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The Hall D Physics Program at JLab

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GlueX is one of the flagship experiments of the 12 GeV era at the Thomas Jefferson National Accelerator Facility (JLab). The energy of the electron accelerator at JLab is presently undergoing an upgrade from 6 GeV to 12 GeV and a 4th experimental hall (Hall D) is being added. The GlueX experimental apparatus consists of a tagged coherent bremsstrahlung photon beam incident on a liquid hydrogen target. The photoproduced mesons, which are created inside of a 2.2 T solenoid, will then pass through a pair of drift chambers and eventually deposit their energy into either of two calorimeters, depending on their respective angles. GlueX will attempt to map out the light meson spectrum and search for meson-gluon hybrids to better understand the confinement of quarks and gluons in quantum chromodynamics (QCD). There is little data on the photoproduction of light mesons and the GlueX experiment will exceed the current photoproduction data by several orders of magnitude in the first year alone. Photoproduction is specifically well suited to search for meson-gluon hybrids because in the flux tube model the production cross-sections are higher for meson-gluon hybrids from photons, with the spins of the virtual quark-antiquark pair aligned, than from other sources such as pions, with the spins of the quark-antiquark pair anti-aligned. There are also other Hall D experiments proposed to look for physics beyond the Standard Model by studying Eta rare or forbidden decay channels such as eta to two neutral pions. The 12 GeV upgrade of the JLab accelerator and the complete physics program of Hall D will be presented.

XXI International Baldin Seminar on High Energy Physics Problems
September 10-15, 2012
JINR, Dubna, Russia

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PoS(Baldin ISHEPP XXI)084

1. The 12 GeV Upgrade at JLab

The 12 GeV upgrade at Thomas Jefferson National Accelerator Facility will increase the energy of its 6 GeV continuous wave electron beam to 12 GeV to allow the expansion of nuclear physics research into poorly explored regions including the photoproduction of light mesons. The new energy of the electron beam will provide scientists with the tools necessary to probe strongly interacting systems including the confinement of quarks and gluons. All three original experimental halls at JLab are undergoing equipment upgrades as well, but the focus of this report will be on the newly constructed 4th experimental hall known as “Hall D”, the technologies utilized, and the planned physics program. The complete experimental program’s details are in Ref. [1].

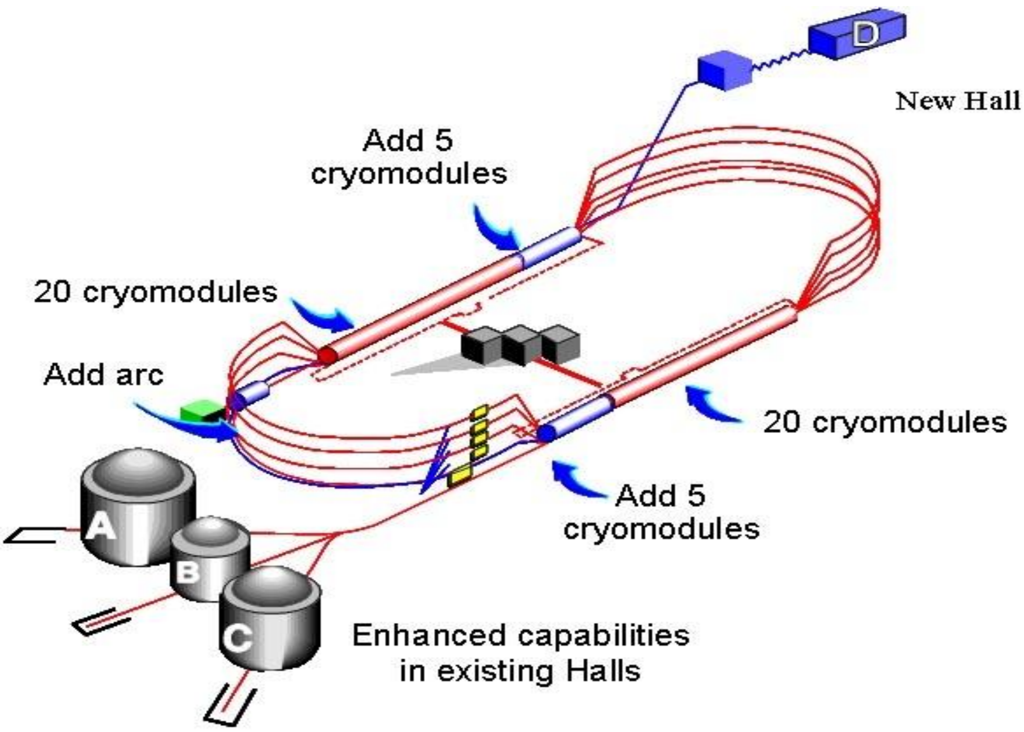

FIGURE 1. The JLab 12 GeV upgrade [1]

