Production cross sections of hyperons and charmed baryons from \(e^+e^-\) annihilation near \(\Upsilon(4S)\)


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Baryon production rates in $e^+e^-$ collision

- $e^+e^- \rightarrow \gamma^* \rightarrow qq \rightarrow \text{Haronization}$
- ex) $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda + \text{anything}$
Hadron production rates in $e^+e^-$ collision

- $e^+e^- \rightarrow \gamma^* \rightarrow qq \rightarrow $Haronization
- ex) $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda + $anything

- Scale on exponential function:
  \[ \frac{\sigma}{\sigma_{had}(2J+1)} \propto \exp(-\alpha m_{had}) \]

- Different slope for mesons and baryons
  - quark counting?
  - what about “exotic” hadrons?
    - $\Lambda(1405), \Xi(1530)$
Baryon production rates in $e^+e^-$ collision

- Baryon production: color suppression to form color-singlet combination among random quark colors
- Diquark-antidiquark production model can explain relatively high production rate
- Relativistic-string model

Baryon production rates in $e^+e^-$ collision

- Higher rates for $\Lambda$ and $\Lambda(1520)$ in ARGUS and LEP.
- $J=0$, light (ud) diquark in $\Lambda$?

Issues

- Feed down is subtracted?
- Large error in ARGUS results
- How about charmed baryons?

- Study at Belle!
Belle data

Integrated luminosity:

- 562. fb⁻¹ @ on Υ(4S) resonance data for charmed baryons ($\sqrt{s} = 10.58 \text{ GeV}$)
- 79.3 fb⁻¹ @ continuum data for hyperons, charmed baryons ($\sqrt{s} = 10.52 \text{ GeV}$)
Mass spectra for hyperons
Reconstruction of $S=-1$ hyperons

- **Λ**
  - All $x_p$

- **Σ**
  - **Σ**($1385)^+$
    - $0.3 < x_p \leq 0.4$
  - **Σ**($0^+)$
    - $0.3 < x_p \leq 0.4$

**Parton Model**
- **π$^-$**
  - IP
  - $c\tau=7.89$ cm
- **p**
  - **Δx**
- **Σ**($0^+)$
  - Or γ

**Graphs**
- Events/(0.25 MeV/c$^2$)
- Events/(1.0 MeV/c$^2$)
- Events/(0.25 MeV/c$^2$)
- Events/(1.0 MeV/c$^2$)

**Formulas**
- $\frac{\text{Events}}{(0.25 \text{ MeV/c}^2)}$
- $\frac{\text{Events}}{(1.0 \text{ MeV/c}^2)}$

**Variables**
- $x_p$
- $c\tau$
- Λ
- Σ
- IP
- p
- Δx

**Equations**
- $\text{M}(\text{pK}^-) \ (\text{GeV/c}^2)$
- $\text{M}(\text{Λγ}) \ (\text{GeV/c}^2)$
- $\text{M}(\text{pK}^-) \ (\text{GeV/c}^2)$
- $\text{M}(\text{pK}^-) \ (\text{GeV/c}^2)$
Reconstruction of $\Xi^-, \Omega^-, \Omega_c^-, \Xi_c^-$

- **$\Xi^-$ and $\Omega^-$:**
  - Plots show invariant mass spectra for $\Lambda\pi^-$ and $\Lambda K^-$.
  - Peaks at specific masses indicated by double-hatched and hatched histograms, respectively.

- **$\Omega_c$ and $\Xi_c$:**
  - Plots for $\Omega_c^0$ and $\Xi_c^0$ show differential cross sections with $x_p$.
  - Cross sections are given for different mass regions.

- **Reconstruction Diagram:**
  - Shows $p\rightarrow \pi^- (\Lambda)(K^-)$ with $c\tau=4.9$ (2.4) cm.

