Measurement of the Helicity Difference in Double - Pion Photoproduction using the CLAS Spectrometer at Jefferson Laboratory

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Prospectus of Dissertation
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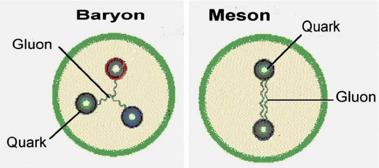
Outline

Outline

What are hadrons?

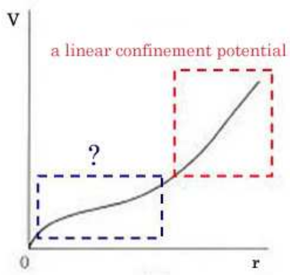
Hadrons are composed of quarks bound by the strong interaction.

- Baryon: qqq
- Meson: $q\bar{q}$



Quantum Chromodynamics (QCD)

- The theory of how quarks and gluons interact with themselves and each other



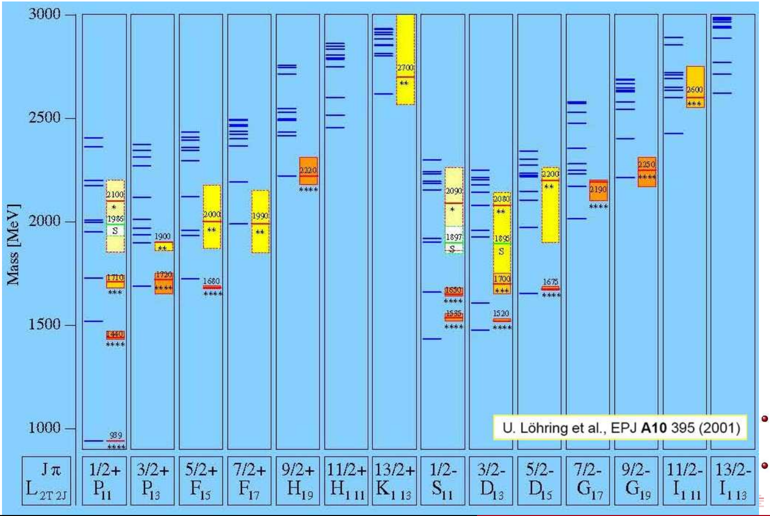
Constituent quark models (QCD-based models)

as the short-range interaction between quarks.

- Gluon-exchange models
- One-boson exchange models
- Instanton-based models

The excited states of the nucleon

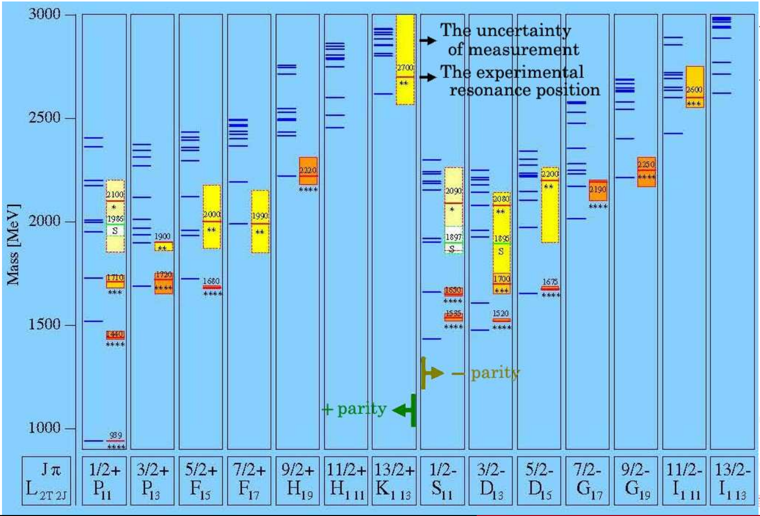
Constituent quark models based on instanton



- The number of $*$'s indicates the ranking of the state according to the particle data group (PDG).
- The four-star is a well established resonance.

The excited states of the nucleon

Constituent quark models: N^* resonances (Isospin $\frac{1}{2}$)



The left part of each column

- **model predictions**

The right part of each column

- **experimental findings**

$L^{J\pi}_{2T\,2J}$

- T Isospin
- π Parity
- J Total spin

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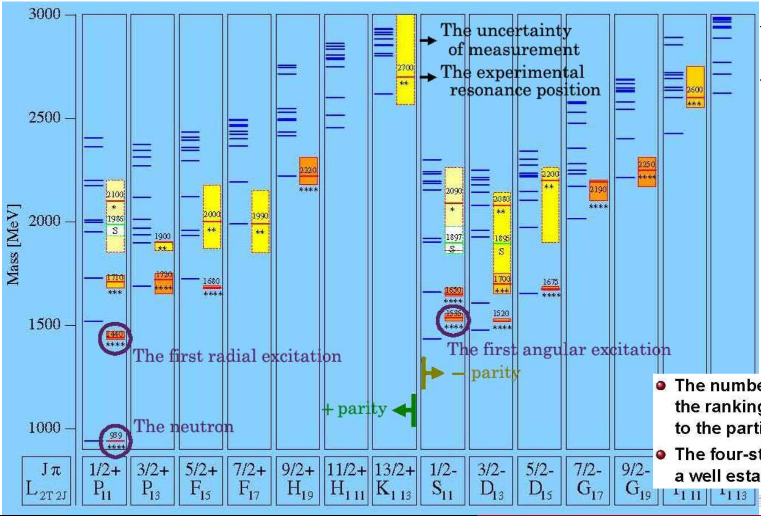

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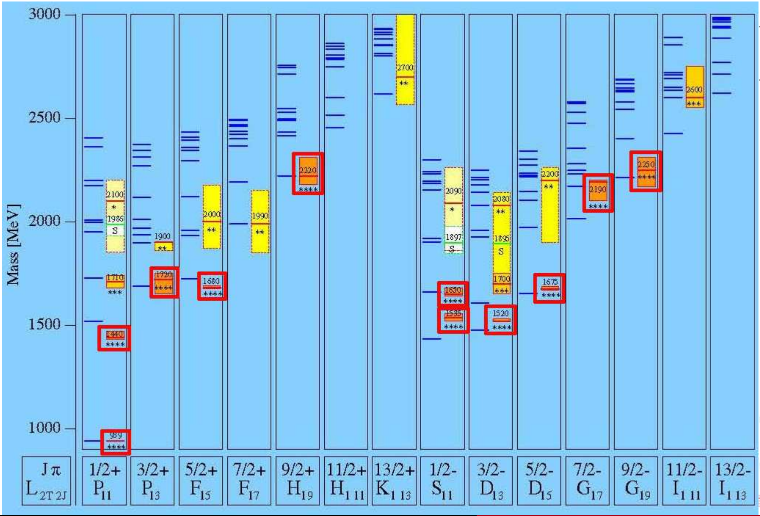

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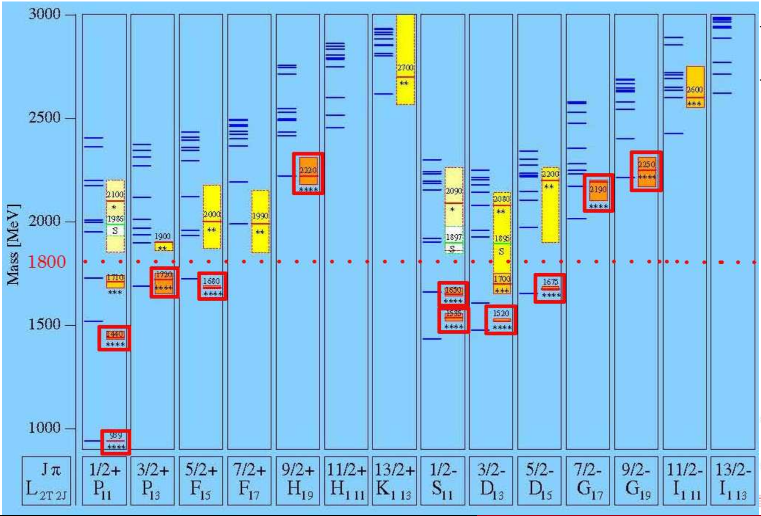

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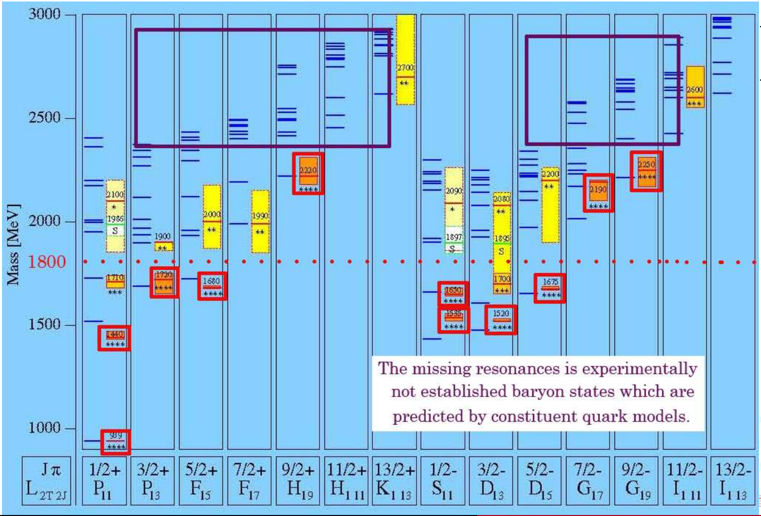

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Why have we not found these missing resonances?

