Neutron DVCS

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Next generation of nuclear physics with JLab12 and EIC
Florida International University

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Outline

- Motivation of DVCS off the neutron

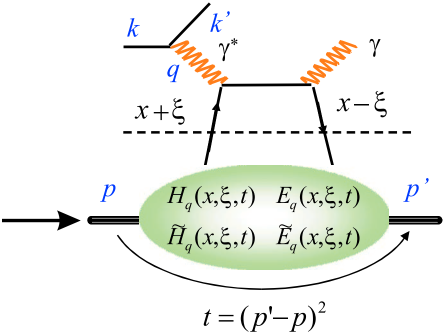
  and experimental challenges

- Experimental program at Jefferson Lab

- Recent (preliminary) results from Hall A

- Outlook at JLab12

Deeply Virtual Compton Scattering (DVCS): $\gamma^* \, p \to \gamma \, p$



Handbag diagram

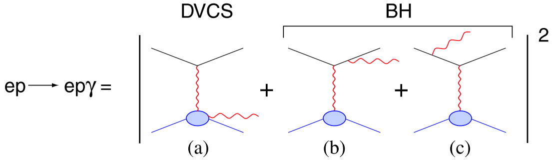
High Q^2
Perturbative QCD

Non-perturbative
GPDs

Bjorken limit:

$$\left.\begin{aligned} Q^2 = \quad -q^2 &\to \infty \\ \nu &\to \infty \end{aligned}\right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

DVCS experimentally: interference with Bethe-Heitler (BH)



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\left(T^{BH}\cdot T^{DVCS}\right)$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\left(T^{BH}\cdot T^{DVCS}\right) + |DVCS|^2$$

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}} - \underbrace{i\pi\, H(x=\xi,\xi,t)} + \ldots$$

Access in helicity-independent cross section — Access in helicity-dependent cross-section

Accessing different GDPs

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (ITSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B kF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BITSA)

$$d\sigma_{LL} = (A + B\cos\phi)\cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

Neutron DVCS

1. Flavor sensitivity of GPDs (when combined with proton DVCS)

$$\mathcal{I}m\mathcal{H} = -\pi\left(\frac{4}{9}H^u + \frac{1}{9}H^d\right) \qquad \text{(Proton)}$$

$$\mathcal{I}m\mathcal{H} = -\pi\left(\frac{1}{9}H^u + \frac{4}{9}H^d\right) \qquad \text{(Neutron)}$$

2. Enhanced sensitivity to GPD E (eg. with long. $\vec{e}$ off unpol. target)
   - LD_2 target ($F_2^n(t) \gg F_1^n(t)$!)

$$A = F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2}\cdot F_2(t)\cdot \mathcal{E}}_{\text{Main contribution for neutron}}$$

   $\tilde{\mathcal{H}}$ is expected small by compensation of u and d distributions in n

   - Contribution of the **angular momentum of quarks** to proton spin:

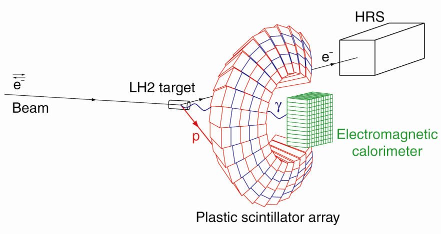
$$J = \frac{1}{2}\int_{-1}^{1} dx\, x[H(x,\xi,0) + E(x,\xi,0)]$$

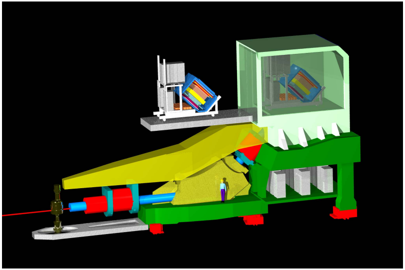
The n-DVCS program at Jefferson Lab

- Hall A:
    - E03-106: Beam helicity-dependent DVCS cross section
    - E08-025: Beam helicity-independent DVCS at 2 beam energies
- Hall B:
    - E12-11-003: Beam spin asymmetries with CLAS12

