K^+ Target Studies with Fluka – Extended

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I. Introduction

As an aid to developing a revised proposal for a possible experiment at Fermilab to obtain up to 1,000 events for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay [1], earlier Monte Carlo simulations [2] have been extended for stopping K^+ particles in a scintillating target.

The Tevatron that provided the beam for the original proposal is no longer available. The Main Injector will provide the beam in the revised proposal. To compensate for a lower beam intensity, a secondary K^+ beam with momentum greater than 550 MeV/c may be needed. Beams of 600, 650, and 710 MeV/c are considered in this report.

II. Components of the Study

Several of the degrading materials used in the previous study [2] were replaced with alternate, and more realistic, materials in the present study. Polyvinyltolulene (scintillator) requires very long lengths due to its low density, leading to substantial loss of beam upstream of the target. Synthetic diamond, although it seeed best in many regards, is not currently available in sufficient sizes or reasonable cost. Brass produces considerable photon and neutron backgrounds. In addition to BeO (density 3.0 g/cm^3), consideration is given to SiO_2 (silica, quartz, glass) and Al_2O_3 (density 3.95 g/cm^3). The density for SiO_2 was taken to be that of the crystal form, 2.65 g/cm^3, although values closer to 2.2 g/cm3 might be more realistic. Aluminum oxide is often sold as a fine powder, but it can be packed into cylinders with nearly the full density. Blocks can also be cut from the mineral corundum (with minor impurities). Boron carbide (B_4C, density 2.52 g/cm^3) was also considered briefly, and was found to be slightly less satisfactory than the other materials.

As for the original studies, the standalone Fluka Monte Carlo code [3] was used for all studies here. The most recent code release was used. It reproduced an earlier case within the accuracy of the random number sequencing.

Also as in the previous studies, the target was treated as a cylinder of solid scintillator (11 H to 10 C atoms) of radius 6 cm and length 1 meter. It was placed to start at $Z = 0$. All degraders, also 6 cm in radius, were placed at $Z < 0$, up to the target. The degrader thickness was estimated from an independent code so as to yield a K^+ momentum near 335 MeV/c at the entrance to the target. The stopping peak was then approximately at 11-12 cm into the target.

III. Beamline and Logic

The beam profiles were obtained from the proposed beamline design. A beam file provided by Jaap Doornbos ('Jaap beam file') from the TRANSPORT code contained a list of X and

Y coordinates, their respective divergences, and momenta for rays computed at 1.5 meters from the end of the second quadrupole. The momenta are for a 500-MeV/c beam, and were rescaled by the nominal beam momentum for other beams. The focal plane was taken to be $Z = 0$ in the setup. Unless otherwise stated, the beam profile was back-traced to a point 1 cm before any degrading materials.

The target and degrader were placed inside a cylindrical 'sides' region. An 'end' region was also placed at the far end of the target. A particle that crossed the boundary from the target or degrader into one of the regions was recorded as having 'escaped.'

Within the target and degrader regions, stopped K^+ particles were identified as those that tracked until they had a momentum $p_K = 0$. Those that decayed in-flight along the way were identified with an internal code number that indicated the production of secondaries from decay, and which also had non-zero momentum. (The requirement of non-zero momentum was needed to prevent K^+ particles which stopped and then decayed from being double-counted.) Finally, K^+ particles that interacted with nuclei and disappeared were identified with a second internal code number for production of secondaries. The list of secondaries was scanned, and the K^+ was identified as 'interacted' if there was no such particle in the list. There are thus four classes of K^+ events: stopped, decayed, interacted, and escaped. The total number of kaons in these groups was about 99.5% of the beam.

IV. Yield Results

The numbers of stopped, decayed, interacted, and escaped K^+, and the total number for 100,000 beam kaons are given in Table I for several combinations of beam momentum and degraders. These numbers are summed over the degrader and target regions. (Note that the 710-MeV/c cases are included to give further illustration of the momentum dependence, and are *not* to be confused with the E949 setup.)

Several trends are evident from the table. First, materials with higher densities shorten the overall length, leading to fewer decayed or escaped kaons and to larger total numbers of stopped kaons. However, there is a cost in terms of more stopped and interacted kaons in the degraders. Heavier nuclei can also cause more multiple scatterings and produce larger backgrounds.

Second, higher beam momenta makes things worse: the total numbers of stopped K^+ are lower, and the numbers of interacted and escaped kaons are both higher. However, a higher beam flux at higher momenta may compensate in part.

Looking into the details, the results in the degrader and target were analyzed in terms of three sub-regions: (1) degrader, $Z < 0$; (2) a 'tail' region with $Z > 0$ but Z less than the start of a stopped K^+ peak; and (3) a 'peak' region for stopped K^+ above a starting point. The starting point of the 'peak' was estimated to be where the counts began to significantly rise above the preceding 'tail' region. The division into 'tail' and 'peak' sub-regions allows for the possibility that acceptance windows might be placed on the location of stopped kaons. Otherwise, the number of stopped K^+ in the target is the sum of the two sub-regions.