Particle	$L_{2I \cdot 2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
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$N(1440)$	P_{11}	****	****	*			***	*	***
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$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****	*			****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
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$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
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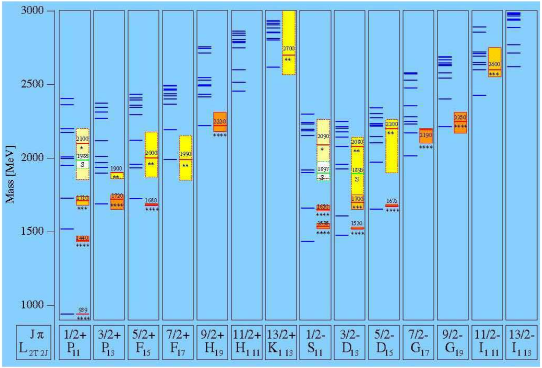

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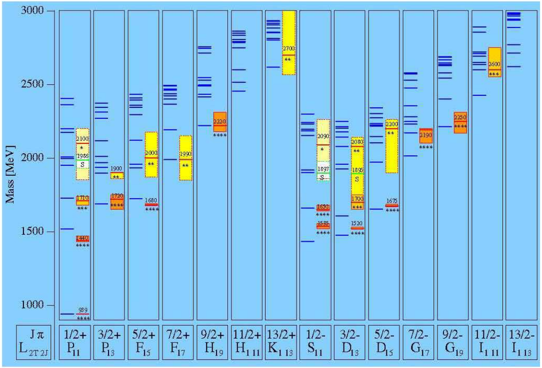

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The modes used in this work: $\gamma N \to N^\star \to \Delta\pi \to N\pi^+\pi^-$

$N\rho$

$N\gamma$

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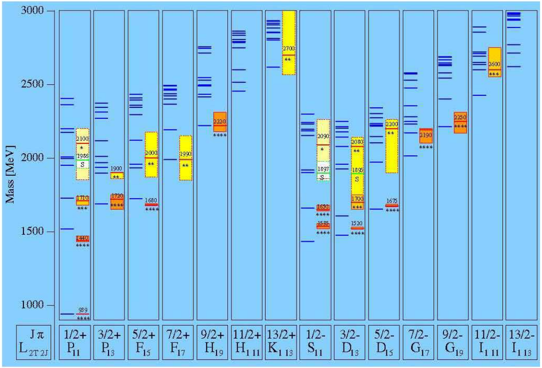

(B) Most channels explored until now include one meson in the final state.

The modes used in this work: $\gamma N \rightarrow N^{\star} \rightarrow \Delta\pi \rightarrow N\pi^{+}\pi^{-}$

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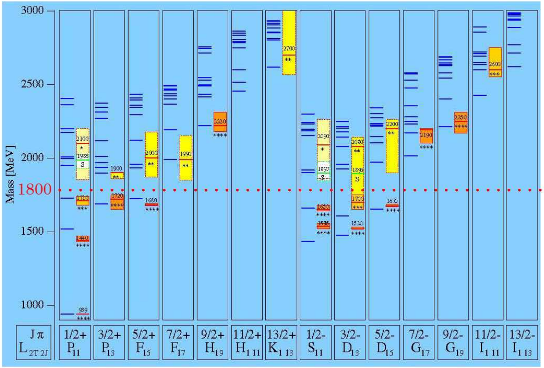

(C) Photoproduction data accumulated in recent years mainly cover masses up to 1800 MeV/c^2.

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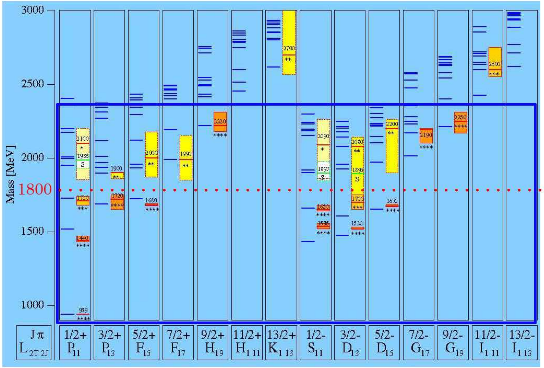
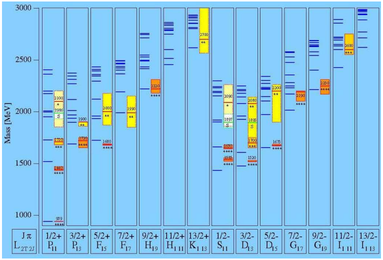


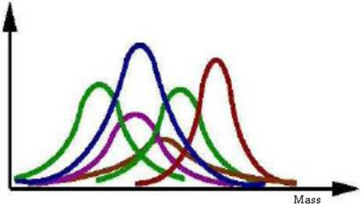
(C) Photoproduction data accumulated in recent years mainly cover masses up to 1800 MeV/c^2.
The CLAS-FROST experiment covers above 1800 MeV/c^2.

Why have we not found these missing resonances?

projection along the mass axis



$\Rightarrow$



The excited states are found as broadly overlapping resonances.

- We can isolate single resonances from these other interference terms by determining the polarization observables.

Motivation for this work

- The cross section of 3-body final states dominates above W $\approx$ 1.7 GeV
- The dominant resonant decay modes leading to $\gamma p \to p\pi^+\pi^-$ include $\Delta\pi$, $N\rho$, and $N\gamma$.

$$\gamma N \to N^\star \to \Delta\pi \to N\pi^+\pi^-$$
$$\gamma N \to N^\star \to N\rho \to N\pi^+\pi^-$$
$$\gamma N \to N^\star \to N\gamma \to N\pi^+\pi^-$$

$\Downarrow$

These modes are difficult to detect

- The need of detectors with a large angular acceptance
- The contribution of the large non-resonant background

$\Downarrow$

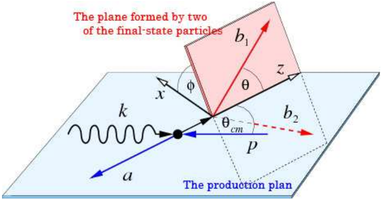
The CLAS-FROST experiment can be a solution of these problems.

- The CLAS spectrometer is nearly-4π detector

Outline

The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



The $\pi^-\pi^+$ final state requires 5 independent invariable.

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{d x_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_{\odot} (\mathbf{I}^{\odot} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\odot}) + \delta_l [\sin 2\beta (\mathbf{I}^{\mathbf{s}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{s}}) + \cos 2\beta (\mathbf{I}^{\mathbf{c}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{c}})] \}$$

- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- $\delta_{\odot,l}$: The degree of polarizaton of the photon beam
- $\vec{\Lambda}_i$: The polarization of the initial nucleon
- $\mathbf{I}^{\odot,\mathbf{s},\mathbf{c}}$: The observable arising from use of polarized photons
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The concept of physics for my dissertation

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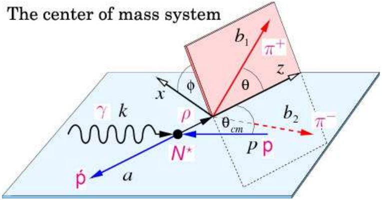

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$\gamma p \to N^\star \to$ ṕ $\rho \to$ ṕ $\pi^+\pi^-$

ϕ, θ_{cm}, k, $m_{p\pi^+}$, and $m_{\pi^+\pi^-}$

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The concept of physics for my dissertation

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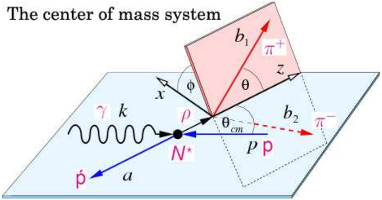

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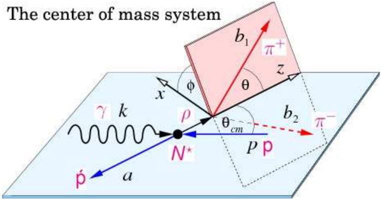
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



