Hyperon form factors & diquark correlations

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Abstract. Using $e^+e^-$ annihilation data taken at the CESR collider with the CLEO-c detector, measurements of hyperon pair production cross sections and elastic and transition electromagnetic form factors have been made at the charmonium resonances: $\psi(2S)$, $\sqrt{s} = 3.69$ GeV, $|Q^2| = 13.6$ GeV$^2$, $L = 48$ pb$^{-1}$; $\psi(3770)$, $\sqrt{s} = 3.77$ GeV, $|Q^2| = 14.2$ GeV$^2$, $L = 805$ pb$^{-1}$; and $\psi(4170)$, $\sqrt{s} = 4.17$ GeV, $|Q^2| = 17.4$ GeV$^2$, $L = 586$ pb$^{-1}$. Results with good statistical precision are obtained with high efficiency particle identification. Systematics of pair production cross sections, and form factors with respect to the number of strange quarks in the hyperons are studied, and evidence is presented for effects of diquark correlations in comparative results for $\Lambda^0$ and $\Sigma^0$, both of which have the same $uds$ quark content but different isospin.

1. Introduction
The presentation at the conference closely follows two papers we have published since then [1] [2]. Unlike the proton and neutron which have been extensively studied by elastic electron scattering because they are available as targets, very little beyond the static properties of ground state hyperons is known. Previous measurements at DM2 [3] and SLAC [4] were limited to $\Lambda^0$ and $\Sigma^0$ hyperons at low energies, had very poor statistics, and were not suitable for study in terms of QCD. Our present measurements overcome all of these limitations.

2. Data Samples and Event Selections
The CESR $e^+e^-$ collider and the CLEO detector used for our measurements has been described elsewhere [5]. Because of page limitations in the Proceedings, we are not able here to present details of our particle identification procedure. However, we present illustrative examples of the three main steps in particle identification in Figures 1, 2, and 3.

3. Summary and Discussion of Results
Because of page limitations, in the following we only present the numerical results for our measurements for production cross sections and branching fractions for the $\Psi(2S)$ data in Table 1, cross sections and form factors for the $\Psi(3770)$ data in Table 2, and for $\Psi(4170)$ data in Table 3.

The data for $\Psi(2S)$ are dominated by resonance production and therefore can not be used for determination of form factors, which can however be determined for $\Psi(3770)$ and $\Psi(4170)$ data, for which the production is almost entirely electromagnetic. These have been determined with the assumption that the cross sections are related to form factors as for nucleons. The absolute cross sections in Tables 1, 2, and 3 have been determined by efficiency determinations...
Figure 1. Invariant mass distributions for $\psi(2S)$ data. The solid red curves show the results of the fits to these spectra, while the dashed red line shows the background component of the fit. Clear peaks corresponding to each hyperon are seen, and their fitted yields are displayed in each panel. The dashed vertical line correspond to the “signal” region used for the momentum plots in Fig. 2.

Figure 2. Momentum distributions for hyperon candidates in the “signal” mass regions defined in Fig. 1 for $\psi(2S)$ data. The narrow peaks at high momentum are due to pair-production of hyperons. The yields at lower momenta are due to hyperons produced in association with other hadrons and the combinatorial backgrounds underneath the hyperon peaks seen in Fig. 1.
by Monte-Carlo simulations. Form factors have been derived from the cross sections by the conventional parameterization in terms of magnetic and electric form factors, \( G_B^M(s) \) and \( G_B^E(s) \) using the relation

\[
\sigma_{BB} = \left( \frac{4\pi\alpha^2\beta_B}{3s} \right) \left[ |G_B^M(s)|^2 + \left( 2m_B^2/s \right) |G_B^E(s)|^2 \right]
\]

although they now represent helicity parallel and perpendicular distributions rather than electric and magnetic form factors. Analysis of angular distributions in our data for \( \Lambda^0 \), \( \Xi^- \), and \( \Xi^0 \), for which we have enough statistics, lead us to the conclusion that \( G_B^E(s) = 0 \) rather than \( G_E/G_M = 1 \). With this additional assumption, we derive \( G_B^M(s) \) for the different hyperons and the ratios as listed in Tables 2 and 3, and illustrated in Fig. 5. The systematic errors in these values are listed in Table 4.

The results presented in Tables 1, 2, and 3, and illustrated in Figures 4 and 5 are the world’s first and only measurements of their kind. Two important new conclusions follow from our measurements:

**I:** As illustrated in Fig. 4, the cross sections for the production of \( \Lambda^0 \) is nearly a factor of 3 larger than that for \( \Sigma^0 \) although both of them have the same uds quark construct. This feature was first observed in the LEP data at high energies, and was ascribed by Wilczek to the different diquark construct between the isospin zero \( \Lambda^0 \) (good diquark) and the isospin 1 \( \Sigma^0 \) (bad diquark). Our observation is an independent confirmation of the “good diquark” \( \Lambda^0 \) and “bad diquark” \( \Sigma^0 \) constructs.

