Contents

1. Director's Summary

The year 2005 has proven to be another outstanding and highly productive year for the Centre. This is evidenced, for example, by the more than 60 refereed publications as well as the production of a 230 page pedagogical volume entitled "Lattice Hadron Physics." This continued high-level of performance is a credit to the ongoing dedication and hard-work of the entire CSSM staff and student team. The research achievements reported for this year range, for example, from new results for pentaquarks and exotics, to advances in lattice QCD techniques, to an improved understanding of the topological structure of QCD, to predictions for strangeness in the nucleon and in neutron stars, and to novel investigations of complex systems, scale-free networks and the stock-market.

This was also a year of continuing change and evolution for the Centre. It was our great pleasure to welcome Lorenz von Smekal into the heart of the Centre as our newest academic staff member. Lorenz prevailed in a highly competitive selection process against a field of very strong candidates. Lorenz started work at the Centre in February after relocating with his family from Germany. We have also inevitably farewelled some key staff. This includes research associates Jianbo Zhang, who has taken up a professorial position in China, and Ping Wang, who has taken up a research associate position in the USA. It was also the last year for Alex Kalloniatis, who after more than five years as a Fellow in the Centre has taken up a position in defence in Canberra. Alex was a very highly valued and senior member of staff, who was always generous with his time and who demonstrated great leadership in the Centre. He will be greatly missed. These departures are balanced by two new research associates who will be joining the Centre in 2006.

The Australian Research Council (ARC) created the CSSM as one of its nine year Special Research Centres (SRCs) in 1997. The year 2005 was then the last of the nine years of formal funding of the Centre as an SRC. However, the ARC specifically provides for the continued existence of its Centres beyond their nine year first-phase and makes available the ARC Discovery Project (DP) funding scheme to continue their research program. In addition to an ongoing DP grant held by Williams, it is with great pleasure that in late 2005 we learnt that in 2006 there will be a new joint DP grant by Williams, Leinweber and von Smekal, a new DP grant by Leinweber and a new ARC Linkage Infrastructure and Equipment Fund (LIEF) grant for a new supercomputer led by Williams, Leinweber and others. Thus the continued funding of the CSSM into 2006 and beyond is now clearly assured. The relocation and re-establishment of the Centre within the School of Chemistry and Physics, both physically and organisationally, is now complete and this is a positive and constructive development for all concerned.

In July, the Centre hosted the Workshop on Light-Cone QCD and Nonperturbative Hadron Physics in Cairns and attracted a large number of international visitors. This received a sponsorship contribution from Jefferson Lab in the US, where the Centre's first Director, Tony Thomas, is now the Chief Scientist. The Centre is enjoying continuing close ties with JLab as well as with its other international peer institutions. During the year, the Centre played host to a number of distinguished visitors who spent significant periods of time with us, including Lex Dieperink (KVI, Netherlands), Vladimir Karmanov (Lebedev, Moscow), Kim Maltman (York, Canada), Lubomir Martinovic (Slovakia), Wally Melnitchouk (JLab), Byung-Yoon Park (Korea), Jan Rafelski (Arizona), Craig Roberts (Argonne), Martin Schaden (Rutgers) and Don Sinclair (Argonne).

When Tony Thomas and I first proposed the Centre back in 1996 it was with the vision of creating a unique research environment, where staff, students and visitors working in a diversity of areas could come together in an open and collegial atmosphere and where the resulting cross-fertilisation of ideas would lead to genuinely new insights and directions. Looking back over the last nine years of Centre achievements, it is deeply satisfying to see the fruits of this vision not only in the core area of strong interaction physics but also in related areas of complex systems and advanced computing.

Finally, it is must be said that the greatest and defining feature of the Centre is its people. I would, in particular, like to acknowledge the Deputy Director, Derek Leinweber, for his collegiality, collaboration and leadership contributions and also Lorenz von Smekal for his outstanding efforts in all areas during his relatively short time with us. I would like to thank our senior Research Associate, Ayse Kizilersu, for taking on the CSSM Seminar series and for her outstanding contributions to workshop and event organisation. As always, the heart of the Centre has been maintained and nurtured by Sharon Johnson and Sara Boffa with great efficiency and dedication and this is much appreciated by us all. We are also grateful to Ramona Adorjan for her excellent maintenance of all of the Centre's computers and peripheral IT equipment.

Anthony G. Williams
Director, CSSM & Director, South Australian Partnership for Advanced Computing (SAPAC)

2. Structure & Management

2.1 Within the Faculty of Science

The Special Research Centre for the Subatomic Structure of Matter is a separate cost Centre within the Faculty of Sciences. The Director is formally responsible to the Executive Dean of the Faculty of Sciences. There is also a Board of Management and an International Advisory Board (membership details given in Appendix A) to provide advice to the Director.

There is a close and mutually beneficial co-operative relationship within the Physics Discipline in the School of Chemistry and Physics. All honours and postgraduate students in the Centre are also students in the Discipline of Physics. All accounting is handled through the School system and the Unix and NT computer systems are tightly integrated with Physics.

2.2 Relationship to the National Institute for Theoretical Physics (NITP)

The National Institute for Theoretical Physics (NITP) is a co-operative venture of the entire Australian physics community, and is quite distinct from the Centre. It is intended to support and stimulate all areas of physics through workshops and postgraduate schools organized jointly with the Centre.

Through the National Advisory Board, efforts are continuing to ensure a sound financial base for the operation of the NITP. In the meantime, the Centre, through its close involvement with the Australian nuclear and particle physics community, is able to perform some of the functions intended for the NITP in its specific research area of strong interaction physics.

2.3 Relationship to the South Australian Partnership for Advanced Computing (SAPAC)

The South Australian Partnership for Advanced Computing (SAPAC) enables discovery, innovation and collaboration by providing e-Research services, expertise and facilities for South Australian researchers. SAPAC provides key e-Research support for all relevant research groups in the form of expert personnel to assist and advise researchers and by providing a variety of training courses as well as helpdesk and user support. It also provides the necessary underlying infrastructure and services necessary for carrying out e-Research through maintaining digital repositories, high-performance computing (HPC), grid and visualisation facilities. For example, SAPAC is currently constructing the South Australian Sustainable Repository (SASR), operating four major HPC facilities, implementing a grid gateway and associated middleware and managing two 3-dimensional visualisation facilities on behalf of the state's research community.

The CSSM has played a central role in the formation and ongoing operation of SAPAC with Prof. Tony Williams as current and founding Director of SAPAC and with Dr. Paul Coddington and Associate Professor Derek Leinweber as Deputy Directors. The CSSM is the largest single user of the facilities managed by SAPAC and has contributed very significantly to the purchase and funding for many of these. The CSSM usage of the SAPAC facilities is primarily to support its extensive lattice QCD program.

3. Strategic Objectives of the Centre

Hadronic matter makes up almost the entire mass of the tangible universe, from the protons and neutrons in nuclei inside atoms and molecules to neutron stars. Unravelling the rich and complex structure of the strongly interacting particles (known generically as hadrons) and their interactions is one of the remaining great challenges in physics.

The marvellous organizing principle for almost all of our understanding of modern physics is referred to as the Standard Model. This brings together in one elegant framework three of the four fundamental interactions in physics: the electromagnetic interaction, the weak interaction (responsible for radioactive decay), and the strong interaction (responsible for hadronic structure and interactions). The strong interaction is widely believed to be described by a theory known as quantum chromodynamics (QCD).

The fundamental constituents of the QCD description of hadronic matter are referred to as quarks (analogs of electrons) and gluons (analogs of photons, but self-interacting). Assuming that QCD is the correct theory for the strong interactions, we will use it to understand the observed structure of hadrons and hadronic matter and to predict important new features. Conversely, when pushed to its limits, QCD may eventually fail to predict the observed hadronic world. This possibility would constitute an extremely interesting outcome and would require major modifications to the Standard Model.

The essential aim of the Centre is to make major advances of international significance in our understanding of the structure of hadronic matter by assembling a world-class research team in Adelaide. With a variety of attacks on the problem being made within the same Centre, progress can be made more rapidly than by a set of isolated individuals or small groups. The cross-fertilisation of this environment offers great opportunities for major breakthroughs in our understanding.

In order to ensure a coherent research program of the highest quality we will continue to attract the very best researchers in the field from around the world for significant periods of time. Through a vigorous program of topical workshops, we involve a significant fraction of the Australian subatomic physics community in the research programs of the Centre. Not only does their involvement strengthen the research programs of the Centre, but also through the close contact with each other, the staff of the Centre and the visiting experts from overseas, their own productivity and enthusiasm are significantly enhanced.

4. National & International Links

4.1 Formal Agreements of Co-operation

The Centre continues to develop its collaborative programs and initiate new ones.

The Centre has formal agreements with:

- Abdus Salam International Centre for Theoretical Physics - Italy
- Argonne National Laboratory - USA
- Bonn University – Germany
- Brookhaven National Laboratory - USA
- Chinese Academy of Sciences (Beijing) - China
- Commissariat à l'Energie Atomique - France
- European Centre for Theoretical Studies in Nuclear Physics and Related Areas (Trento) - Europe
- Indiana University (Bloomington) - USA
- Institute for Nuclear Theory, University of Washington (Seattle) - USA
- Instituto De Fisica Teòrica (IFT-UNESP) - Brazil
- Joint Institute for Nuclear Research (JINR - Dubna) - Russia
- Jülich (FZ) - Germany
- MESON (Medium Energy Science Open Network) involving IUCF Indiana; Yonsei, Korea; RCNP Osaka; KVI Groningen; IMP Lanzhou; TSL Uppsala; NAC Cape Town; SAHA Calcutta; FZ Jülich; CIAE Beijing
- Osaka University - Japan
- Svedberg Laboratory - Sweden
- Thomas Jefferson National Accelerator Facility (Newport News) - USA
- Technical University of Munich - Germany
- TRIUMF (Vancouver) – Canada
- University of Arizona - USA
- Université Blaise Pascal – France
- University of Erlangen – Germany
- University of L'Aquila – Italy
- University of Tübingen - Germany

4.2 Visitor Program

The Centre's visitor program is well established and is strongly supported by prominent overseas scientists who come to the Centre for collaborative research work, and to undertake research in a stimulating environment. During their stay at the Centre most give lectures and seminars to our students and staff (see Appendices E and G) and if a topic is appropriate a Public Lecture is given by the visitor. In many cases the collaborative research projects with these visitors involve postgraduate students. Thus the visitor program is also directly aiding their professional development.

4.3 Workshops and Conferences
International Workshop on Light-Cone QCD and Nonperturbative Hadron Physics 2005 (LC2005)

For the third time at two-year intervals, researchers from around the world descended upon Cairns, Australia, in July to present and discuss recent developments in the field of strong interaction physics. This time it was our pleasure to host an eight day workshop on Light-Cone QCD and Nonperturbative Hadron Physics. Participating were 46 researchers from 14 Countries across the globe. Indeed, 33 experts were from overseas while 5 postgraduate students from the CSSM were able to have their work heard and interact with overseas experts.

Held at the Cairns Colonial Club Resort, the workshop continued the tradition of a program of morning and late afternoon talks allowing ample time for collaborations and discussions in the middle of the day. The program covered broadly the following topics:

- Light-Front Quantization and Field Theory
- Perturbative QCD and Phenomenology
- Light-Front Wave Functions and QCD
- Lattice QCD
- Transverse Lattice QCD
- Confinement
- Vacuum structure and chiral symmetry
- Applications to Nuclear Physics
- Low x Physics
- Dyson-Schwinger Equations
- Hadron spectroscopy and structure
- Effective Hamiltonians and Operator Methods
- Light-Front Thermodynamics and Statistical Physics
- Supersymmetry
- Applications of AdS/CFT to QCD and Light-Front Methods for Matrix theory and String theory.

These themes were spread over the full period to encourage discussion among participants from different backgrounds.

Organized by Derek Leinweber (Chair), Stan Brodsky, John Hiller, Craig Roberts, Lorenz von Smekal and Tony Williams, this international workshop was hosted by the Special Research Centre for the Subatomic Structure of Matter (CSSM) and the National Institute for Theoretical Physics (NITP) in association with the International Light Cone Advisory Committee (ILCAC). Jefferson Laboratory provided some funding as well in the form of a sponsorship. This workshop was a successor to LC2004 held in Amsterdam.

Following previous tradition, sufficient computers and connections for notebooks were provided to enable participants to remain optimally productive throughout the workshop. Similarly, working areas were made available for discussions, complemented by coffee and tea throughout the day. At the end of each day, complimentary

4. National & International Links *(Cont)*

transportation was provided to take participants into Cairns where there is a large variety of excellent restaurants to choose from for the evening meal. Free days were interspersed in the program to enable participants to revitalize and visit some of the exciting local attractions such as the Great Barrier Reef and the Daintree Rain Forest.

In summary, the workshop was engaging and stimulating and we are grateful for the active participation of all those who attended.

4.5 Research Highlights

Marco Bartolozzi

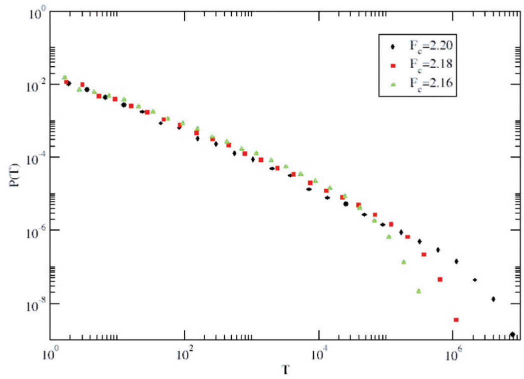
Symbiosis in the Bak-Sneppen model for biological evolution with economic application: M. Bartolozzi, D. B. Leinweber and A. W. Thomas

We have extended the Bak-Sneppen (BS) model for evolution by introducing explicit coupling terms in the fitness of each species of the ecology. We find that the equilibrium configuration of the model can be deeply influenced by the environmental forces, leading to a wider survival probability including species with a lower degree of adaptation.

In our model the degree of adaptation of each species is determined by a self-fitness function, $B(i)$. This is a real number belonging to the interval $(0,1)$. The fitness of each species is, instead, also influenced by the neighbour species, which share their degree of self-adaptation. In a one dimensional grid the fitness of the I and h species is $F(i) = B(i)+\Delta_{i,i+1} B(i+1)+\Delta_{i,i-1} B(i-1)$ where Δ is the fraction of B shared by the species. The dynamics of the mutation of the species follows an extremal dynamics (that is the species to mutate is the less fit) similar to the BS model, but this time the variable to extremise is F and not B. At each time step, once the extrema species, k, is located, its self-fitness and its interactions are drawn again from a uniform distribution, $(0, 1)$.

The results of the simulation show that the system self-organizes to a critical state characterized by a power law distribution in the size of the avalanches of mutations, shown in the figure below. Moreover, we show that the mutual support between the species increases the survival probability in a way that even poorly fit species can survive as long as they are immersed in a healthy environment.

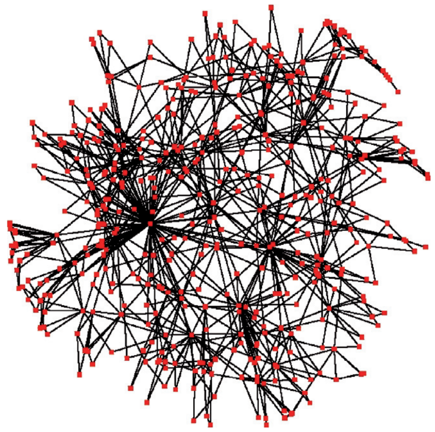
4. National & International Links *(Cont)*



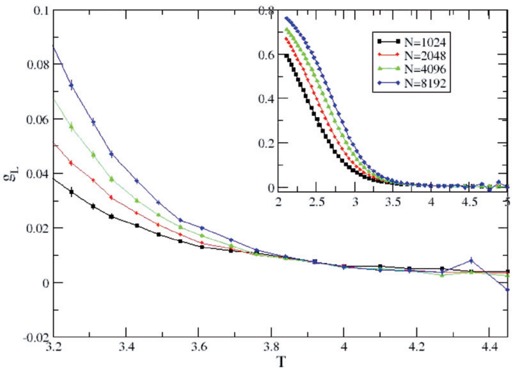
Scale-free networks in complex systems: M. Bartolozzi, D. B. Leinweber , T. Surungan, A. W. Thomas and A.G. Williams

With the availability of larger databases and faster computers, more and more studies are being devoted to the empirical analysis of the characteristic topological structures of complex systems. Despite the different nature of the subjects under exam, it has been found that the networks describing the interactions been the various elementary constituents, show a remarkable homogeneity in their statistical features. In particular the networks are found to be scale free, displaying a robust power law distribution in the connectivity of the nodes, along with high clustering. These empirical findings, apart from bringing structural self-organization problems under a different prospective, open an entirely new area of investigation in computational physics where most of the numerical work in literature has been developed on regular lattices. Not much is known regarding the behaviour of even the well-established models on complex topologies, such as Scale-Free networks.

