Future Physics Opportunities at Jefferson Lab

M.Battaglieri (INFN)
**Future Physics Opportunities at Jefferson Lab**

- **Primary Beam:** Electrons
- **Beam Energy:** 12 GeV
- **Duty Factor (cw) Beam:** 100%
- **Coincidence Experiments:**
  - Four simultaneous beams
  - Independent E and I
- **Polarization:**
  - Spin degrees of freedom
  - Weak neutral currents
- **Add Hall D (and beam line)**
- **Upgrade magnets and power supplies**
- **Luminosity:** $> 10^{7} - 10^{8} \times$ SLAC at the time of the original DIS experiments!
**12 GeV equipment**

**Hall A** – High Resolution Spectrometers and new multipurpose large acceptance detectors
- short range correlations, form factors, and future new experiments: SOLID, MOELLER, SBS

**Hall C** – Super High Momentum Spectrometer (SHMS)
- precise determination of valence q properties in nucleons and nuclei

**Hall D** – GLUEEx detector for photoproduction experiments
- explore origin of confinement by studying hybrid mesons

**Hall B** – Large acceptance detector CLAS12 for high luminosity measurements ($10^{35}$cm$^{-2}$s$^{-1}$)
- Understanding nucleon structure via GPDs and TMDs and hadron spectroscopy
Future (present) projects

- Solenoidal Large Intensity Device – new multipurpose detector facility optimized for high luminosity and large acceptance, enabling very broad scientific program
- Unique capability combining high luminosity ($10^{37-39}$/cm$^2$/s) (more than 1000 times the EIC) and large acceptance, with full $\phi$ coverage to maximize the science return of the 12-GeV CEBAF upgrade

EIC Electron Ion Collider

- Luminosity 100-1000 times that of HERA
- Polarized protons and light nuclear beams
- Nuclear beams of all A ($p\rightarrow U$)
- Center mass variability with minimal loss of luminosity

ePIC detector

- Large acceptance
- Frwrd/Bckw angles
- Precise vertexing
- HRes Tracking
- Excellent PID

- Unique discovery space for new physics up to 38 TeV mass scale, with a purely leptonic probe
- CD-0 approved 2017, ready for CD-1
JLab Scientific mission

• What is the role of gluonic excitations in the spectroscopy of light mesons?
• Where is the missing spin in the nucleon? Role of orbital angular momentum?
• Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
• What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
• Can we discover evidence for physics beyond the standard model of particle physics?

12 GeV experimental program is in full swing

• 33 experiments completed out of 91 approved
• ~8 years of physics ahead (~30 weeks/year)

Future opportunities at CEBAF

• Higher Energy
• Higher luminosity
• Positron beam
Physics with CEBAF at 12 GeV and Future Opportunities


Abstract

We summarize the ongoing scientific program of the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) and give an outlook into future scientific opportunities. The program addresses important topics in nuclear, hadron, and lepton-physics including nuclear tomography, meson and baryon spectroscopy, quark and gluon in nuclei, precision tests of the standard model, and dark sector searches. Potential upgrades of CEBAF are considered, such as higher luminosity, polarized and unpolarized positron beams, and doubling the beam energy.

Keywords:

1 Overview
1.1 Specific Scientific Accomplishments
1.2 Currently Planned Experimental Program
1.3 Future Science Opportunities
1.4 Complementarity with Existing and Future Experimental Facilities Worldwide
1.4.1 The COMPASS Experiment at CERN and Electron-Positron Collider Experiment
1.4.2 Experiments at other Nuclear and Particle Physics facilities
1.4.3 The Electron-Ion Collider (EIC) in the U.S.
1.4.4 The Electron-Ion Collider (EIC) in China

2 Electromagnetic Form Factors and Parton Distributions
2.1 Elastic Form Factors at Ultra Low and High Q^2
2.2 Quark Parton Distributions at High x
2.3 Proton and Kaon Structure
2.4 Two-photon Exchange Physics with Positron Beams

*Corresponding author, email address: [email address]

December 2, 2021

Future Physics Opportunities at Jefferson Lab

M. Battaglieri - INFN
**JEFFERSON LAB** leadership and the USERS community are discussing a possible upgrade of future operations.