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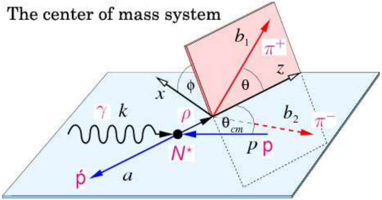

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$\gamma p \to N^\star \to \acute{p}\ \rho \to \acute{p}\ \pi^+\pi^-$

ϕ, θ_{cm}, k, $m_{p\pi^+}$, and $m_{\pi^+\pi^-}$

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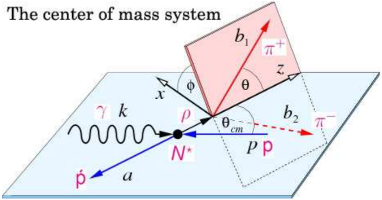
$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^{\mathbf{s}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{s}}) + \cos 2\beta (\mathbf{I}^{\mathbf{c}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{c}})] \}$$

- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- $\delta_{\odot,l}$: The degree of polarizaton of the photon beam $\Rightarrow \delta_\odot$, and δ_l
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $\mathbf{I}^{\odot,\mathbf{s},\mathbf{c}}$: The observable arising from use of polarized photons $\Rightarrow \mathbf{I}^\odot, \mathbf{I}^{\mathbf{s}}, \mathbf{I}^{\mathbf{c}}$
- $\vec{\mathbf{P}}$: The polarization observable

The concept of physics for my dissertation

The 3-particle final state for $\gamma p \to p\pi\pi$



The $\pi^-\pi^+$ final state requires 5 independent invariables.

$\gamma p \to N^\star \to$ ṕ $\rho \to$ ṕ $\pi^+\pi^-$

ϕ, θ_{cm}, k, $m_{p\pi^+}$, and $m_{\pi^+\pi^-}$

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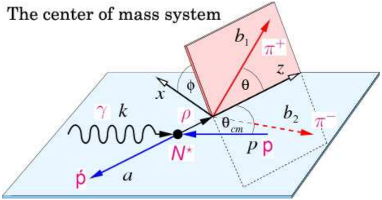
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



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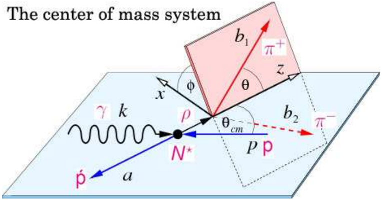
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



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$\gamma p \rightarrow N^\star \rightarrow ṕ\ \rho \rightarrow ṕ\ \pi^+\pi^-$

ϕ, θ_{cm}, k, $m_{p\pi^+}$, and $m_{\pi^+\pi^-}$

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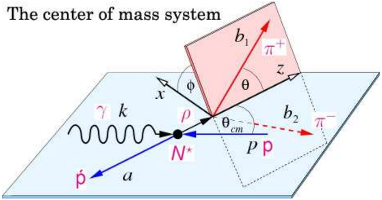
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



The $\pi^-\pi^+$ final state requires 5 independent invariables.

$\gamma p \rightarrow N^\star \rightarrow$ ṕ $\rho \rightarrow$ ṕ $\pi^+\pi^-$

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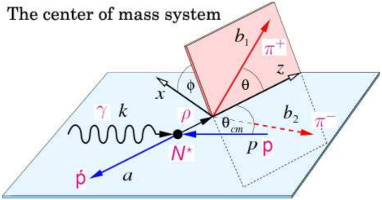
- $I^{\odot, s, c}$: The observable arising from use of polarized photons $\Rightarrow I^\odot, I^s, I^c$

15 observables

- $\vec{P}$: The polarization observable $\Rightarrow$ (P_x, P_y, P_z) $(P_x^\odot, P_y^\odot, P_z^\odot)$ (P_x^s, P_y^s, P_z^s) (P_x^c, P_y^c, P_z^c)

The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$



The combination of the beam and the target for my dissertation

- The circularly-polarized beam $\longrightarrow \delta_\odot$
- The longitudinally-polarized target $\longrightarrow \Lambda_z$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{d x_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

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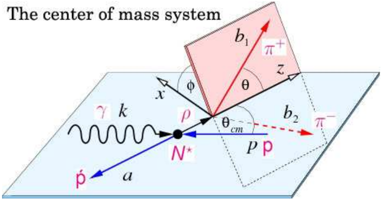
15 observables

- $\vec{\mathbf{P}}$: The polarization observable $\Rightarrow (\mathbf{P_x}, \mathbf{P_y}, \mathbf{P_z})$ $(\mathbf{P}_x^\odot, \mathbf{P}_y^\odot, \mathbf{P}_z^\odot)$ $(\mathbf{P}_x^s, \mathbf{P}_y^s, \mathbf{P}_z^s)$ $(\mathbf{P}_\mathbf{x}^\mathbf{c}, \mathbf{P}_\mathbf{y}^\mathbf{c}, \mathbf{P}_\mathbf{z}^\mathbf{c})$

The concept of physics for my dissertation

The 3-particle final state for $\gamma p \longrightarrow p\pi\pi$



The combination of the beam and the target for my dissertation

- The circularly-polarized beam $\longrightarrow \delta_{\odot}$
- The longitudinally-polarized target $\longrightarrow \Lambda_z$

The differential cross section for $\gamma p \longrightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_{\odot} (\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot}) \}$$

- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- $\delta_{\odot}$: The degree of circular polarizaton of the photon beam
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (0, 0, \Lambda_z)$
- $\mathbf{I}^{\odot}$: The photon polarization asymmetry
- $\vec{\mathbf{P}}$: The polarization observable $\Rightarrow$ $(0, 0, \mathbf{P_z})$ $(0, 0, \mathbf{P}_z^{\odot})$

The concept of physics for my dissertation

The main goal for my dissertation is to measure $\mathbf{P_z^{\odot}}$.

- In the combination of circularly-polarized beam on a longitudinally-polarized target

$$\frac{d\sigma}{d x_i} = \sigma_0 \{ (1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_{\odot} (\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot}) \}$$

- Flipping the polarization of the beam

$\rightarrow$ and $\leftarrow$ indicate circular polarization of the beam

$\Rightarrow$ and $\Leftarrow$ indicate longitudinal target polarization parallel or anti-parallel to the beam

$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) := \frac{d\sigma(\rightarrow\Rightarrow)}{d x_i} - \frac{d\sigma(\leftarrow\Rightarrow)}{d x_i} = 2 \cdot \sigma_0 \{\delta_{\odot} (\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot})\}$$

$$(\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma(\leftarrow\Leftarrow)}{d x_i} - \frac{d\sigma(\rightarrow\Leftarrow)}{d x_i} = 2 \cdot \sigma_0 \{\delta_{\odot} (-\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot})\}$$

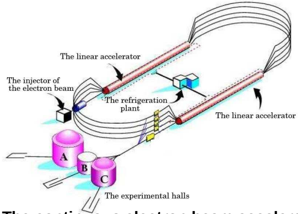
- Flipping the polarization of the beam and the target polarization together

$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) + (\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma_{3/2}}{d x_i} - \frac{d\sigma_{1/2}}{d x_i} = 4 \cdot \sigma_0 \cdot \delta_{\odot} \cdot (\Lambda_z \cdot \mathbf{P_z}^{\odot})$$

Outline

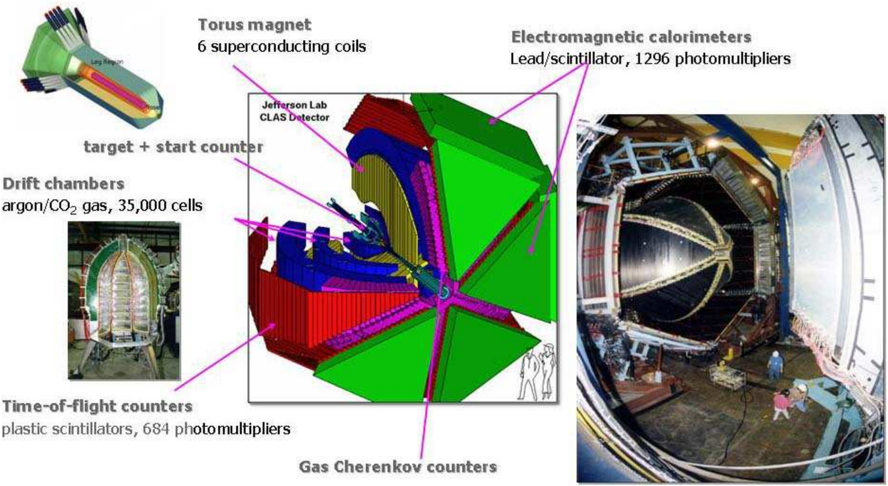
1. Introduction
   - Problems in Hadron Spectroscopy
   - Motivation for this work
2. The concept of physics for my dissertation
3. FROST Experiment
   - Experimental Setup
   - The FROST Data
   - Summary

Jefferson Laboratory in Newport News, VA

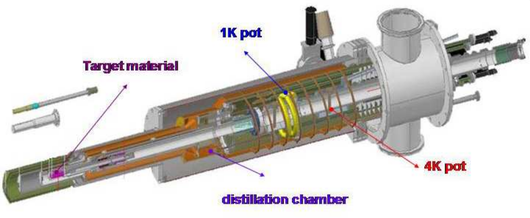


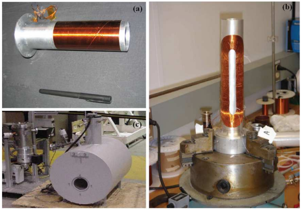
The continuous electron beam accelerator facility (CEBAF) can deliver a continuous electron beam up to 6 GeV.

