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Exploiting Polarization in Peripheral Photoproduction: Strategies for GlueX

Richard Jones
University of Connecticut, Storrs

Questions an experimenter might ask:

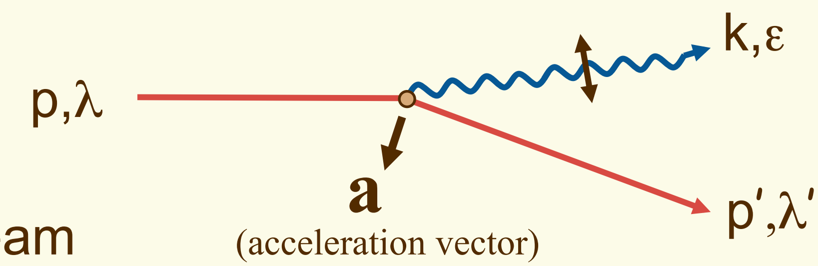
- What states of polarization are available in this beam?
- What general expressions can describe these states?
- How does polarization enter the cross section?
- Why is linear polarization of particular interest?
- What additional information is available with circular polarization?
- How (well) can we measure the polarization state?
- In what situations might target polarization be useful?
- Can we make a beam with helicity $|\lambda| \geq 2$?

What states of polarization are available in this beam?

- All physical polarization states of the photon

$$|\mathbf{k}\varepsilon\rangle$$

are accessible in **CB** beam



- **Linear polarization**
- Circular polarization
- Combinations

> - essentially a **classical** effect
>   - like **synchrotron radiation**
>   - electric field ⟷ **a** vector
>   - magnetic field ⟷ $(\mathbf{v} \times \mathbf{r})$
> - crystal acts like a bending field
> - **p** changes in *discrete steps*, but mostly in *small steps*, like SR
> - vanishes at the photon end-point because **a** becomes parallel to **p**

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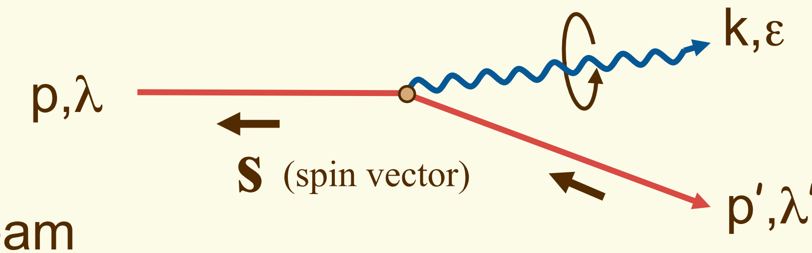

- Linear polarization
- **Circular polarization**
- Combinations

> - essentially a **quantum** effect
> - photon helicity follows electron λ
>   - holds <u>exactly</u> in the chiral limit
>   - consider photon helicity basis $\boldsymbol{\varepsilon}_{\pm}$
>
> $$\bar{u}_{p'\lambda'} A_{\pm} u_{p\lambda} \sim p'_{\perp} \left(\chi_{\lambda'}, (1 \pm 2\lambda) \chi_{\lambda} \right)$$
>
> - vanishes for colinear kinematics
> - **100% helicity transfer !**
> - chiral limit ⟶ photon end-point

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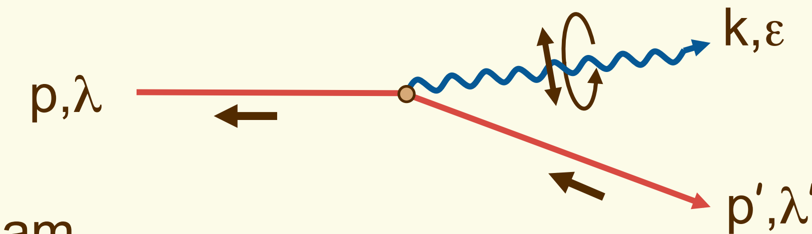