In the present work we have investigated the role played by these networks, and in particular the one generated via the Barabasi-Albert algorithm, by studying their impact on the dynamics of two different models, namely the antiferromagnetic (Af) Ising model and a model for stochastic opinion formation. An example a SFN generated by this algorithm is shown in the figure below.



In the AF Ising model the calculation of the overlap parameter reveals a spin glass behaviour at low temperatures, produced by the random frustration of scale-free network. The critical temperature separating the SG and the paramagnetic phases is found to be $T_c = 4.0(2)$, shown in the figure below for the Binder parameter. Such behaviour is not observed for the same model on regular triangular lattices. Hence the topology of the interactions plays a critical role in the dynamics of this system.



Stochastic Opinion Formation on a Scale-Free Network: M. Bartolozzi, D.B. Leinweber and A.W. Thomas

In the model for opinion formation, the choice of a SFN is further motivated by a series of recent studies on social aggregation. In this case the results of the numerical simulations show that for a certain range in the parameter space, the fluctuations of opinion have a non-trivial turbulent-like dynamics determined by the synchronization of large parts of the network.

In this case the SFN topology plays a key role in the dynamics of the model. In fact, introducing inactive agents and spreading the undecided agents randomly on the network, does not spoil the turbulent-like state even for high concentrations of "gaps'', up to approximately 60% of agents. This is a consequence of the implicit robustness of SFNs against random failures. If instead of selecting randomly the undecided individuals we aim directly to the "hubs'' of the network then the situation changes. In this case the network is disaggregate, composed of very small sub-networks and isolated nodes. Synchronization cannot significantly affect the resulting global opinion and the time series approximates Gaussian noise.

Log-periodic oscillations in western stock markets from 2000: M. Bartolozzi, S. Drozdz, D.B. Leinweber, J. Speth and A. W. Thomas

It is well known that many physical systems undergo phase transitions around specific critical points in the parameter space. Near these points the system is strongly correlated and many characteristic quantities

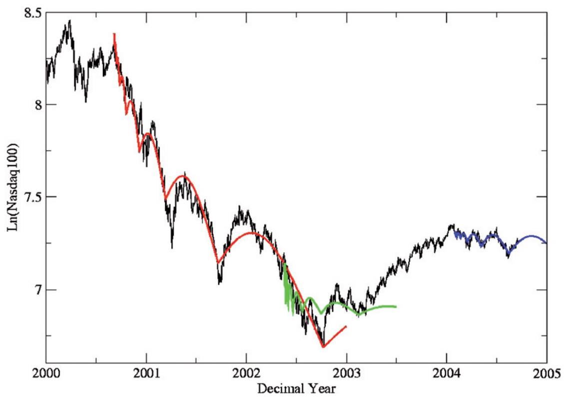
4. National & International Links *(Cont)*

can well be approximated by power laws, related to the scale-invariance of the system in that state. If we assume that $\phi(T)$ is an observable near a critical point, T_c, for a change of scale $T \to \lambda T$ we have that $\phi(\lambda T)=\mu\phi(T)$ since $\phi \approx T^a$ is always a solution of the previous equation for every λ.

A weaker version of the over mentioned scale invariance is the *discrete-scale invariance* (DSI). In this case the system becomes self-similar only for an infinite but countable set of values of the parameter λ which represents a preferential scaling factor that characterizes a hierarchical structure in the system. In this case the solution of the scaling equation can be written in a more generic form as $\phi(T)=A+B\,|T_c-T|^a+C\,|T_c-T|^a \cos(\omega \log|T_c-T|-\varphi)$ where $\omega=2\pi/\lambda$. The dominant power law behaviour, a hallmark of all critical phenomena, and the log-periodic corrections to the leading term are the main features of DSI.

We search for the possible presence of DSI in the dynamics of the stock market. This study has lead to the identification of, at least, three clear log-periodic periods that characterize the behaviour of some of the most important indices worldwide since the year 2000.

Moreover, one of the log-periodic structures found is embedded in a longer one, interestingly, both in the decelerating market phase. A plot showing the log-periodic oscillations of the DAX index for Germany is reported below.



This finding supports the hypothesis of self-similar log-periodicity proposed by Drozdz and coworkers. A non-parametric analysis over these periods has also been performed. The results of the analysis confirm the existence of log-periodic structures. Moreover, we found further evidence for a preferential scaling factor of $\lambda \cong 2$. The presence of a higher order harmonic at a frequency that is double the fundamental can also be related to the fractal structure of the time series. A test on a Weierstrass-type function supports this hypothesis.

Sharada Boinepalli

Electromagnetic Structure of Baryons near the Chiral Regime: S. Boinepalli, D.B. Leinweber, A.G. Williams, J.M. Zanotti and J.B. Zhang

This investigation probes the electromagnetic properties of octet and decuplet baryons in the light quark-mass regime. We merge the advantages of the FLIC fermion action, providing efficient access to the light quark-mass regime, with established techniques for revealing the electromagnetic structure of baryons. All the electromagnetic properties are calculated at the quark level and appropriately combined to compute the baryon level properties. This sheds considerable light on the origin of baryon electromagnetic properties.

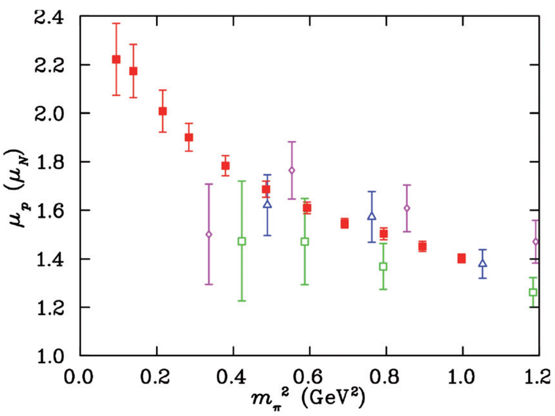
Enabled via supercomputing resources from the Australian Partnership for Advanced Computing (APAC), we are able to search for evidence of chiral non-analytic behavior in charge radii and magnetic moments as the light quark mass regime is approached. Chiral effective field theory predicts the existence of substantial non-analytic behavior even in the quenched approximation of QCD. Our simulations reveal chiral curvature which is in qualitative agreement with the expected leading non-analytic terms. Our results for the neutron are especially interesting as they reveal just how difficult it will be to reveal all the features of chiral effective field theory on a finite space-time volume.

With our attention currently focused on spin-3/2 decuplet baryons we are able to search for deformation in baryon electromagnetic structure via the electric-quadrupole and magnetic-octupole moments for the decuplet baryons. For the first time, we have an unambiguous result indicating the Delta is deformed and plan to publish this conclusive result as a Phys. Rev. Lett.

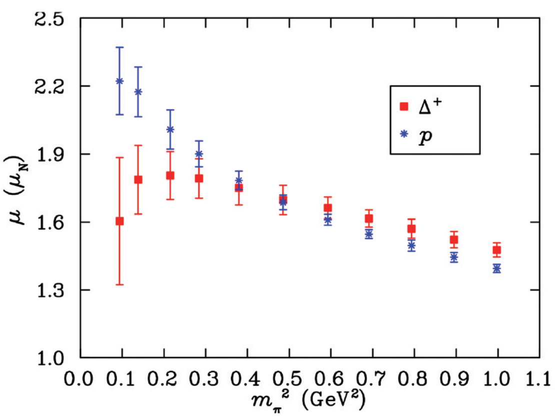
Aspects of these results were presented at the AIP congress in Canberra in January 2005 and in the CASCADES-05 workshop at Jefferson Laboratory, USA.

4. National & International Links *(Cont)*

The figure below shows our FLIC-fermion results (red squares) in the context of results from the QCD-SF collaboration (open symbols) for the magnetic moment of the proton. The squared pion mass plotted on the x-axis is representative of the input quark mass. APAC resources enable us to access the computationally intensive light quark-mass region and hence study the chiral curvature of the electromagnetic properties.



The second figure contrasts the magnetic moment of the proton with the Delta in quenched QCD. Whereas the two baryons are expected to display similar features up to the opening of the Delta decay channel in full QCD, quenched chiral effective field theory predicts that the first nontrivial non-analytic contribution from the pion cloud enters with the wrong sign for the Delta. This opposite trend is apparent in the following figure.



Using the propagators already created at APAC we can also calculate the electromagnetic transition moments from the nucleon to the Delta baryon resonance. These form factors are under intense experimental investigation and provide an interesting opportunity to further elucidate the electromagnetic structure of baryons.

Ian Cloet

Nuclear Medium Modifications to Spin-dependent Structure Functions: I.C. Cloet, W. Bentz, A.W. Thomas

The discovery in the early 80's by the European Muon Collaboration (EMC) that nuclear structure functions differ substantially from those of free nucleons caused a shock in the nuclear physics community. A few years later the EMC discovered the so-called 'spin crisis,' where it was found that the fraction of the spin of the proton carried by its quarks is unexpectedly small. With this background it is surprising that since the discovery of the spin crisis, there has been no experimental and little theoretical investigation of the spin-dependent structure functions of nuclei.

To address this we calculated, in a relativistic framework, the spin-dependent (and spin-independent) structure functions of atomic nuclei. The quark degrees of freedom in nuclei are accessed via the convolution formalism. That is, we assume that a quark distribution in a nucleus can be expressed as the convolution of the quark distribution in a nucleon and the nucleon distribution in the nucleus.

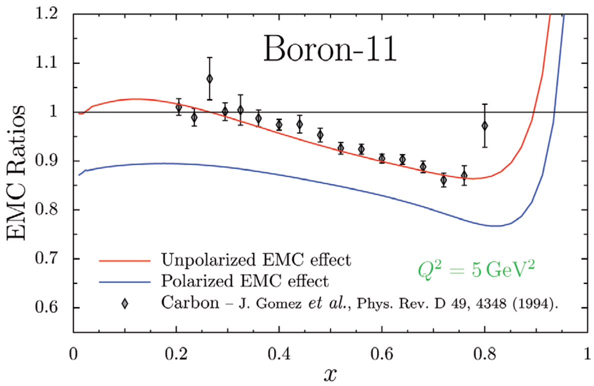
To determine the nucleon distribution functions we utilized a modified Nambu--Jona-Lasinio model, that is both covariant and free of unphysical thresholds for nucleon decay into quarks -- hence incorporating an important aspect of confinement. Coupled with the relativistic Faddeev equation this approach gave excellent results for the quark distribution functions (see Phys.Lett. B 621, 246 (2005).

The nucleon distributions in the nucleus were obtained via a relativistic shell model calculation. Here we derived for the first time the general relativistic expression for the nucleon distributions functions in any spherically symmetric potential. In our case we used a Woods-Saxon shape to approximate the potential felt by a nucleon in the nucleus.

4. National & International Links *(Cont)*

Using this approach we were readily able to reproduce the experimentally measured EMC effect in all nuclei we studied. That is we obtained very good agreement with experiment for the structure function ratio $F^A_{2N}(x)/F_{2N}(x)$ where $F^A_{2n}(x)$ is the isoscalar spin-independent structure function in the atomic nucleus and $F^A_{2n}(x)$ the free structure function.

We then made predictions for the polarized EMC ratio, that is $g^A_{1p}(x)/g_{1p}(x)$, where the g's are spin-dependent structure functions. We found that the medium modifications to the polarized structure functions are about twice that of the unpolarized case (see accompanying figure).



As an example we show results for the spin-independent and spin-dependent structure function ratios for ^{11}B. The top curve is the usual EMC ratio F^A_{2N}/F_{2N}, where F_{2N}, is the isoscalar structure function. Our prediction for the polarized EMC effect, g^A_{1p}/g_{1p}, is the lower curve. We obtain similar results for other nuclei such as ^7Li and ^{27}Al.

An immediate consequence of this result is that since the Bjorken sum rule relates $g_{1p}(x)$, to the spin components of the proton, the reduction of $g_{1p}(x)$ in-medium implies that the fraction of the spin of the proton carried its quarks is also reduced, when the proton is in the atomic nucleus. We find a reduction is of the order 10%, even for light nuclei like ^7Li. This result represents an interesting and exciting challenge for future experiments.

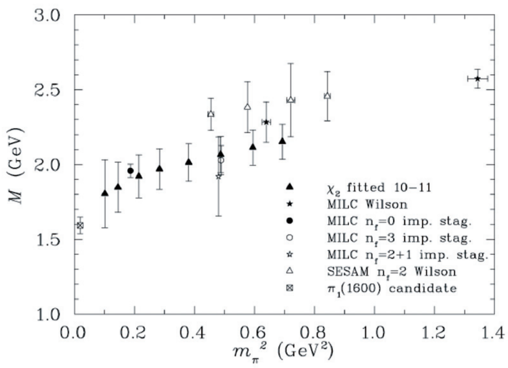
John Hedditch

The Hybrid Exotic Meson at Light Quark Masses: J. N. Hedditch, W. Kamleh, B. G. Lasscock, D. B. Leinweber and A. G. Williams

Simple models of hadrons invariably exclude most of the non-trivial behaviour for the gluonic background of the Standard Model of the Universe. This leads to constraints on the quantum numbers available to mesons. Exotic mesons are postulated states that lie outside these constraints. Thus the presence or absence of such states, sheds considerable light on the importance of gluonic excitations in the hadron spectrum.

This year we have published state-of-the art results for the spin-1, negative parity exotic meson. Our results show evidence of chiral curvature for the exotic meson, which is of considerable interest.

The following figure shows our results (filled triangles) against the previous state of the art in this field. The horizontal scale is the square of the mass of the pion, which is itself a more-or-less linear function of the input quark mass used in our simulations. Our new results are the first in the field to be consistent with experiment.



This year, we have performed a thorough exploration of the source-smearing parameter space for both the gauge and quark field sources used in creating hybrid exotic mesons. Our aim is to design operators that maximize the signal to noise ratio enabling studies of the structure and decay of these mesons.

4. National & International Links *(Cont)*

Mariusz Hoppe

Physics of protein folding: dynamical simulations of simplified mathematical models: M. Hoppe, M. Lohe and A.G. Williams

Complexity in physics

Biologists tell us that all living things are made up of cells, each of which contains thousands of active proteins, and that the protein molecules play crucial roles in nearly all-biological processes.

Biochemists elucidate further and say that proteins are long, flexible polymer chains of various amino acid sequences that are linked end to end, and that in contrast to other polymers, proteins exhibit many remarkable properties:

- They fold up (spontaneously) from an initially random, disordered state, to a unique and very orderly final structure.
- Folding occurs shortly after synthesis and $\sim 1\ \mu s \leq$ duration of folding process $\leq \sim 1$ min.
- There are numerous alternative semi-stable final structures, but only one is biologically active. (Here 'numerous' means: astronomically large number).
- A protein always manages to find just the right shape; the process of folding is quick and reliable - most of the time [1]
- Folding is reversible: proteins can be made to unfold by changing denaturing conditions:
    - pH level
    - high and *low* temperatures

Three things in this list above baffle a physicist:

1. Since the number of alternatives is astronomically large, how can an inanimate collection of many interacting particles (that's what a protein is) always find the same, correct final structure?
2. Given that there are many competing interactions between the particles, and the energy surface is therefore rugged, how can the molecule successfully fold on such short time scales?

Most unusual of all is the phenomenon of *cold unfolding:*

3. What makes the protein come out of its relatively stable folded structure and unfold when the temperature is lowered?

That increase of temperature should cause the protein to unfold is in accord with common experience and is readily understandable, but cold unfolding is a puzzle; it can be likened to watching butter at room temperature melt as temperature of surroundings is increased and then melt again as the temperature is lowered below ambient! This doesn't of course happen with ordinary butter, but experiments show that something analogous does occur with many proteins.

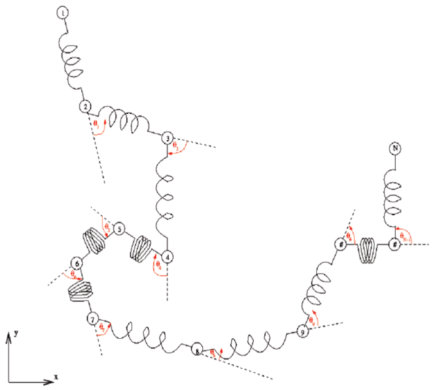
[1] Sometimes protein mis-folding occurs: the protein settles into a wrong final structure; this is the cause of some diseases, like Jacob-Creutzfeldt and Alzheimer.

A Simplified Model

In search of answers to these perplexing questions, a simplified protein-like mathematical "toy" model has been constructed, that will make computer simulations tractable. The model must necessarily be highly idealized and simple because the complexity of biomolecules is such that contemporary supercomputing power prevents realistic all-atom simulations to be carried out on meaningful time scales required for folding.

But irrespective of this limitation, it is expected that the essential aspects of mechanisms responsible for folding and cold unfolding can be understood by study of reduced systems that only crudely resemble real proteins.