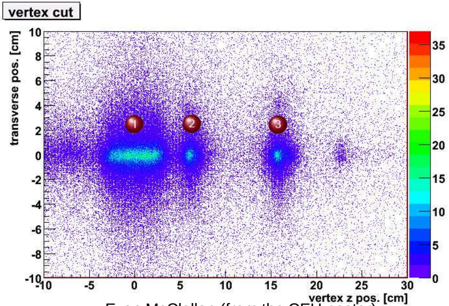
CEBAF Large Acceptance Spectrometer (CLAS)



The Frozen-Spin Target (FROST)







Evan McClellan (from the CEU poster)

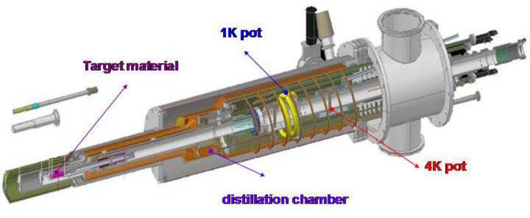
The magnets in the FROST experiment

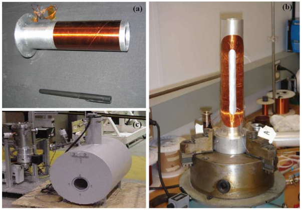
- (a) The longitudinal holding magnet. (About 0.5 T)
- (b) The transvere holding magnet. (Next experiment)
  - Charles Hanretty
- (c) The polarizing magnet. (5 Tesla internal solenoid)

1. Polarized Butanol (C_4H_9OH) (L = 5.0 cm, ϕ = 1.5 cm) $\sim$ 5 g
2. Carbon (^{12}C) (L = 0.15 cm) (6 cm from CLAS center)
3. Polyethylene (CH_2) (L = 0.35 cm) (16 cm from CLAS center)

L: The length and ϕ: The diameter

The Frozen-Spin Target (FROST)





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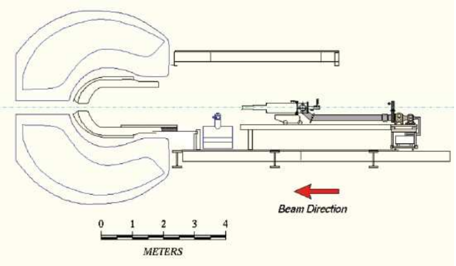
How to polarize the FROST?



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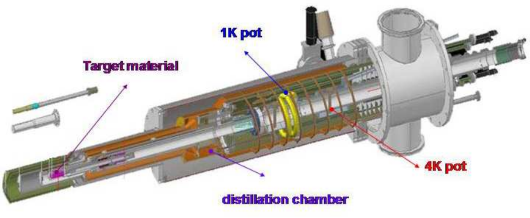

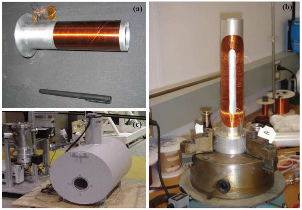

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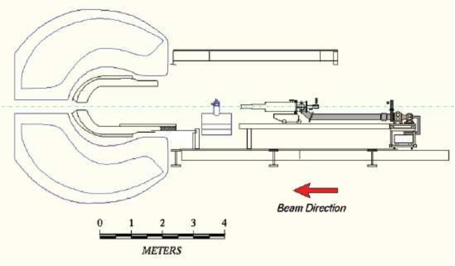

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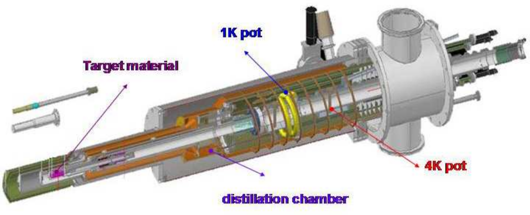

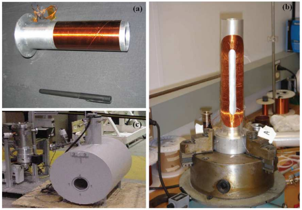

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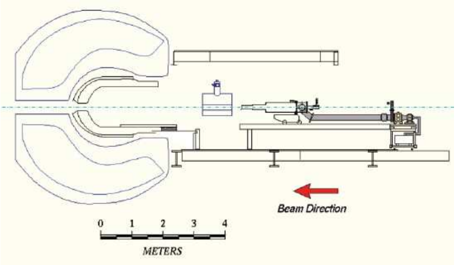

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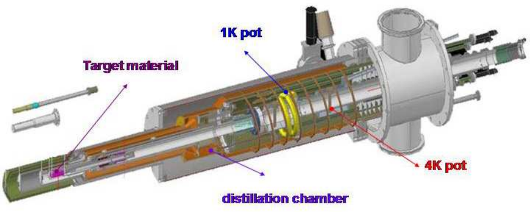

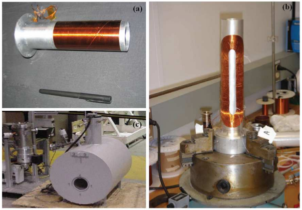

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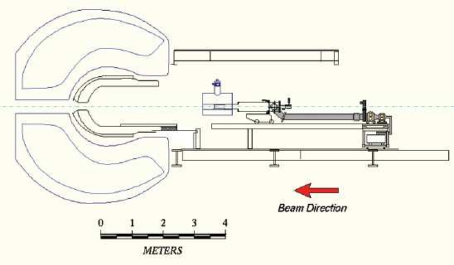
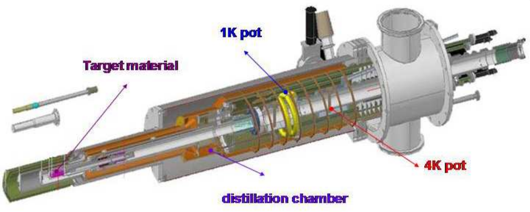
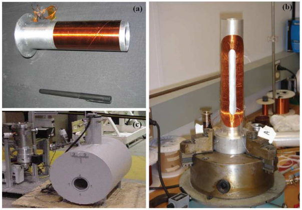


Polarizing mode

* Microwave ON
* 5T magnet ON
* Temperature 0.5 K
* Photon beam OFF

The Frozen-Spin Target (FROST)





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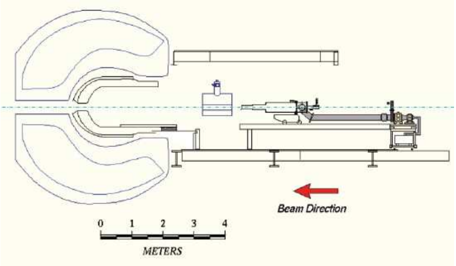

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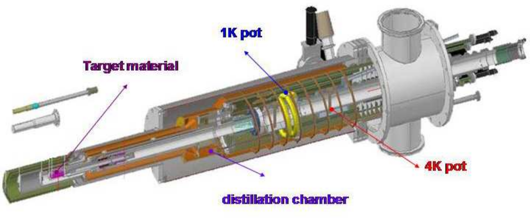

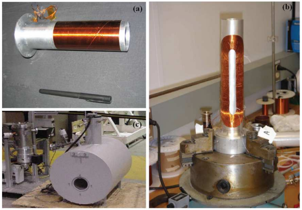

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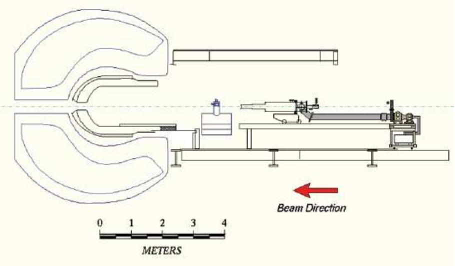

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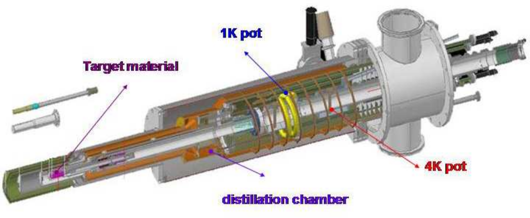

