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Luis W. Alvarez

August 11, 1960

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THE INTERACTIONS OF STRANGE PARTICLES

Luis W. Alvarez

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 11, 1960

Prefatory Note

This Lawrence Radiation Laboratory report is a corrected copy of my "rapporteur talk" at the 1959 Kiev Conference on High Energy Physics. I wrote the document in my hotel room in Kiev, using notes I carried with me, and expanded it with material which arrived, for the most part, after much of the original typing had been done by the very cooperative, but terribly overworked, bilingual stenographers. In view of the haste with which the report was put together, it is not surprising that in August of 1959, after I returned to Berkeley, I sent eight pages of errata to the conference editor. Most of these corrections were of a typographical nature, but perhaps ten percent were changes in numbers, or in interpretations of data. These were given limited circulation as Alvarez Group Memo.129. No changes have been made since August 28, 1959.

The final Kiev report has not yet appeared, and it is now clear that we should have circulated the errata sheets to all members of the Conference last summer, but at the time we were so impressed by the speed with which the mimeographed documents were produced that we expected to have the final printed copies of the corrected conference report so soon as to make that action unnecessary. We are issuing this report now, because it has recently come to our attention that some workers in the field of strange particles have felt handicapped for the past year by not having access to the original Kiev reports.

I wish to thank Professor Arthur H. Rosenfeld for carrying much of the burden in preparing the errata.

THE INTERACTIONS OF STRANGE PARTICLES

Luis W. Alvarez

The rapporteur system, which was introduced to this Conference so successfully last year, makes life much easier for the delegates, but only at the cost of some gray hairs for the rapporteurs. I will try to carry on in the admirable pattern set by Professor Kaplon in the corresponding session last year, but I must, unfortunately, leave out some of the material on the K-nucleus interactions, which has been submitted by emulsion groups from all over the world. I had planned to follow Dr. Kaplon's example (who last year asked Dr. Tripp to make a special report on his deuterium bubble chamber work) by giving some of my assigned time to a representative of the emulsion groups. But the chairman of this session has asked me to use the very limited time available to discuss the interaction of strange particles with protons and neutrons, using data from bubble chambers, counters, and emulsions.

In order that the obvious advantages of the rapporteur system do not penalize those who have submitted important contributions from the emulsion groups, I have asked Dr. Burhop to confer with representatives of the groups concerned, and to prepare a written report on the highlights of the past year's work. It will be inserted in the body of this report (and so it will be available to the delegates before I speak), but in accordance with our chairman's wishes, I shall not refer to it in detail in my talk at the plenary session.

Several contributions on hyperfragments were addressed to me, but it seems more appropriate that they be discussed by Professor Dalitz, who will do so later this morning.

That this paper is not the polished article I would hope to publish is due in part to the fact that it had to be submitted in final form seventy-two hours before the present moment. But three days ago, I had been in possession of much of the data for less than twenty-four hours. Until very recently, data that arrived just before a Conference were suspected of being taken in a sloppy manner, and were therefore not treated very seriously. Since so many of the data from my own group are of this kind, I would like to explain briefly why I believe the situation has changed. The data come from bubble chamber pictures taken for the most part more than a year ago, whose measurements had been completed months ago. They have in the last month been analyzed by an exceedingly complicated computer program, which took several of our best physicists and computer experts about a year to write. The program has been going through the "debugging" process for the past two months, and was starting to print out the thousands of sheets of kinematically fitted data when I left Berkeley a month ago. The machine now does a complete least-squares fitting of kinematical constraints to complicated interactions of strange particles in hydrogen and deuterium in about four seconds per event. So I hope you will agree with me that while in one sense these are "last-minute data," they are data that before the advent of electronic computors would have required years of efforts by a large group of human computers to produce.

It is perhaps appropriate to say a few words here on the way the past year in the field of strange-particle interactions looks in retrospect to this rapporteur. I have had many occasions in the last few months to read and reread the CERN report of 1958. What strikes me particularly is that the subjects that were primarily of interest in the theoretical sessions last summer have become the bread and butter of the experimentalists in the past year. There was much talk of Mandelstam's ideas of poles in the nonphysical energy region, and of extrapolations of angular distributions to cosines with absolute values greater than 1. There was also discussion of the four possible Dalitz scattering-length solutions, and of the application of dispersion relations to K-nucleon problems, and shortly after that came Pais's ideas on the parity of the K's. All of these concepts, which were presented only a year ago, have formed the framework on which so much of the thoughts of the experimentalists have been built for the past year. It is an exciting experience to watch such abstruse theoretical ideas pass into the everyday conversation of experimentalists in so short a period, and in my judgment, it is a complete justification for our annual conference. I hope that this year's theoretical sessions will similarly stimulate the experimental community. In view of what I have just said, I may perhaps be forgiven for occasionally giving an interpretation of some of the experimental results in what Professor Cassells two years ago so aptly called "peasant's theory." I don't want to, and in fact I couldn't encroach on Professor Salam's assignment as theoretical interpreter of the strange-particle interaction data, but I may sometimes lead the way into the more elegant theory he will describe.

