E12-11-107: The LAD Experiment

PAC49 Jeopardy Document

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1 Introduction and Motivation

Since the discovery of quarks, nuclear physicists have been trying to understand the relation between the lower-resolution description of nuclei using protons and neutrons (nucleons), and the underlying higher-resolution description in terms of quarks and gluons. At the intersection of these two paradigms are Short-Range Correlations (SRC): pairs of strongly interacting nucleons whose distance is comparable to their radii. Due to their overlapping quark distributions and strong interaction, SRC pairs serve as a bridge between low-energy nuclear structure, high-density nuclear matter, and high-energy quark distributions; with important consequences for strong-interaction physics, hadronic structure, and astrophysics.

The relative abundance of SRC pairs in nuclei can be extracted from measurements of inclusive (e, e') cross-section ratios for different nuclei at high-Q^2, $x_B > 1$ kinematics [1, 2, 3, 4, 5, 6, 7, 8, 9]. For a fixed value of Q^2, when plotted as a function of x_B, these cross-section ratios scale starting approximately at $x_B \geq 1.5$. The height of the scaling plateau can be used to extract the relative number of high-momentum nucleons (i.e. SRC pairs) in the measured nuclei. We refer to these as the 'SRC scaling coefficients'.

A recent series of publications showed that the extracted SRC scaling coefficients linearly correlate with the strength of the EMC effect in nuclei from ^{3}He to ^{208}Pb [10, 1, 11, 12]. The latter is the slope of the deviation from unity of the isoscalar DIS cross-section ratio for nuclei relative to deuterium in the range $0.3 \leq x_B \leq 0.7$ (Fig. 1 left). The EMC effect is commonly interpreted as evidence for modification of the partonic structure function of bound nucleons [1, 13].

The modification of the internal structure of bound nucleons due to the influence of the nuclear medium is of vast interest for QCD research and can provide new insight into the fundamental mechanism of confinement. As of today, the EMC effect is the only concrete, well-established and well-studied experimental evidence we have for such modification. However, even though it was first observed almost 40 years ago, the origin of the EMC effect is still an open puzzle at the interface of nuclear and particle physics, whose resolution is expected to shed new light on QCD as a whole and specifically on QCD effects in the nuclear medium.

The observation of a correlation between the strength of the EMC effect and the relative number of SRC pairs in nuclei generated new interest in the EMC effect (see CERN Courier cover paper from May 2013; 'Deep in the nucleus: a puzzle revisited' [12]) and gave new insight into its possible origin. Follow-up works proposed models for the underlying dynamics that drive the EMC effect and its correlation with SRC pair abundances, relating and sometimes inspiring activities by various groups; see a recent review in Ref. [1].

Experiment E12-11-107, known as the Large Area Detector (LAD) Experiment [14] was proposed to measured spectator Tagged-DIS (TDIS) off high-momentum nucleons in deuterium to provide new insight into the origin of the EMC effect as a whole and to specifically test the hypothesis that the EMC Effect in nuclei stems largely from the modification of nucleons in SRC pairs.

1.1 Progress since LAD was approved

The LAD Experiment was the first to offer a direct test of the physics behind the EMC-SRC correlation. Since it was proposed, we and collaborators confirmed that the global EMC data can be explained using a