- **Physics with CEBAF at 12 GeV and Future Opportunities**: a white paper submitted to Progress in Particles and Nuclear Physics.
- **Users-organized workshops** (J-Future (Italy), APCTP (S. Korea), ECT* (Italy)).
- **High Energy workshop series**

---

**HIGH ENERGY WORKSHOP SERIES 2022**

We are pleased to announce an upcoming series of summer workshops being organized jointly between the laboratory and the Jefferson Lab Users Organization (JUO) to probe the science that would be opened up by a higher energy electron beam (~20-24 GeV) at Jefferson Lab. We are particularly interested in identifying key measurements that are not possible to access at 12 GeV, that initially utilize largely existing or already-planned Hall equipment, and that leverage the unique capabilities of luminosity and precision possible at Jefferson Lab in the EIC era.

**Organizing Committee:**

Ed Brash, JUO Chair - David Dean - Carlos

---

**Hadron Spectroscopy with a CEBAF Energy Upgrade**

**June 16 & 17**

Marco Battaglieri, Sean Dobbs, Derek Glazier, Alessandro Pilloni, Justin Stevens, Adam Szczepaniak

Recent observations in heavy-quark spectroscopy have provided numerous candidates for hadronic resonances which are exotic in nature, the so-called XYZ and Pc states. With a CEBAF energy upgrade to 20.24 GeV these states and other charmonia may be studied in photoproduction and electroproduction measurements at JLab. This workshop aims to identify the key measurements made other charmonia by such an upgrade, utilizing recent theoretical models for production and evaluating the detector performance requirements.
JLab upgrades: the context

- Lab leadership point of view
- Four pillars: NP, EIC, Data science, Acc. science
- 12 GeV program as the highest priority (but also positron beam and hi-lumi ops)
- CEBAF will remain the prime facility for fixed target electron scattering at hi-lumi
- JLab timeline: +2030!

Cost-effective path to doubling CEBAF energy based on Fixed-Field Alternating Gradient arcs

CEBAF at 22-23 GeV

- FFA recirculation technique (proposed for eRHIC): multiple beam energies confined and recirculated in the same beamline
- No new SRF (1.1 GeV per LINAC), replace the highest recirculation passes with two pairs of FFA arc
- 11 passes to reach 23 GeV
- High energy beam delivered to Hall-D and Hall B suitable for an HS physics program
- Hi-Lumi operations are not an issue
HIGH ENERGY WORKSHOP SERIES 2022

We are pleased to announce an upcoming series of summer workshops being organized jointly between the laboratory and the Jefferson Lab Users Organization (JLuo) to probe the science that would be opened up by a higher energy electron beam (~20-24 GeV) at Jefferson Lab. We are particularly interested in identifying key measurements that are not possible to access at 12 GeV, that initially utilize largely existing or already-planned Hall equipment, and that leverage the unique capabilities of luminosity and precision possible at Jefferson Lab in the EIC era.

Organizing Committee:
Ed Brash, JLUO Chair - David Dean - Carlos Munoz Camacho - Thia Keppel - Bob McKeown - Kent Paschke - Jianwei Qiu - Patrizia Rossi - Justin Stevens

Hadron Spectroscopy with a CEBAF Energy Upgrade
June 16 & 17
Marco Battaglieri, Sean Dobbs, Derek Glazier, Alessandro Pilloni, Justin Stevens, Adam Szczepaniak

The Next Generation of 3D Imaging
July 7
Harut Avagyan, Carlos Munoz Camacho, Jian-Ping Chan, Xiangdong Ji, Jianwei Qiu, Patrizia Rossi

Science at Mid x: Anti-shadowing and the Role of the Sea
July 22,23
John Arrington, Mark Dalton, Thia Keppel, Wally Melnitchouk, Jianwei Qiu

Physics Beyond the Standard Model
August 1
Marco Battaglieri, Bob McKeown, Xiaochao Zheng

J/Psi and Beyond
August 17
Ed Brash, Ian Cloet, Zein-Eddine Meziani, Jianwei Qiu

Measurements of J/ψs near threshold with high statistics, for both electro and photoproduction at JLab with 12 GeV beam, are the community. A CEBAF energy increase (to ~24 GeV) will allow us to ask new questions and provide opportunities for nuclear and particle physics, thus enhancing the physics output of all four experimental halls, using existing (Halls B, C) equipment. This focused one-day workshop aims to (1) identify the key new measurements which could be made possible, (2) specify the corresponding new questions that could be answered and the outstanding puzzles that could be addressed.