Table I: Stopped, decayed, interacted, and escaped K^+ particles for 100,000 beam kaons. The momentum has units MeV/c, and the degrader thickness and 'peak start' positions are in cm.

Momen.	Dgrdr Thick.	Peak Start	Stopped	Decayed	Interact	Escaped	Total
BeO							
500	11.5	7.0	81,410	9,018	4,175	4,898	99,501
550	16.4	6.0	77,017	9,330	5,886	7,260	99,493
600	21.8	6.0	71,605	9,696	7,726	10,547	99,547
650	27.7	5.0	65,822	9,837	9,846	14,049	99,554
710	35.4	3.0	58,512	10,164	12,467	18,503	99,646
Al_2O_3							
500	9.1	6.0	83,951	8,051	3,886	3,614	99,502
550	12.8	5.0	79,959	8,673	5,397	5,488	99,517
600	17.0	5.0	75,409	8,928	7,291	7,888	99,516
650	21.6	4.5	70,230	8,778	9,510	11,031	99,549
710	27.5	2.5	63,526	9,025	11,932	15,200	99,683
SiO_2							
500	13.2	6.0	80,724	9,422	3,721	5,617	99,484
550	18.8	5.0	75,781	9,921	5,350	8,452	99,504
600	24.9	5.5	69,335	10,658	7,173	12,327	99,493
650	31.6	4.0	63,085	10,604	9,059	16,823	99,571
710	40.0	3.0	54,996	10,753	11,456	22,380	99,585

The breakdown of stopped and decayed K^+ in the three sub-regions is shown in Table II. The breakdowns for the interacted kaons are not included as they account for less than 10% of the incident kaons and most of the interactions occur in the degraders. (About 75% of the interactions take place in the BeO degrader at 500 MeV/c, and about 85% for the other materials; the fraction increases quickly with momentum to >95%.)

The loss of stopped K^+ between 500 and 650 MeV/c in this table is larger than the corresponding loss of stopped K^+ in Table I. This extra loss is primarily related to more stops in the degrader. The 710-MeV/c case makes the point clear. A minor benefit of a higher momentum is a comparative reduction of the 'tail' compared to the 'peak' subregion.

V. Common Starting Point

For all of the calculations above, the beam was started at 1 cm upstream of the degrader material for the case. As a result of different degrader thicknesses, these starting points are at different distances from the end of the last beamline quadrupole. There can be extra loss of flux due to decays and escaped particles in the space. Although the method used is considered to be best for assessing the intrinsic performance of the degraders, the results

Table II: Distribution of stopped and decayed K^+ particles in the degrader, 'tail,' and 'peak' sub-regions defined in the text.

	Stopped K^+			Decayed K^+		
Momen.	Dgrdr	Tail	Peak	Dgrdr	Tail	Peak
BeO						
500	9,130	2,599	69,681	3,494	2,458	3,066
550	11,912	2,088	63,017	4,386	1,900	3,044
600	13,958	2,044	55,603	5,302	1,727	2,667
650	15,853	1,621	48,348	6,047	1,194	2,596
710	16,761	825	40,926	6,902	657	2,605
Al_2O_3						
500	9,639	2,252	72,060	2,621	2,129	3,301
550	12,813	1,917	65,229	3,571	1,705	3,397
600	15,552	1,721	58,136	4,265	1,479	3,184
650	17,593	1,475	51,162	4,757	1,230	2,791
710	19,415	714	43,397	5,454	600	2,971
SiO_2						
500	8,135	2,114	70,475	3,951	2,086	3,385
550	10,640	1,882	63,259	5,088	1,918	2,915
600	12,393	1,637	55,305	6,256	1,523	2,879
650	13,580	1,068	48,437	6,786	1,026	2,792
710	14,611	646	39,739	7,511	579	2,663

would not necessarily reflect the overall performance for the experiment.

The cases were thus rerun with a common beam starting point, independent of momentum. A value of 41 cm upstream of the target was used, as in the original report. The 'sides' region was extended to include the additional drift space. Results for some key numbers are shown in Table III.

As expected, the big changes (cf. Table II) are large increases in the number of decays in the beamline/degrader region, and some loss in the stopped K^+ peak. The numbers of interactions and escaped K^+ are not much changed. There is a loss of 5-7% of kaons in the target, whether stopped, decayed, or escaped. In addition, there is a beam survival factor of 0.75-0.80 between 500 and 650 MeV/c from the exit of the quadrupole to the common beamline point, depending on momentum.

VI. Secondaries

In addition to the kaons, production of secondary particles into the detector is also a matter of concern. Here, we consider all particles that 'escaped' into the outside region. Table IV lists the yields for the dominant particles. The results are organized by momentum to

Table III: Distributions of K^+ particles in various regions. The common beamline segment begins at $Z = -41$ cm.