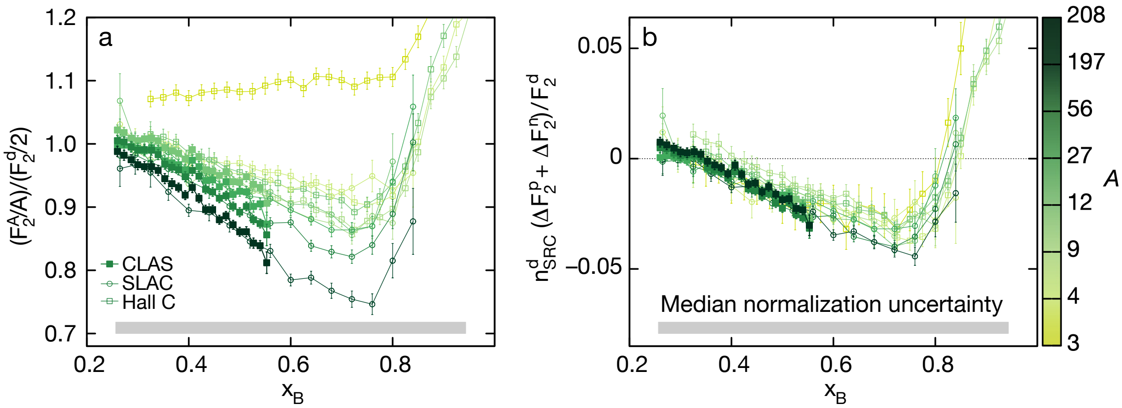

Figure 1: Left: The measured structure function ratio of different nuclei relative to deuterium (no isoscalar corrections applied) adapted from Ref. [15]. CLAS data are from [15], SLAC data are from [16], and Hall C data are from [17]. The deviation from unity in the range from $0.3 < x_B < 0.7$ is the EMC Effect. The magnitude of the effect has a large A-dependent spread. Right: The structure modification per pair (right panel), however, appears to be universal, as expected from the SRC-EMC hypothesis.

universal modification function, a result that was published in Nature, PRL, and Phys Rev Research [15] (e.g. Fig. 1 right). Significant work was put forth by the community to study the relation between SRCs and the EMC effect and to identify the best observable one can measure to obtain quantitative understanding of the partonic structure of high-virtuality nucleons in nuclei. The widespread conclusion of these studies is that spectator-tagging measurements in TDIS reactions is the best way to directly access the structure of bound nucleons and, aside from the proposed EIC program, the LAD experiment is the only experiment approved to measure the structure of neutrons with very high-momentum in deuterium.

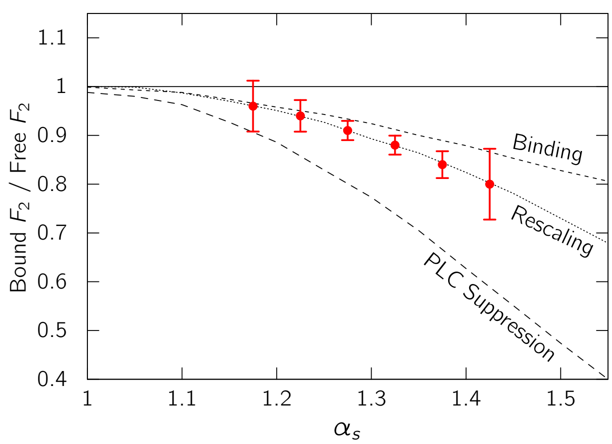

Figure 2: Expected statistical precision for the LAD experiment in the configuration presented to the 2020 ERR, as a function of the spectator light-cone momentum fraction, α_s. The uncertainties are compared to three models of nucleon modification [18].

As detailed below, in recent years our group worked to realize and optimize the LAD experiment. We refurbished the almost thirty-year-old CLAS6 TOF bars with new PMTs and a new laser calibration and monitoring system. Following significant effort by our group and the lab's engineers we developed and manufactured mechanical support frames, and developed a solution for a deuterium target and scattering chamber that offers large backward-angle recoil proton acceptance.

LAD was originally envisioned to measure both spectator protons and spectator neutrons. In order to improve both measurements, we proposed the dedicated spectator-neutron measurement using BAND in Hall B. This allowed us to focus the LAD experiment on the high-precision spectator proton measurement. We added GEM-based tracking, in order to dramatically increase the experimental luminosity and thereby its accuracy. See ERR review for details [19].

The experiment successfully passed an Experiment Readiness Review (ERR) in July 2020 and its projected results are shown in Fig. 2.

Thus, LAD is a trailblazing experiment that is ready to run and is pivotal for our understanding of the EMC effect, reaction mechanisms in TDIS reactions, and the study of bound nucleon structure. It complements the JLab program to measure low-momentum spectator protons in TDIS for free neutron structure studies (e.g. BONUS) and low-momentum light nuclei for mean-field nucleon modification studies (e.g. ALERT), and the CLAS12 BAND measurement of very backward spectator neutrons. Its unique wide-angle coverage, high-resolution, and low backgrounds will also inform theoretical studies of reaction effects and Final-State Interactions in TDIS reactions, that are crucial inputs for the continued development of the EIC program of far-forward spectator tagging. The experiment is at the focus of the research program of a junior faculty member and has two graduate students working on its preparations.