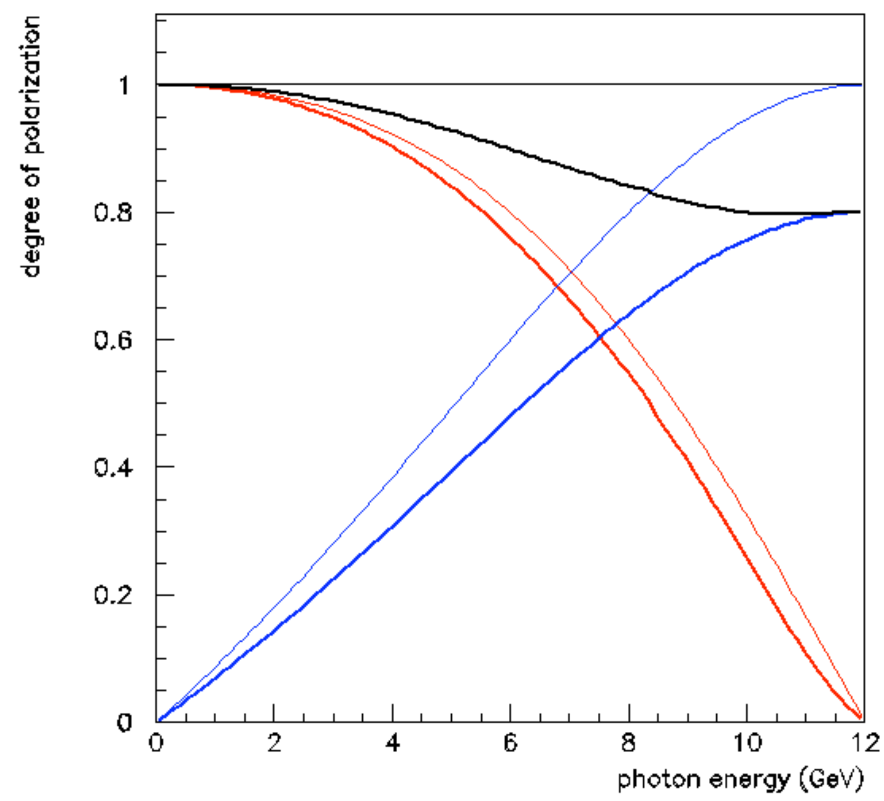
- Linear polarization
- Circular polarization
- **Combinations**

> - both kinds **simultaneously possible**
> - a sort of duality exists between them
>   - linear: disappears at the end-point
>   - circular: disappears as $k \to 0$
> - limited by the sum rule
>
> $$P_o^2 + P_\perp^2 \leq 1$$
>
> - requires **CB radiator** and **longitudinally polarized electrons**

What states of polarization are available in this beam?

- **Linear polarization**
  - ideal curve (theory)
  - expected performance
- **Circular polarization**
  - ideal curve (theory)
  - expected performance
- **Combination**
  - ideal curve (theory)
  - expected performance

= sum in quadrature of linear and circular polarizations



What general expressions can describe these states?

- General description: elliptical polarization
  - degree of linear polarization:

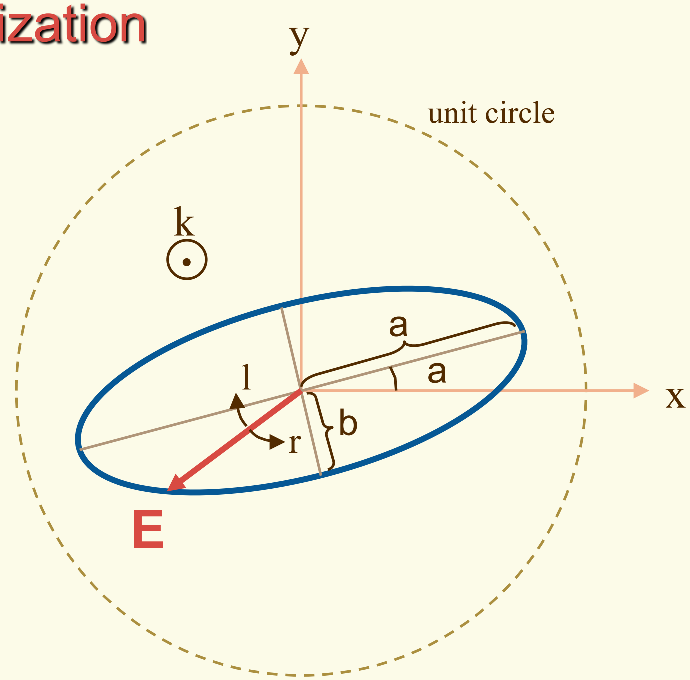
$$P_\perp(\alpha) = \sqrt{|a|^2 - |b|^2} = \textit{eccentricity}$$

  - degree of circular polarization:

$$P_\odot = \begin{cases} +b : \textit{right advance} \\ -b : \textit{left advance} \end{cases}$$

  - net polarization:

$$P = |P_\perp|^2 + |P_\odot|^2 = |a|^2 \leq 1$$



- Information needed: |a|, b, α, sign(l/r)

suggests a description in terms of a 3-vector

What general expressions can describe these states?