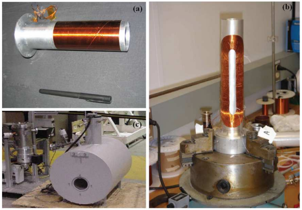

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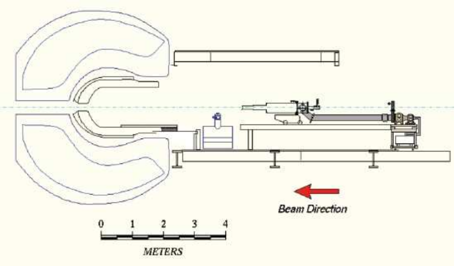

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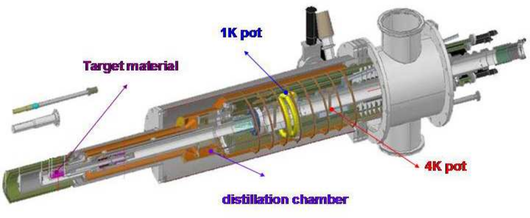

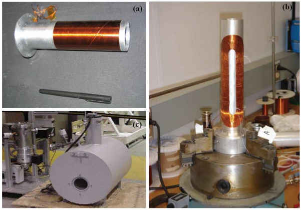

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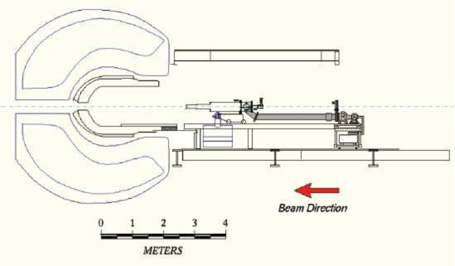
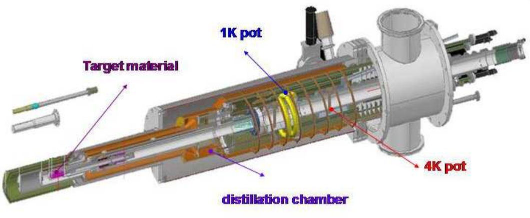
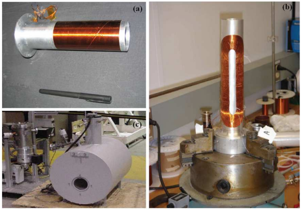


The Frozen-Spin Target (FROST)

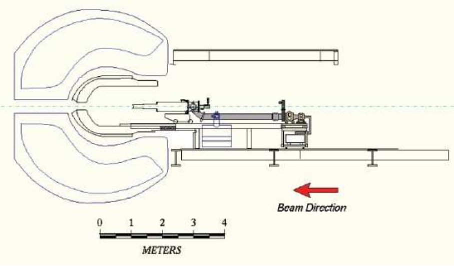




The magnets in the FROST experiment

(a) The longitudinal holding mqgnet. (About 0.5 T)
(b) The transvere holding magnet. (Next experiment)
(c) The polarizing magnet. (5 Tesla internal solenoid)

How to polarize the FROST?



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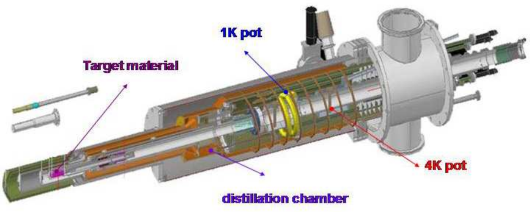

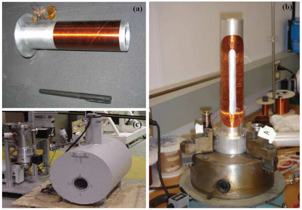

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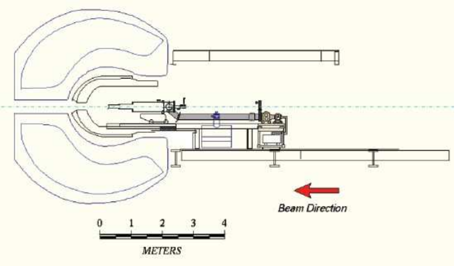
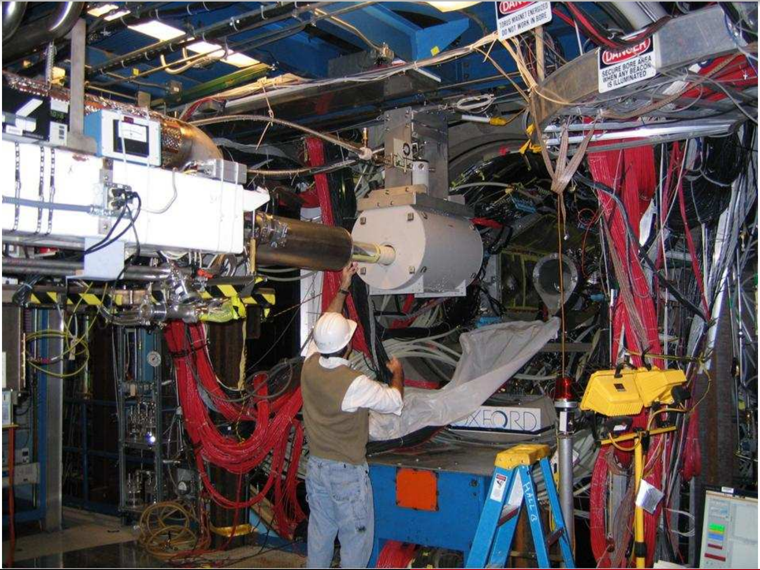


Frozen spin mode

* Microwave OFF
* 5T magnet OFF
* 0.5T magnet ON
* Temperature $\sim$ 0.05 K
* Photon beam ON

The Frozen-Spin Target (FROST) - polarizing mode



The tagging system at CLAS

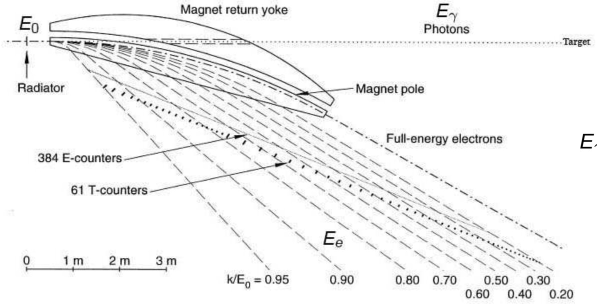
JLAB Hall B bremsstrahlung photon tagger

- E_γ = 20-95 % of E_0
- E_γ up to ∼5.5 GeV

- Circular polarized photon beam
  - longitudinally polarized electron beam
  - The amorphous radiator (poly-crystalline graphite)
- Linearly polarized photon beam
  - unpolarized electron beam
  - The oriented diamod radiator

PARA photon polarization plane is parallel to the floor.

PERP photon polarization plane is perpendicular to the floor.



$$E_\gamma = E_0 - E_e$$

E_γ: The energy of the emitted photon

E_0: The energy of the incident electron

E_e: the energy of the outgoing electron

The FROST Data

The FROST run period: Nov. 3, 2007 - Feb. 12, 2008

Data set: 35 TBytes

Production Data

Beam current: 15 nA

Torus current: 1920 A

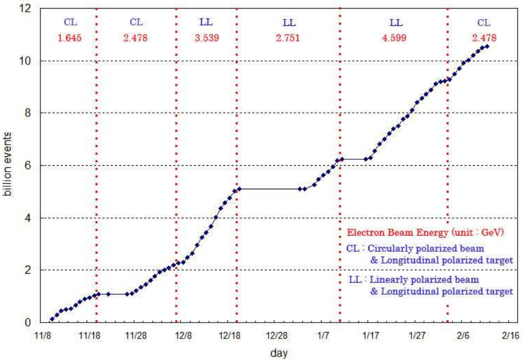
Target:

- Longitudinal polarized target
- Average target polarization ∼ 80 %

Photon beam:

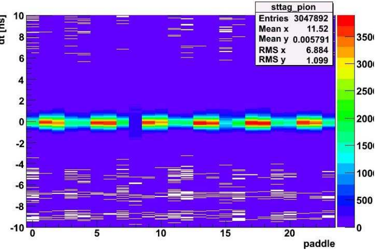
- Circularly and linearly polarized photon beam 0.5 - 2.4 GeV
- Electron beam polarization ∼ 85 %

