

Thomas Jefferson National Accelerator Facility: Exploring the Strong Force

Overview: Peering into the World of Quarks and Gluons

Thomas Jefferson National Accelerator Facility (Jefferson Lab), one of 17 U.S. Department of Energy (DOE) national laboratories, is a global leader in nuclear physics research for investigating the quark structure of matter.

A central quest of nuclear physics involves the fundamental understanding of nuclear matter, starting with quarks and gluons and their dynamics and interactions that make up both the protons and neutrons as well as the nuclei of all atoms. This quest represents the focus of the nuclear physics program within the Office of Science at the DOE. Enabling these studies is Jefferson Lab's world leadership in the development and deployment of large-scale superconducting radiofrequency (SRF) accelerator technology. Two SRF linear accelerators power Jefferson Lab's flagship facility, the Continuous Electron Beam Accelerator Facility (CEBAF). CEBAF produces intense beams of highly polarized electrons at up to 12 GeV of energy that impinge on nuclear targets to investigate quarks (and in some cases gluons) inside protons and neutrons. To reach 100+ GeV energies, and thus more fully investigate gluons, Jefferson Lab has also partnered with Brookhaven National Laboratory in the design and development of the Electron-Ion Collider (EIC).

The strong force determines the interactions among quarks and gluons and is described by the theoretical framework of quantum chromodynamics (QCD). QCD reveals that the strong force is small when quarks are

close together and increases with distance. Gluons are the mediators of the force between quarks, and they can also self-interact. This self-interaction enriches the spectrum of observed phenomena and adds complexity. Probing and stress-testing QCD requires continuous advancement, such as identifying new scientific challenges and opportunities, providing exquisite beams of electrons to carry out the experiments, and developing advanced detector capabilities.

In this brief overview, we touch on the scientific opportunities at CEBAF, the accelerator complex, current detector capabilities, and future prospects.

Scientific Opportunities at CEBAF

CEBAF provides crucial experimental evidence for the nuclear physics community to address the highest-priority questions of the field, as outlined in the 2023 Long Range Plan (LRP) for Nuclear Science (a decadal plan for nuclear physics research and development in the United States) [1]. The essential science questions identified by the global community and prioritized in the LRP report are:

1. How do the mass and spin of the nucleon emerge from the quarks and gluons and their dynamics?
2. How does the quark and gluon structure of the nucleon change when bound to other nucleons in a nucleus?

From these two LRP questions, three major research directions characterize the pursuit of understanding the strong nuclear force. The first research

direction involves understanding the structure and dynamics of quarks and gluons confined in protons, including how quarks and gluons contribute to the proton's mass [2], and the origins of the proton's spin (i.e., solving the proton spin puzzle) [3].

For example, each of the proton's valence quarks only contribute about 3 MeV of mass from their coupling to the Higgs Boson. The gluons are massless. Since the proton mass is 938 MeV, there is a seeming disconnect. It turns out that the quarks are "dressed" by a gluon field inside the proton, and that dressing is coupled with what appears to be a dense gluonic field in the center of the proton where the dynamics of the self-interacting gluons also generate mass. These effects combine to give the full proton mass.

Using J/ψ -photoproduction techniques [4], experimentalists were able to measure the rms radius of the gluons in the center of the proton for the first time (see Figure 1). They found that the rms radius is smaller than the charge radius. These fascinating measurements demonstrate CEBAF's power to unlock new discoveries in nuclear physics.

The second research direction involves the understanding of how quark and gluon properties within the proton affect the structures of complex nuclei. This connects to the second question through femtography, which is widely recognized as the method with the potential to describe the nucleon's internal structure and dynamics as completely as possible. By understanding the femtography of



Figure 1. Recent measurements of a “gravitational” form factor related to the stress-energy tensor in QCD enabled scientists to measure, for the first time, the rms radius of the gluons inside a proton. Experiments were carried out at Jefferson Lab.

