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NUMBER OF DETECTABLE KAON DECAYS AT LAMPF II

by

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ABSTRACT

The maximum number of kaon decays detectable at LAMPF II is estimated for both in-flight and stopping decays. Under reasonable assumptions, the momentum of the kaon beam that optimizes the decay yield occurs at about 6 GeV/c and 600 MeV/c for in-flight and stopping decays, respectively. K^+ decay yields are of the order of 7×10^7 per 10^{14} interacting protons with K^- yields being typically 5 times less.

By measuring decays from such beams, a statistical limit of 10^{-15} on a branching ratio to a particular channel can be placed in a 100-day run. The large number of kaon decays available at LAMPF II thus provides a powerful tool for sensitively examining rare-decay processes of the kaon.

I. INTRODUCTION

Experiments designed to measure kaon decays have been performed by measuring either secondaries from kaons decaying in flight (in-flight beam) or from kaons stopping in a target (stopping beam). A question that arises is, "What would an experimental configuration for measuring such decays look like at LAMPF II?" In the evaluation of this question, two fundamental quantities enter: (1) the maximum number of detectable kaon decays that are available from either an in-flight or stopping beam and (2) the momentum of the beam at which these yields are maximized.

In the following, these quantities are determined analytically by optimizing the kaon-decay yields with respect to kaon-decay momentum for two beam lines that have characteristics similar to ones currently operational at the BNL-AGS.¹ For the in-flight beam, the parameters of the MESB beam are assumed:

$$\frac{\Delta P}{P} = \pm 3\%$$

$$\Delta\Omega = 0.3 \text{ msr}$$

$$L = 45 \text{ m}$$

except that the nominal length of 81 m is reduced to 45 m. For the stopping beam, the parameters of the LESB II are assumed:

$$\frac{\Delta P}{P} = \pm 2.5\%$$

$$\Delta\Omega = 15 \text{ msr}$$

$$L = 15 \text{ m} .$$

The momentum of the incident proton beam is taken to be 16 GeV/c and the kaon production angle is fixed at zero degrees.²

The optimization is based on the SW (Sanford-Wang) cross section³ with KR (kinematic reflection).⁴ Before the results of the in-flight and stopping optimization are presented, the SW cross section is discussed briefly.

II. SANFORD-WANG CROSS SECTION

The SW cross section as a function of kaon momentum P is written as:

$$\left(\frac{d^2N}{d\Omega dP}\right)_{SW} = C_1 P^{C_2} \left(1 - \frac{P}{P_1}\right) \exp \left[-\frac{C_3 P^{C_4}}{P^{C_5}} - C_6 \theta(P - C_7 P_1 \cos C_8 \theta) \right] ,$$

where P_i is the incident proton momentum and the parameters $C_1, C_2, \dots, C_8$ are defined by

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
K^+	0.05897	0.6916	3.744	4.520	4.190	4.928	0.1922	50.28
K^-	0.02210	1.3230	9.671	1.712	1.643	4.673	0.1686	77.27

For low momentum the cross section approaches

$$\left(\frac{d^2 N}{d\Omega dP}\right)_{SW} \rightarrow \begin{cases} 0.059 P^{0.69} K^+ \\ 0.022 P^{1.32} K^- \end{cases}$$

In this region, little experimental data existed at the time the SW parameterization was made. As such, the principle of KR is used to extend the range of validity of the SW cross section. Below about 1 GeV/c the cross section can be written

$$\frac{d^2 N}{d\Omega dP} = \left(\frac{d^2 N}{d\Omega dP_+}\right)_{SW} \frac{P^2}{E} \frac{E_+}{P_+^2},$$

where P_+ is defined from the figure:

The expression gives a stronger P dependence than does the pure SW cross section at low P :

$$\frac{d^2N}{d\Omega dP} \rightarrow c \left(\frac{d^2N}{d\Omega dP_+} \right)_{SW} P^2 .$$

Figure 1 shows results of the expression for 16-GeV/c incident proton energy. The peak of the K^+ flux occurs at 5 GeV/c and is three times that of the K^- flux, which peaks at 3 GeV/c.

