abstract

Bubble chamber is a device we use to study the behaviors of very small particles. In this experiment we were to study the activities of K^- meson by scanning the photographs of 70 mm film of real experiment done with bubble chambers, with K^- beam of momentum 1.5 GeV/c entering the chamber filled with liquid hydrogen of density approximately 0.06gm/cm^3, operating at the Berkeley Bevatron in the 1960's. We obtained

$$\tau = (1.04 \pm 0.05) \times 10^{-8} \text{ sec},$$

$$\sigma_{el} = (0.82 \pm 0.04) \times 10^{-30} \text{ m}^2,$$

and

$$\sigma_{tot} = (3.51 \pm 0.16) \times 10^{-30} \text{ m}^2.$$

We also approximated the proton's effective radius to be

$$R_p = (5.89 \pm 0.14) \times 10^{-16} \text{ m}$$

For K^- decays we obtained the branching ratio of the "tau" (τ) mode, $K^- \rightarrow \pi^+\pi^-\pi^-$,

$$BR = (5.56 \pm 0.10)\%.$$

Introduction

Decays and interactions are governed by many conservation laws. These include the conservation laws of (angular) momentum, electric charge, baryon number, and lepton number for all kinds of decays and interactions. For strong interactions, isospin, parity, and flavor are also conserved. K^- mesons incident on hydrogen nuclei (protons) with momentum 1.5 GeV/c produce many final states, including both long-lived ($>10^{-10}$ sec) particles and short-lived

"resonances." In this laboratory we will concentrate on the long-lived final states, which can be identified by scanning rather than quantitative momentum measurement of the tracks. Selection rules that require weak decays of strange final states cause long strange particle lifetimes. This experiment introduces us to the realm of elementary particles and the conservation laws that govern their interactions and decays.

Theory

When K^- enters the region of hydrogen, the number of K^- decreases due to decays and the inelastic interactions between K^- and the hydrogen nuclei.

If we have a large collection of K^-, $N_{(t)}$, at time t, then $N\Gamma dt$ of them would decay in the next instant dt, where Γ is the decay rate-- the probability per unit time that any given K^- will disintegrate. The mean lifetime is simply the reciprocal of the decay rate: $\tau = 1/\Gamma$. For relativistic K^- traveling in the medium of hydrogen

$$dt = \frac{dx}{v}$$

use v, ν usually means neutrino in Particle Physics.

therefore

$$dN = -\Gamma N dt = -\frac{N dx}{v\tau}$$

It follows that

$$N_{(t)} = N_0 \exp\left(-\frac{x}{\gamma\beta c\tau}\right) \qquad (1)$$

The K^- number N decreases in the hydrogen medium at a rate dN/dt, with respect to the

K^- path length, is directly proportional to the number of incident K^- beam N, the cross section area of all the inelastic interactions, and the number of hydrogen nuclei per unit volume N_H. The number of proton in unit volume is simply given by

$$N_H = \frac{N_a \rho}{A}$$

where N_a is the Avogadro's number, ρ is the mass density of proton in liquid hydrogen, and A is the atomic number of proton. Therefore

$$\frac{dN}{dx} = -\frac{\sigma N_a \rho N}{A}$$

It follows

$$N = N_0 \exp\left(-\frac{x N_a \sigma \rho}{A}\right) \qquad (2)$$

Combining Eqn (1) and (2), we obtain the equation for the number of K^- as a function of path length x in the hydrogen medium due to both decays and all the inelastic interactions

$$N = N_0 \exp\left(-\frac{x}{\gamma\beta c\tau}\right)\exp\left(-\frac{x N_a \sigma \rho}{A}\right) \qquad (3)$$

For short average K^- path length within the fiducial volume, Δx, we approximate

$$\frac{\Delta N_D}{\Delta x} = \frac{dN_D}{dx} \text{ and } \frac{\Delta N_I}{\Delta x} = \frac{dN_I}{dx}$$

where ΔN_D and ΔN_I are the numbers of all decays and inelastic interactions, respectively.

Since decay in flight affects the number of K^-, it affects the number of possible inelastic interactions, and vice versa. We have to modify the number of K^- to

$$N = N_0 - \frac{\Delta N_I + \Delta N_D}{2}$$

according to Appendix (1). Therefore we obtain

$$\frac{\Delta N_D}{\Delta x} = \frac{1}{\gamma\beta c\tau}\left(N_0 - \frac{\Delta N_I + \Delta N_D}{2}\right) \tag{4}$$

and

$$\frac{\Delta N_I}{\Delta x} = \frac{N_a \rho\sigma}{A}\left(N_0 - \frac{\Delta N_I + \Delta N_D}{2}\right) \tag{5}$$

Apparatus and Procedure

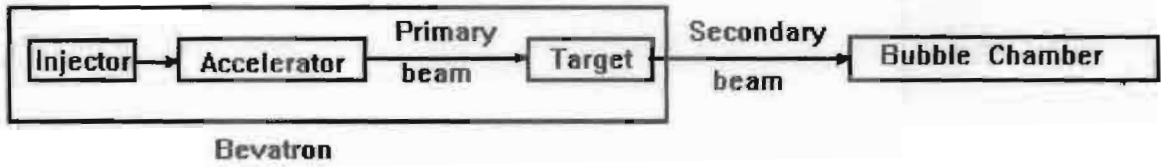


Figure 1: Experimental set-up for the production of K^- and bubble chamber analysis.

The K^-'s are produced in the Bevatron, a large and complex device. Positively charged protons are injected into the Bevatron with an energy typically low. The protons are accelerated in a circular track with magnetic field perpendicularly across it until they reach the desired energy. Then the accelerating voltage is turned off so that the proton gradually spiral inward and strike the target. (See Fig. 2)

At this point an array of particles of many kinds at a spectrum of energies are produced. This is the secondary beam. Using a bending magnet to select the desired moment and a velocity spectrometer to select the desire type of particle, we obtain the desired K^- beam, which is then lead to the bubble chamber for study.

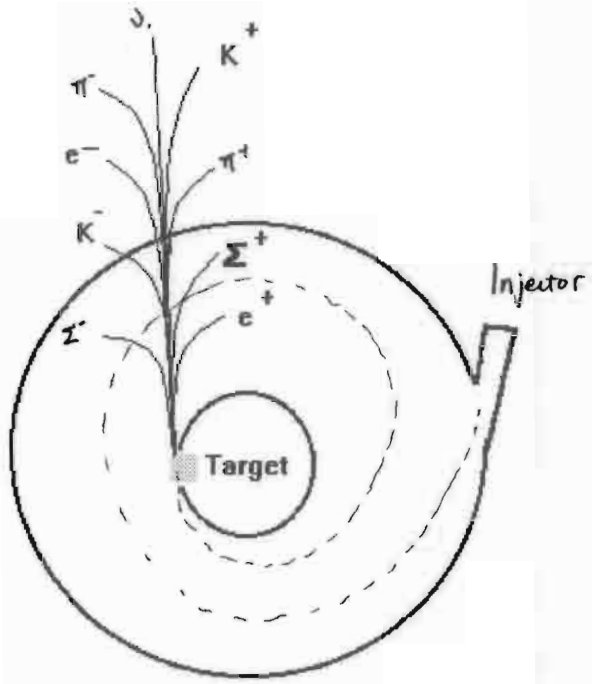


Figure 2: Accelerator and target for production of K^-.

The bubble chamber consists of a closed vessel containing a liquid at a temperature slightly above its normal boiling point but under a sufficient pressure to prevent it from boiling. The pressure of the liquid is suddenly released, and for a fraction of a second, the liquid hydrogen does not boil but in a superheated state. If during this brief period of time, a charged particle (K^- or other charged particles due to decays or inelastic interactions) passes through the liquid, it will serve as a nucleon for the superheated hydrogen nuclei to form bubbles. Therefore a track is left indicating the path of the charged particle. The neutral particles cannot serve as a nucleon and therefore leave no visible tracks. Pictures are taken from three different angles at this moment to record the event. The bubble then collapse under recompression, and the cycle are repeated. A known magnetic field is imposed perpendicularly across the chamber so that from the direction a charged particle curves we can distinguish its sign of charge and from the curvature we can calculate its momentum.

The above procedures to produce the films were actually done at the Berkeley Bevatron in the 1960's. Our procedure in this laboratory is to scan and study 500 of these films. We selected a fixed fiducial region and concentrated on the events taking place in the region, ignoring all the events outside of it. We recorded all events found in the fiducial region with frame number, rough location within the chamber, and the event type. For every tenth frame, we recorded the number of good beam tracks that enter the fiducial region to obtain the total number of incoming tracks.

Data

Roll number: 5450

Frame Number	No Event	Number of Tracks	Collision	Interaction	Decay	Tau" Decay	Location	Length
394	No							
395	No							
396				4-P			0.8/290	8.9
397	No							
398	No							
400	No							
401					1-P		0.5/240	11.5
402				2-P			0.6/180	21.3
403	No							
404		13			1-P		0.5/120	25.0
405					1-P		0.6/120	22.5
406	No							
407	No							
408					1-P		0.5/270	6.8
****					1-P		0.3/180	18.5
409				0-P			0.7/140	28.4
410					1-P		0.2/100	23.3
411				4-P			0.5/240	12.3
412	No							
413	No							
414		10			1-P		0.8/270	1.0
415			2-P				0.4/170	19.5
416	No							
417	No							
418					1-P		0.7/250	2.7
419					1-P		0.8/230	4.5
****					1-P		0.7/230	6.1
420	No							
421	No							
422	No							
423					1-P		0.3/180	19.7
424		5	2-P				0.7/140	26.9