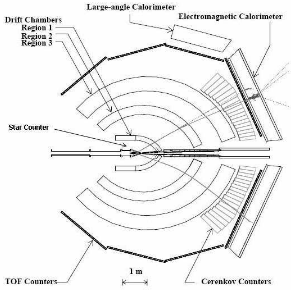
10.5 Billion events



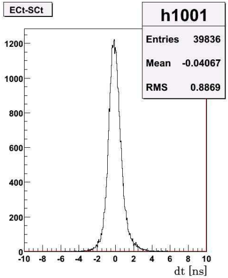
Calibration

ST calibration

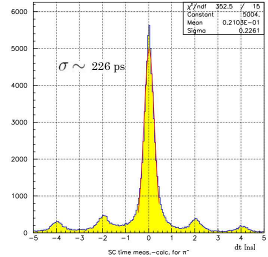




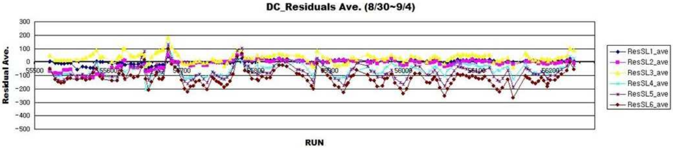
EC calibration



TOF calibration



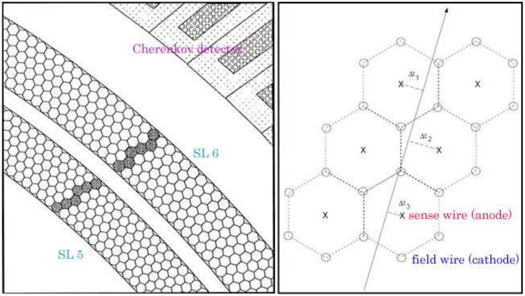
DC calibration



DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire



find the fitted DOCA and drift time.

The quasi-hexagonal pattern with six field wires surrounding one sense wire.

$90\% argon - 10\% CO_2 gasmixture$

DC calibration

How to find the fitted DOCA and drift time?

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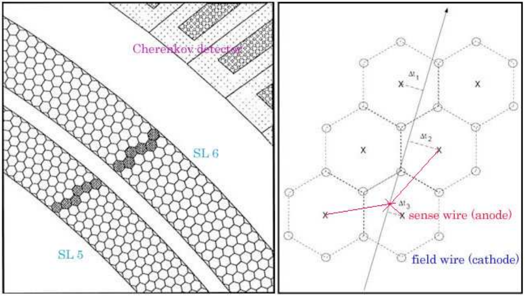

find the fitted DOCA and drift time.

Inside these cells a traversing charged particle ionizes the gas

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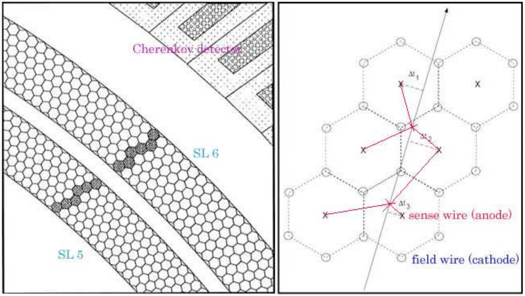

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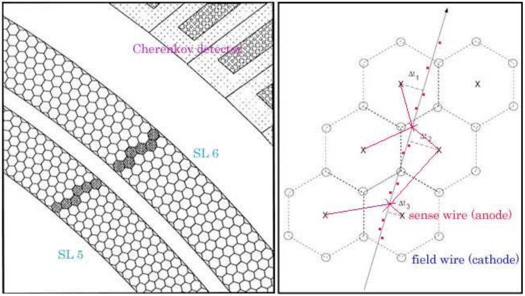

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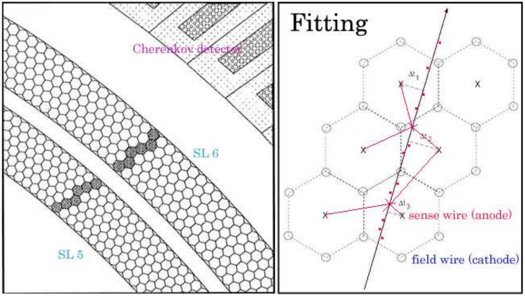

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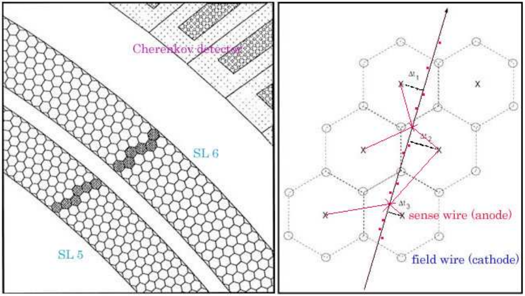

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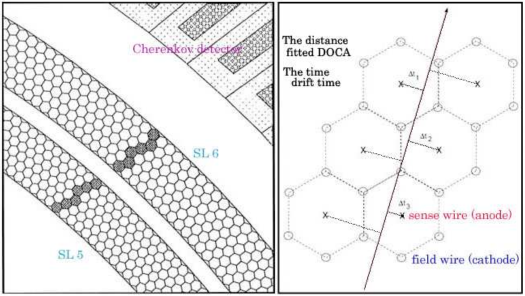
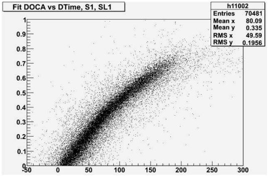
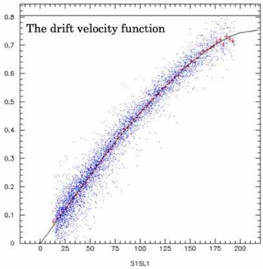






find the fitted DOCA and drift time.

find the drift velocity function using fitting.

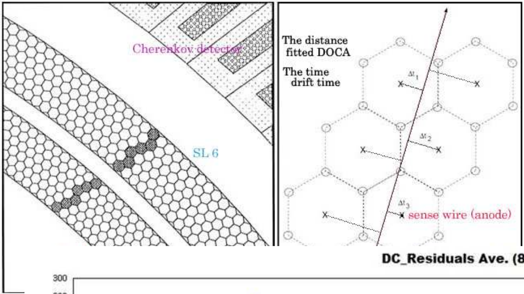
find the calculated DOCA using the velocity and the time

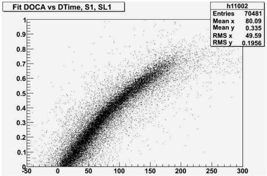
The residual = calculated DOCA - fitted DOCA

DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire

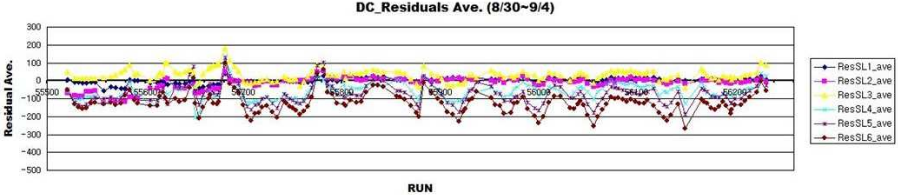


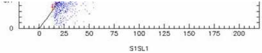


find

find

find



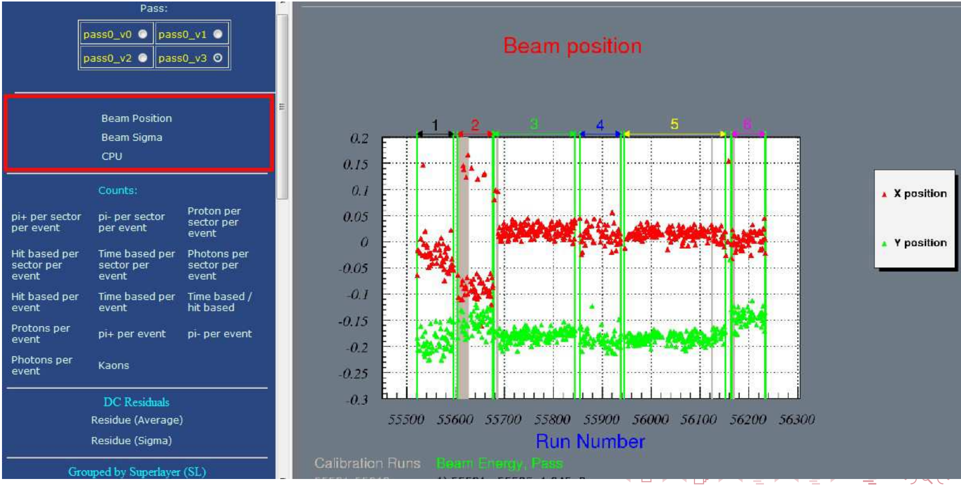


The residual = calculated DOCA - fitted DOCA

Monitoring

The monitoring page has three kinds of plots.

