# TRIUMF

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**CANADA'S NATIONAL LABORATORY**
**FOR PARTICLE AND NUCLEAR PHYSICS**

OPERATED AS A JOINT VENTURE

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

OCTOBER 2005

*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 and cosmology, 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 2004 were: R. Allahverdi, S. Ando, C. Barbieri, P. Capel (from November), W. Chang (until September), R. Cyburt, W. Liao (from October), J.-M. Sparenberg (until September), and L. Theussl. The graduate students associated with the group during 2004 were: N. Supanam, supervised by H. Fearing, and K. Wong, supervised by R. Woloshyn. B. Barrett (University of Arizona) was on sabbatical with the group for several months.

The short term visitors to the Theory group this year included: J. Al-Khalili, K. Amos, C. Aubin, N. Auerbach, S. Bogner, J. Bowers, M. Buechler, W. Dickhoff, B. Fields, K. Foley, H.W. Hammer, S. Hands, D. Harnett, W. Haxton, I. Horvath, F. Khanna, A. Krassnigg, D. Lin, H. Lipkin, M. Mebel, D. Renner, M. Savage, A. Schwenk, A. Steiner, M. Toharia, E. Tomusiak and D. Wilkinson

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

#### Time-dependent analysis of the breakup of $^{11}$Be on $^{12}$C at 67 MeV/nucleon

*(P. Capel; G. Goldstein, D. Baye, Brussels Free Univ.)*

The breakup of $^{11}$Be on $^{12}$C at 67 MeV/nucleon has recently been studied experimentally at RIKEN [Fukuda *et al.*, Phys. Rev. **C70**, 054606 (2004)]. We analyze this dissociation reaction in a semi-classical framework. The resulting time-dependent Schrödinger equation is solved numerically by expanding the projectile wave function upon a three-dimensional spherical mesh. The nuclear interaction between the projectile fragments and the target are modelled by optical potentials. The low-lying $\frac{5}{2}^+$ resonance of $^{11}$Be induces a narrow peak in the breakup cross section. The nuclear interactions between the projectile and the target are found to be responsible for the transition towards this resonance. The good agreement with recent experimental data confirms the validity of the model and leads us to suggest that nuclear induced breakup of halo nuclei may be used as a quantitative probe of their internal structure.

#### Coupling-in-the-continuum effects in Coulomb dissociation of halo nuclei

*(P. Capel; D. Baye, Brussels Free Univ.)*

Coulomb dissociation is one of the main tools used to study the halo structure. It also provides an indirect method for determining the astrophysical $S$-factor of radiative capture reactions at stellar energies. In both cases, the experimental data are usually interpreted with a first-order approximation restricted to the E1 multipole with a possible E2 correction. In this perturbative technique, the breakup is assumed to occur in a single-step transition from the initial bound state towards the continuum. However, higher-order effects corresponding to multi-step transitions occurring in the continuum may still be non-negligible, even at high energies. It is therefore of great importance to assess the validity of the first-order approximation so as to avoid biased analyses of experimental results.

We investigated these higher-order effects by comparing the first-order perturbation theory to the numerical resolution of a time-dependent Schrödinger equation. The calculations have been performed for the breakup on a lead target of $^{11}$Be and $^{8}$B. The populations of the different partial waves composing the $^{10}$Be-neutron or $^{7}$Be-proton continuum reveal that couplings in the continuum remain significant even at high impact parameters and high projectile-target relative velocities. Although the total breakup cross section is fairly well described at a first-order approximation, its partial-wave components reached by the first-order transitions are significantly depleted towards other partial waves after the closest approach. The information extracted by assuming the validity of the first-order approximation is affected by an energy distortion. Another distortion is caused by the presence of a resonance as exemplified by the $\frac{5}{2}^+$ resonance of $^{11}$Be. Such effects may partly explain discrepancies between direct and indirect measurements of the astrophysical $S$-factor of the $^{7}$Be($p$,$\gamma$)$^{8}$B reaction at stellar energies.