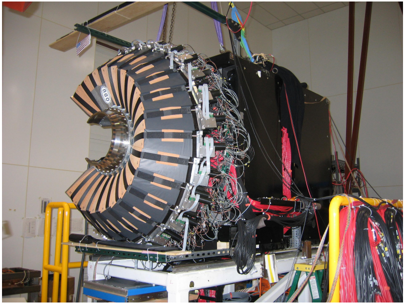
Hall A DVCS experimental setup

High Resolution Spectrometer

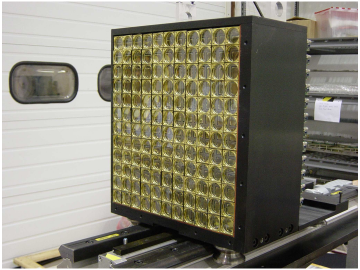




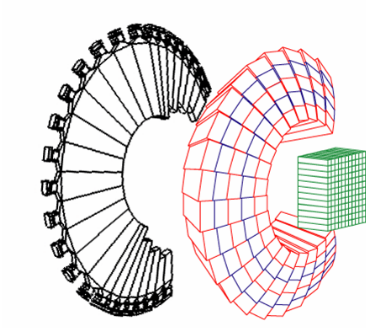
100-channel scintillator array



132-block PbF_2 electromagnetic calorimeter



Neutron detection (proton veto)

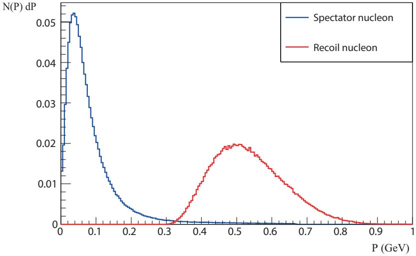


Charged particle veto in front of scintillator array:

- Proton: signal in both detectors
- Neutron: signal only in thick scintillator

Impulse approximation

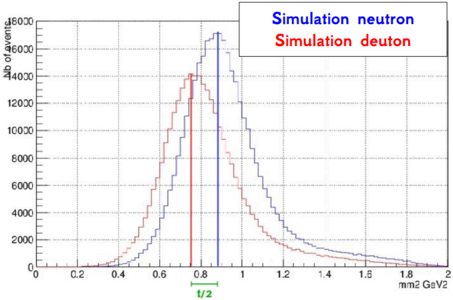
$$D(\vec{e}, e'\gamma)X = d(\vec{e}, e'\gamma)d + n(\vec{e}, e'\gamma)n + p(\vec{e}, e'\gamma)p + \dots$$



FSI between the np pair should be small

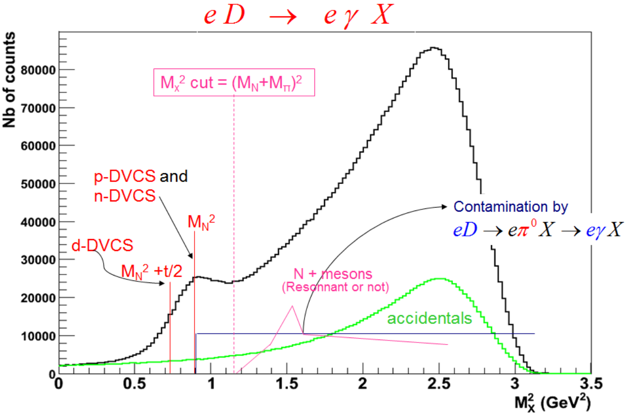
Neutron and coherent deuteron

$$M_X^2 = (n + q - q')^2 = M_n^2 + \left(1 - \frac{M_n}{M_d}\right) t \simeq M_n^2 + \frac{t}{2}$$



Coherent d separated using kinematical separation in the M_X^2 spectrum

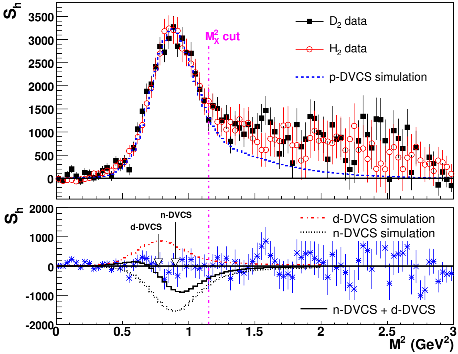
Missing mass & exclusivity



Exclusivity ensured by a cut at the π-production threshold

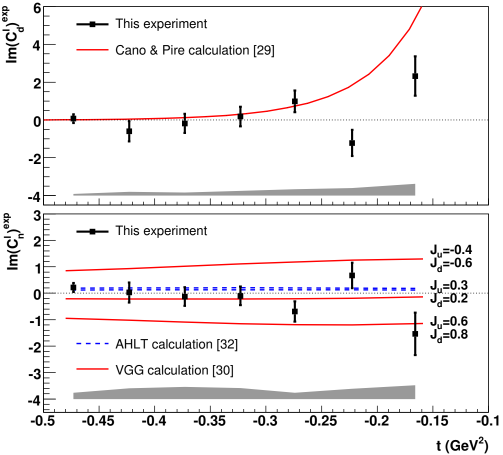
Helicity signal

$$S_h = \int_0^{\pi} (N^+ - N^-)\, d\phi - \int_{\pi}^{2\pi} (N^+ - N^-)\, d\phi \,,$$