Although this may not be the logical place for it, I believe most of the delegates will be happy to have an up-to-date table of the physical constants of the strange particles. No one has appeared on the scene anxious to be the Birge or the Du Mond of the strange particles, so the values in the Table I are not presented as the best fit to all the data available. They are merely Barkas and Rosenfeld's best estimates of the true values and their errors, as of the middle of 1959, and as such are revisions of the 1958 published values of Barkas and Rosenfeld. (They would like to hear from those whose data have not been included in their tabulation.) The most noteworthy changes are the mass differences between neutral and charged K's, a mass for the neutral cascade hyperon, and a more accurate mass value for the Σ^0.

Acknowledgments

When I reread this manuscript in final form, ready to go to the reproduction department, I was upset to find that I had neglected to mention some of the most important contributors to our group's efforts in the past year. Without operating bubble chambers, we would have nothing to report, so it is most appropriate that I acknowledge the tremendous performance of our operating crews, headed by Robert Watt and Glenn Eckman, and under the general direction of James Donald Gow. The Bevatron crews, under the direction of Edward J. Lofgren, William Wentzel, and Harry Heard, have been unfailingly cooperative, an attitude that is well known to high-energy physicists from all over the world. Our colleagues in the data analysis sections of the group, Hugh Bradner, Jack Franck, Jerry Russell, and

Frank Solmitz (to mention only a few names), have put forth herculean efforts in the development of new techniques, and in the utilization of old ones. And in this same area, as I mentioned earlier in this report, a major revolution in computer analysis has taken place in the last year, due largely to the efforts of J. Peter Berge, William Humphrey, Arthur Rosenfeld, James Snyder, Frank Solmitz, and Horace Taft. And finally, we are, of course, greatly indebted to the corps of graduate students and scanners, many of whose names will be known to you when the Twelfth Annual High Energy conference is again held in this country.

In concluding this introduction, I would like to express my thanks to the various members of my group at Berkeley, and in particular to Dr. Robert Tripp, who gathered data from many sources and sent me off to Kiev with notebooks full of information. And finally, I should like to acknowledge the patience and skill of the typists who prepared this manuscript, and the invaluable help of my scientific secretaries, Dr. A. L. Lyubimov and Dr. N. I. Petukhova.

Table I

Masses and mean lives of elementary particles; July 1959
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particle listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)		Mean life (sec)	
Photon	γ	1	0				stable	
Leptons	ν	1/2	0				stable	
	e^-	1/2	0.510976 ± 0.000007	(a)			stable	
	μ^-	1/2	105.70 ± 0.06	(a)			$(2.261 \pm 0.007) \times 10^{-6}$	(r)
Mesons	π^+	0	139.63 ± 0.06	(a)	4.60 ± 0.15 ($\pi^+ - \pi^0$)	(a)	$(2.56 \pm 0.05) \times 10^{-8}$	(a)
	π^0	0	135.04 ± 0.16	(a)			$< 4 \times 10^{-16}$	(d)
	K^+	0	494.0 ± 0.2	(g)	3.9 ± 0.6 ($K^0 - K^+$)	(i)	$(1.224 \pm 0.013) \times 10^{-8}$	(h)
	K^0	0	497.9 ± 0.6	(i)			K_1: $(1.00 \pm 0.038) \times 10^{-10}$	(e)
							K_2: $(6.1^{+1.6}_{-1.1}) \times 10^{-8}$	(c)
Baryons	p	1/2	938.213 ± 0.01	(a)			stable	
	n	1/2	939.506 ± 0.01	(a)			$(1.04 \pm 0.13) \times 10^{+3}$	(a)
	Λ	1/2	1115.45 ± 0.12	(j)			$(2.505 \pm 0.086) \times 10^{-10}$	(k)
	Σ^+	1/2	1189.55 ± 0.21	(l)	$6.76 \pm .33$ ($\Sigma^- - \Sigma^+$)	(m)	(B. Chambers: 0.75 ± 0.1; Emulsions: 0.93 ± 0.09) $\times 10^{-10}$	(b)
	Σ^-	1/2	1196.39 ± 0.34	(n)	$4.45 \pm .4$ ($\Sigma^- - \Sigma^0$)		$(1.59^{+0.1}_{-0.09}) \times 10^{-10}$	(o)
	Σ^0	1/2	1191.94 ± 0.53	(p)			$(< 0.1) \times 10^{-10}$ theoretically $\simeq 10^{-19}$	(s)
	Ξ^-	?	1319.1 ± 0.5	(f)			$(1.9^{+0.6}_{-0.4}) \times 10^{-10}$	(f)
	Ξ^0	?	1311 ± 8	(q)			1.5×10^{-10} (1 event)	(q)

