PAULO BEDAQUE
Associate Professor of Physics

Education:

B.Sc.	Universidade de Sao Paulo, Brazil, 1989
M.S.	Universidade de Sao Paulo, Brazil, 1985
Ph.D.	University of Rochester, Rochester, 1994

Experience in Higher Education:

1994-1996	Massachusetts Institute of Technology	Research Associate
1996-1999	Inst. for Nuclear Theory, U. of Washington	Research Associate
1999-2001	Inst. for Nuclear Theory, U. of Washington	Res. Asst. Professor
2001-2006	Lawrence Berkeley Laboratory	Divisional Fellow
2006	Lawrence Berkeley Laboratory	Senior Scientist
2006-2007	University of Maryland	Assistant Professor
2007-present	University of Maryland	Associate Professor

Synergistic Activities:

Co-organizer of INT Workshop on Effective Field Theory and Nuclear Physics, Seattle, 1999
Co-convenor of Few-Body Systems Workgroup of "Chiral Dynamics 2003", Bonn, Germany, 2003
Organizer of “Berkeley Effective Summer”, Berkeley, 2003
Organizer of “Berkeley Summer of Lattice”, Berkeley, 2004
Co-Organizer of the “2005 National Nuclear Physics Summer School”, Berkeley, June 2005
Co-Organizer of the ECT* “Effective Theories in Nuclear Physics and Lattice QCD”, Trento, Italy, July 2005
Advisory Board, “VIII Latin American Symposium on Nuclear Physics and Applications”, Chile, 2009
Editorial Board, PMC Physics A
Steering Committee, National Nuclear Physics Summer School, 2009-present
Co-convener of Few-Body working group, “Chiral Dynamics 2009”, Bern
Advisory Board, “IX Latin American Symposium on Nuclear Physics and Applications”, Ecuador, 2011

Recent Research

A. *Variation of Fundamental Constant and BBN*

Many speculations on the Physics beyond the Standard Model energies suggest that Standard Model parameters actually vary over cosmological time scales. For instance, in theories including extra dimensions the value of the standard model parameters are related to the sizes and geometry of the compactified dimensions. As the Universe expands and the usual 4 dimensions increase in size by many orders of magnitude it is reasonable to expect that the internal dimensions vary too, causing the value of fundamental "constants" to change. One way to test this possibility and constrain models is to look at the phenomenological consequences such a variation of fundamental constants would have in cosmology. The aspects of cosmology where this effect is more easily examined are those where i) the physics is well understood and ii) occurred as early as possible in the history of the Universe. Big Bang Nucleosynthesis (BBN) is a natural candidate. BBN is well understood, involves physics at the nuclear scale only and occurred when the Universe was just a minute old.

In collaboration with Thomas Luu (Livermore) and Lucas Platter (Gothemburg) we considered the effect of a variation on the value of the light (up and down) quark masses on the primordial abundances of deuterium and ^{4}He. We found the the BBN inputs whose change is more important to the abundances are the neutron decay rate, the proton-neutron mass difference and the binding energies of the deuteron and ^{4}He. We used a combination of a variety of effective field theories (chiral perturbation theory, pionless nuclear effective theory, chiral nuclear effective theory) and lattice results in order to bound the effect of the quark mass change on those quantities. We fed then these changes into a standard BBN code and calculated how the abundances changed. Judicious care was taken by propagating the uncertainties in the effective theory/lattice estimates through a Monte Carlo procedure on the BBN code. The final result we found was that quark mass changes larger than about 1% change the ^{4}He abundance by more than the observational error and are therefore ruled out. This result is valid regardless of the photon-to-baryon-number-ratio η assumed, as long as η satisfies the WMAP bounds. On the other hand, any change of quark masses of the order of a few percent can be cancelled by a change on the assumed value of η within the WMAP bounds and the deuterium abundance, therefore, puts no constraint on the quark mass variation.

The value of the quark masses in the Standard Model is given by the product of the Higgs expectation value v and a Yukawa coupling. It may seem unlikely that all the Yukawa change by the same amount by having the Yukawa couplings of different flavors change in tandem. A more likely scenario would be that v itself changes over cosmological scales, dragging all quark masses together. In this scenario other quantities of relevance to BBN, besides the up and down quark masses, would also change. The most important ones are the value of the Fermi constant G_F which impacts the neutron lifetime, the electron mass and the strange quark mass. We are currently adding the change in these parameters in order to constrain the variation of v during the BBN epoch.