A forward-traveling kaon with a P_+ of 1.4 GeV/c in the laboratory has zero momentum in the cm frame. For P_+ equal to 8.5 GeV/c, the corresponding P has zero momentum in the laboratory. The SW cross section between 1.4 GeV/c and 8.5 GeV/c is thus used via the principle of KR to evaluate the cross section between 1.4 GeV/c and 0 GeV/c, respectively.

As a side point, the maximum kaon momentum allowed for a 16-GeV/c incident proton is 11.9 GeV/c if Fermi momentum be ignored.

The kaon data of KEK at 12.9 GeV/c incident-proton momentum⁵ provide a check on the absolute value of the SW cross section, for K^+ and K^- mesons, as well as a check on the shape of the cross section below 2 GeV/c. In Figs. 2 and 3, the KEK data have been normalized to the SW cross section at 1.79 GeV/c. For the K^+ data, the normalization required increasing the measured cross section by 13%, and for the K^- data, the normalization required increasing the cross section by 30%. These shifts are within the normalization uncertainty of the data. The two measurements at 735 MeV/c support the KR hypothesis.

III. IN-FLIGHT BEAM

A magnetic spectrometer is the typical apparatus for measuring in-flight decays. The aperture of the dipole employed in such a spectrometer is usually limited to 1 m in the direction of the field. The maximum momentum of secondaries from kaon decay in the cm frame or the equivalent maximum transverse-momentum P_T in the laboratory is about 225 MeV/c. Define D by the following construction:

$$\theta = \frac{0.5}{D[\text{m}]} = \frac{P_T}{P/2} = \frac{0.225}{P[\text{GeV}/c]/2}$$

$$D[\text{M}] = 1.1 \times P[\text{GeV}/c] .$$

Then the secondaries from decays that occur within D of the dipole can all be detected by the spectrometer. The width of the dipole is assumed to be at least 1 m, and decays within any detector upstream of the dipole are ignored.

Although it is expensive to increase the aperture beyond 1 m, no difficulty is encountered in allowing the decay volume to lengthen. Even at 9 GeV/c, D is only 10 m. If the length D is taken as that which is characteristic for an experiment measuring decays in flight, then the acceptance is independent of kaon momentum and is roughly 14%:

$$(C\tau = 3.71 \text{ m} \quad m_k = 0.494 \text{ GeV}/c)$$

$$f = 1 - \exp \left(- \frac{D}{\frac{P}{m_k} C\tau} \right)$$

$$f = 1 - \exp \left(\frac{1.1 \times P}{\frac{P}{0.494} \times 3.71} \right)$$

$$= 14\% .$$

Often, the reconstructed kaon mass or missing transverse momenta are significant constraints and are necessary in rejecting background. MCS (Multipole-Coulomb-Scattering) at low momentum and fixed angular resolution at high momentum cause the experimental mass resolution as measured in a spectrometer to broaden. The percentage background under the mass peak then increases and hence the sensitivity to a given decay decreases.

Neglecting these types of experimental considerations, the number of useful detectable decays is then:

$$N(P) = f \times \frac{dN(P)}{d\Omega dP} \times e^{-L/\left(\frac{P}{m_k} \times C\tau\right)} \Delta P \Delta\Omega \quad ,$$

where L is the length of the beam line, ΔP its momentum acceptance, and $\Delta\Omega$ its angular acceptance. Assuming that L is 45 m and that ΔP and $\Delta\Omega$ are constant, the maximum yields occur at 6.8 GeV/c and 4.5 GeV/c for K^+ and K^- decays, respectively (Fig. 4). At these momenta the K^+ yield is 5.4 times that of the K^- yield.

In reality, $\Delta P/P$ remains constant for a given beam line because bending angles and apertures are fixed. Under these conditions, the optimization occurs at a momentum about 1 GeV/c higher than at the above (Fig. 4). At this momentum, the yield is 10% higher than at the lower momentum for fixed $\Delta P/P$.