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For this new compilation of recent data we have not tampered with the masses of the electrons, muons, pions and nucleons. These are relatively stable and are best treated systematically. Hence the values quoted for these particles are taken directly from the tables of reference (a).

Footnotes for Table 1

(a) From compilations of Cohen, Crowe and DuMond, Nuovo cimento 5, 541, (1957) and Fundamental Constants of Physics (Interscience, New York, 1957).

(b) From the compilations in the appendix to the report of the 1958 International Conference on High Energy Physics at CERN.

(c) Bardon, Lande, Lederman, and Chinowsky, Ann. Phys. 5, 156 (1958), and Crawford, Cresti, Douglass, Good, Kalbfleisch, and Stevenson, Phys. Rev. Letters 2, 361 (1959). The weighted average of the two results is done in the second reference.

(d) Orear, Harris, and Taylor, Phys. Rev. 106, 327 (1957).

(e) τ_{K_1} is a weighted average of decay rates corresponding to the mean lives in the 1958 CERN report, but changed so that the Berkeley result from associated production is now $0.94 \pm 0.05 \times 10^{-10}$ sec, based on 512 K_1 decays, (Crawford, Cresti, Good, Kalbfleisch, Stevenson, and Ticho, private communication.

(f) These values come from 17 Ξ^- found in the Berkeley 20-inch propane chamber by Fowler, Birge, Eberhard, Good, Ticho, and Powell (private communication). In addition, 21 other Ξ^- have been found under varying conditions, but they hardly improve the Berkeley mass and mean life, so they have not been included.

(g) $M_{K^+} = 3\,M_\pi + Q_\tau$, where Q_τ is the weighted average of values reported by Heckman, Smith, and Barkas, Nuovo cimento 4, 1529 (1956). The uncertainty in M_π has of course been treated as common to all experiments. We have assumed that the K^- is the antiparticle of the K^+ and shares the same mass and lifetime. The present experimental mass of the K^- is consistent with this assumption, namely 493.4 ± 0.5 Mev (R.S. White, compilation of all emulsion data for 1957 Rochester Conference).

(h) τ_{K^+} from weighted average of the decay rates corresponding to the following mean lives: $1.227 \pm 0.015 \times 10^{-8}$ sec (Alvarez, Crawford, Good, and Stevenson, (private communication)); $1.211 \pm 0.026 \times 10^{-8}$ sec (V. Fitch and R. Motley, Phys. Rev. 101, 496 (1956); Phys. Rev. 105, 265 (1957); and private communication.) The quoted errors are statistical only. We have assumed that the K^- is the antiparticle of the K^+ and shares the same mean life. The present experimental mean life is consistent with this assumption, namely $\tau_{K^-} = 1.25 \pm 0.11 \times 10^{-8}$ sec (W.H. Barkas, 1957 Rochester Conference).

(i) From the compilation by A.H. Rosenfeld, F.T. Solmitz, and R.D. Tripp, Phys. Rev. Letters 2, 110 (1959).

(j) The mass of the Λ hyperon is derived using only recent data: Emulsion Q values are the following:
W.H. Barkas et al. (1957) Padua-Venice Conference), 37.45 ± 0.17
Bogdanowic et al. (Nuovo cimento 11, 727 (1959)), 37.58 ± 0.18
A. Pevsner (John Hopkins University private communication) 37.71 ± 0.16

These are not independent, as systematic errors tend to be the same for all. The resultant value is 37.58 ± 0.13 Mev. One recent accurate cloud chamber cosmic-ray measurement is also included. Armenteros et al. (1957 Padua-Venice Conference) find 37.9 ± 0.4 Mev for the Q value. This is combined with the emulsion data to give $Q = 37.61 \pm 0.12$.

(k) τ_Λ from weighted average of the decay rates corresponding to the following mean lives, in units of 10^{-10} sec:

2.95 ± 0.4, U.C. K^- (b)
2.29 ± 0.14, Columbia, Pisa, Bologna (b)
2.75 ± 0.41, Columbia, (b)
3.04 ± 0.64, Jungfrau (b)
2.08 ± 0.38, Michigan (b)
2.63 ± 0.21, E. Boldt, D.O. Caldwell, Y. Pash, Phys. Rev. Letters 1, 148 (1958)
2.72 ± 0.16, Crawford, Cresti, Good, Kalbfleisch, Stevenson, and Ticho (private communication).