A schematic of the current accelerator with the major upgrades indicated is depicted in Figure 1. The present design involves three independent electron beams being recirculated through two superconducting linacs, one to five times, eventually being delivered simultaneously to the three existing experimental halls, “Hall A”, “Hall B”, and “Hall C”. The maximum total current is 280 μA with 89% polarization. The current maximum gain is 1.2 GeV/pass and with the addition of five new cryomodules to the existing twenty cryomodules in each linac, the maximum gain will be increased to 2.2 GeV/pass. Five of the new cryomodules are able to accomplish the same gain as twenty of the older design modules. Halls

A, B, and C will be able to receive a new maximum energy of 11 GeV. An additional recirculation magnetic arc is being added to allow the new Hall D to receive electrons recirculated 5.5 times with a maximum energy of 12 GeV. The 12 GeV electron beam will then be used to produce a linearly-polarized 9 GeV photon beam using the coherent bremsstrahlung technique.

2. Physics in Hall D

Mesons, described by QCD, can be grouped into nonets by their respective values of the vector sum of spin and angular momentum (*J*), parity (*P*), and charge conjugation (*C*), together represented as J^{PC}. Using the model of a quark antiquark pair to form a bound meson, certain J^{PC} are allowed while others are impossible to form. Combinations of the four lightest quarks (*up*, *down*, *strange*, *and charm*) are sufficient to explain nearly all light (< 3GeV/c^2) mesons and the J^{PC} measured in most experiments have been consistent with a single quark antiquark pair. Any J^{PC} that require additional degrees of freedom beyond that of a quark antiquark pair, such as 0^{--}, 0^{+-}, 1^{-+}, etc., are referred to as exotic.

QCD predicts not only quark antiquark bound states, but additional mesons involving excited gluons containing gluonic degrees of freedom, known as hybrid mesons [2]. These hybrid mesons can be thought of as a quark antiquark pair with a constituent gluon. The additional gluonic degrees of freedom produce not only allowed J^{PC}, but exotic J^{PC}. The definitive observation of a meson with exotic J^{PC} would be a definitive observation of a meson with more constituents than a quark antiquark pair.

2.1 The GlueX Experiment

The primary experiment taking place in Hall D is known as “GlueX” that seeks to understand the confinement of quarks and gluons in quantum chromodynamics (QCD). The hermetic GlueX detector, consisting of a solenoid and a sandwich of drift chambers and two calorimeters, is the subject of the next section. GlueX will utilize the coherent bremsstrahlung technique to take the 12 GeV electron beam incident on a diamond wafer and turn it into a 9 GeV photon beam. Hall D will exceed the current photoproduction data by several orders of magnitude by putting 10^7 tagged (uniquely identified in time and energy from their respective beam bunch) photons per second on the liquid hydrogen target.

Predictions of the lightest exotic hybrids from lattice QCD produce a mass of 1.3 GeV to 2 GeV and GlueX has a mass reach up to 2.8 GeV [2]. One of the current leading candidates for a hybrid meson is the $\pi_1(1600)$ with exotic J^{PC} values of 1^{-+} [3,4]. The $\pi_1(1600)$ has been observed in several different experiments and GlueX hopes to produce the state in larger numbers than any previous experiment. The production cross-section for hybrids is smaller than normal mesons, and to resolve the small quantities of hybrids among the large quantities of normal mesons a technique known as amplitude analysis will be used. Amplitude analysis takes the invariant mass spectrum of several states that are close in mass and fits their angular distribution in every individual mass bin. The fit determines the J^{PC} of each of the states which is necessary to see if a state has exotic J^{PC} quantum numbers.

The incident photon can be thought of as a virtual quark antiquark pair with their spins aligned while a pion would have the spin of the quark antiquark pair antialigned. In the Flux Tube Model hybrid mesons with exotic J^{PC} can be produced using a photon beam while production via a pion beam would require a spin flip of one of the quarks to reach exotic J^{PC} values [5]. The linearly polarized photons produced will provide an excellent opportunity to search for exotic hybrid mesons because linearly polarized photons are able to probe spin observables. Linearly polarized photons create an angular distribution of products proportional to the angle between the production plane and the polarization vector while circularly or unpolarized photons would not.

2.2 η Rare Decay Proposal

The η is the most massive member of the pseudoscalar meson octet with a mass of 547.9 MeV and an extremely narrow width of only 1.3 KeV. All lower order strong and electromagnetic decays are either forbidden or strongly suppressed with the leading order contributions coming from $O(p^6)$. This suppression allows for the testing of chiral perturbation theory at $O(p^6)$ and provides the ability to look for charge (C), parity (P), and CP violation in a variety of decay channels. The primary channels studied will be $\pi^o 2\gamma$ (chiral perturbation theory at $O(p^6)$), $2\pi^o$(CP,Parity), 3γ(Charge), and $\pi^o\gamma$(Charge). In Hall D the η production mechanism will be $\gamma P \rightarrow \eta$ and with $4\text{x}10^7$ γs per second, there will be $3\text{x}10^5$ boosted ηs produced in a day. In order to achieve the primary physics goals, the forward electromagnetic calorimeter will need to be upgraded from 4x4 cm^2 lead glass blocks to 2x2 cm^2 lead tungstate blocks. This upgrade will increase both the energy resolution and the spatial resolution of the calorimeter both for the η rare decay program and for all future experiments.