III. STOPPING BEAM

A stopping beam consists of a beam line, beam degrader, and target. The momentum spread of a beam line is about 3% of the momentum, and the straggling in the degrader and target is about 2% of the range. For a beam in the momentum range 0.5 to 1.5 GeV, the pions, kaons, and protons are well separated in range so that a thin target will suffice to stop the bulk of the kaons without directly selecting pions or protons.

The stopping flux in such a totally absorbing target is

$$N(P) = \frac{d^2 N}{d\Omega dP} \times e^{-L/\left(\frac{P}{m_k} \times C\tau\right)} \times e^{-R(P)/\Lambda} \Delta P \Delta\Omega \quad .$$

Here, L is again the length of the beam line, Λ is the absorption length of the degrader material, and $R(P)$ is the length of the degrader necessary to stop a kaon of momentum P . MCS and subsequent leakage from the degrader are ignored. In addition, the absorption length is assumed to be independent of momentum. For carbon and lead, it is taken to be

$$\Lambda_{K^+} = \begin{cases} 253 \text{ gm/cm}^2 & C \\ 655 \text{ gm/cm}^2 & Pb \end{cases}$$

and

$$\Lambda_{K^-} = \begin{cases} 77.4 \text{ gm/cm}^2 & C \\ 210 \text{ gm/cm}^2 & Pb \end{cases}$$

for K^+ and K^- , respectively. These lengths correspond to cross sections of

$$\sigma_{K^+} = A^{2/3} \times 15 \text{ mb}$$

and

$$\sigma_{K^-} = A^{2/3} \times 48 \text{ mb} ,$$

where A is the atomic number. Below 2 GeV/c these cross sections are not constant, but the values used are a reasonable average over the variations encountered.

In practice, only stopping K^+ beams are used to measure kaon decays, because the K^- is absorbed before it has a chance to decay. Stopping K^- beams are used, on the other hand, in the study of kaonic atoms.

The K^- yields are shown in Figs. 5 and 6 for carbon and lead degraders. For carbon, the maximum yield is reduced by a factor of 17 owing to decays along the 15-m beam line (Fig. 5). The effect of including KR in the SW cross section is to reduce the expected yield by 28% and to shift the optimum momentum by only 50 MeV/c, from 750 MeV/c to 800 MeV/c. Figure 6 shows the effect of using different degraders. Yields vary because the kaon range is proportional to $1/Z$, but the absorption length is proportional to $1/A^{2/3}$. If MCS did not reduce the flux and if background from nuclear interactions did not affect the given

measurement, then the degrader with highest A/Z ratio should produce the largest useful stopping flux. For lead, the peak of the yield occurs at 1040 MeV/c, and the increase over that yield using a carbon degrader is 2.5.

If the optimization is done keeping $\Delta P/P$ fixed, then the optimum momentum shifts upward by about 100 MeV/c for a net increase in yield of 10%.

Maximum yields of K^+ occur at 1380 MeV/c and 1500 MeV/c for carbon and lead degraders, respectively, with the yield being twice as high if lead is used instead of carbon (Fig. 7). For K^+ , optimization occurs at a higher momentum than that for K^- , because the absorption length is three times longer than for K^- . If 48 mb/nucleon were used instead of 15 mb/nucleon, then the K^+ spectrum would have the same shape as the K^- spectrum. For carbon, the peak would shift from 1380 MeV/c to 800 MeV/c with a decrease of 10 in yield.

At the optimum momenta for the lead degrader, 71% and 87% of the K^+ and K^- interact and are absorbed (Fig. 8). The backgrounds generated by these unwanted interactions may severely limit the performance of a given stopping experiment. Let us assume, for the purpose of this discussion, that the maximum useful yield is limited at the point at which the degrader absorbs 50% of the incident flux. On the basis of this assumption, the optimum momenta drop from 1500 MeV/c to 1035 MeV/c and from 800 MeV/c to 625 MeV/c, with decreases in yields of 1.3 and 2.7 for the K^+ and K^- beam, respectively.

