Any kind of $1/2^+$ octet hyperon EM form factor timelike behaviors by a measurement of the hyperon polarizations in $e^+e^- \to Y\bar{Y}$ processes

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Outline

INTRODUCTION

An application of the SU(3) symmetry to a **classification of mesons and baryons** revealed theoretically an existence of **"quarks"**, and induced the idea
- **"mesons" are bound states of quarks and antiquarks,**
- **"baryons" are compound of 3 quarks**,

therefore it was natural to expect that **they have some EM structure** to be described by some EM form factors (FFs).

The $1/2^+$ octet hyperons $Y = \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-$ **contain always at least one strange quark**
$\Lambda^0 = uds$, $\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$, $\Xi^0 = uss$, $\Xi^- = dss$
therefore they are also called to be **"strange baryons".**

INTRODUCTION

Since $1/2^+$ octet hyperons $Y = \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-$ are **particles with the spin** $S = 1/2$
$\Longrightarrow$ their EM structure is **completely described by 2 independent functions** of one variable
(in timelike region it is the total energy squared $s = W^2$)
the **"Sachs electric FF"** $G_E^Y(s)$
the **"Sachs magnetic FF"** $G_M^Y(s)$.
They can be expressed through the **Dirac** $F_1^Y(s)$ and the **Pauli** $F_2^Y(s)$ FFs of hyperons

$$\begin{aligned} G_E^Y(s) &= F_1^Y(s) + \frac{s}{4m_Y^2} F_2^Y(s) \\ G_M^Y(s) &= F_1^Y(s) + F_2^Y(s) \qquad (1) \end{aligned}$$

where m_Y is the hyperon mass.

INTRODUCTION

From (1) ($\sigma_{tot}^{c.m.}(e^+e^- \to Y\bar{Y})$) the **equality**

$$G_E^Y(4m_Y^2) \equiv G_M^Y(4m_Y^2) \quad (2)$$

automatically follows **at the production threshold of hyperon-antihyperon pair** in electron-positron annihilation.

$F_1^Y(s)$, $F_2^Y(s)$ FFs are obtained as **coefficients in a decomposition of the hyperon matrix element of the EM current J_μ^{EM} into maximum number of linearly independent covariants** constructed from the four momenta p_1, p_2, Dirac γ-matrices and Dirac bispinors of the hyperons

$$< Y \mid J_\mu^{EM} \mid Y >= e\bar{u}(p_2)\{\gamma_\mu F_1^Y(s) + \frac{i}{2m_Y}\sigma_{\mu\nu}(p_2 - p_1)_\nu F_2^Y(s)\}u(p_1). \quad (3)$$

CURRENT DETERMINATION OF | $G_E^Y(s)$ | and | $G_M^Y(s)$ | BEHAVIORS

The electric $G_E^Y(s)$ and magnetic $G_M^Y(s)$ FFs are very **suitable in extracting experimental information** on the hyperon EM structure from measured e.g.

the **total cross section**

$$\sigma_{tot}^{c.m.}(e^+e^- \to Y\bar{Y}) = \frac{4\pi\alpha^2\beta_Y(s)}{3s}\{|\ G_M^Y(s)\ |^2 + \frac{2m_Y^2}{s}\ |\ G_E^Y(s)\ |^2\} \quad (4)$$

or the **differential cross section**

$$\frac{d\sigma(e^+e^- \to Y\bar{Y})}{d\Omega} = \frac{\alpha^2\beta_Y(s)}{4s}\{|\ G_M^Y(s)\ |^2\ (1+\cos^2\theta) + \frac{4m_Y^2}{s}\ |\ G_E^Y(s)\ |^2 \sin^2\theta\} \quad (5)$$

where $\beta_Y(s) = \sqrt{(1 - \frac{4m_Y^2}{s})}$ is the **velocity of produced hyperon** and θ **scattering angle**.