(l) M_{Σ^+} weighted average (allowing for common systematic uncertainties) of

1189.28 ± 0.28 Mev (W.H. Barkas, 1957 Padua-Venice Conference),
1189.6 ± 0.4 (M.S. Swami, Phys. Rev. 114, 333 (1959),
1190.3 ± 0.5 Mev (R.S. White, 1957 Rochester Conference).

(m) Derived from emulsion data only.

(n) M_{Σ^-} from the following $M_{\Sigma^-} - M_{\Sigma^+}$ mass differences:

6.39 ± 0.47 Mev (Barkas, Dyer, Giles, Heckman, Mason, Nickols and Smith, Phys. Rev. 112, 622 (1958),
7.10 ± 0.92 Mev (Chupp, Goldhaber, Goldhaber, and Webb),

6.9 ± 1.0 Mev (M. S. Swami, Phys. Rev. 114, 333 (1959),
7.46 ± 0.72 Mev (K. Collaboration - Presented by Prowse at Padua-Venice Conference, 1957).

(o) τ_{Σ^-} is a weighted average of the decay rates corresponding to the mean lives in the 1958 CERN report with the addition of a result from associated production, $\tau_{\Sigma^-} = 1.45 \pm 0.12 \times 10^{-10}$ sec (Crawford, Cresti, Good, Kalbfleisch, Stevenson, and Ticho, (private communication).

(p) Berge, Rosenfeld, Ross, Solmitz, and Tripp have observed the reaction $\Sigma^- + p \rightarrow \Sigma^0 + n$ and report a $\Sigma^- - \Sigma^0$ mass difference of 4.45 ± 0.4 Mev (private communication). We have not folded in older results with a much larger uncertainty, namely
$M_{\Sigma^0} = 1192.6 \pm 3.5$, Eisler et al., Nevis-60 Report R-198 (1957);
$M_{\Sigma^0} = 1191.6 \pm 3.3$, M. Lynn Stevenson, Phys. Rev. 111, 1707 (1958).

(q) Alvarez, Eberhard, Good, Graziano, Ticho, and Wojcicki, Phys. Rev. Letters 2, 215 (1959).

(r) R.A. Swanson, R.A. Lundy, V.L. Telegdi, and D.D. Yovanovitch, Phys. Rev. Letters 2, 430 (1959). The mean life of μ^+ was measured.

(s) Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, K^- Interactions in Hydrogen, UCRL-3775, May 1957.

I. K^+ INTERACTIONS

The interaction of K^+ mesons with protons is the simplest one involving strange particles, since the only reaction possible (below the threshold for creating an additional pion) is an elastic scattering. The fact that neutral V-particles are not reaction products makes a study of the K^+-p scattering ideally suited to counter techniques and to emulsion techniques, as was reported last year. For those who prefer to think in terms of kinetic energy rather than of momentum, low-energy K particles are very generous—$2 M_k$ is close to 10^3 Mev; therefore, one merely squares the momentum (in Mev/c), and divides by 10^3 to obtain the energy. For example, 200 Mev/c is 40 Mev.

Taddeus F. Kycia, Leroy T. Kerth, and R.G. Baender, from Berkeley, have submitted new counter data in the 450-to 600-Mev/c range. They have measured the total across sections at three energies, and studied the angular distribution at the middle energy. Table II and Fig. 1 give their results.

Table II

Total cross section data for K^+ - p, from Kycia, Kerth, and Baender.

Kinetic energy	Total cross section
175 ± 26 Mev	16.3 ± 1.7 mb
225 ± 25 Mev	15.2 ± 1.3 mb
275 ± 25 Mev	16.3 ± 1.7 mb

The new data are in satisfactory agreement with those from last year's emulsion experiments (σ_T = 21.3 ± 4.5 mb at 200 to 350 Mev), and of course are of considerably greater accuracy. Last year's data merely indicated the isotropy which is so clearly shown this year. Kerth et al. have done a phase-shift analysis of their angular data, and find, before the application of any physical arguments, three possible solutions:

The data can be fitted with either pure S waves, or with two different forms of P-wave interaction, but not by a combination of S and P waves. The fact that both σ and $\frac{d\sigma}{d\Omega}$ remain substantially unchanged with energy over a wide range is the physical argument that throws out the p-wave solutions. So the only acceptable solution for the K^+-nucleon system in the I = 1 state is a repulsive interaction, with $\delta_0^{'} = -33.4 \pm 2.3^\circ$. Kerth et al. have attempted to combine all K^+ - p data with the K^- - p data from the bubble chamber, in a subtractive application of the dispersion relations, with the hope that they might evaluate the sign or signs of the parity of the Λ - K and Σ - K systems relative to the proton. When I last talked with them, they were discouraged by the scarcity of data in important energy regions. But I am sure Professor Salam will have more to say about this.