1.2 Experimental Details

LAD will measure scattered electrons from deep inelastic scattering on neutrons in deuterium, while "tagging" the recoiling spectator proton. This measurement will be made as a function of quark momentum fraction reconstructed using spectator proton information as $x' = Q^2/2q_\mu(p_d^\mu - p_s^u)$, and of the spectator light-cone momentum fraction given by $\alpha_s = (E_s - \vec{p}_s \cdot \vec{q})/m_N$, where the spectator four-momentum is $p_s^\mu = \langle E_s, \vec{p}_s \rangle$, the deuteron four-momentum is p_d^μ, and m_N is the nucleon mass. The goal of the experiment is to extract the ratio of the bound-nucleon $F_2^{\text{bound}}(x'|\alpha_s)$ structure function to that of the free nucleon, $F_2(x)$ as a function of α_s. This can be estimated by taking a ratio of tagged-DIS cross sections at high-x', i.e., $x' > 0.5$, where medium modification effects are large, to the tagged-DIS cross section at $x' = 0.3$, where F_2 shows no medium modification. Therefore, reach in both α_s out to 1.5 and x' are important for making an impactful measurement. Simulations performed by graduate student Sara Ratliff showing anticipated uncertainties are shown in Fig. 2.

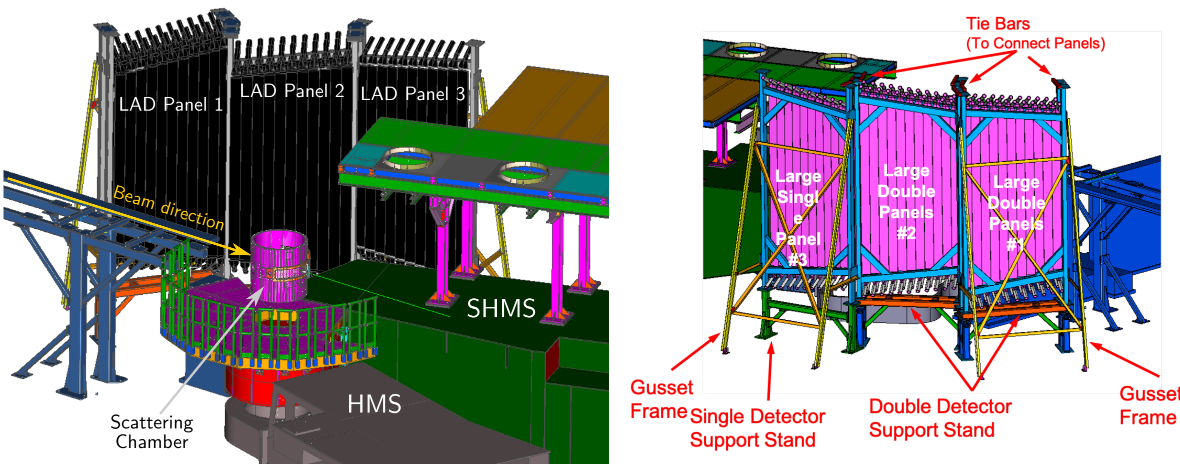

Figure 3: Layout of the LAD detector in Hall C. (left) View from downstream. GEMs will be positioned between the scattering chamber and the LAD panels. (right) View from upstream. The LAD scintillators mounted on their support frames in the hall. The bars are shown in magenta, the individual panel mounting frames are shown in light blue, and the support frames to position the panels in the Hall are indicated by the arrows.

In the LAD experiment, an 11 GeV electron beam will be scattered from a 20 cm liquid deuterium target in Jefferson Lab Hall C, with both the Super High Momentum Spectrometer (SHMS) and the High Momentum Spectrometer (HMS) being used to detect electrons in DIS kinematics. Recoiling spectator protons will be detected in two layers of GEM detector, to measure the proton target vertex, and in the LAD detector, to measure the proton flight time. LAD is comprised of three panels, each approximately 2 m × 4 m, of scintillator bars. The 55 scintillators came originally from the CLAS-6 time-of-flight detector [20], and were refurbished at Old Dominion University. The panels cover between 90° and 160° in the back left quadrant from the target, accepting ≈ ±20° in azimuth. Proton momentum (over the range of 200 MeV/c to 600 MeV/c) will be measured via time-of-flight over an approximately 5 m flight path. The two larger-angle panels will be composed of two layers of scintillators each, in order to better measure the energy deposited by protons that "punch thru" the first layer. LAD will measure both flight time and energy deposited in order to reject pions and improve the signal to noise. An illustration of the experimental set up in Hall C is shown in Fig. 3.