### Determination of $S_{17}(0)$ from published data

*(R.H. Cyburt, B. Davids, B.K. Jennings)*

The experimental landscape for the $^{7}$Be+$p$ radiative capture reaction is rapidly changing as new high precision data become available. We present an evaluation of existing data, detailing the treatment of systematic errors and discrepancies, and show how they constrain the astrophysical S factor ($S_{17}$), independent of any nuclear structure model. With theoretical models robustly determining the behaviour of the sub-threshold pole, the extrapolation error can be reduced and a constraint placed on the slope of S17. Using only radiative capture data, we find $S_{17}(0)$ = 20.7 ± 0.6 (stat) ± 1.0 (syst) eV b if data sets are completely independent, while if data sets are completely correlated we find $S_{17}(0)$ = 21.4 ± 0.5 (stat) ± 1.4 (syst) eV b. The truth likely lies somewhere in between these two limits. Although we employ a formalism capable of treating discrepant data, we note that the central value of the S factor is dominated by the recent high precision data of Junghans *et al.*, which imply a substantially higher value than other radiative capture and indirect measurements. Therefore we conclude that further progress will require new high precision data with a detailed error budget.

### Universal energy dependence of radiative capture cross sections

*(R.H. Cyburt, B.K. Jennings)*

We continue the work by Jennings, which determined that the low energy shape of radiative capture cross sections to be dominated by the non-linear nature of the sub-threshold pole. We show that these cross sections, or equivalently the astrophysical S-factor is determined primarily by the sub-threshold pole and the normalization of the regular Coulomb function. With this behaviour established, we provide simple functional forms that can be used to fit cross section data. We also show that this analysis is consistent with other studies of the E→0 behaviour of S-factors, though such expansions have a small radius of convergence, making them ill-suited for determining the shape outside the radius of convergence. We present results for $^{3}$He($\alpha,\gamma$)$^{7}$Be, $^{3}$H($\alpha,\gamma$)$^{7}$Li,$^{7}$Be($p,\gamma$)$^{8}$B, and $^{7}$Li($n,\gamma$)$^{8}$Li.

### Three-particle model for halo/deformed nuclide reactions

*(R.H. Cyburt, B. Davids, B.K. Jennings)*

We set out to describe two particle systems, one a composite of two particles, being either a halo nucleus or deformed by its interaction with the third. We find a set of 2-body potentials describing each 2-body channel. Using these potentials, we solve the three-body problem for several benchmark nuclei, including $^{6}$He, $^{6}$Be, $^{8}$Li and $^{8}$B. We show that we can reproduce the structure of these compound nuclei as well as their production cross sections.

### Hybrid potential/R-matrix models for the $^{12}$C+$\alpha$ system

*(J.-M. Sparenberg)*

Hybrid models which combine the potential model, for the description of the background, with the R-matrix model, for the description of discrete states, have been developed. Physical parameters of discrete states are converted into formal R-matrix parameters, taking into account the potential background. The nuclear part of this potential is constructed by a new variant of an inversion method based on supersymmetric quantum mechanics. The method has been applied to $^{12}$C + $\alpha$ $S$-wave elastic phase shifts.

### Construction of a $\Lambda$-$\Lambda$ 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 $^{1}S_0$ $\Lambda$-$\Lambda$ 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 $\Lambda$-$N$ 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 Fadeev formalism based on the two-cluster resonating-group-method kernel.

### 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 was studied using a semi-classical 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 Jefferson Lab. It is found that rescattering is strongly reduced in parallel kinematics with respect to perpendicular ones.

The one-hole spectroscopic function has been measured at Jefferson Lab for different nuclei, by the E97-006 collaboration. This experiment focused on the region at high missing energy and missing momenta, where the effects of short-range and tensor correlations can be studied directly. The data obtained show that a sizable contribution to the experimental cross section comes from processes involving the rescattering of the detected proton, against other nucleons in the target. These effects are to be subtracted in order to obtain meaningful results.

Comparison of the experimental data with both theoretical predictions of short-range correlated strength and our rescattering calculations suggests that the results in parallel kinematics are reliable up to the pion emission threshold for $^{12}$C. Other effects, such as meson exchange currents, will have to be addressed in order to explain the data in perpendicular kinematics.

### Nucleon-nucleus optical potential at low energy and proton capture

*(C. Barbieri, B.K. Jennings)*

Nucleon capture reactions at low energy like $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ play an important role in the understanding of stellar evolution. In this regime, the nuclear optical potential that describes the nucleon-nucleus interaction can present substantial energy dependence and is expected to be sensitive to the surface of the target nucleus. Such low-energy correlations have been considered for $^{16}$O in earlier works, based on the self-consistent Green's function theory (SCGF).

