Plans for Nuclear and Particle Physics at Bonner Lab

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Introduction

The High Energy and Nuclear Physics groups work closely together on a wide range of experiments. This cooperation strengthens both groups and brings different viewpoints to the various projects. Believing that experimental physicists should be trained to design and construct instruments, we often take on hardware construction projects. We construct our apparatus in the Bonner Lab and ship it to accelerator laboratories where the experiments are performed in collaboration with other physicists from around the U. S. and the world. The BL groups are currently working on experiments at Fermilab (near Chicago), Brookhaven (on Long Island), CERN (Geneva, Switzerland), and CEBAF at Jefferson Lab (Newport News, Virginia). Data analysis is done mostly in BL using our networked workstations. Information about BL history, roster, recent progress reports to the DOE and more is available at http://www.bonner.rice.edu/bonner.

Future Directions in Nuclear Physics at BL

Although prosaically yclept, the Standard Model provides an astonishingly good description of the fundamental particles and their interactions. The electro-weak sector is beautifully and precisely calculable from photon exchange in Quantum Electrodynamics (QED) with the addition of the gauge bosons (W and Z) to mediate the weak interaction. The strong interaction sector – the force between quarks that is mediated by gluon exchange – is described remarkably well at high energies (short distances) by Quantum Chromodynamics (QCD). However, the energy range that is relevant to Nuclear Physics is much lower; the experiments are simpler, but QCD, unfortunately, cannot be calculated perturbatively, meaning it has almost no predictive capability. Some of the important fundamental issues in non-perturbative QCD remain mysterious, such as the mechanism of confinement, the connection between QCD and the strong force that binds the protons and neutrons in nuclei, and the role of strangeness in hadronic matter. QCD also predicts the existence of new types of matter and states of matter that remain undetected despite prodigious effort. These are some of the intriguing new emphases in the study of hadronic interactions – a field that has been the major area of investigation at Bonner Lab for most of its existence. Below we expand on a few topics that will occupy the Bonner Lab Nuclear Group for several years.

Search for new states of matter — the Quark Gluon Plasma

An inescapable prediction of QCD is the existence of a new **state** of matter at sufficiently high energy densities, the Quark Gluon Plasma (QGP). In the QGP the quarks are deconfined and in thermal equilibrium with the gluons. This state of matter last existed in our universe some 13 billion years ago – more precisely, about ten millionths of a second after the Big Bang – although it may still lurk in the cores of very dense stars. While very interesting, accessibility is problematic. We will attempt to create this novel state of matter in the laboratory by colliding very high-energy Gold nuclei and observing the space-time evolution of the collision. The only places to do these experiments will be at two accelerators presently being constructed: the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN.

Bonner Lab has been a major player in the design and construction of the Solenoidal Tracker at RHIC (STAR) since its inception in 1989. When this detector comes on line in 1999, we will use it to search for not only the QGP, but for myriad other exotic effects that almost certainly will become accessible in this unexplored region of ultrahigh energy density.

Late in the next decade, much higher energies (a factor of 25) will become available at the LHC. The BL High Energy Group is involved in the CMS detector design and construction (see below). This detector is ideally suited to detect predicted QGP signatures, such as color screening of some of the $c\bar{c}(J/y)$ and $b\bar{b}(\Upsilon)$ resonances and the quenching of jets in the dense plasma. We expect to be homesteaders in this most exciting future at the energy density frontier.

The spin structure of a nucleon — Where's the Spin?

Nobody doubts that the spin of a proton is 1/2. QCD says the proton is a mix of three spin-1/2 valence quarks (*uud*) and the usual field-theory-dictated sea of quark-antiquark pairs ($q\bar{q}$) – all bound together by the exchange of spin-one gluons. Hence, the proton spin is the result of the sum of the spin of the quarks, the gluons, and residual orbital angular momentum according to the following obvious relation.

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Naively, one expects the gluon spins to sum to zero, the orbital angular momentum to be zero and the sea quarks to all pair off to zero so that the entire proton spin is due to the three valence quarks. In a previous experiment that we did at CERN, dubbed the Spin Muon Collaboration, we showed that the spin carried by the quarks, $\Delta\Sigma$, is not unity, but instead is only 1/4. This surprising result is widely known as the "spin crisis." Hence the search is on for the missing spin.