**II:** As illustrated in Fig. 5, while pQCD predicts a \( q^{-4} \) variation of timelike form factors, we observe an additional dependence on the number of s-quarks in the hyperons.

**Figure 3.** Invariant mass distributions for hyperon candidates in \( \psi(2S) \) data in the pair-production region given by \( E(B)/E(\text{beam}) = 0.99 - 1.01 \). The solid red curves show the result of the fit to this spectrum described in the text, while the dashed red line shows the background component of the fit.
Table 1. Summary of cross section and branching fraction results from $\psi(2S)$ data. The systematic uncertainties are taken from Table 4. Note that the results for protons are borrowed from our Ref. [6]. The uncertainties in our present results are smaller than our results in Ref. [6] by factors two or larger.

| $N(\psi(2S)$ | $N_H$ | $\epsilon_B$ (%) | $\sigma_B$ (pb) | $B \times 10^4$ | $B \times 10^4$ (prev.) [6] | BES-III [7] |
|---------------|-------|------------------|----------------|-----------------|---------------------|----------------|
| $p^+$         | 6519 ± 82 | 42 ± 8 | 71.6 | 244.7 ± 2.1 ± 0.1 | 3.71 ± 0.05 ± 0.15 | 3.75 ± 0.09 ± 0.23 | 3.97 ± 0.02 ± 0.12 |
| $\Sigma^0$    | 2665 ± 56 | 14 ± 2 | 48.6 | 145.6 ± 0.3 ± 0.1 | 2.22 ± 0.05 ± 0.11 | 2.25 ± 0.11 ± 0.16 | 2.44 ± 0.03 ± 0.11 |
| $\Sigma^+$    | 1874 ± 46 | 15 ± 2 | 33.0 | 151.4 ± 0.3 ± 0.4 | 2.31 ± 0.06 ± 0.10 | 2.51 ± 0.15 ± 0.16 | 2.78 ± 0.05 ± 0.14 |
| $\Xi^-$       | 3580 ± 61 | 17 ± 2 | 48.2 | 199.9 ± 0.3 ± 0.4 | 3.03 ± 0.05 ± 0.14 | 2.66 ± 0.12 ± 0.20 | 2.78 ± 0.05 ± 0.14 |
| $\Xi^0$       | 1242 ± 38 | 8 ± 1 | 25.6 | 131.6 ± 0.3 ± 0.7 | 1.97 ± 0.06 ± 0.11 | 2.02 ± 0.10 ± 0.15 | — |
| $\Omega^- $   | 326 ± 19 | 1 ± 1 | 25.8 | 33.7 ± 0.3 ± 0.6 | 0.52 ± 0.03 ± 0.03 | 0.47 ± 0.03 ± 0.05 | — |
| $A \Sigma$    | 30 ± 5 | 0.2 ± 0.1 | 0.9 | 8.1 ± 1.5 ± 0.5 | 0.123 ± 0.023 ± 0.008 | — |

Table 2. Summary of cross section and form factor results from $\psi(3770)$ data. The systematic uncertainties are taken from Table 4. The results for protons are borrowed from our Ref. [6]. The cross sections $\sigma_B$ (BES-III) are calculated from the results in Ref. [9] assuming $\mathcal{L}$ (BES-III) = 2.9 fb$^{-1}$ and $C$ (BES-III) = 0.8. Note that the electromagnetic $\sigma_B$ in column 3 are generally smaller than the resonance decay cross sections from $\psi(2S)$ in Table I by orders of magnitude. Note that $G_M$ (prev.) [6] were derived assuming $G_E = G_M$.

| $B$ | $N(\psi(3770)$ | $\epsilon_B$ (%) | $\sigma_B$ (pb) | $\sigma_B$ (BES-III) [6] | $G_M \times 10^2$ | $G_M \times 10^2$ (prev.) [6] |
|-----|----------------|------------------|----------------|------------------------|-------------------|-----------------------------|
| $p^+$ | 406 ± 39 | 74.8 | 1.08 ± 0.09 ± 0.04 | 1.48 ± 0.06 ± 0.03 | 1.18 ± 0.10 ± 0.06 |
| $\Sigma^0$ | 142 ± 20 | 84.0 | 1.08 ± 0.07 ± 0.02 | 0.98 ± 0.04 ± 0.02 | 0.71 ± 0.06 ± 0.03 |
| $\Sigma^+$ | 200 ± 19 | 32.3 | 1.02 ± 0.04 ± 0.04 | 0.82 ± 0.04 ± 0.04 | 0.73 ± 0.04 ± 0.03 |
| $\Xi^-$ | 240 ± 17 | 55.0 | 0.71 ± 0.05 ± 0.03 | 1.28 ± 0.04 ± 0.03 | 1.14 ± 0.09 ± 0.04 |
| $\Xi^0$ | 111 ± 12 | 24.6 | 0.71 ± 0.08 ± 0.03 | 1.28 ± 0.07 ± 0.03 | 0.81 ± 0.11 ± 0.03 |
| $\Omega^-$ | 40 ± 6 | 29.5 | 0.71 ± 0.03 ± 0.01 | 0.71 ± 0.00 ± 0.01 | 0.63 ± 0.01 ± 0.03 |
| $A \Sigma^0$ | 39 ± 5 | 10.8 | 0.43 ± 0.08 ± 0.04 | — | 0.77 ± 0.07 ± 0.03 |