We have considered the nuclear self-energy obtained from SCGF calculations in a restricted model space and extended it the full momentum or coordinate spaces. This has been applied to proton scattering and the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ reaction. The results show that this method can lead to a simultaneous description of the bound nucleons (both particle and hole orbitals) and scattering states. However, the phase shifts for the $l$=1 partial waves present difficulties analogous to those encountered in reproducing the corresponding hole spectroscopic factors.

### Hadron masses in medium and neutron star properties

*(C.Y. Ryu, C.H. Hyun, S.W. Hong, Sungkyunkwan Univ.; B.K. Jennings)*

We have investigated the properties of the neutron star with relativistic mean-field models. We incorporate in the quantum hadrodynamics and in the quark-meson coupling models a possible reduction of meson masses in nuclear matter. The equation of state for neutron star matter is obtained and is employed in the Oppenheimer-Volkov equation to extract the maximum mass of the stable neutron star. We find that the equation of state, the composition and the properties of the neutron stars are sensitive to the values of the meson masses in medium.

### The shell model and projection operator formalisms

*(B.K. Jennings)*

Shell models try to solve the nuclear many-body problem in a restricted space and take into account the restricted space by using effective interactions. In this paper two different approaches to generating the effective interaction are considered, one based on the projection operator formalism and the other on unitary transformations. The two approaches are derived in a parallel manner so that the difference becomes apparent. The effective interaction obtained in the two approaches is very different. For example in one approach it is energy independent while in the other it is energy dependent.

### Effective operators within the *ab initio* no-core shell model

*(B.R. Barrett, I. Stetcu, Arizona; P. Navratil, Lawrence Livermore National Lab; J.P. Vary, Iowa State)*

We implement an effective-operator formalism for general one- and two-body operators, obtaining results consistent with the no-core shell-model (NCSM) wave functions. In the NCSM formalism, we compute electromagnetic properties using the two-body cluster approximation for the effective operators and obtain results which are sensitive to the range of the bare operator. To illuminate the dependence on the range, we employ a Gaussian two-body operator of variable range, finding weak renormalization of long range operators (e.g. quadrupole) in a fixed model space. This is understood in terms of the two-body cluster approximation which accounts mainly for short-range correlations. Consequently, short-range operators, such as the relative kinetic energy, will be well-renormalized in the two-body cluster approximation.

## Nuclear Astrophysics, Cosmology

### Precision primordial $^{4}$He measurement with CMB experiments

*(R.H. Cyburt; G. Huey, B.D. Wandelt, UIUC)*

Big bang nucleosynthesis (BBN) and the cosmic microwave background (CMB) are two major pillars of cosmology. Standard BBN accurately predicts the primordial light element abundances ($^{4}$He, D, $^{3}$He and

$^7$Li), depending on one parameter, the baryon density. Light element observations are used as a baryometer. The CMB anisotropies also contain information about the content of the universe which allows an important consistency check on the big bang model. In addition CMB observations now have sufficient accuracy not only to determine the total baryon density, but also resolve its principal constituents, H and $^4$He. We present a global analysis of all recent CMB data, with special emphasis on the concordance with BBN theory and light element observations. We find $\Omega_B h^2 = 0.025 + 0.0019 - 0.0026$ and $Y_p = 0.250 + 0.010 - 0.014$ (fraction of baryon mass as $^4$He) using CMB data alone, in agreement with $^4$He abundance observations. With this concordance established we show that the inclusion of BBN theory priors significantly reduces the volume of parameter space. In this case, we find $\Omega_B h^2 = 0.0244 + 0.00137 - 0.00284$ and $Y_p = 0.2493 + 0.0006 - 0.001$. We also find that the inclusion of deuterium abundance observations reduces the $Y_p$ and $\Omega_B h^2$ ranges by a factor of $\sim$2. Further light element observations and CMB anisotropy experiments will refine this concordance and sharpen BBN and the CMB as tools for precision cosmology.