- **Events Distribution:**
  - Histograms for $\Omega_c^0$ and $\Xi_c^0$ with fit results and backgrounds.
  - Events are distributed within specific mass ranges.
Mass spectra for charmed baryons

![Graphs showing mass spectra for different charmed baryons such as $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Sigma_c(2455)^0$, and $\Sigma_c(2520)^0$. The graphs display invariant mass spectra and differential cross sections with specified momentum ranges, e.g., $0.58 < x_p \leq 0.60$ for some regions.]
Inclusive differential cross sections, hyperons

“Inclusive” cross sections (including feed-down) are obtained as a function of hadron scaled momentum ($x_p$). $x_p = p/\sqrt{s/4 - M^2}$ (M, p : mass and CM momentum)

Continuum data

Error bar represent statistical fluctuation.
Inclusive differential cross sections, hyperons

"Inclusive" cross sections (including feed-down) are obtained as a function of hadron scaled momentum ($x_p$).

$$x_p = \frac{p}{\sqrt{s/4 - M^2}}$$  \hspace{1cm} (M, p : mass and CM momentum)

Error bar represent statistical fluctuation.
Inclusive differential cross sections, hyperons

“Inclusive” cross sections (including feed-down) are obtained as a function of hadron scaled momentum \( x_p \).

\[ x_p = \frac{p}{\sqrt{s/4 - M^2}} \] (M, p : mass and CM momentum)

Peaks around \( x_p \sim 0.2-0.3 \)
→ hyperons are produced in soft processes.

Peak positions for \( \Omega^- \) and \( \Xi(1530) \) seem slightly higher than the other hyperons.

Total cross sections for \( S=-1 \) hyperons are obtained using Hermite interpolation assuming \( d\sigma/dx_p = 0 \) at \( x_p = 0,1 \).
Inclusive differential cross sections, charmed baryons

- In order to increase statistics, both of on \( \Upsilon(4S) \) and continuum data are used.
- B-meson decay contribution concentrate in low \( x_p \), and is eliminated by selecting \( x_p > 0.44 \).
Inclusive differential cross sections, charmed baryons

Sum of on $\Upsilon(4S)$ and continuum

Absolute B.F. for $\Omega_c, \Xi_c$ is unknown.
Inclusive differential cross sections, charmed baryons

FIG. 6. Differential cross sections of charmed baryon production with and without radiative corrections. The closed circles are shifted slightly to the left for clarity. The error bars include the statistical uncertainties of real data and the uncertainties of the MC statistics.

- (a) $\Lambda_c^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (b) $\Lambda_c(2595)^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (c) $\Lambda_c(2625)^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (d) $\Sigma_c(2455)^0 + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (e) $\Sigma_c(2520)^0 + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (f) $\Omega_c^0 \rightarrow \Omega^- \pi^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (g) $\Xi_c^0 \rightarrow \Xi^- \pi^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction

- (h) $\Xi_c^0 \rightarrow \Omega^- K^+ + c.c.$
  - w/o radiative correction
  - w/ radiative correction
Inclusive differential cross sections, charmed baryons

Peaks around $x_p \sim 0.6-0.7$

→ charm quarks are produced in $e^+e^- \rightarrow \gamma^* \rightarrow cc$.

Peak positions for heavier particles seem higher.

More energetic fragmentation process is necessary to produce heavy particle?

Total cross sections of excited states are obtained by fitting Lund fragmentation model.
Comparison of visible cross section with previous measurements

![Graphs showing comparison of visible cross section with previous measurements.](image-url)
Comparison of visible cross section with previous measurements

Cross sections before feed-down subtraction are consistent with previous measurements but much higher precision.
Feed-down subtracted (direct) cross section

\[
\sigma/(2J+1) \text{ (pb)}
\]

Inclusive cross sections

Direct cross sections

\[
\Lambda, \Sigma^0, \Xi^-, \Lambda(1520), \Sigma(1385)^+, \Xi(1530)^0, \Omega^-
\]

\[
\Lambda_c^+, \Sigma_c(2455)^0, \Sigma_c(2520)^0, \Lambda_c(2593)^+, \Lambda_c(2625)^+
\]
Results for hyperons

Fit with $a_0 \exp(a_1 m)$, Slope parameter $-7.3 \pm 0.3$ (GeV/c$^2$)$^{-1}$

Exponential with same slope of $S=-1$
Results for hyperons

- Suppression
- $\Sigma(1385)$: 33% with $2.3\sigma$
- $\Xi(1530)$: 22% with $4.6\sigma$

Fit with $a_0\exp(a_1m)$, Slope parameter $-7.3\pm 0.3$ (GeV/c$^2$)$^{-1}$

No enhancement
Note: inclusive cross sections are consistent with ARGUS.