426	No							
427				0-P + V			0.5/230	7.2
****			2-P				0.4/180	16.1
428	No							
429				2-P			0.6/120	25.3
****					1-P		0.5/190	14.2
430				4-P			0.3/110	23.6
431	No							
432			2-P				0.3/180	17.8
433					1-P		0.3/210	14.5
****			2-P				0.3/130	22.3
434					1-P		0.4/150	21.4
****				0-P			0.6/140	22.9
****			2-P				0.7/130	26.2
435	No	8						
436			2-P				0.2/260	13.2
****				2-P			0.4/120	26.0
437	No							
438				2-P			0.5/130	24.0
****					1-P		0.6/140	23.4
439					1-P		0.5/170	21.4
440	No							
441	No							
442					1-P		0.3/190	17.4
443				4-P			0.4/250	10.6
444				2-P			0.8/260	3.9
****					1-P		0.9/90	28.1
445		11		2-P + V			1.0/270	0.4
446					1-P		0.9/280	2.1
447				0-P			0.3/280	10.9
448				0-P			0.4/220	12.8
449	No							
450				2-P			0.2/230	13.4
451					1-P		0.5/280	7.2
452				2-P + V			0.6/230	5.1
453	No							
454					1-P		0.5/100	29.3
455		11			1-P		0.7/240	3.0
****				2-P			0.7/230	8.2
456	No							
457				2-P			0.3/180	19.2
458	No							
459				2-P			0.8/270	0.3
460	No							
461					1-P		0.2/100	23.6
462				2-P			0.7/180	17.0
463	No							
464	No							
465	No	10						
466	No							
467	No							
468					1-P		0.7/230	7.8
469	No							
470					1-P		0.4/230	12.4
471	No							
472					1-P		0.9/240	1.9
473				0-P			0.7/270	10.8
474	No							
475	No	10						
476	No							
477	No							
478				2-P			0.8/260	1.0
479	No							
480				0-P			0.8/220	8.0
****				2-P			0.3/180	16.1
481					1-P		0.5/230	12.9

482					1-P		0.7/190	14.6
483				2-P			0.4/260	9.3
484	No							
485	No	12						
486	No							
487				0-P + V			0.9/240	4.2
488	No							
489						3-P	0.8/140	27.1
490	No							
491	No							
492	No							
493	No							
494				0-P			0.3/260	11.2
****					1-P		0.4/200	17.5
495	No	5						
496					1-P		0.6/250	5.3
497				0-P			0.7/280	2.6
498	No							
499	No							
500	No							
501	No							
502				0-P			0.8/240	4.4
5.3				2-P			0.4/130	26.2
504	No							
505	No	6						
506	No							
507					1-P		0.7/200	14.7
***				2-P + V			0.7/40	26.6
508				4-P			0.7/270	1.1
****					1-P		0.8/240	4.9
509	No							
510				2-P			0.5/170	18.8
511			2-P				0.4/130	24.4
****				2-P			0.4/140	23.0
512						3-P	0.1/20	18.0
513	No							
514	No							
515	No	6						
516	No							
517				2-P + V			0.8/240	1.9
518								
519			2-P				0.6/260	4.6
520	No							
521						3-P	0.5/240	8.3
522	No							
523	No							
524				0-P			0.4/110	24.5
525		11		4-P			0.5/130	27.2
526	No							
527					1-P		0.4/270	8.4
528				2-P			0.8/260	0.5
529	No							
530					1-P		0.6/230	9.5
****				2-P + V			0.5/190	16.3
531	No							
532				2-P + V			0.5/230	8.6
****					1-P		0.7/100	28.3
533	No							
534				2-P			0.4/190	16.1
535	No	6						
536					1-P		0.2/140	19.4
537					1-P		0.8/270	0.5
538				2-P + V			0.7/190	13.5
539	No							
540	No							
541					1-P		0.6/210	11.5

542	No							
543				2-P			0.6/230	10.4
****				2-P			0.8/250	0.4
544					1-P		0.1/190	19.2
545		12			1-P		0.9/240	3.3
546	No							
547	No							
548	No							
549	No							
550			2-P				0.4/180	18.2
551				2-P			0.9/240	2.6
552	No							
553	No							
554	No							
555	No	4						
556	No							
557					1-P		0.9/140	27.3
****			2-P				0.8/140	27.5
558	No							
559					1-P		0.5/120	25.1
****				2-P			0.6/150	25.7
560	No							
561	No							
562				2-P			0.8/250	2.2
563	No							
564	No							
565	No	12						
566	No							
567	No							
568	No							
569				0-P			0.4/180	17.1
570	No							
571				2-P			0.1/80	20.7
572				2-P			0.6/240	7.8
573				2-P			0.2/230	14.6
574	No							
575		13		2-P			0.6/280	3.3
576				0-P			0.5/160	15.8
577					1-P		0.6/130	28.1
****				2-P			0.5/170	17.8
****			2-P				0.8/240	5.6
578					1-P		0.2/270	12.0
579				2-P			0.5/190	14.5
580					1-P		0.8/250	5.2
****				2-P			0.5/220	13.7
581				2-P			0.7/260	3.6
582					1-P		0.9/240	1.1
583	No							
584	No							
585	No	3						
586				0-P			0.9/230	0.3
****					1-P		0.8/230	3.3
****					1-P		0.2/210	14.3
587	No							
588							0.7/240	6.2
589	No							
590	No							
591				2-P			0.8/260	1.6
592	No							
593			2-P				0.2/180	16.8
594					1-P		0.5/250	7.7
595	No	9						
596					1-P		0.8/260	1.0
****				2-P			0.4/270	7.8
597				0-P			0.5/240	8.1
598				2-P			0.4/230	11.5

599				0-P			0.5/130	23.9
600				2-P			0.4/130	14.4
****				2-P			0.6/260	5.4
601					1-P		0.6/220	10.3
602	No							
603	No							
604	No							
605		10			1-P		0.4/230	9.0
606				0-P			0.8/240	3.9
****				2-P			0.3/190	16.0
607			2-P				0.2/100	21.6
608	No							
609	No							
610				2-P			0.5/190	15.1
611	No							
612	No							
613	No							
614	No							
615	No	9						
616			2-P				0.8/240	3.9
617				2-P			0.5/240	7.4
618	No							
619	No							
620	No							
621			2-P				0.2/180	16.9
622					1-P		0.8/140	26.0
623				2-P			0.6/250	5.4
624	No							
625	No	9						
626	No							
627				2-P			0.7/300	1.7
628	No							
629	No							
630				2-P			0.2/140	18.1
631			2-P				0.8/160	22.8
632	No							
633	No							
634			2-P				0.6/240	6.9
635	No	8						
636	No							
637				4-P + V			0.7/260	3.8
638	No							
639	No							
640	No							
641	No							
642			2-P				0.4/100	25.1
642	No							
644	No							
645	No	11						
646					1-P		0.6/270	2.3
647	No							
648				2-P			0.5/130	24.0
649				2-P			0.5/160	20.6
650	No							
651	No							
652	No							
653	No							
654	No							
655	No	9						
656	No							
657	No							
658	No							
659	No							
660					1-P		0.5/120	26.3
661	No							
662	No							

663	No							
664	No							
665		6			1-P		0.4/180	18.0
666				2-P			0.3/90	23.4
667	No							
668			2-P				0.5/100	25.7
****					1-P		0.8/140	27.0
669					1-P		0.7/150	24.9
670			2-P				0.8/260	2.4
671			2-P				0.9/250	0.6
672	No							
673							0.4/150	19.9
****			2-P				0.6/100	29.0
674					1-P		0.6/240	6.0
****					1-P		0.1/90	21.7
675	No	12						
676				2-P			0.8/240	6.7
677					1-P		0.3/190	15.0
678					1-P		0.7/240	7.8
****				2-P			0.6/240	9.0
****				2-P			0.7/270	4.4
679	No							
680	No							
681				2-P			0.5/120	20.8
****				2-P			0.2/260	12.7
682			2-P				0.6/240	7.3
683				2-P + V			0.8/220	8.6
684	No							
685		10			1-P		0.9/250	2.7
686				2-P			0.3/260	10.7
687					1-P		0.3/110	23.8
688			2-P				0.7/240	6.8
****				2-P			0.5/180	16.8
689			2-P				0.2/170	18.8
690				2-P + V			0.4/210	13.7
691					1-P + V		0.1/170	18.1
****					1-P + V		0.8/250	4.4
****				2-P + V			0.6/230	8.7
692	No							
693	No							
694				2-P			Center	13.9
****				2-P			0.5/230	9.6
****						3-P	0.5/230	10.8
695		12		2-P			0.6/230	12.7
696	No							
697					1-P		0.4/250	8.4
****			2-P				0.5/130	29.9
****					1-P		0.7/230	9.9
698					1-P		0.7/270	2.5
699	No							
700	No							
701					1-P		0.4/250	10.9
702				2-P			0.3/250	9.4
703					1-P		0.3/120	21.4
****				2-P			0.4/120	24.1
704					1-P		0.4/260	7.7
****			2-P				0.8/120	28.8
705	No	11						
706				2-P			Center	17.1
707	No							
708					1-P		0.3/90	24.9
709					1-P		0.9/250	3.7
****				2-P			0.7/250	7.6
****					1-P		0.6/130	22.7
****				2-P			0.5/110	25.9
710							0.8/280	0.6

711	No							
712					1-P		0.6/110	28.5
713				2-P			0.8/270	0.2
714	No							
715	No	12						
716	No							
717			2-P				0.7/200	12.5
718	No							
719	No							
720	No							
721	No							
722					1-P		0.3/270	13.0
723	No							
724					1-P		0.7/300	4.1
****					1-P		0.6/270	4.8
725		14		2-P			0.4/320	10.1
726	No							
727	No							
728	No							
729	No							
730	No							
731					1-P		0.6/240	8.4
732	No							
733	No							
734	No							
735	No	7						
736	No							
737	No							
738	No							
739				2-P			0.4/320	10.6
740	No							
741	No							
742				2-P			0.9/240	1.1
743					1-P		0.5/240	8.5
744	No							
745	No	4						
746	No							
747	No							
748					1-P		0.8/270	0.9
749	No							
750	No							
751	No							
752	No							
753					1-P		0.8/250	3.2
754					1-P		0.7/300	3.0
755	No	12						
756	No							
757	No							
758					1-P		0.8/260	0.5
759	No							
760					1-P		0.3/250	10.9
761					1-P		0.2/170	18.9
762					1-P		0.5/270	6.2
763	No							
764	No							
765	No	7						
766					1-P		0.6/260	2.8
767	No							
768					1-P		0.4/150	22.7
****				2-P'			0.7/230	5.0
769				2-P			0.4/180	17.2
770	No							
771				4-P			0.7/230	9.1
772	No							
773	No							
774					1-P		0.8/270	1.1

