Positron Program at Jefferson Lab

e+@JLab

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(i) Positron White Paper
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The EPJ A Topical Issue about an experimental positron program at CEBAF has been released and will be distributed by Jefferson Lab.

*D. Higinbotham, contact person*

- This document constitutes the final *JLab Positron White Paper*, gathering 19 single contributions and a summary article, all peer-reviewed.

(Jefferson Lab Positron Working Group) A. Accardi et al. EPJ A 57 (2021) 261
Experimental scenarios for DIS, VCS ($\gamma^* p \rightarrow \gamma p$), and CLFV ($e^+ N \rightarrow \mu^+ X$) need further evaluation.

Opportunities for polarized target experiments would deserve more considerations.

TPE Physics in elastic scattering globally asks for low beam energies,

Nucleon Structure Physics and Beyond the Standard Model Physics ask for high beam energies.
Experimental scenarios for DIS, VCS \((\gamma^*p \rightarrow \gamma p)\), and CLFV \((e^+N \rightarrow \mu^+X)\) need further evaluation.

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TPE Physics in elastic scattering globally asks for low beam energies,

Nucleon Structure Physics and Beyond the Standard Model Physics ask for high beam energies.
Assuming 36 weeks/year of beam and 50% accelerator efficiency, this is 4.8 years of running.

Operating Hall D with a positron beam is currently studied to understand, among others, the effect of $e^+$ annihilation on the photon energy profile and polarization.
Measurements of polarization transfer observables in electron elastic scattering off protons question the validity of the 1γ exchange approximation (OPE) of the electromagnetic interaction.

If TPE, the electromagnetic structure of the nucleon would be parameterized by 3 generalized form factors i.e. 8 unknown quantities.

TPE can only be calculated within model-dependent approaches.

e⁺ @ JLab have the unique opportunity to bring a definitive answer about TPE.
A modified CLAS12 hosting an electromagnetic calorimeter in place of the Central Neutron Detector maps out the $2\gamma$-effects in the $(Q^2, \varepsilon)$ space, providing a conclusive answer about the relevance of $2\gamma$-effects.

\[ R_{2\gamma} = \frac{\sigma_{e^+}}{\sigma_{e^-}} \approx 1 + \delta_{2\gamma} \]
Generalized Parton Distributions (GPDs) encode the correlations between partons and contain information about the internal dynamics of hadrons which express in properties like the angular momentum or the distribution of the forces experienced by quarks and gluons inside hadrons.

\[
\rho_H^q(x, b_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i b_\perp \cdot \Delta_\perp} [H^q(x, 0, -\Delta^2_\perp) + H^q(-x, 0, -\Delta^2_\perp)]
\]

\[
\lim_{t \to 0} \int_{-1}^{1} x [H^q(x, \xi, t) + E^q(x, \xi, t)] \, dx = J^q
\]

\[
\int_{-1}^{1} x \sum_q H^q(x, \xi, t) \, dx = M_2(t) + \frac{4}{5} \xi^2 d_1(t)
\]

- Unpolarized e\(^+\) combined with unpolarized e\(^-\) access the real part of the Compton Form Factors.
- Polarized e\(^+\) combined with polarized e\(^-\) access the imaginary part of the Compton Form Factors (CFFs) and higher twist effects.
Because of the virtuality of the final photon, DDVCS allows a direct access to GPDs at $x \neq \pm \xi$, which is of importance for their modeling and for the investigation of nuclear dynamics through sum rules.

$$F(\xi', \xi, t) = \mathcal{P} \int_{-1}^{1} dx \, F_+(x, \xi, t) \left[ \frac{1}{x - \xi'} \mp \frac{1}{x + \xi'} \right] - i\pi F_+(\xi', \xi, t)$$

$$F_+(x, \xi, t) = \sum_q \left( \frac{e_q}{e} \right)^2 \left[ F^q(x, \xi, t) \mp F^q(-x, \xi, t) \right]$$

Following the sign change of $\xi'$ around $Q'^2=Q^2$, the CFF $\mathcal{H}$ and $\mathcal{E}$ change sign, providing a testing ground of GPDs universality.
The lepto-production of a lepton-pair off the nucleon involves two Bethe-Heitler like mechanisms.

Integrating over the lepton-pair angles provides a beam charge and polarization dependence similar to DVCS.

\[ d^7\sigma_P = d^7\sigma_{BH1} + d^7\sigma_{BH2} + d^7\sigma_{DDVCS} + P\ d^7\tilde{\sigma}_{DDVCS} - e\left[d^7\sigma_{BH12} + d^7\sigma_{INT1} + P\ d^7\tilde{\sigma}_{INT1}\right] + d^7\sigma_{INT2} + P\ d^7\tilde{\sigma}_{INT2} \]
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\[
d^7\sigma_P^e = d^7\sigma_{BH_1} + d^7\sigma_{BH_2} + d^7\sigma_{DDVCS} + P d^7\tilde{\sigma}_{DDVCS} - e \left[ d^7\sigma_{BH_12} + d^7\sigma_{INT_1} + P d^7\tilde{\sigma}_{INT_1} \right] + d^7\sigma_{INT_2} + P d^7\tilde{\sigma}_{INT_2}
\]

\[
d^5\sigma_P^e = d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} + P d^5\tilde{\sigma}_{DDVCS} - e \left[ d^5\sigma_{INT_1} + P d^5\tilde{\sigma}_{INT_1} \right]
\]
Nucleon tomography

LoI12-15-005
M. Boer, A. Camsonne, K. Gnanvo, E. Voutier, Z. Zhao et al.