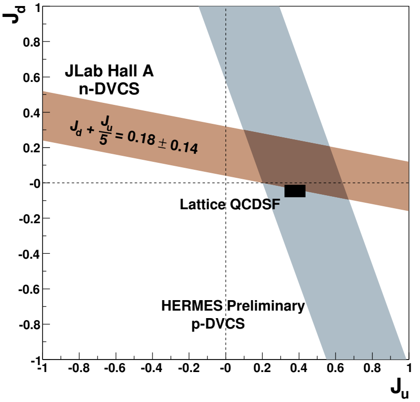


No significant signal after LD_2–LH_2 subtraction

E03-106 results



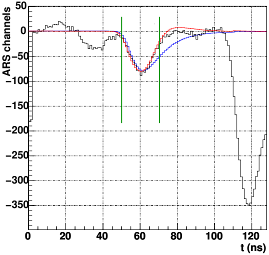
Model-dependent sensitivity to J_u, J_d



Helicity-dependent nDVCS cross-section compatible with zero, BUT still sets constraints to GPD combinations (and J_u, J_d models. . .)

E03-106: lessons learnt

- LD_2–LH_2 subtraction very sensitive to calorimeter calibration (drifts)
  LD_2 and LH_2 running should be interleaved
- Significant contamination from π^0's that was hard to subtract
  high γ threshold → **reduced with improved trigger+electronics**
- Recoil particle detection/tagging extremely difficult at high luminosity

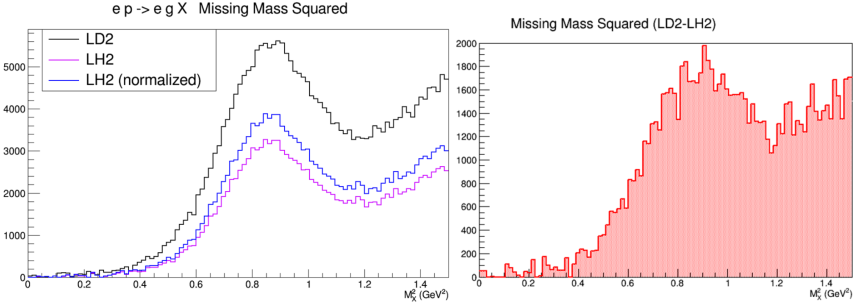


- Large background + low recoil momentum
- Charge exchange reaction difficult to measure/estimate

No recoil detector anymore → **less deadtime and higher statistics**

E08-25 nDVCS experiment

- Ran in 2010
- No recoil detection → higher luminosity
- Improved trigger and DAQ → reduced deadtime
- Interleaved LD_2 and LH_2 running



$Q^2 = 1.75$ GeV^2, $x_B = 0.36$ at $E_b = 4.45$ and $E_b = 5.55$ GeV

C. Desnault's PhD thesis

Analysis method

$$\sigma = |BH|^2 + \Gamma_0(x_B, Q^2, t, \varphi) 1 C_0(\xi, t) + \Gamma_1(x_B, Q^2, t, \varphi)\ C_1(\xi, t)\ \cos\varphi + \Gamma_2(x_B, Q^2, t, \varphi)\ C_2(\xi, t)\ \cos 2\varphi$$

$$\xi \simeq \frac{x_B}{2 - x_B}$$

$\boxed{C_i(\xi, t)\text{: combinations of GPDs}}$

$$\begin{aligned} N^{\mathrm{Exp}}(\mathbf{i}_e) &= N_{\mathbf{i}_e} - N^{BH}_{\mathbf{i}_e} \\ N^{\mathrm{MC}}(\mathbf{i}_e) &= \mathcal{L}\Big[\sum_i C_i \underbrace{\int_{x \in \mathbf{i}_e} \Gamma_i \cdot \cos(i\varphi) \otimes \text{Acc.}}_{\text{MC sampling}} \Big] \end{aligned}$$

- MC includes real radiative corrections (both external and internal).

$$\chi^2 = \sum_{\mathbf{i}_e} \frac{\left[N^{\mathrm{Exp}}(\mathbf{i}_e) - N^{MC}(\mathbf{i}_e)\right]^2}{\left[\sigma^{\mathrm{Exp}}(\mathbf{i}_e)\right]^2} \Rightarrow \left\{ \begin{array}{l} C_0 \\ C_1, \ldots \end{array} \right.$$