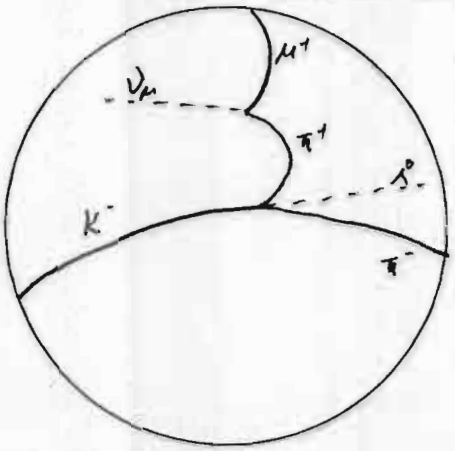
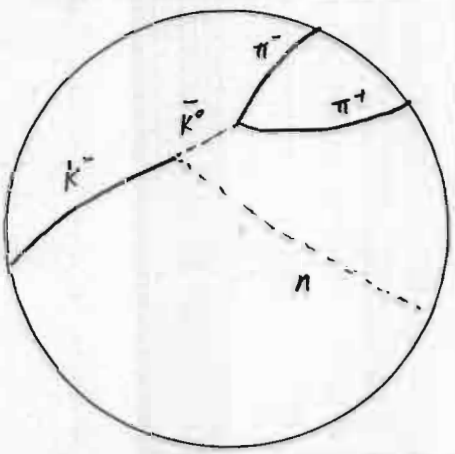
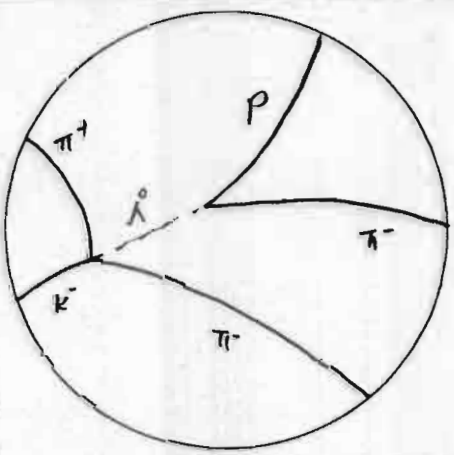
775	No	10						
776	No							
777	No							
778	No							
779	No							
780				2-P			0.2/110	21.6
****				2-P			0.4/100	26.4
781	No							
782				2-P			0.2/270	13.0
783					1-P		0.5/230	10.1
784				0-P			0.7/260	3.6
****			2-P				0.5/290	6.2
785	No	6						
786				2-P			0.1/180	17.5
****				2-P			0.5/170	19.5
787	No							
788	No							
789			2-P				0.5/90	26.9
790					1-P		0.8/140	27.9
791	No							
792				2-P			0.3/140	22.7
793	No							
794	No							
795		15		2-P			0.3/190	15.9
796	No							
797				0-P			0.5/30	8.1
798					1-P		0.6/220	11.6
799	No							
800					1-P		0.6/170	20.6
****					1-P		0.8/280	0.7
801				0-P			0.2/170	19.5
802	No							
803			2-P				0.6/210	11.9
804	No							
805	No	14						
806				2-P			0.6/220	12.7
807	No							
808					1-P		0.5/190	15.6
****				2-P			0.5/260	7.4
809	No							
810					1-P		0.6/170	19.0
811	No							
812	No							
813	No							
814	No							
815		13	2-P				0.8/250	2.2
816	No							
817				4-P			0.5/230	11.1
****				2-P			0.4/90	24.8
818				2-P			0.6/100	28.8
819					1-P		0.3/240	11.8
****				2-P + V			0.6/220	10.4
820	No							
821					1-P		Center	16.9
****				2-P			0.1/140	19.4
822					1-P		0.6/140	22.5
****					1-P		0.6/220	10.7
823					1-P		0.5/220	12.7
824	No							
825	No	12						
826	No							
827					1-P		0.7/180	17.8
****					1-P		0.6/130	26.9
828				2-P + V			0.8/260	1.5
****				2-P			0.4/230	11.8
829	No							

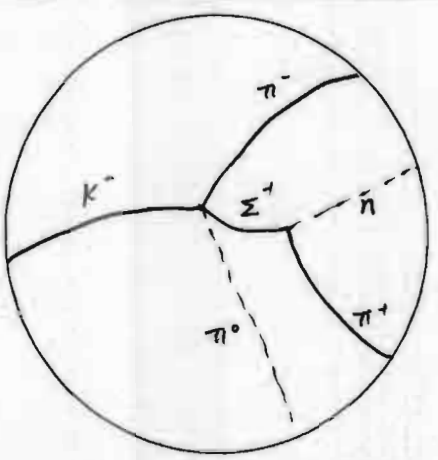
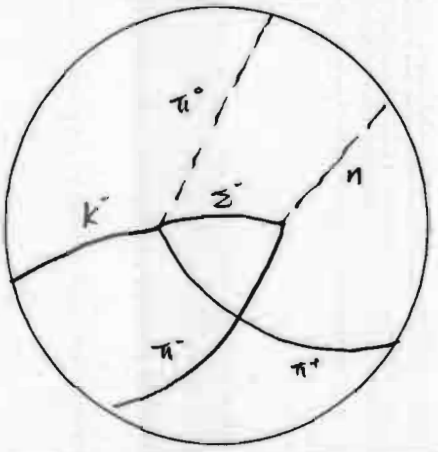
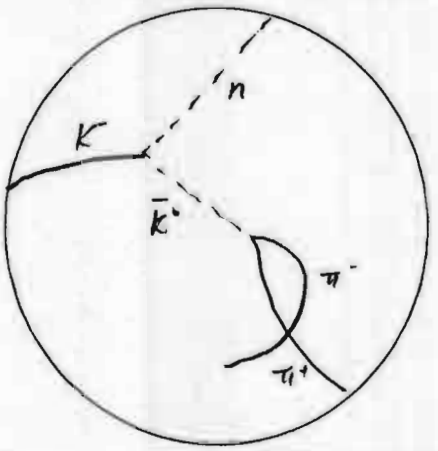
830	No							
831	No							
832				2-P + V			0.9/220	3.5
833				2-P			0.6/180	17.7
834	No							
835	No	10						
836				2-P			0.6/210	12.1
837					1-P		0.3/270	10.2
838	No							
839					1-P		0.5/190	14.9
840	No							
841	No							
842	No							
843	No							
844				2-P			Center	16.7
845		7						
846					1-P		0.8/260	1.6
847	No							
848	No							
849					1-P		0.5/240	7.7
850	No							
851	No							
852	No							
853				2-P			0.6/120	29.5
854	No							
855		10		2-P			0.3/100	24.1
856	No							
857					1-P		0.7/140	25.0
858	No							
859				2-P			0.3/150	21.6
****					1-P		0.8/270	1.3
****					1-P		0.5/300	0.1
****					1-P		0.4/300	8.4
860					1-P		0.9/230	3.3
****					1-P		0.7/140	25.8
****			2-P				0.6/260	6.0
861	No							
862			2-P				0.4/100	27.1
863						3-P	0.8/250	3.1
864				0-P			0.6/100	28.8
865		11			1-P		0.6/110	23.1
866					1-P		0.3/290	11.0
867	No							
868	No							
869	No							
870					1-P		0.2/230	14.1
871					1-P		0.8/250	4.4
872						3-P	0.8/170	20.5
873				2-P			0.4/140	23.5
874				2-P			0.8/270	1.1
****			2-P				0.7/140	25.2
875		14			1-P		0.7/230	6.7
876	No							
877	No							
878					1-P		0.3/240	10.6
879				4-P			0.4/140	24.1
880					1-P		0.2/170	20.7
881				0-P + V			0.8/280	2.8
882					1-P		0.2/180	17.4
883	No							
884				0-P + V			0.4/260	8.5
****				2-P			0.7/220	9.9
****				2-P			0.8/170	21.2
885		10			1-P		0.1/120	19.4
886	No							
887				2-P			0.5/170	19.4

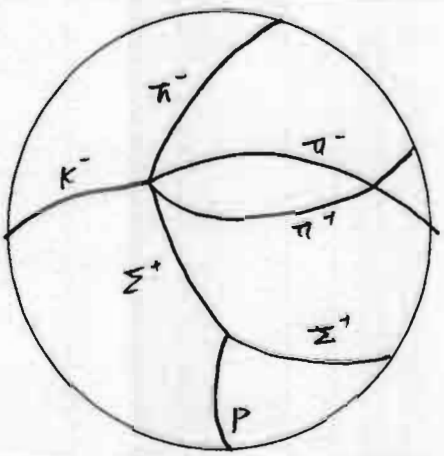
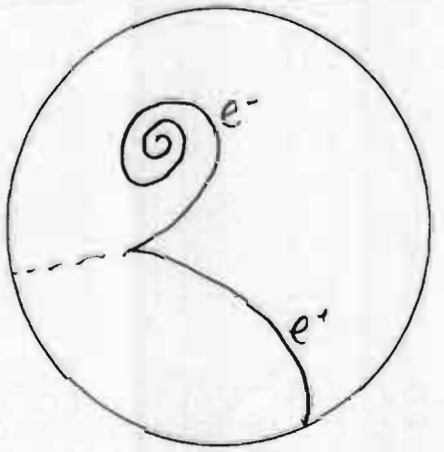
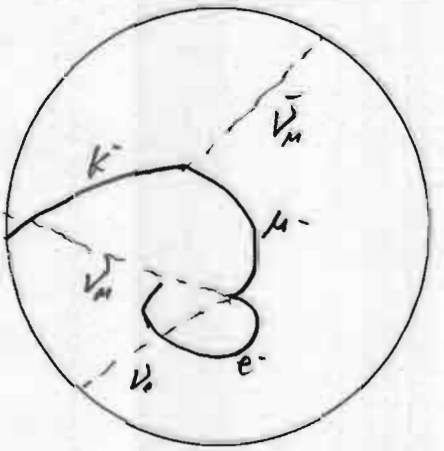
****					1-P		0.5/170	19.2
888			2-P				0.7/290	1.4
889	No							
890					1-P		0.9/250	0.3
****				2-P			0.4/60	27.6
891	No							
892					1-P		0.2/270	12.4
893					1-P		0.8/260	0.8
894					1-P		0.7/260	3.5
895		11			1-P		0.8/270	1.4
****			2-P				0.2/170	19.7
896			2-P				0.6/160	21.2
897	No							
898					1-P		0.4/180	17.6
899	No							
900			2-P				0.8/270	1.3
901					1-P		0.2/90	23.5
902					1-P		0.9/290	0.4
****					1-P		0.3/180	17.3
903	No							
904				0-P			0.6/270	3.5
****			2-P				0.5/270	6.3
905		9			1-P		0.3/180	16.4

Table 1: Measurement of events. Note that "n-P" indicates "n-prong," "V" indicates "vee," location is measured in polar coordinates with radii in unit of fiducial region radius and angle in unit of degrees, and path length is measured in centimeter. A "****" indicates a roll number identical to the roll number just above it.

