Dr Peter Boyle

Full Name :	Dr Peter Andrew Boyle
College:	Science and Engineering
School:	Physics and Astronomy
UoE Lecturer:	April 2005 - present
Degrees :	First Class BSc Mathematics and Physics, The University of Glasgow, 1994 PhD in Theoretical Particle Physics, The University of Edinburgh, 1997
PPARC Personal fellowship:	University of Glasgow, Sept 1997 - Sept 2000
UoE post-doctoral researcher:	September 2000 - April 2005 Long-term assignment to Columbia University, Jan 2001- Nov 2004
Columbia University visiting scholar:	Jan 2001- Nov 2004
RCUK Fellowship:	April 2005 - April 2010
UoE Lecturer:	April 2005 - present

Research interests

My research interests are the study of low energy QCD in all its aspects, and particularly the use of Lattice QCD and computer simulation as a theoretical tool to experimental discovery. The computational demands are great and I have pushed the technological boundaries of high performance computing in order to advance Lattice QCD.

High performance computing

My development of the QCDOC supercomputer began a long term collaboration with IBM research. Our 10 Tflop/s computer influenced the subsequent BlueGene/L design by my collaborators in IBM. The success of BlueGene/L makes this a transfer of technology of global importance. The physics results of the Riken-Brookhaven-Columbia-UKQCD collaboration over the last five years have been produced using my QCDOC computer. This includes the physics research described below.

At IBM's invitation, I am member of the design team for the next generation BlueGene/Q supercomputer. This is a many hundred million dollar project for IBM, and direct academic collaboration is quite unique. My design responsibility is for the performance critical memory prefetch engine, and I have engaged in a novel co-design of the memory system and optimised QCD application code to ensure best performance. The impact of this aggressive design optimisation is broad and extends to many applications across high performance computing. The BlueGene/Q supercomputer I have secured for the University of Edinburgh will enable Riken-Brookhaven-Columbia-UKQCD physics programme over the next five years.

Lattice QCD

Much exciting physics and potential for discovering new, additional laws of nature lies in the process where by quark flavours are changed. An example of this is in the beta decay of the neutron to a proton, which at some level constitutes alchemy. The transmutation of elements mediated by this process was truly surprising 100 years ago, and was indicative of a new weak nuclear force. This was only truly understood in terms of force carrying bosons (analogous to the photon) in the seventies with the development of the standard model of particle physics. This development owes much to the Higgs mechanism that generates a large mass for these force carriers, which as a consequence makes the processes rare.

Flavour changing remains a key area in which to search for new physics, in a process that is directly analogous to the historical understanding of the weak nuclear force. The constants of nature within the standard model that admit flavour changing are the elements of the Cabbibo-Kobayashi-Maskawa quark mixing matrix for which the 2008 Nobel Prize was awarded. The precise details of these constants must be understood to know the degree of asymmetry between matter and anti-matter (CP violation). Such an asymmetry is required to explain our existence as a remnant excess of matter after the big bang. It is still not known if the standard model is the underlying reason for so much remnant matter, and there are good reasons to believe that additional flavour changing mechanisms be present in order to explain how much "stuff" is present in our universe.

I apply a novel approach to Lattice QCD that eliminates accidental mixing of vector and axial currents, called domain wall fermions (DWF). This is essential for interesting electro-weak physics that couples via the V-A current.

This enables predictions of experimentally topical phenomena that urgently require precise theoretical prediction. I focus particularly on CP violating processes that will, in partnership with experiment, lead to better constraining the fundamental parameters of the standard model. Accurate study of this area may lead to observed discrepancies that detect physics beyond the standard model.

My principal focus is on flavour physics in the Kaon sector, which may be treated well by Lattice QCD as it involves no large energy scales of order the lattice cut-off. I have led RBC-UKQCD's recent work on the Kaon/anti-Kaon mixing parameter B_K which contributes to one of the important constraints on the unitarity triangle of the CKM matrix. My work has led to a reduction in the uncertainty on this parameter from around 15% to around 3.5% in the last four years, and is the world's best calculation of this quantity.

A further constraint of interest to me is that on the CKM matrix element V_{us}. This appears to be most simple for lattice QCD to constrain using semi-leptonic kaon decay form factor $f_+(0)$. This kaon decay is directly analogous to the beta decay of the neutron. I have produced the world's best determination of the form factor, and this is the best lattice theoretical constraint on V_{us} My calculations of $f_+(0)$ and B_K were recognised as the best in the CERN *Flavour in the LHC era* working group report.

