Possible $N^*(1688) \to K^+\Lambda$ Production in 3-BeV $p+p \to K^+ + \Lambda + p$ †

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There is some possible evidence of a $B=2$, $S=-1$ hyperon-nucleon resonance with a mass of about 2.375 BeV. The data for this come from large-angle K^+ production in about 3-BeV proton-proton collisions. We believe that part, if not all, of this effect may be due to the production and subsequent decay of the $N^*(1688) \to K^+ + \Lambda^0$ in the proton-proton collision.

IN this paper we want to discuss the effect of

$$p+p \to N^*(1688)+p$$
$$\searrow K^+ + \Lambda$$

on the momenta spectra of K^+ mesons from 3-BeV proton-proton collisions. There is a measured[1–3] apparent non-phase-space structure in the K^+ momenta spectra that we believe can be partially explained from $N^*(1688)$ production. This is contrary to the explanation of this structure as being due to a possible hyperon-nucleon resonance.

Feynman diagrams that can account for the $p+p \to N^*(1688)+p$ reaction are shown in Fig. 1. They include π and K exchange, with and without final-state K^+ interaction. The models[4–6] for K-meson production in proton-proton collisions relate the production cross section of $p+p \to K^+ + \Lambda + p$ to the coupling constant $g_{NN\pi}$ ($g_{K\Lambda N}$), the on-the-energy-shell production cross section $\sigma(\pi+N \to K+\Lambda)$ [the on-the-energy-shell scattering cross section $\sigma(K+N \to K+N)$], and the final-state interactions of the particles.

The $N^*(1688) \to K^+\Lambda$ is a possible final-state interaction of $K^+\Lambda$ in 3-BeV proton-proton collisions with K^+ production. The $N^*(1688)$ (the "900 MeV" resonance[7] in the direct channel $\pi+p$ collision) is documented[8] as having the branching ratios for decay of $\geq 85\%$ for πN ($\pi^- p$ and $\pi^0 n$) and $\sim 2\%$ for $K^0\Lambda$. From charge independence we expect the positively charged $N^*(1688)$ to have the same branching ratios for decay, i.e., $\geq 85\%$ for πN ($\pi^+ n$ and $\pi^0 p$) and $\sim 2\%$ for $K^+\Lambda$.

In general, final-state particle interactions other than the suggested $N^*(1688)$ are possible in 3-BeV proton-proton collisions with K^+ production. In the spirit of the various models[4–6] we examined the results for the known KY, YN, and NK resonances; in the range of values of the S_{KY}, S_{YN}, and S_{NK} possible in 3-BeV proton-proton collisions in $p+p \to K+Y+N$, we examined the results for the on-the-energy-shell cross sections $\sigma(\pi+N \to K+Y; S_{KY})$, $\sigma(Y+N \to Y+N; S_{YN})$, and $\sigma(K+N \to K+N; S_{NK})$. The total energy in the KY center-of-mass frame is $S_{KY}=(k_K+k_Y)^2$; the kinematics of $p+p \to K^+ + Y + N$, in which the four-momenta k are defined, are shown in Fig. 2.

As mentioned previously, there is the KY, $N^*(1688) \to K^+\Lambda$ resonance; this is, however, the only apparent KY resonance kinematically possible in 3-BeV proton-proton collisions. Except at small S_{YN} there are no

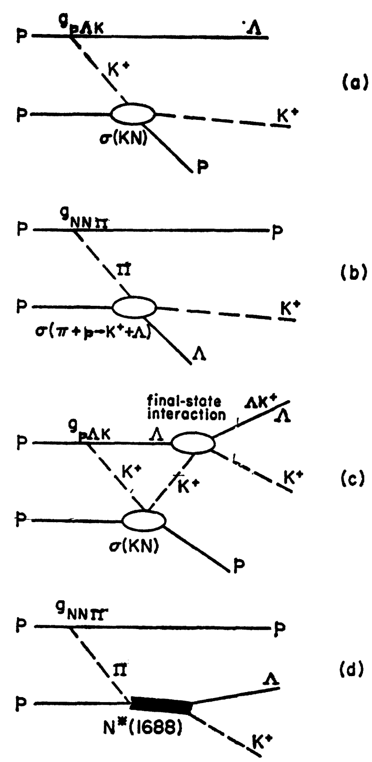

FIG. 1. K^+ meson production in $p+p \to p+\Lambda+K^+$ with K and π exchange and with and without final-state K^+ interaction. (a) K^+ exchange with $K^+ + p$ scattering vertex. (b) π exchange with $\pi + p \to K^+ + \Lambda$ production vertex. (c) K^+ exchange with final-state K^+ interaction. (d) π exchange with final-state $N^*(1688)^+ \to K^+ + \Lambda$.