[1] P. F. Bedaque, T. Luu, L. Platter, Phys. Rev. C **83**, 045803 (2011) [arXiv:1012.3840 [nucl-th]]

(P. Bedaque, T. Luu (Livermore), L. Platter (Chalmers Inst. of Tech.))

B. Vortons

One of the main possibilities for the state of hadronic matter at the high densities present in the core of neutron stars is the formation of quark matter. If that is the case, color superconductivity is almost certain to occur. At asymptotically high densities the pattern of Cooper pairing is the one of the color-flavor-locked (CFL) phase. The low-lying excitations in the CFL phase form an octet of pseudoscalars named, in analogy to the zero density case, pions, kaons and etas. At lower, more realistic densities, the effect of the non-negligible strange quark mass is to act as a chemical potential for the kaons. At most relevant values of the parameters, this effective chemical potential leads to the condensation of K^0, a phase suggested by Prof. Bedaque in the past and known as "$CFL + K0$". It was observed by Kaplan and Reddy that this phase supports a topological soliton akin to Witten's superconducting cosmic strings, extensively researched in grand unified theories as a possible seed for galaxy formation. These strings arise when the condensation of two different scalars compete energetically. Inside of the vortex, the absence of one condensate triggers the condensation of the second one. In our case the two condensates are the K^0 (outside the vortex) and K^+ (inside the vortex). As the K^+ is a charged field, its condensation makes the inside of the vortex to be superconducting. This has a a side effect to stabilize *closed* vortex lines, a configuration known as a vorton. We made a more detailed, realistic study of the existence of vortons in the CFL-K0 phase, specially inside neutron stars. It was the first time when an attempt was made to quantify its size, charge, etc. In order to do that we had to clarify and correct several points in the literature. The most important refers to a point where CFL-K0 vortons differ from superconducting cosmic string loops: the electromagnetic fields are not shielded inside neutron stars but are in the high temperature environment of the Early Universe. The bottom line of this study was that vortons will stabilize if and only if there a significant amount of electric charge in their cores, in addition to the current they have to carry. Their radii would be in the several hundred fermi range. This study was done in collaboration with Aleksey Cherman (DAMPTP, Cambridge) and Evan Berkowitz.

The charge the vortons have to charge is cancelled by electrons (positrons). These electrons will be attracted to the vorton and will orbit them, just like electrons orbit nuclei under more normal conditions. In fact, the only difference between these and atoms is the shape of the "nucleus", toroidal in our case. If the vorton is large enough and the electron orbits small enough, they will effectively neutralize the vorton charge, leading to their instability (the Coulomb repulsion between opposite sides of the vorton is the dominant stabilizing force in the vorton, notwithstanding inaccurate claims in the literature). It is important then to estimate the size of the electron cloud around a vorton. We are currently studying, with the help of two high school students, Geoffrey Ji and Nathan Ng, the "atomic" structure of "vortonium" (that is, a vorton plus its electron cloud). Since this is a many-electron system we are using the Thomas-Fermi approximation.

[1] P. Bedaque, E. Berkowitz, A. Cherman, DOE/ER/40762-494, to appear in Phys. Rev. C (July 2011) [arXiv:1102.4795 nucl-th]]

(P. Bedaque, A. Cherman (DAMPT, Cambridge), E. Berkowitz, Geoffrey Ji, Nathan Ng (Montgomery Blair High School))