I introduced a new approach to SU(2) Chiral perturbation theory when treating the Kaon in lattice extrapolations. This novel application treated the Kaon as very massive, while treating only the pions as active chiral pseudoscalar mesons. This yielded a much more convergent, and therefore systematically rigorous approach. The approach has been internationally adopted by the RBC, UKQCD, MILC, PACS-CS and ETMC collaborations.

I have recently studied nucleon decay matrix elements relevant for detecting new physics at the GUT scale. My programme of research on form factors that yielded the critical semileptonic kaon decay form factor and allowed me to determine the pion electromagnetic form factor and c harge radius from Lattice QCD. Lattice QCD can be used to rigorously compute the distribution amplitudes of the hadronic decay products of B mesons, and I have calculated the first and second moments of the distribution amplitudes of quarks within the pion, kaon, rho, and K* light mesons.

I have recently computed the charged neutral pion mass difference, which is an interesting first step beyond purely QCD to understand electromagnetic effects which is necessary at the percent scale.

I have a long term interest in improving the matching between lattice QCD calculations and theoretically more convenient renormalisation schemes, such as $\overline{MS}$. I have revolutionised the approach used for matching B_K in the last two years, with the introduction of a volume averaging method that yields a ten-fold improvement in precision, with a simultaneous ten-fold reduction in numerical cost. This work is continuing, and I am developing a step-scaling technique to minimise perturbative errors in performing this matching.

I will continue to improve my calculation of the kaon semi-leptonic form factor and neutral kaon mixing amplitude. These are the two quantities which I have identified as particularly important to impacting our broader understanding of the universe. I presently lead the field and intend to consolidate this by improving my precision to around 0.1% for $f_+(0)$ and 0.5% for B_K in the next three years using BlueGene/Q.

I will use our theoretically pristine domain wall fermion approach to make accurate determinations of the $K \to \pi\pi$ decay, which will introduce a new, horizontal constraint on the important CKM matrix unitarity triangle. I will develop a new approach to determine the long distance effects in rare kaon decays, which are one key area where new flavour changing physics might be discovered.

As lattice kaon physics becomes increasingly precise incorporating isospin breaking and electromagnetic effects becomes important to produce sub-percent scale errors. These are challenges that I expect to be within reach of the next generation computers I am developing.

Knowledge transfer & industrial collaboration

Since 2007 I have held a contracted Collaboration Agreement to co-design the BlueGene/Q supercomputer chip with IBM Research and Columbia University. I have led the design of the prefetching memory controller and CPU-core to memory switch bridge. This has involved design, verification, timing closure and layout of the component using IBMs cutting edge silicon process in close collaboration with the BlueGene team at Watson. The design methodology is advanced and pushes technological boundaries in both power consumption and soft-error tolerance, in addition to performance boundaries. The project is a unique level of academic-industrial collaboration on IBM's core HPC technology, and on a many hundred million dollar project with significant US national security implications.

I have co-authored four joint patent applications with IBM Research and Columbia University that have gone through initial disclosure with the US Patent Office. These are in the field of cache coherent computer memory system design (1) and prefetching computer memory controller design (3). They have not yet been awarded, but have been disclosed and constitute first rate and legally verifiable knowledge transfer.

My development & prototyping project with IBM Research was singled out in the 2009 STFC Particle Physics Advisory Panel Report as an opportunity for KE with the computing industry. The BlueGene line of computers has done much to advance the state of computation science, covering many disciplines. The entire BlueGene team was awarded a 2009 Presidential Medal for Technology and Innovation. The BlueGene/L computer was the fastest computer in the world for a record duration, and was influenced by our QCDOC design with IBM.
I am honoured to be invited to work with them, and proud of both their confidence in me. This component of my work will impact the entire breadth of computational science.

Research grants & Contracts

1997 Principal investigator: PPARC personal fellowship (£64k)
1999 Co-Investigator: Theory panel special programme grant, (£60k)
2005 Principal Investigator: RCUK fellowship (£125k)
2005 Co-Investigator: PPT rolling grant (£1,060,455)
2007 Contract W0752350: Collaboration Agreement with IBM Watson & Columbia University to develop BlueGene/Q
2007 Co-Investigator: Software development for UKQCD (£221k)
2007 Co-Investigator: Operation of QCDOC (£134k)
2008 Co-Investigator: PPT rolling grant (£2,476,181)
2009 Leader of the Domain Wall Fermion research programme (2010-2012). The £6.6million pound UKQCD HPC award presently clearing STFC and DBIS. The DWF programme I lead comprises 4 professors and 5 lecturers with associated post-doctoral researchers and graduate students across four institutions.
Should result in peta-scale BlueGene/Q supercomputer located in the ACF at the University of Edinburgh.