CURRENT DETERMINATION OF | $G_E^Y(s)$ | and | $G_M^Y(s)$ | BEHAVIORS

In the case of the total cross section **from one measured value of $\sigma_{tot}^{c.m.}(e^+e^- \to Y\bar{Y})$ at some energy one has to specify two independent numbers | $G_E^Y(s)$ | and | $G_M^Y(s)$ |.**
As we have an experience from the protons

a)**either equality of both EM FFs is applied** in (4), - it can be used only at the neighborhood of the production threshold $s = 4m_Y^2$ in e^+e^- annihilation,

b)**or at higher energies, due to the factor $\frac{2m_Y^2}{s}$, a negligible contribution , i.e. $G_E^Y(s) \approx 0$, is assumed.**

Both assumptions are model ingredients leading to hyperon magnetic FF | $G_M^Y(s)$ | behavior not to be very reliable.

CURRENT DETERMINATION OF | $G_E^Y(s)$ | and | $G_M^Y(s)$ | BEHAVIORS

More powerful in determination of | $G_E^Y(s)$ | and | $G_M^Y(s)$ | **is a measurement of the differential cross section** (5), under an assumption that there are colliders **with enough large integrated luminosity** L.

Such accelerating facilities now exist, mainly the **SLAC PEP-II asymmetric-energy e^+e^- collider** and also the **BEPC II double -ring e^+e^- collider in Beijing**, at which at some discrete values of energies for protons differential cross section $\frac{d\sigma(e^+e^-\to p\bar{p})}{d\Omega}$ has been measured, giving a **new model independent information on the EM structure of the proton in timelike region** for the first time.

CURRENT DETERMINATION OF | $G_E^Y(s)$ | and | $G_M^Y(s)$ | BEHAVIORS

The **method is transparent** if differential cross section (5) is rewritten into the form

$$\frac{d\sigma(e^+e^- \to Y\bar{Y})}{d\Omega} = a(s) + b(s)\cos^2\theta \tag{6}$$

where

$$a(s) = \frac{\alpha^2\beta_Y(s)}{s}\{\frac{1}{4} \mid G_M^Y(s) \mid^2 + \frac{m_Y^2}{s} \mid G_E^Y(s) \mid^2\} \tag{7}$$

$$b(s) = \frac{\alpha^2\beta_Y(s)}{s}\{\frac{1}{4} \mid G_M^Y(s) \mid^2 - \frac{m_Y^2}{s} \mid G_E^Y(s) \mid^2\}. \tag{8}$$

CURRENT DETERMINATION OF | $G_E^Y(s)$ | and | $G_M^Y(s)$ | BEHAVIORS

The latter method is **very effective for stable protons**, but **all $1/2^+$ octet hyperons are weakly decaying particles** with the mean life $\sim 10^{-10}s$, besides Σ^0-hyperon - the mean life of which is $\sim 10^{-20}s$.

As a result the **angular distribution of created hyperon-antihyperon pairs has to be reconstructed from the secondary particles appearing in the electron-positron annihilation processes**.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

Till now an **experimental determination of absolute values of hyperon complex EM FFs** in timelike region has been discussed.

However, for the complete determination of the hyperon EM FFs in timelike region it is **necessary to know the following four combinations** of FFs

$$|G_E^Y(s)|^2, |G_M^Y(s)|^2, Re[G_E^Y(s)G_M^{Y*}(s)], Im[G_E^Y(s)G_M^{Y*}(s)], \quad (9)$$

and they **can not be specified without measurements of polarizatios** in the $e^+e^- \to Y\bar{Y}$ processes.

Further, explicit forms of **vector and tensor polarizations of final particles** in the $e^+e^- \to Y\bar{Y}$ processes in the framework of the one photon exchange approximation **are calculated**.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

In order to calculate the **single and double spin polarization observables** one is in need of the matrix element of $e^+e^- \to Y\bar{Y}$ in the framework of the one-photon exchange approximation, which is defined by the formulae

$$\begin{aligned} \mathcal{M} &= \frac{e^2}{k^2} j_\mu J_\mu, \\ j_\mu &= \bar{u}(k_2)\gamma_\mu u(k_1), \\ J_\mu &= \bar{u}(p_2)\left[F_1^Y(s)\gamma_\mu + F_2^Y(s)\frac{i\sigma_{\mu\nu}k_\nu}{2m_Y}\right]u(p_1), \end{aligned} \tag{10}$$

where $s = k^2 \geq 4m_Y^2$.
We emphasize, that the **c.m. system of the reaction** $e^+e^- \to Y\bar{Y}$ **is the most suitable for the analysis of polarization effects**.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

