Study of the nature of the confinement in the GlueX experiment

V.V. Berdnikov\textsuperscript{b}, A.S. Somov\textsuperscript{a}, S.V Somov\textsuperscript{b}, I.A. Tolstukhin\textsuperscript{b,\textdagger}, for the GlueX Collaboration

\textsuperscript{a}Thomas Jefferson National Accelerator Facility, Newport News, Virginia, 23606, USA
\textsuperscript{b}National Research Nuclear University “MEPhI”, Moscow, 115409, Russian Federation

Abstract

Confinement is a fundamental property of quantum chromodynamics (QCD) associated with the unique role of the gluonic field responsible for binding quarks in hadrons. Understanding the role of gluons in the confinement of quarks is one of the most tantalizing topics in modern particle physics to be explored. The new experiment GlueX has been recently constructed at Jefferson Lab [1]. The experiment was designed to search for hybrid mesons with exotic quantum numbers using a beam of linearly polarized photons incident on a liquid hydrogen target. The spectrum of these states and their mass splitting from normal mesons may yield information on confinement. In addition, these observations in combination with detailed chromodynamics calculations such as on the Lattice can provide important tests for our understanding of the role of gluons. The production of exotic mesons is expected to be enhanced in $\gamma p$ interactions, where the experimental data is very limited. We present the description of the GlueX detector, beam line, and first results of the commissioning with photon beam.

© 2015 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

Keywords: Detectors; Nuclear physics; GlueX experiment; Hybrid mesons; Confinement.

1. Introduction

The origin of exotic quantum numbers can be explained based on the so-called flux tube model [2], the model which has so far been successfully verified for heavy quarks using lattice QCD calculations [3]. In the flux tube

\textdagger Corresponding author. Tel.: +7-903-188-40-71.
E-mail address: ivantol@jlab.org
model, the gluonic field, or the «flux tube» can have an angular momentum \((m)\), which can be combined with the quantum numbers of a quark-antiquark system. When the flux tube is in its ground state \((m = 0)\), mesons with conventional \(J^{PC}\), are produced. Excitations of the flux tube can result in production of hybrid mesons with \(J^{PC}\) forbidden for conventional mesons. Linear combinations of the excited transverse modes of the flux tube are eigenstates of parity and have \(J^{PC} = 1^{+}\) and \(J^{PC} = 1^{-}\). When these quantum numbers are combined with those of the quark-antiquark system with \(L = 0\) and \(S = 1\) (quark spins aligned) three of the six possible \(J^{PC}\) have exotic combinations: \(0^{+}\), \(1^{+}\), and \(2^{+}\).

Recent lattice calculations predict masses of hybrid mesons with \(J^{PC} = 0^{+}\), \(1^{+}\), and \(2^{+}\) to be between 1.8 GeV and 2.8 GeV and \(J^{PC} = 1^{+}\) to be the lightest state. These predictions define the energy region for the experimental search for light hybrid mesons. Several experiments have reported on observing three exotic states \(\pi_{1}^{0}(1400)\), \(\pi_{1}^{0}(1600)\) and \(\pi_{1}^{0}(2015)\) with \(J^{PC} = 1^{+}\).

Using linearly polarized photon beams to search for exotic states is expected to have some advantages compared to using beams of pions. In the case of the \(\pi\)-beam, production of exotic mesons is expected to be suppressed because a spin flip of the quark is required. In contrast, according to the vector dominance model, linearly polarized photons can be presented as a virtual quark-antiquark state with \(L = 0\) and \(S = 1\), i.e., no spin flip is required. Large photoproduction cross-sections for exotic mesons are also predicted by recent lattice calculations of the radiative decay of charmonium states into hybrid mesons with exotic quantum numbers [4].

During the past few decades several experiments have searched for exotic mesons using different beam particles and energies. Two new experiments dedicated to search for states with exotic quantum numbers are currently under construction: PANDA at GSI [5] and GlueX at Jefferson Lab [1]. PANDA will perform a search for exotic states in proton-antiproton annihilation while GlueX will use a beam of linearly polarized photons. The GlueX experiment will collect a data sample a few orders of magnitudes larger than all existing photoproduction data.