The BlueGene/Q system will be procured under the the Collaboration Agreement I hold with IBM Research, to jointly develop the prototype, and for which I lead an academic team designing the memory prefetch engine and coherent switch interface.

RAE status

Category A in the 2008 RAE submission.

Research Superision

First supervisor: Jamie Hudspith from 2009
First supervisor: Chris Kelly, from 2006
First supervisor: Rudy Arthur, from 2008

Second supervisor: Dr David Antonio (graduated 2008)
Dr Antonio was awarded second prize at the departmental level for his work with me.

Teaching experience

I held a five year RCUK fellowship from April 2005, but have taught at least one course each year. Computational Methods is a large cohort with as much as 88 hours contact time in a semester.

2005-2009 Course organiser for Computational Methods 3H:
2008,2009 Jointly teaching Maple for Research Methods 3H:
2007-2009 I have supervised four undergraduate projects

Administration and Additional responsibilities

2005-2009 I have played the leading UK role in the international (UK/US/Japan) RBC-UKQCD collaboration developing the world's leading dynamical chiral fermion simulation programme, and have been the chair of the bi-weekly collaboration meetings, and several topical working groups.
2004-2009 Technical direction of six million pound QCDOC installation at the Advanced Computing Facility on behalf of UKQCD, including machine burn-in, maintainance and management.
2004-2009 Managed the research exploitation (physics prioritisation & scheduling, code development, quality assurance) of QCDOC for UKQCD's domain wall fermion programme. I believe this reflects my colleagues

confidence in my physics judgement, technical skills, fairness and determination to operate by consensus.
2005-2009 played role of spokesman for the US/Japan/UK RBC-UKQCD collaboration.
2006-2009 Managed IT provision for PPT research group .
2008-present Principal IT user for PPT within school IT management organisation.
2007 Academic liaison for upgrade of School of Physics and Astronomy undergraduate computing labs
2005-2009 Oversaw rolling grant post-doctoral researchers Dr. James Zanotti and Dr. Jan Wennekers.

Committees

2005-2008: School Computing Committee
2008-present: Computing Policy Oversight Group
2009: Computing Task Force: reviewing teaching of computing within School of Physics and Astronomy

Esteem factors

2004 Invited plenary talk, Lattice 2004, Fermilab
2004 Invited plenary talk, SciDAC all hands meeting, Brookhaven National Laboratory
2004 Gordon Bell prize finalist & talk at Supercomputing 2004
2007 Invited plenary talk, Lattice 2007, Regensburg
2008 Invited talk, Frontiers and Challenges for Lattice QCD, Trento 2008
2009 Invited plenary review, Kaon 2009, Tsukuba
2009 Invited Paper, Computer Physics Communications 40th Anniversary

National invitations and Invited lectures

1998 *Investigation of Systematic Effects in the Quenched Upsilon Spectrum* Ohio State University
1998 *Investigation of Systematic Effects in the Quenched Upsilon Spectrum* University of Kentucky
1998 *Current Renormalisation for Semi-leptonic $B \to D$ Decays* University of Wales, Swansea.
1999 *Renormalisation of NRQCD currents for semileptonic $B \to D$ decays to order $\alpha_s \frac{\vec{p}}{M}$* Neumann Institüt Fur Computing, Forschungzentrum Jülich, Germany
1998 *Assembly coding the Wilson delta term for Alpha processors*. University of Wuppertal, Germany
2000 *Non-perturbative B phenomenology from numerical QCD simulations* Royal Society Edinburgh
2003 *QCDOC operating system.* BlueGene Workshop, Brookhave National Laboratory, USA
2003 *Boosted Fermion fields*, UKQCD meeting. Liverpool
2004 QCDOC and BlueGene workshop, BNL (USA)
2004 *Performance of the QCDOC supercomputer,* National Nuclear Security Agency, Washington.
2004 USQCD SciDAC all hands meeting, BNL (USA)
2004 *Momentum Boosted Fermion Fields* Columbia University, NY, USA.
2005 QCDOC and BlueGene workshop, NeSC.
2005 *The QCDOC supercomputer,* University of Regensburg. Germany
2007 *2+1 flavour DWF simulations by RBC and UKQCD*, DESY-Zeuthen. Germany
2009 *The RBC-UKQCD physics programme*, KEK, Japan
2009 *UKQCD's software strategy*, KEK, Japan
2009 *BAGEL QCD package*, Tsukuba University, Japan
2009 *RBC-UKQCD's physics programme*, Tsukuba University, Japan

Refereeing

I have refereed papers for the Physical Review D (American Physical Society) and Computer Physics Communications journals (Elsevier).