- General description: Stokes parameterization
  - ✓ Define

$$p_x = p\, sin(\theta)\, cos(2\alpha)$$
$$p_y = p\, sin(\theta)\, sin(2\alpha)$$
$$p_z = p\, cos(\theta)$$

where $\sin(\theta) = eccentricity$

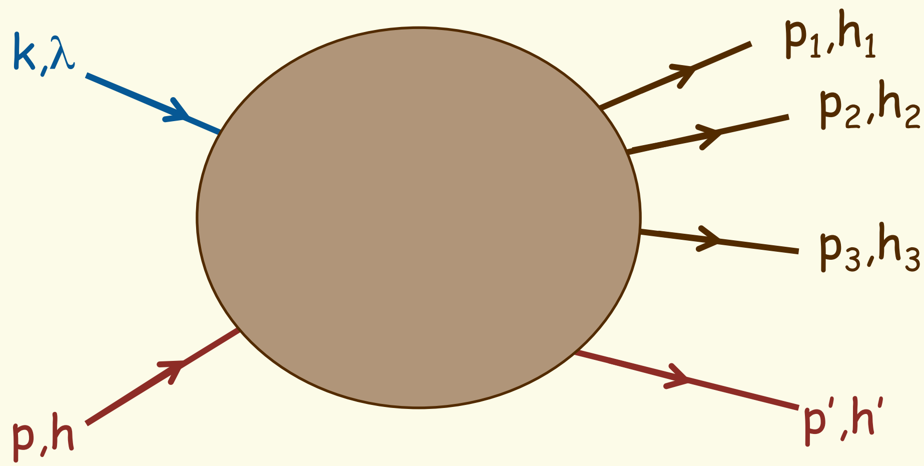
  - ✓ Note that $\alpha \to \alpha + \pi$ is an identity operation on the state.
  - ✓ For **k** along the z-axis:
    - **p** = $\pm\hat{\mathbf{z}}$ corresponds to ± helicity of the photon
    - **p** = $+\hat{\mathbf{x}}$ corresponds to linear polarization in the xz plane
    - **p** = $-\hat{\mathbf{x}}$ corresponds to linear polarization in the yz plane
    - **p** = $\pm\hat{\mathbf{y}}$ corresponds to linear polarization along the 45° diagonals

What general expressions can describe these states?

	± helicity basis	|x>, |y> basis
spinor	$\begin{pmatrix} \cos\frac{\theta}{2}\, e^{-i\alpha} \\ \sin\frac{\theta}{2}\, e^{i\alpha} \end{pmatrix}$	$\begin{pmatrix} \cos\frac{\theta}{2}\, e^{i\alpha} + \sin\frac{\theta}{2}\, e^{-i\alpha} \\ i\cos\frac{\theta}{2}\, e^{i\alpha} - i\sin\frac{\theta}{2}\, e^{-i\alpha} \end{pmatrix}$
density matrix	$\begin{pmatrix} \frac{1+\cos\theta}{2} & \frac{\sin\theta\, e^{-2i\alpha}}{2} \\ \frac{\sin\theta\, e^{2i\alpha}}{2} & \frac{1-\cos\theta}{2} \end{pmatrix}$	$\begin{pmatrix} \frac{1+\sin\theta\cos 2\alpha}{2} & \frac{-i\cos\theta+\sin\theta\sin 2\alpha}{2} \\ i\frac{\cos\theta+\sin\theta\sin 2\alpha}{2} & \frac{1-\sin\theta\cos 2\alpha}{2} \end{pmatrix}$
	$= \frac{1}{2}(1 + \mathbf{p}\cdot\boldsymbol{\sigma})$	$= \frac{1}{2}(1 + p_x\sigma_z + p_y\sigma_x + p_z\sigma_y)$

How does polarization enter the cross section?

- Consider some general reaction: $\gamma p \rightarrow B + M$



- Assume somewhere the reaction can be cut in two **across one line**

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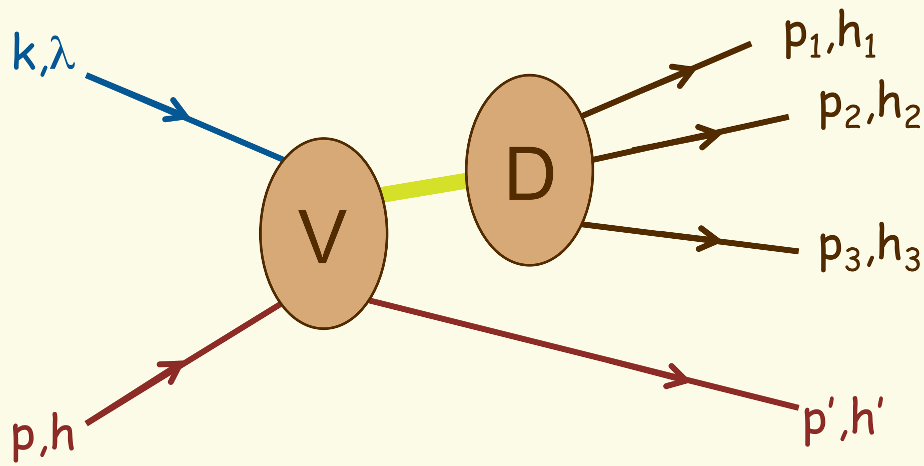