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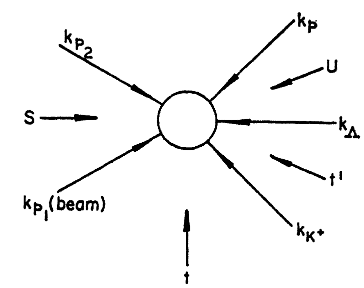

FIG. 2. Kinematics of $p+p \to K^+ + \Lambda + p$. The four-momentum $k \equiv (i\mathbf{P}, \sqrt{(P^2+M^2)})$. $M_{\Lambda p}^2 \equiv (k_{p1}+k_{p2}-k_{K^+})^2$. In terms of three-momenta in the laboratory frame, $M_{\Lambda p}^2 = (E_{p1}+M_p-E_{K^+})^2 - (P_{p1}-P_{K^+})^2$. Also $S \equiv (k_{p1}+k_{p2})^2$; $t' \equiv (k_\Lambda + k_{K^+})^2$; $t \equiv (k_{p1}-k_{K^+})^2$.

well-established YN resonances.[3,9,10] Because of the lack of a true hyperon particle beam only limited data are available on on-the-energy-shell YN interactions. Because of the lack of a true hyperon particle beam on the "horizon," final-state particle interactions now offer an important alternative mechanism for the study of YN interactions. There are no apparent NK resonant states kinematically possible in 3-BeV proton-proton collisions. Finally, we do not pursue the four-body final states, $p+p \to K+Y+N+\pi$, that could produce channels for K^* and Y^* resonances; the four-body cross section is small (Table I)[11] and the phase space is small in 3-BeV proton-proton collisions.

How do possible final-state interactions in 3-BeV proton-proton collisions affect the K^+ momenta spectra? In particular, how much can be understood about final-state interactions if the data are just the K^+ momenta spectra at several different laboratory angles relative to the proton beam? We refer to this type of experiment as $p(p,K^+)YN$. In contrast, $p(p,p)N\pi$, KY describes the analogous experiment in which the final-state proton spectra are measured.[12] Complete knowledge of $\sigma(p+p \to K^+ + Y + N)$ is lacking from $p(p,K^+)YN$ data; because of this it is possible, and probable, that the $N^*(1688) \to K^+\Lambda$ produces a pseudo YN resonance, $\bar{M}_{YN} \pm \Delta\bar{M}_{YN}$. To substantiate this we estimate the $\bar{M}_{YN} \pm \Delta\bar{M}_{YN}$ based on the assumption that

$$p+p \to N^*(1688)+p \quad N^*(1688) \searrow K^+ + \Lambda$$

occurs and that $p(p,K^+)YN$ data are used to analyze it. We also estimate the yield into this channel based on the models[4–6] and the Feynman diagram of Fig. 1(d).

To calculate the non-phase-space structure in the data of the $p(p,K^+)YN$ cross section

$$d^2\sigma'/dM_{\Lambda p}dt = \sigma(p(p,K^+)YN)$$

we would assume that we have the $N^*(1688) \to K^+\Lambda$ production cross section

$$d^2\sigma'/dM_{K\Lambda}dt' = \sigma(p+p \to N^*(1688)+p) . \quad N^*(1688) \searrow K^+ + \Lambda$$

These cross sections are related by a Jacobian, a kinematical factor. Thus

$$\frac{d^2\sigma}{dM_{\Lambda p}dt} = \frac{d^2\sigma'}{dM_{K\Lambda}dt'} \mathcal{J}\begin{pmatrix} M_{K\Lambda} & t' \\ M_{\Lambda p} & t \end{pmatrix} .$$