Publications

SPIRES search link (h-factor = 18)

Reviews

1. **"Lattice Kaon Physics"** P.A. Boyle PoS **KAON09**, 002 (2009) *Plenary at KAON 2009, Tsukuba, Japan, June 2009*

2. **"2+1 flavour Domain Wall Fermion simulations by the RBC and UKQCD collaborations"**
   P. Boyle [RBC Collaboration and UKQCD Collaboration]
   PoS **LAT2007**, 005 (2007) [arXiv:0710.5880 [hep-lat]]
   Plenary at 25th International Symposium on Lattice Field Theory, Regensburg, Germany, 30 Jul - 4 Aug 2007

3. **An Overview of the QCDSP and QCDOC Computers**
   P.A. Boyle, D. Chen, N.H. Christ, M. Clark, S.D. Cohen, C. Cristian, Z. Dong, A. Gara, B. Joo, C. Jung, C. Kim, L. Levkova, X. Liao, G. Liu, R.D. Mawhinney, S. Ohta, K. Petrov, T. Wettig, A. Yamaguchi
   IBM Journal of Reasearch and Development, JRD42, 2004.

4. **"The QCDOC project"**
   P. Boyle *et al.*
   Nucl. Phys. Proc. Suppl. **140**, 169 (2005)
   Plenary at 22nd International Symposium on Lattice Field Theory (Lattice 2004), Batavia, Illinois, 21-26 Jun 2004

Articles

The articles [3-6] below are my most important recent publications. I have some TOPCITE cited early papers [13,17,18], and recently [3,4], while another two recent papers are becoming well cited [5,6].
I was the lead author of articles [6,7,13] below and review [5] above, and played one of several leading roles in many others [3,4,5,9].
I was sole author of articles [1,15] below and review [1] above.
I was both lead and sole author of many conference proceedings.

1. P.A. Boyle "The BAGEL assembler generation library", Computer Physics Communications (2009) j.cpc.2009.08.010

2. C. Kelly, P. A. Boyle and C. T. Sachrajda, "Continuum results for light hadrons from 2+1 flavor DWF ensembles," PoS **LAT2009** (2009) 087 [arXiv:0911.1309 [hep-lat]].

3. ⋆C. Allton *et al.* [RBC-UKQCD Collaboration], "Physical Results from 2+1 Flavor Domain Wall QCD and SU(2) Chiral Perturbation Theory," Phys. Rev. D **78** (2008) 114509 [arXiv:0804.0473 [hep-lat]].

4. ⋆C. Allton *et al.* [RBC and UKQCD Collaborations], "2+1 flavor domain wall QCD on a $(2\mathrm{fm})^3$ lattice: light meson spectroscopy with Ls = 16," Phys. Rev. D **76** (2007) 014504 [arXiv:hep-lat/0701013].

5. ⋆P. A. Boyle *et al.*, "Kl3 semileptonic form factor from 2+1 flavour lattice QCD," Phys. Rev. Lett. **100** (2008) 141601 [arXiv:0710.5136 [hep-lat]].

6. ⋆D. J. Antonio *et al.* [RBC Collaboration and UKQCD Collaboration], "Neutral kaon mixing from 2+1 flavor domain wall QCD," Phys. Rev. Lett. **100** (2008) 032001 [arXiv:hep-ph/0702042].

7. D. J. Antonio *et al.* [RBC Collaboration and UKQCD Collaboration], "Localization and chiral symmetry in 3 flavor domain wall QCD," Phys. Rev. D **77** (2008) 014509 [arXiv:0705.2340 [hep-lat]].

8. P. A. Boyle *et al.*, "The pion's electromagnetic form factor at small momentum transfer in full lattice QCD," JHEP **0807** (2008) 112 [arXiv:0804.3971 [hep-lat]].

9. Y. Aoki *et al.*, "Non-perturbative renormalization of quark bilinear operators and B_K using domain wall fermions," Phys. Rev. D **78** (2008) 054510 [arXiv:0712.1061 [hep-lat]].