Here is a first such construction:



This is a minimal "ball-and-spring" protein model, which

- consist of N interacting particles constrained to a flexible, chain-like structure that remains always intact;
- possesses a large number of degrees of freedom;
- exhibits non-linear interactions of various kinds, both between nearest and distant neighbour particles;
- has two types of particles (for now):
- polar (that like contact with water), and
- hydrophobic (that tend to avoid contact with water).

The choice of only two particle types is a sensible first approximation (even though real proteins are made from a set of twenty different amino acid types) because in fact the hydrophobic effect due to immersion in water (i.e. cell environment) is the dominant driving force that causes folding.

The Hamiltonian of the system is chosen to be:

$$H(x,y,p_x,p_y) = \sum_{i=1}^{N} \frac{p_{x,i}^2 + p_{y,i}^2}{2m_i} + \sum_{i=1}^{N-1} V_{\text{spring}}(\vec{r}_i, \vec{r}_{i+1}) + \sum_{i=2}^{N-1} V_{\text{flex}}(\vec{r}_{i-1}, \vec{r}_i, \vec{r}_{i+1}) + \sum_{i=1}^{N-2} \sum_{j=i+2}^{N} V_{\text{nonlocal}}(\vec{r}_i, \vec{r}_j)$$

where

$$V_{\text{spring}}(\vec{r}_i, \vec{r}_{i+1}) = \alpha \left(r_{i,i+1} - r_0\right)^2$$
$$V_{\text{flex}}(\vec{r}_{i-1}, \vec{r}_i, \vec{r}_{i+1}) = \beta(1 - \cos\theta_i)$$
$$V_{\text{nonlocal}}(\vec{r}_i, \vec{r}_j) = \gamma\left(\frac{1}{r_{ij}^{12}} - \frac{c_{ij}}{r_{ij}^{6}}\right)$$

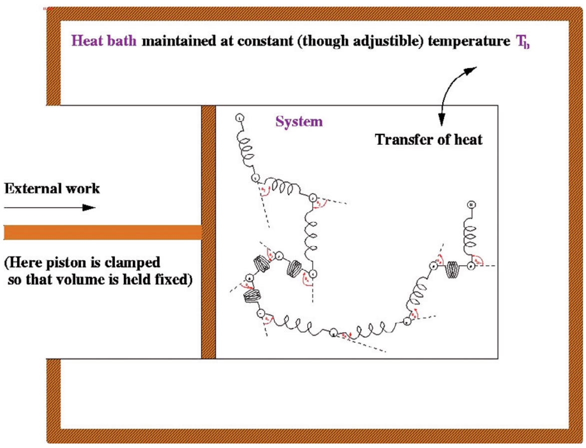
and $r_{ij} \equiv \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ is the distance between i^{th} and j^{th} particles

4. National & International Links *(Cont)*

Here the first two potential energy terms represent the resistance of the chain to stretching and bending; the last potential energy term is an effective hydrophobic effect of water, such that water molecules are not treated explicitly (too high computational cost). The presence of this term favours clustering of hydrophobic particles (to the extent that depends on specific sequence and choice of parameters).

Moreover, since proteins behave differently at various temperatures (they fold to a unique 3-D shape for $T \cong$ 37°C, unfold above and below this T, and sometimes they mis-fold for unknown reasons), the equations of motion cannot be those of ordinary classical mechanics, because these do not make reference to temperature. Instead, modified Hamilton's equations that are coupled to a heat bath are used to calculate motions of the minimal model:

$$\dot{q}_i = \frac{\partial H}{\partial p_i}, \quad \dot{p}_i = -\frac{\partial H}{\partial q_i} \quad \xrightarrow[\text{thermostats}]{\text{Nosé–Hoover}} \quad \dot{q}_i = \frac{\partial H}{\partial p_i}, \quad \dot{p}_i = -\frac{\partial H}{\partial q_i} - \xi_i p_i, \quad \dot{\xi}_i = \frac{1}{Q}\left(\sum_{j=1}^{N} \frac{p_j^2}{m_j} - gkT_b\right)$$

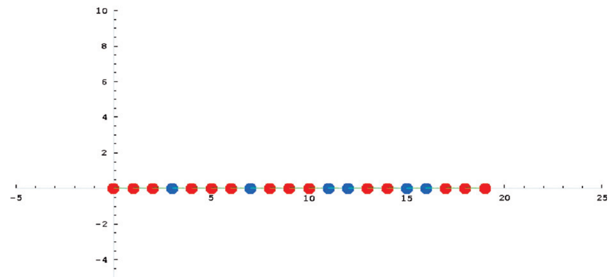


All the ingredients above imply that non-trivial dynamics are to be expected, with possible emergent, collective behaviour, self-organization, criticality, or even onset of chaos.

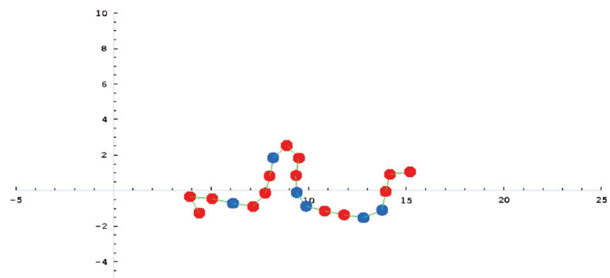
Mathematica vs Fortran 90

Mathematically speaking, the equations of motion that are being solved in this work, constitute a system of nonlinear, coupled ODEs. These can only be solved numerically with a computer. Such preliminary calculations have been performed and animations of resulting motions generated with *Mathematica.*

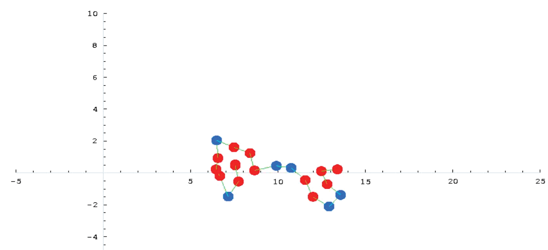
Here are some examples of selected frames from animations of twenty particle sequences (red ones are hydrophobic (H); blue are polar (P)):



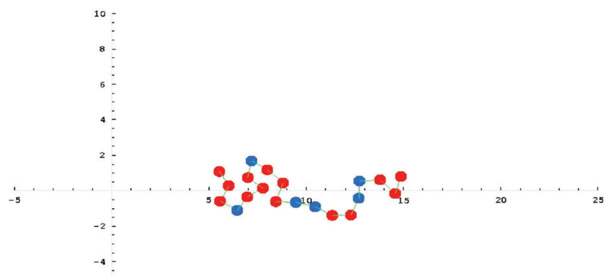
1st frame from animation of sequence S1



An intermediate frame from animation of sequence S1

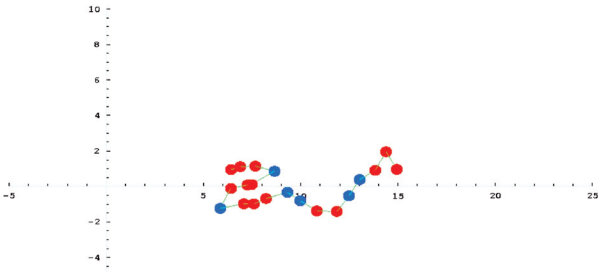


A final frame in this animation: two hydrophobic globules

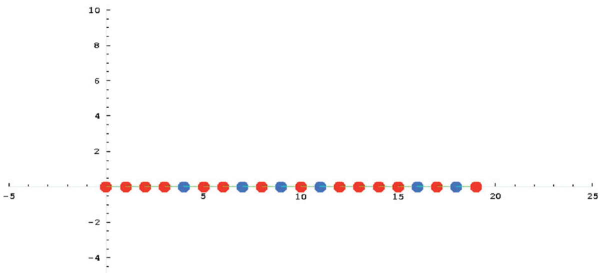


Final frame in animation of S1 but starting from a different initial condition

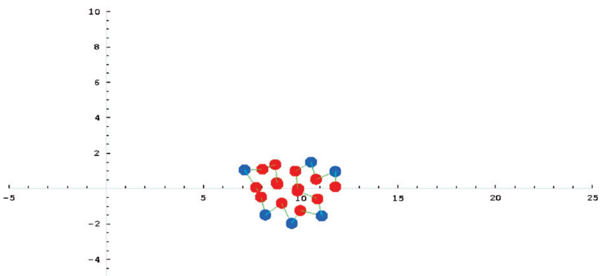
4. National & International Links *(Cont)*



Final shape is not the same; moreover, right hand tail doesn't want to cluster – even when time of simulation is extended.



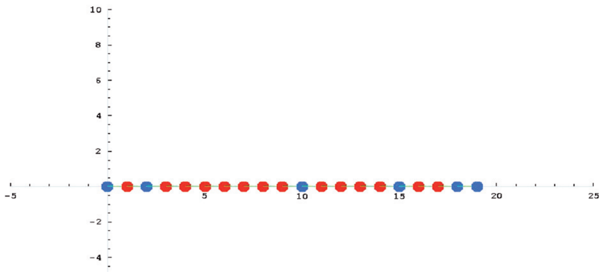
Initial configuration

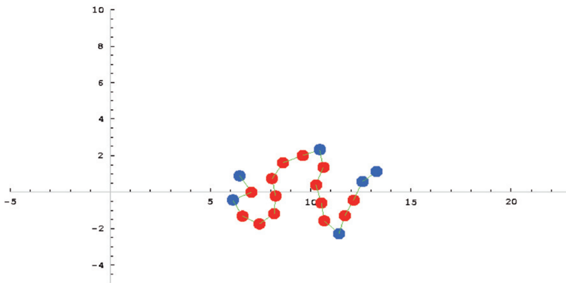


Final configuration

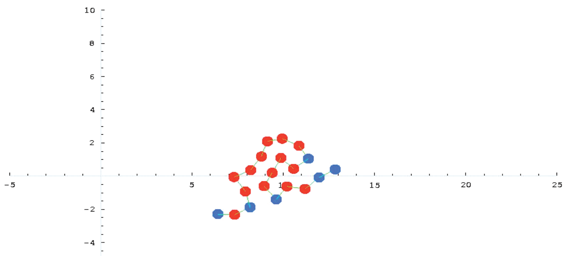
This particular sequence folds very nicely and quickly (i.e. when the parameters in the equations of motion are chosen properly) with all the hydrophobic particles tightly packed within the interior of the molecule, away from surrounding water – which is to be expected.

When the animation is seen live, the particles oscillate about their final positions; this is indicative of thermal agitation, which can be amplified or diminished by appropriately tuning the temperature parameter, T_b, in the equations of motion.





Some intermediate configuration



Last frame in animation.
However, there is no assurance that this is a final configuration; a longer simulation time could show the protein is doing still other things.

The extension to 3-D has already been made. At present most of the work is taken up with coding a routine in Fortran 90/95 (eventually to be parallelized with message passing interface (MPI)) that will solve the same set of differential equations. The need for such a step arises because very long dynamical simulations must be achieved, the particle number of sequences should be increased, and various refinements incorporated into the model – all of which would overburden *Mathematica's* calculational capacity.

Thus far there are some already apparent findings:

- The model as presented here does exhibit folding.
- Like proteins, it has many alternative stable structures.
- But, unlike proteins, it does not necessarily fold to a unique structure each time.
- As required, high temperatures prevent the model from folding up, or cause it to unfold if the starting state was a compressed conformation.
- There is no cold unfolding.

4. National & International Links *(Cont)*

In addition, there are many parameters that can be independently adjusted. A systematic investigation is lacking to discover what values constitute a suitable choice, and how they affect the overall behaviour. The same can be said about the potential energy functions; they are plausible but arbitrary – what then determines a specific choice of their functional form?

Despite its shortcoming, the model holds a promise for a fruitful avenue of research, but it has to be 'repaired' so that it folds to a unique structure, and unfolds at cold temperatures. These two things are crucial because without them, the most essential (and remarkable) properties of proteins are missing. In fact, without them, the model does not even represent proteins, and the whole research becomes erroneous.

Assuredly though, this brings us back to the list of questions at the beginning of this article – questions which a physicist is baffled by when faced with complexity and perplexity of protein folding. The aim of this research is to find these answers – or at least get closer to finding them.

Alex Kalloniatis

Solving the Strong CP Problem within QCD: A.C. Kalloniatis, S.N. Nedelko

This report is the final installment in the development of an analytically tractable model of the QCD vacuum based on the idea of domains of constant but randomly oriented gluon field strength. At the outset the aim was to encapsulate within a single model *simultaneous* and *interconnected* solutions to three key and longstanding problems in analytical QCD: a mechanism for the confinement of quarks in hadrons such as the proton and pion, the manifestation of spontaneously broken chiral symmetry which explains why the pion is so low in mass, and finally a solution to the axial U(1) problem, which seeks to understand why the eta-prime meson is so heavy (at 958 MeV) when the pion (so similar in many respects to the eta-prime) is so light (at 140 MeV). In previous reports between 2000 and 2004 we have reported on how the domain model achieves this. The final surprise to emerge in this work was that the very same model offered a solution to a fourth outstanding problem in QCD: the strong CP problem. Though initially identified in the domain model the solution was then found to be valid for full QCD independent of model analyses.

The strong CP problem arises as follows. The most general Lorentz, gauge and renormalization group invariant action for QCD admits an additional gluonic term involving the scalar product of gluon electric and magnetic fields $\mathrm{E}\cdot\mathrm{B}$ multiplied by a coefficient ε. Because a magnetic field B involves a cross-product it and thus the whole term is odd under the parity transformation $x \rightarrow -x$. In fact it is odd under a combined transformation which swaps particles for antiparticles (C) and space-parity (P) designated CP. The question is then: what is the size of this CP-violating parameter ε? Using effective chiral theories, the contribution of such a term to the electric dipole moment (EDM) of the neutron can be computed and thus from the EDM the value of ε determined (Crewther, di Vecchia, Veneziano and Witten, 1979). At best only an extremely small upper bound on the EDM can be established experimentally giving $\varepsilon < 10^{-9}$. Such a small value demands either an extraordinary (and unknown) fine tuning mechanism or simply that the value is exactly zero. This in turn requires some symmetry argument. To date the most credible explanation is due to Peccei and

4. National & International Links *(Cont)*

Quinn (1977), who invoke a new non-QCD symmetry. This was seen to demand the existence of a new particle, the axion, whose detection remains unverified to date despite being a popular candidate for dark matter. New experiments to be conducted at JLab, USA, are hoped to close the window on this exotic particle. For various reasons it was decided quite early that no mechanism was available in QCD that could solve this problem, and this was connected intimately to the afore-mentioned $U(1)$ and confinement problems.

Intimately connected to these arguments was an assumption of integer-value for the topological charge, essentially the integral over space of $E \cdot B$, of the gluon configurations dominating the QCD vacuum and responsible for quark confinement. Crewther (1977) has emphasized that integer topological charge was inconsistent with a solution to the $U(1)$ problem. The domain model, as reported in previous annual reports, is built on hyper-spherical regions of constant gluon field strength with no constraint on the topological charge. Rather the topological charge is a function of the size of and average field strength in the domains. Thus fractional, and even irrational values are dynamically possible. The latter possibility will be crucial in the sequel.

An important insight gained in (Crewther, 1980) was that at certain values of ε the breaking of CP could go from being explicit to *spontaneous* (namely the action is CP-invariant but the vacuum not), a result foreseen even before the formulation of QCD by Dashen (1971). Crewther used QCD anomalous Ward identities combined with the assumption of no light axial U(1) meson to determine this value of ε to be $\varepsilon_c = \varepsilon$. Arguments using effective chiral Lagrangians by Witten and Veneziano confirmed this result. A key input into the latter analysis is a specific representation of the axial anomaly in the effective chiral theory.

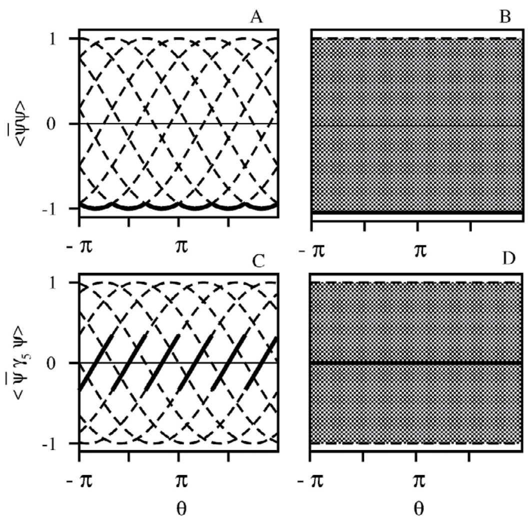


Figure 1: CP-even chiral order parameter for rational and irrational topological charge (A,B) and the CP-odd chiral order parameter for the two choices of topological charge (C,D).

