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OBSERVATION OF CHARMED BARYON PRODUCTION IN e^+e^- ANNIHILATION

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Accelerator Center, Stanford University, California

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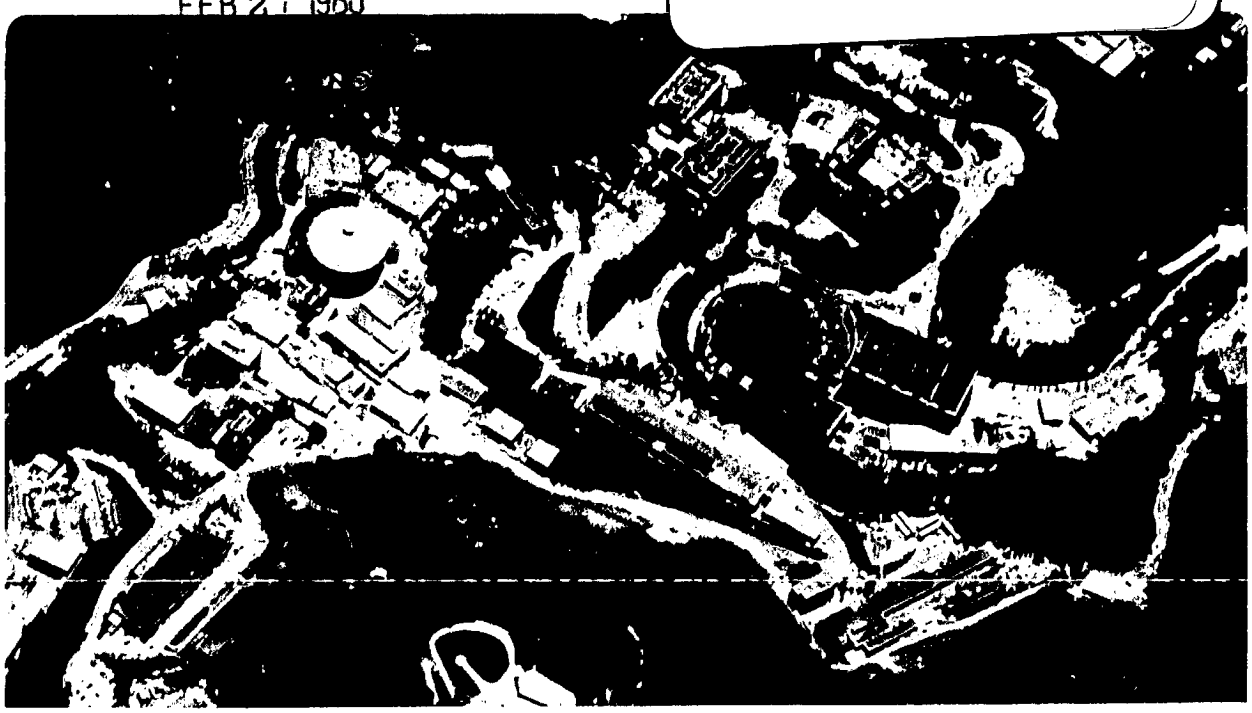

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OBSERVATION OF CHARMED BARYON PRODUCTION IN e^+e^- ANNIHILATION*

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ABSTRACT

We observe a peak in the $pK^-\pi^+$ and $\bar{p}K^+\pi^-$ invariant mass spectra at 2.285 ± 0.006 GeV/c^2, which we associate with the lowest-lying charmed baryon (Λ_c). We measure a cross section times branching ratio of 0.037 ± 0.012 nb at $E_{cm} = 5.2$ GeV with a substantial fraction of the events produced with an equal recoiling mass. We also present new measurements of inclusive p and Λ cross sections, allowing an estimate of the branching ratio $B(\Lambda_c \to pK^-\pi^+) = 0.022 \pm 0.010$.

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Our present understanding of the charmonium states and of charmed mesons leads us to expect the existence of weakly decaying charmed baryons.[1] Evidence for the production of such charmed baryons has been reported in neutrino interactions,[2] photon interactions,[3] and p-p interactions.[4] In an experiment with the SLAC-LBL Mark II detector at the SPEAR e^+e^- storage ring of the Stanford Linear Accelerator Center, we observe the $pK^-\pi^+$ and $\bar{p}K^+\pi^-$ decay modes of what appears to be the lowest-lying charmed baryon (Λ_c). As in the case of the charmed mesons, the baryon is associated with recoil masses equal to or greater than its observed mass. Together with a new measurement of the inclusive proton and Λ cross sections, reported here, we are able to estimate the absolute branching ratio of the Λ_c state to the $pK\pi$ channel.