As we proceeded through the scan, we found roughly 20 different event. We recorded ten of them:

frame Number	Interactions	Observations
402	$K^- + p \rightarrow \pi^+ + \pi^- + \Lambda^0$ $\pi^+ \rightarrow \mu^+ + \upsilon_\mu$	
427	$K^- + p \rightarrow n + \overline{K}^0$ $\overline{K}^0 \rightarrow \pi^+ + \pi^-$	
445	$K^- + p \rightarrow \pi^+ + \pi^- + \Lambda^0$ $\Lambda^0 \rightarrow p + \pi^-$	

457	$K^- + p \rightarrow \pi^- + \pi^0 + \Sigma^+$ $\Sigma^+ \rightarrow n + \pi^+$	
486	$K^- + p \rightarrow \pi^+ + \pi^0 + \Sigma^-$ $\Sigma^- \rightarrow n + \pi^-$	
487	$K^- + p \rightarrow n + \overline{K}^0$ $\overline{K}^0 \rightarrow \pi^+ + \pi^-$	

508	$K^- + p \rightarrow \pi^+ + \pi^- + \pi^- + \Sigma^+$ $\Sigma^+ + p \rightarrow \Sigma^+ + p$	
526	$\gamma \rightarrow e^+ + e^-$	
530	$K^- \rightarrow \mu^- + \upsilon_\mu$ $\mu^- \rightarrow e^- + \overline{\upsilon}_e + \upsilon_\mu$	

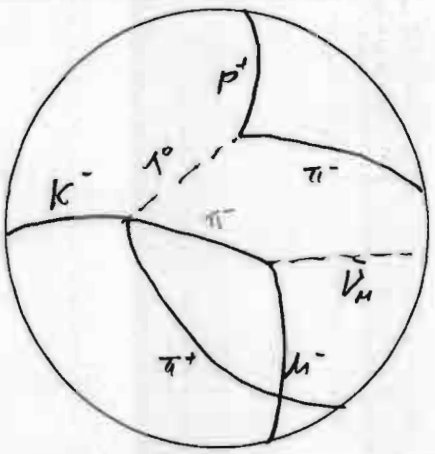
574	$K^- + p \Leftrightarrow \pi^+ + \pi^- + \overset{0}{\Lambda}$ $\pi^- \rightarrow \mu^- + \overline{\upsilon}_\mu$	

Table 2: Observation of events.

Analysis

Total number of decays (ΔN_D)	144
number of "tau" decays (N_τ)	8
Total number of interactions	137
Number of elastic collisions (ΔN_{el})	41
Number of inelastic interactions (ΔN_I)	178
Total number of tracks for the selected 50 films (N_{50})	486
Average track length for the 500 films before events (Δx)	0.2894m

Table 3: Summary of the events.

1) Branching ratio

From Table 3, we can easily find the branching ratio of "tau" decay for K^-

$$BR \equiv \frac{N_\tau}{\Delta N_D} = \frac{8}{144} = 5.56\%$$

Since N_τ and ΔN_D are not statistically independent, the error for BR is propagated according to

$$\sqrt{\frac{8\times 144}{(144+8)^3}} = 1.81\%$$

Therefore we obtained the branching ratio

$$\boxed{BR = (5.6\pm 1.8)\%}$$

The value from the Particle Data Table in the library is (5.59±0.05)%. Our experimental result falls in this range.

2) Total number of incident K^- particles for 500 films

From Table 3 the total incoming K^- particles for 50 random films is 486, and the standard deviation is given by Poisson statistics to be $\sqrt{486} = 22.0$. Therefore the total number of incident K^- particles for 500 films is simply given by

$$N_0 = (486\pm 22.0)\times 10 = \boxed{4900\pm 200}$$

3) Correction for the cross section area

The difficulty in observing and identifying a small angle of K^- p elastic scattering introduces a systematic error to the observations. Assume the bubble size is about 0.3 mm and that for recoil lengths greater than 1 cm we have a good scanning efficiency at all azimuth angles. Using the range-momentum graph in Review of Particle Properties (RPP), we could

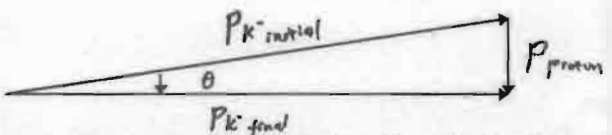


Figure 4: Transfer of momentum from K^- to P_p.

convert the assumption to a momentum of $P_p = 0.143$ GeV/c. Then the incident K^- and the scattered K^- have almost the same momentum (≈1.5 GeV/c), and from Fig. 4 we have $P_{K\theta} \approx P_p$. So we obtained $\theta = 0.0935 rad$. We know that the differential cross section at small angle has been measured to be approximately $\frac{d\sigma}{dt} = 70 mbarn/(GeV/c)^2$ where t is the square of the invariant 4-momentum transfer, and at small angle $t \approx (P\theta)^2$. Therefore we can convert the small angle to the correction for the elastic cross section area (See Fig. 5)

$$t_{\min} \cong (P_K \theta_{\min})^2 = P_p^{\,2} = 20.45 (MeV/c)^2$$

therefore

$$\Delta\sigma_{el} \approx (\Delta t) \times \left(\Delta\sigma/\Delta t\right) = 0.143 \times 10^{-30} m^2$$

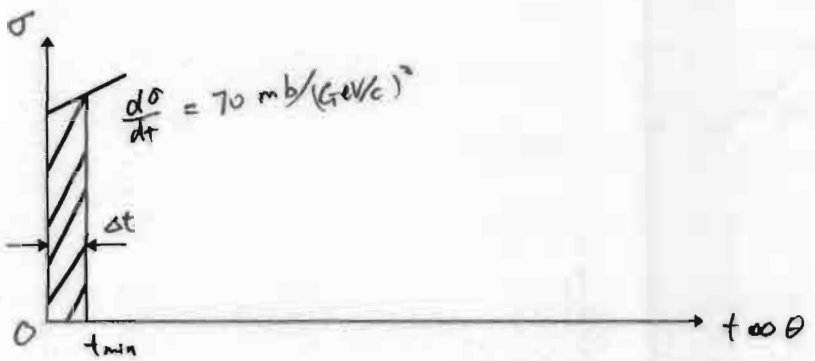


Figure 5: Cross section area versus the square of the invariant 4-momentum transfer.

4) Correction of the systematic error for the number of decays

Since υ is massless, some of the decays such as $K^- \to \mu^- + \upsilon_\mu$ will be neglected when these decays occur with nearly zero degree to the incident beam if the momentum change is small. For the decay $K^- \to \mu^- + \upsilon_\mu$, the neutrino momentum is (See Appendix 2)

$$P_\upsilon = \frac{M_{K^-}{}^2c^4 - M_\mu{}^2c^4}{2\left(E_{K^-}c + P_{K^-}c^2\right)} = 37.8\,MeV/c$$

Therefore the momentum of muon is

$$P_\mu = 1538\,MeV/c$$

which corresponds to the nearly maximum momentum of the muon in the relativistic momentum diagram in Appendix 3. Assume the minimum decay angle at which good scanning efficiency can be realized is $\theta_1 = \theta_2 \approx 0.0953 radian$. (See Fig. 6)

Figure 6: Scanning angle.

Since the Kaon is spinless, its decay will be isotropic in the center of mass. The relationship between the lab angle θ and CM angle θ' is

$$\tan\theta = \frac{\sin\theta'}{\gamma_k\left(1 + \frac{\beta_k}{\beta_\mu}\cos\theta'\right)}$$

which for our purposes can be approximated at small angles by $\theta = \theta'/2$. It follows that

$$\theta' = 2\theta = 0.191 rad \quad \text{and} \quad \frac{0.191 rad}{\pi rad} = 0.0303$$

Therefore the fraction of kaon decays of 1-prong we miss is simply 6.06% since the angles in Fig. 6 may be below the visible track. We found in Table 3 that the total number of decays is $\Delta N_D = 144$, and from Review of Particle Properties we know that the branching ratio for $K^- \to \mu_- + \upsilon_\mu$ mode is 50%. Therefore the corrected value for the number of all decays is

$$\Delta N_\mu = 144 + 144 \times 50\% \times (1 + 6.06\%) = \boxed{149}$$

5) Calculation of K^- life time

Substituting $N_0 = 4900 \pm 200$, $\Delta N_D = 149$, and $\Delta x = 0.2894m$ in to Eqn 4

$$\frac{\Delta N_D}{\Delta x} = \frac{1}{\gamma\beta c\tau}\left(N_0 - \frac{\Delta N_I + \Delta N_D}{2}\right)$$

we obtained

$$\boxed{\tau = (1.04 \pm 0.05) \times 10^{-8} \text{ sec}}$$

The life time of K^- given in Review of Particle Properties is $(1.237 \pm 0.003) \times 10^{-8}$ sec. Our result does not fall into this range. It is very likely that it is mainly due to the uncertainty of the counting of incident K^- tracks due to the difficulty in determining the parallel incident tracks.