Table 3. Summary of cross section and form factor results from $\psi(4170)$ data. The systematic uncertainties are taken from Table 4. The results for protons are borrowed from our Ref. [6]. Note that the $\sigma_B$ in column 3 for hyperon pair production at $\psi(4170)$ are smaller by factors 4 to 10 than those for $\psi(3770)$ in Table II.

| $B$ | $N(\psi(4170)$ | $\epsilon_B$ (%) | $\sigma_B$ (pb) | $G_M \times 10^2$ | $|Q|^4 G_M [3770]/|Q|^4 G_M [4170]$ |
|-----|----------------|------------------|----------------|-----------------|---------------------------|
| $p^+$ | 61 ± 14 | 64.9 | 0.23 ± 0.05 ± 0.01 | 0.73 ± 0.08 ± 0.02 | 1.28 ± 0.16 |
| $\Sigma^0$ | 19 ± 7 | 46.0 | 0.09 ± 0.04 ± 0.02 | 0.47 ± 0.09 ± 0.04 | 1.92 ± 0.27 |
| $\Sigma^+$ | 33 ± 8 | 30.7 | 0.23 ± 0.06 ± 0.04 | 0.75 ± 0.09 ± 0.06 | 1.16 ± 0.18 |
| $\Xi^-$ | 18 ± 5 | 53.2 | 0.08 ± 0.02 ± 0.01 | 0.44 ± 0.06 ± 0.01 | 1.80 ± 0.25 |
| $\Xi^0$ | 7 ± 3 | 25.8 | 0.06 ± 0.03 ± 0.01 | 0.40 ± 0.08 ± 0.04 | 1.89 ± 0.41 |
| $\Omega^-$ | 7 ± 3 | 25.8 | 0.06 ± 0.03 ± 0.01 | 0.39 ± 0.08 ± 0.04 | 0.92 ± 0.23 |
| $A \Sigma^0$ | 7.0 ± 3 | 10.8 | 0.155 ± 0.06 ± 0.01 | 0.50 ± 0.05 ± 0.02 | 0.72 ± 0.25 |

Table 4. Summary of systematic uncertainties. The total systematic uncertainty listed in the sum in quadrature of the individual contributions.

| $\psi(2S)$ branching fractions | $A^0$ | $\Sigma^0$ | $\Sigma^+$ | $\Xi^-$ | $\Xi^0$ | $\Omega^-$ |
|-------------------------------|-------|----------|----------|--------|--------|--------|
| $\psi(2S)$ Track reconstruction | 2 | 2 | 2 | 2 | 2 | 2 |
| Particle ID                   | 2 | 2 | 2 | 2 | 2 | 2 |
| $\pi^0/\gamma$ reconstruction | 0 | 2 | 2 | 0 | 2 | 0 |
| $\psi(2S)$ Hyperon reconstruction | 2 | 2 | 2 | 2 | 2 | 2 |
| $\psi(2S)$ Total              | 4.1 | 4.9 | 4.2 | 4.7 | 5.4 | 5.8 |
| $\psi(3770)$ track reconstruction | 1 | 1 | 1 | 1 | 1 | 1 |
| $\psi(3770)$ Particle ID       | 2 | 2 | 1 | 3 | 2 | 3 |
| $\psi(3770)$ Hyperon reconstruction | 2 | 2 | 2 | 2 | 2 | 2 |
| $\psi(3770)$ Total             | 4.1 | 6.5 | 4.8 | 5.2 | 4.2 | 9.7 |
| $\psi(4170)$ Track reconstruction | 5 | 16 | 17 | 2 | 18 | 5 |
| $\psi(4170)$ Total             | 6.2 | 16.5 | 17.4 | 18.7 | 18.5 | 7.4 |
Figure 4. Summary of cross section results. pQCD predicts that the production cross sections vary is $q^{-4}$, or the ratio $\sigma(3770) / \sigma(4170)$ which should be equal to 2.74 for all hyperons. The data show clear differences for this ratio between baryons containing 0, 1, or 2 strange quarks.

Figure 5. The pQCD prediction for the corresponding ratio of $G_M$ at $\psi(3770)$ and $\psi(4170)$ is 1.5. Our results show different values for baryons containing 0, 1, and 2 strange quarks.
Figure 6. Illustrates the summary of all existing time-like form factors as functions of $|Q^2|$. Results from the present analysis are shown by the filled circles ("NU"). Results from previous measurements by the DM2 [3] and BaBar [4] Collaborations are also shown with closed triangles and open circles, respectively. The first panel shows measurements of proton timelike form factors for comparison from BaBar [10], Fermilab E760/E835 [11][12][13], BES [14], and analyses of CLEO data (NU) [15][16].

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