Even though we are dealing with separated kaon beams, there may be substantial pion contamination. Pions have an absorption length closer to that of a K^- rather than to that of a K^+ . Accordingly, depending on the fraction of the contamination, the degrader for the K^+ beam may also be limited to a thickness similar to that which limits the K^- beam.

IV. SUMMARY

The agreement of the SW cross section using KR with the KEK data at 12.9 GeV/c gives confidence that the SW cross section with KR can be used to predict cross sections at 16 GeV/c. In proceeding from these cross sections to estimating the maximum number of useful kaon decays, many simplifying assumptions have been made. The assumptions are reasonable, however, so that numbers in the following tables do give a rough guide as to the maximum kaon-decay yields that are possible at LAMPF II.

The main assumptions, aside from beam-line constraints, are that 14% of the in-flight decays are detectable, that the degrader length is limited by the requirement that no more than 50% of the beam be absorbed, and that 50% of the stopping decays are detectable. Under these conditions the maximum detectable kaon-decay yields occur at the following momenta:

	In-Flight	Stopping (Lead)
	GeV/c	GeV/c
K^+	6.8	1.0 ↑ 0.63
K^-	4.5	0.63

The optimum K^+ momentum for the stopping beam depends on the pion contamination. The 1 GeV/c optimum corresponds to a beam of pure positive kaons, whereas the 0.63 GeV/c optimum corresponds to a beam with a large pion contamination.

At the above momenta, the kaon-decay yields per $\Delta P \Delta \Omega$ and per interacting proton are:

	In-Flight	Stopping (Lead)
	Yield/SR/GeV/Int. P	Yield/SR/GeV/Int. P
K^+	6.0×10^{-3}	1.6×10^{-3} ↑ 2.8×10^{-4}
K^-	1.1×10^{-3}	6.8×10^{-5}

Using the parameters of the LESB II and MESB beams, the maximum detectable yields per 10^{14} interacting protons are:

	MESB	LESB II
	Yield/ 10^{14} Int. P	Yield/ 10^{14} Int. P
K^+	7.3×10^7	1.8×10^8 ↑ 3.2×10^7
K^-	1.3×10^7	7.5×10^6

The K^+/K^- yield ratios are

	MESB	LESB II
K^+/K^-	5.6	24 ↑ ↓ 4.1

and the yields of the MESB beam with respect to the LESB II beam are

	K^+	K^-
MESB/LESB II	0.41 ↑ ↓ 2.4	1.7

These ratios increase if MCS and background generation in the degrader are also taken into account.

Finally, consider the number of decays from the medium-energy beam of positive kaons. Assuming 10^{14} interacting protons per second, one could in principle be sensitive to 7×10^{14} decays in a 100-day run:

$$N = 10^2 \text{ day} \cdot 10^5 \frac{\text{s}}{\text{day}} \cdot 7 \times 10^7 \frac{K^+}{\text{s}} = 7 \times 10^{14} .$$

A statistical limit of 1.4×10^{-15} on a branching ratio for a particular channel could then be placed. Comparable sensitivity is expected using the stopping beam. The large number of kaon decays available at LAMPF II from either an in-flight or stopping beam thus provides a powerful tool for sensitively examining the rare-decay processes of the kaon.

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Fig. 1. Kaon production cross section at 0° in p-Be collisions at 16 GeV/C.

Fig. 2. Comparison of SW cross section with KEK data for K^+ production at 0° in P Be collisions at 12.9 GeV/c.

Fig. 3. Comparison of SW cross section with KEK data for K^- production at 0° in p-Be collisions at 12.9 GeV/c.

Fig. 4. Number of kaons at the exit of a 45-m beam line.

Fig. 5. Number of K^- stopping using a carbon degrader for a 15-m beam line.

Fig. 6. Number of K^- stopping using either carbon or lead degrader for a 15-m beam line.

Fig. 7. Number of K^+ stopping using either carbon or lead degrader for a 15-m beam line.

Fig. 8. Absorption in lead and decay probability versus P_K . $R(P)$ is the kaon range in lead.