6) Calculation of cross section

Substituting $\Delta N_I = 178$, $\Delta x = 0.2894m$, $N_a = 6.02 \times 10^{23}$, $\rho = 0.06 gm/cm^3$, $A = 1.008$, $N_0 = 4900 \pm 200$, and $\Delta N_D = 149$ into Eqn 5

$$\frac{\Delta N_I}{\Delta x} = \frac{N_a \rho \sigma}{A}\left(N_0 - \frac{\Delta N_I + \Delta N_D}{2}\right)$$

we obtained the elastic cross section σ_{el} and total cross area σ_{tot}

$$\sigma_{el} = (0.81 \pm 0.04) \times 10^{-30} m^2 \quad \text{and} \quad \sigma_{tot} = (3.47 \pm 0.16) \times 10^{-30} m^2$$

Adding the correction obtained at 3) $\Delta\sigma_{el} \approx 0.143 \times 10^{-30} m^2$, we obtain

$$\boxed{\sigma_{el} = (0.82 \pm 0.04) \times 10^{-30} m^2 \quad \text{and} \quad \sigma_{tot} = (3.51 \pm 0.16) \times 10^{-30} m^2}$$

The graph of the cross section versus laboratory K^- beam momentum in the Review of Particle Properties gives the elastic cross section σ_{el} and total cross area σ_{tot}

$$\sigma_{el} = 0.85 \times 10^{-30} m^2 \quad \text{and} \quad \sigma_{tot} = 3.30 \times 10^{-30} m^2$$

which lie in the ranges we obtained.

7) Calculation of proton's "effective" radius

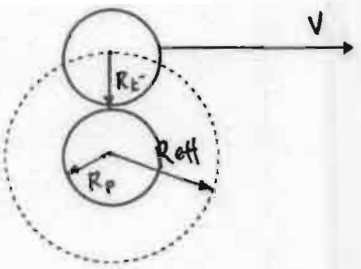


Figure 7: "Geometrical" model in which a K^- sees a proton "effective radius."

Assume proton and K^- have approximately the same effective radius, then from

$$\sigma_{tot} = \sigma_{geo} = \pi(R_{eff})^2 = (3.51 \pm 0.16) \times 10^{-30} m^2$$

we have

$$\boxed{R_{eff} = (5.29 \pm 0.12) \times 10^{-16} m^2 \times 4}$$

From the equation

$$r = r_0 A^{1/3} \quad \text{with } r_0 = 1.2 \times 10^{-15} m$$

where A again is the atomic number. Substituting A = 1.008 for hydrogen we obtain

$$r = 1.2 \times 10^{-15} m$$

This is twice as large as the effective radius R_{eff} we obtained above. ~~It may be that K^- has a effective radius three times as large as the proton has.~~

8) Resonance

The total cross-section as a function of beam momentum exhibits "bumps" that are attributed to the formation of a short-lived "resonance" particle. Assuming that the K meson and the proton were to combine to form a single resonant particle at the beam momentum, we would

find the rest mass of the resonance, which is the total combined energy of a incident K^- and a stationary p in the CM frame of these two particles. This CM has a velocity relative to the lab

$$\beta_{CM} = \frac{P_{tot}c}{E_{tot}} = 0.596 \Rightarrow \gamma_{CM} = 1.25$$

where P_{tot} and E_{tot} are the total momentum and energy, respectively, of the K^- and p in the lab frame. Since

$$E_{lab} = \gamma_{CM} E_{CM} = \sqrt{(P_{K^-}c)^2 + (M_{K^-}c^2)^2} + M_p c^2$$

Therefore we have

$$E_{CM} = 2020 MeV \Rightarrow \boxed{M_{Resonance} = 2020 MeV/c^2}$$

The quantum numbers of this resonance state are summarized in Table 4

	K^-	p	"resonance"
Electric charge	-1	+1	0
All lepton number	0	0	0
baryon number	0	1	1

Table 4: Quantum numbers of the "resonance."

Since we don't know about the nature of this $K^- + p \rightarrow$ "resonance" interaction, strong ~~or weak~~, ~~we don't know if~~ flavors are conserved. Even for a strong interaction, spin, isospin, and parity can not be determined because they in general can take on more than one value and depend on the relationship between spin and statistics.

Conclusion

From special relativity we know the measured life time of a particle in a system moving with velocity corresponding to γ with respect to its own rest frame is given by

$$\tau = \gamma\tau_{\square}$$

where $\tau_{\square}$ is the proper life time, which is the life time measured at the particle's rest system. From our measurement we found τ is very short, and since γ is always larger than or equal to 1, it follows that $\tau_{\square}$ is even smaller. Therefore it is not feasible to measure the K^- lifetime at rest. This experiment actually provides a way to verify the validity of the special theory of relativity.

We measured the various parameters of K^- and compared them with those of K^+, with results agreeing within experimental errors. Therefore we can conclude that particles and their corresponding antiparticles have the same mass, the same lifetime, and opposite electric charge. They can be pair-produced from pure energy. This is also a verification of the mass-energy equivalence.

wrong In your derivation you have used the relativistic argument already So what you measured is the proper lifetime

Reference

Frauenfelder, Hans and Ernest Henley. "Subatomic Physics". Prentice-Hall, Inc. 1974.

Griffiths, David. "Introduction to Elementary Particle". John Wiley& Sons, Inc. 1987.

Perkins, Donald. "Introduction to High Energy Physics". Addison-Wesley Publishing Company, Inc. Third Ed. 1987.

"Reaction Dynamics for Scanners", Stevenson, M.L.: Physics Notes of Lawrence Berkeley Laboratory: No. 300, Oct. 31, 1986, pp. 1-23.

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Appendices

1) Derivation of the effective number of meson average over the target length

For simplicity let $a \equiv \frac{1}{c\gamma\beta\tau}$ and $b \equiv \frac{N_a \sigma \rho}{A}$ then Eqn. 3 becomes

$$N = N_0 \exp(-ax)\exp(-bx)$$

then the number of K^- average over the target length is

$$N = N_0 \int_0^{\Delta x} \frac{\exp[-(a+b)x]}{\Delta x} dx = \frac{N_0}{-\Delta x(a+b)} \{\exp[-(a+b)\Delta x]\}$$

Approximate the exponential function to second order of Δx, we have

$$N = \frac{N_0}{-\Delta x(a+b)} \left[1 - 1 - (a+b)\Delta x + \frac{(a+b)^2(\Delta x)^2}{2} \right] = N_0 - \frac{aN_0\Delta x + bN_0\Delta x}{2} \qquad (8)$$

Similarly we approximate

$$\frac{\Delta N_I}{\Delta x} = \frac{dN_I}{dx} = aN_0 \quad \text{and} \quad \frac{\Delta N_D}{\Delta x} = \frac{dN_D}{dx} = bN_0$$

$$\Rightarrow \Delta N_I = aN_I\Delta x \quad \text{and} \quad \Rightarrow \Delta N_D = N_D\Delta x \qquad (9)$$

Substituting Eqn. (9) into Eqn. (8), we obtain

$$N = N_0 - \frac{\Delta N_I + \Delta N_D}{2} \tag{10}$$

2) Calculation of the neutrino and muon momentum in lab frame

Lab Frame

$$\begin{cases} M_{K^-} = 493.7\,MeV/c^2 \\ M_{\mu} = 105.7\,MeV/c^2 \\ M_{\upsilon_\mu} = 0 \\ P_{K^-} = 1.5GeV/c \end{cases}$$

Figure 7: Neutrino and muon in Lab frame

Conservation of momentum

$$\vec{P}_{K^-} = \vec{P}_{\upsilon_\mu} + \vec{P}_{\mu} \Rightarrow P_{K^-} = -P_{\upsilon_\mu} + P_{\mu} \Rightarrow P_{\mu} = P_{K^-} + P_{\upsilon_\mu} \tag{11}$$

Conservation of energy

$$E_{K^-} = E_{\upsilon_\mu} + E_{\mu} \Rightarrow E_{K^-} = \sqrt{(P_{\upsilon_\mu}c)^2 + (M_{\mu}c^2)^2} \tag{12}$$

Combining Eqn. (11) and Eqn. (12) and solving for P_{υ_μ}, we obtain

$$P_{\upsilon_\mu} = \frac{M_{K^-}{}^2c^4 - M_{\mu}{}^2c^4}{2(E_{K^-}c + P_{K^-}c^2)} = 37.77\,Mev/c^2$$

so

$$P_{\mu} = 1538\,MeV/c$$

3) Relativistic vector diagram for $K^- \rightarrow \overline{\mu} + \upsilon_\mu$ decay

Lab Frame CM Frame

Figure 7: Momenta in lab and CM frames.

From "Reaction Dynamics for Scanners", we have

$$P_\mu^* = \frac{(M_{K^-}c^2 + M_\mu c^2)(M_{K^-}c^2 - M_\mu c^2)}{2M_{K^-}c^2} = 236\,MeV/c$$

$$E_\mu^* = \frac{(M_{K^-}c^2)^2 + (M_\mu c^2)^2}{2M_{K^-}c^2} = 258\,MeV$$

$$\eta_0 = \frac{P_{K^-}}{M_{K^-}} = \frac{1.5GeV/c}{M_{K^-}c^2} = 3.038$$

$$\gamma_0 = \sqrt{\eta_0^2 + 1} = 3.19$$

$$\gamma_0 P^* = 754.4\,MeV/c$$

$$\eta_0 E_\mu = 783.8\,MeV$$

Using these values, we can construct momentum vector diagram

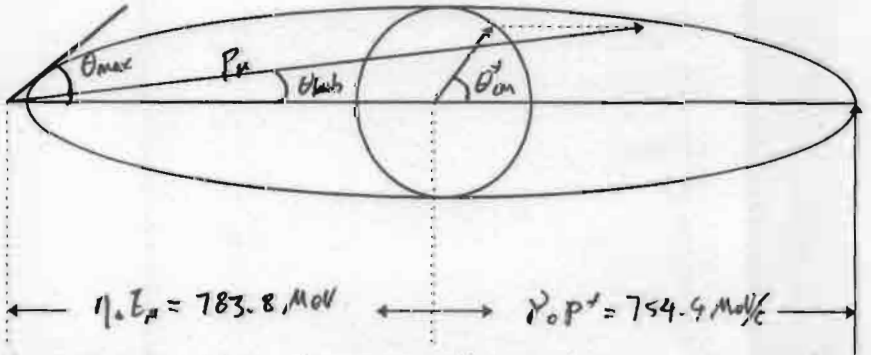


Figure 8: Relativistic Momentum vector diagram for $K^- \rightarrow \overline{\mu} + \upsilon_\mu$ decay.