If the natural width of the $N^*(1688)$ were essentially zero there would appear in the $p(p,K^+)YN$ data a non-phase-space peak in the K^+ momenta spectra. In fact, because the $N^*(1688)$ width is relatively small, ~ 0.1 BeV, we can estimate the width $\Delta\bar{M}_{YN}$, of the pseudo YN resonance, to be simply estimated from kinematics. In the 3-BeV proton-proton collision assume $p+p \to N^*(1688)+p$. This production process of

$$p+p \to N^*(1688)+p \quad N^*(1688) \searrow K^+ + \Lambda$$

is now reinterpreted. Let the process be produced under the assumption that the mass $N^*(1688) = 1.688$ BeV. At 3-BeV incident beam proton energy this corresponds to the final-state proton having an energy of 3.03 BeV, a momentum of 0.725 BeV/c, in the (p,p) c.m. frame. As a means of evaluating $(k_p + k_\Lambda)^2 = M_{\Lambda p}^2$, the (total energy)^2 in Λp c.m., we refer the final-state proton to the $N^*(1688)$ c.m. frame; this proton has 1.302 BeV/c momentum in the $N^*(1688)$ c.m. frame. Letting $N^*(1688) \to \Lambda + K^+$ decay isotropically we evaluate the $M_{\Lambda p}^2$ with a mean value of $(\bar{M}_p \cong 2.41$ BeV$)^2$, a maximum value of (2.53 BeV), and a minimum value of (2.27 BeV). Because $N^*(1688)$ has a mass of (1.688 ± 0.1) BeV, we estimate the pseudo resonance $YN = \Lambda p$ to have the mass $\bar{M}_p \pm \Delta\bar{M}_p \cong (2.41 \pm 0.2)$ BeV. This result is consistent with data from $p(p,K^+)YN$.[1–3]

We estimate the yield into the $p+p \to N^*(1688)+p$ channel using the models,[4] the Feynman diagram of Fig. 1(d), and the available data on the approximate total yield into the channel $p+p \to K^+ + \Lambda + p$. The

TABLE I. Some partial cross sections for 2.85-BeV proton-proton collisions.

Reaction	Cross section (μb)
(A) $p+p \to p+\Lambda^0+K^+$	51
(B) $p+p \to p+\Sigma^0+K^+$	13
(C) $p+p \to n+\Sigma^+ + K^+$	47
(D) $p+p \to$ all strange particles	$\sigma_T \sim 180$

[9] H. G. Dosch, Phys. Letters **14**, 162 (1965).

[10] The maximum momentum K^+ part of the K^+ momentum spectra from $p(p,K^+)YN$ is that most sensitive to the low-energy YN interaction in the S-wave YN effective range approximation. See also Refs. 3 and 5.

[11] R. J. Louttit *et al.*, Phys. Rev. **123**, 1465 (1961).

[12] G. B. Chadwick *et al.*, Phys. Rev. **128**, 1823 (1962).

TABLE II. Estimate of K^+ yield from measured[a] $p+p\to p+N^*(1688)$ at 3 BeV in the experiment in which the final proton momentum is measured, i.e., $p(p,p)N^*(1688)$.[b]

$\theta_{p\ \mathrm{lab}}$[c] (deg)	$d\sigma(N^*(1688))/d\Omega$ (mb/sr)	2% $K^+\Lambda$ decay $\sigma(N^*\to K^+\Lambda)$ (mb/sr)
2.72	~1	~0.02
4.51	~1	~0.02
8.53	~1	~0.02
12.17	~0.5	~0.01
17.75	~0.2	~0.04

[a] See Ref. 12.
[b] The net yield from $N^*(1688)\to K^+\Lambda$ of K^+ is about 2 μb based on column (3), i.e., data on $N^*(1688)$ production and $\sigma(K^+\Lambda)/\sigma(\pi^+p+\pi^0n)$ ~2%. The net yield from $N^*(1688)\to K^+\Lambda$ of K^+ is about 3 μb based on the known ratio $\sigma(p+p\to p+N^*)/\sigma(p+p\to K^++\cdots)\approx\frac{1}{4}$ and on $\sigma(p+p\to K^++Y+N)\sim 111\ \mu$b.
[c] $\theta_{p\ \mathrm{lab}}$ is proton laboratory angle in $p(p,p)N^*$ measurement.

data for the latter are tabulated in Table I, and the estimates of yield in Table II.

