How to Build a Very-Low-Momentum K^- Beam at a Kaon Factory

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by

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ABSTRACT

Design considerations for the construction of a very low momentum (~ 400 MeV/c) K^- beam at a high-flux proton accelerator are discussed. Possible uses of such a beam are described.

I. INTRODUCTION

Low-momentum charged kaon (K^-) beams have had low-to-moderate intensities and large pion contaminations. To reduce the pion contamination ($K^-/\pi^- \sim 1/100$ at production), electrostatic separation can be used in the beam line. Separated beams have been operated at 800 MeV/c with $\sim 10^5$ K^-/s and $K^-/\pi^- \sim 1/10$.¹ Several beams have been operated with lower momenta but with very low intensities and inferior purities. For example, a 430-MeV/c K^- beam at the Zero Gradient Synchrotron (ZGS) had a flux of ~ 1000 K^-/s and $K^-/\pi^- \sim 1/100$.² High-flux, low-momentum K^- beams are difficult to construct because the production cross section falls very rapidly and the decay probability in the beam channel rises as the momentum is decreased.

At a high-flux proton accelerator (a "kaon factory"), there are several possible ways to produce low-momentum kaon beams. A conventional separated beam, such as LESBI at the Alternating Gradient Synchrotron (AGS),³ would produce $\sim 10^5$ K^-/s at 400 MeV/c. However, the beam would also contain $\sim 10^7$ π^-/s , making it impossible to identify individual kaons or measure their momenta. There are three possible ways of improving this situation.

- (1) Produce a cleaner definition for the K^- source to make the separation more complete.
- (2) Produce a higher momentum, separated beam and lower the momentum with degraders.
- (3) Produce a higher momentum, separated beam and lower the momentum by elastic scattering.

Each of these designs is discussed in Sec. III.

II. DESIGN PROBLEMS

The cross section for low-energy K^- production in p-nucleus collisions falls quite rapidly as the kaon momentum is decreased. The cross section is shown in Fig. 1 for incident 28-GeV protons. This descent can be understood via the model of kinematic reflection.⁴ The basic assumption of this model is that secondary particle production is forward-backward symmetric in the nucleon-nucleon center-of-mass system. This allows one to relate the production of low-energy kaons to the production of high-energy kaons in the laboratory. Equating the Lorentz-invariant cross sections for forward-produced kaons (denoted by a + subscript) and backward-produced kaons (denoted by a - subscript), we find

$$E_+ \frac{\partial^3 \sigma_+}{\partial p_+^3} = \frac{E_+}{p_+^2} \frac{\partial^2 \sigma_+}{\partial p_+ \partial \Omega_+} = \frac{E_-}{p_-^2} \frac{\partial^2 \sigma_-}{\partial p_- \partial \Omega_-} \quad (1)$$

or

$$\frac{\partial^2 \sigma_-}{\partial p_- \partial \Omega_-} \bigg/ \frac{\partial^2 \sigma_+}{\partial p_+ \partial \Omega_+} = \frac{E_+ p_-^2}{E_- p_+^2} \quad (2)$$

Because the cross section for the production of high-energy kaons is a slowly varying function of kaon energy, the laboratory cross section for the production of low-energy kaons falls faster than the square of the momentum as this momentum is decreased. The available data agree well with this model. Thus, in designing low-momentum K^- beams, one is faced with low yields at production.

The problem is compounded by the high probability of K^- decay in the beam channel. The low K^-/π^- ratio at production necessitates electrostatic separation in the beam channels. The resulting beam lines are longer than one would like: the low-energy separated beams at the AGS are ~ 15 -m long. The survival probability for charged kaons as a function of momentum is shown in Fig. 2 for several flight path lengths.

The conjunction of the small production cross section for low-momentum K^- and their large probability of decaying in the beam line has resulted in very low usable K^- rates at low momenta.

III. CANDIDATE DESIGNS

A. Beam Design Similar to Existing Beams

A high-intensity (~ 100 - μ A), 15- to 25-GeV proton accelerator (a kaon factory) is capable of producing a very large flux of low-momentum kaons. Consider a beam line similar to LESBI and LESBII at the AGS, with the following characteristics.

Length	:	15 m
Ω	:	7.5 msr
Production Angle:	:	10.5
$\Delta P/P$	:	$\pm 2\%$
Target	:	3-in.-long platinum

Such a beam transports $\sim 3 \times 10^3$ $K^-/10^{12}$ incident protons at 400 MeV/c. With 30 μ A (2×10^{14} protons/s) incident on the production target, $\sim 6 \times 10^5$ K^-/s at 400 MeV/c would emerge from the channel. Unfortunately, the K^-/π^- ratio at the end of the channel would be $< 1/100$. The large contamination would make experiments very difficult, if not impossible.

The measured K^-/π^- ratio at 800 MeV/c is $\sim 1/10$. Electrostatic separators should work better at lower momenta because of the larger difference between the pion and kaon velocities. However, this is offset by the rapid decrease in kaon production yields and the small survival probability. Several methods of improving the K^-/π^- ratio are discussed below.