Rosenbluth-like separation of the DVCS cross section

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$
$$\left|\mathcal{T}^{DVCS}\right|^2 \propto 1/y^2 = (k/\nu)^2$$

BKM-2010 – at leading twist $\to$ 7 independent GPD terms:

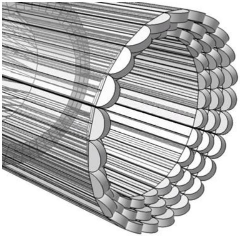
$$\left\{\Re\mathrm{e}, \Im\mathrm{m}\left[\mathcal{C}^{\mathcal{I}}, \mathcal{C}^{\mathcal{I},V}, \mathcal{C}^{\mathcal{I},A}\right](\mathcal{F})\right\}, \qquad \text{and} \qquad \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}*).$$

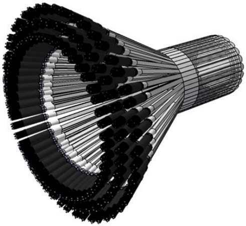
φ-dependence provides 5 independent observables:

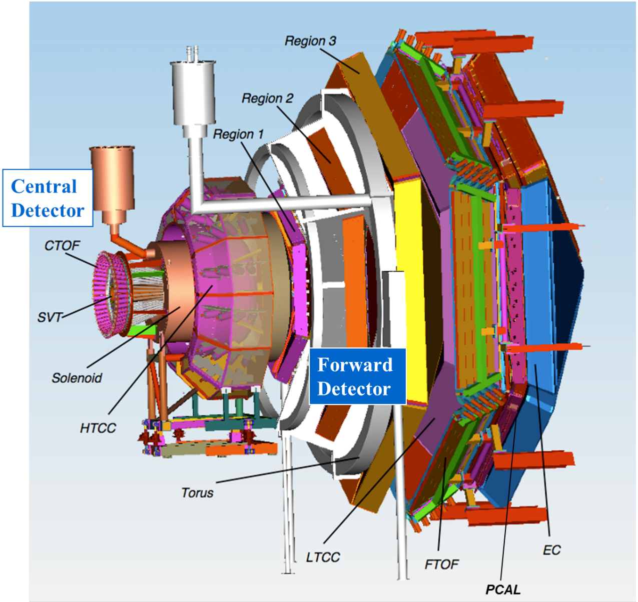
$$\sim 1, \sim \cos\varphi, \sim \sin\varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)$$

The measurement of the cross section at two or more beam energies for exactly the same Q^2, x_B, t kinematics, provides the additional information in order to extract all leading twist observables independently.

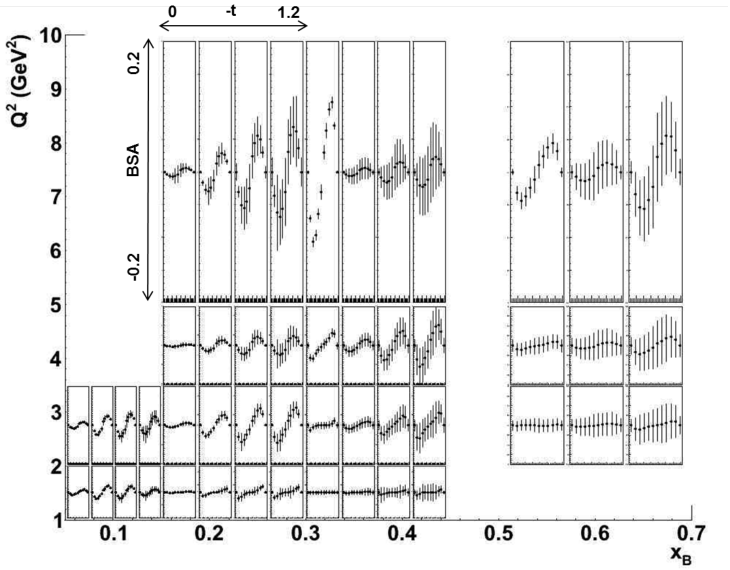
E12-11-003: DVCS sur le neutron avec CLAS12