Physics Beyond the Standard Model
August 1
Marco Battaglieri, Bob McKeown, Xiaochao Zheng

J/Psi and Beyond
August 17
Ed Brash, Ian Cloet, Zein-Eddine Meziani, Jianwei Qiu

Measurements of J/ψs near threshold with high statistics, for both electro and photoproduction at JLab with 12 GeV beam, are the community. A CEBAF energy increase (to ~24 GeV) will allow us to ask new questions and provide opportunities for nuclear and particle physics, thus enhancing the physics output of all four experimental halls, using existing (Halls B, C) equipment. This focused one-day workshop aims to (1) identify the key new measurements which could be made possible, (2) specify the corresponding new questions that could be answered and the outstanding puzzles that could be addressed.
Hadron Spectroscopy with CEBAF@12 GeV: GLUEX

**Exotic Meson Photoproduction**

Primary goal for GlueX: Resonant (?) P-wave in $\gamma p \rightarrow \eta\pi N$

- Total
- $D_1^-$
- $D_1^+$
- $D_2^-$

**Photoproduction of J/ψ**

- Searching for evidence of photoproduction of pentaquark state
- Connection to proton mass radius: Phys Rev D 104(2021)054015

- GLUEX experiment is the leaden meson spectroscopy program at 12 GeV
- First results available
- PWA to extract sub-leading waves in progress

Jim Napolitano
2022 JLQO Meeting

Excellent data quality, continuing analysis for unambiguous extraction of P-wave

Jim Napolitano
2022 JLQO Meeting
Hadron Spectroscopy: the physics case

Ordinary baryons:
- Proton, stable
- Neutron, $\tau \sim 10^3 s$
- Baryon $\Lambda$, $\tau \sim 10^{-10} s$

Ordinary mesons:
- Pion, $\tau \sim 10^{-8} s$
- Kaon, $\tau \sim 10^{-8} s$
- $J/\psi$, $\tau \sim 10^{-20} s$

Exotic matter:
- Hybrid mesons
- Tetraquarks
- Pentaquarks
- Glueballs

- The energy upgrade will provide the unique capability of covering light and charm $q$ physics with the same machine
- Photoproduction is a preferred production mechanism to unravel the internal structure
- Photon polarisation is a key tool in disentangling production mechanisms
- Interpretation requires theory support
- Luminosity is an issue ...

Pentaquarks candidates from LHCb

JPAC interpretation:
Virtual state in the $\Sigma^+_c \bar{D}^0$ channel

Pentaquark @ JLab

Not surprising the GlueX observed no signal of $P_c$: $\sigma(\gamma p \rightarrow J/\psi p) = O(1 \text{ nb}) \gg 10^2 \times \sigma(e^- p \rightarrow P_c \text{ + anything})$, much higher statistics is needed.
Hadron Spectroscopy status

Modern Hadron Spectroscopy in the Snowmass 2021 Exercise

Summary of Topical Group RF07
(Rare Processes and Precision Measurements Frontier)
Richard Lebed, Arizona State University

The charmonium spectrum is crowded by states that do not fit into (p-bar) QM

The major experiments

Currently ongoing (with future upgrades approved or proposed), hadron spectroscopy is among major goals

- **LHCb** (CERN, E.U.) ✓
- **Belle II** (KEK, Japan) ✓
- **BESIII** (IHEP, China) ✓
- **GlueX** (JLab, U.S.) ✓

Currently running, hadron spectroscopy is a minor focus

- **CMS** (CERN, E.U.) ✓
- **ATLAS** (CERN, E.U.) ✓

Future facilities

- Electron-Ion Collider [EIC] (approved: BNL, U.S.) ✓
- Super Tau-Charm Facility (proposed: China) ✓
- **PANDA** (planned: FAIR, Germany)
- **JLab24** (proposed, U.S.) ✓