2. GlueX Experiment

The upgrade of the CEBAF electron beam energy from 6 GeV to 12 GeV will provide a unique high-intensity beam of linearly polarized photons produced using a bremsstrahlung technique [6]. A schematic view of the GlueX beamline is shown in Fig. 1.

![GlueX beamline](image)

Fig. 1. A schematic view of the GlueX beam line.

The photon beam is produced by a 12 GeV electron beam incident on a thin (20 \(\mu\)m) diamond radiator. Coherent radiation from the diamond crystal lattice results in sharp monochromatic peaks in the photon energy spectrum. In order to suppress the contribution from background originating from the incoherent bremsstrahlung production, i.e., to increase the fraction of linearly polarized photons in the energy region of interest between 8.4 GeV and 9.1 GeV (the coherent peak region), the photon beam is passed through a collimator situated about 75 m downstream from the radiator. The photon energy will be determined with an accuracy of about 0.1 % by measuring the energy of the electron after radiation. The collimated photons will subsequently be sent to the GlueX liquid hydrogen target.
One of the key components of the Hall-D photon beam line is the pair spectrometer, which is installed after the photon collimator in front of the GlueX detector. The spectrometer will measure the energy of a beam photon by detecting an $e^+e^-$ pair produced by the photon in a thin converter. The main purpose of the spectrometer is to measure the spectrum of the collimated photon beam and determine the fraction of linearly polarized photons in the coherent peak energy region. The layout of the Hall D pair spectrometer is presented in Fig. 2. Electron-positron pairs are created by beam photons inside a thin converter with a typical thickness of $\sim 10^3$ radiation lengths.

![Fig. 2. Schematic plan view of the pair spectrometer (a) and the dipole magnet with vacuum chamber (b).](image)

Produced leptons are deflected in a dipole magnet with an effective field length of about 0.9 m. The magnet is operated at a nominal field of 1.8 T. A 1.5 meter long vacuum chamber is installed after the magnet. Electrons and positrons are registered in two layers of scintillator detectors: a high-granularity hodoscope and a set of coarse counters, denoted on Fig. 2 as PS and PSC, respectively. The detectors are organized into two arms positioned symmetrically with respect to the photon beamline. Each PS hodoscope consists of an array of thin scintillator tiles. Tiles with two different sizes $1\times10\times30$ mm$^3$ and $2\times10\times30$ mm$^3$ are used. The light from each tile is collected by means of wavelength shifting fibers and is detected by a Hamamatsu silicon photomultiplier (SiPM) with a sensitive area of $3\times3$ mm$^2$ [7]. The hodoscope energy resolution varies between 12 MeV and 20 MeV for 6 GeV and 12 GeV reconstructed photons, respectively. Energy spectrum of beam photons measured with the pair spectrometer during the first Hall-D commissioning run is presented in Fig. 3. Peaks in the energy spectrum (regions enhanced with linearly polarized photons) correspond to photons produced in coherent bremsstrahlung process from the diamond crystal. During the commissioning phase the Jefferson Lab accelerator provided a 5 GeV electron beam, which energy was about a factor of two smaller than the nominal beam energy of 12 GeV.

![Fig. 3. Photon energy spectrum measured with the PS hodoscope during the first commissioning run with a diamond radiator.](image)
The GlueX is a magnetic spectrometer optimized to provide almost $4\pi$ coverage for charged tracks and photons originating from exotic meson decays. The spectrometer layout is presented in Fig. 4. The photon beam is incident on a 30-cm LH$_2$ target positioned inside a solenoid magnet. The target is surrounded by a start counter (ST) made of plastic scintillator, that provides event timing information. It is used to identify the beam bunch (coming every 2 ns) from which the interaction at the target occurs.

![Fig. 4. Schematic plan view of the GlueX detector.](image1)

Charged tracks are reconstructed with the Central and Forward drift chambers, shown on Fig. 5 [8]. The CDC is a 28-layer, 1.5-m long straw tube chamber with 3522 straw tubes. The FDC consists of four separate packages; each package contains six cathode-wire-cathode planes [9]. Cathode strips are oriented at ±75 degrees with respect to the wires. This strip orientation provides information on the position along the hit wire, improving the pattern recognition. Wires and cathode strips are instrumented with the single side readout. The position resolution of the CDC is about 150 μm. Momentum resolution of tracks reconstructed with the CDC and FDC is $\sigma_{p/p} \approx 1 - 3\%$.