Our work in the domain model uncovered the possibility of solutions to the anomalous Ward identities in addition to those seen by Crewther. This was already reported a year ago, where, for rational values of the topological charge of the confining gluon fields additional values of ε_c exist where the Dashen phenomenon of spontaneous CP breaking occurs. The new insight comes when the topological charge is an irrational number: the values of ε_c where the Dashen phenomenon occurs is *dense* in the interval $[0,2\varepsilon]$. This is indicated in Figure 1 which show the CP-even (A,B) and CP-odd (C,D) order parameters of spontaneous chiral symmetry breaking as functions of the theta parameter. The panels (A,C) are for rational topological charge while (B,D) are for irrational values. The dotted lines indicate various solutions of the anomalous Ward identities while the solid line indicates the "physical" solution (namely satisfying certain constraints that the solutions are stable minima). The cusps in the solid line of panel A represent the points where the Dashen phenomenon occurs: different solutions cross indicating a vacuum degeneracy (and thus spontaneous CP breaking) at these points. At corresponding points in panel C the physical solution jumps indicating the two vacua have opposite CP-properties. However in panel B the spectrum of physical solutions is dense: for any given value of ε_c there is another in an infinitesimal neighborhood. This means that the "jumps" in the CP-odd order parameter are concentrated around the value zero as seen in panel D. This means that no fine-tuning of ε is needed: the CP-odd chiral order parameter is exactly zero for all ε. At this level the mechanism is model independent, relying only on identifying classes of solutions to the anomalous Ward identities. However the physical interpretation of this mechanism at present is only possible through the domain model which enables identification of the topological charge of confining gluon fields. The extension of this statement to all CP-odd quantities comes about using an alternative to the Witten-Veneziano representation of the axial anomaly which explicitly depends on the topological charge of confining gluon fields and satisfies every symmetry constraint on the form of this term. Using this in effective chiral theories, we observed that all CP-even zero momentum quantities are proportional to the CP-even chiral order parameter (panels A and B), while all CP-odd quantities are proportional to the CP-odd order parameter (panels C and D). For example the CP-violating, and never observed, decay process of an eta meson to two pions can be computed from such a representation. For irrational topological charge this decay is absolutely suppressed, consistent with observations.

The conclusion of these investigations is that if the topological charge of confining gluon fields is rational an explanation for the absence of strong interaction CP-violation outside of QCD, such as the Peccei-Quinn axion, is necessary. If the charge is irrational no such particle is required. Conversely, if an axion is finally detected profound insights will be gained into the nature of gluon fields causing confinement and spontaneous chiral symmetry breaking. This work has been published in *Physical review* D 73: 034006, 2006.

4. National & International Links *(Cont)*

Effective fermion theories on branes in "Clash-of-Symmetries" approach to mass generation: A.C. Kalloniatis, R.R. Volkas and D.P. George.

More than 20 years ago, Rubakov and Shaposhnikov suggested that our $(3+1)$-dimensional universe might be a scalar field domain wall or kink residing in an underlying $(4+1)$-dimensional spacetime. They also pointed out that there was a natural way to localise massless fermions to such a domain wall, utilising an observation that went back to Jackiw and Rebbi in the 1970s: the 5-d Dirac equation coupled to a scalar field kink background admits a localised 4-d chiral zero mode as a solution. In recent years, much attention has been paid to extra-dimension and brane-world models, partly because string/M-theory requires extra dimensions but also for their intrinsic interest.

Arkani-Hamed, Dimopoulos and Dvali pointed out that extra dimensions are experimentally allowed to be "large" provided only gravity is allowed to propagate into the extra dimensions or "bulk". Randall and Sundrum subsequently showed that extra dimensions may even be infinitely large, with a dynamical localisation mechanism for gravitons explaining why the world appears 4-d. More recently, a number of authors have combined the Rubakov-Shaposhnikov and Randall-Sundrum ideas by exploring models where the universe is a domain wall containing localised fermion zero-modes and dynamically localised gravity.

In a separate development, Davidson, Toner, Volkas and Wali showed that scalar field domain wall brane-world models have the potential to realise spontaneous symmetry breaking in a different way, an approach they dubbed the "clash of symmetries." Using the observation that there is often more than one way to embed a subgroup in a parent group, they showed that kink configurations can give rise to symmetry breaking patterns that vary as a function of the extra dimension coordinate. The hope is that model-builders might be able to simplify the often unwieldy Higgs sectors required in standard model extensions by using this more powerful method of symmetry breaking.

With the above as background and motivation, the present work has focussed on analysing a toy model of Yukawa boson-fermion interactions in five space-time dimensions in an intrinsically quantum field-theoretic way. A scalar kink background-field is introduced in the fifth dimension which generates the four dimensional domain wall or brane. In the Rubakov-Shaposhnikov approach, the resulting Dirac equation is treated in an essentially classical way.

The on-going research is to integrate out quantum fluctuations of the scalar field to naturally generate quartic fermion interactions. The situation then becomes analogous to the Nambu--Jona-Lasinio model whereby a fermion mass is dynamically generated through such effective interactions. Moreover, adopting a factorisation *ansatz* for the fermion field in order to separate its dependence on the fifth dimension from the remaining four, a final four-dimensional effective fermion field theory is arrived at.

From the Schwinger-Dyson (or gap) equation, dynamical mass generation can be studied. This work is still in progress, in particular through the search for more natural ways of achieving the factorisation of the fermion field.

4. National & International Links *(Cont)*

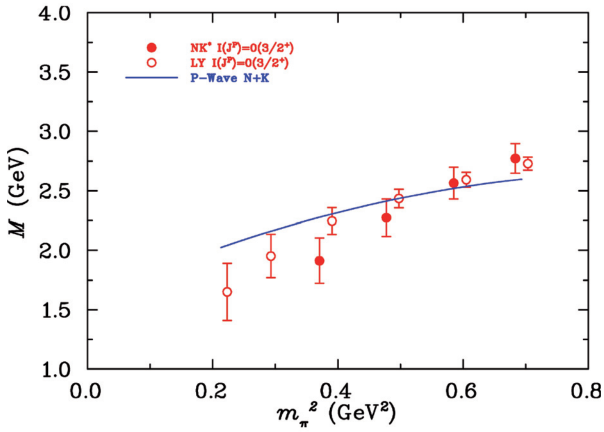
Ben Lasscock

Search for Spin-1/2 and 3/2 Pentaquark Resonances in Lattice QCD: B. G. Lasscock, W. Kamleh, D. B. Leinweber, W. Melnitchouk, A. W. Thomas, A. G. Williams, R. D. Young and J. M. Zanotti

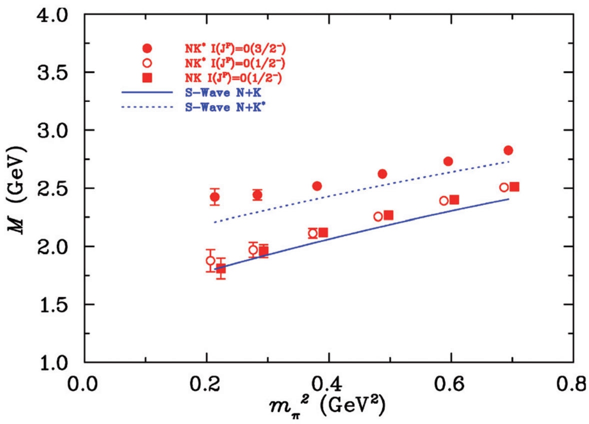
2005 saw a world-wide gathering of physicists, both experimentally and theoretically, focused on determining the possible existence of a Pentaquark baryon resonance. Pentaquarks are a postulated form of baryon, like the proton. But where the proton only requires three quarks to describe its properties, Pentaquark baryons require five. Under the assumption of the existence of the particle, experimentalists have determined the electric charge and strangeness of this state. However, other properties including the spin, parity and isospin are as yet undetermined. Moreover, recent high statistics experiments have reported non-observations of the Pentaquark. Hence, it is unclear whether it exists at all.

We are unraveling some of the mystery of the Pentaquark resonance using numerical simulations of QCD, which provide a first principles approach to resolving the nature of QCD. In our study of spin-1/2 Pentaquarks, we proposed a computationally inexpensive technique of identifying resonances on the lattice, and explored the widest possible basis of local Pentaquark operators searching for evidence of the Pentaquark resonance. Our conclusions are that there is no evidence supporting the existence of a spin-1/2 Pentaquark. However, a positive parity spin-1/2 state could not be ruled out.

With a generous allocation of computer time from the Australian Partnership for Advanced Computing (APAC) we were able to perform the world's first analysis of the existence of a spin-3/2 Pentaquark baryon. We are excited to have discovered evidence supporting the existence of Pentaquark resonance in quenched QCD. We have observed the standard lattice resonance signature of binding, i.e. the mass of the Pentaquark state is smaller than its lowest energy decay channel for quark masses slightly larger but near the physical regime. This behaviour, common to established baryon resonances, is the standard signature of a resonance on the lattice and indicates the existence of a Pentaquark resonance in quenched QCD.



This figure shows the mass of the spin-3/2, isospin-zero, positive-parity Pentaquark state extracted with two different interpolating fields. These points are compared with the lowest energy non-interacting two-particle state indicated by the line. Interestingly, the mass of the spin-3/2 state becomes smaller than the non-interacting two-particle energy at the lighter quark masses, i.e., we observe binding.



This figure shows the masses of both spin-1/2 and spin-3/2, isospin-zero, negative-parity Pentaquark states, which are compared with two-particle decay channels. Here we see no evidence of binding in the spin-3/2 channel. This is interesting because it was thought that the anomalously small decay width of the Θ^+ baryon might be explained by a Pentaquark with these quantum numbers. In this case, its decay to $N+K$ must be via a D-wave decay, which would consequently be suppressed. We also see excellent agreement in the mass of the two negative parity spin-1/2 Pentaquark states extracted from different interpolating fields.

4. National & International Links *(Cont)*

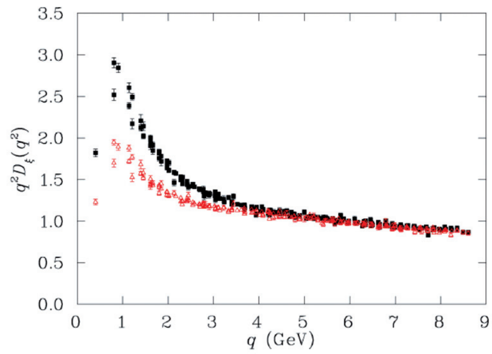
Derek Leinweber

Dynamical FLIC Fermions: W. Kamleh, D.B. Leinweber, A.G. Williams

Due to computational cost, the majority of calculations in lattice QCD are still performed using the quenched approximation of QCD. In this case, the effects of the dynamical sea quarks are simply "turned off." However, with continued access to modern supercomputing resources, and break throughs in the formulation of efficient fermion actions such as the FLIC-fermion action, the CSSM Lattice Collaboration has gained the capability of performing unquenched or full-QCD simulations, which include sea quark effects.

The Hybrid Monte Carlo algorithm is a well-tested and optimised method for generating unquenched gauge configurations. We have implemented a version of the Hybrid Monte Carlo algorithm for FLIC fermions, a novel implementation which applies generally to actions with smeared gauge-field links. Currently, we are able to generate both even and odd flavour configurations, through the use of the Rational HMC algorithm. The addition of a set of unquenched QCD gauge-field configurations will significantly broaden the CSSM's lattice research capabilities.

Our exploratory calculations and feasibility studies have been sufficient to allow us to perform the first study of the effects of dynamical-FLIC quarks on the gluon propagator and the FLIC-Overlap quark propagator. The following figure illustrates the manner in which the gluon propagator is screened by the dynamical-FLIC sea quarks. In the quenched approximation, where the effects of sea-quark loops in the QCD vacuum are not included, the quenched gluon propagator (black squares) experiences strong enhancement at small momentum transfers q. Upon including dynamical quark degrees of freedom, this infrared enhancement is strongly suppressed, as illustrated by the red triangles. The computional resources for this study were provided by the South Australian Partnership for Advanced Computing (SAPAC).



FLIC-Overlap Quark Propagator: W. Kamleh, P. Bowman, A.G. Williams, D.B. Leinweber, J.B. Zhang

The quark propagator is a fundamental quantity in QCD. Through a study of the mass function and renormalisation function in momentum space, we can gain insight into the infrared and ultraviolet properties of the propagator. In the infrared we can directly observe the dynamical generation of mass. In the ultraviolet we can calculate the running quark mass, useful for making connections with perturbation theory. The use of FLIC-Overlap fermions gives a particularly nice form of the quark propagator, essentially free of lattice artefacts at tree level. We have performed a study of the FLIC-Overlap propagator in the quenched approximation, and found improvement over the standard Wilson Overlap. We have also studied the effects of dynamical quarks on the FLIC-Overlap quark propagator where the effects are observed to be more subtle.

Power Counting Regime of Chiral Extrapolation and Beyond: D.B. Leinweber, A.W. Thomas and R.D. Young

Dynamical chiral symmetry breaking in QCD gives rise to an octet of light mesons recognized as the (pseudo) Goldstone bosons of the symmetry. These light mesons couple strongly and give rise to a quark-mass dependence of hadron observables which is non-analytic in the quark mass. The Adelaide Group has played a leading role in emphasizing the role of this physics in the chiral extrapolation of lattice simulation results

The established, model-independent approach to chiral effective field theory is that of power counting, the foundation of chiral perturbation theory. However, this requires one to work in a regime of pion mass where the next term in the truncated series expansion makes a contribution that is negligible. Given the emphasis on determining the nucleon mass to 1%, such neglected contributions must be constrained to the fraction of a percent level. As there is no attempt to model the higher-order terms of the chiral expansion, one simply obtains the wrong answer if one works outside this power-counting regime.

4. National & International Links *(Cont)*

We have strictly shown that finite-range regularization (FRR) is mathematically equivalent to minimal subtraction schemes such as dimensional regularization to any finite order one wishes to work. However, there is now growing recognition that resummation of the chiral expansion is necessary to make accurate contact with current lattice simulation results of full QCD. The resummation technique exploited in our finite-range regularization of chiral effective field theory has the particular advantage that model-independent lattice simulation results are used to constrain the parameters of the chiral expansion.

We have illustrated how the chiral extrapolation problem has been solved and are now using FRR techniques to identify the power-counting regime (PCR) of chiral perturbation theory. To fourth-order in the expansion at the 1% tolerance level, we find the pion mass must be constrained to a regime less than 0.18 GeV for the PCR, extending only a small distance beyond the physical pion mass.

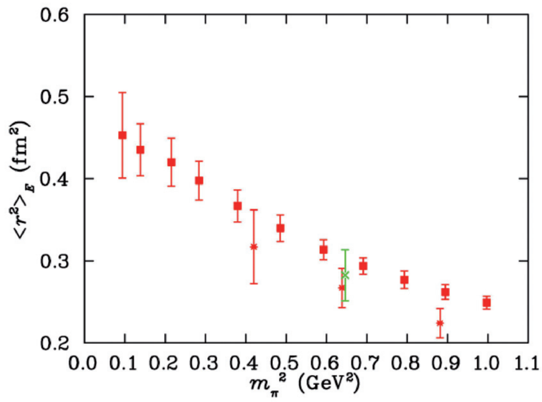
Strangeness in the Nucleon: D.B. Leinweber, S. Boinepalli, I.C. Cloet, A.W. Thomas, P.Wang, A.G. Williams, R.D. Young, J.M. Zanotti and J.B. Zhang

An ongoing chief aim of the CSSM Lattice Collaboration is to determine the electromagnetic structure of the proton and neutron (collectively referred to as the nucleon). These are under intense experimental investigation at accelerator facilities around the world. Most notably, Jefferson Laboratory in Newport News, Virginia will resolve the individual quark-favor contributions to proton structure. For example, one will learn not only the magnetic moment of the proton (precisely known already), but also the magnetic moment contributions of the up-quark, down-quark and strange-quark sectors of the proton individually.

Genuine predictions of these properties have been made this year; predictions which will ultimately test our understanding of QCD. Indeed, this research program reached a pinnacle when our precise determination of the strange-quark contribution to the magnetic moment of the proton was accepted for publication in Phys. Rev. Lett., the most prestigious journal in our field.

Our precise determination of the strange magnetic moment of the proton is $G_M^s = -0.046 +/- 0.019\ \mu_N$. This value is consistent with the latest experimental measurements but an order of magnitude more precise and poses a tremendous challenge for future experiments.

We are currently performing a similar analysis for the strange quark contribution to the proton's charge radius. The outstanding quality of our results obtained from APAC resources is reflected in the following figure where our results for the proton charge radius (filled squares), are compared with the current state of the art. Plotted as a function of the squared pion mass, reflecting the quark masses used in the numerical simulations, our results are breaking new ground in accessing the light quark-mass regime of Nature, with relatively high accuracy.