The data sample used in this analysis represents an integrated luminosity of 9150 nb^{-1}. Of this 4000 nb^{-1} was obtained during a scan of the region 4.5-6.0 GeV and 5150 nb^{-1} was obtained during a run at the center-of-mass energy 5.2 GeV. Additional data at other energies are used for the inclusive cross-section measurement.

Detailed descriptions of the Mark II detector have been given elsewhere.[5] The trigger for this experiment requires one track to register in the drift chambers and the appropriate time-of-flight counter (0.75 of 4π solid angle) as well as a second track to register in the inner layers of the drift chamber (0.85 of 4π).

Particle identification is accomplished by the time-of-flight (TOF) system with a measured resolution for hadron tracks of $\sigma = 0.300$ nsec. This allows a 1σ separation for K-π at 1.35 GeV/c and for K-p at 2.0 GeV/c momentum. Each track is assigned weights $W(\pi)$, $W(K)$, $W(p)$ corres-

ponding to its possible identities. Each weight is proportional to the probability that if the particle has the assumed identity, its flight time would have the measured value, and the normalization is such that the sum of all weights corresponding to a given track is unity. The track is called a proton if its momentum is less than 2.0 GeV/c and $W(p) > 0.5$. Kaons are identified for momenta less than 1.4 GeV/c by $W(K) > 0.5$. All other tracks not positively identified as muons or electrons are called pions.

We are searching for charmed baryon signals in various channels and report here results for the $pK\pi$ channel. To reduce the effects of beam-gas backgrounds, proton events which do not also contain an antiproton are required to have a net observed charge $< +1$. This additional requirement reduces the efficiency for protons relative to antiprotons by 21% as measured from the antiproton data sample.

Figure 1(a) shows the invariant mass distribution for the $pK^-\pi^+$ combinations and charge conjugate $\bar{p}K^+\pi^-$ with the requirement that the mass recoiling against the $pK\pi$ system be greater than 2.2 GeV/c^2. A significant enhancement is observed at $M(pK\pi) = 2.285$ GeV/c^2 in these channels which have the quantum numbers of the Cabibbo-favored weak decay of the Λ_c. Figure 1(b) shows the complementary mass distribution for those $pK\pi$ combinations with recoil mass less than 2.2 GeV/c^2. No enhancement is observed in Fig. 1(b), indicating that the observed signal is associated with an equal or larger recoil mass. In Fig. 1(c) we show the invariant mass distribution for the channels $pK^+\pi^-$ and $pK^-\pi^-$ and their charge conjugates with the same cuts as in Fig. 1(a). These channels have quantum numbers inconsistent with a Λ_c decay and do not exhibit any structure.

The curve in Fig. 1(a) shows that the data are well fit to a Gaussian error function plus a background shape determined from a fit to Fig. 1(c). The signal consists of 39 ± 8 events above a background of 20 events.

For those $pK\pi$ combinations with total measured energy within 0.03 GeV of the beam energy, Fig. 1(d) shows the beam energy constrained mass defined as $M_c = \sqrt{E^2_{beam} - p^2_{pK\pi}}$. The 10 ± 4 events in the peak near $M_c = 2.285$ GeV/c^2 imply that the reaction $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ is the source of 26 ± 11% of the observed $pK\pi$ signal.

The fit to Fig. 1(a) yields a mass of 2.286 ± 0.007 GeV/c^2 and an rms width of 0.010 GeV/c^2. The quoted error includes a systematic component of 0.006 GeV/c^2 due to uncertainties in the magnetic field and the geometrical reconstruction. These error sources are checked by measurement of the $K^o \to \pi^+\pi^-$ and $D^o \to K^-\pi^+$ masses in the data sample. A shift in the mass of the observed $pK\pi$ signal of 0.003 GeV/c^2, for example, would require a change in the magnetic field which would displace these masses from their present agreement with nominal values by one standard deviation (0.001 GeV/c^2 for M_{K^o} and 0.0025 GeV/c^2 for M_{D^o}). The mass determined from the spectrum of Fig. 1(d) is 2.284 ± 0.008 GeV/c^2. This is consistent with the mass value determined above but is subject to different systematic errors[6] and to a larger statistical error. Combining the two mass determinations our best estimate of the mass of the charmed baryon is then 2.285 ± 0.006 GeV/c^2. As expected for the weak decay of a charmed baryon, the measured width agrees with the calculated detector resolution.