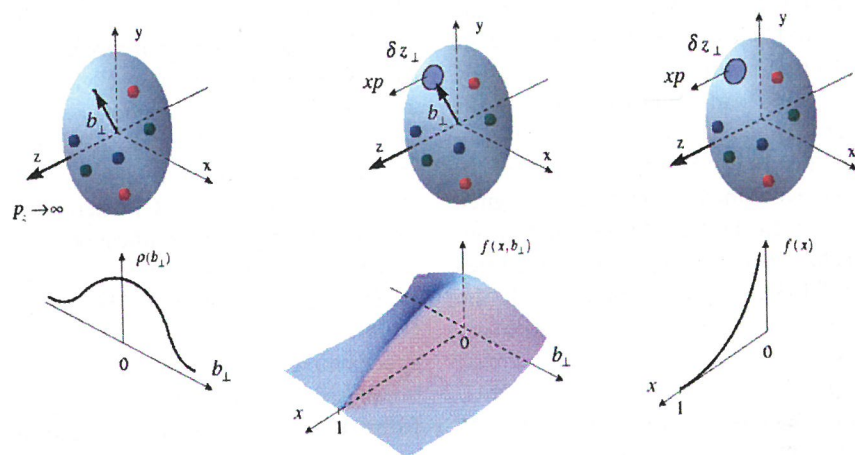


Figure 2. The left graph shows that elastic scattering of electrons off the proton probe the charge and magnetization density as a function of the impact parameter $b_{\perp}$. The right-hand graph shows the one-dimensional dependence of the parton distribution functions. The middle graph shows the combined information available from the GPDs.

the proton, we aim to understand also the nature of the strong force inside the nucleus.

For this purpose, we measure generalized parton (quark and gluon) distributions (GPDs) in the proton. The GPDs are 3D objects that describe the distribution of the quarks in three kinematic quantities: (1) the longitudi-

nal momentum fraction x of the active quark in the infinite momentum frame, (2) the 4-momentum transfer t to the proton, and (3) the skewness ξ describing the momentum transfer to the active quark [5]. GPDs describe the 3D distribution of the exclusive processes that are one of the cornerstones of Jefferson Lab’s experimental pro-

gram. Figure 2 illustrates what the GPDs describe in the quark distribution functions. Knowing the GPDs, we can ask questions like, What is the quark momentum distribution at a specific transverse impact parameter?

A third research direction involves the stress testing of QCD predictions—specifically testing the theories’ abilities to predict multi-quark (beyond the two- and three-quark hadrons) systems, such as a five-quark system, which requires the introduction of nonstandard exotic quantum numbers. This theme explores in detail the role of quarks and gluons in such exotic systems or states [6].

The CEBAF Accelerator Complex

CEBAF was built in Newport News, Virginia, USA, during the years 1986 to 1995. The main unique features of this accelerator are the combination of 100% duty factor with high average beam current but low bunch charge, very high-quality polarization, and high energy, all enabling coincident electron scattering and photon-induced reactions. CEBAF was the first large-scale deployment of SRF beam acceleration and the first large-scale application of multipass beam recirculation.

Although originally designed to achieve 4 GeV, by 2000 [7], CEBAF produced beam energies of 6 GeV, allowing world-class electron scattering experiments to be performed in three experimental halls. Moreover, it has consequently been upgraded [8, 9] to achieve 12 GeV and has been operating at this higher energy since 2017 (Figure 3).

Another innovation in CEBAF design is beam recirculation, where the electron beam passes multiple times through both linear accelerators (linacs), gaining energy on each pass. This approach allows very efficient



Figure 3. The CEBAF Accelerator includes two antiparallel 1-GeV linacs connected by two magnetic arcs. A beam is delivered to experimental Halls A, B, and C at 11 GeV, and D at 12 GeV. The total distance around the accelerator racetrack is 7/8 of a mile.

use of superconducting linacs—with only two one-GeV linacs, recirculation allows the electron beams to reach 12 GeV. This works because relativistic electrons take the same flight time through the CEBAF linacs and only need to be separated and directed to different magnetic arcs with increasing strength, proportional to the electrons' energies.