By combining the constraints of charge symmetry with new chiral extrapolation techniques and recent low mass lattice QCD simulations of the individual quark contributions to the electric charge radii of the baryon octet we have obtained an accurate determination of the strange electric charge radius of the proton. While this analysis provides a value in agreement with the best current data, the theoretical error is comparable with that expected from future HAPPEx results from JLab. Together with our earlier determination of G_M^s, this result considerably constrains the role of hidden flavor in the structure of the nucleon. We find $G_E^s\ (Q^2 = 0.1\ GeV^2) = +0.001 +/- 0.004 +/- 0.004$, where the errors are statistical and systematic respectively.

Chiral and Continuum Extrapolation of Partially-Quenched Lattice Results: C. R. Allton, W. Armour, D. B. Leinweber, A. W. Thomas and R. D. Young

We have been analyzing a large sample of partially quenched, two-flavor lattice QCD simulation results for the vector meson created by the CP-PACS collaboration. Using finite-range regularised chiral effective field theory, we have been successful in accounting for and removing lattice artefacts, allowing a determination of the rho-meson mass that may be confronted with experiment.

For the first time, discretisation, finite-volume and partial quenching artefacts are treated in a unified framework which is consistent with the low-energy behaviour of QCD. This analysis incorporates the leading infrared behaviour dictated by partially-quenched chiral effective field theory. As the two-pion decay channel cannot be described by a low-energy power-counting scheme alone, a highly-constrained model for the decay channel of the rho-meson is introduced. The latter is essential for extrapolating lattice results from the quark-mass regime where the rho meson is observed to be a physical bound state.

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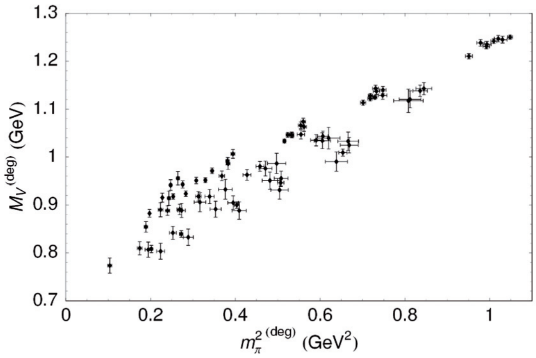
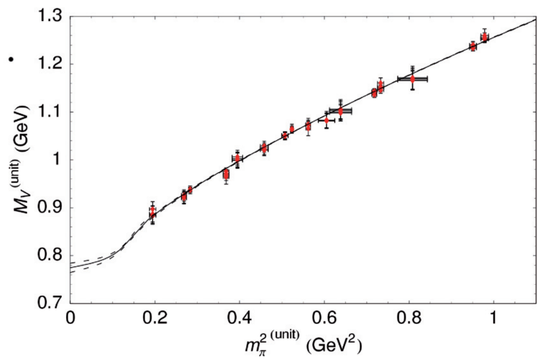


The figure above illustrates the partially quenched QCD calculations of the rho-meson mass from the CP-PACS collaboration. The 80 lattice data points are from lattices having different lattice spacings, volumes and sea-quark masses. The figure below illustrates the same 80 lattice data points, after correcting the lattice results with partially-quenched finite-volume chiral effective field theory to restore the infinite-volume, continuum and quark-mass unitarity limits. The central curve displays the best-fit and extrapolation to the physical point at $0.02\ \mathrm{GeV}^2$.



Gluon Flux-Tube Distribution and Linear Confinement in Baryons : F. Bissey, F-G. Cao, A. R. Kitson, A. I. Signal, D. B. Leinweber, B. G. Lasscock and A. G. Williams

The CSSM Lattice Collaboration is enjoying an ongoing collaboration with the New Zealand Lattice QCD Group based at Massey University and using New Zealand's national supercomputer, Helix. We have been exploring the possibility of directly observing the formation of flux tubes between three static quarks carrying the quantum numbers of a baryon.

Using three-point function techniques, correlations between the vacuum action density and the positions of quarks are used to identify the formation of gluon flux-tubes within baryons. A high-statistics approach based on the translational and rotational symmetry of the four-dimensional lattice volume is adopted to avoid the need for gauge-dependent smoothing techniques.

Vacuum field fluctuations are found to be suppressed in the presence of static quarks such that flux tubes represent the expulsion or suppression of gluon-field fluctuations. The characteristic flux tube diameter of the ground state potential is found to be 0.4 fm. The node connecting the flux tubes is larger approaching 0.5 fm with a slightly larger suppression of the vacuum action.

By considering numerous different link paths in the creation of the static quark sources, we are able to explore the dependence of the observed flux tubes on the source shape. In particular, T, L and Y shapes are considered to access a variety of flux-tube topologies including the ground state. T-shape paths are observed to relax towards a Y-shape topology as opposed to a Δ shape. L-shape topologies give rise to a large potential.

A key point of interest is the distance at which flux-tube formation occurs. Our visualizations indicate that the transition to flux-tube formation occurs when the distance of the quarks from the centre of the triangle is greater than 0.5 fm, corresponding to an inter-quark distance exceeding 1 fm. At inter-quark separations the order of 1.24 fm, flux tubes are manifest. The diameter of the flux tubes remains approximately constant as the quarks move to large separations. As it costs energy to expel the vacuum field fluctuations from the flux-tube region, a linear confinement potential is felt between quarks in baryons just as in mesons.

Upon identifying the precise geometry of the flux tube formation, we are able to perform a quantitative comparison between the flux tube length and the associated static-quark potential. For every source considered we find the flux-tube length and associated potential to provide a universal string tension. With this new knowledge, one can conclude that the flux tube configuration of the ground state potential for large quark separations is that which minimizes the flux tube length.

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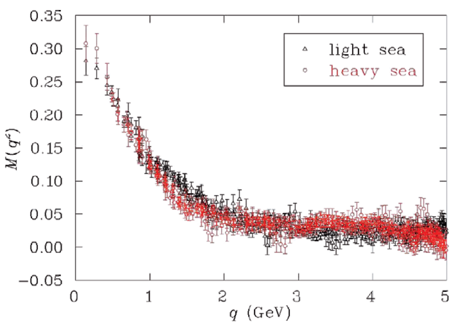
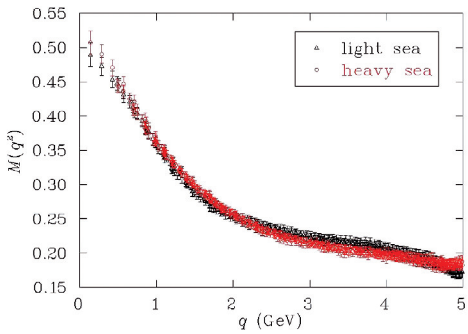
Maria Parappilly

Scaling behavior of the quark propagator in full QCD: P. Bowman, U. Heller, M.B. Parappilly, D.B. Leinweber, L. von Smekal, A.G. Williams and J.B. Zhang

We study the scaling behavior of the quark propagator on two lattices with similar physical volume in Landau gauge with 2+1 flavors of dynamical quarks. We use configurations generated with an improved staggered (AsqTad) action by the MILC collaboration. The calculations are performed on $28^3 \times 96$ lattices with a lattice spacing of $a = 0.090$ fm and on $20^3 \times 64$ lattices with lattice spacing of $a = 0.125$ fm. These two sets have approximately the same physical volume.

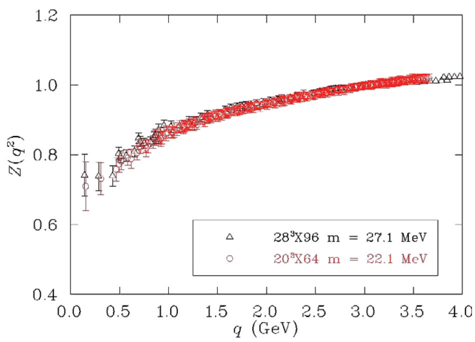
In figures below, the nonperturbative quark mass function is illustrated. We hold the valence quark mass fixed and vary the sea quark mass. Clearly the dependence over this small range of sea quark masses is weak. Unfortunately we only have two dynamical sets to compare, and for the lightest valence quark the data are rather noisy. In this study we focus on the Landau gauge quark propagator in full QCD, and extend our previous work to a finer lattice with lattice spacing $a = 0.090$ fm but similar physical volume.

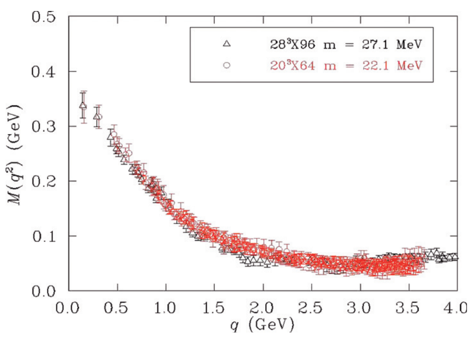




These figures show the unquenched quark mass function for the two different values of the light sea quark mass on the fine lattice (14.0 MeV and 27.1 MeV). The valence quark masses are m = 14.0 MeV (top) and m = 135.6 MeV (bottom), the lightest and heaviest in our current sample respectively.

The scaling behavior of the momentum space quark propagator is examined by comparing the results on these two lattices. Our results show that there are no significant difference in the wave-function renormalization function and the quark mass function on the two sets of lattices. Therefore the scaling behavior is good already at the coarser lattice spacing of $a = 0.125$ fm. In Figures below, we show the quark propagator from the fine lattice for full QCD with the light quark mass set to m = 27.1 MeV. This is compared with data from the coarse lattice by a simple linear interpolation from the four different data sets so the running masses are the same at $q^2 = 3.00$ GeV.





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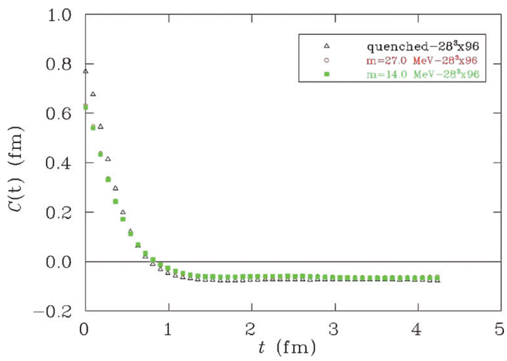
Comparison of wave-function renormalization function and mass function for two different lattices. Triangles corresponds to the quark propagator at mass m = 27.1 MeV from 28^3 x 96 with lattice spacing a = 0.090 fm. The open circles are the data from 20^3 ux 64 with lattice spacing a = 0.125 fm obtained by interpolating four different set of light quark masses making the M(q^2) value matched for both lattices at q= 3.00 GeV. The computional resources for this study were provided by the South Australian Partnership for Advanced Computing (SAPAC).

Positivity violation of the gluon propagator in full QCD: P. Bowman, U. Heller, M.B. Parappilly, D.B. Leinweber, L. von Smekal, A.G. Williams and J.B. Zhang

We are also performing studies on the positivity of the gluon spectral function in Landau gauge. We found a violation of spectral positivity for gluon propagator as anticipated. An infrared suppressed propagator always violates reflection positivity and we are presenting evidence for it in this study. Violation of positivity is another signal for confinement.

When a real space propagator C (t) (schwinger function) becomes negative, reflection positivity becomes violated. The positivity test also shows good scaling on our comparison of the real space propagator on two different lattices with different lattice spacings. The violation of positivity of the gluon propagator is investigated both in the quenched and the unquenched case. Our results signal a strong violation of positivity in the gluon propagator on fine as well as on coarse lattices.



The real space propagator C (t) plotted as a function of dimensionful t for two bare light sea quark masses in unquenched and quenched case. It is clear from the plot that positivity is violated in both cases.The computional resources for this study were provided by the South Australian Partnership for Advanced Computing (SAPAC).

Lorenz von Smekal

Quark confinement and unification constraints for topological defects: L. von Smekal, T. Tok and Ph. de Forcrand

There has been substantial progress in recent years in the description of the temperature phase transition of non-Abelian gauge theories from a disordered phase with confinement at low temperatures to a high-temperature phase with long-range order in Polyakov loop correlations. For the pure gauge theory without quarks, this transition can be qualitatively and quantitatively well described in terms of the dynamics of certain topological defects called center vortices in a finite Euclidean $1/T \times L^3$ volume.

Qualitatively, at low temperatures, center vortices can spread to lower their free energy. Their proliferation disorders the Wilson loop and leads to confinement. As the temperature is increased vortices piercing temporal $1/T \times L$ planes are squeezed more and more. They can no-longer spread arbitrarily and this is what drives the phase transition. In the thermodynamic limit ($L \to \infty$), their free energy approaches zero (infinity) for T below (above) T_c. In the high temperature phase, macroscopic regions of Polyakov loops of a definite center sector appear, which are separated by interfaces whose tension suppresses these types of vortices leading to an area law for certain spatial loops introduced by 't Hooft as the dual to the usual Wilson loop. For the gauge group $SU(2)$ a full quantitative analysis of this transition is in the garage.

While the techniques can be extended to compute interface tensions for $SU(N)$ with $N \geq 3$ and phase coexistence, the nagging question remains as to what the significance is of these qualitatively and quantitatively quite compelling results when dynamical quarks with their fundamental charges are included. Even in presence of quite heavy dynamical quarks the picture becomes rather murky. Upon encircling an interface (which is a line-defect in 3 dimensions) they pick up a non-trivial phase corresponding to their fundamental charge. This multivaluedness thus seems to have a dramatic effect on the dynamics of the same topological defects that appear to describe the phases of the pure gauge theory so beautifully. Should it be true that the phase structure changes abruptly when going from infinitely heavy to no-matter-how-large but finite

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quark masses? At least it would seem rather unnatural to assume that there are entirely different mechanisms in either case, which nevertheless lead to a smooth limit.

In light of this question we study the tantalising possibility for the coexistence of quarks and interfaces by simple unification constraints in theories with several gauge groups. In particular, we explore the old idea that the topological defects of one gauge group coincide with those of another gauge group. In QCD for example one might simply combine the $SU(3)$ with $U(1)$ defects, realising that quarks have fractional electric charges and interact with both, gluons and photons. This allows for a remarkable phase cancellation when quarks encircle combined center-vortex/Dirac sheets to make these combined interfaces unobservable as in the pure gauge theory. Their dynamics might thus provide a smooth connection of quark confinement to that of static fundamental charges in the pure gauge theory.

Of course, the defect-unification constraint induces a coupling between the two gauge groups. The dynamics of the formation/suppression of one kind of defect is now tied to the other. In a first study we have explored this effect in a toy model $U(1) \times U(1)$.

Consider the 4d compact pure Abelian gauge theory with Wilson action for the gauge group $U(1) \times U(1)$ with two couplings $\beta i = 1/ei^2$. Without any constraints the phases are trivially determined by the 2 independent $U(1)$ factors. The phase transitions at β_c just above 1 can be seen in the monopole densities, the string tension and the *helicity modulus.* Especially the (temporal) helicity modulus has recently reemerged as a suitable and convenient order parameter for compact $U(1)$. It measures the susceptibility of the theory to static external fluxes and plays a role analogous to that of 't Hooft's (electric) fluxes albeit being more easily amenable to simulations.

The phase diagram changes dramatically when the two $U(1)$ factors are constrained to always have the same monopole content. One large enough β (small coupling) suffices to suppress the monopoles in both $U(1)$ groups, no matter how strong the second coupling is. We are left with only 2 phases (rather than the original 4 without constraint), the same for both $U(1)$'s, and the mixed phases no-longer exist. The transition occurs at somewhat smaller values of β; we estimate $\beta_c \approx 0.4$ along the diagonal $\beta 1 = \beta 2$ and 0.6 near the axes where one of the two β's approaches zero. Both string tensions are the same also for $\beta 1 \neq \beta 2$ and vanish at the transition line in the two coupling plane. These correspond however to Wilson loops of charges (1,0) and (0,1) (in units of e). More interesting for our purposes are the half-odd integer cases (1/2, $\pm$ 1/2) which can exist in $U(1) \times U(1)$ with monopole unification constraint because of the same phase cancellation as described above. Instead of the corresponding Wilson loops we measured the helicity moduli which mimic the response to the presence of the various types of static charges. Our preliminary data shows a very different behaviour of equal versus opposite fluxes. It is a first indication that fields with equal electric charges in both $U(1)$'s are confined by the condensation of the unified monopoles, while oppositely charged ones are not.

Our toy model serves to demonstrate that in theories with several gauge groups it can be deceiving to study the individual factors separately, especially when there are mechanisms by which the defects of one gauge group are forced to coincide with those of another. Such unification constraints have been suggested to arise naturally from grand unified theories, with topological defects such as e.g. the $SU(5)$ monopole. They might manifest themselves in the presence of fundamental fields such as quarks in QCD or other particles with fractional charges in several gauge groups.

The probably most interesting property of the toy model $U(1) \times U(1)$, however, is its capacity to confine equal charge doublets whereas oppositely charged ones do not see the unified monopoles but only the topologically trivial gauge field fluctuations, and thus retain a Coulomb-like behaviour at any coupling. An analogous mechanism might in the end explain how to confine quarks but not electrons.