S. Zhao et al. EPJ A 57 (2021) 240

- The SoLID apparatus completed with muon detectors at large and forward angles, enables DDVCS measurements with both polarized electron and polarized positron beams.

- The initial Lol discussed electron BSA measurements over a 50 days run parasitic to the J/Ψ approved experiment.
- Completing this program with a 50 days positron beam run would provide unpolarized BCA data.
Pseudo-data are generated from an extended VGG version including all CFFs.

A local fit method at the leading twist and leading order is applied to experimental observables, considering 8 unknown CFFs and electron only or electron and positron scenarios.

**Positron beams improve CFF determination, particularly Re[H].**

A minimal luminosity of $10^{37} \text{ cm}^{-2}\text{s}^{-1}$ is needed to cover efficiently the accessible phase space.
Deep inelastic scattering

Structure functions

- Charged and electromagnetic currents access different quark flavor combinations.
- High luminosity and polarization capabilities may compensate the small center-of-mass energy at CEBAF, and enable access to charged current physics.

\[
\frac{d^2\Delta\sigma_{PL}^e}{dx\,dy} = \frac{1}{2} \left[ \frac{d^2\Delta\sigma_{P(-1)}^e}{dx\,dy} - \frac{d^2\Delta\sigma_{P(+1)}^e}{dx\,dy} \right] = -\frac{4\pi\alpha^2}{yQ^2} (1 + eP)^2 \left( G_F \frac{M_W^2}{4\pi\alpha} \frac{Q^2}{Q^2 + M_W^2} \right)^2 [Y + g_{5W}^e + eY_1 g_{1W}^e]
\]

Polarized electron off protons

\[\begin{align*}
g_{1W}^- &= \Delta u + \Delta \bar{d} + \Delta s + \Delta c \\
g_{5W}^- &= -\Delta u + \Delta d + \Delta \bar{s} - \Delta c \\
g_{1W}^+ &= \Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c} \\
g_{5W}^+ &= \Delta \bar{u} - \Delta d - \Delta s + \Delta \bar{c}
\end{align*}\]

Leading order

Direct access to \(\Delta\Sigma\)

\[g_{1W}^- + g_{1W}^+ = \Delta\Sigma\]

Access to the polarized strange PDF free of hadronization ambiguities

\[g_{5W}^- (p) - g_{5W}^- (n) + g_{5W}^+ (n) - g_{5W}^+ (n) = 2[\Delta c + \Delta \bar{c}] - 2[\Delta s + \Delta \bar{s}]\]
Deep inelastic scattering

Strangeness Tagging

W. Melnitchouk, J.F. Owens, EPJ A 57 (2021) 311

- Charm production via charged current exchange preferentially couples to the strange content of the nucleon.

\[ e^+ + p \rightarrow \bar{\nu}_e + c + X \quad e^- + p \rightarrow \nu_e + \bar{c} + X \]

- While the physics interest of this channel has been established, a realistic experimental scenario is yet to be elaborated and evaluated.
Comparing unpolared electron and positon DIS scatterings accesses the $C_{3q}$ axial-axial neutral current coupling, and the $F_{3}^{YZ}$ structure function.

$$L = \frac{G_F}{\sqrt{2}} \sum_q \left[ C_{1q} \ell \bar{\gamma}^\mu \gamma_5 \ell \bar{q} \gamma_\mu q + C_{2q} \ell \bar{\gamma}^\mu \gamma_5 \ell \bar{q} \gamma_\mu q + C_{3q} \ell \bar{\gamma}^\mu \gamma_5 \ell \bar{q} \gamma_\mu q \right].$$

$$A_{d}^{e^+e^-} \approx -108 Y(\gamma) R_q(x)(2C_{3u} - C_{3d}) Q^2 \quad \text{(in ppm/GeV^2)}$$

$$A_{d}^{e^+e^-} = \frac{d\sigma(e^+d) - d\sigma(e^-d)}{d\sigma(e^+d) + d\sigma(e^-d)}$$

$$A_{d}^{e^+e^-} = \frac{G_F g_A^e}{2\sqrt{2} \pi \alpha} \frac{F_{3}^{YZ}}{F_1} Q^2$$

\[PR12-21-006\]

(SoLID and Hall A Collaborations) X. Zheng et al.

In the Lepto-Quark (LQ) scenario, up to 14 different LQs may mediate transitions between quarks and leptons.