$P_{\mu(\min)} = 783 - 754.4 = 28.6 MeV / c$

$P_{\mu(\max)} = 783 + 754.4 = 1537 MeV / c$

Therefore Figure 9 shows the diagram when $P_\mu \approx 1537 MeV / c$

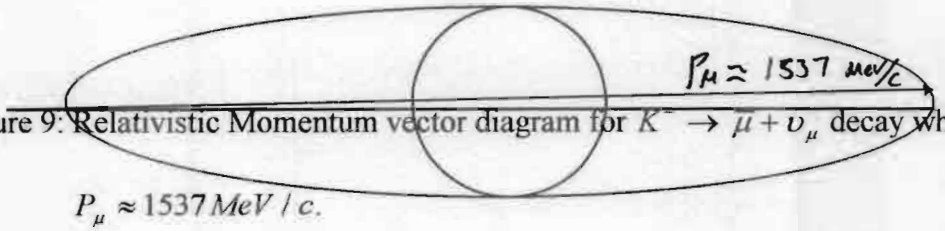


Figure 9: Relativistic Momentum vector diagram for $K^- \rightarrow \overline{\mu} + \upsilon_\mu$ decay when $P_\mu \approx 1537 MeV / c$.

Therefore $\theta_{lab} = \theta_{CM}^{*} \approx 0^0$, and obviously that the decay is hard to detect in this case.

Raw Data

Attached at the end are the raw data taken when scanning the films.

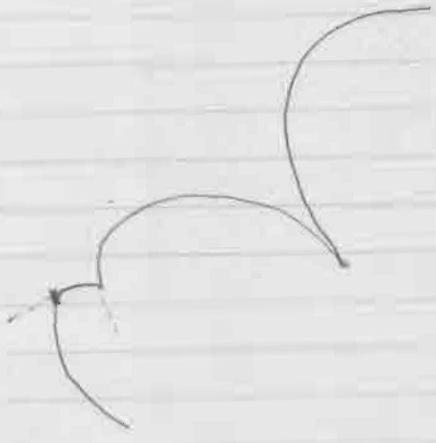
573

$K^- \to \pi^- + \pi^+ + \pi^-$

575

623

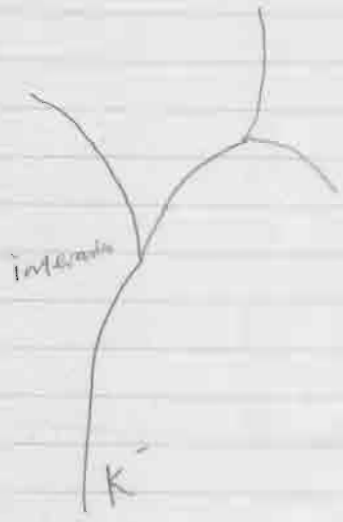
645



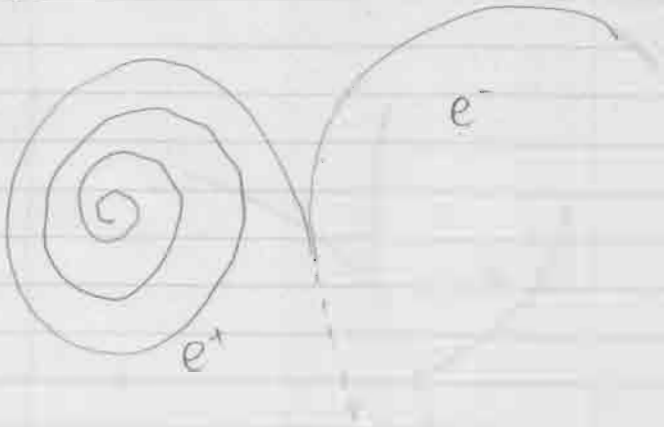
676

67

510

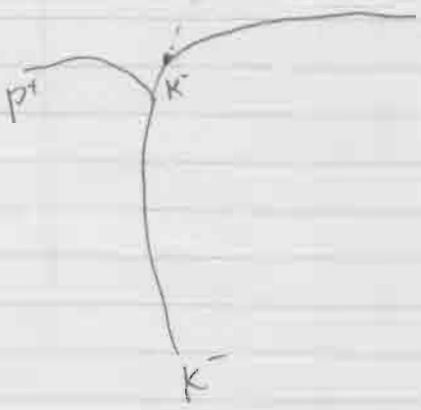


526

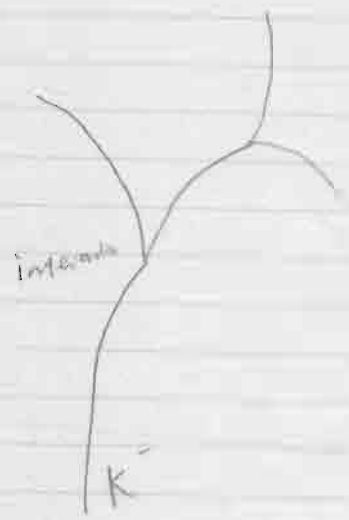


530

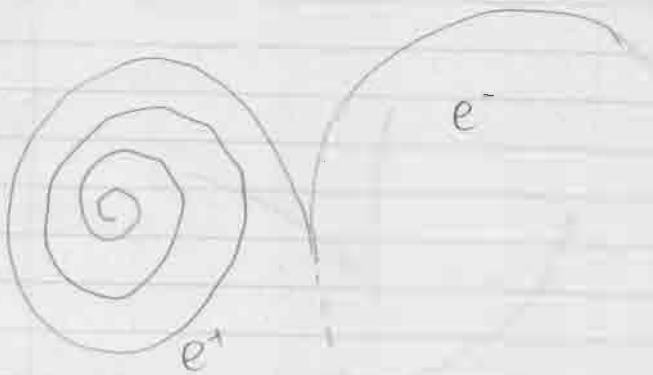
550



510

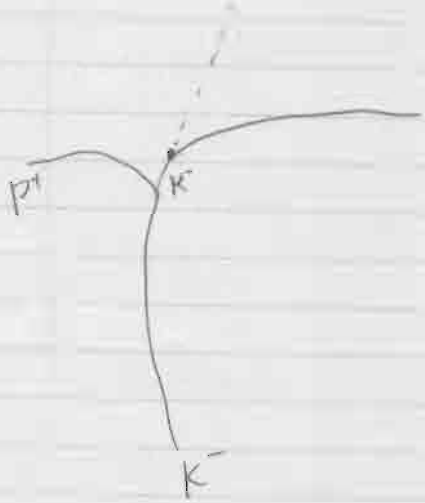


526



530

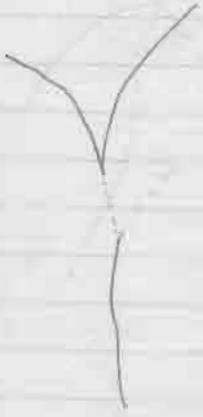
550



430

roll #5450 Frame # 399

roll #5450 Frame # 427



Frame # 402

(e)

$K^- + P \rightarrow \bar{K}^0 + \pi$

$\bar{K}^0 \rightarrow \pi^+ + \pi^-$

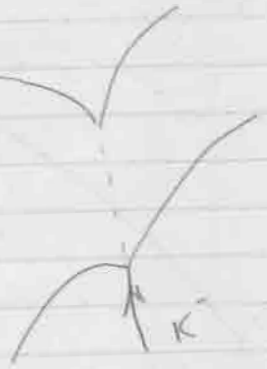
552

559

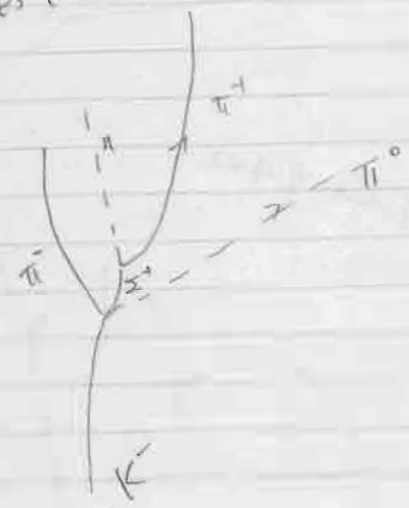
562.