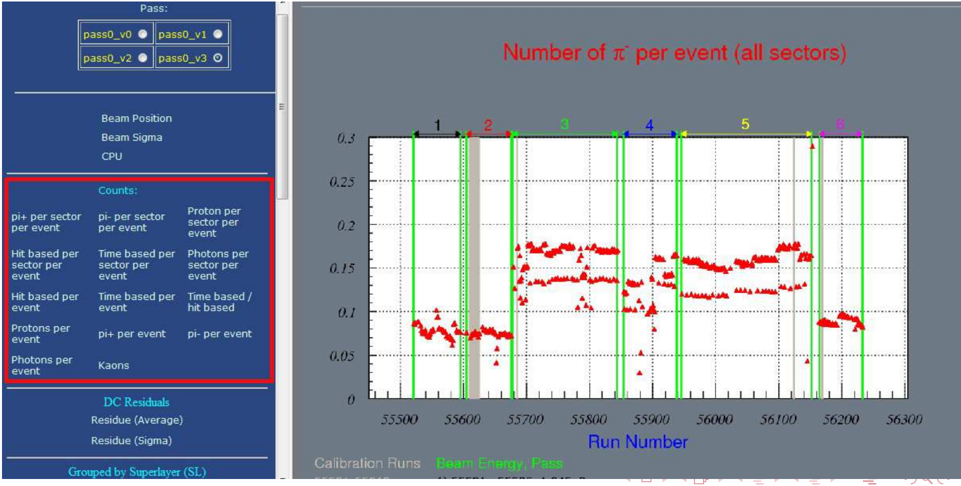
(1) The plot for checking that the system is working properly.



Monitoring

The monitoring page has three kinds of plots.

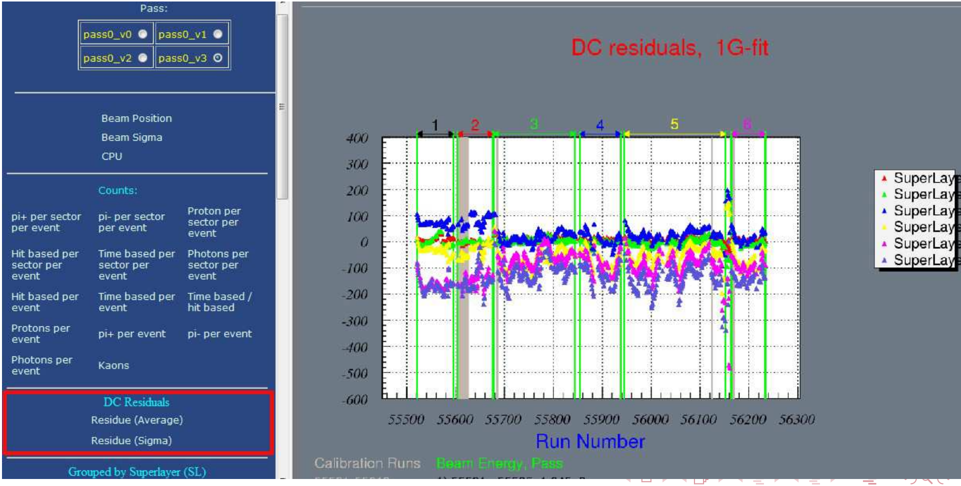
(2) The plot for useful information on some basic particle properties



Monitoring

The monitoring page has three kinds of plots.

(3) The plot for checking the quality of the existing calibration.



The analysis for my dissertation

The combination of differential cross sections for the measurement of $\mathbf{P_z}^{\odot}$

$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) + (\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma_{3/2}}{dx_i} - \frac{d\sigma_{1/2}}{dx_i} = 4 \cdot \sigma_0 \cdot \delta_{\odot} \cdot (\Lambda_z \cdot \mathbf{P_z}^{\odot})$$

Targets for the FROST experiment $\rightarrow C_4H_9OH$, ^{12}C, and CH_2

$$\mathbf{P_z}^{\odot} \propto \left\{ \left(\frac{d\sigma_{3/2}(\mathrm{H,C,O})}{dx_i} - \frac{d\sigma_{3/2}(\mathrm{C,O})}{dx_i} - \frac{d\sigma_{3/2}(\mathrm{H,unpolarized})}{dx_i} \right) - \left(\frac{d\sigma_{1/2}(\mathrm{H,C,O})}{dx_i} - \frac{d\sigma_{1/2}(\mathrm{C,O})}{dx_i} - \frac{d\sigma_{1/2}(\mathrm{H,unpolarized})}{dx_i} \right) \right\}$$

$$\mathbf{P_z}^{\odot} \propto \left\{ \frac{d\sigma_{3/2}(\mathrm{H,polarized})}{dx_i} - \frac{d\sigma_{1/2}(\mathrm{H,polarized})}{dx_i} \right\}$$

$$\mathbf{P_z}^{\odot} \propto \left(N^{+} - N^{-} \right)$$

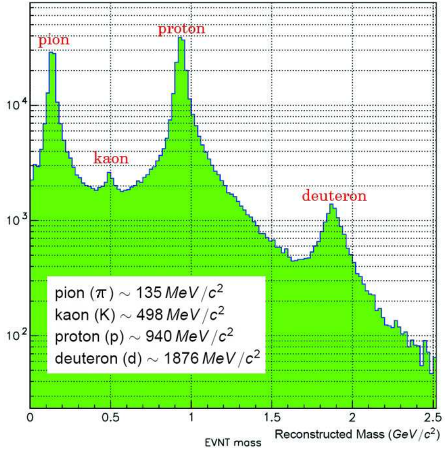
N^{+}: The positive photon helicity $(\rightarrow\Rightarrow + \leftarrow\Leftarrow)$

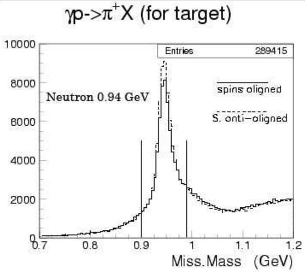
N^{-}: The negative photon helicity $(\leftarrow\Rightarrow + \rightarrow\Leftarrow$

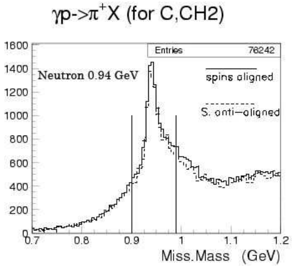
Sample analysis $\gamma p \rightarrow \pi^+ n$

Particle identification $\rightarrow m = \frac{p}{v}$

* measured charged-particle momenta (from DC)
* The flight time from the target to the respective TOF counters.





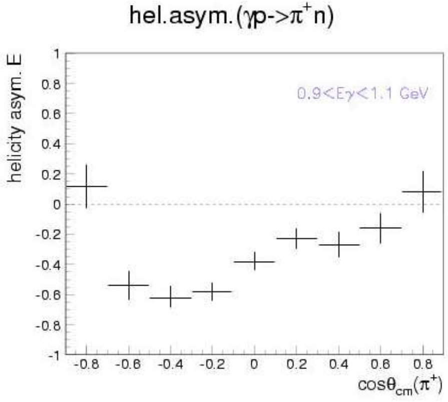


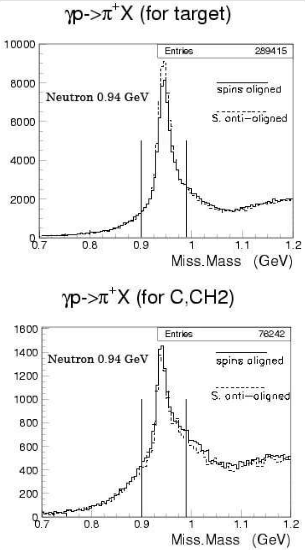
Sample analysis $\gamma p \rightarrow \pi^+ n$

Helicity asymmetry for $\gamma p \rightarrow \pi^+ n$

$$E_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

(N^+ is positive photon helicity, N^- is negative photon helicity)





Summary

- The goal of my dissertation is to determine the helicity difference in the reaction, $\gamma p \to p\pi^+\pi^-$.
- The FROST experiment has already taken the data.
- The data is in the process of the calibration.
- My current contribution in the FROST experiment is

  * I reconstruct the data.
  * I undertake the part of the DC calibration.
  * I manage and update the monitoring web.

Quantum numbers in Schrödinger's three-dimensional model

Orbitals - regions in space where electrons are most likely to be found

The principal quantum number (n = 1, 2, 3, 4 ...)

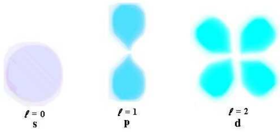
* This number describes the SIZE of the orbital.
* This number has a dependence on the distance between the electron and the nucleus.

The angular quantum number (l = 0, 1, 2 ... n-1)

* This number describes the SHAPE of the orbital.
* This number gives the orbital angular momentum the through the relation $L^2 = \hbar^2 l(l+1)$.