To determine a cross section, the detection efficiency has been calculated to be 0.13 ± 0.025 for the observed Λ_c momentum distribution.

The $26^{\pm}7$ $pK\pi$ signal events observed in the 5450 nb^{-1} integrated luminosity within 0.05 GeV of 5.2 GeV c.m. energy correspond to

$$\sigma(\Lambda_c + \bar{\Lambda}_c) \cdot B(\Lambda_c \to pK^-\pi^+) = 0.037^{\pm}0.012 \text{ nb},$$

where $\sigma(\Lambda_c + \bar{\Lambda}_c)$ is defined as the inclusive cross section $\left[\sigma(\Lambda_c) + \sigma(\bar{\Lambda}_c)\right]$. The data are consistent with equal cross sections for both charge states.

To obtain an estimate of the total production of charmed baryons we have measured the inclusive cross sections for p and Λ from 3.52 to 7.40 GeV. Because of substantial beam-gas contamination in proton events, only antiprotons are used for these measurements. Two or more observed tracks are required and valid identification of antiprotons is insured by a stricter TOF weight cut of 0.7 for momenta greater than 1.2 GeV/c. The observed $\bar{p}$ sample includes contributions from weakly decaying hyperons. For Λ and $\bar{\Lambda}$ production, only multihadron events with three or more detected tracks are used. The Λ and $\bar{\Lambda}$ are identified from the invariant mass distribution of all neutral $p\pi$ pairs identified by TOF. In addition, the decay products of the Λ and $\bar{\Lambda}$ are required to originate from a secondary vertex. To reduce beam-gas contamination to less than 4%, Λ (but not $\bar{\Lambda}$) events are required to have total observed charge < +1. With these cuts, our Λ and $\bar{\Lambda}$ background subtractions are both $\lesssim$ 15% at all energies.

The efficiency for detection of antiprotons is calculated from a Monte Carlo model which generates $\bar{p}$ tracks with a momentum distribution corresponding to an invariant cross section[7]

$$E\frac{d^3\sigma}{dp^3} \propto e^{-bE}$$

and which then chooses the other nucleon and a number of pions according to the remaining phase space. After adjustment of the slope parameter b and the mean particle multiplicity at each energy, this form gives a good description of the data. The overall detection efficiency for antiprotons

is approximately 58% over the entire range 3.7 - 7.4 GeV.[8] The efficiency for Λ and $\bar{\Lambda}$ detection is determined by the same Monte Carlo model with the parameters obtained from the antiprotons. The efficiency ranges from 10% at 3.67 GeV to 13% at 7.4 GeV, including the branching ratio for $\Lambda \to p\pi^-$. In this case also, the Monte Carlo calculation reproduces the observed Λ momentum and multiplicity distributions. As an additional check on our Λ efficiency calculations, we have verified that the ratio of single Λ's and $\Lambda\bar{\Lambda}$ pairs detected in well identified $\psi \to \Lambda\bar{\Lambda}$ events at $E_{c.m.}$ = 3.095 GeV are correctly reproduced by the Monte Carlo simulation program.

Our results for inclusive production of p and Λ are presented in Fig. 2 as the ratio of the inclusive production cross section to the μ-pair cross section. Figure 2(a) shows $R(p+\bar{p}) \equiv 2 \cdot \sigma(\bar{p})/\sigma_{\mu\mu}$ and Fig. 2(b) shows $R(\Lambda+\bar{\Lambda}) \equiv \left[\sigma(\Lambda) + \sigma(\bar{\Lambda})\right]/\sigma_{\mu\mu}$. The estimated overall systematic errors in R are $\pm$17% and $\pm$27% for the p and Λ, respectively, and are not shown in Fig. 2. These systematic errors are dominated by the model dependence of the Monte Carlo calculations, and are expected to vary slowly over our energy region.