Gauge fixing in presence of Gribov copies: M. Ghiotti, A. Kalloniatis, D. Mehta, L. von Smekal, A. G. Williams

In the covariant continuum formulation of gauge theories, in terms of local field systems, one has to deal with the redundant degrees of freedom due to gauge invariance. Within the language of local quantum field theory, the machinery for that is based on the so-called Becchi-Rouet-Stora-Tyutin (BRST) symmetry which is a global symmetry and can be considered the quantum version of local gauge invariance. In short, one starts out from the representations of a BRST algebra on indefinite metric spaces with assuming the existence (and completeness) of a nilpotent BRST charge Q_B. The physical Hilbert space can then be defined as the equivalence classes of BRST closed (which are annihilated by Q_B) modulo exact states (which are BRST variations of others).

In QED this machinery reduces to the usual Gupta-Bleuler construction. For the generalization thereof, in non-Abelian gauge theories, all is well in perturbation theory also. Beyond perturbation theory, however, there is a problem with such a construction that has not been fully and comprehensively addressed as yet. It relates to the famous Gribov ambiguity, the existence of so-called Gribov copies that satisfy the Lorentz condition (or any other local gauge fixing condition) but are related by gauge transformations, and thus physically equivalent. As a result of this ambiguity, the usual definitions of a BRST charge fail to be globally valid.

A rigorous non-perturbative framework is provided by lattice gauge theory. Its strength and beauty derives from the fact that gauge-fixing is not required. However, in order to arrive at a non-perturbative definition of non-Abelian gauge theories in the continuum, from a

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lattice formulation, we need to be able to perform the continuum limit in a formally watertight way. And there is the gap in our present understanding. The same problem as described above comes back to haunt us in another dress when attempting to fix a gauge via BRST formulations on the lattice. There it is known as the Neuberger problem which asserts that the expectation value of any gauge invariant (and thus physical) observable in a lattice BRST formulation will always be of the indefinite form $0/0$. At the CSSM, we work on possible solutions to this problem in the following particularly promising directions:

Curci-Ferrari mass and the Neuberger problem: A. Kalloniatis, L. von Smekal, A. G. Williams

The BRST algebra requires the introduction of further unphysical degrees of freedom. These are the Faddeev-Popov ghosts and anti-ghosts which violate the Spin-Statistics Theorem of local quantum field theory on positive definite metric (Hilbert) spaces. Contrary to what the name anti-ghost might suggest, however, in the usual linear covariant gauges the treatment of ghosts and anti-ghosts is completely asymmetric. On the other hand, it is also known for many years that it is possible to extend the BRST algebra to be entirely symmetric w.r.t. ghosts and ant-ghosts. This additional symmetry arises naturally in the Landau gauge but can also be extended to more general gauges the so-called Curci-Ferrari gauges at the expense of quartic ghost self-intertactions.

The most interesting feature of these gauges for our purpose, however, is that they allow the introduction of a mass term for ghosts. While such a Curci-Ferrari mass m breaks the nilpotency of the BRST and anti BRST charges, which is known to result in a loss of unitarity and which therefore meant that this relatively old model received little attention for many years, it also serves to regulate the Neuberger zeroes in a lattice formulation.

We have explicitly demonstrated this effect in a simple model where the zeroes in the numerator and denominator of expectation values become proportional to m^2 and allow to compute a finite value for $m^2 \to 0$ via l'Hospital's rule.

Extended double lattice BRST without Neuberger problem: M. Ghiotti, L. von Smekal, A. G. Williams

For the $SU(N)$ gauge theory on a finite four-dimensional lattice things are naturally much more complicated than in the toy model. For the first time here, we have developed a full lattice formulation of the time-honored model by Curci and Ferrari with its extended double BRST/antiBRST and ghost-mass term. We have extended Neuberger's no-go-theorem to include the ghost/anti-ghost symmetric case of the non-linear covariant Curci-Ferrari gauges for $m^2=0$, a setting explicitly excluded in Neuberger's original work. At non-vanishing Curci-Ferrari mass the partition function of the model used as the gauge-fixing device can be shown to be polynomial in m^2 and thus non-vanishing. In this way regularising the Neuberger zeroes, the leading power of that polynomial can be extracted from a suitable number of derivatives $(w.r.t.\ m^2)$ before the limit $m^2 \to 0$ is taken, in the spirit of l'Hospital's rule. This gives rise to a modified lattice BRST model without Neuberger problem. The independence of the gauge parameter in this class of non-linear covariant gauges is maintained, the topological nature of the model, and the nilpotency of the BRST and antiBRST charges are recovered for $m^2 \to 0$. The continuum limit of the resulting lattice model is intricate, however, and remains to be further studied.

Landau gauge Jacobian and BRST symmetry: M. Ghiotti, A. Kalloniatis, A. G. Williams

In perturbation theory, a common method to include gauge transformations in the functional measure is to use the so-called Faddeev-Popov trick: it basically deals with an apparent change of variables with respect to the gauge fields, via a gauge-fixing condition, and the appearance of a functional determinant. Though it's naively considered in literature a change variables, it is not, because, the determinant does not carry any modulus. This is due to the fact that in perturbation theory, this determinant is always positive definite, and therefore the absolute value would be redundant. Our proposal is, in order to include finite gauge transformations, only influent in the non-perturbative regime, to treat the Faddeev-Popov trick as a genuine change of variables. We show that, to re-write the absolute value of the determinant in terms of a functional integral, we need to introduce new fields.

These new fields form a new double BRST algebra, alongside the standard fields we have in perturbation theory, such as the ghosts and anti-ghosts, the gauge fields and the Nakanishi Lautrup field, which already form a double BRST algebra. These two uncoupled algebras constitute a new doubly extended BRST algebra such that new and old fields form four doublets. It is then possible to write the gauge-fixing Lagrangian density in terms of algrebraic variations, though it is not a BRST-exact quantity because of the presence of a trace over the extended space of doublets. This obstruction is not totally unexpected, because the absolute value of a determinant cannot generate a topological invariant. At last, we show how it is possible, at least formally, to determine the number of Gribov copies per orbit. If we knew how to actually calculate such a quantity, the problem to go beyond perturbation theory would be solved. This problem is still open.

Topological quantum field theory for gauge fixing in compact U(1) lattice gauge theory: D. Mehta, M. Schaden, L. von Smekal, A. G. Williams

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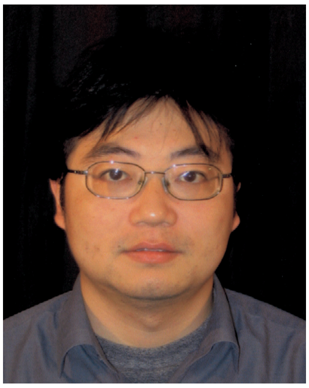
Topological quantum field theories (of Witten type) on the gauge group can provide another promising generalisation of the perturbatively approved Faddeev-Popov method. The problem here is that the partition function of the topological model to be used as the gauge fixing device computes a topological invariant such as the Euler character of the gauge group which may vanish. This is in fact the case for the straightforward generalization of the standard BRST quantization, and it manifests itself as the Neuberger problem of the corresponding lattice BRST formulation.

To avoid the problem, one can think of other, non-vanishing topological invariants, or, as we propose here, modify the underlying manifold so that the Euler character no-longer vanishes. In particular, we use the methods of stereographic projection to decompactify the group. This corresponds to introducing coordinates on different patches. Restricting to a certain patch amounts to eliminating certain Gribov copies and leads to a non-vanishing result. This is being explored in the compact $U(1)$ lattice gauge theory, where the resulting, gauge-fixed version can be put to the test for the many known features of the unfixed lattice model in various dimensions.

Putting together the results from different patches in non-standard ways might furthermore allow to fix the gauge up to a discrete rest symmetry. This might lead to the intriguing interpretation that the topological invariant that matters is not the Euler character of the lattice gauge group, which vanishes, but that of a corresponding orbifold which doesn't. The methods can be straight forwardly extended to include at least the non-Abelian gauge group $SU(2)$.



Ping Wang

Liquid-gas phase transition and Coulomb instability of asymmetric nuclear systems: P. Wang, D.B. Leinweber, A.W. Thomas and A.G. Williams.

The determination of the properties of hadronic matter at finite temperature and density is a fundamental problem in nuclear physics. In particular, the study of liquid-gas phase transition in medium energy heavy-ion collisions is of considerable interest. Many intermediate-energy collision experiments have been performed to investigate the unknown features of the highly excited or hot nuclei formed in collisions. Theoretically, much effort has been devoted to studying the equation of state for nuclear matter and to discussing the critical temperature, T_c. The calculated critical temperature of symmetric nuclear matter lies in the range 13 – 24 MeV for various phenomenological models. For finite nuclei, there is another temperature which is called the limiting temperature, T_{lim}. Below the limiting temperature, nuclei can exist in equilibrium with the surrounding vapor. When the temperature is higher than T_{lim} the nuclei are unstable and will fragment. This is called Coulomb instability.

In this paper, we extended the chiral SU(3) quark mean field model to finite temperature and density. The liquid-gas phase transition of infinite nuclear matter and the Coulomb instability of finite nuclei at finite temperature are discussed in this model. All the parameters have been determined in earlier papers. The critical temperatures for two-phase coexistence of symmetric nuclear matter, T_c, is 15.82 MeV (square root case) and 17.9 MeV (linear case). Both of these values are close to the recent experimental value, 16.6±0.86 MeV. The limiting temperature T_{lim} decreases with increasing mass number. This means that when the temperature is higher than the limiting temperature, the heavy nuclei will fragment to light nuclei. Numerical results show that there is a relationship between T_{lim} and T_c. For larger T_c, the calculated T_{lim} is also larger.

Neutron stars and strange stars in the chiral SU(3) quark mean field model: P. Wang, S. Lawley, D.B. Leinweber, A.W. Thomas and A.G. Williams

Hadronic matter under extreme conditions has attracted a lot of interest in recent years. On the one hand, many theoretical and experimental efforts have been devoted to the discussion of heavy ion collisions where the temperature is high. On the other hand, the physics of neutron stars has become a hot topic which connects astrophysics with high density nuclear physics. In 1934, Baade and Zwicky suggested that neutron stars could be formed in supernovae. The first theoretical calculation of a neutron star was performed by Oppenheimer and Volkoff, and independently by Tolman. Observing a range of masses and radii of neutron stars will reveal the equations of state (EOS) of dense hadronic matter.

We have investigated neutron stars and strange hadronic stars in the chiral SU(3) quark mean field model. The Λ, Σ and Ξ hyperons are included in the model. The proton and hyperon contributions to the system are important at high baryon density when β- equilibrium is achieved, and soften the EOS of hadronic matter. The maximun pure neutron star mass is about $M = 1.8M_{sun}$ with a corresponding radius R = 11.5 km and central density ρ_c = 1.05 fm^{-3}. For the strange hadronic stars, the maximum masses are about $1.45M_{sun}$ and the corresponding radii and central density are R = 11.5 km and ρ_c = 1.0 fm^{-3}. When the central densities are

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between 3_{P0} and 6_{P0}, the masses of stars are in the range $1.25M_{sun} < M < 1.45M_{sun}$ (strange hadronic stars), $1.32M_{sun} < M < 1.7M_{sun}$ (proton-neutron stars with β - equilibrium) and $1.48M_{sun} < M < 1.8M_{sun}$ (pure neutron stars). If the masses of stars are larger than $0.5M_{sun}$, the typical values of radii are 11.5-12.5 km (strange hadronic stars), 11.0-12.5 km (proton-nuetron stars with β - equilibrium) and 11.5-13.0 km (pure neutron stars), respectively. The nucleon crust has little effect to the masses of stars. It increases the radii of stars by 0.5-1 km when their masses are larger than about $1M_{sun}$.

Jianbo Zhang

Scaling of non-perturbative renormalization of composite operators with overlap fermions: J. Zhang, Derek B. Leinweber and Anthony G. Williams

Following the previous project in which we computed non-perturbatively the renormalization constants of composite operators with overlap fermions in a quenched QCD. This project studies the scaling behavior of the renormalization constants.

Lattice QCD is a unique tool enabling us to compute the non-perturbative behavior of QCD from first principles using large scale numerical simulations. Computing the matrix elements of fermionic currents in QCD is necessary for determining a variety of low energy physical quantities such as the quark masses, hadronic decay constants, electromagnetic and weak form factors. The renormalization of lattice operators is an essential ingredient needed to relate the matrix elements computed using numerical simulations on lattice to the corresponding ones defined in a continuum renormalization scheme, like the $\overline{MS}$ scheme, used in experimental data analysis. In principle, the renormalization of quark bilinear can be computed by lattice perturbation theory. However, lattice perturbation theory is very difficult beyond one loop order, and its slow convergence demands on the alternative method.

We compute non-perturbatively the renormalization constants of composite operators on three lattices with similar physical volumes and different lattice spacings for the overlap fermion action by using the regularization independent scheme. The quenched gauge configurations were generated with a tadpole improved plaquette plus rectangle action. We test the continuum relation $Z_A = Z_V$ and $Z_S = Z_P$ and find that they agree well above $\mu = 1.6$ GeV. We perform a renormalization group analysis at the 4-loop level and remove the $(pa)^2$ error in vertex function. The matching of renormalization constants to $\overline{MS}$ scheme at 2.0 GeV is also carried out. The scaling behavior of the renormalization constants are investigated using the data from three lattices, The approach of the renormalization constants to the continuum limit is explored.

5. Postdoctoral and Student Training

The Centre plays an important role in the training of honours and postgraduate students. All students in the Centre are also students of the Discipline of Physics in the School of Chemistry and Physics. The students associated with the Centre in 2005 are listed in Appendix B.

Students of the Centre are given opportunities to develop their presentation skills through the Centre's seminar program. The students are also encouraged to participate in our workshops and to interact with the many visiting researchers who spend time at the Centre.

During 2005 four undergraduate summer students joined the CSSM. These students have teamed up with staff and pursued research in a wide range of projects from parallel code development in lattice QCD, to analytic studies of the chiral properties of QED, to computational studies of complex systems. (See Appendix B for student information.).

6. Computing and Administration Services

6.1 Computing and Infrastructure

The Centre has a diverse and powerful array of computing equipment to support its research activities. Professor Tony Williams oversees the entire Centre's computing infrastructure while the Centre's Computing Officer, Ms. Ramona Adorjan, undertakes the day-to-day management and maintenance. Ms. Adorjan also provides computer support for visitors and during workshops.

The Centre's computer network is fully integrated with that of the Discipline of Physics. The Centre has 19 Digital Unix workstations, 26 Linux Pentium Computers, and 5 personal computers with the Windows operating system and several laser printers (black/white and colour).

The Centre's Computing Officer also provides invaluable assistance in the operation and management of the Orion supercomputer, a Sun Technical Compute Farm managed by SAPAC which consists of 40 E420R nodes connected by a high-speed Myrinet network as well as standard 100 Mbit/s switched Fast Ethernet. There are now almost two Terabytes of hard disks on Orion for data storage.

6.2 Administrative Services

The Centre is an extremely busy and diverse place to work. Ms. Sara Boffa and Mrs. Sharon Johnson provide the administrative support to the Centre. Some of the duties undertaken include the organization/coordination of the administrative side of Centre's many workshops/conferences and its visitor program. They also undertake the general day-to-day administrative duties associated with the Centre, which include the collation and preparation of the Annual Report and the Centre's publications information, which is required by DEST.

Since the relocation of the CSSM back to the Physics Building, the administrative support area has been enlarged and refurbished to provide a more comfortable working environment as well as to incorporate a very professional appearance.

7. Other Activities

7.1 Community Involvement and Public Lectures

Cornell University ArXiv

We continue to offer a mirror of the Cornell University scientific e-print archive at http://xxx.adelaide.edu.au/ as a preprint service to the Australian Scientific community. The Australian domain dominated the site traffic with significant numbers of requests from the Australian National University, University of Melbourne, University of New South Wales, Sydney University, and the Flinders University. In international usage, Japan and New Zealand led the traffic.

Promotional Material

Brochures, posters, pens, cups and Annual Reports of the Centre were distributed to all visitors to the CSSM and school visit students and teachers. The Centre's 2004 Annual Report was mailed to all high school physics teachers in South Australia, Physics Departments of other Australian universities and Heads of other Special Research Centres in Australia.

7.2 Publicity and Marketing of Centre Activities

The Centre continues its efforts to raise its profile in the wider community and to provide the public with information on theoretical physics.

School Visits

Assoc. Professor Leinweber hosted students from Gleeson College at CSSM on 22 September. Assoc. Professor Leinweber gave a presentation and the students were enthusiastic in their questions.

Newspaper/Magazine Articles/Radio Interviews

- "Elementary findings that matter". The Independent Weekly, January. A story about the nine years of success of the CSSM based on interviews with Professor Tony Williams, Assoc. Professor Derek Leinweber and Dr. Lorenz von Smekal
- "Strange particles a quark of nature". Adelaidean, University of Adelaide publication, 6 August, based on an interview with Assoc. Professor Derek Leinweber.