High polarization of the electron beam is yet another important feature of CEBAF. It is achieved by illuminating gallium arsenide (GaAs) semiconductor material with polarized laser light to induce spin-polarized electron photoemission. Polarized source technology significantly advanced over the nearly three decades of CEBAF operation with the adoption of a strained-layer GaAs/gallium arsenide phosphide (GaAsP) superlattice photocathode material, currently deployed, which ensures an increase of polarization from the initial 35% to currently 90%.

Unique Detectors and Equipment

With the completion of the 12 GeV upgrade, CEBAF beam energy can be up to 12 GeV, converted to 9 GeV photons for Experimental Hall D, and up to 11 GeV to Halls A, B, and C. Electron beams can be simultaneously delivered to all four experimental halls at different energies. Each experimental hall is instrumented with specialized experimental equipment designed to exploit the CEBAF beam. The detector and data acquisition capabilities at CEBAF, when coupled with the high-energy electron beams, provide the highest luminosity (10^{39} e/cm²/s) capability in the world. The CEBAF staff designs, constructs, and operates the complete set of equipment to enable this world-class experimental

nuclear physics program, in close collaboration with a large domestic and international user community of more than 1,650 annual users worldwide (including professors, post-docs, and students). Completing currently approved high-priority experiments will require more than 10 years of running at optimal capacity.

Hall D features GlueX [10], a large-acceptance spectrometer for experiments with a broadband, linearly polarized photon beam and includes experiments that explore the spectrum of light mesons, charmonium production, and strange baryons. Coherent Bremsstrahlung, which is produced by electrons interacting with a diamond radiator target, provides linearly polarized photons in a coherent peak at about 9 GeV. These photons are directed toward a hydrogen target. The GlueX spectrometer (see Figure 4) incorporates drift chambers, time-of-flight scintillator detectors, calorimetry, and Detection of Internally Reflected Cherenkov (DIRC) Cherenkov detectors for particle identification.

CEBAF Large Angle Spectrometer at 12 GeV (CLAS12) [11] in Hall B (Figure 5) is a large acceptance spectrometer designed to detect, over broad kinematics, particles emerging from the interaction of the electron beam with a fixed target. In operation since 2018, CLAS12 has already

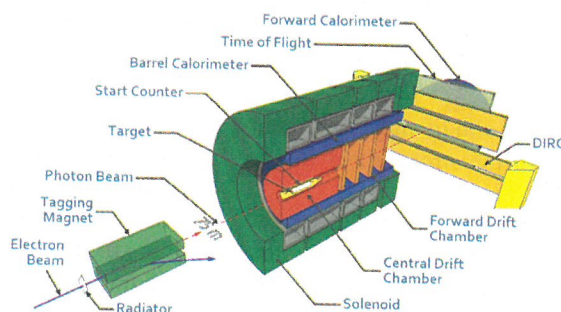


Figure 4. Left: The photo of Hall D shows the solenoid and a platform upstream containing the cryogenic target equipment and electronics racks. Right: the schematic picture of the spectrometer.