As described below, LAD is being constructed for this experiment at JLab and ODU using the decommissioned time-of-flight detectors from the CLAS6 spectrometer. The GEM trackers were previously used by the PRad experiment and are being re-commissioned by UVA.

The LAD experiment will be run by members of the SRC group, a collaboration among MIT, ODU, GWU, Tel Aviv U, Jefferson Lab, and other institutions. This group has a record of significant publications and successful experiments.

Figure 4: Left: One panel (11-bars) of the LAD detector lying flat on its frame; (right) Two panels of the LAD detector as stored on the storage cart in the ESB. Six panels of the LAD detector stored on the 2nd cart can be seen on the right side of the picture.

2 Work Done on the LAD Detector

A very large amount of preparatory work on the LAD detectors (scintillator arrays, GEMs, and ancillary structures) has been carried out since the experiment was approved.

2.1 LAD Scintillator Refurbishment

The 132 scintillator bars were decommissioned from the original CLAS detector and refurbished at Old Dominion University. The scintillators are 5-cm thick, 22-cm wide, and range in length from two to four meters. One panel of eleven bars can be seen in Fig. 4. Each bar was tested for time resolution and signal height. Defective PMTs were replaced. Approximately sixty 3" replacement PMTs were purchased by Kent State, MIT, and Tel Aviv University and fifty 2" PMTs were provided by George Washington University. The refurbishing was performed primarily by undergraduate students under the supervision of Tom Hartlove and Larry Weinstein.

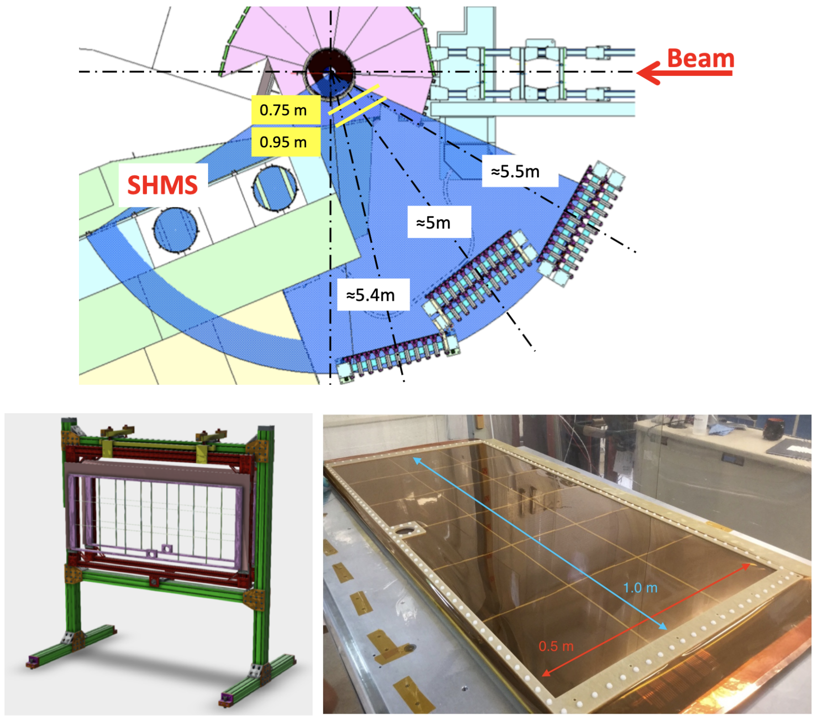

Figure 5: Top: illustration of the LAD detector in Hall C including the five scintillator planes located 5 to 5.5 m from the target, and the two pairs of GEM detectors, located 0.75 and 0.95 m from the target center. Left: one pair of GEM planes on their support stand. Right: the large-area GEM detectors shown here, built by the Liyanage group at the University of Virginia for the PRad experiment, which will be refurbished and used for the LAD expreiment. Photo credit: Xinzhan Bai, UVa

2.2 Detector Support Structures

The refurbished scintillator bars are mounted on 12 new frames, designed and built by Hall C (see Fig. 4left). Each frame is about 5-m tall by 2.5-m wide. The frames are stored in the ESB on two carts designed and built by Hall C (see Fig. 4). There are three large frames designed to support and position the five panels in Hall C (see Fig. 3 right). These have been designed by Hall C and have passed engineering review.