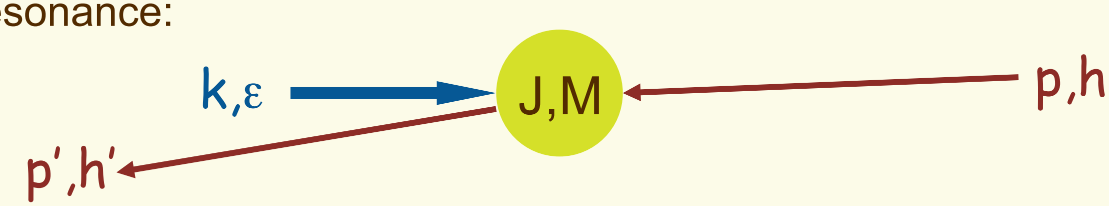
- Assume somewhere the reaction can be cut in two <u>across one line</u>

$$d\sigma_\lambda = \sum_{J,M} \left| V^{J,M}_{\lambda,h,h'}(s,t) \right|^2 \left| D^{J}_{M,h_1\ldots} \right|^2 d\Omega$$

- Reaction factorizes into a sum over resonances labelled by J,M
- **Quite general, eg. not specific to t-channel reactions**

How does polarization enter the cross section?

- For simplicity, consider a single resonance X
- Let $\mathbf{J,n_J}$ be the *spin* and *naturality* of particle X
- Consider a partial wave **J,M** in which X is observed as an isolated resonance:



$$\Gamma^{J,M}_{h,h'}(\varepsilon) = \sum_{\lambda,\lambda'} \left(V^{J,M}_{\lambda,h,h'}\right) \rho_{\lambda,\lambda'}(\varepsilon) \left(V^{J,M}_{\lambda',h,h'}\right)^*$$

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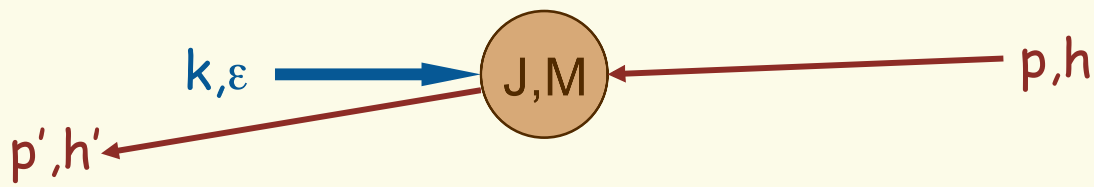

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$$= \left(\left|V^{J,M}_{+,h,h'}\right|^2 + \left|V^{J,M}_{-,h,h'}\right|^2\right) + p_z \left(\left|V^{J,M}_{+,h,h'}\right|^2 - \left|V^{J,M}_{-,h,h'}\right|^2\right)$$

$$+ 2p_x \,\Re\left(V^{J,M}_{+,h,h'} V^{J,M\,*}_{-,h,h'}\right) - 2p_y \,\Im\left(V^{J,M}_{+,h,h'} V^{J,M\,*}_{-,h,h'}\right)$$

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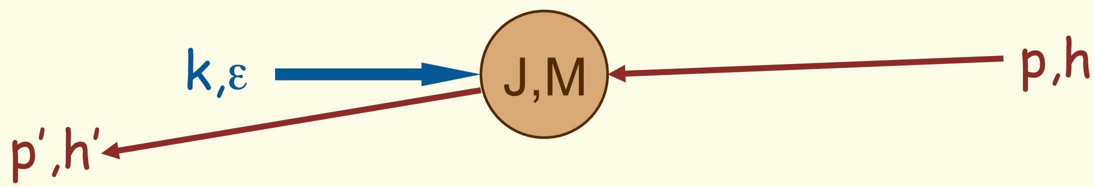

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- unpolarized

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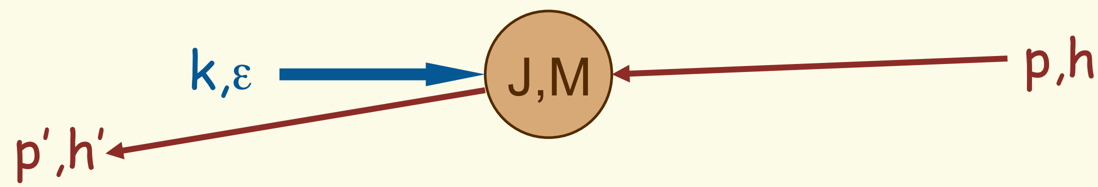

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- unpolarized
- circular piece

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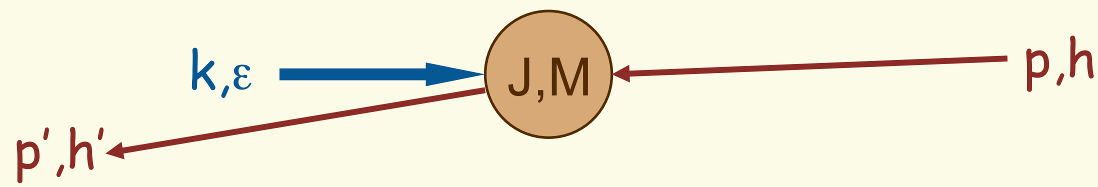