The **EM currents** j_μ **and** J_μ **are conserved**, namely $k \cdot j = k \cdot J = 0$, therefore in the c.m. system of $e^+e^- \to Y\bar{Y}$ reaction $j_0 = J_0 = 0$. Then the matrix element $\mathcal{M}$ is determined only by product of spatial components of currents,

$$\begin{aligned} \mathcal{M} &= -\frac{e^2}{s}\vec{j}\cdot\vec{J} \\ |\mathcal{M}|^2 &= \frac{e^4}{s^2} j_{ik} W_{ik}, \end{aligned} \tag{11}$$

where

$$j_{ik} = j_i j_k^* \qquad W_{ik} = J_i J_k^*.$$

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

The EM current $\vec{J}$ can be expressed through two-component spinors φ_1 and φ_2

$$\vec{J} = \sqrt{s}\varphi_1^+ \left[G_M^Y(s)(\vec{\sigma} - \vec{n}\vec{\sigma}\cdot\vec{n}) + \frac{2m_Y}{\sqrt{s}} G_E^Y(s)\vec{n}\vec{\sigma}\cdot\vec{n} \right] \varphi_2 \qquad (12)$$

where we denote

$$\vec{F} = \sqrt{s} \left[G_M^Y(s)(\vec{\sigma} - \vec{n}\vec{\sigma}\cdot\vec{n}) + \frac{2m_Y}{\sqrt{s}} G_E^Y(s)\vec{n}\vec{\sigma}\cdot\vec{n} \right], \qquad (13)$$

$\vec{\sigma}$ are Pauli matrices and $\vec{n}$ is the unit vector along the three momentum $\vec{q}$ of the hyperon .

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

If **both initial leptons are unpolarized** lepton tensor takes the form

$$j_{ij} = (\,\delta_{ij} - m_i m_j) \tag{14}$$

and the vector polarization of the final hyperon or antihyperon is

$$\vec{P} = \frac{j_{ij}\, Tr[F_i F_j^\dagger \vec{\sigma}]}{j_{ij}\, Tr[F_i F_j^\dagger]}. \tag{15}$$

Calculating the traces in the numerator and denominator, respectively, **one finds the only P_y polarization component to be different from zero**

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

$$P_x = 0 \tag{16}$$

$$P_y = -\frac{\frac{1}{\sqrt{\tau}} Im(G_M^*(t)G_E(t)) \sin 2\vartheta}{\frac{1}{\tau}|G_E|^2 \sin^2\vartheta + |G_M|^2(1+\cos^2\vartheta)}; \tag{17}$$

$$P_z = 0. \tag{18}$$

In other words, **even annihilation of unpolarized electron and positron lead to a polarization of the created final hyperon** in direction of the y-axis, which is orthogonal to the scattering plane.

POLARIZATIONS IN $e^+e^- \rightarrow Y\bar{Y}$ PROCESSES

Recently such measurement of the polarization of the Λ-hyperon in the process $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ has been carried out
Patrik Adlarson(BESIII Collab.), Contribution in MESON'18 Conference, 7.-12.6.2018, Cracow (Poland)
whereby **polarization is experimentally accessible in weak parity violating decays** of Λ-hyperons - daughter particles are emitted according to polarization of mother hyperon.

They have measured the asymmetry parameter α_- for $\Lambda \rightarrow p\pi^-$ to be overestimated by more than 15 percent in comparison with the PDG value.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

Knowing the latter author are able from the measured angular distribution

$$I(\cos\theta_\Lambda) = \frac{1}{4\pi}(1 + \alpha_- P_y \cos\theta_\Lambda) \tag{19}$$

to determine P_y of the Λ polarisation.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

If at least one of the initial leptons is longitudinally polarized the corresponding lepton tensor takes the form

$$j_{ij} = (\,\delta_{ij} - m_i m_j + \lambda i \varepsilon_{ijl} m_l\,). \tag{20}$$

and the vector polarization of the final hyperon or antihyperon is again in the form

$$\vec{P} = \frac{j_{ij}\,Tr[F_i F_j^\dagger \vec{\sigma}]}{j_{ij}\,Tr[F_i F_j^\dagger]}. \tag{21}$$