The place where both $\Delta\Sigma$ and ΔG can be measured precisely is at the soon-to-be-completed RHIC. The detector that will be able to do the measurement is the one we are building, the STAR detector. The measurement is made possible because RHIC can accelerate not just heavy ions, but polarized protons as well. BL people have played key roles in defining the physics program accessible with polarized protons colliding at 250 GeV per beam, as well as much of the instrumentation essential for realizing that program. The potential here for discovery of something beyond what can be explained in QCD is as great as it gets.

New types of matter: Exotic Mesons and Baryons

All matter that we know of consists of rigidly defined combinations of fundamental particles. Baryons such as the proton and neutron are known to be combinations of three quarks (qqq). The hundreds of known mesons are combinations of $q\bar{q}$'s in all their whimsically yclept flavors (up, down, strange, charm, and bottom – no bound tops, of course) and allowed spins and parities. The spectrum of states – the singlets, octets, nonets, etc. – resulting from this simple picture is both rich and definitive. Many multiplets have been mapped out and the coupling strengths to many final states are known. Nothing in QCD prohibits other combinations of quarks and gluons from being stable and there is a long history of searches for what are called exotic states, i.e., non–qqq or $-q\bar{q}$ states. Recently, convincing evidence for at least one such state has been published and independently confirmed. Low energy QCD allows a rich spectrum of hybrid mesons containing a constituent gluon. Furthermore, QCD predicts that states with only gluons (“glueballs”) should exist in the mass range around 1.5 to 2 GeV. Since glueballs and conventional states are likely to be strongly mixed by the hadronic interaction, we can untangle their relative strengths only by measuring a variety of production and decay amplitudes. This requires the sophisticated detectors and data acquisition systems that are just now becoming available.

The 2 GeV mass region for the baryons also has problems. All models of hadronic structure predict many more states than have been found experimentally. For example most models predict 45 Ξ states with a mass below 2.5 GeV and only 11 have been observed. If one adds in the possibility of hybrid baryons, i. e. baryons containing valence gluons ($qqq + g's$), a profusion of states should be found in this mass region.

The new CEBAF electron accelerator is the ideal facility to search for hybrid mesons and baryons. Numerous experiments have been proposed and Bonner Lab is actively involved.

Strangeness in Nuclei

Throughout the past sixty years nuclei have been studied by various means, usually by bombarding them with almost the entire zoo of particles from photons on up and deducing the response of the nucleus by close examination of what gets ejected from the collision site. A different take on the strong interaction in nuclei can be had by injecting a strange quark or two and measuring what that added degree of freedom brings. In addition, the best possible calculations predict the existence of strange matter, multiquark systems that are either stable or nearly so with respect to the strong interaction, such as the 6 – quark H_0 doubly strange dibaryon *(uuddss*). Also there is speculation that the Λ(1405) may be an unbound five – quark system. We are currently involved in experiments designed to answer both questions. One, at Brookhaven, is searching for H_0 production in heavy ion collisions and another, at CEBAF, examines the radiative decays of the Λ(1405). If the H_0 is discovered, it will naturally be the subject of intense investigation for many years to come. We would certainly capitalize upon our investment by continuing these studies with the STAR detector at RHIC and then with the CMS detector at the LHC.

• Future Directions in High Energy Physics at BL

The Standard Model (SM) of particle physics has been remarkably successful in explaining the current body of particle physics data, but it has a host of arbitrary parameters and leaves unanswered fundamental questions. We know that the SM is not complete, and future work in the field falls into two categories: precision tests of the SM and the search for physics beyond the SM. The two most important ``loose ends" in the SM are the origin of mass and the origin of CP violation. It is thought that the Higgs mechanism generates mass, and the direct observation of the Higgs particle is a crucial confirmation. CP violation can be accommodated in the SM, but it is not yet known if the CP violation we observe is consistent with an origin only in the SM.

There is a general consensus that new physics must enter at or before the TeV mass scale for the SM to be consistent. The leading candidate for physics beyond the Standard Model is Supersymmetry (SUSY), which postulates a fermion partner for every boson, and a boson partner for every fermion. The search for SUSY, or some other new physics, will be a major effort at the highest energy machines.

The Bonner Lab is involved in experiments that attack these questions on several fronts.

KTeV: CP Violation in the neutral Kaon System and Rare K Decays

CP violation was discovered more than 30 years ago, but its origins remain unclear. CP violation is important because it is one of three conditions necessary for the generation of the baryon asymmetry of the universe (the other two being a violation of baryon number conservation and departure from thermal equilibrium). To date CP violation has been seen only in the neutral Kaon system, and it can be accommodated in the SM with an appropriate choice of parameters. But it is also clear the CP violation we see in the Kaon system is too small to generate the baryon asymmetry of the universe. There is a deep puzzle here that is of fundamental importance to both particle physics and astrophysics.

