: the $B(M1 : 2^+_{ms} \to 2^+_1)$ value (as shown in Fig. th1) and the g factors for the one-phonon symmetric (2^+_1) and one-phonon mixed-symmetric state (2^+_{ms}) (shown in Fig. th2).

From these results, it is clear that the strongest signatures for MSSs in this region come at mid-shell, which is also where the g factors of the two one-phonon states are approximately the same.

An analysis of the microscopic wavefunctions of the 2^+_1 and 2^+_{ms} states showed a clear evolution of proton/neutron content of these states consistent with the results shown in Figs. th1 and th2. These results were in disagreement with similar predictions made by the proton-neutron version of the interacting boson model (IBM-2). However, it was shown that an approximate energy degeneracy of the quadrupole phonon excitations of the proton and neutron subsystems leads to a restoration of collective proton-neutron mixed-symmetry structure near mid-shell, and it is only inside this region where the predictions of the IBM-2 should be accurate. This microscopic mechanism thus provided the first explanation for the existence of pronounced collective mixed-symmetry structures in weakly-collective nuclei.

Low-momentum interactions with smooth cutoffs

(S.K. Bogner, R.J. Furnstahl, S. Ramanan, OSU; A. Schwenk)

Nuclear interactions with variable momentum cutoffs, known generically as $V_{\mathrm{low}\,k}$, show great promise for few- and many-body calculations. Changing the cutoff leaves observables unchanged by construction, but shifts contributions between the potential and the sums over intermediate states in loop integrals. These shifts can weaken or largely eliminate sources of nonperturbative behaviour. As a result, in practice, few- and many-body calculations can be greatly simplified or converge more rapidly by lowering the cutoff. This has been observed with variational methods, the coupled-cluster (CC) approach and for nuclear matter.

Nucleon-nucleon potentials evolved to low momentum have generally been formulated with a sharp cutoff on relative momenta. However, a sharp cutoff has technical disadvantages in some applications and can lead to slow convergence, for example at the 10–100 keV level in few-body calculations using harmonic oscillator bases, see Fig. th3. This motivates using smooth momentum-space regulators as an alternative. We have generalized low-momentum interactions to smooth cutoffs [Bogner *et al.*, Nucl. Phys. A, in press, nucl-th/0609003], both through renormalization group methods and using a multi-step process based on the Bloch-Horowitz approach.

In Fig. th3, we find greatly improved convergence for calculations of the triton binding energy in a harmonic oscillator basis, compared to results with a sharp cutoff. Similar results are found for the deuteron binding energy. The difference between the converged results in Fig. th3 is a measure of the differences in the short-range three-body interactions with the different regulators. As demonstrated in Fig. th4, even a slight evolution of chiral EFT interactions to lower momenta is beneficial.

The renormalization group preserves the long-range part of the interaction, and consequently the renormalization of long-range operators, such as the quadrupole moment, the radius and $\langle 1/r \rangle$, is found to be small. This shows that low-energy observables in the deuteron are reproduced without short-range correlations in the wave function. There are immediate applications that can be made using the developed low-momentum interactions with smooth cutoffs. Variational calculations using hyperspherical harmonics, the NCSM and CC approach should benefit from the improved convergence. Tests for all of these are in progress.

Dependence of the $^1\mathrm{S}_0$ superfluid pairing gap on nuclear interactions

(A. Schwenk; K. Hebeler, B. Friman, GSI)

Superfluidity plays a central role in strongly-interacting many-body systems ranging from nuclei, halos and neutron stars to cold atoms. The isospin dependence of nuclear pairing gaps shows striking trends over a range of isotopes, the β-decay of the two-neutron halo in ^{11}Li is suppressed due to pairing, similar to neutrino emission in neutron star cooling, and resonant Fermi gases exhibit vortices and superfluid characteristics in thermodynamic and spectroscopic properties.

For relative momenta $k \lesssim 2$ fm^{-1}, nucleon-nucleon (NN) interactions are well constrained by the existing scattering data [Bogner *et al.*, Phys. Rept. **386**, 1 (2003)]. The model dependence for larger momenta shows up prominently, for instance, in the $^3\mathrm{P}_2$ superfluid pairing gaps for Fermi momenta $k_\mathrm{F} > 2$ fm^{-1} [Baldo *et al.*, Phys. Rev. **C58**, 1921 (1998)]. In Hebeler *et al.* [nucl-th/0611024], we have studied in detail the dependence of the $^1\mathrm{S}_0$ superfluid gap (for $k_\mathrm{F} < 1.6$ fm^{-1}) on nuclear interactions at the BCS level, and on the resolution scale. Starting from chiral EFT and conventional NN interactions, we use the renormalization group to generate low-momentum, phase-equivalent interactions $V_{\mathrm{low}\,k}$ with sharp and smooth regulators. Figure th5 demonstrates that the gap is practically independent of the NN interaction used. Consequently, the BCS gaps are well constrained by the NN phases. As shown, isospin symmetry breaking leads to small but significant charge dependences in the pairing gaps.

In Fig. th6, we find that the cutoff dependence is very weak for sharp or sufficiently narrow smooth regulators with $\Lambda > 1.6$ fm^{-1}. As long as the cutoff is large compared to the dominant momentum components in the Cooper bound state, the gap depends very weakly on the cutoff. Below this scale, which depends on the density and the smoothness of the regulator, the strength of the bound state decreases, since the momentum modes that build up the Cooper pairs are integrated out.

We conclude that the uncertainties in $^1\mathrm{S}_0$ superfluidity are due to an approximate treatment of induced interactions and dispersion effects, which go beyond the BCS level, as well as due to three-nucleon interactions. Finally, we emphasize that our results are obtained at the BCS level, and thus should be considered as a theoretical benchmark and not as a prediction of the physical pairing gap.

Are low-energy nuclear observables sensitive to high-energy phase shifts?

(S.K. Bogner, R.J. Furnstahl, R.J. Perry, OSU; A. Schwenk)

Conventional nucleon-nucleon potentials with strong short-range repulsion require contributions from high-momentum wave function components even for low-energy observables such as the deuteron binding energy. For example, if such interactions are simply truncated at a low-momentum scale 2 fm^{-1}, the deuteron binding energy and the S-wave phase shifts down to zero energy are drastically altered. This can lead to the misconception that *details* of strong-interaction dynamics above some energy scale are relevant to low-energy nuclear structure and reactions.