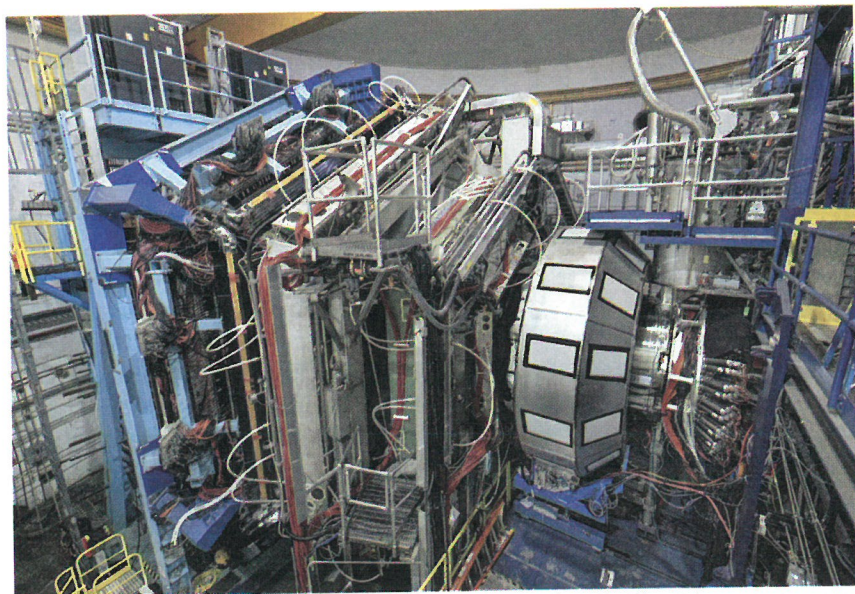


Figure 5. The CLAS12 spectrometer in Hall B. The photograph shows the detector complex during a maintenance period in 2023. Its overall extension is about 13 m. The beam is coming from the right. The Central Detector and the superconducting solenoid magnet are seen in the center right, the Forward Detector and the superconducting torus magnet are seen to the left.

completed several measurements on different targets, from hydrogen to heavy nuclei, to study the microscopic structure of both protons and neutrons, the spectrum of hadrons produced in these reactions, and the behavior of the strong force in the nuclear medium. It has two main components: the Forward Detector to measure particles emitted from the target in a polar angle range from 5° to 35° and the Central Detector to measure particles in a polar angle range from 35° to 125° . The two separate detectors are built around superconducting magnets that have the dual function of deflecting charged particles so that their momenta can be inferred from the curvature of their trajectory and of shielding sensitive elements from the radiation background mostly produced by the interaction of the electron beam with atomic electrons.

Most experiments in Hall C use the High Momentum Spectrometer

(HMS) and the Super High Momentum Spectrometer (SHMS) to execute either single arm or coincidence experiments at high luminosities using beam currents of up to 80 μA . The HMS and SHMS are general-purpose spectrometers designed to produce a relatively uniform angular acceptance over the momentum and target length acceptance. The HMS covers a scattering angle range of 10.5 to 90 degrees, and the SHMS covers a range of 5.5 to 40 degrees. The detector packages at the focal plane of both spectrometers are similar and consist of a timing hodoscope for the trigger and drift chambers for reconstructing the scattered particles' positions, angles, and momenta at the target. Particle identification is done through time-of-flight, calorimeters, Cherenkov, and aerogel detectors. Recent experiments have used the Neutral Particle Spectrometer (NPS) to detect photons and neutral pions (from its two-photon de-

cay) in coincidence with electrons in the HMS. The NPS consists of a dipole magnet that sweeps low energy charged particles out of the acceptance followed by a calorimeter made of 1,080 blocks of lead tungstate to detect photons. These spectrometers allow precise and reproducible measurements of small cross-sections for inclusive, exclusive, and semi-inclusive reactions.

Since 2021, Hall A (Figure 6) has executed a series of precision measurements of the elastic electric and magnetic form factors of the neutron and proton that will double or triple the momentum transfer range of previous data. The neutron form factor experiments used the upgraded Big-Bite Spectrometer (BBS) to detect electrons and the Super Bigbite Spectrometer (SBS) to detect protons and neutrons. The BBS is a dipole magnet with a detector package consisting of five gas electron multiplier detectors for reconstructing scattered particles' positions, angles and momenta at the target, a scintillator plane for fast timing, a Cherenkov detector, and a lead glass calorimeter used for the trigger and additional particle identification. The BBS has an angular acceptance of up to 50 msr. The SBS is also a dipole magnet that has a large hadron calorimeter behind the magnet. The SBS has an angular acceptance of up to 70 msr. The BBS and SBS offer flexibility to be used with different detector packages and other detectors in future experiments that will study the semi-inclusive and tagged deep inelastic reactions.