The KTeV experiment at Fermilab is studying CP violation in the neutral Kaon system to unprecedented accuracy. An experiment currently running at CERN, NA48, is in direct competition. The results of KTeV and NA48 will severely constrain the CP-violating parameters in the SM. These measurements, coupled with the measurements about to be undertaken in the neutral B system will over-constrain the SM. Within the next 2-3 years we will know whether or not the

CP violation we observe has its origins in the SM. After 30 years we are on the verge of a major step forward in our understanding of CP violation.

KTeV is also carrying out a series of precision measurements of rare K decays. We have recently been the first to observe the decay $K_L \rightarrow p^+ p^- e^+ e^-$ and an associated asymmetry that is both CP and T violating. This is the first observation of a quantity that is directly T-violating.

The BL group made major contributions to the construction of the charged-particle spectrometer and has participated fully in the data acquisition and analysis.

D0 at Run II: Search for New Physics and Precision Tests of the SM

The Fermilab collider detectors, D0 and CDF, are in the final stages of major upgrades. A 5-year collider run is expected to start in 2000. This run, with much-improved detectors and a factor of 10 greater luminosity, has tremendous discovery potential. The Tevatron represents the energy frontier until the turn-on of the Large Hadron Collider in 2005.

Supersymmetry (SUSY) is the prime candidate (but not the only candidate) for physics beyond the SM. An all-out search will be made for any hint of supersymmetry, or some other physics beyond the SM, in the upcoming run. If SUSY exists, there is a real chance it will be found in Run II. The Rice group has contributed a key analysis technique that will be applied to this search.

Our current information indicates that the Higgs may be as light as 100GeV. If so, the Fermilab collider detectors have a chance to see it. An all-out search for the Higgs will be launched during Run II.

A key factor in advancing our knowledge of CP violation is information about the neutral B system. The B-factories at SLAC and in Japan will begin taking data in 1999. The Fermilab colliders are also a powerful tool for studying CP violation in the neutral B system. Information from the neutral Kaon system, and from both the hadron colliders and the e^+e^- colliders will be necessary to completely pin down the origin of CP violation.

In addition to the searches for new physics, D0 and CDF will pursue a wide range of precision tests of the SM, both in electroweak and strong interactions. These tests will include measurements of the top quark production and decay, precision measurements of the W mass, studies of jet cross sections, and dozens of others.

The upgraded D0 detector will have a state-of-the-art scintillating fiber tracker. The design of the Sci-fi tracker was based largely on simulations done at BL. The software that will form tracks from the individual counts is also largely being done at BL. The testing of the 80,000 channels of the solid-state readout devices (the Visible Light Photon Counters) relies on a data-acquisition system designed and built at BL.

Search for the Higgs and grand unification: CMS at CERN

The next generation facility will be the Large Hadron Collider. BL is participating in the construction of a new experiment, the CMS detector, which will operate at the LHC. A total of 1650 physicists at 149 institutions around the world are involved in the construction of this experiment. This will be the very best opportunity to answer some of the fundamental questions in particle physics.

The origin of mass in the standard model is the last open question in the unification of the electromagnetic and weak forces. It is thought that this will be resolved by the discovery of the Higgs boson, most likely at CMS. However, the standard model lacks aesthetic appeal in that it has 19 free parameters that must be measured experimentally and cannot be predicted from first principles. This is somewhat reminiscent of the role played by the periodic chart of the elements as tabulated in the nineteenth century. It did a fine job of categorizing and had some predictive power, but missed out completely on the underlying reason it works - the structure of outer electrons in the case of the periodic chart. The correct fundamental theory, quantum mechanics, was discovered in the early decades of the twentieth century and not only explained the periodic table, but all of chemistry and atomic and molecular physics. Evidence favoring a more fundamental theory of elementary particles – present candidates include supersymmetry and string theory – should be seen at the LHC. In that case we could be on our way to finding the Holy Grail of physics, the theory that unifies all the forces of nature including gravity – Einstein's dream of so many years ago.