3. The GlueX Detector in Hall D

The complete GlueX apparatus is shown in Figure 2. The GlueX detector starts with a 2.2 T solenoid surrounding a barrel calorimeter. Inside the barrel calorimeter lays a central straw tube chamber and a forward drift chamber surrounding a start counter scintillator and a liquid hydrogen target. All forward moving particles with a scattering angle of less than 10^o will hit a time of flight scintillator array and a lead glass calorimeter.

Each detector will provide a different piece of information. The drift chambers will provide the trajectories of the charged particles while the calorimeters measure the energy of primarily neutral particles. The solenoid will cause charged particles to deflect and, with analysis, the deflection as measured by the drift chambers will provide the momentum of the bending particle. All of the detector's measurements will then be used together to extract the J^{PC} of the created mesons. The following sections contain descriptions of the technologies used in each of the detectors.

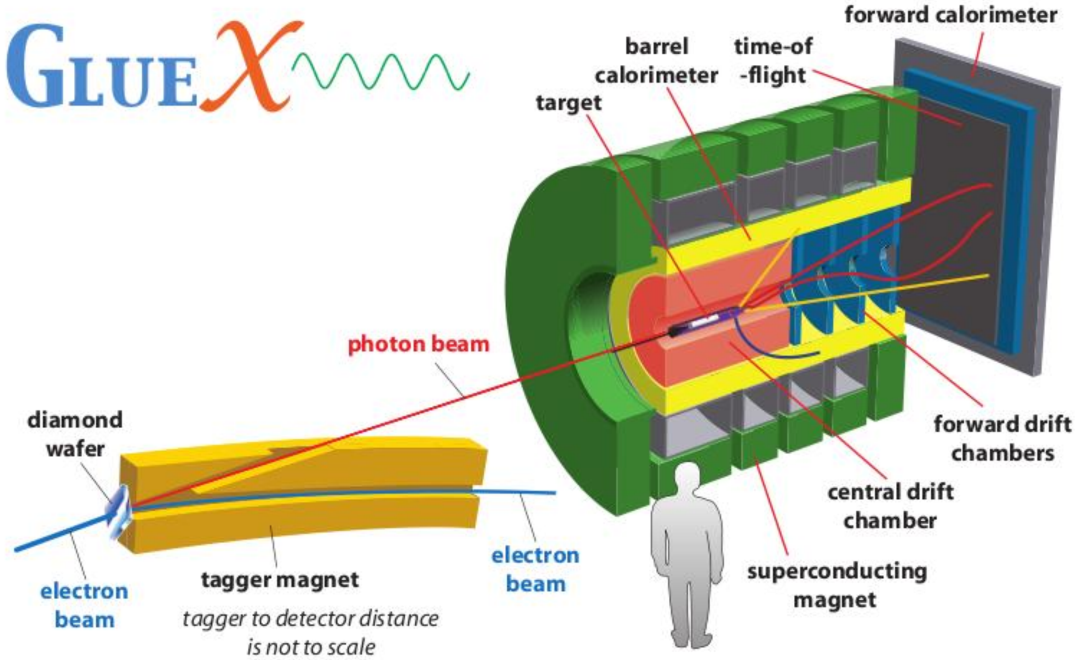

FIGURE 2. The GlueX Experiment in Hall D at JLab with each of the detector subsystems labeled.

3.1The GlueX Central Drift Chamber and Forward Drift Chamber

The Central Drift Chamber (CDC) is a large cylinder surrounding the target and the start counter with an inner radius of 20 cm and an outer radius of 120 cm. There are 3500 1.5 m long straw tubes inside the CDC [6]. The straws are oriented in two directions: axial (12) and stereo (16), in order to provide better spatial resolution in the z or longitudinal coordinate. The expected position resolution of the CDC is 150 μm.

The Forward Drift Chamber (FDC) consists of four identical packages of cathode strip chambers. The packages consist of groups of cathode strip planes oriented +- 75^o with respect to the wires and each group is the rotated by 60^o with respect to each other. The expected position resolution of the FDC is 200 μm.