2.3 Laser calibration system

LAD will use a laser calibration system to calibrate the time and pulse-height response of all 55 LAD scintillators. This system was built for monitoring and calibrating large-scale scintillator arrays. It was successfully commissioned and used for the BAND experiment. It provides time-walk corrections, absolute time calibration, and TOF-drift correction for scintillators [21].

2.4 Large-area GEM detectors

LAD will use two sets of large-area ($\approx 0.6 \times 1.3$ m^2) GEM detectors positioned just outside the scattering chamber to measure the target vertex of the outgoing protons. The two sets of GEMs will be separated by 20 cm. By matching the electron and proton target vertex for $(e, e'p)$ events, we can dramatically reduce accidental coincidences, thus allowing us to increase the experimental luminosity. The large-area GEM detectors built by the Liyanage group at the University of Virginia for the PRad experiment will be refurbished by that group and used for the LAD experiment (see Fig. 5).

3 Work Done through the ERR Process

To complete the ERR process, mature designs were developed for the key hardware—the deuterium target, scattering chamber, LAD support frames, cable trays—and new simulation studies were completed to assess the final detector placements, the new GEM detectors, and the higher planned luminosity. This work is summarized in the following sections.

3.1 Target Design

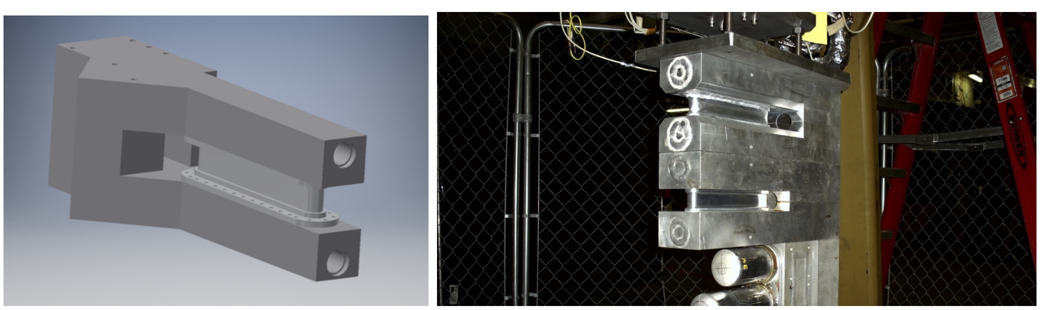

Figure 6: Left: CAD rendering of the LAD target cell, produced by D. Meekins; (right) photo HAPPEX target ladder, similar to what is designed for LAD.

A new liquid deuterium target has been designed specifically for the LAD Experiment by Jefferson Lab Target group. The target cell will be 20 cm long, and the design is based on the target used in the HAPPEX experiment, though the cell length has been reduced and the design has been modified to increase the acceptance at backward angles. Our target system also calls for a ladder with a carbon multi-foil and carbon hole targets for beam checkout and optics. A CAD illustration of the target cell is shown in Fig. 6 left, while a photograph of how the cell would sit in the target ladder (from HAPPEX) is shown in Fig. 6 right.