Assoc. Professor Derek Leinweber contributed to a series of newspaper articles in The Advertiser.

- "Swinger's Delight". Probes the mystery of cricket ball swing with an emphasis on the role of humidity. Can you Believe it?, Adelaide Advertiser, 31 December.
- "To be or not to be". The weird, ghostly worlds of Einstein's mind". Describes, in an engaging manner, the essential idea of non-locality and challengers to realism that Einstein pondered extensively during the emergence of quantum mechanics. Can you Believe it? Adelaide Advertiser, 24 December.
- "Striving for Gold". Reviews the ancient Alchemist's dream to turn lead into gold and reveals the manner in which it is done with modern-day nuclear physics. Can you Believe it? Adelaide Advertiser, 8 October.
- "Behind the Seams". Explores the aerodynamics behind cricket ball swing. Can you Believe it? Adelaide Advertiser, 10 September.
- "Need for Speed". Describes what makes a modern supercomputer super. Can you Believe it? Adelaide Advertiser, 23 July.
- "Explosive Origins". Reveals the origin of the elements of the periodic table. We are made of star dust. Can you Believe it?. Adelaide Advertiser, 2 July.

Assoc. Professor Leinweber's vizusalizations appeared in the following magazines:

- "Lattice QCD" Kurt Riesselman *et al.* "Contributed visualization of QCD vacuum action-density structure." Symmetry Magazine, published jointly by Fermilab and the Stanford Linear Accelerator Facility (SLAC) (2005)
- "UKQCD/IBM/Columbia QCDOC Lattice QCD Machine" Harry Yeates *et al.* Contributed visualization of QCD vacuum structure."PC Plus Magazine (www.pcplus.co.uk), published in the UK" (2005)

7. Other Activities *(Cont)*

- "Proceedings of the 58th Scottish Summer School in Physics" Ralf Kaiser *et al.* Contributed visualization of baryon flux tubes. "Published by Institute of Physics Publishing, UK" (2005).
- "The Search for QCD Exotics" Alex R. Dzierba *et al.* Contributed visualization of meson flux tubes. "Postepy Fizyki (Advances in Physics), Polish Physical Society" (2005).

"The Centre's web page and Cool Links to Hot Topics in Physics"

The Centre and National Institute for Theoretical Physics have received many requests for links to the latest and greatest hot physics topics. The Centre's web pages are managed by Derek Leinweber and Tony Williams and feature links to the "Subatomic Particle Adventure", educational web sites explaining subatomic particles, information on Careers in Physics and "Cool Links to Hot Topics in Physics". Following the Centre's welcome page, the "Cool Links to Hot Topics in Physics" page is now the second most popular page on the CSSM site. Visit the "Cool Links to Hot Topics in Physics" section, the "Magazine Rack," other "Link Collections," the "Toy Box" or perhaps follow some "Kids' Links".

8. Financial Statement

Carry forward 2005	$334,103
2005 Income	
ARC	$696,460
Adelaide University	$416,631
Sundries	$12,140
Income Total	$1,459,334
2005 Expenditure	
Salaries/staff benefits	$461,089
Scholarships	$72,088
Workshops/Conferences	$55,940
Visitor Program	$24,161
Staff/student travel	$58,623
Equipment	$37,795
Consumables/Maintenance, etc.	$65,008
Contribution to Univ of Adel toward refurbishment cost of CSSM	$130,000
Contribution to SAPAC for Supercomputer Usage	$40,000
Expenditure Total	$944,704
Surplus Balance at 31 December, 2005:	*$514,630*

Appendices

Appendix A

International Advisory Board

- Professor Wolfram Weise (Chair)
  Director, ECT*, Trento and Professor of Physics, Technical University, München
- Professor Alex Dzierba
  Indiana University
- Professor Tetsuo Hatsuda
  University of Tokyo
- Professor Larry McLerran
  Brookhaven National Laboratory

Board of Management Membership

Professor Neville Marsh,
Deputy Vice-Chancellor (Research)

Professor P. Rathjen, Executive Dean,
Faculty of Sciences

Professor A.G. Williams
(Director, CSSM)

Assoc. Professor D.B. Leinweber
(Deputy Director, CSSM)

Assoc. Professor I.R. Afnan
(Flinders University)

Professor B.H.J. McKellar FAA
(University of Melbourne)

Professor R. Delbourgo FAA
(University of Tasmania)

Appendix B

Personnel Directory for the CSSM

- **Director and Deputy Director**
  Director: Professor Anthony G. Williams
  Deputy Director: Assoc. Professor Derek B. Leinweber

- **Support Staff**
  PA to the Director: Mrs. Sharon Johnson
  Administrative Assistant: Ms. Sara Boffa
  Computing Officer: Ms. Ramona Adorjan

- **Other Academic Staff:**
  Dr. Paul Coddington
  Dr. Rodney J. Crewther
  Assoc. Professor Max Lohe (Biedenharn Fellow)
  Dr. Ayse Kizilersü
  Dr. Ray Protheroe
  Dr. Lorenz von Smekal
  Dr. Tasrief Surungan

- **Research Fellows:**
  Dr. Alex Kalloniatis (Aust. Res. Fellow)

- **Postdoctoral Fellows:**
  Dr. Jianbo Zhang
  Dr. Ping Wang

- **Postgraduate Students:**
  Marco Bartolozzi (Ph.D.)
  Sharada Boinepalli (Ph.D.)
  Ian Cloet (Ph.D.)
  Ben Crouch (Ph.D.)
  Marco Ghiotti (Ph.D.)
  John Hedditch (Ph.D.)
  Mariusz Hoppe (Ph.D.)
  Ben Lasscock (Ph.D.)
  Sarah Lawley (Ph.D.)
  Dhagash Mehta (Ph.D.)
  Maria Parappilly (Ph.D.)

- **Honours Students**
  Jonathan Carroll
  James Chappell
  Bao Loc Nguyen
  Skye Platten
  Sebastian Wende

- **Undergraduate Students: Summer Scholars**
  Sam Edwards
  Dustin De Jonge
  Peter Moran
  Jonathan Rogozinski

- **CSSM Associates at Other Australian Institutions:**

  Australian National University:
  Dr. Brian Robson

  James Cook University:
  Assoc. Professor Ian Whittingham

  Swinburne Institute of Technology:
  Professor Tien Kieu

  The Flinders University of South Australia:
  Assoc. Professor Iraj R. Afnan
  Assoc. Professor Reginald T. Cahill
  Dr. Boris Blankleider

  The University of Melbourne:
  Professor Bruce H.J. McKellar
  Assoc. Professor Ken Amos
  Assoc. Professor Girish Joshi
  Dr. Lloyd Hollenberg
  Assoc. Professor Ray Volkas

  The University of New South Wales:
  Professor Victor Flambaum
  Assoc. Professor Chris Hamer
  Dr. O. Sushkov

  The University of Tasmania:
  Professor Robert Delbourgo

- **CSSM Associates at International Institutions:**

  Austria:
  Dr. Steven Bass (Innsbruck, Austria)

  Brazil:
  Dr. Fernando Steffens (Mackenzie Presbiteriana Universidade, Brazil)

  Canada:
  Professor Kim Maltman (York University, Toronto)

Appendix C

Plenary presentations at international conferences and workshops

Assoc. Prof. D.B. Leinweber, "Scale-Free Avalanche Dynamics in the Stock Market". Economics Colloquium: International Conference on Econophysics, Australian National University, Australia – November.

Assoc. Prof. D.B. Leinweber, "Role of Centre Vortices in Dynamical Mass Generation". LC2005, International Workshop on Light-Cone QCD and Nonperturbative Hadron Physics, Cairns, Australia – July.

Dr. P. Wang, "Convergence of chiral effective theory for nucleon magnetic moments".
LC2005, International Workshop on Light-Cone QCD and Nonperturbative Hadron Physics, Cairns, Australia – July.

Dr. L. von Smekal, "Confinement and Unification Constraints for Topological Defects". Workshop on Light-Cone QCD and Nonperturbative Hadron Physics, Cairns, Australia – July.

Professor A.G. Williams, "Lattice QCD and the subatomic structure of matter". International Research Conference on Quantum Field Theory and Its Ramifications, University of Tasmania, Australia – December.

Professor A.G. Williams, "Lattice QCD studies of pentaquarks and exotics". Workshop on Computational Hadron Physics", University of Cyprus, Cyprus – September.

Professor A.G. Williams, "An overview of recent results". LC2005, International Workshop on Light-Cone QCD and Nonperturbative Hadron Physics, Cairns, Australia – July.

Presentations at international and national conferences and workshops

Mr. M. Bartolozzi, "Scale-free networks in complex systems". Queensland University of Technology, Brisbane, Australia – December.

Mr. M. Bartolozzi, "Stochastic opinion formation in scale-free networks". Econophysics Colloquium, Australian National University, Australia – November.

Ms. S. Boinepalli, "Electromagnetic structure of Ξ^{0} and Ξ^{-}." Workshop on Cascade Physics: A New Window on Baryon Spectroscopy, Jefferson Lab, Newport News Virginia, USA – December.

Mr. I.C. Cloet, "Partons in the Medium". The Challenges of QCD and the opportunities of the 12GeV Upgrade, Jefferson Lab, Newport News Virginia, USA – June.

J.N. Hedditch, "1^{-+} exotic on the lattice with FLIC fermions". The Third Asia-Pacific Conference on Few-Body Problems in Physics, Nakhon Ratchasima, Thailand - July.

J.N. Hedditch, "Meson Phenomenology from the Lattice". Australian Institute of Physics 16th Biennial Congress 2005, Australian National University, Canberra – February.

Dr. A. Kizilersü, "Solving some of the mysteries of non-perturbative physics", International Research Conference on Quantum Field Theory and its Ramifications, Hobart, Australia – November.

Assoc. Prof. D.B. Leinweber, "Power Counting Regime of Chiral Extrapolation and Beyond". 23rd International Symposium on Lattice Field theory (LATTICE 2005). Trinity College, Dublin – July.

Ms. M. Parappilly, "The scaling behaviour of quark propagator in full QCD Particles and Nuclei", International Conference, Santa Fe, New Mexico, USA – October.

Ms. M. Parappilly, "The quark and gluon propagators from full QCD". AIP National Congress, Canberra, Australia – January.

Dr. L. von Smekal, "A Toy Model of (Graud) Unified Monopoles". 23rd International Symposium on Lattice Field theory (LATTICE 2005). Trinity College, Dublin – July.

Professor A.G. Williams, "Light-quark FLIC fermion simulations of the 1^{-+} exotic meson". 23rd International Symposium on Lattice Field Theory (LATTICE 2005), Trinity College, Dublin – July.

Dr. J.B. Zhang, "Scaling of nonperturbative renormalization of composite operators with overlap fermions". International Conference on QCD and Hadronic Physics, Beijing, China – June.

Keynote Talk

Assoc. Prof. D.B. Leinweber, "Visually Revealing the Secrets of QCD". Australian Institute of Physics National Congress 2005, Australian National University, Australia – February.

Appendix D

2005 Publications

Editors

"Lattice Hadron Physics" Volume in the pedagogical series Springer Lecture Notes in Physics. Edited by A.C. Kalloniatis, D.B. Leinweber and A.G. Williams, Vol. 663 (230 pages), Springer, Berlin Heidelberg 2005.

"Proceedings of the Workshop on QCD Down Under" edited by: A. Kizilersü, A.W. Thomas and A.G. Williams, Vol. 141, Nucl. Physics B (Proc. Suppl.) (2005).

Book Chapters

P.O. Bowman, U.M. Heller, D.B. Leinweber, A.G. Williams and J.B. Zhang, "Quark Propagator from LQCD and its Physical Implications". Lecture Notes in Physics (Springer-Verlag) Volume 663 "Lattice Hadron Physics" (2005) 17-63.

W. Kamleh, "Generalised Spin Projection for Fermion Actions". Lecture Notes in Physics (Springer-Verlag) Volume 663 "Lattice Hadron Physics" (2005) 65-69.

D.B. Leinweber, W. Melnitchouk, D.G. Richards, A.G. Williams and J.M. Zanotti, "Baryon Spectroscopy in Lattice QCD". Lecture Notes in Physics (Springer-Verlag) Volume 663 "Lattice Hadron Physics" (2005) 71-112.

D.B. Leinweber, A.W. Thomas and R.D. Young, "Hadron Structure and QCD: Effective Field Theory for Lattice Simulations". Lecture Notes in Physics (Springer-Verlag) Volume 663 "Lattice Hadron Physics" (2005) 113-129.

J.M. Zanotti, D.B. Leinweber, W. Melnitchouk, A.G. Williams and J.B. Zhang, "Hadron Properties with FLIC Fermions". Lecture Notes in Physics (Springer-Verlag) Volume 663 "Lattice Hadron Physics" (2005) 199-225.

Journals

A. Alexandru, I. Horvath and J. Zhang, "Reality of the fundamental topological structure in the QCD vacuum". Phys. Rev D72, (2005) 034506, 1 – 5.

C.R. Allton, W. Armour, D.B. Leinweber, A.W. Thomas, R.D. Young, "Chiral and continuum extrapolation of partially-quenched hadron masses." Proc. of Sc. PoS (LAT2005) (2005) 049 1-5

C.R. Allton, W. Armour, D.B. Leinweber, A.W. Thomas, R.D. Young, "Chiral and continuum extrapolation of partially-quenched lattice results." Phys. Lett. B628 (2005) 125-130.

M. Bartolozzi, D.B. Leinweber, A.W. Thomas, "Stochastic opinion formation in scale-free networks." Phys. Rev. E72, (2005) 046113, 1-10.

M. Bartolozzi, S. Drozdz, D.B. Leinweber, J. Speth and A.W. Thomas, "Self-Similar Log-Periodic Structures in Western Stock Markets from 2000." Int. Jrn. of Mod. Phys. C16 (2005) 1347-1361.

M. Bartolozzi, D.B.Leinweber, and A.W. Thomas, "Self-organized criticality and stock market dynamics: an empirical study." Physica A 350 (2005) 451-465.

F. Bissey, F-G. Cao, A. Kitson, B.G Lasscock, D.B. Leinweber, A.I. Signal, A.G. Williams and J.M. Zanotti. "Gluon field distribution in baryons." Nucl. Phys. B141 (Proc. Suppl.) (2005) 22-25.

S. Boinepalli, W. Kamleh, D.B. Leinweber, A.G. Williams, J.M. Zanotti. "Improved chiral properties of FLIC fermions." Phys. Lett. B616 (2005) 196-202.

P.O. Bowman, U.M. Heller, D.B. Leinweber, M.B. Parappilly, A.G. Williams and J.B. Zhang, "Unquenched quark propagator in Landau gauge." Phys. Rev. D71, (2005) 054507, 1-7.

T.M.R. Byrnes, M. Loan, C.J. Hamer, F.D.R. Bonnet, D.B. Leinweber, A.G. Williams and J.M. Zanotti, "The Hamiltonian limit of (3+1)D SU(3) lattice gauge theory." Nucl. Phys. B141, (Proc. Suppl.) (2005) 253-258.

I.C. Cloet, W. Bentz and A.W. Thomas, "Spin-Dependent Structure Functions in Nuclear Matter and the Polarized EMC Effect". Phys. Rev. Lett. PRL 95, (2005) 052302 1-4.

I.C. Cloet, W. Bentz and A.W. Thomas, "Nucleon quark distributions in a covariant quark-diquark model". Phys. Lett. B621 (2005) 246-252.

R.J. Crewther, S.D. Bass, F.M. Steffens, A.W. Thomas. "Decoupling heavy particles simultaneously." Nucl. Phys. B141, (Proc. Suppl.) (2005) 159-164.

T. Draper, N. Mathur, J. Zhang, A. Alexandru, Y. Chen, S. Dong, I. Horvath, F. Lee and S. Tamhankar, "Locality and scaling of quenched overlap fermion." Proc. Of Science (2005) 120.1–6.

T. Draper, A. Alexandru, Y. Chen, S. Dong, I. Horvath, F. Lee, N. Mathur, H.B. Thacker, S. Tamhankar, J. Zhang, "Improved measure of local chirality." Nucl. Phys. B140 (Proc. Suppl) (2005) 623 – 625

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M. Ghiotti, A.C, Kalloniatis and A.G. Williams, "Landau gauge Jacobian and BRST symmetry." Phys. Lett B628 (2005) 176 – 182.

J. Hedditch, B.G. Lasscock, D.B. Leinweber, A.G. Williams, and J.M. Zanotti, "FLIC Mesons: hybrids and exotics." Nucl. Phys. B141, (Proc. Suppl.) (2005) 43-46.

J. Hedditch, W. Kamleh, B.G. Lasscock, D.B. Leinweber, A.G. Williams, and J.M. Zanotti, "1^{-+} exotic meson at light quark masses." Phys. Rev D72 (2005) 114507 1-8.