- Electron and positron beams have **different sensitivity** to LQs.
- Beam **polarization** would distinguish between left- and right-handed LQs.
Towards $e^+$ beams @ CEBAF

- The JLab positron source built on the **PEPPo** (Polarized Electrons for Polarized Positrons) experiment which demonstrated the feasibility of using bremsstrahlung radiation of **MeV Polarized Electrons** for producing Polarized Positrons.

\[ p_e = 8.2 \text{ MeV/c} \quad P_e = 85\% \quad I_e = 1 \mu\text{A} \quad t_W = 1 \text{ mm} \quad \mathcal{P} < 10 \text{ W} \]

(PEPPo Collaboration) D. Abbott et al. PRL 116 (2016) 214801

J. Grames, E. Voutier et al. JLab Experiment E12-11-105 (2011)
The design of the JLab positron source evolved towards the today’s latest concept:

- High duty cycle, intensity, and polarization distinguish JLab positron beam from any past or existing others.
The design of the JLab positron source evolved towards the today’s latest concept:

- Momentum Selection Chicane
- Beam Compression Chicane
- Positron Production Target

$P = 120 \text{ kW}$

beam power

Nominal
- $I_{e^+} > 100 \text{ nA} @ P_{e^+} = 60\%$
- $I_{e^+} > 3 \mu\text{A} @ P_{e^+} = 0\%$

Very challenging
- $I_{e^+} = 1 \mu\text{A} @ P_{e^+} = 60\%$
- $I_{e^+} = 10 \mu\text{A} @ P_{e^+} = 0\%$

*High duty cycle, intensity, and polarization* distinguish JLab positron beam from any past or existing others.
Towards $e^{+}$ beams @ CEBAF

- The positron yield ($e^{+}/e^{-}$) scales with the beam power ($\text{Beam Energy} \times \text{Beam Intensity}$) and depends on the thickness of the production target.

- It is sensitive to the collection system characteristics which can be mimic by an angular and a momentum acceptance.

- Selection of $e^{+}$ momentum allows to operate the source from low to highly polarized modes.

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Towards $e^+$ beams @ CEBAF

1/6 segment of the $e^+$ target

- The electron beam deposits a power of **17 kW** in the **4mm** W target.
- The water channel with turbulent water flows at a speed of **2 m/s** and a **22°C** inlet temperature.
- The beam spot RMS size is **1.5 mm**.
- The rotation speed of the target is **4 m/s**.

- The tungsten target will operate at an **average temperature** of **258°C** with a **peak temperature** at **376°C** at each rotation cycle.
- The cooling water reaches a temperature of **61°C**.
- The expected life time of the target is a bit more than **1 year** equivalent CEBAF operation.
Towards $e^+$ beams @ CEBAF

- A FODO lattice combined with a matching section at the entrance ensure the smallest beam size and the largest momentum dispersion at the middle of the chicane where an efficient momentum collimation is achieved.

- A cavity at the entrance of a magnetic chicane creates a correlation between the momentum dispersion and the bunch length.
- The chicane is designed to feature the appropriate $R_{56}$ to optimally compress the bunch length ($\Delta z$).

$$p_0 = 60 \text{ MeV/c}$$

$$k = 3.81 \text{ m}^{-1}$$

$$C = 23.3$$

$$R_{56} = -0.25 \text{ m}$$

Work of Sami Habet (UCLab/JLab) and of Yves Roblin (JLab)
Other challenges to address:

- **Reduction of beam emittance** and **momentum dispersion** at the source;
- Polarized electron gun capable of **1 mA** currents with a life time > **1 kC**;
- High field (up to **2.5 T**) **DC solenoid** in high X-ray environment;
- High energy **spin rotators**;
- **Polarity reversal** of CEBAF magnets;
- **Transport of e**+** beams** to and into CEBAF;
- **e**+** beam diagnostics** and **polarimetry**.

A path towards **e**+**@CEBAF** is currently studied along the lines:

- Pursing **R&D** in all the areas required for **e**+**@CEBAF**;
- Constructing at the **LERF** a prototype **e**+** injector** operating with **8 MeV** electron beams;
- Producing **e**+** beams suitable** for **CEBAF acceleration**;
- Upgrade to the final **120 MeV e**+** injector**.
Towards $e^+$ beams @ CEBAF

- A **new tunnel** would transport the positron beams from the LERF to CEBAF.
- The **connection** would occur in the **arc region** dealing, among others with different beam elevations at the LERF and CEBAF.
A rich and high impact experimental program asking for intense CW polarized and unpolarized positron beams at JLab has been elaborated, accounting for about 5 calendar years of CEBAF running.

Such beams would be a worldwide « première ».

An R&D and construction plan is under progress, which goal is the production at the LERF of positron beams suitable for CEBAF acceleration within the 5 coming years.
A rich and high impact experimental program asking for intense CW polarized and unpolarized positron beams at JLab has been elaborated, accounting for about 5 calendar years of CEBAF running.

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An R&D and construction plan is under progress, which goal is the production at the LERF of positron beams suitable for CEBAF acceleration within the 5 coming years.

- Several challenges to address from beam production, instrumentation, and transport to experimental halls.
- The Positron White Paper is not exhaustive and there exists opportunities for many other channels.

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