If we assume that about half of the $p+p\to K^++\Lambda+p$ goes by $N^*(1688)\to K^++\Lambda$ decay, in the kinematically allowed region $(k_p+k_\Lambda)^2\cong(2.41\text{ BeV})^2$, we have the branching ratio

$$\frac{\sigma(p(p,p)N^*(1688)+K^+)}{\sigma(p+p-K^++Y+N)}=\frac{\frac{1}{2}(51\ \mu\mathrm{b})}{111\ \mu\mathrm{b}}\approx\frac{1}{4},$$

i.e., $p(p,p)N^*$ accounts for $\frac{1}{4}$ of whole K^+ yield. Using $\bar{M}_p\pm\Delta\bar{M}_p=(2.41\pm0.2)$ BeV and $\sigma(p+p\to K^++Y+N)_T=111\ \mu$b, we estimate the total yield into the $N^*(1688)\to K^++\Lambda$ channel to be

$$\sigma(p+p\to N^*(1688)+p)\cong 3\ \mu\mathrm{b}$$
$$\searrow K^++\Lambda.$$

Now, however, if we use the $p(p,p)N^*(1688)$ data[12] and the $\approx 2\%$ $N^*(1688)\to K^++\Lambda$ branching ratio, we estimate

$$\sigma(p+p\to N^*(1688)+p)\cong 2\ \mu\mathrm{b}$$
$$\searrow K^++\Lambda.$$

Three sources of K^+-mesons from proton-proton collisions at 3 BeV are combined to give K^+ meson and $M_{\Lambda p}$ spectra; $p+p\to K^++\Lambda+p$ phase space,[13] $p+p\to K^++\Sigma^0+p$ phase space, and $p+p\to N^*(1688)+p$ resonance production. The relative yields of $K^+\Lambda:K^+\Sigma$ are kept at 1:1 to be consistent with a small amount of bubble-chamber data.[11] Figure 3 shows the $M_{\Lambda p}$ and the P_K distributions for laboratory-analyzed K^+ mesons produced from a proton target with Fermi energy. Figure 4 shows the M_{Λ_p} and the T_K distributions in the $(p+p)$ c.m. for isotropically produced K^+ mesons. Each of the distributions shows the effect of increasing the relative contributions of $N^*(1688)$ from zero to 25 to 50%. It is clear from these distributions that there is an enhancement at the $M_{\Lambda_p}=2.41$-BeV mass. This enhancement is the result of assuming only the observation of the K^+ meson in 3-BeV proton-proton collisions when there is a significant contribution from a $K^++\Lambda$ resonance, the $N^*(1688)\to K^++\Lambda$, in the production process.

[13] R. M. Sternheimer, in *Methods of Experimental Physics, Nuclear Physics* (Academic Press Inc., New York, 1961), Vol. 5, Part B, Appendix 1.

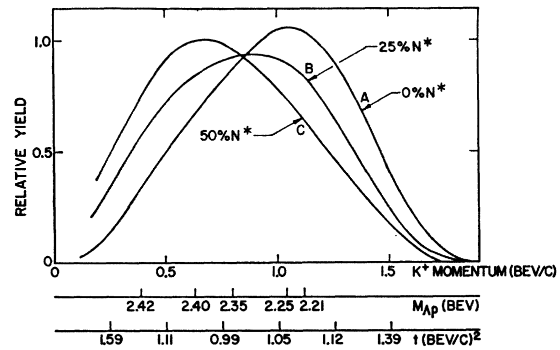

FIG. 3. K^+ meson spectra for 3-BeV proton-proton collisions assuming the target proton has an average Fermi momentum of 180 MeV/c. The K^+ mesons are produced at 30° to the incident proton beam. The P_K is the laboratory momentum of the K^+ meson. The M_{Λ_p} is the total energy in the Λ_p c.m. for $p+p\to K^++\Lambda+p$. The t is the square of the four-momentum transfer between the incident proton and the produced K^+ meson.

(a) curve A is composed of

50%	$p+p\to K^++\Lambda+p$	phase space and
50%	$p+p\to K^++\Sigma^0+p$	phase space.

(b) curve B is composed of

25%	$p+p\to N^*(1688)+p$, $\searrow K^++\Lambda$	resonance production,
25%	$p+p\to K^++\Lambda+p$	phase space and
50%	$p+p\to K^++\Sigma^0+p$	phase space.

(c) curve C is composed of

50%	$p+p\to N^*(1688)+p$, $\searrow K^++\Lambda$	resonance production and
50%	$p+p\to K^++\Sigma^0+p$	phase space.