In Bogner *et al.* [nucl-th/0701013], we have used the similarity renormalization group (SRG) as a tool to demonstrate unequivocally that this intuition is incorrect. Two-nucleon interactions derived via the SRG decouple low-energy physics from detailed high-momentum dynamics, by evolving the Hamiltonian towards the diagonal in momentum space (see also Bogner *et al.* [nucl-th/0611045]). Using SRG potentials, we have shown that high-energy details in wave functions and operators are irrelevant to low-energy observables. When we set the high-momentum components above a relative momentum k_max to zero in Fig. th7, the low-energy phase shifts (and expectation values in the deuteron) are practically unchanged. We have applied a similar test to the SRG-evolved deuteron momentum distribution to show that high-momentum effects in low-energy bound states are captured by scale-dependent low-momentum operators.

Renormalization group analysis of nuclear current operators

(S. Nakamura; S. Ando, Sungkyunkwan)

Electroweak processes in fewnucleon systems have been of interest in nuclear physics. Nuclear current operators for those processes come from either phenomenological models or nuclear effective field theory (NEFT). Although detailed expressions and behaviours of the current operators based on these two approaches are in general different from each other, it has been reported that the two approaches give essentially the same reaction rates. This implies equivalence between the two approaches in describing the lowenergy electroweak processes. We study the relation of them employing a renormalization group analysis. We reduce the model space of the current operators for the neutrinoinduced disintegration of the deuteron using the Wilsonian renormalization group equation. We essentially reach a single effective operator at a certain small model space that is relevant to pionless theory. Therefore, we conclude that, as long as reactions with the kinematics included in the small model space are concerned, the external probe cannot find details of small scale physics which appear as the differences among the nuclear operators. We understand why the different operators give the same observables in this way.

Relativistic propagators

(B.K. Jennings)

In a previous paper [Cooper *et al.*, Nucl. Phys. **A556**, 579 (1993)] an attempt was made at comparing various relativistic propagators. Since observables are Lorentz invariant it was assumed that the propagators would be Lorentz invariant as well. A recent work [Amghar *et al.*, Nucl. Phys. **A714**, 213 (2003)] made a different assumption for the propagator, namely that it should be able to be written in a form that does not explicitly depend on the centre of mass momentum. This is a more general version of the propagator than used in the previous work by the present author. The implications of the more general propagator have been explored and the exact nature of the differences clarified.

ECT* school on Renormalization Group and Effective Field Theory Approaches to Many-Body Systems

(A. Schwenk, U. Washington/TRIUMF; J. Polonyi, Strasbourg)

Over the past five years, there have been important developments based on effective field theory and the renormalization group in atomic, condensed matter, nuclear and high-energy physics. These powerful and versatile methods offer novel approaches to study complex and strongly interacting many-body systems in a controlled manner.

We have organized the first ECT* school on Renormalization Group and Effective Field Theory Approaches to Many-Body Systems, Feb. 27–March 10, 2006 in Trento, Italy. The ECT* school was interdisciplinary with the aim to foster student contacts across physics subfields, and focused on recent renormalization group and effective field theory applications to atomic (Bose-Einstein condensation, resonant Fermi gases, QED in atoms), condensed matter (Fermi liquids, superconductivity, low-dimensional Fermi systems, frustrated systems), nuclear (chiral interactions, few-body systems, nucleonic matter, density functional theory, neutron stars) and high-energy many-body systems (quark matter, colour superconductivity, gauge theories). The lectures are available on-line at the ECT* school Web site (TRIUMF-hosted) http://www.triumf.info/hosted/ECT/ and will be published in Springer Lecture Notes in Physics. By all accounts the school was a great success (see Fig. th8).

Astrophysics and Cosmology

Neutron matter at finite temperature

(L. Tolós, B. Friman, GSI; A. Schwenk)

The nuclear equation of state plays a central role in astrophysics ranging from the structure of neutron stars, to neutron star mergers and core-collapse supernovae. Astrophysics probes the equation of state at the extremes of isospin and temperature. The mass of a neutron star depends mainly on the equation of state of neutron-rich matter up to densities $\rho < 4\rho_0$ [Kalogera and Baym, Astrophys. J. **470**, 61 (1996)], where $\rho_0 = 0.16$ fm^{-3} is the saturation density, while supernova explosions are most sensitive to the properties of nucleonic matter at subnuclear densities and MeV temperatures. Many of the crucial regimes are extrapolations from the conditions reached with existing and upcoming experimental facilities. Therefore, reliable theoretical input is needed.

Renormalization group methods coupled with effective field theory offer the possibility of a new and systematic approach to nuclear matter. For low-momentum interactions $V_{\mathrm{low}\,k}$ with cutoffs around 2 fm^{-1}, the strong short-range repulsion in conventional nucleon-nucleon (NN) interactions and the tensor force are tamed. At sufficient density, Pauli blocking eliminates the shallow bound states, and thus the particle-particle channel becomes perturbative in nuclear matter [Bogner *et al.*, Nucl. Phys. **A763**, 59 (2005)]. In addition, the corresponding leading-order three-nucleon (3N) interaction becomes perturbative in light nuclei for $\Lambda \lesssim 2$ fm^{-1} [Nogga *et al.*, Phys. Rev. **C70**, 061002(R) (2004)]. Consequently, the Hartree-Fock (HF) approximation is a good starting point, and perturbation theory (in the sense of a loop expansion) around the HF energy becomes tractable.

At finite temperature, the loop expansion around the HF energy can be realized by the perturbative expansion of the free energy, where the momentum dependence of the self-energy is treated perturbatively. Our results for the free energy per particle are shown in Fig. th9 for temperatures $T = 3$, 6 and 10 MeV (for details see Tolós *et al.* [nucl-th/0611070 and in preparation]). For the $T = 6$ MeV results, we provide error estimates by varying the cutoff over the range $\Lambda = 1.9$ fm^{-1} (lower curve) to $\Lambda = 2.5$ fm^{-1} (upper curve). As expected the error grows with increasing density. From Fig. th9, we observe that the equation of state becomes significantly less cutoff dependent with the inclusion of the second-order NN contributions. Moreover, we find a very good agreement with the model-independent virial equation of state [Horowitz and Schwenk, Phys. Lett. **B638**, 153 (2006)] at low densities and similar results as the variational calculations of Friedman and Pandharipande (FP) [Nucl. Phys. **A361**, 502 (1981)].