3.2 The GlueX Forward Calorimeter

The Forward Calorimeter (FCAL) consists of 2800 4 cm x 4 cm x 45 cm lead glass blocks located downstream of the center of the liquid hydrogen target and is shown in Figure 2. The glass used is type F8-00 glass composed of 45% PbO, 42.8% SiO_2, 10.4% K_2O, and 1.8% Na_2O with a density of 3.6 g/cm^3, a radiation length of 3.1 cm, and an index of refraction of 1.62. The lead glass blocks are optically separated from each other using aluminized Mylar foil and will be read out using a FEU 84-3 photomultiplier tube (PMT). Each PMT will be powered by a custom Cockcroft-Walton base [7]. The Cockcroft-Walton base takes a supply voltage of only

24 V and locally generates HV up to 2000 V using an inductive boost circuit and a diode-capacitor Cockcroft-Walton multiplier chain.

3.3 The GlueX Barrel Calorimeter

The Barrel Calorimeter (BCAL) is a 4 m long cylinder lining the inside of the solenoid with an inner radius of 65 cm and an outer radius of 90 cm, as is seen in Figure 2. It consists of alternating sheets of lead and scintillator fibers creating a sandwich of passive and active detector layers, respectively [8]. The lead, when struck by a particle, creates showers of particles that then produce light in the scintillating fibers. The cylinder is comprised of 48 identical wedge shaped modules to form the complete cylinder. The scintillating fibers have a 1 mm diameter and are glued into longitudinal grooves in the lead. The BCF-20 double-clad fast green scintillator fibers made by Bicron have an emission peak at 492 nm, a decay time of ~3 ns, and produce 8000 photons/MeV. The complete BCAL exists within the solenoid, and standard PMTs are adversely affected by such a strong magnetic field. The light collection will be performed using Silicon Photomultipliers (SiPM), a solid state device with a gain of 10^6 and that is insensitive to the magnetic fields present, which are the subject of a later section.

3.4 Silicon Photomultipliers

SiPMs or Multi-Pixel Photon Counters (MMPCs) are a type of photon measuring detector made of multiple avalanche photodiode (APD) pixels operating in Geiger mode. Each pixel produces an output pulse when it senses photons and the total output of the SiPM is the sum of all of the pixel's output. The largest use of SiPMs in Hall D will be to instrument the BCAL, but they will also be used in several other detectors. A 4x4 array of 3 mm x 3 mm SiPMs made by Hamamatsu is shown in Figure 3. The output of the SiPMs is read out using fADC 250s.

SiPMs have numerous advantages over traditional PMTs [9]. They have high gain (10^6) while requiring no high voltage and still maintain a high, greater than 20%, photon detection efficiency. SiPMs are also extremely compact and most importantly to Hall D, SiPMs are able to operate in several Tesla magnetic fields. SiPMs also have a few disadvantages including a higher noise rate (can be reduced by cooling the detectors), limited range in gain, cross talk and after pulses of order 10% - 20%, nonlinearity with high pixel occupancy, and radiation hardness [9]. A typical dark ADC spectrum of a 1 mm x 1 mm SiPM is shown in Figure 4 where the first peak is the pedestal value, the second peak is a single pixel, the third peak is two pixels, and so on. Timing is yet another strength of SiPMs. The intrinsic time response of the SiPMs is less than 30 ps. The SiPM dead time is between 10 ns and 50 ns where the larger pixels take longer to recover than the smaller pixels. With their intrinsic quick recovery time, SiPMs are capable of handling signals at the MHz level.

Another major concern about the SiPMs is their radiation hardness, specifically against neutron damage, and expected lifetime; a study was completed to address the issue [9]. The test setup involved exposing SiPMs to a total equivalent dosage of 13 years of high intensity running in Hall D by placing them in Hall A during the PRex experiment with a 1 GeV electron beam and a solid lead target. Exposure of the SiPM to radiation had the collective effects of increasing the dark current and decreasing the signal amplitude proportional to the neutron fluence, but did not affect the width of the pulse produced [9]. Most radiation damage from (hadrons, photons, and high energy leptons) in SiPMs is caused by a primary knock on atom being removed from its lattice site [10]. Other problems include the creation of Frenkel pairs - interstitial atoms and vacancies. The effect of the damage is proportional to the energy of the radiation impacting the detector. Overall, the SiPMs will last 9 years in Hall D with an uncertanty of 30%.

4. Conclusions

GlueX is poised to answer important questions about QCD, including the search for exotic hybrid mesons, utilizing JLab's new 12 GeV electron beam and through the use of advanced new detector technologies. Custom detectors used in conjunction with custom readout electronics will be pushed to deliver high data rates at high resolution. Hall D is complete and the GlueX apparatus is currently under construction. Overall, the experiment is on schedule to be ready to start collecting data when the beam is first available in 2014.

Acknowledgments

I would like to thank my colleagues from the GlueX collaboration, specifically E. Smith, M. Shepherd, and Y. Qiang, for helpful communications and suggestions.

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