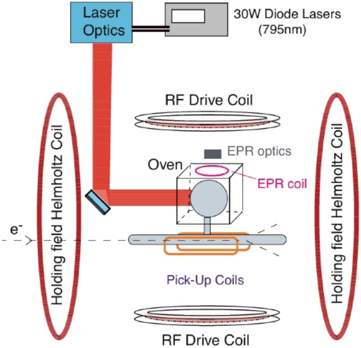


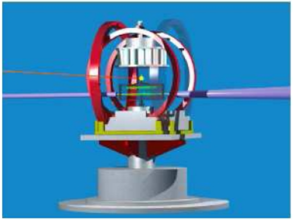
E12-11-003: projections



Polarized ^3He target

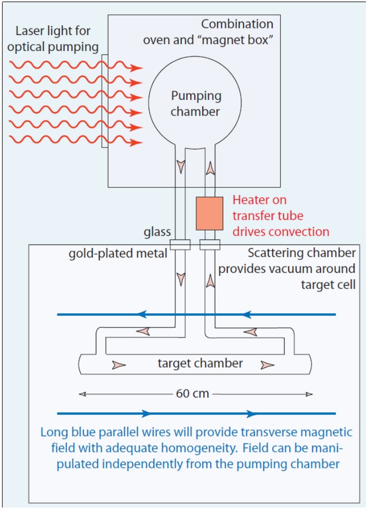
- n lum. of 10^{36}/cm^2/s (14 atm$\times$40 cm)
- "Background" luminosity:
  - p in ^3He + entrance/exit windows
  - 10^{37}/cm^2 total luminosity
- Polarization: 50%
  - Nuclear physics dilution factor 0.86 (d-state)
  - -2.8% p polarization
  - Long. & Trans.





^{3}He target upgrade

- Separate polarization and tgt volumes
  - Increase throughput by factor 10–100
  - Cool and/or compress ^{3}He in target area by a factor of 10 (10K at 10 atm$\times$20 cm)
  - Rapid cycling of ^{3}He through target
    - Reduce depolarization effect of tgt density, beam current, tgt walls
    - Replace thick glass with thin metallic walls
- Neutron luminosity of 10^{37}/cm^2/s
  - Proton luminosity $2 \cdot 10^{37}$/cm^2/s
  - Endcaps $\leq 10^{37}$/cm^2/s
- Target polarization: $0.5 \cdot (0.86n - 0.028p)$



DVCS on polarized neutron

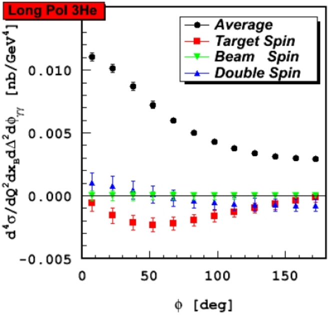
$$\vec{n}(\vec{e}, e'\gamma) \qquad \text{via} \qquad {}^3\vec{H}e(\vec{e}, e)X$$

- Long or Trans normal polarization
- Target single spin cross sections
  - $d\sigma \sim \sin\phi$ (twist-2): $\mathcal{I}$m[BH·DVCS]
  - Unpolarized protons in ^{3}He cancel
- Target double spin
  - $d\sigma \sim c_0 + c_1 \cos\phi$: $\mathcal{R}$e[BH^2+(BH·DVCS)+DVCS^2]
  - Unpolarized protons cancel
- Transverse sideways: $\sin\phi \longrightarrow \cos\phi$
- All other “neutron” observables (total σ, beam-spin) have large incoherent proton contributions

Cross section projections (at 10^{37} cm^{-2}s^{-1})

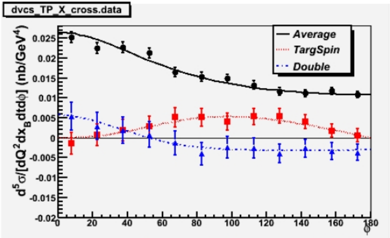
$Q^2 = 4$ GeV^2, $x_B = 0.36$, $k = 8.8$ GeV,

$t_{min} - t = 0.15$ GeV^2, 20 days

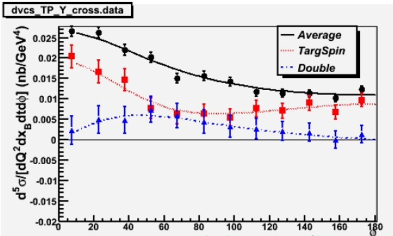


- 50%×80% polarization

$Q^2 = 2.3$ GeV^2, $x_B = 0.36$, $k = 8.8$ GeV, $t = -0.26$ GeV^2, 10 days



Polarization sideways ($\|$) to (e, e') plane



Polarization normal ($\perp$) to (e, e') plane

C. Hyde

Summary

- Neutron DVCS is a required complement to the proton program:
  - Flavor separation of GPDs
  - Access to different combinations of GPDs
- Very challenging experimentally:
  - Difficult to detect at high luminosities
  - Efficiencies, charge exchange, etc hard to estimate
- Hall A program in Hall A provided some initial results and contraints
- Approved program with CLAS12 off unpolarized neutrons
- Possibilites of polarized nDVCS with high luminosity ^{3}He target

Acknowledgements

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