Recommendations from RF07

- **Continued & expanded support** for researchers at Belle II and BESIII:
  a big U.S. physics footprint for a small U.S. investment;
  training can be carried over to future Super Tau-Charm Facility

- **U.S. facilities: support & training** for junior researchers at GlueX,
  many of whom will then staff the upcoming EIC or possible JLab24

- **Support for U.S. cross experiment/theory initiatives** such as JPAC
to carry out intricate multi-level amplitude analyses

- **Support for U.S. multi-institution theory initiatives**, including lattice,
to broaden researchers’ perspectives and generate new collaborations

XYZ: Who ordered them?

$X Y Z P$ states have hadronic transitions to narrow charmonium states with surprisingly large rates

Some are explicitly 4-quark effects, e.g., $Z_c^+(3900) \rightarrow J/\psi \pi^+$

- **54** observed exotics, both tetraquarks and pentaquarks
- A naïve count estimates well over 100 more exotics are waiting to be discovered
- Light q spectrum shows exotic candidates too: $\pi_1(1600), f_0(1710), \Phi(2170)$
- Little is know about the internal structure
Z_c(3900) in CLAS24

In 50 days: 210k events

Similar exercise for:
- γ p → Λ Z_c(4000) → (p π) (J/Ψ K^+): 33k produced
- γ p → Λ c D^0 → (p π K^+) (π K^+): 450k produced
- To be folded in electron detection efficiency (min Θ_e)

<table>
<thead>
<tr>
<th>meson</th>
<th>σ (nb)</th>
<th>total branch ratio</th>
<th>#/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/Ψ</td>
<td>1.9</td>
<td>6%</td>
<td>21000</td>
</tr>
<tr>
<td>X(3872)</td>
<td>12</td>
<td>0.3%</td>
<td>3800</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>0.7</td>
<td>0.06%</td>
<td>33</td>
</tr>
<tr>
<td>Z_c(3900)</td>
<td>5.1</td>
<td>0.6%</td>
<td>4200</td>
</tr>
<tr>
<td>Z_c(4000)</td>
<td>1</td>
<td>0.4%</td>
<td>440</td>
</tr>
<tr>
<td>D^+Λ_c</td>
<td>100</td>
<td>0.25%</td>
<td>42000</td>
</tr>
</tbody>
</table>

- Overall acceptance ~12%
- ~25k Zc(3900) detected in 50 days (assuming 5900 pb^-1 corresponding to L=10^{35} cm^2 s^-1)
Heavy exotics with GLUEX

- Simulations performed with baseline GlueX-II spectrometer
- Assumes modest beam-line upgrades to handle higher energy electrons

- Ann extension of the current program seems to be possible
- Requires to detect large mom tracks
- Effect on resolution and PID as well as efficiency

S.Dobbs, J.Stevens

E(peak) = 16.5 GeV
P(peak) ≈ 35%

E(peak) = 10.5 GeV
P(peak) ≈ 70%

E(peak) = 9 GeV
P(peak) ≈ 80%

E(e−) = 22 GeV

γn → J/ψπ−p, J/ψ → e+e−

E(e−) = 17 GeV

Zc(3900)

E(e−) = 22 GeV

Zc(3900)

- Assumes 1 year @ 500 pb−1, Br(Zc− → π−J/ψ) = 5%
- N(Zc(3900)J/ψπ−): 17 GeV = 1700, 22 GeV = 3400
- Uses JPAC prediction, assumes pure neutron target
Physics opportunities: SIDIS/TMD

SIDIS @JLAB

- JLab12: a leading provider of information on 3D nucleon structure
- Dihadron production: qualitatively new opportunities to study the non-perturbative QCD
- Understanding the hadronization process
- Measurement of multiplicities and spin azimuthal asymmetries for all combinations of beam and target polarizations to access underlying TMDs

Opportunities with 24 GeV

- Enhancing the range in transverse momentum $P_T$ of hadrons
- Enhancing the $Q^2$ range
- Enhancing the $x$-range