We note that the rise previously reported[9] in $R(p+\bar{p})$ and $R(\Lambda+\bar{\Lambda})$ is confirmed here with more precision. We observe for the first time clear steps in both $R(p+\bar{p})$ and $R(\Lambda+\bar{\Lambda})$ in the range of 4.5 to 5.2 GeV c.m. energy, although the R values probably continue to rise more slowly at higher energies. Within the quoted errors, our measurements of $R(p+\bar{p})$ are consistent with previous experiments.[7,9] Our values of $R(\Lambda+\bar{\Lambda})$ are considerably higher than the previous measurements[9] but have been obtained with larger solid angle, improved vertex reconstruction and a more sophisticated efficiency calculation.[10]

The coincidence of the location of this step with the threshold for production of an object near the mass of the observed $pK\pi$ signal is consistent with its interpretation as the lowest-lying charmed baryon. The observed step sizes of $\Delta R(p+\bar{p}) = 0.31 \pm 0.06$ and $\Delta R(\Lambda+\bar{\Lambda}) = 0.10 \pm 0.03$ would indicate a Λ/p ratio for charmed baryon decays of $41 \pm 15\%$ after explicitly removing protons which arise from Λ decay, but not from other weakly decaying strange baryons.

We can use our measurement of $R(p+\bar{p})$ and the measured $\sigma.B$ for the $pK\pi$ signal at 5.2 GeV to estimate the absolute branching ratio for the $pK\pi$ decay mode. We make the following assumptions: (i) the observed step in $R(p+\bar{p})$ is due entirely to the onset of charmed baryon pair production;[11] (ii) all charmed baryons cascade down to the Λ_c state;[12] and (iii) the probability for a charmed baryon to give a proton (as opposed to a neutron) as a final product is 0.6 ± 0.1.[13] Using the relationship

$$\sigma(\Lambda_c + \bar{\Lambda}_c) = \frac{\Delta R(p+\bar{p})}{0.6}\,\sigma_{\mu\mu}$$

we find an inclusive cross section

$$\sigma(\Lambda_c + \bar{\Lambda}_c) = 1.7 \pm 0.4 \text{ nb}$$

at 5.2 GeV. Thus the cross section to produce pairs of charmed baryons is 0.85 nb. With these assumptions, the branching ratio is then estimated to be

$$B(\Lambda_c \to pK^-\pi^+) = 2.2 \pm 1.0\% \ .$$

In conclusion, our observation of a narrow state with the proper quantum numbers, associated with equal and higher recoil masses, and at a mass compatible with the observed threshold in p and Λ production, argues for the interpretation of this state as the charmed baryon, Λ_c.

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6. An error which increases the magnitude of the momentum causes an increase in the directly calculated mass but a decrease in the mass calculated with the beam energy constraint.
7. R. Brandelik et al., Nucl. Phys. B148, 189 (1979).

8. Included in these efficiencies are corrections for low momentum antiprotons (< 0.3 GeV/c) which range out or are not tracked successfully (from + 9 % to +15%), corrections for antiprotons with momenta greater than 2.0 GeV/c (from 0% to +5%) and corrections for nuclear absorption (+8%), TOF electronic efficiency (+3%) and initial state radiation (-15% to -5%). For the Λ efficiencies, the low momentum (< 0.5 GeV/c) correction is +20% to +33% and the nuclear absorption corrections are +10% for Λ and +13% for $\bar{\Lambda}$.
9. M. Piccolo et al., Phys. Rev. Lett. 39, 1503 (1977).
10. An extensive Monte Carlo simulation of the detector, including the generation of drift-chamber coordinates, has been performed. The quoted efficiencies are derived from a complete reconstruction of Λ events so that tracking and vertex formation inefficiencies are explicitly included.
11. At 5.2 GeV, the Λ_c can also be produced in association with a D meson via the final states $\Lambda_c\bar{D}^0\bar{p}$ or $\Lambda_c D^-\bar{n}$. Approximately 20% of the Λ_c events have recoil masses above Dp threshold, providing an upper limit for such associated production in this sample.
12. This neglects weak decays from all other charmed baryons, consistent with predictions and present experiments. See references 1-3.
13. This value is slightly model dependent. The quoted value was estimated from our measurement of $\Delta R(\Lambda+\bar{\Lambda})$ and $\Delta R(p+\bar{p})$ and a simple isospin statistical model.

TABLE I

Inclusive p and Λ production. Estimated systematic errors of ±17% and ±27%, respectively are not included.