Frame # 438

Frame # 445

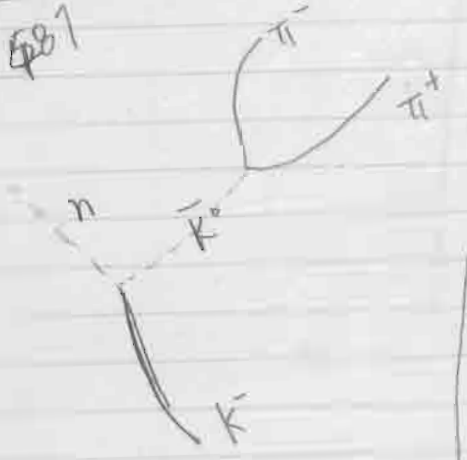


Frame # 457

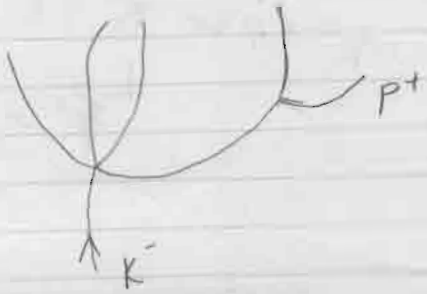


Frame # 480

Frame # 487



508



(1)

Roll # 5450

incoming tracks	Frame #		Event: Elastic diffraction	interaction	tau decay	decay	Length	Location
	0394	No						
	0395	No	~~5 prong~~					~~5, 310°~~
	0396			4 prong			8.9 cm	0.8, 290°
	0397	No						
	398	No						
	~~399~~		~~2 prong~~				2.1 cm	~~0.8/260°~~
				~~No prong~~			6.2 cm	~~0.8/230°~~
	400	No						
	401			[illegible]		1 prong	11.5 cm	0.5/240°
	402			2 prong			21.3 cm	0.6/180°
13	403	No						
	404					1 prong	25.0 cm	0.5/120°
	405					1 prong	22.5 cm	0.6/120°
	406	No						
	407	No						
	408					1 prong	6.8 cm	0.5/270
	[illegible]					1 prong	18.5 cm	0.3/180
	409			No Prong			28.4 cm	0.7/140
	410				Tau		23.3 cm	0.2/100
	411			4 prong			12.3 cm	0.5/240
	412	No						
	413	No						
10	414					1 prong	1.0 cm	0.8/270°
	415		2 prongs ~~elastic~~	[illegible]			19.5 cm	0.4/170°
	416	No						
	417	No						
	418					1 prong	2.7 cm	0.8/250°
	419					1 prong	4.5 cm	0.8/230°
						1 prong	6.1 cm	0.7/230°
	420	No						
	421	No						
	422	No						
	423							
5	424		2 prong	[illegible]		1 prong	19.7 cm	0.3/180
						~~2 prong~~	26.7 cm	0.7/140

(3)

# Track	Frame #	No Events	Collisions	Interactions	Decay	Tau Decay	Location	Length
	453	No						
	454				1 prong		0.6/100	29.3
11	455				1 prong		0.7/240°	3.0
				2 prong			0.7/230°	8.2
	456	No		~~2 prong~~			~~0.3/180°~~	~~19.2~~
	457			2 prong			0.3/180°	19.2
	458	No						
	459			2 prong			0.8/270	0.3
	460	No			1 prong		0.2/100	23.6
	461				1 prong		0.7/100°	23.6
	462			2 prong			0.7/180°	17.0
	463	No						
	464	No						
10	465	No						
	466	No						
	467	No						
	468				1 prong		0.7/230	7.8
	469	No						
	470				1 prong		0.4/230	12.4
	471	No						
	472				1 prong		0.9/240	1.9
	473		2 prong				0.7/220	10.8
	474	No						
10	475	No						
	476	No						
	477	No						
	478		2 prong				0.8/260°	1.0
	479	No						
	480		No prong				0.8/220	8.0
			2 prong				0.3/180°	16.1
	481			1 prong			0.5/230	12.9
	482			1 prong			0.7/190°	14.6
	483		2 prong				0.4/260°	9.3
	484	No						
12	485	No						

Tracks	Frame #	Crosses No ~~detection~~	Collisions	divergence	Decay	Tan decay	bearing	length
~~5~~	~~425~~			2 prong			~~0.9/130~~	~~23.3~~
	426	No					05/230	7.2
	427			0 prong + V			0.4/180	16.1
			2 prongs					
	428	No					0.6/120°	25.2
	429			2 prong			0.5/190°	14.2
					1 prong		0.3/110°	23.6
				4 prongs				
	430							
	431	No					0.3/180°	17.8
	432		2 prong		1 prong		0.3/210	14.5
	433						0.3/130°	22.3
			2 prongs				0.4/150°	4.4
	434				1 prong		0.6/140°	22.9
				No prong			0.7/130°	26.2
			2 prong					
8	435	No					0.2/260	13.2
	436		2 prong				0.4/120	26.0
			~~2 prong~~	2 prong			~~0.6/130~~	
	437	No					0.5/130°	24.0
	438			2 prong			0.6/140°	23.4
					1 prong		0.5/170°	21.4
	439				1 prong			
	440	No						
	441	No					0.3/190°	17.4
	442				1 prong		0.4/250°	10.6
	443				4 prong		0.8/260°	3.9
	444			2 prong			0.9/190°	28.1
					1 prong		1.0/270°	0.4
				2 prong + V			0.9/280	2.1
11	445							
	446	No			1 prong		0.3/280°	10.9
	447			0 prong	~~1 prong~~		0.4/220°	12.8
	448			0 prong				
	449	No					0.2/230	13.4
	450			2 prong			0.5/280	7.2
	451				1 prong		0.6/230°	5.1
	452			2 prong + V				

(4)

Trans #	No ear	# Trades						
~~# Trans~~	~~Trans #~~	~~No Ear~~	Collarum	dorsum	Pelvic	tan Pelvic	location	length
486	No							
487				0 prong + V			0.9/240	4.2
488	No							
489						3 prong	8.8/140°	27.1
490	No							
491	No							
492	No							
493	No							
494				0 prong			0.3/260	11.2
					1 prong		0.4/200	17.5
495	No	5						
496					1 prong		0.6/250	5.3
497				0 prong			0.7/280°	2.6
498	No							
499	No							
500	No							
501	No							
502				0 prong			0.8/240°	4.9
503				2 prong + thin			0.4/130°	26.2
504	No							
505	No	6						
506	No							
507				~~1 prong~~	1 prong		0.7/200	14.7
				2 prong + V	~~2 prong + V~~		0.9/140°	26.6
508				4 prong + V	~~4 prong~~		0.7/270°	1.1
				~~1 prong~~	1 prong		0.8/240	4.9
509	No							
510				2 prong + V			0.5/170°	18.8
511			2 prong				0.4/130	24.4
				2 prong + knob			0.4/140	23.0
512						3 prong	0.1/20°	18.0
513	No							
514	No							
515	No	6						
516	No							

(5)

# Tracks	Frame #	No events	Collision	Interaction	Decay	two decay	location	length
0	517			2 prong + V			0.8/240	1.9
	518	No						
	519		2 prong				0.6/260	4.6
	520	No						
	521					3 prong	05/240	8.3
	522	No						
	523	No						
	524			0 prong			0.9/110	24.5
11	525			4 prong			0.5/130	27.2
	526	No						
	527				1 prong		0.9/270°	8.4
	528			2 prong			0.8/260°	0.5
	529	No						
	530				1 prong		0.6/230	9.5
				2 prong + V			0.5/190°	16.3
	531	No						
	532			2 prong + V			0.5/230	8.6
					1 prong		0.7/100	20.3
	533	No						
	534			2 prong			0.4/190°	16.1
6	535	No						
	536				1 prong		0.2/140°	19.4
	537				1 prong		0.8/270	0.5
	538			2 prong + V			0.7/190	13.5
	539	No						
	540	No						
	541				1 prong		0.6/210	11.5
	542	No						
	543			2 prong			0.6/230	10.4
				2 prong			0.8/250	0.4
	544				1 prong		0.1/190°	19.2
12	545				1 prong		0.9/240	3.3
	546	No						
	547	No						
	548	No						
	549	No						

6

Tran #	No event	# Track	Collision	direction	decay	Tau decay	track	length
			2 prong + ∠				0.4/180	18.2
550				2 prong			0.9/240	2.6
551								
552	No							
553	No							
554	No							
555	No	4						
556	No				1 prong		0.9/140	27.3
557			2 prong				0.8/190	27.5
558	No				1 prong + V		0.5/120	25.1
559				2 prong			0.6/150	25.7
560	No							
561	No			2 prong + knk			0.8/250	2.2
562								
563	No							
564	No							
565	No	12						
566	No							
567	No							
568	No			0 prong			0.4/180	17.1
569								
570	No						0.1/80	20.7
				2 prong			0.6/240	7.8
571				2 prong			0.2/230	14.6
572				2 prong + ∈				
573								
574	No			2 prong + V			0.6/280	3.3
575		13		0 prong + V			0.5/160	15.8
576					1 prong		0.6/130	28.1
577				2 prong + V			0.5/170	17.8
			2 prong				0.8/240	5.6
					1 prong		0.2/270	12.0
578				2 prong			0.5/190	14.5
579					1 prong		0.8/250	5.2
580				2 prong + ∈			0.5/220	13.7
							0.7/260	3.6

(7)

# tracks	Frame #	No event	Collision	Interaction	decay	trans decay	location	length
	582				1 prong		0.9/240	1.1
	583	No						
	584	No						
3	585	No						
	586			0 prong			0.9/230°	0.3
					1 prong		0.8/230°	3.3
					1 prong		0.2/210°	14.3
	587	No					0.7/240°	6.2
	588							
	589	No						
	590	No						
	591			2 prong			0.8/260°	1.6 cm
	592	No						
	593		2 prong				0.2/180°	16.8
	594				1 prong		0.5/250	7.7
9	595	No						
	596				1 prong		0.8/260	1.0
				2 prong + V			0.4/270°	7.8
	597			0 prong + V			0.5/240	8.1
	598			2 prong			0.4/230	11.5
	599			0 prong			0.5/130	23.9
	600			2 prong			0.4/130	14.4
				2 prong			0.6/260	5.4
	601				1 prong		0.6/220	10.3
	602	No						
	603	No						
	604	No						
10	605			[illegible]	1-P		0.4/230	9.0
	606			0 prong + V			0.8/240	3.9
				2 prong			0.3/190°	16.0
	607		2p + kink				0.2/100°	21.6
	608	No					~~0.5/190°~~	~~15.1~~
	609	No					0.5/190°	15.1
	610			2 p				
	611	No						
	612	No						
	613	No						

8

# Tracks	Frame	No Branch	Collision	Intersection	decay	Tau Decay	Location	Length
	614	No						
9	615	NO						
	616		2p + 2p				0.8/240	3.9
	617			2p			0.5/240	7.4
	618	NO						
	619	NO						
	620	No						
	621		2p				0.7/180	16.9
	622				1-p		0.8/140	26.0
	623			2p + kink			0.6/250	5.4
	624	No						
9	625	No						
	626	NO						
	627			2p			0.7/300	1.7
	628	NO						
	629	NO						
	630			2p			0.2/140	18.1
	631		2p				0.8/160	12.8
	632	NO						
	633	No						
	634		2p				0.6/240	6.9
8	635	No						
	636	NO						
	637			4-p+Vtx			0.7/260	3.8
	638	No						
	639	No						
	640	No						
	641	NO						
	642		2p				0.4/100	25.1
	643	NO						
	644	NO						
11	645	No						
	646				1p		0.6/270	2.3
	647	NO						
	648			2p			0.5/130	24.0
	649			2p			0.5/160	30.6