![Fig. 5. The Central (a) and Forward (b) drift chambers.](image2)
Calibration and alignment of the FDC and CDC have been performed using cosmic rays and a sample of charged tracks acquired during the beam test. After calibration, the FDC space point resolution of tracks was found to be ~ 200 μm.

Reconstruction of photons is performed using lead-scintillator (barrel) and lead glass (forward) calorimeters (Fig. 6). The barrel calorimeter (BCAL) consists of 48 modules. Each module is 4-meter long and is made from approximately 17k scintillating fibers sandwiched between layers of lead. All 48 modules are stacked to form a cylindrical shape, which is inserted into the GlueX solenoid magnet. The BCAL readout is performed using arrays of silicon photomultipliers instrumented on both sides of the module. Position and energy resolutions of reconstructed photons are 0.5/√E cm and (5.5/√E + 2)% respectively, where energy E is given in units of GeV.

Particle identification (PID) is performed using time measured by the Start Counter, the forward Time-Of-Flight (TOF) wall, and the BCAL. Time information can be combined with dE/dx measurements in the CDC. The typical time resolution of the TOF is about 120 ps, which provides separation of pions and K-mesons in the forward direction in the momentum range below 1.2 GeV/c. Identification of kaons will be significantly improved in the momentum range of up to a few GeV/c by installing several bars of the BaBar DIRC [10]. This will dramatically increase the number of potential hybrid decay modes that GlueX can investigate and will reduce experimental backgrounds from misidentified particles.

The quantum numbers J^PC of the observed mesons will be determined using a partial wave analysis (PWA). The GlueX PWA software is being intensively tested using Monte Carlo simulations.

3. Conclusion

GlueX is the new experiment at Jefferson Lab, which physics program is intended to improve our knowledge of strong interactions. The main goal of the experiment is to search for gluonic excitations. Being optimized for the search of mesons with exotic quantum numbers the detector is well suited to study physics topics such as the Primakoff production of pseudoscalar mesons, charged pion polarizability, and many others. The experiment is expected to collect a data sample a few orders of magnitudes larger than all existing photoproduction data. GlueX was successfully brought into operation during the first commissioning runs; the detector commissioning stage is expected to be finished in the middle of 2016.
Acknowledgements

This work was supported by the US Department of Energy contract No. DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates the Thomas Jefferson National Accelerator Facility. Authors would like to thank their colleagues from the GlueX collaboration for their help.

References

1. The GlueX Collaboration, https://halldweb1.jlab.org/wiki/index.php/Main_Page.
2. N. Isgur and J. E. Paton, A Flux Tube Model for Hadrons in QCD, Phys.Rev.D 31, 2910 (1985).
3. SESAM Collaboration, G. Bali et al. Glueballs and string breaking from full QCD, Nucl.Phys.Proc.Suppl. 63,209 (1998).
4. J.J. Dudek, R. Edwards and C.E. Thomas. Exotic and excited-state radiative transitions in charmonium from lattice QCD. Phys.Rev.D 79, 094504 (2009).
5. The PANDA Collaboration, http://www-panda.gsi.de.
6. W. Kaune, G. Miller, W. Oliver, R. W. Williams and K. K. Young. Inclusive Cross-Sections for Pion and Proton Production by Photons Using Collimated Coherent Bremsstrahlung. Phys.Rev.D. 11, 478 (1975).
7. Tolstukhin, A. Somov, S. Somov, A. Bolozdynya. Recording of Relativistic Particles in Thin Scintillators. Instruments and Experimental Techniques. 2014. Vol. 57. No 6. pp. 658-661.
8. V. Haarlem et al.. The GlueX central drift chamber: design and performance, Nucl. Instrum. Methods A 622 (2010) 142.
9. V. Berdnikov, S. Somov, L. Pentchev, B. Zihlmann. A drift detector system with anode and cathode readout in the GlueX experiment. Instruments and Experimental Techniques. 2015. Vol. 58. No 1, pp. 25-29.
10. The GlueX Collaboration, M. Dugger et. al. A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC. arXiv: physics.ins-det/1408.0215.