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- unpolarized
- circular piece
- linear pieces

$$= \left(\left|V^{J,M}_{+,h,h'}\right|^2 + \left|V^{J,M}_{-,h,h'}\right|^2\right) + p_z \left(\left|V^{J,M}_{+,h,h'}\right|^2 - \left|V^{J,M}_{-,h,h'}\right|^2\right)$$

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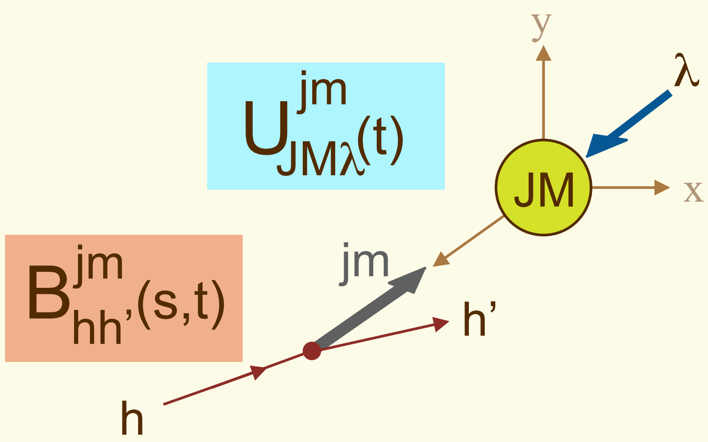
How does polarization enter the cross section?

- **Summary of results from the general analysis**
  - ✓ One circular and two linear polarization observables appear.
  - ✓ One unpolarized + **two polarization observables** are sufficient to separate the four helicity amplitudes (one phase is unobservable).
  - ✓ **Any 2 of the 3 polarization states** would be sufficient, but having access to all three would provide ***useful control of systematics***.
- **Specific results for t-channel reactions**
  - ➢ Break up **V** into a sum of allowed t-channel exchanges.
  - ➢ Exploit **parity** to eliminate some of the terms in the expansion.
  - ➢ Use the two **linear polarization observables** to construct a filter that gives *two very different views of the same final states*.
  - ➢ Analogous to a **polaroid filter.**

Why is linear polarization of particular interest?

- sum over exchanges (jm)

$$V^{J,M}_{\lambda,h,h'} = \sum_{jm} B^{j,m}_{h,h'} U^{j,m}_{J,M,\lambda}$$



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- superimpose ±m states

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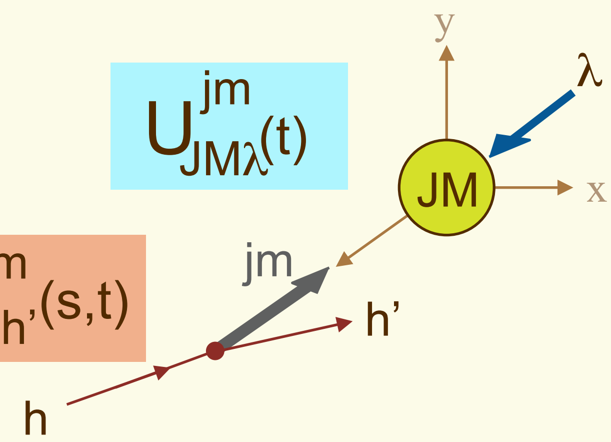
$$U^{j,m}_{J,M,\pm} = U^{j,m}_{J,M,\lambda} \pm (-1)^{\lambda} U^{j,m}_{J,M,-\lambda}$$



$U^{jm}_{JM\lambda}(t)$

$B^{jm}_{hh'}(s,t)$

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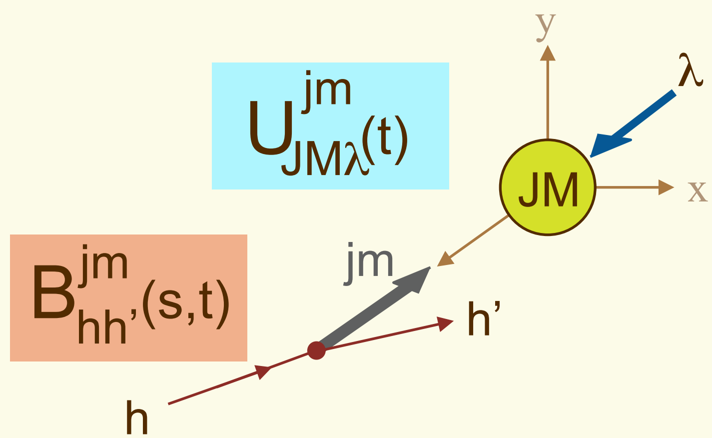