Our results for the energy per particle are shown in Fig. th10. In contrast to the variational energy, the low-density behaviour at second order is in good agreement with the virial equation of state. This highlights the importance of a correct finite-temperature treatment of second and higher-order contributions. This work is part of a program to improve the nuclear equation of state input for astrophysics, and to provide error estimates, for example, for the neutron star mass and radius predictions.

Neutrino breakup of $A = 3$ nuclei in supernovae

(E. O'Connor, A. Schwenk; C.J. Horowitz, Indiana; D. Gazit, N. Barnea, Jerusalem)

We have recently developed a description of low-density nuclear matter (composed of neutrons, protons and alpha particles) in thermal equilibrium based on the virial expansion [Horowitz and Schwenk, Nucl. Phys. **A776**, 55 (2006)]. The virial equation of state makes model-independent predictions for the conditions near the neutrinosphere in supernovae (SN), for low densities $\rho \sim 10^{11-12}$ g/cm^3 and high temperatures $T \sim 4$ MeV. In particular, the resulting alpha particle concentration differs from all equations of state currently used in SN simulations, and the predicted large symmetry energy at low densities has been confirmed in near Fermi-energy heavy-ion collisions [Kowalski *et al.*, Phys. Rev. C, in press].

We have extended the virial expansion to include ^{3}H and ^{3}He nuclei, and predict significant mass-three fractions (∼10) near the neutrinosphere in SN [O'Connor *et al.*, in preparation]. The second virial coefficients involving $A = 3$ nuclei are calculated directly from the corresponding nucleon-^{3}H and nucleon-^{3}He scattering phase shifts. While alpha particles are often more abundant due to the large binding energy ($E_4 =$ 28.3 MeV compared to $E_3 \sim 8$ MeV), we show that mass-three nuclei are important for energy transfer, in particular for the more energetic μ and τ neutrinos with $E_{\nu_{\mu,\tau}} \sim 20$ MeV. For neutrinos with these energies, we find that the energy transfer cross sections and the neutrino energy loss for $T \gtrsim 4$ MeV are dominated by breakup of the loosely-bound ^{3}H and ^{3}He nuclei. Our predictions for the inelastic neutral-current cross sections are based on microscopic two- and three-nucleon interactions, including full final state interactions and meson-exchange currents.

Bound-state effects on light-element abundances in gravitino dark matter scenarios

(R.H. Cyburt; J. Ellis, CERN; B.D. Fields, Illinois; K.A. Olive, V.C. Spanos, Minnesota)

If the gravitino is the lightest supersymmetric particle and the long-lived next-to-lightest sparticle (NSP) is the stau, the charged partner of the tau lepton, it may be metastable and form bound states with several nuclei. These bound states may affect the cosmological abundances of ^{6}Li and ^{7}Li by enhancing nuclear rates that would otherwise be strongly suppressed. We consider the effects of these enhanced rates on the final abundances produced in Big Bang nucleosynthesis (BBN), including injections of both electromagnetic and hadronic energy during and after BBN. We calculate the dominant two and threebody decays of both neutralino and stau NSPs, and model the electromagnetic and hadronic decay products using the PYTHIA event generator and a cascade equation. Generically, the introduction of bound states drives light element abundances further from their observed values; however, for small regions of parameter space bound state effects can bring lithium abundances in particular in better accord with observations. We show that in regions where the stau is the NSP with a lifetime longer than 10^3–10^4 s, the abundances of ^{6}Li and ^{7}Li are far in excess of those allowed by observations. For shorter lifetimes of order 1000 s, we comment on the possibility in minimal supersymmetric and supergravity models that stau decays could reduce the ^{7}Li abundance from standard BBN values while at the same time enhancing the ^{6}Li abundance.

Kaon condensation and composition of neutron star matter in modified quark-meson coupling model

(C.Y. Ryu, C.H. Hyun, B.T. Kim, Sungkyunkwan; S.W. Hong, Sungkyunkwan/TRIUMF)

We use the modified quark-meson coupling (MQMC) model to study the composition profile of neutron star matter and compare the results with those calculated by quantum hadrodynamics (QHD). Both MQMC and QHD model parameters are adjusted to produce exactly the same saturation properties so that we can investigate the model dependences of the matter composition at high densities. We consider the possibility of deep kaon optical potential and find that the composition of matter is very sensitive to the interaction strength of kaons with matter. Onset densities for the kaon condensation are studied in details by varying the kaon optical potentials. We find that the MQMC model produces the kaon condensation at a lower density than QHD. The presence of kaon condensation changes drastically the population of octet baryons and leptons. Once the kaon condensation takes place, the population of kaons builds up very quickly, and kaons become the dominant component of the matter, making the neutron star matter a kaonic matter. We find that the ω-meson plays an important role in increasing the kaon population and suppressing the hyperon population.

Particle Physics

Shadow Higgs from a scale-invariant hidden $U(1)_s$ model

(W.F. Chang, Academia Sinica; J.N. Ng, J.M.S. Wu)

We study the phenomenology of the Higgs sector in a classically conformal model with gauge group that of the standard model (SM) plus a hidden U(1). We show the viability of a light hidden sector Higgs, and we explore its impact on SM Higgs physics testable at the LHC.