$E_{c.m.}$ (GeV)	$R(p+\bar{p})$	$E_{c.m.}$ (GeV)	$R(\Lambda+\bar{\Lambda})$
3.52	.390 ± .035	3.52	.057 ± .025
3.67	.371 ± .014	3.67	.073 ± .012
3.77	.388 ± .009	3.77	.083 ± .009
3.94	.346 ± .025	4.02	.049 ± .013
4.05	.354 ± .020		
4.16	.354 ± .012	4.16	.080 ± .011
4.241	.355 ± .019	4.27	.088 ± .018
4.353	.358 ± .031		
4.427	.398 ± .015	4.42	.085 ± .014
4.55	.434 ± .030	4.55	.083 ± .022
4.65	.444 ± .030	4.65	.166 ± .034
4.75	.471 ± .032	4.75	.106 ± .030
4.84	.536 ± .031	4.84	.117 ± .024
4.95	.539 ± .031	4.95	.141 ± .030
5.045	.534 ± .034	5.045	.174 ± .035
5.145	.678 ± .038	5.145	.204 ± .037
5.20	.674 ± .011	5.21	.163 ± .011
5.276	.661 ± .061		
5.575	.686 ± .043	5.575	.200 ± .059
5.871	.742 ± .077	5.871	.156 ± .067
6.573	.790 ± .021	6.573	.256 ± .019
7.40	.96 ± .21	7.40	.220 ± .043

FIGURE CAPTIONS

1. The combined $pK^-\pi^+$ and $\bar{p}K^+\pi^-$ mass distribution (a) for recoil masses greater than 2.2 GeV/c^2, and (b) for recoil masses less than 2.2 GeV/c^2. (c) The $pK^+\pi^-$ and $pK^-\pi^-$ (and charge conjugate states) mass distribution for recoil masses greater than 2.2 GeV/c^2. (d) The beam energy constrained mass distribution for events with $pK^-\pi^+$ or $\bar{p}K^+\pi^-$ energy within 0.03 GeV of the beam energy.

2. (a) $R(p+\bar{p})$ as a function of $E_{c.m.}$. (b) $R(\Lambda+\bar{\Lambda})$ as a function of $E_{c.m.}$. Errors are statistical only.