for m=0, only ± = n_j survives

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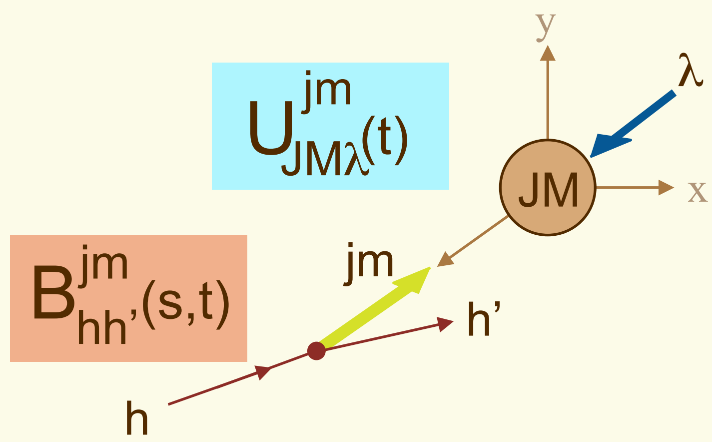

for m=0, only ± = n_j survives

- redefine exchange expansion in basis of good parity

$$V^{J,M,\pm}_{\varepsilon,h,h'} = V^{J,M}_{\varepsilon,h,h'} \pm n_J (-1)^M V^{J,-M}_{\varepsilon,h,h'} \qquad \textit{where } V^{J,M}_{\varepsilon,h,h'} = \sum_{jm} B^{j,m}_{h,h'} U^{j,m}_{J,M,\varepsilon}$$

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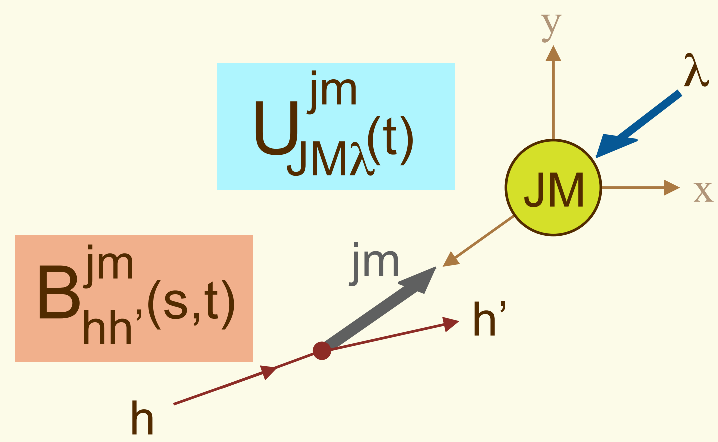

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$$= \sum_{jm} B^{j,m}_{h,h',\pm\varepsilon}\, U^{j,m}_{J,M,\varepsilon}$$

photon polarization (x: ε=-1, y: ε=+1)

naturality of exchanged object n_j

Why is linear polarization of particular interest?

In the amplitude leading to a final state of spin J,|M| and parity r, only exchanges of naturality +r [-r] can couple to y-polarized [x-polarized] light.

caveat

- Selection of exchanges according to naturality is only exact in the high-energy limit (leading order in 1/s).
- For m≠0 partial waves there may be non-negligible violations at GlueX energies.

Why is linear polarization of particular interest?

$$\Gamma^{J,|M|,\pm}_{h,h'} = \sum_{\varepsilon\varepsilon'} \left(V^{J,M,\pm}_{\varepsilon,h,h'}\right) \rho_{\varepsilon\varepsilon'} \left(V^{J,M,\pm}_{\varepsilon',h,h'}\right)^*$$

- density matrix is now needed in the |x>, |y> basis

Why is linear polarization of particular interest?

$$\Gamma_{h,h'}^{J,|M|,\pm} = \sum_{\varepsilon\varepsilon'} \left(V_{\varepsilon,h,h'}^{J,M,\pm}\right) \rho_{\varepsilon\varepsilon'} \left(V_{\varepsilon',h,h'}^{J,M,\pm}\right)^*$$

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$$\begin{aligned}\Gamma_{h,h'}^{J,|M|,\pm} = \sum_{j,j',m,m'} & \left[\frac{1-p_x}{2}\right] B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\pm}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,+}^{j',m'}\right)^* \\ + & \left[\frac{1+p_x}{2}\right] B_{h,h'}^{j,m,\mp} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,-}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* \\ + & \frac{p_y}{2} \Re \left\{ B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* \right\} \\ - & \frac{p_z}{2} \Im \left\{ B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* \right\}\end{aligned}$$

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& + \left[\frac{1+p_x}{2}\right] B^{j,m,\mp}_{h,h'} \left(B^{j',m',\mp}_{h,h'}\right)^* U^{j,m}_{J,M,-} \left(U^{j',m'}_{J,M,-}\right)^* \\
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\end{aligned}$$