10. P. A. Boyle, J. M. Flynn, A. Juttner, C. T. Sachrajda and J. M. Zanotti, "Hadronic form factors in lattice QCD at small and vanishing momentum transfer," JHEP **0705** (2007) 016 [arXiv:hep-lat/0703005].

11. D. J. Antonio *et al.* [RBC and UKQCD Collaborations], "First results from 2+1-flavor domain wall QCD: Mass spectrum, topology change and chiral symmetry with L(s) = 8," Phys. Rev. D **75** (2007) 114501 [arXiv:hep-lat/0612005].

12. P. A. Boyle, M. A. Donnellan, J. M. Flynn, A. Juttner, J. Noaki, C. T. Sachrajda and R. J. Tweedie [UKQCD Collaboration], "A Lattice Computation of the First Moment of the Kaon's Distribution Amplitude," Phys. Lett. B **641** (2006) 67 [arXiv:hep-lat/0607018].

13. P. Boyle and C. Davies [UKQCD Collaboration], "One loop renormalization of lattice NRQCD currents for semileptonic B –¿ D(*) decays to order p/M," Phys. Rev. D **62** (2000) 074507 [arXiv:hep-lat/0003026].

14. K. C. Bowler *et al.* [UKQCD Collaboration], "Quenched QCD with O(a) improvement. I: The spectrum of light hadrons," Phys. Rev. D **62** (2000) 054506 [arXiv:hep-lat/9910022].

15. P. Boyle [UKQCD Collaboration], "A novel gauge invariant multi-state smearing technique," J. Comput. Phys. **179** (2002) 349 [arXiv:hep-lat/9903033].

16. H. P. Shanahan, P. Boyle, C. T. H. Davies and H. Newton [UKQCD Collaboration], "A Nonperturbative calculation of the mass of the B_c," Phys. Lett. B **453** (1999) 289 [arXiv:hep-lat/9902025].

17. G. S. Bali and P. Boyle, "A lattice potential investigation of quark mass and volume dependence of the Upsilon spectrum," Phys. Rev. D **59** (1999) 114504 [arXiv:hep-lat/9809180].

18. P. Lacock, C. Michael, P. Boyle and P. Rowland [UKQCD Collaboration], "Hybrid mesons from quenched QCD," Phys. Lett. B **401** (1997) 308 [arXiv:hep-lat/9611011].

19. P. Lacock, C. Michael, P. Boyle and P. Rowland [UKQCD Collaboration], "Orbitally excited and hybrid mesons from the lattice," Phys. Rev. D **54** (1996) 6997 [arXiv:hep-lat/9605025].

20. J. M. Flynn *et al.*, "Kl3 and pion form factors using partially twisted boundary conditions," arXiv:0812.4265 [hep-lat].

21. P. A. Boyle, D. Brommel, M. A. Donnellan, J. M. Flynn, A. Juttner and C. T. Sachrajda [RBC Collaboration and UKQCD Collaboration], "Parton Distribution Amplitudes and Non-Perturbative Renormalisation," arXiv:0810.1669 [hep-lat].

22. P. A. Boyle *et al.*, "K(l3) form factor with N(f) = 2+1 dynamical domain wall fermions," J. Phys. Conf. Ser. **110** (2008) 102012.

23. M. A. Donnellan *et al.*, "Lattice Results for Vector Meson Couplings and Parton Distribution Amplitudes," PoS **LAT2007** (2007) 369 [arXiv:0710.0869 [hep-lat]].

24. D. J. Antonio *et al.*, "K(l3) form factor with N(f) = 2+1 dynamical domain wall fermions: A progress report," arXiv:hep-lat/0702026.

25. C. Albertus *et al.* [RBC and UKQCD Collaborations], "B - $\bar{B}$ mixing with domain wall fermions in the static approximation," PoS **LAT2007** (2007) 376.

26. P. A. Boyle *et al.*, "K(l3) form factor with N(f) = 2+1 dynamical domain wall fermions," PoS **LAT2007** (2007) 380.

27. D. J. Antonio *et al.* [UKQCD and RBC Collaborations], "K to pi semileptonic form factor with 2+1 flavor domain wall fermions on the lattice," PoS **KAON** (2008) 010.

28. P. A. Boyle, M. A. Donnellan, J. M. Flynn, A. Juttner, J. Noaki, C. T. Sachrajda and R. J. Tweedie, "The first moment of the kaon distribution amplitude from N(f) = 2+1 domain wall fermions," PoS **LAT2006** (2006) 111 [arXiv:hep-lat/0610025].