In the range from 1000 to 2500 Mev/c, a group from MIT has reported recently (Phys. Rev. Letters 2, 117 (1959)) that σ_r for K^+-p is still approximately constant at 17 mb (Fig. 2).

The K^+-neutron interaction is one step more complicated than the K^+-p, since now charge exchange is allowed. The study of the charge-exchange process has had a rather interesting history. K^+ mesons were observed to disappear in flight in nuclear emulsion with a cross section per neutron, at 225 Mev, of 3.74 ± 0.5 mb. The first two attempts to observe the neutral K's were quite disappointing. In fact, the first attempt, by Robert Birge, Hans Courant, Robert Lanou, and Marian Whitehead showed no θ^{0}'s in a cloud chamber, when between 6 and 20 had been expected. Their next experiment, in a propane bubble chamber, showed two θ^{0}_{s}' when six had been expected. They have now submitted the results of a new counter experiment, which has shown quite conclusively that the disappearing K mesons do in fact give rise to the expected number of neutral K's. The experimental arrangement is quite ingenious (Fig. 3); the target is completely surrounded by a guard counter, so that a K^+ can be certified to have disappeared, and not merely to have been scattered through a large angle. Surrounding the target at a distance of approximately 50 cm is a dodecahedron consisting of 12 pentagonal plastic scintillators, each with its own photomultiplier. From the kinematics of the interactions one can show that the minimum opening angle of any θ^{0}_{1} is too great for both pions to be detected by one pentagon. Therefore, by a suitable display of pulses on an oscilloscope, one may measure the cross section for charge-exchange scattering, the approximate angular distribution of the neutral K's, and the branching ratio for all neutral K's into the short-lived charged decay mode. For the branching ratio, they find 1/3 ± 8%, in agreement with the more extensive data from associated-production experiments. They used nuclear emulsion (which was never developed), as a target in one experiment, and found $\lambda_{ch.\,ex.}$ = 250 ± 25 cm. This is to be compared with the latest European Collaboration, and UCLA value of 212 ± 30 cm at the same energy. They also used C, Cu, and W targets. The results are shown in Table III.

Corrections for Coulomb repulsion, nuclear shielding, double scattering in the nucleus, and the effect due to the reaction's being endothermic were made to the raw data. Two center-of-mass angular distributions were assumed; one was uniform, and the other was strongly peaked forward, as suggested by the UCLA emulsion work of Stork et al.

At present, the rest of our information concerning the K^+-nucleon interaction in the I = 0 state must come from an optical-model analysis of the interaction of K^+ mesons with the complex nuclei in emulsion. (At Berkeley, and probably at other laboratories as well, extensive experiments with separated K^+ beams in hydrogen and deuterium bubble chambers will start at the end of the summer, so next year at Rochester the deductions concerning the I = 0 state will come from inherently simpler input data.) I am faced with two difficulties in reporting the data I have received from the UCLA group, of Ehsan Helmy, Oliver R. Price, Derek Prowse, Donald H. Stork, and Harold K. Ticho. In the first place, I am not competent to judge the technical aspects of the analysis. Secondly, since the "final copy" of this report is largely typed, it is only through the courtesy of the secretariat that I can add the following covering letter from Harold Ticho,

Table III

Charge-exchange cross section per neutron (in mb) (with corrections)						
	250 Mev		200 Mev		175 Mev	
	peaked	uniform	peaked	uniform	peaked	uniform
W	4.47 ± .45	4.78 ± .50	5.07 ± .58	5.44 ± .66		
Cu			6.30 ± .80	6.48 ± .86		
C	6.42 ± 1.03	5.91 ± 1.03	6.13 ± 1.22	5.36 ± 1.19	4.92 ± 2.15	4.02 ± 1.80

plus the summary table from the UCLA paper. "The slide" (Fig. 4) represents the results of the K^+ scattering work at UCLA, using nuclear emulsion. We have done an optical-model calculation with an IBM computer to get the real and imaginary potentials, and then used multiple-scattering theory in nuclear matter to deduce the $T = 0$ phase shifts. (The $T = 1$ phase shifts are given by K^+-p scattering).