	Stopped K^+		Decayed K^+		Interact.	Escaped	
Momen.	Dgrdr	Peak	Dgrdr	Peak	BmLine	Dgrdr	Target
BeO							
500	8,452	64,421	7,676	2,793	3,428	1,521	2,889
550	11,172	59,255	10,097	2,853	5,144	3,443	3,392
600	13,433	53,303	9,276	2,527	7,133	6,235	3,534
650	15,182	47,048	8,744	2,564	9,445	9,487	3,767
710	16,545	40,667	7,789	2,550	12,177	16,060	3,756
Al_2O_3							
500	8,753	66,010	10,705	2,982	3,085	937	2,604
550	12,093	60,836	9,804	3,202	4,680	2,053	3,269
600	14,639	54,935	9,361	2,956	6,539	3,963	3,766
650	16,868	49,173	8,680	2,658	8,775	6,391	4,074
710	18,685	42,254	8,000	2,878	11,399	10,052	4,590
SiO_2							
500	7,527	65,387	7,108	3,143	2,960	2,045	3,164
550	9,996	60,056	10,182	3,265	4,502	4,251	3,800
600	11,928	53,626	9,312	2,707	6,428	7,169	4,504
650	13,251	47,545	8,707	2,774	8,579	10,763	5,098
710	14,573	39,502	7,840	2,688	11,125	15,267	6,173

emphasize the comparisons between materials. The beam starting points for Table I are used.

In the table, no discrimination has been made on the number of daughter layers, or the origins of the particles. For example, π^0s are not tracked, and the daughter photons are included in the γ column. Most of the μ^+ particles come from the decay of the K^+. The fact that the μ^+ numbers are reduced in going to higher momenta reflects the reduction in the stopped and decayed K^+.

The table does not include escaped K^0 and $\bar{K}^0$ particles. About 900, 1400, 2000, and 2500 K^0 were produced at 500, 550, 600, and 650 MeV/c, respectively. The numbers are about 2/3 as large for $\bar{K}^0$.

Many of the yields have, at most, modest dependence on beam momentum. But attention is drawn specifically to the γ and n numbers. Not only do they increase significantly with beam momentum, even for the same degrader material, they also depend on the material. The best material for photons is BeO, while SiO_2 is best for neutrons. Aluminum oxide is best for protons, π^-, and K^+, but it is the worst for e^+, photons, and neutrons.

Table IV: Yields of the dominant particles that 'escape' from the degrader and target into a detector region.

Mom.	Dgrdr	p	e^+	e^-	γ	n	μ^+	π^+	π^-	K^+
500	BeO	1174	15,476	19,109	133,718	21,821	57,722	18,604	1604	4,898
500	SiO2	1006	15,809	19,073	147,397	18,724	57,917	18,733	1600	5,617
500	Al2O3	996	15,838	19,004	154,959	21,815	58,291	18,648	1434	3,614
550	BeO	1182	15,925	18,594	142,147	28,064	55,319	18,086	1961	7,260
550	SiO2	1189	16,599	19,035	164,426	23,490	55,224	18,116	1985	8,452
550	Al2O3	1034	17,082	19,313	180,325	27,901	55,938	17,935	1772	5,488
600	BeO	1346	15,755	17,824	147,986	33,916	52,180	17,366	2357	10,547
600	SiO2	1398	17,086	18,155	181,723	28,440	51,5140	17,689	2323	12,327
600	Al2O3	1110	17,413	18,860	201,247	35,150	53,224	17,567	2101	7,888
650	BeO	1834	15,835	17,225	158,701	41,797	48,204	16,714	2705	14,049
650	SiO2	2021	17,145	17,381	194,714	34,180	47,526	16,816	2741	16,823
650	Al2O3	1339	18,075	17,910	224,178	43,982	50,260	16,388	2472	11,031
710	BeO	3039	16,503	16,243	170,558	50,017	43,780	16,034	3355	18,503
710	SiO2	3512	17,540	16,205	209,723	41,108	41,108	16,115	3329	22,380
710	Al2O3	1768	18,929	17,634	249,733	53,965	45,699	15,776	2936	15,200

VII. Conclusions

The stopped K^+ numbers for the 'peak' sub-region in Table II (divided by 100,000) are good estimates of the stopping efficiencies for the $K^+ \to \pi^+\nu\bar{\nu}$ experiment design, including all stopped K^+ in the target. The yield is reduced by about 25% in raising the beam momentum from 550 to 650 MeV/c, at the expense of stopped and decayed K^+ in the degrader.

Because trigger scintillators and beam monitors may also be needed upstream, the net stopping efficiency might be slightly lower but still quite good. Due to its high density, Al_2O_3 appears to be best for reducing the degrader length, but it also produces higher backgrounds. If the latter are not critical issues, it might be the best material. Otherwise, BeO appears to be a satisfactory choice.

References

[1] Fermilab proposal P996.

[2] J.R. Comfort, "K^+ Target Studies with Fluka," Fermilab DocDB Kaon Physics 718 (2009).

[3] Fluka Monte Carlo code. See http://www.fluka.org/fluka.php and references therein.