JLab 6 GeV to 12 GeV upgrade as an example

Observation of SSAs in $ep \rightarrow e' \pi^+ \pi^- X$


$$d\sigma_{LU} \propto \lambda e \sin(\phi_R) \left( xe(x)H_1^u(z, M_h) + \frac{1}{2} f_1(x)G_1^u(z, M_h) \right)$$

Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons

Quark gluon correlations may be very significant

CLAS12 kinematical coverage

$K_T$-dependence $g_1(x, k_T)$

$Q^2$-dependence of Sivers $f_1^+(x, k_T)$

• Large acceptance of CLAS12 allows studies of $P_T$ and $Q^2$-dependence of SSAs in a wide kinematic range (most critical for TMD studies)

• Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down transverse momentum dependence and the non-trivial $Q^2$ evolution of TMD PDFs in general, and Sivers function in particular.

CLAS6

COMPASS HERMES/JLab25

JLab12
Physics opportunities: SIDIS/TMD

- Possible to more cleanly separate pure twist-2 CFFs with suppressed higher twist (3) contributions
- The relevant $Q^2$ range for the $Q_n$ scaling test significantly increases with 18/22 GeV beam

Increase of $Q^2$ range

Increase of $P_T$ range

- TMDs universal, so what is the origin of the difference observed?
- What is the origin of the “high” $P_T$ (0.8-1.8) tail? Perturbative/non perturbative contributions? significantly increases with 18/22 GeV beam
- JLab: not enough energy to produce large $P_T$
- HERMES: not enough luminosity to access large $P_T$

Larger $P_T$ range and high luminosity is the key for a better insight
Physics opportunities: GPD and exclusive reactions

- Exp and theor. motivations
- Nucleon tomography: GPD, TMD, PDF, FF, ...
- Nucleon angular momentum
- Forces distribution in the proton: Gravitational FF
- DVCS as leading exclusive channel to extract GPDs
- proton and neutron data
- Observables: Xsec (Hall-A/C), Asym (Hall-B)
- Lattice progress
- Role of higher twists
- Future:
  - polarized positron beam: charge asymmetry
  - hi-lumi: DDVCS
  - higher energy: extended kinematics

Multi-dimensional mapping of the nucleon

A complete picture of nucleon structure requires the measurement of all these distributions.
Physics opportunities: nuclear structure

Nuclear PDFs
- Large coverage in valence region
- Significant contribution expected

Nuclear DVCS
- Coherent He DVCS
- Large SBA observed

Hadronization
- Fragmentation dynamics
- Transport coefficient

Alert
- A Low Energy Recoil Tracker
- Tagging nuclear reactions

Nuclear Structure @ JLab
- Nuclear structure still remains to be understood (EMC)
- Use both structure functions (PDF, GPD, TMD, …) and other measurements (SRC, hadronization, x>1, …)

Short Range Correlations
- pn dominance observation
- 3N SRC will be studied at hi-lumi/hi-E

Incoherent He DVCS
- Unexplained behaviour
- A new kind of EMC effect?

Color Transparency

Nuclear TMDs

Incoherent DVCS
Physics opportunities: BSM

Expanding the Primakoff program @ 24 GeV
- Precision measurement of decay width $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ and transition form factor $F(\pi^0 \rightarrow \gamma\gamma)$ via the Primakoff effect off an electron target
- Measure neutral axial coupling of proton via Primakoff effect
- Search for new sub-GeV gauge bosons (scalars and pseudoscalars) via the Primakoff production

Beyond hadronic physics with secondary beams at 24 GeV
- LDM (if it exists): extension of the BDX experiment
- Neutrino beam: up to $10^{18}$ nu/year/mq, with Decay-At-Rest Energy spectrum
- Muon beam: focused beam, up to $10^{10}$ mu/s with energy up to 14 GeV
- Extension of e4nu program successfully running at 12 GeV

Searching for Light Dark Matter in a Beam-Dump experiment
- Extension of the current LDM searches at 24 GeV
- Unique sensitivity to LDM scenarios (inelastic LDM)
- Complementarity to the current program
CLAS12 HI-LUMI upgrade