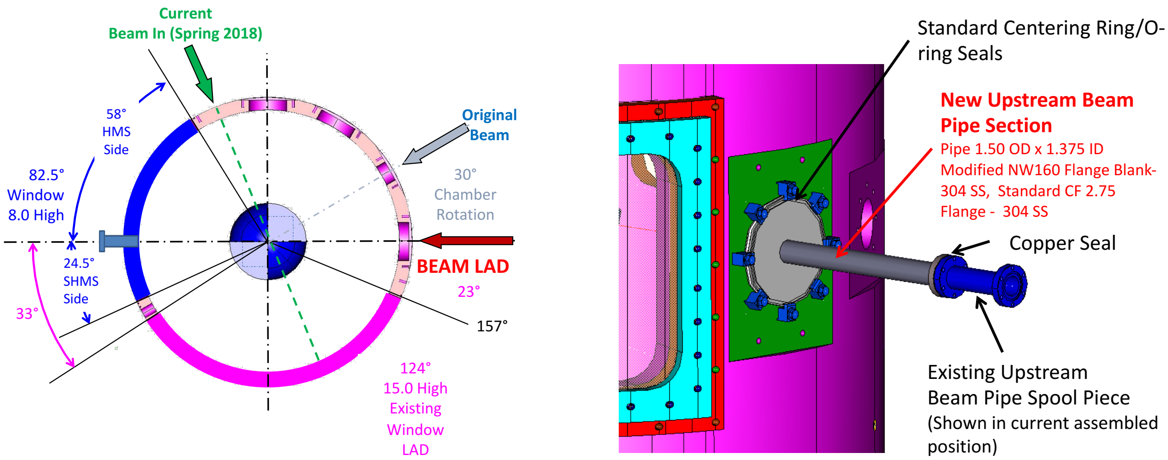

Figure 7: Left: new design for the orientation of the scattering chamber; Right: CAD illustration of the design for the upstream interface.

3.2 Scattering Chamber

A new design was developed (in cooperation with Walther Kellner) for the layout of the scattering chamber to ensure that the particles of interest pass through thin windows (Fig. 7). This design calls for rotating the existing Hall C scattering chamber by 30° so that the larger 15" GEP window can act as the window for the LAD detector. In this position, the current HMS window will cover both the HMS, the beam-exit and the SHMS. The upstream beam pipe will interface with the scattering chamber through an existing target viewport openings. New centering rings, seals, and beampipe have been desgined for this interface.

3.3 LAD Electronics and Cables

In order to place the five planes of LAD scintillators in their optimum position and to remove unnecessary material between the target and the scintillators, the SHMS cable tray will be significantly modified (temporarily) (Fig. 8). This will include lowering the cables and their supports in order to reduce multiple scattering of protons between the target and LAD. This will take three technicians approximately one week to accomplish. In addition, there are detailed plans for connecting the 220 LAD signal cables and 110 LAD HV cables from the LAD scintillators to a patch panel near the detector, and then from the patch panel to LAD electronics racks in the SHMS hut. This will require about two weeks of work to add or enlarge holes in the SHMS concrete cover, and to run all of the cables.

3.4 Simulations

Extensive new simulation studies were completed as part of the ERR process to assess the rates, background levels, and expected reach of the experiment. These studies were important since the configuration of the beam, target, and detectors have evolved considerably since the experiment was approved. The important changes include the addition of GEM detectors for vertexing, the final positioning of the GEMs and LAD, and increase in the proposed luminosity (relevant for accidental background rates).

A fast Monte Carlo simulation was developed to rapidly assess different configurations in order to facilitate optimization. The simulation goes far beyond what was developed for the rate estimates in the LAD proposal. The simulation models the multiple scattering of recoiling protons through the material in the windows and GEMs, includes microscopic detector response, allowing studies of background rejection by comparing proton timing and dE/dx, and most importantly includes the new GEM detectors and the vertexing information they provide. The expected statistical precision based on the running plan presented at the ERR is shown in Fig. 2.

We also performed simulation studies to show that the occupancy in the GEM detectors would not interfere with their ability to track recoil protons. We developed a Geant4 simulation based on that used

Figure 8: The SHMS cable tray showing the modification steps needed for LAD. 1: Cable tray support poles will be replaced and shortened. 2: The middle cable tray will be disassembled and secured to the lower tray. 3: The upper cable tray will disassembled and the cables will rest on a table near the pivot. 4: Support brackets will be installed on the support poles to carry the flexible hoses.

in the PRad experiment, and modeled the flux of low-energy electrons and photons that would induce background hits in the GEMs. We found that even if the background hit rate exceeds 5 GHz, the GEMs can still identify the correct vertex over 90% of the time, and that a thin layer of polyethylene can reduce the background rate enormously without compromising vertex resolution.

A preliminary Geant4 simulation of the entire LAD detector including the GEMs has been developed and further simulation studies are under way.

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