A very narrow shadow extra Z-boson at colliders

(W.F. Chang, Academia Sinica; J.N. Ng, J.M.S. Wu)

We consider the phenomenological consequences of a hidden Higgs sector extending the standard model (SM), in which the "shadow Higgs" are uncharged under the SM gauge groups. We consider a simple U(1) model with one Higgs singlet. One mechanism which sheds light on the shadow sector is the mixing between the neutral gauge boson of the SM and the additional U(1) gauge group. The mixing happens through the usual mass-mixing and also kinetic-mixing, and is the only way the "shadow Z" couples to the SM. We study in detail modifications to the electroweak precision tests (EWPTs) that the presence of such a shadow sector would bring, which in turn provide constraints on the kinetic-mixing parameter, s_ϵ, left free in our model. The shadow Z production rate at the LHC and ILC depends on s_ϵ. We find that observable event rate at both facilities is possible for a reasonable range of s_ϵ allowed by EWPTs.

Direct CP violation in $B^\pm \to p\bar{p}K^{(*)\pm}$

(C.Q. Geng, Y.K. Hsiao, Nat. Tsing Hua Univ.; J.N. Ng)

We study the direct CP violation in $B^\pm \to p\bar{p}K^{(*)\pm}$ decays in the standard model. We point out that these three-body baryonic B decays can be important tools for detecting the direct CP violation in the charged B system, in which there are no conclusive signatures yet. In particular, we show that the direct CP violating asymmetry in $B^\pm \to p\bar{p}K^{*\pm}$ is around 22 which supports the recent data by the BaBar collaboration.

Unconventional neutrino mass generation, neutrinoless double beta decays, and collider phenomenology

(C.S. Chen, C.Q. Geng, Nat. Tsing Hua Univ.; J.N. Ng)

We study a model in which lepton number violation is solely triggered by a dimension 4 hard breaking term in the scalar potential. A minimal model which contains a SU(2) triplet with hypercharge $Y = 2$, and a pair of singlet doubly charged scalar fields in addition to the standard model (SM) Higgs doublet is constructed. The model is technically natural in the sense that lepton number is preserved in the limit that the hard term vanishes. SM phenomenology restricts the vacuum expectation value of the triplet scalar field $v_T < 5.78$ GeV. Neutrino masses controlled by v_T are generated at the two loop level and are naturally to the subeV range. In general they exhibit normal hierarchy structure. Here the neutrino mass term does not dominate neutrinoless double beta decays of nuclei. Instead the short distance physics with doubly charged Higgs exchange gives the leading contribution. We expect weak scale singly and doubly charged Higgs bosons to make their appearances at the LHC and the ILC.

Neutrino number asymmetry and cosmological birefringence

(C.Q. Geng, S.H. Ho, Nat. Tsing Hua Univ.; J.N. Ng)

We study a new type of effective interactions in terms of the CPT-even dimension-six Chern-Simons-like term to generate the cosmological birefringence. We use the neutrino number asymmetry to induce a nonzero rotation polarization angle in the data of the cosmic microwave background radiation polarization.

Charged Higgs on $B^- \to \tau\bar{\nu}_\tau$ and $\bar{B} \to P(V)\ell\bar{\nu}_\ell$

(C.H. Chen, NCKU; C.Q. Geng, Nat. Tsing Hua Univ.)

We study the charged Higgs effects on the decays of $B^- \to \tau\bar{\nu}_\tau$ and $\bar{B} \to P(V)\ell\bar{\nu}_\ell$ with $P = \pi^+, D^+$ and $V = \rho^+, D^{*+}$. We concentrate on the minimal supersymmetric standard model with nonholomorphic terms at a large $\tan\beta$. To extract new physics contributions, we define several physical quantities related to the decay rate and angular distributions to reduce uncertainties from the QCD as well as the CKM elements. With the constraints from the recent measurement on the decay branching ratio of $B^- \to \tau\bar{\nu}_\tau$, we find that the charged Higgs effects could be large and measurable.

$\eta^{(\prime)}$ productions in semileptonic B decays

(C.H. Chen, NCKU; C.Q. Geng, Nat. Tsing Hua Univ.)

Inspired by the new measurements on $B^- \to \eta^{(\prime)} \ell \bar{\nu}_\ell$ from the BaBar Collaboration, we examine the constraint on the flavour-singlet mechanism, proposed to understand the large branching ratios for $B \to \eta' K$ decays. Based on the mechanism, we study the decays of $\bar{B}_{d,s} \to \eta^{(\prime)} \ell^+ \ell^-$ and find that they are sensitive to the flavour-singlet effects. In particular, we show that the decay branching ratios of $\bar{B}_{d,s} \to \eta' \ell^+ \ell^-$ can be as large as $O(10^{-8})$ and $O(10^{-6})$, respectively.

Implications of the hyperCP data on B and τ decays

(C.H. Chen, NCKU; C.Q. Geng, Nat. Tsing Hua Univ.)

If the hyperCP three events for the decay of $\Sigma^+ \to p\mu^+\mu^-$ are explained by a new pseudoscalar (axial-vector) boson $X_{P(A)}$ with a mass of 214.3 MeV, we study the constraints on the couplings between $X_{P(A)}$ and fermions from the experimental data in K and B processes. Some implications of the new particle on flavour changing B and τ decays are given. Explicitly, we show that the decay branching ratios of $B_s \to \phi X_{P(A)} \to \phi\mu^+\mu^-$, $B_d \to K_0^*(1430)P(A) \to K_0^*(1430)\mu^+\mu^-$ and $\tau \to \mu X_{P(A)} \to \mu\mu^+\mu^-$ can be as large as $2.7\ (2.8) \times 10^{-6}$, $7.4\ (7.5) \times 10^{-7}$ and $1.7\ (0.14) \times 10^{-7}$, respectively.

$B \to \eta^{(\prime)}(\ell^-\bar{\nu}_\ell, \ell^+\ell^-, K, K^*)$ decays in the quark-flavour mixing scheme

(A.G. Akeroyd, C.H. Chen, NCKU; C.Q. Geng, Nat. Tsing Hua Univ.)