In fall 2025, the installation of the Measurement of a Lepton Lepton Electroweak Reaction (MOLLER) experiment [12] will begin. The design of the MOLLER experimental equipment is optimized to measure a small parity-violating asymmetry in Møller electron scattering with a polarized



Figure 6. Group of staff and graduate students posing under the beam-line in Hall A between the Super BigBite Spectrometer (left) and the BigBite Spectrometer (right).

electron beam at an unprecedented high scattered electron flux with controlled systematic error at the 1% level. The target will be a liquid hydrogen cell (125 cm long), and the beam current will be 65 μA . A precision collimation system is designed to accept all Møller scattered electrons with polar scattering angles between 5 and 17 milli-radian while minimizing the background. The spectrometer system is a combination of two toroid magnets that focus and separate the Møller electrons at the main detector located ~ 28 m from the target. Each toroid magnet has seven coils, which allow for full azimuthal angle coverage, because Møller scattering involves identical particles.

Prospects for the Future

The Solenoidal Large Intensity Detector (SoLID) [13] represents the next frontier of precision CEBAF experiments and was identified in the 2023 LRP as a strategic opportunity for the field. SoLID will capitalize on the DOE's investment in delivering CE-

BAF's highest luminosities (10^{37} – 10^{39} electrons/ $\text{cm}^2/\text{second}$) and will position the CEBAF user community to carry out high-precision 3D momenta imaging of the proton. This can unveil the origin of the proton's spin and map out uncharted phase space to probe physics beyond the Standard Model.

SoLID (Figure 7) will provide access to probing strong color fields within the proton, which is currently considered the origin of the proton's mass. Three years of high-priority experiments for SoLID have already been approved. Furthermore, SoLID will enable important design synergies with the EIC's Electron-Proton/Ion Collider detector for Jefferson Lab to deploy streaming data and software and hardware capabilities that will firmly benefit both projects and the DOE mission.

Another exciting future CEBAF upgrade possibility is extending the energy reach of the CEBAF accelerator up to 22 GeV. This should be possible within the existing tunnel layout, without energy increase in the linacs, by increasing the number of linac recirculations. The community is developing a compelling scientific case for this upgrade [14]. The energy upgrade is built around an innovative approach to recirculate the beam through fixed field alternating gradient (FFAG) magnets [15]. This approach will replace some fixed-energy single beam-lines in the CEBAF arcs with FFAG beam-lines (Figure 8), which can pass



Figure 7. The CLEO-II superconducting solenoid magnet is being refurbished inside the SRF Test Lab for the SoLID detector system to be eventually deployed in Hall A at CEBAF.

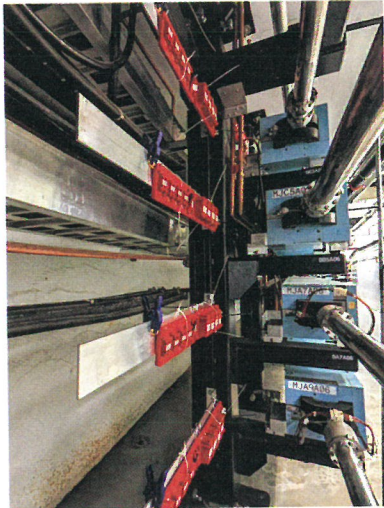


Figure 8. FFAG magnet materials are being tested during the Fiscal Year 2025 run to characterize their resilience to radiation. Pictured are a set of the FFAG magnets near the CEBAF arcs.

multiple beams and a large range of beam energies within one compact aperture.

In addition, another innovative program can be implemented preceding the energy upgrade and during its preparations: A polarized positron beam program could enable a novel set of unique nuclear physics measurements. This builds on the demonstration that polarized positrons can be created in CEBAF by using a polarized electron beam to generate polarized bremsstrahlung radiation, which then creates polarized positrons through pair production in a high-Z target.

Preconceptual design studies for both these upgrade possibilities are ongoing.

Summary

In this laboratory portrait, we have touched on just a few of the exciting scientific and technical directions of Jefferson Lab's nuclear physics program. The future is bright with discov-

eries yet to be made by this excellent facility for nuclear science.

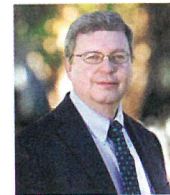
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