"At both energies, the S-wave phase shifts appear to be small. There is one region with 60% probability that the P-wave phase shifts be inside at 93 Mev, and two regions for 227 Mev. If our experimental result that charge exchange at 227 Mev is peaked forward is taken into account, then the good-fit region is made smaller." I think the main conclusion that one can draw is that there is P-wave at our energies in $T=0$.

The final results of the UCLA group are given in Table IV, for two values of R_0. The values are cross sections for the elementary reactions listed at the left, as calculated from an optical-model analysis. Professor Dallaporta will have some remarks to make from the floor concerning his group's different results on the angular distribution in the charge-exchange reaction.

Finally, a few words on the implication of the K^+-scattering data. As Dalitz pointed out at CERN last year, a repulsive K^+ - p potential, as well as the presence of both S and P waves in the $I = 0$ state, are difficult to reconcile with a scalar K, but appear fairly directly with a pseudoscalar K. Further information concerning this important and as yet unsettled question may come, as said earlier, from a dispersion-relationship analysis of more accurate K^+ and K^- scattering data, and finally, Moravcsik (Phys. Rev. Letters 2, 352, (1959)) has pointed out that there is some evidence from the photo production of K^+ mesons that the K^+ is pseudoscalar. So at the moment, one might bet that Nature has simplified matters by making both kinds of mesons pseudoscalar, but the present betting odds are not terribly impressive.

Table IV

Cross sections for K^+-nucleon reactions (mb)

Reaction	R_0 = 1.07 fermi 93 Mev	R_0 = 1.07 fermi 227 Mev	R_0 = 1.20 fermi 93 Mev	R_0 = 1.20 fermi 227 Mev
$K^+ + p \rightarrow K^+ + p$	14.7 ± 1.7	14.7 ± 1.7	14.7 ± 1.7	14.7 ± 1.7
$K^+ + n \rightarrow K^+ + n$	10.2 ± 3.3	12.6 ± 3.3	7.9 ± 3.1	9.1 ± 3.2
$K^+ + n \rightarrow K^o + p$	4.5 ± 1.1	8.5 ± 1.9	5.6 ± 1.6	7.3 ± 1.7
$K^+ + n$, total	14.7 ± 3.8	20.1 ± 3.9	13.5 ± 3.6	16.4 ± 3.8

II. K^- INTERACTIONS

K^- - p Interactions at Low Energy

This section describes work done at the Lawrence Radiation Laboratory, as the University of California Radiation Laboratory has recently been renamed in honor of our founder and late director, Ernest O. Lawrence. Our bubble chamber group has continued its program of investigating interactions in hydrogen and deuterium, both at rest, and in flight at a variety of momenta. Although there is overlapping of effort in the H_2 and D_2 groups, the following men have contributed particularly to the hydrogen work: J. Peter Berge, William E. Humphrey, Paul Nordin, Jr., Arthur H. Rosenfeld, Ronald R. Ross, J.N. Snyder, Frank T, Solmitz, Robert D. Tripp and Mason B. Watson. Since the CERN conference last year, no new pictures have been taken in hydrogen in the "stopping beam," but three in-flight exposures have been made at average momenta of 180, 310, and 410 Mev/c. All the in-flight interactions reported last year came from anomalously high-energy K's in the stopping beam. Table V gives a measure of the increase in the in-flight data since the 1958 CERN report. (The path length in each momentum interval is given in such units that the number of observed events divided by that path length is equal to the cross section in millibarns.)

Table V

Path length of K^- in H_2 (definition of path length is in the text)

Energy (Mev/c)	Data from CERN(1958)	Additional since CERN
50-150	0.75	0.81
150-250	1.4	2.3
250-300	0.2	1.0
300-350	-	1.7
400	-	2.4

At the time of the CERN meeting, no analysis had been made of the K^- - p interactions at rest; all of the short time available for analysis was concentrated on the in-flight events. Now, a year later, the total population of in-flight events has been processed by the IBM 704 electronic computer, and thousand of events at rest have been analyzed.

The situation in deuterium is somewhat different. For the conference last year, all efforts were concentrated on analyzing the reactions at rest, to find the branching ratios for the various hyperon channels. The results as reported by Tripp were consistent with the hypothesis of charge independence in K^- -hyperon reactions. Shortly after the CERN meeting, an examination of the $K^- + d \rightarrow \Lambda + \pi^- + p$ data suggested the possibility that parity was not conserved in a strong interaction involving strange particles, but the evidence was not conclusive enough to warrant publication. In order to settle the question, the total number of such events was increased by a factor of 4 in a new exposure this spring. The new data confirm our original belief that the apparent fore-aft asymmetry in the Λ decay was indeed due to a statistical fluctuation. At the present moment, αP from 200 events, is -0.06 ± 0.12, as contrasted to the early value of $+0.65 \pm 0.26$. I know of no data from any source that show convincingly that parity is not conserved in strong interactions involving strange particles. The present total number of deuterium interactions is approximately 12,000, of which a small fraction was obtained in a 300-Mev/c beam; in all other cases, the beam was designed to stop in the chamber.