← y polarization

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$$+ \left[\frac{1+p_x}{2}\right] B_{h,h'}^{j,m,\mp} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,-}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^*$$ ← x polarization

$$+ \frac{p_y}{2} \Re \left\{ B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* \right\}$$ ← ±45° polarization

$$- \frac{p_z}{2} \Im \left\{ B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* \right\}$$ ← circular polarization

Why is linear polarization of particular interest?

$$\Gamma_{h,h'}^{J,|M|,\pm} = \sum_{\varepsilon\varepsilon'} \left(V_{\varepsilon,h,h'}^{J,M,\pm}\right) \rho_{\varepsilon\varepsilon'} \left(V_{\varepsilon',h,h'}^{J,M,\pm}\right)^*$$

- density matrix is now needed in the |x>, |y> basis

$$\begin{aligned}
\Gamma_{h,h'}^{J,|M|,\pm} = \sum_{j,j',m,m'} & \left[\frac{1-p_x}{2}\right] B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\pm}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,+}^{j',m'}\right)^* && \leftarrow \text{y polarization} \\
& + \left[\frac{1+p_x}{2}\right] B_{h,h'}^{j,m,\mp} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,-}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^* && \leftarrow \text{x polarization} \\
& + \frac{p_y}{2} \Re\left\{B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^*\right\} && \leftarrow \pm 45^\circ \text{ polarization} \\
& - \frac{p_z}{2} \Im\left\{B_{h,h'}^{j,m,\pm} \left(B_{h,h'}^{j',m',\mp}\right)^* U_{J,M,+}^{j,m} \left(U_{J,M,-}^{j',m'}\right)^*\right\} && \leftarrow \text{circular polarization}
\end{aligned}$$

- **unpolarized nucleons ⇒ mixed exchange terms vanish**

Why is linear polarization of particular interest?

$$\Gamma^{J,|M|,\pm}_{h,h'} = \sum_{\varepsilon\varepsilon'} \left(V^{J,M,\pm}_{\varepsilon,h,h'}\right) \rho_{\varepsilon\varepsilon'} \left(V^{J,M,\pm}_{\varepsilon',h,h'}\right)^*$$

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\Gamma^{J,|M|,\pm}_{h,h'} = \sum_{j,j',m,m'} & \left[\frac{1-p_x}{2}\right] B^{j,m,\pm}_{h,h'} \left(B^{j',m',\pm}_{h,h'}\right)^* U^{j,m}_{J,M,+} \left(U^{j',m'}_{J,M,+}\right)^* && \leftarrow \text{y polarization} \\
& + \left[\frac{1+p_x}{2}\right] B^{j,m,\mp}_{h,h'} \left(B^{j',m',\mp}_{h,h'}\right)^* U^{j,m}_{J,M,-} \left(U^{j',m'}_{J,M,-}\right)^* && \leftarrow \text{x polarization} \\
& + \frac{p_y}{2} \Re \left\{ B^{j,m,\pm}_{h,h'} \left(B^{j',m',\mp}_{h,h'}\right)^* U^{j,m}_{J,M,+} \left(U^{j',m'}_{J,M,-}\right)^* \right\} && \leftarrow \pm 45^\circ \text{ polarization} \\
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\end{aligned}$$

- **unpolarized nucleons ⇒ mixed exchange terms vanish**

What additional information is available with circular polarization?

- Does this mean that circular polarization is useless without a polarized target?

NO

- What circular polarization cannot do (alone):
  - affect the total yields of anything
  - any dependence of the differential cross section on α
  - produce interference between exchanges of opposite parity
  - reveal any unique information that is otherwise unobservable
- What circular polarization can do:
  - generate interferences between final states of ±M
  - together with either p_x or p_y can provide the same information as having both p_x and p_y (**2 out of 3 rule**)
  - provide a useful consistency check, control over systematics

How (well) can we measure the polarization state?

- Linear polarization measurement – method 1
  - measure distribution of **(φ_{GJ}-α)** in ρ_0 photoproduction
  - dominated by natural exchange (eg. Pomeron), spin non-flip
  - distribution $\sim sin^2(\theta_{GJ})\ [\ p_x cos(2\varphi_{GJ}) + p_y sin(2\varphi_{GJ})\ ]$
  - non-leading contribution (spin-flip) is governed by small parameter **$(t/s)^{½}$ – expect 10% corrections at GlueX energies**
  - large cross section, clean experimental signature make this method ideal for continuously monitoring $p_\perp$
  - An absolute method is needed, *independent of assumptions of high-energy asymptotics*, to calibrate this one.

How (well) can we measure the polarization state?