**New BBN limits on physics beyond the standard model from $^4$He**
*(R.H. Cyburt; B.D. Fields, UIUC; K.A. Olive, E. Skillman, Minnesota)*

A recent analysis of the $^4$He abundance determined from observations of extragalactic HII regions indicates a significantly greater uncertainty for the $^4$He mass fraction. The derived value is now in line with predictions from big bang nucleosynthesis when the baryon density determined by WMAP is assumed. Based on this new analysis of $^4$He, we derive constraints on a host of particle properties which include: limits on the number of relativistic species at the time of BBN (commonly taken to be the limit on neutrino flavours), limits on the variations of fundamental couplings such as $\alpha_{em}$ and $G_N$, and limits on decaying particles.

**Exotic particle decay scenarios in the early universe**
*(R.H. Cyburt; J. Ellis, CERN; B.D. Fields, UIUC; K.A. Olive, V.C. Spanos, Minnesota)*

We generalize our treatment of the radiative decay of an unstable particle in the universe to include decay channels which can produce hadrons as well as electro-magnetic radiation. Just as the EM-decay case, the highly non-thermal injection spectra of injected particles are rapidly "cooled" and brought into a quasi-static or thermal equilibrium with the background plasma. Further interactions with the plasma, either $n - p$ conversion or nuclide dissociation, will change the predictions of the standard big bang nucleosynthesis (BBN) scenario. Due to the general concordance between standard BBN and observations, this non-standard model of the early universe is highly constrained. We present detailed discussions of the thermalization history of the particle spectra, and the subsequent change to the light element abundances. By adopting these constraints and a particular model for the decaying particle, we can place strong limits on its mass and the temperature of reheating.

**What's next for big bang nucleosynthesis?**
*(R.H. Cyburt)*

Big bang nucleosynthesis (BBN) plays an important role in the standard hot big bang cosmology. BBN theory is used to predict the primordial abundances of the lightest elements, hydrogen, helium and lithium. Comparison between the predicted and observationally determined light element abundances provides a general test of concordance and can be used to fix the baryon content in the universe. Measurements of the cosmic microwave background (CMB) anisotropies now supplant BBN as the premier baryometer, especially with the latest results from the WMAP satellite. With the WMAP baryon density, the test of concordance can be made even more precise.

Any disagreement between theory predictions and observations requires careful discussion. Several possibilities exist to explain discrepancies: (1) observational systematics (either physical or technical) may not be properly treated in determining primordial light element abundances, (2) nuclear inputs that determine the BBN predictions may have unknown systematics or may be incomplete, and (3) physics beyond that included in the standard BBN scenario may need to be included in the theory calculation. Before we can be absolutely sure new physics is warranted, points (1) and (2) must be addressed and ruled out. All of these scenarios rely on experimental or observational data to make definitive statements of their applicability and range of validity, which currently is not at the level necessary to discern between these possibilities with high confidence. Thus, new light element abundance observations and nuclear experiments are needed to probe these further.

Assuming concordance is established, one can use the light element observations to explore the evolution from their primordial values. This can provide useful information on stellar evolution, cosmic rays and other nuclear astrophysics. When combined with detailed models, BBN, the CMB anisotropy and nuclear astrophysics can provide us with information about the populations or environments in which the light elements are observed. Precision cosmology becomes precision astrophysics.

### Primordial nucleosynthesis and the age of cosmological enlightenment

*(R.H. Cyburt)*

Big bang nucleosynthesis (BBN) theory has long predicted the light element abundance pattern produced during the first minutes after the big bang. These predictions rely on careful analyses of nuclear cross section data to accurately and precisely describe this early epoch. We review the current status of BBN, discussing its concordance with light element abundance observations and the parameter determinations from the anisotropies in the cosmic microwave background. The future of primordial nucleosynthesis hinges on new experimental and observational data. BBN remains a powerful probe of the early universe, which can help illuminate and constrain fundamental questions in nuclear and particle astrophysics.

## Lattice QCD

### An alternate smearing method for Wilson loops

*(F. Okiharu, Nihon; R.M. Woloshyn)*

A gauge field link smearing method developed for calculations with staggered fermions, namely the use of unitarized fat7 links, is applied to mesonic and baryonic Wilson loop calculations. This method is found to be very effective for reducing statistical fluctuations for large Wilson loops. Examination of chromo-electric field distributions shows that self-interactions of the static sources are reduced when unitarized fat7 smearing is used but long-distance inter-quark effects are unchanged. This method was applied to the calculation of the static quark-antiquark potential and the three-quark potential in the baryon. The colour field distribution in the baryon was calculated but there was not enough sensitivity to see, unambiguously, the formation of flux tubes in the three quark system.