In the quark-flavour mixing scheme, η and η' are linear combinations of flavour states $\eta_q = (u\bar{u}+d\bar{d})/\sqrt{2}$ and $\eta_s = s\bar{s}$ with the masses of m_{qq} and m_{ss}, respectively. Phenomenologically, m_{ss} is strictly fixed to be around 0.69, which is close to $\sqrt{2m_K^2 - m_\pi^2}$ by the approximate flavour symmetry, while m_{qq} is found to be 0.18 ± 0.08 GeV. For a large allowed value of m_{qq}, we show that the BRs for $B \to \eta^{(\prime)} X$ decays with $X = (\ell^-\bar{\nu}_\ell,\ \ell^+\ell^-)$ are enhanced. We also illustrate that $BR(B \to \eta X) > BR(B \to \eta' X)$ in the quark-flavour mixing scheme, in contrast to the reversed inequality in the flavour-singlet mechanism. Moreover, we demonstrate that the decay branching ratios (BRs) for $B \to \eta^{(\prime)} K^{[*]}$ are consistent with the data. In particular, the puzzle of the large $BR(B \to \eta' K)$ can be solved. In addition, we find that the CP asymmetry for $B^\pm \to \eta K^\pm$ can be as large as -30, which agrees well with the data. However, we cannot accommodate the CP asymmetries of $B \to \eta K^*$ in our analysis, which could indicate the existence of some new CP violating sources.

Expectations on $B \to \left(K_0^*(1430), K_2^*(1430)\right)\phi$ decays

(C.H. Chen, NCKU; C.Q. Geng, Nat. Tsing Hua Univ.)

As the annihilation contributions play important roles in solving the puzzle of the small longitudinal polarizations in $B \to K^*\phi$ decays, we examine the similar effects in the decays of $B \to K_{0,2}^*(1430)\phi$. For the calculations on the annihilated contributions, we adopt that the form factors in $B \to K^{(*)}\phi$ decays are parameters determined by the observed branching ratios (BRs), polarization fractions (PFs) and relative angles in experiments and we connect the parameters between $B \to K_{0(2)}^*\phi$ and $B \to K^{(*)}\phi$ by the ansarz of correlating $< K_n^*(1430)\phi|(V-A)_\mu|0 >$ to $< K^{(*)}\phi|(V-A)_\mu|0 >$. We find that the BR of $B_d \to K_0^{*0}(1430)\phi$ is $(3.69 \pm 0.47) \times 10^{-6}$. By using the transition form factors of $B \to K_2^*(1430)$ in the light-front quark model (LFQM) and the second version of Isgur-Scora-Grinstein-Wise (ISGW2), we show that BR of $B_d \to K_2^{*0}(1430)\phi$ is a broad allowed value and $(1.70 \pm 0.80) \times 10^{-6}$, respectively. In terms of recent BaBar observations on BRs and PFs in $B_d \to K_2^{*0}(1430)\phi$, the results in the LFQM are found to be more favourable. In addition, we demonstrate that the longitudinal polarization of $B_d \to K_2^{*0}(1430)\phi$ is always $O(1)$ with or without including the annihilation contributions.

Effective Field Theory and Chiral Perturbation Theory

Renormalization group analysis of pion production operator

(S. Nakamura; A. Gårdestig, South Carolina)

Chiral perturbation theory is expected to be a powerful framework to study pion production in nucleon-nucleon collision. Usually, pion production operators consist of interactions all of which are present in the chiral Lagrangian. However, there is a concern that we may need to add terms, which are not included in the chiral Lagrangian, to the pion production operators. This is because we use a cutoff regularization which possibly violates the chiral symmetry.

In order to clarify a consequence of using the cutoff regularization, we start with chiral next-to-leading order (NLO) pion production operator, and introduce a cutoff using a Wilsonian renormalization group equation. After the running of the operator, we obtain the effective operator which is to be parameterized by the chiral NLO operator plus higher order counter terms. We found the accuracy of the parameterization to be suffciently good, which led us to conclude that the introduction of the cutoff does not generate the chiral symmetry violating interaction, at least, not at a practical level.

Baryon chiral perturbation theory with virtual photons and leptons

(N. Supanam, H.W. Fearing)

The general Lagrangian for baryon chiral perturbation theory with virtual photons to fourth order has been constructed about a decade ago. In this work the Lagrangian will be extended by including the lepton fields, as well as photons, as explicit degrees of freedom. We construct the hermitian Lagrangian built from pions and nucleons, external scalar, pseudoscalar, vector, and axial-vector fields, virtual photons, and leptons, which are parameterized in terms of $J^W_\mu = \bar{l}\gamma_\mu(1-\gamma_5)\nu_l$. We consider only terms quadratic in the lepton fields and at most linear in G_F. We apply this procedure to neutron beta decay and will compute radiative corrections to the axial-vector coupling constant g_A, which plays an important role in hadronic weak-interaction.

Ordinary muon capture on a proton in manifestly Lorentz invariant baryon chiral perturbation theory

(S. Ando, Sungkyunkwan; H.W. Fearing)

A manifestly Lorentz invariant form of baryon chiral perturbation is used to evaluate the amplitude for ordinary muon capture on the proton, through the first four orders in the expansion parameter. Expressions for the low energy constants in terms of physical quantities are obtained in each of the several renormalization schemes which have been proposed for forcing the relativistic approach to obey the same counting rules as obtained in heavy baryon chiral perturbation theory. The advantages and disadvantages of these schemes are discussed, using the muon capture results as an example, with the aim of gaining insight as to which scheme is preferable for practical calculations.

A relativistic chiral perturbation theory calculation of radiative muon capture

(H.W. Fearing)

For some time now, since the TRIUMF measurement of radiative muon capture (RMC) on the proton, there has been a puzzle regarding the value of the induced pseudoscalar coupling G_P. Recent data from PSI for ordinary muon capture (OMC) seems to confirm the prediction of chiral symmetry. New TRIUMF data on the orthopara transition rate has been important but still the TRIUMF RMC measurement, interpreted in the standard theory, suggests a value of G_P which is significantly too high.

We have thus begun a new full fledged calculation of RMC on the proton in the framework of relativistic chiral perturbation theory. This builds on the infrastructure of our similar calculation of OMC but is much more complicated, involving more than a hundred diagrams. One must first calculate the sub processes of radiative pion capture and pion photoproduction to evaluate some of the low energy constants. Then one needs the weak-electromagnetic-NN contact diagram. The end result should be the complete RMC amplitude to fourth order in the momentum. It will contain two ingredients not present in the existing standard calculations, namely an explicit calculation of the gauge term, which is normally put in only via minimal coupling, and a relaxation of the usual on-shell approximation for the weak and electromagnetic vertices.