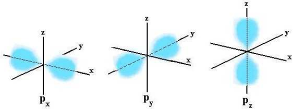
The magnetic quantum number (m_l = -l,-l+1, ..., 0 ... ,l-1, 1)

* This number describes an orbitalś ORIENTATION in space.
* This number is the eigenvalue, $L_2 z = m_l \hbar$.
* This is the projection of the orbital angular momentum along a specified axis.



The spin quantum number (m_s = -1/2 or +1/2)

* This number describes the SPIN in which an electron spins
* This number is the eigenvalue, $L_2 z = m_l \hbar$.
* This is the projection of the orbital angular momentum along a specified axis.



Quantum numbers in Schrödinger's three-dimensional model

* The principal quantum number (n = 1, 2, 3, 4 ...)
* The angular quantum number (l = 0, 1, 2 ... n-1)
* The magnetic quantum number (m_l = -l,-l+1, ..., 0 ... ,l-1, 1)

Graphical Representation of Allowable Combinations of Quantum Numbers

Shell n	Subshell l	Subshell Notation	Orientation m	Number of Orbitals
1	0	1s	0	1
2	0	2s	0	1
	1	2p	−1 0 +1	3
3	0	3s	0	1
	1	3p	−1 0 +1	3
	2	3d	−2 −1 0 +1 +2	5
4	0	4s	0	1
	1	4p	−1 0 +1	3
	2	4d	−2 −1 0 +1 +2	5
	3	4f	−3 −2 −1 0 +1 +2 +3	7

The concept of physics for my dissertation

The main goal for my dissertation is to measure $\mathbf{P}_z^{\odot}$.

- In the combination of circularly-polarized beam on a longitudinally-polarized target

$$\frac{d\sigma}{d x_i} = \sigma_0 \{ (1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_{\odot} (\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot}) \}$$

$$(\rightarrow\Rightarrow) := \frac{d\sigma(\rightarrow\Rightarrow)}{d x_i} = \sigma_0 \{ (1 + (+\Lambda_z) \cdot \mathbf{P_z}) + (+\delta_{\odot}) (\mathbf{I}^{\odot} + (+\Lambda_z) \cdot \mathbf{P_z}^{\odot}) \}$$

$$(\leftarrow\Rightarrow) := \frac{d\sigma(\leftarrow\Rightarrow)}{d x_i} = \sigma_0 \{ (1 + (+\Lambda_z) \cdot \mathbf{P_z}) + (-\delta_{\odot}) (\mathbf{I}^{\odot} + (+\Lambda_z) \cdot \mathbf{P_z}^{\odot}) \}$$

$$(\leftarrow\Leftarrow) := \frac{d\sigma(\leftarrow\Leftarrow)}{d x_i} = \sigma_0 \{ (1 + (-\Lambda_z) \cdot \mathbf{P_z}) + (-\delta_{\odot}) (\mathbf{I}^{\odot} + (-\Lambda_z) \cdot \mathbf{P_z}^{\odot}) \}$$

$$(\rightarrow\Leftarrow) := \frac{d\sigma(\rightarrow\Leftarrow)}{d x_i} = \sigma_0 \{ (1 + (-\Lambda_z) \cdot \mathbf{P_z}) + (+\delta_{\odot}) (\mathbf{I}^{\odot} + (-\Lambda_z) \cdot \mathbf{P_z}^{\odot}) \}$$

- Flipping the polarization of the beam

$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) := \frac{d\sigma(\rightarrow\Rightarrow)}{d x_i} - \frac{d\sigma(\leftarrow\Rightarrow)}{d x_i} = 2 \cdot \sigma_0 \{ \delta_{\odot} (\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot}) \}$$

$$(\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma(\leftarrow\Leftarrow)}{d x_i} - \frac{d\sigma(\rightarrow\Leftarrow)}{d x_i} = 2 \cdot \sigma_0 \{ \delta_{\odot} (-\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P_z}^{\odot}) \}$$

- Flipping the polarization of the beam and the target polarization together

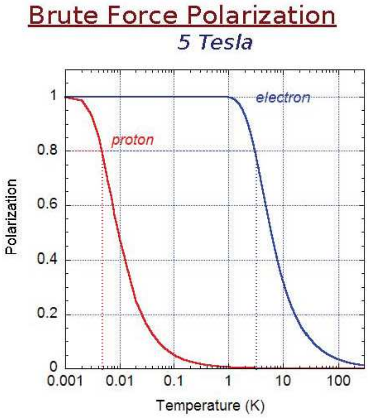
$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) + (\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma_{3/2}}{d x_i} - \frac{d\sigma_{1/2}}{d x_i} = 4 \cdot \sigma_0 \cdot \delta_{\odot} \cdot (\Lambda_z \cdot \mathbf{P_z}^{\odot})$$

The Frozen-Spin Target (FROST)

How to polarize the spin

(1) Use brute force to polarized free electrons in the target material.

(2) Use microwaves to “transfer” this polarization to nuclei.



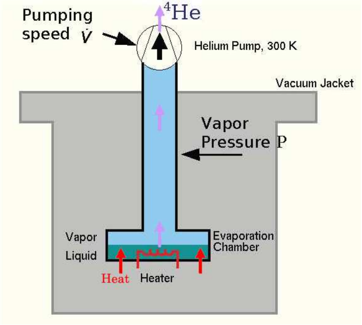
Dilution factor of butanol (C_4H_9OH)

$$f = \frac{9+1}{(6\times4+1\times9+8\times1+1\times1)+(6\times4+8\times1)} = \frac{10}{74} = 0.135$$

$$\left({}^1_1H \quad {}^{12}_{6}C \quad {}^{16}_{8}O\right)$$

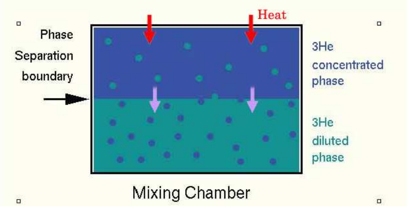
How do we make the low temperature?

Refrigeration below 4.2 K – Evaporative Cooling



In absence of a heater, liquid will absorb heat from surrounding and temperature will drop.

^{3}He/^{4}He Dilution Refrigeration

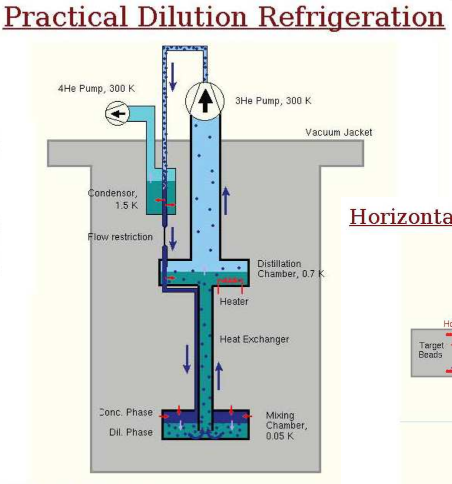


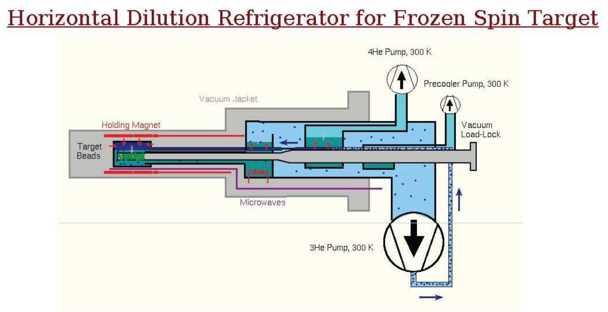
The specific heat of a ^{3}He atom is higher in the lower, dilute phase than in the upper, concentrated phase.

$$C_d > C_c$$

^{3}He will abssorb energy when it dissolves into the dilute phase.

How do we make the low temperature?



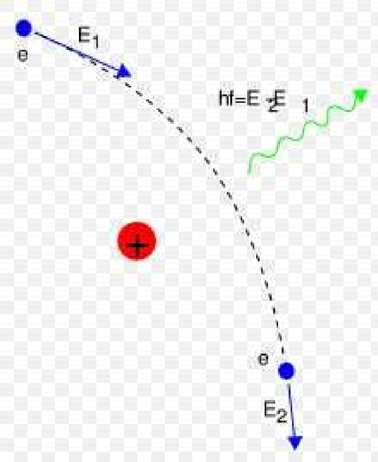


Bremsstrahlung

Bremsstrahlung is electromagnetic radiation produced by the deceleration of a charged particle, such as an electron,
when deflected by another charged particle, such as an atomic nucleus.

The term is also used to refer to
the process of producing the radiation.

Bremsstrahlung has a continuous spectrum.



Sample analysis $\gamma p \rightarrow \pi^+ n$

Helicity asymmetry for $\gamma p \rightarrow \pi^+ n$

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(N^+ is positive photon helicity, N^- is negative photon helicity)