### Staggered fermions and topology in lattice QCD

*(K.Y. Wong, SFU; R.M. Woloshyn)*

The spectral properties of a variety of improved staggered operators are studied in quenched QCD. The systematic dependence of the infrared eigenvalue spectrum on i) improvement in the staggered operator, ii) improvement in the gauge field action, iii) lattice spacing and iv) lattice volume, is analyzed. It is observed that eigenmodes with small eigenvalues and large chirality appear as the level of improvement increases or as one approaches the continuum limit. These eigenmodes can be identified as the “zero modes” which contribute to the chirality associated, via the index theorem, with the topology of the background gauge field. This gives evidence that staggered fermions are sensitive to gauge field topology. After successfully identifying these would-be chiral zero modes, the distribution of the remaining non-chiral modes is compared with the predictions of random matrix theory in different topological sectors. Excellent agreement is obtained.

### Lattice simulations with twisted mass QCD

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

Recently a new variation of Wilson-like fermions has been proposed for lattice QCD. It features an axial rotation of the Wilson term relative to the mass term. This removes the possibility of accidental zero modes at non-zero quark mass thus solving the “exceptional configuration” problem. However the new action violates invariance and quark-flavour symmetry at non-zero lattice spacing. A quenched QCD simulation with the twisted mass action is being undertaken to investigate questions such as the effect of using different definitions of the twist angle and the size of flavour symmetry breaking in the hadron mass spectrum. The scaling of hadron masses with lattice spacing is also being investigated.

## 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, South Carolina; 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.

### Radiative corrections and internal degrees of freedom in ChPT

*(N. Supanam, Suranaree Univ. of Technology; H.W. Fearing)*

In the usual approach photons, leptons, and weak currents are included in ChPT as fixed external fields. For radiative corrections however, and for calculating things like electromagnetic isospin violation, such fields have to be included as explicit degrees of freedom so that they can be included as internal lines in diagrams. To do this one first needs to derive the most general ChPT Lagrangian involving nucleons, pions, photons, leptons, Ws and Zs all as internal degrees of freedom. As a first application we intend to apply this Lagrangian to radiative corrections to neutron beta decay, which should give as a result expressions for the two constants of the EFT approach in terms of the low energy constants of ChPT. This should resolve a major flaw in the EFT approach, namely the fact that the EFT constants are specific to the given process whereas the ChPT LECs can be obtained from other processes, thus in principle allowing a prediction of the radiative corrections to beta decay.

**Ordinary muon capture in RelChPT and relativistic renormalization schemes**
*(S. Ando, H.W. Fearing)*

A major effort this past year has been devoted to understanding the various approaches to relativistic chiral perturbation theory (RelChPT) and specifically to a calculation of ordinary muon capture in this formalism. RelChPT has the advantage over the standard heavy baryon ChPT of allowing one to easily obtain a result to one higher order. However there are difficulties with the renormalization and there have been several proposals to resolve these difficulties. One of our primary goals has been to explore in the context of a practical calculation these various proposals and to try to understand what is best for doing real calculations.

We have now completed the main calculation of ordinary muon capture on the proton in the sense that we have results for the weak form factors $g_V$, $g_A$, $g_M$, and $g_P$ and for the isovector and isoscalar nucleon electromagnetic form factors in terms of the low energy constants (LEC's) of the relativistic theory. We are now looking at and comparing the additional finite renormalizations required by the various proposed schemes. The longer term goal is to apply these same techniques to radiative pion capture, RMC, and perhaps other simple processes.

**Effective field theory of the deuteron with dibaryon field**
*(S. Ando; C.H. Hyun, Seoul/Sungkyunkwan)*

Pionless effective field theory with dibaryon fields is reexamined for observables involving the deuteron. The electromagnetic form factors of the deuteron and the total cross section of radiative neutron capture on the proton, $np \to d\gamma$, are calculated.