BL has responsibility for the design and construction of several parts of the trigger electronics for the "end cap muon system," a project that is funded solely by the US and is being built by a collaboration of US university groups. We must design and build complex electronic circuits that push the state of the art in electronics and data transmission technology. We are also responsible for the development of the muon system trigger detectors, which must be both fast and cheap since the total area required is conveniently measured in acres. Scintillator is far too expensive for the purpose, so we have been working to develop a promising new technology called multi-gap resistive plate chambers. The tracking software we developed for D0 is being recycled and extended for use in the CMS.

• Future Directions in Theoretical Physics at BL

In the Standard Model all elementary particles acquire their masses indirectly, from their coupling to a scalar field Φ. The field Φ fluctuates, not about zero, but about a constant value **v**; particle masses are proportional to **v**. The Higgs boson, the physical manifestation of the Φ field, remains to be discovered. For theorists the task is to better understand the $\lambda\Phi^4$ theory that governs the dynamics of the Φ field. Our research here has led to a picture that reconciles non-trivial vacuum properties with the ‘triviality’ theorems proved by mathematical physicists. Our results are controversial because they imply that conventional perturbative ideas are misleading and that the Higgs mass is likely to be much larger than usually expected.

We have recently re-derived our results from a quite new perspective, based on a ‘particle’ rather than a ‘field’ viewpoint. This gives a very intuitive description of the physics. The constant field can be thought of as a spontaneously formed Bose-Einstein (BE) condensate of ‘phion’ particles. The Higgs particles are the ‘phonon’ excitations of this condensate. The underlying ‘phions’ are real particles with a tiny mass, but are not directly observable. Instead, one would observe the Higgs, which is a coherent state of ‘phions.’ The mass of the Higgs is much, much heavier than the mass of the phions. Our key observation is that the interaction potential between ‘phions’ is not just a short-range repulsion but also involves a long range $-1/r^3$ attraction caused by phions exchanging a virtual pair of phions (in the same way that the Coulomb potential between charged particles is due to exchange of a virtual photon). It follows that a dilute gas of phions with **n** particles per unit volume has an energy density consisting of **n**, $\mathbf{n}^2$ and $\mathbf{n}^2 \ln \mathbf{n}$ terms only. These terms reflect, respectively, the particles' individual rest-energies, short-range repulsion between particle pairs, and long-range attraction between pairs. The last term involves a ln **n** factor because the $-1/r^3$ interaction would give an infinitely negative (log-divergent) contribution were it not for a ‘screening’ mechanism that cuts off the interaction at some r(max) that depends on **n**, the background density of intervening particles. Provided the phion mass is sufficiently small, then the energy density is minimized when **n** has a *non-zero* value; that is, empty space is unstable to the spontaneous creation of phions which then form a BE condensate. This description of the Higgs physics is complementary to the quantum-field-theory approach and reproduces results we had previously obtained with the latter methods.

In the future we hope to look at many interesting ramifications of the ‘spontaneous BE condensate' picture of the Higgs mechanism. We will also study the $\lambda\Phi^4$ theory with other methods, including, through collaborators in Italy, lattice simulations. Our results suggest that the Φ field may be more fundamental than the other fields and has a deep connection with gravity. There are reasons to speculate that the Φ field drives 'inflation' in cosmological models of the early universe.

The majority of particle physicists expect that the Higgs boson will be discovered at the Large Hadron Collider (LHC), along with a rich spectrum of supersymmetric particles. If so, there will be lots of exciting work for theorists and phenomenologists to make sense of the data, extract the particle properties, and identify the underlying theory. Clearly, Bonner Lab would want to be involved in this excitement, both experimentally and theoretically. However, perhaps supersymmetry and the Higgs will not show up at LHC. Then deeper thinking will be needed and the data will conceal more subtle hints of how the Standard Model really works and what lies beyond it. The ideas outlined above may then come into their own.

• Summary

The topics discussed above are in the forefront of Nuclear and Particle Physics research primarily because they address crisply defined questions whose answers are crucial to further progress in these fields. We are aided in this quest by the construction of new accelerators CEBAF, RHIC, the main injector at FNAL, and LHC, as well as by technological advances that allow the construction of complex new detectors to track the large number of reaction products – up to several thousand in the heavy ion experiments. At BL we have amassed the technical expertise that enables us to take on significant detector development and construction projects. This has been demonstrated by the construction funds that we received for the SMC experiment ($0.5M), the STAR project ($1.5M), and our scheduled share of the US CMS project ($2M). More than the majority of the university groups in these collaborations, we are well positioned to make disproportionate contributions to such projects because of the close cooperation between our Nuclear and High Energy Groups.