If the measured[1–3] non-phase-space structure in the $p(p,K^+)YN$ data is a real YN resonance at $(k_p+k_\Lambda)^2=(2.36\text{ BeV})^2$ it should be S invariant. But, if the non-phase-space structure is principally due to the pseudo resonance, then we would find the pseudo mass $\bar{M}_{\Lambda_p}$ to increase with S. Furthermore, at a fixed S the $\bar{M}_{\Lambda_p}$ peak should be most prominent over phase space at the large t. This is evident from $p(p,p)N^*(1688)$ data.[12] This t dependence means that the K^+ momenta spectra from $p(p,K^+)YN$ experiments at large K^+ laboratory angles would show the $\bar{M}_{\Lambda_p}$ peak to be most prominent over phase space. It is this difference of momentum transfer t which contributes to the apparent discrepancy between the results in the different $p(p,K^+)YN$ experiments.[1–3] There appears to be the largest resonance enhancement in the Piroue results, from which the mass of the suggested YN state is measured to be 2.36 BeV, which are obtained with K^+

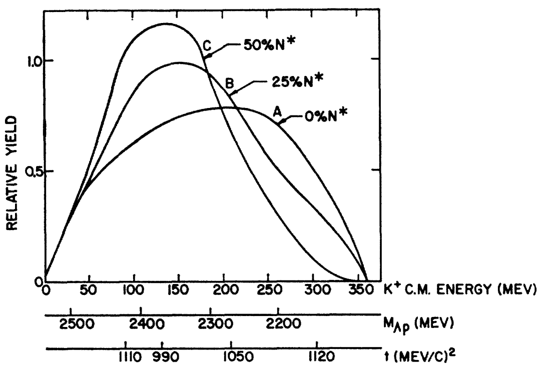

FIG. 4. K^+ meson spectra for 3-BeV proton-proton collisions assuming the target proton is at rest. The K^+ mesons are produced in the c.m. of the proton-proton with an isotropic distribution. The T_K is the K^+ meson kinetic energy in the proton-proton c.m. The $M_{\Lambda p}$ is the total energy in the Λ_p c.m. for $p+p \to K^+ + \Lambda + p$. The t is the square of the four-momentum transfer between the incident proton and the produced K^+ meson.

(a) curve A is composed of

50%	$p+p \to K^+ + \Lambda + p$	phase space and
50%	$p+p \to K^+ + \Sigma^0 + p$	phase space.

(b) curve B is composed of

25%	$p+p \to N^*(1688)+p$, $N^* \to K^+ + \Lambda$	resonance production
25%	$p+p \to K^+ + \Lambda + p$	phase space and
50%	$p+p \to K^+ + \Sigma^0 + p$	phase space.

(c) curve C is composed of

50%	$p+p \to N^*(1688)+p$, $N^* \to K^+ + \Lambda$	resonance production and
50%	$p+p \to K^+ + \Sigma^0 + p$	phase space.

production from a 2.95-BeV proton beam and with θ(proton-K^+, laboratory)$=30°$. The Piroue data are not only obtained with greater apparent accuracy at large laboratory angles but they extend to sufficiently low K^+ momenta to determine the full shape of the K^+ momentum spectrum.

{*Note added in proof.* We received an unpublished report recently from E. Bierman, A. P. Colleraine, and U. Nauenberg. They studied associated production in proton-proton collisions in a hydrogen bubble chamber exposed to a 5 BeV/c proton beam. They find a significant $N^*(1688)$ production; there do, however, seem to remain some serious questions about the exact angular momentum states involved. They do not find any significant enhancement in the directly measured (hyperon, nucleon) invariant mass at 2375 MeV as suggested by the earlier P. A. Piroue results. They do see a "peak" in the (hyperon, nucleon) mass in $p+p \to K^+ + \Lambda + p$ but this peak is centered at a mass of about 2550 BeV. This is consistent with our suggestion that the mass of the pseudo resonance has its origin in a ΛK^+ resonance at 1688 MeV. W. Chinowsky *et al.* [Bull. Am. Phys. Soc. **11**, (1966)] report that 25% of events in $K^+ + \Lambda^0 + p$ are in a $1675 < M_{K\Lambda} < 1950$ MeV peak with no evidence for any hyperon-nucleon states $1609 < M_{\Lambda p} < 2700$ MeV.

Although these new results do not rule out a possible (hyperon, nucleon) 2375 MeV resonance as suggested by P. A. Piroue, it makes it considerably less likely. There is, however, one important difference between the E. Bierman and the P. A. Piroue results; although they both cover the same range of (hyperon, nucleon) invariant mass the bubble-chamber data, E. Bierman, is averaged over all the reaction-produced K^+ mesons while the counter data, P. A. Piroue, are all for relatively large momentum transfer between the beam proton and the reaction-produced K^+ meson.}

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