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

Calculating the traces in the numerator and denominator, respectively, one finds the vector polarization components

$$P_x = -\frac{2\sin\theta \cdot Re[G_{Ep}(s)G^*_{Mp}(s)]\tau}{|G_{Ep}(s)|^2\sin^2\theta/\tau + |G_{Mp}(s)|^2(1+\cos^2\theta)} \quad (22)$$

$$P_y = -\frac{\frac{1}{\sqrt{\tau}} Im(G^*_M(t)G_E(t))\sin 2\vartheta}{\frac{1}{\tau}|G_E|^2\sin^2\vartheta + |G_M|^2(1+\cos^2\vartheta)}; \quad (23)$$

$$P_z = \frac{2\cos\theta|G_{Mp}(s)|^2}{|G_{Ep}(s)|^2\sin^2\theta/\tau + |G_{Mp}(s)|^2(1+\cos^2\theta)}, \quad (24)$$

assuming 100% i.e. $\lambda = 1$ longitudinal polarization of the electron.

POLARIZATIONS IN $e^+e^- \rightarrow Y\bar{Y}$ PROCESSES

In a similar procedure one can find explicit forms of double spin polarization observables in the $e^+e^- \rightarrow Y\bar{Y}$ process, where we are interested for components of the polarizations of created hyperons and antihyperons simultaneously. Then the corresponding tensor of polarization is

$$P_{kl} = \frac{j_{ij}\,Tr[F_i \sigma_k F_j^\dagger \sigma_l]}{j_{ij}\,Tr[F_i F_j^\dagger]} \tag{25}$$

where $k, l = x, y, z$.

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

Calculating the trace in the numerator and similarly the trace in the denominator, **considering unpolarized incoming leptons**, one finds

$$
\begin{aligned}
P_{xx} &= \frac{|G_M^Y(s)|^2 \cos^2\vartheta - \frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta}{\frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta + |G_M^Y(s)|^2(1+\cos^2\vartheta)}; \\
P_{yy} &= \frac{|G_M^Y(s)|^2 (1+\sin^2\vartheta) - \frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta}{\frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta + |G_M^Y(s)|^2(1+\cos^2\vartheta)}; \\
P_{zz} &= \frac{|G_M^Y(s)|^2 \sin^2\vartheta - \frac{1}{\tau}|G_E^Y(s)|^2 \cos^2\vartheta}{\frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta + |G_M^Y(s)|^2(1+\cos^2\vartheta)}; \\
P_{xy} &= P_{yx} = 0; \\
P_{xz} &= P_{zx} = \frac{\frac{1}{\sqrt{\tau}} Re[G_M^{Y*}(s) G_E^Y(s)] \sin 2\vartheta}{\frac{1}{\tau}|G_E^Y(s)|^2 \sin^2\vartheta + |G_M^Y(s)|^2(1+\cos^2\vartheta)}; \\
P_{yz} &= P_{zy} = 0
\end{aligned}
\qquad (26)
$$

POLARIZATIONS IN $e^+e^- \to Y\bar{Y}$ PROCESSES

Considering the longitudinally polarized electron or positron for components $P_{xx}, P_{yy}, P_{zz}, P_{xy}, P_{yx}, P_{xz}, P_{zx}$ one finds identical expressions with (26), **but the last two components are now nonzero as well**

$$P_{yz} = P_{zy} = -2\frac{\frac{1}{\sqrt{\tau}} Im[G_M^{Y*}(s)G_E^Y(s)]\sin\vartheta}{\frac{1}{\tau}|G_E^Y(s)|^2\sin^2\vartheta + |G_M^Y(s)|^2(1+\cos^2\vartheta)}. \quad (27)$$

Every of components P_{kl} characterize a polarization of the hyperon Y in the direction k, if antihyperon $\bar{Y}$ is polarized at the direction l and they all are calculated for 100% polarization of one of the initial leptons.

CONCLUSIONS

The single-spin and double spin polarizations of the created hyperons in the process $e^+e^- \to Y\bar{Y}$, dependent on the state of a polarization of the initial leptons, has been demonstrated.

It was shown, that **even annihilation of unpolarized electron and positron lead to a polarization of the created final hyperon** in direction of the y-axis, which is orthogonal to the scattering plane. This effect is already confirmed by BESIII Collaboration in Beijing recently by a measurement polarization in the process $e^+e^- \to \Lambda\bar{\Lambda}$.

Thank you for your attention.