Lattice QCD

Lattice operator renormalization factors from high β simulation

(I. Allison, R.M. Woloshyn; E. Dalgic, H.D. Trottier, SFU; J. Shigemitsu, OSU)

Lattice QCD plays a crucial role in the extraction of many quantities from current high energy experiments. In the present climate, where these experiments are looking to test the limits of QCD, precision in the necessary lattice calculations is vital. These calculations involve not only the extraction of non-perturbative matrix elements but also any associated renormalization coefficients.

In the past, the extraction of these coefficients has relied upon lattice perturbation theory, but as demands on precision have increased, so has the difficulty in computing the needed higher order perturbative corrections. We have been looking at an alternative method of extracting the needed renormalization coefficients which makes use of Monte Carlo methods at weak coupling. The central idea of this approach is to run simulations at various (small) values of the strong coupling constant, measuring the required operator. The desired renormalization coefficient can then be extracted from an expansion of the result in the strong coupling constant. We are studying the application of this method to the calculation of current operators through the simulation of current-current correlation functions in the perturbative regime.

The spectrum of tmLQCD with quark and link smearing

(A.M. Abdel-Rehim, R. Lewis, R.G. Petry, Regina; R.M. Woloshyn)

Twisted mass lattice QCD (tmLQCD) offers the prospect of doing simulations at relatively small quark masses. Experience has shown that although pion signals are very clear the correlators for other hadrons tend to have significant statistical fluctuations in the quark mass region of interest. We have investigated the use of smeared sink operators as a way to overcome this problem. The hadron spectrum was studied for quenched twisted mass lattice QCD with up, down, and strange quarks. Gaussian smearing was used for quark fields, and stout link smearing for gauge fields. Smeared correlators were found to be dominated by the ground state with a small contribution from excited states, leading to an improved determination of some ground state masses. However this method was not always better than doing multi-exponential fits to unsmeared correlators since the latter typically have smaller statistical errors. The overall conclusion is that sink smearing is useful but not suffcient to lead to a precise determination of the baryon spectrum at small quark masses.

Strange quarks in quenched twisted mass lattice QCD
(A.M. Abdel-Rehim, R. Lewis, Regina; R.M. Woloshyn, J.M.S. Wu)

In the twisted mass scheme for lattice fermions there is no unique way to introduce the strange quark. In our work two twisted doublets, one containing the up and down quarks and the other containing the strange quark with an SU(2)-flavour partner, were used for studies in the meson sector. The doublet containing the strange quark was not degenerate in mass and the twist was applied using a twist generated by an operator aligned in flavour space with the mass splitting. The relevant chiral perturbation theory for this set-up was developed.

Quenched QCD simulations (where the partner of the strange quark is not active) were performed. Pseudoscalar meson masses and decay constants were computed. It was found that there was a significant splitting between states that could be naturally identified as members of the kaon doublet. A comparison was made to the case of an untwisted strange quark, in which case the kaon splitting but mixing between opposite parity states, induced by twisting in the up-down sector, could not be avoided.

Two-loop HISQ mass renormalization factors
(H.D. Trottier, E. Dalgic, SFU; J.M.S. Wu)

We calculate to two-loop order in lattice perturbation renormalization factors needed for high precision quark mass computations, and for matching the lattice theory to continuum in the highly improved staggered fermion formulation of lattice QCD.

Miscellaneous

The complex gap in colour superconductivity
(P.T. Reuter)

Suffciently cold and dense quark matter is a colour superconductor. In the limit of asymptotically large quark chemical potentials, $\mu \gg \Lambda_{\mathrm{QCD}}$, quarks are weakly coupled, and interact mainly via singlegluon exchange. In this regime of weak coupling, the colour-superconducting gap ϕ can be computed within the fundamental theory of strong interactions, quantum chromodynamics. To do so, it is crucial to take into account the specific energy and momentum dependence of the gluon propagator in dense quark matter. Since the gluon propagator depends on energy and momentum, the gap is also a function of energy and momentum and therefore a complex quantity.

We solve the gap equation for colour superconducting quark matter in the 2SC phase, including both the energy and the momentum dependence of the gap, $\phi = \phi(k_0, \mathbf{k})$. For that purpose a complex Ansatz for ϕ is made. The calculations are performed within an effective theory for cold and dense quark matter. The solution of the complex gap equation is valid to subleading order in the strong coupling constant g and in the limit of zero temperature. We find that, for momenta suffciently close to the Fermi surface and for small energies, the dominant contribution to the imaginary part of ϕ arises from Landaudamped magnetic gluons. Further away from the Fermi surface and for larger energies the other gluon sectors have to be included into Imϕ. We confirm that Imϕ contributes a correction of order g to the prefactor of ϕ for onshell quasiquarks suffciently close to the Fermi surface, whereas further away from the Fermi surface Imϕ and Reϕ are of the same order. Finally, it is shown that Imϕ contributes to the decay of quasiquark excitations in a colour superconductor through the emission of gluons.

WZW term and anomaly inflow in odd dimensions
(W. Liao)

It is shown that Wess-Zumino-Witten (WZW) type actions can be constructed in odd dimensional spacetimes using Wilson line or Wilson loop. WZW action constructed using Wilson line gives anomalous gauge variations and the WZW action constructed using Wilson loop gives anomalous chiral transformation. The WZW action constructed using Wilson line can not be considered as action localized on boundary spacetimes since it can give anomalous gauge transformations on separated boundaries. It is shown that the anomaly inflow mechanism can be implemented by using the WZW action constructed using Wilson line in odd dimensional gauge theories. In this mechanism chiral fermions are localized on two branes. The quantum anomalies given by localized chiral fermions are cancelled by anomalies in the WZW action which flow into the branes. This offers a new way to generalize gauge theory and construct anomaly free gauge theory in odd dimensional space-times with chiral fermions on boundary space-times.