C. *Deuterium and Helium Condensates*

It was recently pointed out by Gabadadze and collaborators that light elements (deuterium and ${}^4He$), when compressed so that the typical distance between atoms (l) is in between atomic and scalar densities, and for a wide range of temperatures, lead to Bose-Einstein condensation. At these densities, atoms are crushed and we have nuclei immersed in a sea of electrons. For temperatures below $T_{cryst} \sim 180\alpha/l$ the energy of nuclei is dominated by the Coulomb energy and they will form a crystal. Above this temperature but below $T_{Bose} \sim 1/(Ml^2)$ the nuclei will Bose condense. That means that for light bosonic nuclei there is a range of temperatures where this nuclear condensate is possible. Matter in this phase may occur in low mass brown dwarfs, failed stars not massive enough to burn helium or even deuterium. More importantly, it may be realized in experiments on Earth, either through the use of diamond anvils or through inertial confinement experiments. Even though the pressures obtained in these experiments are currently a factor of 10-100 below the estimated interesting range, it seems worthwhile to investigate this kind of matter theoretically given the large effort put into the inertial confinement program. From the purely theoretical point of view this system presents us with a rich variety of interesting phenomena, largely unexplored at this point, including a number of unusual solitons (semi-local monopoles, Alice strings, ...) known to exist in abstract models but not realized in Nature.

The first step in our study of this system was the determination of the symmetry breaking pattern caused by the condensation. We pointed out that whether the system is in the ferromagnetic or nematic phase hinges on the value of the deuteron-deuteron s-wave scattering lengths in the spin 0 and 2 channels. This is a tiny effect, however, exponentially suppressed by Coulomb effects. Discarding this tiny difference in energy between these two phases, for all practical purposes, the rotation symmetry is enhanced from $SO(3)$ to $SU(3)$ and there is no distinction between ferromagnetic and nematic phases. We were able to establish a power counting scheme that organized the calculation of any observable in powers of l/a_0 (a_0 is the Bohr radius). We are using this formalism to understand the spectrum of quasiparticles and other properties of the system. Of particular interest is the potential between two charges (either impurities or the deuteron themselves). The reason is that the Bose condensate is particularly effective in shielding the Coulomb force. Physically, this is due to the fact that it cost very little energy for charged bosons (as opposed to charged fermions) to pile up in a region around the charge. In fact, a tree level calculation gives a Debye screening distance that vanishes for infinitely heavy deuteron. We are now calculating the smaller (by powers of α) but longer range force that survives the screening in order to assess the enhancement of nuclear fusion rates in high density deuterium.

[1] P. Bedaque, M. Buchoff and A. Cherman, JHEP 1104 (2011) 094 [arXiv:1007.1972 [hep-ph]]

(P. Bedaque, M. Buchoff (Lawrence Livermore), A. Cherman (DAMPT, Cambridge))

D. Noise in Lattice QCD Extraction of Nuclear Forces

The understanding of nuclear forces directly from QCD is one of the Holy Grails of Nuclear Physics. Recently some attempts in computing scattering observables from lattice QCD renewed the hopes of achieving that goal. The main difficult found in these studies is the exponential growth of the noise-to-signal ratio at large Euclidean times t. At large t it can be shown that the growth rate of the noise-to-signal ratio is given by $2M - 3E_\pi$, where M is the nucleon mass and E_π is the minimum energy a pion can have in the lattice. For usual periodic boundary conditions E_π is just the pion mass m_π. Three years ago, in collaboration with A. Walker-Loud [1], we devised a method to increase E_π while leaving M fixed. It consisted of considering lattice QCD in a "parity orbifold", namely, in a lattice double the size but identifying the field in the extra part of the lattice with the parity flipped fields in the original part of the lattice. This construction amounts to having the original lattice with extra terms at the boundary between the lattice and its parity double. This construction enforces anti-periodic boundary conditions for the pion, eliminating its zero-mode, while leaving the nucleon fields unaffected. The numerical implementation suffered from technical problems and only recently, in collaboration with Andrei Alexandru, that the algorithm was implemented. We are now performing an exploratory quenched calculation of the one- and two-nucleon correlators. In the case of the usual periodic boundary conditions we can identify the region with exponential growth of the noise-to-signal ratio (as well as a region where the error is dominated by coupling to $\bar{N}N$ states at smaller t). A similar calculation with the parity orbifold action should then give us the evidence that the noise is indeed reduced. If this idea proves useful we plan to collect the resources needed for a serious dynamical calculation of nuclear forces.

[1] P. Bedaque and A. Walker-Loud, Phys.Lett. B660 (2008) 369-375.

(P. Bedaque, A. Alexandru (George Washington Univ.))