The low energy constants of vector(photon)-dibaryon-dibaryon vertices in the effective Lagrangian are fixed by the one-body vector(photon)-nucleon-nucleon interactions. This scheme for fixing the values of the low energy constants satisfactorily reproduces the results of the effective range theory. We also show that, by including higher order corrections, one can obtain results that are close to those of the accurate potential model.

**The $np \to d\gamma$ cross sections at the BBN energies**
*(S. Ando, R.H. Cyburt; S.-W. Hong, Sungkyunkwan; C.H. Hyun, Seoul/Sungkyunkwan)*

The total cross sections for the radiative neutron capture on a proton, $np \to d\gamma$, and its inverse reaction $d\gamma \to np$ are evaluated at the big bang nucleosynthesis energies. We employ the effective field theory with dibaryon field to describe the two-nucleon reactions with external electromagnetic probe. Electromagnetic transition amplitudes are obtained up to next-to leading order and the total cross sections for the inverse reaction are calculated up to 2.3 MeV above the threshold photon energy. We compare our results with relevant experimental data and other theoretical calculations, and discuss the impact on BBN predictions. We show that the error in the cross section at BBN energies is not lower than 1%. Higher order calculations do not improve this accuracy.

**Few-Body and Medium Energy Processes**

**Exact numerical solution of a 3-body Bethe-Salpeter equation**
*(L. Theussl)*

We present a benchmark calculation of binding energies and wave functions of a bound state composed of three equal-mass, scalar particles in the Bethe-Salpeter framework. Ground and excited states, including different orbital angular momenta, as well as different masses of the exchanged particle are considered.

**Bethe-Salpeter equation with non-planar diagrams**
*(L. Theussl)*

We present a formalism that allows the inclusion of an infinite number of crossed diagrams in a Bethe-Salpeter equation. The method is illustrated and numerical benchmark results are presented for a simple two-body system of scalar particles.

**Form factors in the "point-form" of relativistic quantum mechanics: single- and two-particle currents**
*(B. Desplanques, Grenoble; L. Theussl)*

Electromagnetic and Lorentz-scalar form factors are calculated for a bound system of two spin-less particles exchanging a zero-mass scalar particle. Different approaches are considered including solutions of a Bethe-Salpeter equation, a "point form" approach to relativistic quantum mechanics and a non-relativistic one. The comparison of the Bethe-Salpeter results, which play the role of an "experiment" here, with the ones obtained in "point form" in single-particle approximation, evidences sizable discrepancies, pointing to large contributions from two-body currents in the latter approach. These two-body currents 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 to be insufficient to remedy all the shortcomings of the "point form" form factors evidenced in impulse approximation.

## Particle Physics

### Toward precision measurements in solar neutrinos

*(P.C. de Holanda, Campanis State; W. Liao; A.Yu. Smirnov, Moscow/INR)*

Solar neutrino physics enters a stage of precision measurements. In this connection we present a precise analytic description of the neutrino conversion in the context of LMA MSW solution of the solar neutrino problem. Using the adiabatic perturbation theory we derive an analytic formula for the $\nu_e$ survival probability which takes into account the non-adiabatic corrections and the regeneration effect inside the Earth. The probability is averaged over the neutrino production region. We find that the non-adiabatic corrections are of the order $10^{-9} - 10^{-7}$. Using the formula for the Earth regeneration effect we discuss features of the zenith angle dependence of the $\nu_e$ flux. In particular, we show that effects of small structures at the surface of the Earth can be important.

### Lepton flavour violation in extra dimension models

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

Models involving large extra spatial dimension(s) have interesting predictions on lepton flavour violating processes. We consider some 5D models which are related to neutrino mass generation or address the fermion masses hierarchy problem. We study the signatures in low energy experiments that can discriminate the different models. The focus is on muon-electron conversion in nuclei, $\mu \to e\gamma$ and $\mu \to 3e$ processes and their $\tau$ counterparts. Their links with the active neutrino mass matrix are investigated. We show that in the models we discussed, the branching ratio of $\mu \to e\gamma$-like rare process is much smaller than the ones of $\mu \to 3e$-like processes. This is in sharp contrast to most of the traditional wisdom based on four dimensional gauge models. Moreover, some rare tau decays are more promising than the rare muon decays.