29. D. J. Antonio *et al.*, "K –¿ pi l nu form factor with N(f) = 2+1 dynamical domain wall fermions," PoS **LAT2006** (2006) 101 [arXiv:hep-lat/0610080].

30. C. Allton *et al.* [UKQCD Collaboration], "Light meson masses and non-perturbative renormalisation in 2+1 flavour domain wall QCD," PoS **LAT2006** (2006) 096 [arXiv:hep-lat/0610119].

31. D. J. Antonio *et al.* [UKQCD Collaboration], "Light meson masses and decay constants in 2+1 flavour domain wall QCD," PoS **LAT2005** (2006) 080 [arXiv:hep-lat/0512009].

32. D. J. Antonio *et al.* [RBC and UKQCD Collaborations], "Baryons in 2+1 flavour domain wall QCD," PoS **LAT2005** (2006) 098 [arXiv:hep-lat/0511011].

33. P. Boyle *et al.*, "The QCDOC project," Nucl. Phys. Proc. Suppl. **140** (2005) 169.

34. P. A. Boyle *et al.*, "QCDOC: Project Status And First Results," J. Phys. Conf. Ser. **16** (2005) 129.

35. P. A. Boyle *et al.*, "The status of user software on QCDOC," Nucl. Phys. Proc. Suppl. **140** (2005) 829.

36. P. A. Boyle *et al.*, "Hardware and software status of QCDOC," Nucl. Phys. Proc. Suppl. **129** (2004) 838 [arXiv:hep-lat/0309096].

37. P. A. Boyle, "Four-momentum boosted fermion fields," Nucl. Phys. Proc. Suppl. **129** (2004) 358 [arXiv:hep-lat/0309100].

38. P. A. Boyle, C. Jung and T. Wettig [QCDOC collaboration], "The QCDOC supercomputer: Hardware, software, and performance," eConf **C0303241** (2003) THIT003 [eConf **C0303241** (2003 ECONF,C0303241,THIT001.2003) THIT002] [arXiv:hep-lat/0306023].

39. G. S. Bali and P. Boyle, "Perturbative Wilson loops with massive sea quarks on the lattice," arXiv:hep-lat/0210033.

40. P. A. Boyle *et al.*, "Status of and performance estimates for QCDOC," Nucl. Phys. Proc. Suppl. **119** (2003) 1041 [arXiv:hep-lat/0210034].

41. G. S. Bali, P. Boyle and C. T. H. Davies, "Where do perturbative and non-perturbative QCD meet?," Nucl. Phys. Proc. Suppl. **106** (2002) 796 [arXiv:hep-lat/0110105].

42. P. Boyle and G. S. Bali, "The static potential to O(alpha**2) in lattice perturbation theory," Nucl. Phys. Proc. Suppl. **106** (2002) 811 [arXiv:hep-lat/0110118].

43. P. A. Boyle *et al.*, "Status of the QCDOC project," Nucl. Phys. Proc. Suppl. **106** (2002) 177 [arXiv:hep-lat/0110124].

44. L. Marcantonio, P. Boyle, C. T. H. Davies, J. Hein and J. Shigemitsu [UKQCD Collaboration], "The unquenched Upsilon spectrum," Nucl. Phys. Proc. Suppl. **94** (2001) 363 [arXiv:hep-lat/0011053].

45. J. Hein, P. Boyle, C. T. H. Davies, J. Shigemitsu and J. H. Sloan [UKQCD Collaboration], "Semi-leptonic decays heavy-light to heavy-light," Nucl. Phys. Proc. Suppl. **83** (2000) 298 [arXiv:hep-lat/9908058].

46. P. Boyle [UKQCD Collaboration], "The heavy quarkonium spectrum from quenched lattice QCD," arXiv:hep-lat/9903017.

47. P. Boyle and C. Davies [UKQCD collaboration], "Current renormalisation in NRQCD for semi-leptonic B –¿ D decays," Nucl. Phys. Proc. Suppl. **73** (1999) 378 [arXiv:hep-lat/9809044].

48. P. Lacock, C. Michael, P. Boyle and P. Rowland [UKQCD Collaboration], "Hybrid and orbitally excited mesons in quenched QCD," Nucl. Phys. Proc. Suppl. **63** (1998) 203 [arXiv:hep-lat/9708013].

49. P. Boyle [UKQCD Collaboration], "Heavy meson spectroscopy at beta = 6.0," Nucl. Phys. Proc. Suppl. **63** (1998) 314 [arXiv:hep-lat/9710036].