On the nature of science
(B.K. Jennings)

The scientific method is observationally constrained model building, not induction, falsification or methodological naturalism. The observations must be carefully done and reproducible. The models must be logical, internally consistent, predictive and as simple as possible. Both observations and models should be peer reviewed for error control. The goal of science is to construct models that make the maximum number of correct postdictions and predictions with the minimum number of assumptions. Supernatural explanations are rejected not a priori but when, as is usually the case, they lead to no testable predictions for future observations. In general, if you want your model to be accepted you must show that it makes more correct precise predictions with fewer assumptions than the competing models. There is a surfeit of models that make fewer predictions. As models are improved their predictive powers increase. We see progress with time, the models become less wrong, probably not absolutely right, but less wrong. There appears to be convergence towards the probably unreachable goal of a model of everything. The same can not be said for the philosophical and metaphysical implications of the models. Here there is no obvious convergence or at least the convergence is much slower. There is no overwhelming reason to believe the philosophical and metaphysical implications of presently accepted models. They will probably change in unpredictable ways when new improved models come along. The only important, enduring property of a model is its predictions for observations. Thus the metaphysical baggage – the action at a distance, the ether, the caloric, the many worlds, the objective reality – should not be taken too seriously. However, they frequently play a useful pedagogical role.

The scientific method
(B.K. Jennings)

The nature of the scientific method is controversial with claims that a single scientific method does not even exist. However the scientific method does exist. It is the building of logical and self consistent models to describe nature. The models are constrained by past observations and judged by their ability to correctly predict new observations and interesting phenomena. Observations do not prove models correct or falsify them but rather provide a means to rank models: models with more ability to predict observations are ranked higher. The observations must be carefully done and reproducible to minimize errors. They exist independent of the models but acquire their meaning from their context within a model. Model assumptions that do not lead to testable predictions are rejected as unnecessary. Both observations and models should be peer reviewed for error control. Consistency with observation and reason places constraints on all claims to knowledge, including religious.

On the quantum wave function *(E.D. Cooper, Univ. College of the Fraser Valley; B.K. Jennings)*

In analogy with classical probabilities, the quantum mechanical wave function is a property of the combined observerquantum system and not of the quantum system alone. This means that probability in the quantum world is observer dependent just as in the classical world. Thus this approach respects the correspondence principle, unlike variants of the Copenhagen and many-worlds interpretations of quantum mechanics. Moreover, this approach eliminates the need for action-at-distance or consciousness. It also rejects what is frequently called realism.

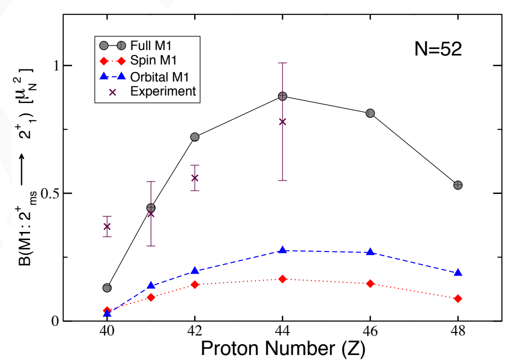

Fig. th1. Evolution of the total, orbital, and spin $B(M1:\ 2^+_{ms} \rightarrow 2^+_1)$ values for N = 52 isotones.

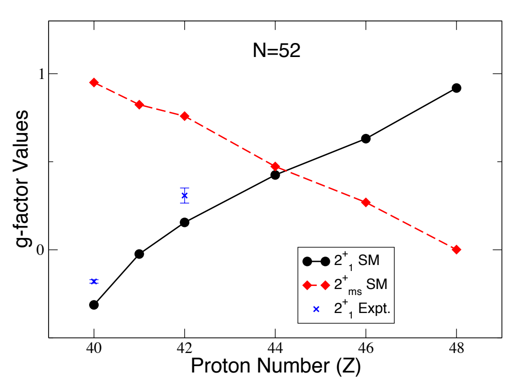

Fig. th2. Predicted evolution of the g factors for the 2_1^+ and 2_{ms}^+ states across the series of N = 52 isotones. The g factors are an indication of the proton-neutron content of the states.

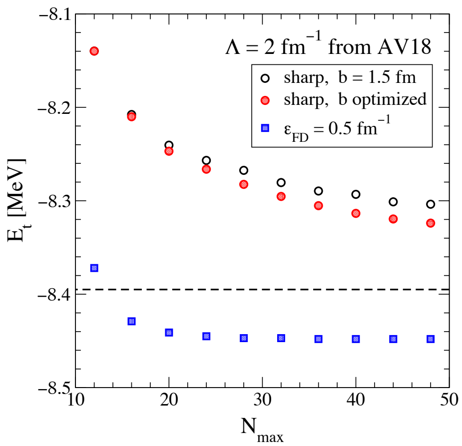

Fig. th3. The triton binding energy E_t calculated from a direct diagonalization in a harmonic oscillator basis of the low-momentum Hamiltonian derived from the Argonne v_{18} potential with cutoff $\Lambda = 2\ \mathrm{fm}^{-1}$, as a function of the size of the oscillator space ($N_{\max}\ \hbar\omega$ excitations). The open circles are calculated with a sharp cutoff for a fixed oscillator parameter b while the filled ones correspond to optimizing b at each $N_{\max}$. The dashed line indicates the exact Faddeev result using the sharp-cutoff interaction, and shows the slow convergence of the diagonalization at the 100 kev level. The squares are for a smooth regulator (of Fermi-Dirac form).

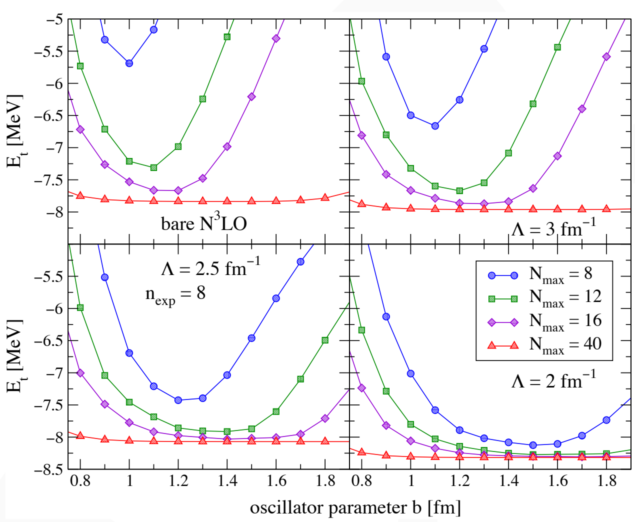

Fig. th4. Dependence of the triton binding energy E_t as a function of oscillator parameter b for a bare N^{3}LO chiral potential (upper left) and evolved to low momenta $\Lambda = 3.0$, 2.5 and 2.0 fm^{-1} with exponential regulator $n_{\exp} = 8$. Results are presented for three smaller spaces $N_{\max} = 8$, 12 and 16, along with the converged $N_{\max} = 40$ energy.