B. Cleaner Definition for the K^- Source

The design of the low-energy separated beams at the AGS calls for complete separation of the kaon and pion beam spots at the mass slit. Nevertheless, the resulting beams are comprised primarily of pions. Some of these pions may actually be muons resulting from pion and kaon decay in the beam line. It is estimated that there are two muons for each kaon at the final focus.⁵ Muons produced in decays at some distance from the production target ("cloud" muons) do not appear to originate from the target. They produce a larger image at the mass slit than particles produced in the target. Similarly, cloud pions resulting from decays of long-lived particles (kaons, hyperons) and pions that scatter from magnet pole tips will also produce a large image. It is these particles that are not included in the beam calculations and that probably are responsible for the large beam contaminations.

Most low-momentum beams for bubble chambers have had two stages of separation to remove muons and other contaminants and to define the particle source. The resulting beams were comprised predominantly of kaons but had very low intensities (~ 10 K/pulse). These beams also tended to be very long (> 30 m), about twice as long as LESBI. If a two-stage beam were constructed at a kaon factory, with an acceptance of ~ 7.5 msr and a length of 20 m, the K^- flux at 400 MeV/c would be $9 \times 10^4/s$ in a $\pm 2\%$ momentum bite. The beam contamination should be low, probably comparable to the K^- flux. Larger fluxes are possible with a larger beam acceptance.

This beam could also be used to transport higher momentum kaons. For example, at 800 MeV/c, the beam would deliver 2×10^7 K^-/s with $\Delta p/p = \pm 2\%$ and a small pion contamination.

C. Lowering the Beam Momentum with Degraders

As was discussed in Sec. II, the major problems with very low momentum kaon beams are the low production flux and large kaon decay probability. These can be circumvented if the beam line transports and separates higher momentum kaons and the momentum is then lowered near the experiment. One method of lowering the beam momentum is with degraders. Degraders have been used in low-energy beams as a means of separating out pions⁶ and to produce very low momentum anti-protons.⁷

In Table I we show the expected K^- fluxes at 400 MeV/c as a function of the kaon momentum before the degrader. For these calculations, it has been assumed that the higher momentum part of the channel is 10-m long and the 400-MeV/c portion is 7-m long. The optimum occurs with the upstream portion transporting ~ 600 MeV/c. The flux advantage over the two-stage separated 400-MeV/c beam

appears to be about 1 order of magnitude. However, no loss factor has been included for the effects of multiple scattering and straggling in the degrader. It may also be that 17 m is too short for the necessary beam components. The beam purity may not be as good in the two-stage separated beam. The 600-MeV/c portion of the beam would be expected to deliver 20 to 50 pions for each kaon striking the degrader. The smaller π^- interaction probability will result in an even larger pion fraction in the emerging beam. However, the final pion momentum is ~ 500 MeV/c, so most of the pions would not pass a momentum slit in the last stage of the beam.

The resulting beam could then be expected to enjoy a modest flux advantage over the two-stage separated beam (maybe a factor of 2 to 3), but it would have a poorer purity and a much larger spot size.

D. Lowering the Beam Momentum by Elastic Scattering

This design is based on large-angle elastic scattering of higher momentum K^- on a CH_2 target. The electrostatic separation takes place in the high-momentum (~ 1 GeV/c) portion of the beam. At this momentum, the extra beam length required for the separators does not result in large beam losses. Because the beam incident on the CH_2 target is enriched in kaons, the beam composed of particles scattered by the target will also be enriched in kaons. There is no need for further separation allowing a substantially shorter beam at 400 MeV/c.

To estimate yields, we shall assume that the high-momentum portion of the beam has the characteristics described in Sec. III.A. above. The incident 1-GeV/c beam would then contain $\sim 2 \times 10^8$ K/s and ~ 10 pions for each kaon. The kinematics of K^-p elastic scattering is shown in Fig. 3: 400-MeV/c K^- are produced near 90° in the laboratory. The cross sections are taken from Ref. 8. If the scattering target consists of 10 cm of CH_2 , the yield of 400-MeV/c K^- is

$$\begin{aligned}
 (\#K^-/s @ 400 \text{ MeV/c}) &= (\#K^-/s @ 1 \text{ GeV/c}) \times N_{av} \times \rho_{CH_2} \times L_{CH_2} \times 8/14 \times \frac{d\sigma}{d\Omega^*} \times \frac{d\Omega^*}{d\Omega} \times \Delta\Omega \quad (3) \\
 &= (2 \times 10^8) \times (6 \times 10^{23}) \times (0.95) \times (10) \times \left(\frac{8}{14}\right) \times (1.3 \times 10^{-27}) \times \left(\frac{0.05}{0.08}\right) \times \Delta\Omega \\
 &= 5 \times 10^5 \Delta\Omega/s .
 \end{aligned}$$

We have not included the 400-MeV/c K^- produced by the reaction $K^-n \rightarrow K^-n$; however, some K^- will be lost before they emerge from the target.