(9)

# Tracks	Frame #	No Events	Collision	Annihilation	decay	Tau decay	location	length
	650	No						
	651	No						
	652	No						
	653	No						
	654	No						
9	655	No						
	656	No						
	657	No						
	658	No						
	659	No						
	660				1-p		0.5/120	26.3
	661	No						
	662	No						
	663	No						
	664	No						
6	665				1-p		0.4/180	18.0
	666			2p			0.3/90	23.4
	667	No						
	668		Collision 2p				0.5/100	25.7
	[illegible]				1-p		0.8/140	77.0
	669				1-p		0.7/150	24.9
	670		2p				0.8/260	2.4
	671		2p				0.9/250	0.6
	672	No						
	673					3p	0.4/150	19.9
			2p				0.6/100	29.0
	674				1p		0.6/240	6.0
					1p		0.1/90	21.7
12	675	No						
	676			2p + decay			0.8/240	6.7
	677				1p		0.3/190	15.0
	678				1p		0.7/240	7.8
				2p			0.6/240	9.0
				2p			0.7/270	4.4
	679	No						
	680	No						

(10)

# Track	Frame	No event	Collision	disintegration	decay	tau decay	location	length
6	681			2P			0.5/170	20.8
				2P			0.2/160	12.7
	682		2P				0.6/240	7.3
	683			2p+V			0.8/220	8.6
	684	No						
10	685				1P		0.9/250	2.7
	686			2P			0.3/260	10.7
	687				1P		0.3/110	23.8
	688		2p + knot				0.7/240	6.8
				2P			0.5/180	16.8
	689		2P				0.2/170	18.8
	690			2p+V			0.4/210	13.7
	691				1P+V		0.1/170°	18.1
					1P+V		0.8/250	4.4
				2p+V			0.6/230	8.7
	692	No						
	693	No						
	694			2p+knot			Center	13.9
				2P			0.5/230	9.6
						3 p.	0.5/230	10.8
12	695			2P			0.6/230	12.7
	696	No						
	697				1P		0.4/250	8.4
			2p-				0.5/130	29.9
					1P		0.7/230	9.9
	698				1P		0.7/270	2.5
	699	No						
	700	No						
	701				1P		0.4/250	10.9
	702			2P			0.3/250	9.4
	703				1P		0.3/120	21.4
				2P			0.4/120	24.1
	704				1P		0.4/260	7.7
			2P				0.8/120	28.8
11	705	No						
	706			2P			Center	17.1
	707	No						

# tracks	Track #	No Events	Collision	Dissociation	decay	tau decay	location	length
	708				1P		0.3/90	24.9
	709				1P		0.9/250	3.7
				2P			0.7/250	7.6
					1P		0.6/130	22.7
							0.5/110	25.9
				2P			0.8/280	0.6
	710							
	711	NO			1P		0.6/110	28.5
	712						0.8/270	0.2
	713			2P			~~0.7/200~~	~~12.5~~
	714	NO						
12	715	No						
	716	NO					0.7/200	12.5
	717		2P					
	718	NO						
	719	NO						
	720	NO						
	721	NO			1P		0.3/270	13.0
	722							
	723	NO			1P		0.7/300	4.1
	~~724~~				1P		6.6/270	4.8
							0.4/320	10.1
14	725			2P				
	726	NO						
	727	NO						
	728	NO						
	729	NO						
	730	NO			1P		0.6/240	8.4
	731							
	732	NO						
	733	NO						
	734	NO						
7	735	NO						
	736	NO						
	738	NO					04/320	10.6
	739			2P				
	740	NO						

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# Tracks	Frame #	Nb events	Collisions	Interactions	Decay	Tau Decay	Location	Length
	742			2 P			09/240	1.1
	743				1 P		0.5/240	8.5
	744	No						
4	745	No						
	746	No						
	747	No			1 P		0.8/270	0.9
	748							
	749	No						
	750	No						
	751	No						
	752	No			1 P		0.8/250	3.2
	753				1 P		0.7/300	3.0
	754							
12	755	No						
	756	No			1 P		0.8/260	0.5
	757	No						~~12.9~~
	758	No			1 P		0.3/350°	10.9
	759				1 P		0.2/170	18.9
	760				1 P		0.3/270	6.2
	761							
	762							
	763	No						
	764	No						
7	765	No			1 P		0.6/260	2.8
Interesting	766	~~No~~		~~1 P~~			~~0.7/230~~	~~5.0~~
	767	No			1 P		0.4/150	22.7
	768			2 - P			0.7/230	5.0
	~~769~~						0.4/180	17.2
	769			2-P+hv				
	770	No					0.7/230	9.1
	771			4 - P				
	772	No						
	773	No			1 P		0.8/270	1.1
	774							
10	775	No						
	776	No						

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# Tracks	Frame #	No Event	Collision	Interaction	decay	Two Decay	location	length
	778	No						
	779	No					0.2/110	21.6
	780			2P			0.4/100	26.4
				2D				
	781	No					0.2/270	13.0
	782			2P			0.5/230	10.1
	783	No			1P		0.7/260	3.6
	784			0P			0.5/290	6.2
			2P					
6	785	No					0.1/180	17.5
	786			2P			0.5/170	19.5
				2P				
	787	No						
	788	No					0.5/90	26.9
	789		2P				0.8/140	27.9
	790				1P			
	791	No					0.3/140	22.7
	792			2P				
	793	No						
	794	No					0.3/190°	15.9
				2-P				
15	795							
	796	No					0.5/300	8.1
	797			0-P			0.6/220	11.6
	798				1P		0.6/170	20.6
	799	No			1P		0.8/280	0.7
	800				1P		0.2/170	19.5
	801			0P	τ			
	802	No					0.6/210	11.9
	803		2P					
	804	No						
14	805	No					0.6/220	12.7
	806			2P				
	807	No					0.5/190	15.6
	808				1P		0.5/260	7.9
				2P				
	809	No					0.6/170	19.0
					1P			

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# Tracks	Frame #	No Event	Collision	Interaction	Decay	tau Decay	Location	length
	811	No						
	812	No						
	813	No						
	814	No						
13	815		2P					
	816	No					0.8/250	7.2
	817			4P				
				2P			0.5/230	11.1
							0.9/90	24.8
	818			2P			0.6/100	28.8
	819				1P		0.3/240	11.8
				2P+V			0.6/220	10.4
	820	No						
	821				1P		Cenc	16.9
				2P			0.1/140	19.9
	822				1P		0.6/140	26.5
					1P		0.6/220	10.7
	823				1P		0.5/220	12.7
	824	No						
12	825	No						
	826	No						
	827				1P		0.7/180	17.8
					1P		0.6/130	26.9
	828			2P+V			0.8/260	1.5
				2P			0.4/230	11.8
	829	No						
	830	No						
	831	No						
	832			2P+V			0.9/220	3.5
	833			2P			0.6/180	17.7
	834	No						
10	835	No						
	836			2P			0.6/210	12.1
	337				1P		0.3/270	10.2
	338	No						
	339				1P		0.5/190	14.9
	340	No						
	341	No						

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Tracks	Frame #	No Event	Collision	Interaction	Decay	tau Decay	Location	length
	342	No						
	343	No						
	344			2-p			Center	16.7
7	345							P
	346				1 P		0.8/260	11.6
	347	No						
	348	No						
	349				1P		0.5/240	7.7
	350	No						
	351	No						
	352	No						
	353			2P			0.6/80	29.5
	354	No		2P			0.6/110	29.5
10	355			2P			0.3/100	29.1
	356	No						
	357				1P		0.7/140	25.0
	358	No						
	359			2P			0.3/150	21.6
					1P		0.8/270	1.3
					1P		0.5/300	0.4
					1P		0.4/300	8.4
	360				1P		0.9/230	3.3
					1P		0.7/140	25.8
			2P				0.6/260	6.0
	361	No						
	362		2P				0.4/100	27.1
	363					3P	0.8/250	3.1
	364			DP			0.6/100	28.8
11	665				1P		0.6/140	23.1
91	666				1P		0.3/290	11.0
	667	No						
	668	No						
	669	No						
	670				1P		0.2/230	14.1
	671				1P		0.8/250	4.4
	672					3P	0.8/170	20.5

(16)	903	No						
	904			0P			0.6/270	3.5
		-	2P				0.5/270	6.3
9	905				1P		0.13/180	16.4
# Tracks	Frame	No Event	Collision	Interaction	Decay	tau decay	location	length
	873			2P + kink			0.9/140	23.5
	874			2P			0.8/270	1.1
			2P				0.7/140	25.2
14	875				1P		0.7/230	6.7
	876	No						
	877	No						
	878				1P		0.3/240	10.6
	879			4P			0.4/140	24.1
	880				1P		0.2/170	20.7
	881			0P+V			0.8/280	7.8
	882				1P		0.2/180	17.4
	883	No						
	884			0P+V	[illegible]		0.4/260	8.5
	[illegible]			2P+<			0.7/270	9.9
	[illegible]			2P			0.8/176	21.2
10	885				1P		0.1/170	19.4
	886	No						
	887			2P			0.5/170	19.4
	[illegible]				1P		0.5/170	19.2
	888		2P				0.7/290	1.4
	889	No						
	890				1P		0.9/250	0.3
				2P			0.4/60	27.6
							~~0.2~~	~~12.4~~
	891	No						
	892				1P		0.2/270	12.4
	893				1P		0.8/260	0.8
	894				1P		0.7/260	3.5
11	895				1P		0.8/270	1.4
	[illegible]		2P				0.2/170	19.7
	896		2P				0.6/160	21.2
	897	No						
	898				1P		0.4/180	17.6
	899	No						
	900		2P				0.8/270	1.3
	901				1P		0.2/90	23.5
	902				1P		0.9/270	0.4
					1P		0.3/180	17.3