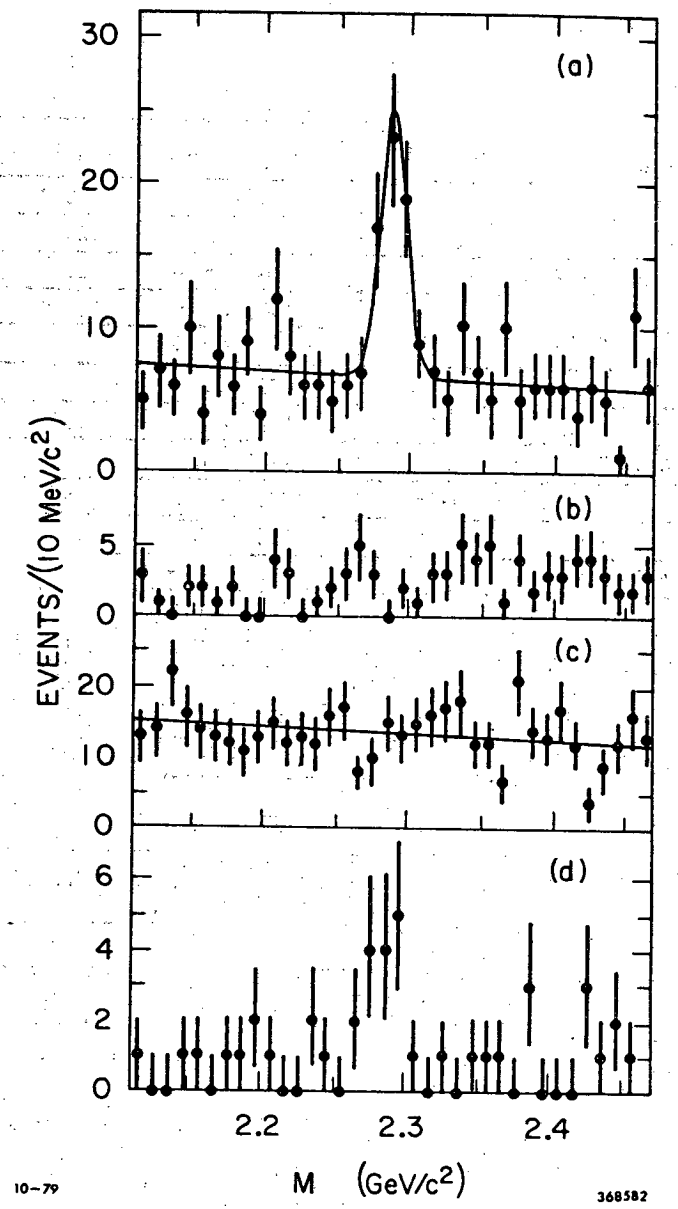

Fig. 1

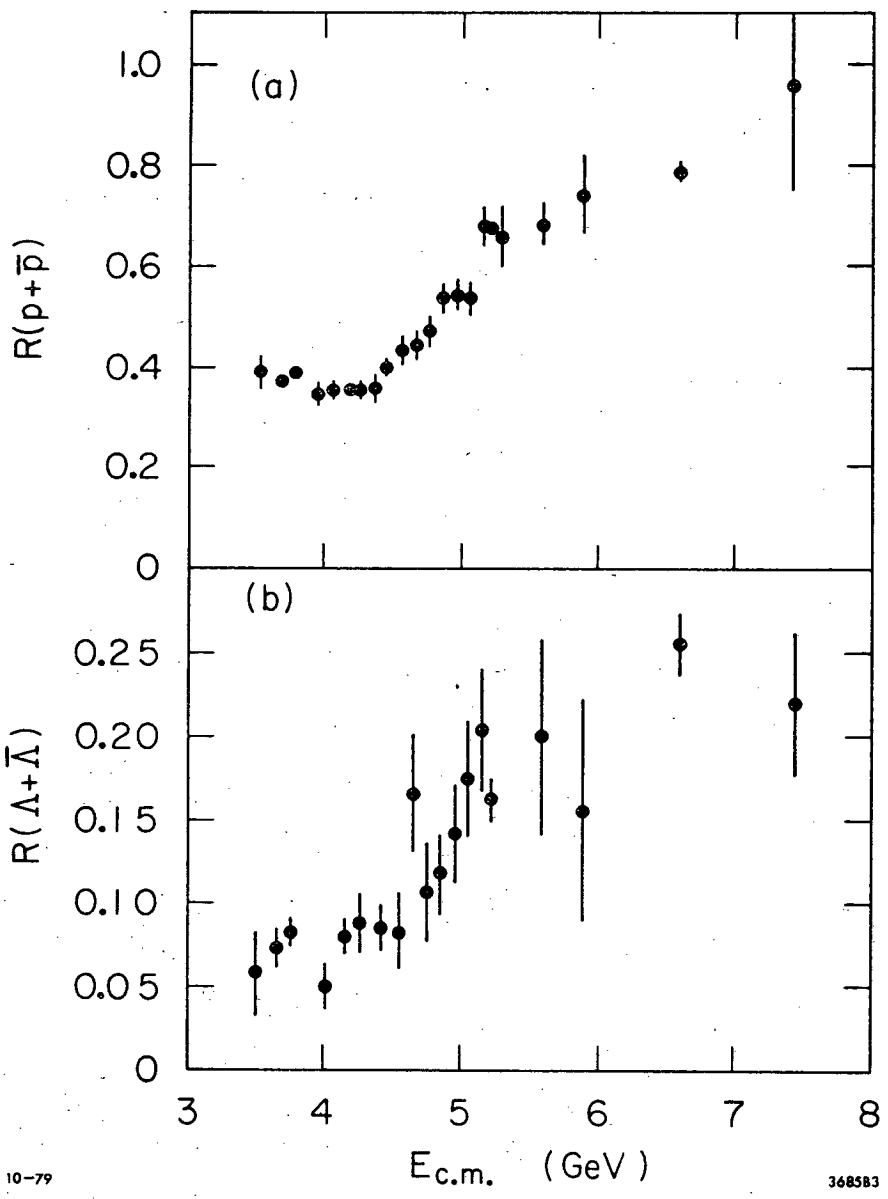
(a)
(b)
R(p+p̄)
R(Λ+Λ̄)
1.0
0.8
0.6
0.4
0.2
0
0.25
0.20
0.15
0.10
0.05
0
3
4
5
6
7
8
E c.m. (GeV)
10-79
3685B3

Fig. 2

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