Perhaps the most interesting new development in the $K^- + p$ and $K^- + d$ field comes not from bubble chambers, but from three theoretical physicists at the University of Maryland, T.B. Day, G.A. Snow, and J. Sucher. They have taken a fresh look at the important question, "From what angular momentum states in a K-mesic hydrogen atom is the K meson absorbed?" In our first paper on K^- absorption in hydrogen, we assumed that the K^- were captured from the 1S state. We said at the time that this assumption was poorly justified, but it permitted some interesting speculation about the relative magnitude, and the phase angle between the $I = 0$ and $I = I$ amplitude for Σ production. It was later shown that even a small P-wave capture rate could compete effectively with the 2 P - 1 S radiative transition, so the capture had to be thought of as occurring from both S and P states. Additional weight was apparently given to this idea when our group reported at CERN last year that the Σ^- to Σ^+ ratio from $K^- + p$ reactions in flight at low momentum was 7:1, rather than 2:1, as it is at rest. The 7 : 1 ratio was interpreted (with reservations) by Kaplon as the true S - state ratio and the 2 : 1 ratio was ascribed to an admixture of P-wave capture from the 2 P state. Now that Day, Snow, and Sucher have shown that captures at rest come almost exclusively from S states, it can be noted that the 7 : 1 ratio came from 14 Σ^- and 2 Σ^+ events. If each number were displaced toward the other by one standard deviation, their ratio would be the normal 2 : 1.

Day, Snow, and Sucher point out that during the time the K is cascading through atomic orbits toward the proton or deuteron, it is a small neutral object which can penetrate close to the protons in the hydrogen molecules. The unscreened electric field of a proton is of the order of 10^9 volts per cm ($13.5/10^{-8}$ cm). As a consequence of the Stark effect, the wave function oscillates rapidly ($\sim 10^{15}$ sec^{-1}) between all the orbital angular-momentum states (including the S state) with the same radial quantum number n. From the atomic thermal velocity, one knows that the time spent in a high-field region is about 10^{-13} sec. Since the capture rate from an S state is exceedingly high ($4.7 \times 10^{17}/n^3$ sec^{-1}), the K^- or K^- d atom has a high probability of undergoing a capture reaction in one such encounter. Day, Snow, and Sucher go into considerably more detail in their recent preprint, but it is sufficient to note here that most of the K^- will be captured from h S levels, where n is greater than 3. The angular momentum which was in the orbital motion of the K^- before it encountered the strong electric field is taken up by the relative motion of the proton (the source of the perturbing field) and the center of mass of the π-hyperon system. The same arguments apply, of course, to Σ^- capture and Ξ^- capture at rest in H and D. Unfortunately, they do not apply to K^- capture in the helium bubble chamber, because the extra electron around the K^- He ion prevents penetration into high-field regions.

Now, with the Day, Snow, and Sucher theorem available to us, we can pull our old data out of the drawer, and in fact add a lot of new data to them, and restate the conclusions of three years ago.

1. According to the argument of Treiman and others the isotropy of the decay products from the Σ^+ and Σ^- hyperons assures us that their spin is 1/2. (The new data in this area will be given in Prof. Glasser's report).

2. In view of the results of Cool et al. showing that the decay mode $\Sigma^+ \rightarrow p + \pi^0$ is a good analyzer, we can use the observed symmetry of the decay protons from $K^- + p \rightarrow \Sigma^+ + \pi^-$ as evidence that parity is conserved in strong interactions involving strange particles ($\alpha \rho_\Sigma = 0.02 \pm 0.10$).

3. The relative amplitudes and phases of the I = 1 and I = 0 states in which Σ production takes place have significance again and are now known more accurately because the separation of direct and indirect Λ's is now much clearer (the reasons for this, together with the branching ratios involved, will be given directly after this discussion).