The beam line, which collects the low-momentum kaons, should be short to minimize decay losses, should have a large solid angle acceptance, and should provide some momentum selection. This last requirement is discussed below. Assuming this part of the channel to have $\Delta\Omega = 50$ msr and to be 5 m in length, the yield of 400-MeV/c K^- is only $5 \times 10^3/s$.

The pion contamination of the beam will be quite low. The kinematics of π^-p elastic scattering is shown in Fig. 3. It is apparent that elastically scattered π^- will not be transported by the beam. However, more complicated final states could yield 400-MeV/c π^- at the correct angle. Because the K^-/π^- ratio at 1 GeV/c is 1/10, we would expect the K^-/π^- ratio at 400 MeV/c to be of the order of 1.

IV. SUMMARY

Apparently, the beam using elastic K^-p scattering results in too low a flux to be useful. It seems as if the beam using degraders has some flux

advantage over the two-stage electrostatically separated beam. Exactly how large this advantage is depends upon the details of the beam's designs and upon how severe the loss is as a result of the effects of the degrader. To determine the properties of the beams in these two designs, detailed calculations are required. Evidently, high-flux K^- beams can be constructed at 400 MeV/c with small pion contamination.

V. DISCUSSION

The principal interests in a low-momentum K^- beam are the recoilless production of Σ hypernuclei, the production of polarized $\Sigma^\pm$, and the study of the total K^-p and K^-d cross sections.

Evidence of Σ^0 hypernucleus production has been published.⁹ The experiment was performed at 720 MeV/c where the Σ^0 recoil momentum is ~ 130 MeV/c. One would expect more copious hypernucleus production for lower recoil momenta.¹⁰ The strangeness-exchange cross sections for $K^-n \rightarrow \Lambda\pi^-$ and $K^-n \rightarrow \pi^-\Sigma^0$ and the hyperon recoil momenta as a function of the K^- momentum are shown in Fig. 4. An experiment at or below 400 MeV/c should result in an improved signal-to-noise. For this experiment, an energy loss spectrometer-channel measuring the (K^-, π^-) reaction is needed.

Polarized $\Sigma^\pm$ can be produced by the reaction $K^-p \rightarrow \Sigma^\pm\pi^\mp$ at ~ 400 MeV/c because of the interference of the resonant $D_{3/2}$ (Y^*1520) amplitude with the large nonresonant s-wave amplitude.¹¹ Polarizations of ~ 0.6 are feasible. It would be of great interest to study decay asymmetries in $\Sigma^+ \rightarrow p\gamma$, $\Sigma^- \rightarrow n e^- \bar{\nu}$, and $\Sigma^\pm \rightarrow \Lambda e^\pm \nu$. For these experiments, a beam momentum resolution of $\sim 2\%$ is sufficient to determine the Σ polarization.

The total $K^\pm p$ and $K^\pm d$ cross sections have been measured down to ~ 375 MeV/c although the uncertainties get large below ~ 500 MeV/c^{12,13}. The total and differential cross sections are of interest both as a means of searching for new resonances and to provide input into partial wave analyses.

ACKNOWLEDGEMENTS

I have had very useful conversations with E. Blackmore, R. J. Macek, and V. D. Sandberg.

The calculations of K^-p and π^-p elastic scattering kinematics were carried out by Benjamin D. Hoffman.

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Fig. 1. Cross section for K^- production from 28-GeV proton-nucleus interactions.

Fig. 2. Charged kaon survival probability as a function of momentum for several flight path lengths.

Fig. 3. Kinematics for K^-p and π^-p elastic scattering for 1-GeV/c incident momentum.

Fig. 4. Strangeness-exchange cross sections and hyperon recoil momenta as a function of incident momentum.

TABLE I

EXPECTED K^- FLUXES AT 400 MeV/c AS A FUNCTION OF THE
KAON MOMENTUM BEFORE THE DEGRADER

P_{initial} (MeV/c)	K^- Flux/s at Production Target ^a	Carbon Degradar Thickness (g/cm ²)	Interaction Probability ^b	Decay Probability ^c	K^- Flux at End of Channel (400 MeV/c)	Multiple Scattering Angle (mr)	P_{π^-} (MeV/c)
1000	1×10^9	215	0.994	0.976	1.4×10^5	95	620
900	8×10^8	168	0.982	0.979	3.0×10^5	91	600
800	6×10^8	125	0.95	0.983	5.0×10^5	84	580
700	4.7×10^8	86	0.87	0.986	8.0×10^5	78	555
600	3.8×10^8	53	0.72	0.991	9.6×10^5	66	500
500	2×10^8	23	0.46	0.994	6.5×10^5	50	455

^aAssuming channel acceptance $\frac{\Delta p}{p} \Delta \Omega = \pm 15 \text{ msr } \%, 2 \times 10^{14} \text{ p/s on target, and 40\% targeting efficiency.}$

^bAssuming a 40-mb interaction cross section.

^cAssuming 10 m at high momentum, 7 m at 400 MeV/c.