- Linear polarization measurement – method 2
  - uses the well-understood QED process of pair-production
  - analyzing power ~30%, calculated to percent accuracy
  - GlueX pair spectrometer also provides a continuous monitor of the collimated beam intensity spectrum
  - thin O(10^{-4} rad.len.) pair target upstream of GlueX is compatible with continuous parallel operation
- Linear polarization measurement – method 3
  - calculated from the measured intensity spectrum
  - to be reliable, must fit both precollimated (tagger) and collimated (pair spectrometer) spectra.

How (well) can we measure the polarization state?

- Circular polarization measurement – method 1
  - calculated from the known electron beam polarization
  - well-understood in terms of QED (no complications from atomic form factors, crystal imperfections, etc.)
  - relies on a polarimetry measurement in another hall, reliable beam transport calculations from COSA
  - can be used to calibrate a benchmark hadronic reaction
  - once calibrated, the GlueX detector measures its own p_z
- Circular polarization measurement – method 2
  - put a thin magnetized iron foil into the pair spectrometer target ladder, measure p_z using pair-production asymmetry

In what situations might target polarization be useful?

✓ **More experimental control over exchange terms**

- Unpolarized nucleon SDM ⇛ cross section is an incoherent sum of positive and negative parity contributions.
- Polarization at the nucleon vertex gives rise to new terms that contain **interferences between + and – parity** that change sign under target polarization reversal.

But

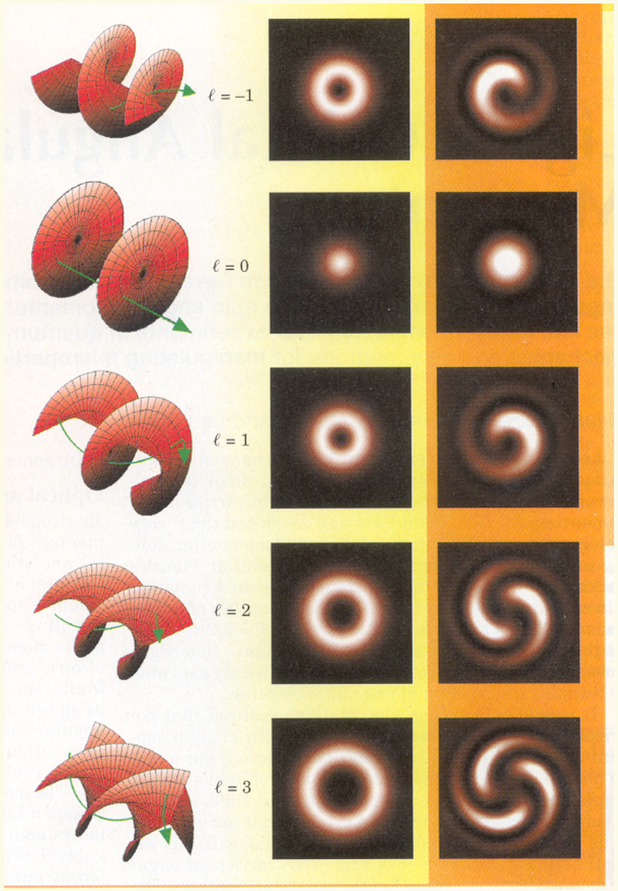
- The new terms represent an additional complication to the partial wave analysis.
- A real simplification does not occur unless **both the target and recoil spins** are polarized / measured.
- **Spin structure of the baryon couplings is not really the point.**

Can we make a beam with helicity $|\lambda| \geq 2$?

- **Example:** how to construct a state with m=2, <k> = $k\hat{z}$
  1. start with a E2 photon in the m=2 substate
  2. superimpose a E3 photon in m=2 with amplitude 1
  3. superimpose a E4 photon with m=2 with amplitude 1
  4. continue indefinitely
- **Result:**
  1. a one-photon state with m=2
  2. not an eigenstate of momentum k, but a state that is arbitrarily well collimated along the z axis

Can we make a beam with helicity $|\lambda| \geq 2$?

- Padgett, Cordial, Alen, *Physics Today* (May 2004) 35. **Light's Orbital Angular Momentum**
  - a new way to think about light
  - can be produced in a crystal
- How might gammas of this kind be produced?
  - from a crystal
  - using laser back-scatter
- Problems
  - transverse size
  - phase coherence



Summary and conclusions:

- ✓ Simultaneous linear and circular polarization is **possible** and **useful** for resolving the spin structure of the production amplitude.
- ✓ Linear polarization is of unique interest in t-channel reactions for isolating exchanges of a **given naturality** to a **given final state**.
- ✓ Circular polarization can be used by observing **changes in angular distributions** (not yields) with the flip of the beam polarization.
- ✓ Target polarization introduces interference between terms of opposite parity, but these terms are **non-leading in 1/s**.
- ✓ The restriction of exchange amplitudes of a given parity to particles of a given naturality **a leading-order in 1/s** argument – not exact.