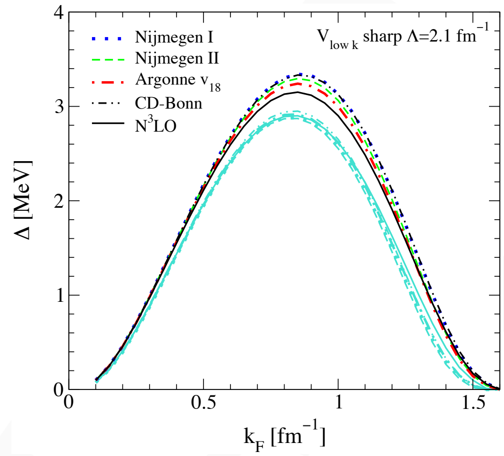

Fig. th5. The ^{1}S$_0$ superfluid gap Δ versus Fermi momentum k_{F} for sharp cutoffs derived from various charge-dependent NN interactions. The lines indicated in the legend are the neutron-proton gaps, whereas the grey lines show the neutron-neutron gaps.

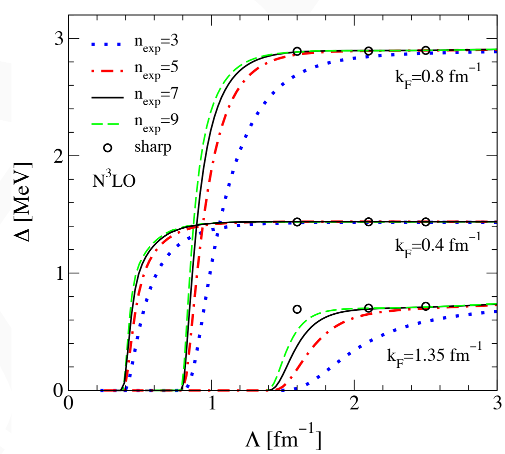

Fig. th6. Results for the neutron-neutron gaps as a function of the cutoff Λ for three densities and various regulators, starting from the N^{3}LO chiral interaction.

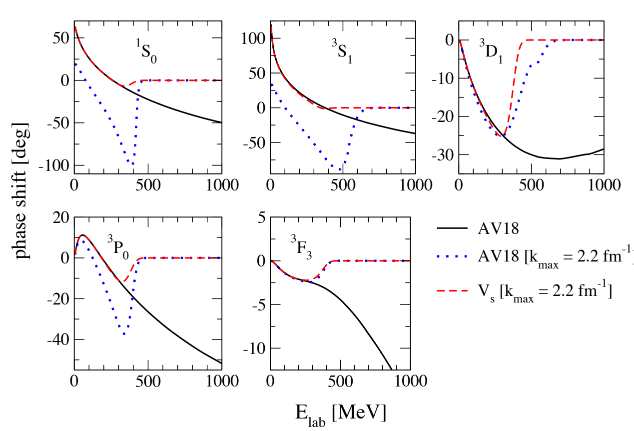

Fig. th7. Phase shifts in selected channels for the Argonne v_{18} potential and when intermediate momenta $k > k_{\rm max} = 2.2$ fm^{-1} are excluded. We contrast the latter results to the phase shifts obtained from the SRG-evolved V_s potential for $\lambda \equiv s^{-1/4} = 2$ fm^{-1} and the additional constraint $k_{\rm max} = 2.2$ fm^{-1}.

Fig. th8. Participants of the first ECT* school (46 from 12 countries).

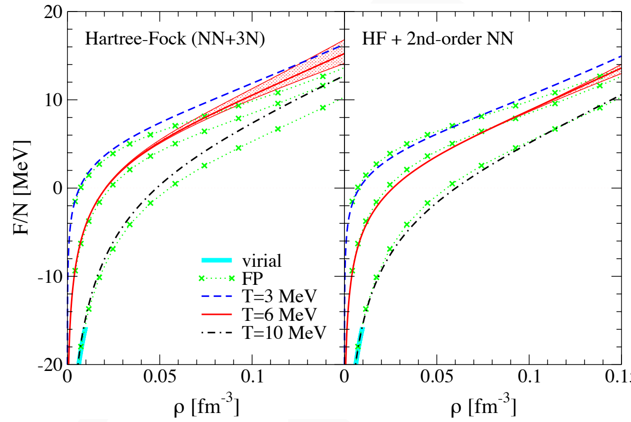

Fig. th9. The free energy per particle F/N as a function of density ρ. The left figure gives the first-order NN and 3N contributions. Second-order anomalous and normal NN contributions are included in the right figure.

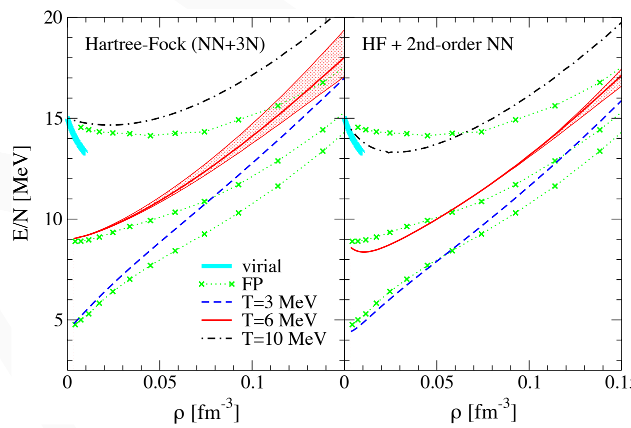

Fig. th10. The energy per particle E/N as a function of density ρ to first and second order as in Fig. th9.