- CLAS12 High Luminosity operation included in the Lab Agenda
- Upgraded tracker (DC to μ-RWELL)

μ-RWELL features and performance:
- Compactness
- Easy assembly and powering
- Intrinsic spark quenching
- Gas gain: $10^4$
- Rate capability HR version: 10 MHz/cm²
- Rate capability LR version: 100 kHz/cm²
- Spatial resolution: down to 60 μm
- Time resolution: 5-6 ns

Rate requirements:
- Upgrade stage 1: average 5 kHz / cm², maximum rate ~7kHz / cm²
- Upgrade stage 2: average 15 kHz / cm², maximum rate ~20kHz / cm²
- Largest chamber 1500 cm x 50 cm

Same technology proposed for EIC: barrel tracker and low mass end cap (and PRAD-II)

Summary: Goals for the Upgrades

- Stage-1: Achieve luminosity of $2 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$ for normal CLAS12 running with charged particle reconstruction efficiency of >85%
  Can be achieved within 3 years with budget of $5-2M$

- Stage-2: Define a configuration of CLAS12 operations for two orders of magnitude higher luminosity, > $10^{37} \text{cm}^{-2} \text{s}^{-1}$
  More MC studies, detector R&D and engineering are needed. TF conclusion, can be done in 7-10 years time frame with under $10M$ budget.
JLAB positron beam

- Positron beam of high energy (up to 11 GeV), high current ($I_{e^+}$~0.5-1uA), high polarisation ($P_{e^+}$~60%)

From JLab PAC48 Report:
“The Committee sees great physics potential in a positron program. We encourage a vigorous effort to explore the technical feasibility of providing positron beams, and we are looking forward to receiving further proposals in this area. Clearly, it is difficult at the present stage to predict the characteristics of positron beams that will be achievable.”
Light Dark Matter search with positron beams

A' Production mechanisms - e±

A’-strahlung

$\sim \varepsilon^2 \alpha^3$

NON-RESONANT annihilation

RESONANT annihilation

$\sim \varepsilon^2 \alpha^2$

$\sim \varepsilon^2 \alpha$

e± annihilation on thin target - PADME@JLAB

Missing mass search:
- Independent of A’ decay mechanism
- Bump hunt (monophoton@collider)
- Need a positron beam
- Limited $M_A$ accessible
- 1 GeV beam: $M_A < 31$ MeV
- 5 GeV beam: $M_A < 71$ MeV

Reusable PADME components:
- Target - PADME carbon target Calorimeter -
- Ecal meets all requirements of the experiment (energy resolution, angular resolution, size)
- Veto System - technology and front-end electronics from PADME veto can be reused

New equipment:
- DAQ system - suitable for a CW beam

e± annihilation on thick target

- Active beam-dump experiment (à la NA64 but with positron)
- Clear signal (peak) due to the annihilation: $M_A = \sqrt{2(m_e E_{max})}$
- Missing energy $\exp(e^- Z \rightarrow e+ Z' A'$ with $A'$ invisible)
- 11 e+ beam, low current
- Active target (calorimeter)
- Exclusion plots based on $10^{13}$ POT
- Detector: ECAL to measure $e+$, HCAL to veto
Conclusions

• JLab@12 GeV Physics program is in full swing
• High Luminosity upgrade in progress (CLAS12 x2) to reduce the run time for the current ops
• Positron beam under development: new opportunity in GPDs, two-photons and BSM physics programs
• CEBAF 20+ GeV upgrade is technical feasible
• New physics opportunities at high energy:
  ‣ Hadron spectroscopy: XYZ states, using a photon beam to understand production mechanisms and structure
  ‣ SIDIS/TMD: significant enhancement of x and $Q^2$ range important for better interpretation of the current theory
  ‣ Exclusive reaction and Nuclear structure will benefit from a larger kinematic range
  ‣ BSM physics: unique opportunity to measure Primakoff scattering on electrons and extend LDM reach with secondary muon and neutrino beams
  ‣ Other topics: anti-shadowing phenomenon, precise charmonium production near threshold, …
• JLab at higher energy will bridge the current physics program to EIC hera

The lab and the user community are building the (bright) future of Jefferson Lab