Exponential with same slope of $S=-1$

Suppression
Heavy spin=1 diquark in decuplet members?

ss$\bar{s}$ suppression?
Results of charmed baryons

\[ \sigma / (2J+1) \ (\text{pb}) \]

Slope parameters
\[ \Lambda_c : -6.3 \pm 0.5 \ (\text{GeV}/c^2)^{-1} \]
\[ \Sigma_c : -5.8 \pm 1.0 \ (\text{GeV}/c^2)^{-1} \]

consistent

Suppression for \( \Sigma_c \) family by the factor of \( \sim 3 \)
Discussion

- Assuming that a c-quark picks up a diquark from vacuum,
  - Schwinger-like “tunnel effect” of diquark and anti-diquark
    \[ \sigma \propto \exp(-\pi \mu^2 / \kappa) \]
    - \( \mu \): diquark mass
    - \( \kappa \): gluonic string tension
- \( \Lambda_c \): spin-0 light diquark (“good” diquark),
- \( \Sigma_c \): spin-1 heavy diquark (“bad” diquark)
- Difference of production rates may be related with diquark structure in \( \Lambda_c \) and \( \Sigma_c \).

\[ \Lambda_c(2286)^+ \]

\[ \Sigma_c(2455) \]
Discussion

- Assuming that a c-quark picks up a diquark from vacuum,
  - Schwinger-like “tunnel effect” of diquark and anti-diquark
    \[
    \sigma \propto \exp\left(-\pi \mu^2 / \kappa\right) \quad \mu: \text{diquark mass} \quad \kappa: \text{gluonic string tension}
    \]
  - \( \Lambda_c \): spin-0 light diquark (“good” diquark),
  - \( \Sigma_c \): spin-1 heavy diquark (“bad” diquark)
  - Difference of production rates may be related with diquark structure in \( \Lambda_c \) and \( \Sigma_c \).
  - Quark model prediction by T. Yoshida et al, PRD92, 114029 (2015)
    \( \Lambda_c(2593) \ (1/2^-) \) and \( \Lambda_c(2625) \ (3/2^-) \)
    are composed of \( (qq)_{\ell=0} \) diquark with \( L=1 \) excitation relative to charm quark.

T. Yoshida et al
PRD92, 114029 (2015)
Discussion

- Assuming that a c-quark picks up a diquark from vacuum,
  - Schwinger-like “tunnel effect” of diquark and anti-diquark
    \[ \sigma \propto \exp\left(-\pi \mu^2 / \kappa\right) \]
    \( \mu \): diquark mass
    \( \kappa \): gluonic string tension

- \( \sigma(\Sigma_c)/\sigma(\Lambda_c) = 0.27 \pm 0.07 \)
- mass difference of spin-1 and 0 diquarks
  \[ m(ud_1)^2 - m(ud_0)^2 = (8.2 \pm 0.8) \times 10^4 \ (\text{MeV}/c^2)^2 \]
  ref. \( 490^2 - 420^2 = 6.4 \times 10^4 \ (\text{MeV}/c^2)^2 \)

- Slightly higher than reference but consistent with the spin-1/0 diquark mass difference!
Summary

• Production cross sections of hyperons and charmed baryons are measured near the \( \Upsilon(4S) \) energy using Belle data.
• \( d\sigma/dx_p \) distributions for hyperons
  • Slightly higher Peak positions for \( \Omega^- \) and \( \Xi(1530) \)
• \( d\sigma/dx_p \) distributions for charmed baryons
  • Peak positions for heavier particles seem higher.
• “Inclusive” total cross sections for hyperons
  • Consistent with previous measurements with much higher precision
• Direct total cross sections
  • Clear exponential dependence on baryon masses
  • No enhancements for \( \Lambda, \Lambda(1520) \)
  • Suppression of decuplet hyperons and \( \Sigma_c \) family
  • Suggesting diquark structure in ground and low-lying \( \Lambda_c, \Sigma_c \)
• Next, exotic candidates, heavier \( \Lambda_c \) resonances …
  • Input of absolute B.F. for \( \Xi_c \) is helpful