J. Hedditch, B.G. Lasscock, D.B. Leinweber, A.G. Williams, W. Kamleh and J.M. Zanotti, "Light-Quark FLIC fermion simulations of the 1^{-+} Exotic meson." Proc. Of Science PoS (LAT2005) (2005) 040 1 – 6.

I. Horvath, A. Alexandru and J.B. Zhang, "The reality of the fundamental Topological Structure in the QCD Vacuum." Phys. Rev. D72 (2005) 034506.

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I. Horvath, A. Alexandru, J.B. Zhang, Y. Chen, S.J. Dong, T. Draper, F.X. Lee, K.F. Liu, N. Mathur, S. Tamhankar and H.B. Thacker, "Inherently global nature of topological charge fluctations in QCD." Phys. Lett. B612 (2005) 21-28.

A.C. Kalloniatis, J.D. Carroll, and B-Y. Park, "Neutral pion decay into $\overline{\nu}\nu$ in dense Skyrmion matter." Phys. Rev. D71, (2005) 114001, 1-7.

A.C. Kalloniatis, S.N. Nedelko, "CP-violating theta parameter in the domain model of the QCD vacuum." Phys. Rev. D71, (2005) 054002, 1-11.

A.C. Kalloniatis, L. von Smekal and A.G. Williams, "Curci-Ferrari mass and the Neuberger problem." Phys. Lett. B609 (2005) 424-429.

A.C. Kalloniatis, B-Y. Park, "Neutral pion decay in dense Skyrmion matter." Phys. Rev. D71 (2005) 034010, 1-8.

W. Kamleh, P.O. Bowman, D.B. Leinweber, A.G. Williams, J. Zhang, "Fat link irrelevant clover overlap quark propagator." Phys. Rev. D71, (2005) 094507, 1-11.

W. Kamleh, P.O. Bowman, D.B. Leinweber, A.G. Williams, J.B. Zhang, "Properties of the FLIC overlap quark propagator." Nucl. Phys B141, (Proc. Suppl.) (2005) 217-222.

B.G. Lasscock, J. Hedditch, D.B. Leinweber, A.W. Thomas, R.D. Young, W. Melnitchouck, A.G. Williams, and J.M. Zanotti, "Search for the pentaquark resonance signature in lattice QCD." Phys. Rev D72, (2005) 014502, 1-22.

B.G. Lasscock, D.B Leinweber, W. Melnitchouk, A.W. Thomas, A.G. Williams, R.D. Young, and J. M. Zanotti, "Spin-3/2 pentaquark resonance signature in lattice QCD". Phys.Rev. D72 (2005) 074507 1-10.

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D.B Leinweber, R.D. Young, and A.W. Thomas, "Extrapolation of lattice QCD results beyond the power-counting regime." Nucl. Phys. A755 (2005) 59c-70c.

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K. Maltman, "Constituent quark models and pentaquark baryons." J. Phys. Conf. Ser. 9 (2005) 205-208.

K. Maltman, "Issues in the Extraction of m_s and V_{us} from Hadronic τ Decay Data". Nucl. Phys. B144 (2005) 65-72.

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J. Skullerud, P.O. Bowman, A. Kizilersu, D.B. Leinweber, and A.G. Williams, "Quark-gluon vertex in arbitary kinematics." Nucl. Phys. B141 (Proc. Suppl.)(2005) 244-249.

S. Tamhankar, A. Alexandru, Y. Chen, S.J. Dong, T. Draper, I. Horvath, F.X. Lee, K.F. Liu, N. Mathur and J.B. Zhang, "Charmonium Spectrum from Quenched QCD with Overlap Fermions." Nuclear Physics B140 (Proc. Suppl) (2005) 1-10.

A.W. Thomas, D.B. Leinweber, J.D. Ashley, and R.D. Young, "Finite Volume Dependence of Hadron Properties and Lattice QCD." J. Phys. Conf. Ser. 9 (2005) 321-330.

T. Tok, K. Langfeld, H. Reinhardt, L. von Smekal, "The Gluon Propagator in Lattice Landau Gauge with twisted boundary conditions." PoS LAT2005:334 1-5.

L. von Smekal, T. Tok, P. de Forcrand, "A toy model of (grand) Unified monopoles." PoS LAT2005:314 1-6.

P. Wang, D.B. Leinweber, A.W. Thomas, and A.G. Williams, "Liquid-gas phase transition in nuclear matter including strangeness." Phys. Rev. C70, (2005) 055204 1-8.

P. Wang, S. Lawley, D.B. Leinweber, A.W. Thomas, and A.G. Williams, "Neutron stars and strange stars in the chiral SU(3) quark mean field model." Phys. Rev. C72, (2005) 045801 1-8.

P. Wang, D.B. Leinweber, A.W. Thomas, and A.G. Williams, "Liquid-gas phase transition and Coulomb instability of asymmetric nuclear systems." Nucl. Phys. A748 (2005) 226-240.

P. Wang, D.B. Leinweber, A.W. Thomas, A.G. Williams, "Chiral SU(3) quark mean-field model for hadronic systems." Nucl. Phys. B141, (Procl. Suppl.) (2005) 273-278.

R.D. Young, D.B. Leinweber, A.W. Thomas, "Finite-range regularisation and chiral extrapolation." Nucl. Phys. B141, (Proc. Suppl.) (2005) 233-237.

R.D. Young, D.B. Leinweber, and A.W. Thomas, "Leading quenching effects in the proton magnetic moment." Phys. Rev. D71, (2005) 014001, 1-9.

J.M. Zanotti, B. Lasscock, D.B. Leinweber, and A.G. Williams, "Scaling of fat-link irrelevant-clover fermions." Phys. Rev. D71 (2005) 034510 1-5.

J.B. Zhang, N. Mathur, S.J. Dong, T. Draper, I. Horvath, F.X. Lee, D.B. Leinweber, K.F. Lui and A.G. Williams, "Nonperturbative renormalization of composite operators with overlap fermions." Phys. Rev. D72 (2005) 114509 1-18.

J.B. Zhang, P.O. Bowman, R.J. Coad, U.M. Heller, D.B. Leinweber, and A.G. Williams, "Quark propagator in Landau and Laplacian gauges with overlap fermions" Phys. Rev. D71 (2005) 014501 1-8.

J.B. Zhang, P.O. Bowman, R.J. Coad, U.M. Heller, D.B. Leinweber, and A.G. Williams, "Overlap quark propagator in Landau and Laplacian gauges." Nucl. Phys. B141 (Proc. Suppl.) (2005) 15-21.

Appendix E

Visitor Program

December
- Prof Lex Dieperink
  Kernfysisch Versneller Institute, Netherlands
- Dr. Yuichi Hoshino,
  Kushiro National College of Technology, Japan
- Dr. Waseem Kamleh
  Trinity College, Dublin, UK
- Dr. D. Sinclair,
  Argonne National Laboratory, USA.

November
- Dr. Yuichi Hoshino,
  Kushiro National College of Technology, Japan

October
- Dr. Yuichi Hoshino,
  Kushiro National College of Technology, Japan

July
- Dr Waseem Kamleh
  Trinity College Dublin, UK
- Prof Vladimir Karmanov
  Lebedev Physical Institute Moscow, Russia
- Dr Wally Melnitchouk
  Jefferson Laboratory, USA
- Prof Johann Rafelski
  University of Arizona, USA
- Dr Martin Schaden
  Rutgers University, USA
- Dr Stewart Wright
  Argonne National Laboratory, USA

June
- Dr Patrick Bowman
  Indiana University, USA
- Dr Waseem Kamleh
  Trinity College Dublin, UK
- Prof Johann Rafelski
  University of Arizona, USA
- Dr Martin Schaden
  Rutgers University, USA
- Dr James Zanotti
  Desy, Germany

May
- Dr Ingo Bojak
  Swinburne University, Australia

- Dr Lubomir Martinovic
  Institute of Physics Dubravska, Slovakia

April
- Dr Francois Bissey
  Massey University, New Zealand
- Prof Kim Maltman
  York University, Canada
- Dr Craig Roberts
  Argonne National Laboratory, USA

March
- Prof Steve Cotanch
  North Carolina State University, USA
- Prof Kim Maltman
  York University, Canada
- Dr Craig Roberts
  Argonne National Laboratory, USA
- Dr Zhi-Zhong Xing
  Institute for High Energy Physics, Chinese Academy of Sciences, Beijing

February
- Prof Kim Maltman
  York University, Canada
- Prof Byung-Yoon Park
  Chungnam National University, Korea
- Prof Helen Quinn
  Stanford University, USA

January
- Dr Francois Bissey
  Massey University, New Zealand
- Dr Michael Bromley
  Charles Darwin University, Australia
- Prof Kim Maltman
  York University, Canada
- Dr Wally Melnitchouk
  Jefferson Laboratory, USA
- Prof Byung-Yoon Park
  Chungnam National University, Korea
- Dr Don Sinclair
  Argonne National Laboratory, USA
- Prof Anthony Thomas
  Jefferson Laboratory, USA

Appendix F

Service

Service to the Discipline - International

- Committee Member for the International Light Cone Advisory Committee (ILCAC), Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams.

Service to the Discipline - National

- Director: Centre for the Subatomic Structure of Matter: Professor A.G. Williams
- Director: South Australian Partnership for Advanced Computing, Professor A.G. Williams
- Director: National Institute for Theoretical Physics, Professor A.G. Williams
- Alternate Member of the Management Committee for the ARC Complex Open Systems Research Network (COSNet): Professor A.G. Williams
- Deputy Director, CSSM: Assoc. Professor D.B. Leinweber
- Deputy Directors: South Australian Partnership for Advanced Computing, Dr. P. Coddington and Assoc. Professor D.B. Leinweber
- Member: Board of the Australian Institute for High Energy Physics (AUSHEP), Professor A.G. Williams
- Project Board Member: South Australian Broadband and Research and Education Network (SABRENet), Professor A.G. Williams.
- S.A. Representative, Australian Institute of Nuclear Science and Engineering (AINSE) Nuclear and Particle Physics Representative for South Australia, Assoc. Professor D.B. Leinweber.

Service to the Discipline – Local

- Chief Examiner: Physics for the Foundation Studies Program of Eynesbury College, Assoc. Professor D.B. Leinweber.
- Science Writer: The Advertiser Newspaper Column: Can You Believe It?, Assoc. Professor D.B. Leinweber.

International Conferences/Workshops: Membership of International Advisory Committees

- XXIII International Symposium on Lattice Field Theory, Dublin, Ireland, July, 2005 Professor A.G. Williams
- Conference on Few-Body Problems in Physics, Committee Third Asia-Pacific Conference, Thailand, (July 2005) Assoc. Professor D.B. Leinweber.

International Conferences/Workshops - Local Organizing Committee

- Workshop on Light-Cone QCD and Nonperturbative Hadron Physics (LC2005), Cairns, Australia, Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams

University of Adelaide Committees

- IT Committee, School of Chemistry and Physics, Professor A.G. Williams
- Member of the Physical Sciences Sub-Committee for Level D Promotions – Professor A.G. Williams
- Member, Faculty of Sciences Postgraduate Committee – Professor A.G. Williams
- Member of School Board, School of Chemistry and Physics – Professor A.G. Williams
- Member of Research Committee, School of Chemistry and Physics – Professor A.G. Williams
- Member, Curriculum Committee, School of Chemistry and Physics – Assoc. Prof. D.B. Leinweber and Professor A.G. Williams
- Program Coordinator: High Performance Computational Physics HPCP(Hons), University of Adelaide, Assoc. Professor D.B. Leinweber and Professor A.G. Williams
- Organiser: Department of Physics Colloquium, Dr. L. von Smekal.
- Strategic Marketing Committee: Faculty of Sciences, University of Adelaide, Assoc. Professor D.B. Leinweber
- Verticle Structuring Committees: Electromagnetism and Quantum Mechanics, Discipline of Physics, University of Adelaide, Assoc. Professor D.B. Leinweber

Refereeing (Journals)

- Few-Body Systems (Elementary Particles and Fields): Dr. A. Kizilersü and Dr. L. von Smekal
- Journal of Physics A: Professor A. G. Williams.
- Journal of Physics G: Professor A.G. Williams.
- International Journal of Modern Physics A: Professor A.G. Williams.
- Modern Physics Letters A: Professor A.G. Williams.
- Physica A: Assoc. Professor D.B. Leinweber
- Physical Review B, C, D: Drs A. Kalloniatis and A. Kizilersü, Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams.
- Physical Review Letters: Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams
- Physics Letters: Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams.
- Nuclear Physics A: Dr. L. von Smekal and Professor A.G. Williams.
- Nuclear Physics B: Professor A.G. Williams

Refereeing (Granting Agencies)

- Australian Research Council: Dr. A. Kizilersü, Assoc. Professor D.B. Leinweber and Professor A.G. Williams.
- (U.S.) Department of Energy: Assoc. Professor D.B. Leinweber and Professor A.G. Williams.
- (U.S.) National Science Foundation: Assoc. Professor D.B. Leinweber, Dr. L. von Smekal and Professor A.G. Williams.

Appendix G

Talks given at the CSSM

Dr. Jim Bashford (University of Tasmania, Hobart) 19 December "On mesoscale modelling of DNA-protein interactions."

Dr Sundance Bilson-Thompson (CSSM) 22 December "Kelper: the under-sung hero of modern physics."

Dr Lex Dieperink (The Netherlands) 6 December "The physics of neutron stars."

Prof. Yuichi Hoshino (Japan) 23 November "Mass singularity and confinement QED3."

Assoc. Prof. Derek Leinweber (CSSM) 4 November "Visually Revealing the Secrets of QCD"

Dr. Rod Crewther (CSSM) 2 November "Running couplings for the simultaneous decoupling of heavy Quarks."

Dr. Sundance Bilson-Thompson (CSSM) 28 October "An update on the Helon Model: topological preons meet loop quantum gravity."

Prof. Takashi Yamamoto (University of Tsukuba, Japan) 26 October "Introduction to the Macdonald polynomials – Applications in physics."

Ms. Sharada Boinepalli (CSSM) 19 October "Electromagnetic structure of baryons."

Mr. Mariusz Hoppe (CSSM) 5 October "Studies of complexity and chaos in idealized protein – like system."

Mr. Jonathon Carroll (CSSM) 14 September "Twinkle, twinkle, little star …", neutron stars : 1934-present."

Mr. James Chappell (CSSM) 7 September "Honours practice talk "Superstatistics: new distribution functions."

Mr. Bao-Loc Nguyen (CSSM) 22 August "Lie algebras and quantum groups in Physics."

Mr. Marco Bartolozzi (CSSM) 24 August "Scale-free networks in complex systems."

Dr. Stewart Wright (Argonne, USA) 3 August "Meson trajectories and confinement."

Dr. Lubomir Martinovic (Bratislava University, Slovakia) 25 July "Spontaneous symmetry breaking and kink states in DLCQ."

Prof. Vladimir Karmanov (Lebedev University, Russia) 26 July "New developments in light-front dynamics."

Prof. Jan Rafelski (Arizona University, USA) 29 June "Strangeness and the discovery of the Quark-Gluon Plasma."

Dr. Martin Schaden (Rutgers University , USA) 28 June "Equivariant BRST on the lattice."

Dr. Ingo Bojak (Swinburne University of Technology, Melbourne) 24 May "Electrocortical Rhythms and Aneaesthesia."

Dr. Boris Blankleider (Flinders University of South Australia) 18 May "Generalized parton distributions for dynamical equation models."

Assoc. Prof. Derek Leinweber (CSSM) 11 May "Chiral extrapolations of lattice QCD results."

Dr. Ping Wang (CSSM) 4 May "Neutron stars and strange stars in a chiral SU(3) quark mean field model."

Dr. Jianbo Zhang (CSSM) 27 April "Nonperturbative renormalization with overlap fermions."

Dr. Francois Bissey (Massey University, New Zealand) 19 April "The 3-quark potential and flux tubes on the lattice."

Prof Kim Maltman (York University, Canada) 20 April "Some new results on the standard model prediction for the anomalous magnetic moment of the Muon."

Dr. Craig D. Roberts (Argonne National Labs, USA) 5 April "Poincare Covariant Faddeev equation and nucleon electromagnetic form factors."

Mr. Jonathan Carroll (CSSM) 29 March "Compact objects in particle astrophysics."

Dr. Alex Kalloniatis (CSSM) 22 March "Solving the strong CP problem."

Prof. Zhi-Zhong Xing (Beijing University, China) 8 March "Neutrino masses and matter-antimatter asymmetry."

Ms. Sarah Lawley (CSSM) 8 February "The phases of asymmetric matter in 2-flavor NJL model."

Ms. Maria Parapilly (CSSM) 25 January "Unquenched quark propagator."

Ms. Sharada Boinepalli (CSSM) 25 January "Electromagnetic properties of octet baryons."

Mr. Ben Lasscock (CSSM) 25 January "The pentaquark resonance signature in lattice QCD."

Mr. John Hedditch (CSSM) 25 January "A broad look at mesons from lattice QCD."