### Charged lepton electric dipole moments from TeV scale right-handed neutrinos

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

We study the connection between charged lepton electric dipole moments, $d_l$ $(l = e, \mu, \tau)$, and seesaw neutrino mass generation in a simple two Higgs doublet extension of the standard model plus three right-handed neutrinos (RHN) $N_a$, $a = 1, 2, 3$. For RHN with hierarchical masses and at least one with mass in the 10 TeV range we obtain the upper bounds of $|d_e| < 9 \times 10^{-30}$ e-cm and $|d_\mu| < 2 \times 10^{-26}$ e-cm. Our scenario favors the normal mass hierarchy for the light neutrinos. We also calculated the cross section for $e^-e^- \to W^-W^-$ in a high luminosity collider with constraints from neutrinoless double beta decay of nuclei included. Among the rare muon decay experiments we find that $\mu \to e\gamma$ is most sensitive and the upper limit is $< 8 \times 10^{-13}$.

### Leptogenesis from a sneutrino condensate re-examined

*(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.

### Scenarios of modulated perturbations

*(R. Allahverdi)*

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 fluctuations during inflation. We discuss generalization and various possible implementations of this mechanism, and present some specific particle physics examples. 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 will then be modified accordingly in each case.

### Enhanced reheating via Bose condensates

*(R. Allahverdi; R. Brandenberger, A. Mazumdar, McGill)*

In supersymmetric extensions of the particle physics standard model, gauge invariant combinations of squarks and sleptons (flat directions) can acquire large expectation values during a period of cosmological inflation. If the inflaton sector couples to matter fields via these flat directions, then new channels for efficient reheating, in particular via parametric resonance instabilities, are opened up. These can lead to efficient reheating induced by the flat directions even if the bare coupling constants are small. We discuss various channels which yield this "enhanced reheating" effect, and we address some cosmological consequences.

### Leptogenesis as the source of dark matter and density perturbations

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We investigate the possibility that the entropy producing decay of a right-handed sneutrino condensate can simultaneously be the source of the baryon asymmetry, of gravitino dark matter, and of cosmological density perturbations. For generic values of soft supersymmetry breaking terms in the visible sector of 1–10 TeV, condensate decay can yield the dark matter abundance for gravitinos in the mass range 1 MeV to 1 TeV, provided that the resulting reheat temperature is below $10^6$ GeV. The abundance of thermally produced gravitinos before and after sneutrino decay is then negligible. We consider different leptogenesis mechanisms to generate a sufficient asymmetry, and find that low-scale soft leptogenesis works most naturally at such temperatures. The condensate can easily generate sufficient density perturbations if its initial amplitude is $\sim \mathcal{O}(M_{\rm GUT})$, for a Hubble expansion rate during inflation $>10^9$ GeV. Right-handed sneutrinos may therefore at the same time provide a source for baryogenesis, dark matter and the seed of structure formation.

### Gravitino production from reheating in split supersymmetry

*(R. Allahverdi; A. Jokinen, A. Mazumdar, NORDITA)*

We discuss gravitino production from reheating in models where the splitting between particle and sparticle masses can be larger than TeV, as naturally arising in the context of split supersymmetry. We show that such a production typically dominates over thermal contributions arising from the interactions of gauginos, squarks and sleptons. We constrain the supersymmetry breaking scale of the relevant sector for a given reheat temperature. However, the situation changes when the gravitinos dominate the universe and decay before nucleosynthesis. We briefly describe prospects for a successful baryogenesis and a viable neutralino dark matter in this case.

## Miscellaneous

### Creating nuclear data representations and error budget accounting

*(R.H. Cyburt)*

Great effort is exerted by experimentalists to beat down and understand the overall error budget in their experiments, in particular nuclear cross section data. In principle, an equally rigorous formalism for combining data should be used when determining data representations and their uncertainties. We present such a formalism here. We detail the treatment of statistical and systematic uncertainties, showing how correlations impact a maximum likelihood analysis. We also clarify the nature of discrepant data and how to quantify the magnitude of the discrepancy. Though the precise definitions presented here are not set in stone, their results are particularly robust, thus other types of analyses should agree quantitatively. Data analysis is limited directly by the data, and can be improved upon in two ways: (1) new, more accurate and precise data are obtained, and (2) old data can be excluded given sufficient reason. We conclude with a discussion of propagating cross section representations into thermal rates and uncertainties, which are then readily available for use in nuclear astrophysics calculations.