Assuming charge independence, the production ratios are related by the equations

$$\frac{\Sigma^- + \Sigma^+}{2\Sigma^0} = \frac{3}{2} r^2 + 1 ,$$

$$\frac{\Sigma^-}{\Sigma^+} = \left| \frac{re^{i\Phi} + \sqrt{\frac{2}{3}}}{-re^{i\phi} + \sqrt{\frac{2}{3}}} \right|^2 ,$$

where $\frac{\tau_+}{\tau_0} = re^{i\Phi}$ and $\tau_\pm$ is the Σ^- production amplitude in the state of isotopic spin I = 0 or 1. The new values are

$$r = 0.31 {}^{+0.12}_{-0.17} , \quad r \text{ necessarily} \geq 0.14$$

$$|\Phi| = 56 {}^{+7}_{-56} \text{ deg.}$$

We had hoped by now to obtain this phase angle with smaller uncertainties, but it turns out to be extremely sensitive to our experimental errors.

Amati and Vitale have devised a relationship based on global symmetry, namely we have

$$(\Sigma^- + \Sigma^+ - 4\,\Sigma^0)^2 + 4\,(\Sigma^0 - \Sigma^+\Sigma^-) \geqslant 0.$$

We find

$$-1.0 \pm 3.8 \geqslant 0,$$

so we need more data before we can make a sensitive test.

K^- - p Production Ratios

As mentioned in the preceding section, the separation of indirect and direct Λ's at rest (with or without the intermediate Σ^0) has been accomplished in a cleaner manner this year. This is due partly to the thoroughness of the computer analysis and partly to a new technique for distinguishing neutral in-flight events from those occurring at rest (the simple check on the collinearity of charged $\Sigma^\pm$ and π^+ is not applicable to the neutral hyperons). The difficulty is that the Λ / Σ^0 ratio is known to be small at rest, but to increase considerably with energy. Therefore a small contamination of "at rest" events by in-flight events could appreciably change the measured ratio at rest. For every measured K event the computer prints the ratio of the incoming momenta, as measured by both curvature and residual range. A population of events was chosen in which the momentum ratio showed that the K had "more than stopped" by at least 0.7 standard deviations. In this way, the in-flight contamination was reduced to about 1%. Then a maximum-likelihood calculation was made, comparing the experimental spectrum with the theoretical spectrum (flat for Λ from Σ^0 and line for direct Λ) with the Λ/Σ^0 ratio as the variable. A further small subtraction was made to account for $\Lambda\,\pi^+\pi^-$ events seen.

The final results are the following percentages of hyperons produced by K^- absorption in hydrogen at rest. (It is worth noting that our group has always listed the hyperons in the order shown in the table, rather than in the more logical order Σ^-, Σ^0, Σ^+, Λ. So long as the ratios were 4 : 2 : 2: 1/2, it didn't matter that some people didn't notice the transposition we made to take account of the difficulty of separating the two neutral categories.)

$$\Sigma^-\,\pi^+ = 44 \pm 1\%$$
$$\Sigma^+\,\pi^- = 20 \pm 1\%$$
$$\Sigma^0\,\pi^0 = 28 \pm 2.5\%$$
$$\Lambda\,\pi^0 = 8 \pm 1.5\%$$
$$\Lambda\pi^+\,\pi^- = 0.13 \pm 0.06\%$$

(Note: The errors are correlated; only the diagonal terms in the error matrix are shown.)

Next, in Table VI, I want to give the cross sections for interactions in flight. Note that at 400 Mev/c the reaction cross section exceeds $\pi\lambda^2$, so p waves must be appreciably involved. Figure 5 shows the cross sections for the production of Σ^- and the production of Σ^+ as a function of K^- momentum. Figure 6 shows the angular distributions for these productions at 400 Mev/c; the anisotropy indeed shows a large p-wave contributions.

Table VI

$K^- - p$ Interactions at 300 and 400 Mev/c

Event type	Cross sections (mb) P_{lab} = 305 ± 25 Mev/c	P_{lab} = 400 ± 15 Mev/c
$\Sigma^- \pi^+$	7.2 ± 2.2	8.9 ± 2.0
$\Sigma^+ \pi^-$	10.3 ± 2.6	8.8 ± 2.0
$\Sigma^0 \pi^0 + \Lambda \pi^0 \pi^0$	3.65 ± 2.4	6.3 ± 2.2
$\Lambda \pi^0$	6.5 ± 3.0	7.4 ± 2.3
$\Lambda \pi^+ \pi^-$	0.7 ± 0.7	2.1 ± 0.9
$\overline{K}^0 N$	4.1 ± 2.3	5.1 ± 2.5
All hyperons	28.4 ± 4.7	33.5 ± 4.1
(I = 0 Absorption)	(11.0 ± 7.2)	(18.0 ± 6.6)
(I = 1 Absorption)	(17.4 ± 7.7)	(14.6 ± 6.5)
Elastic Scattering	62 ± 8	50 ± 6
Total	94.6 ± 9	88.6 ± 8
$\pi\lambda^2$	33	20

Perhaps the greatest efforts of the $K^- - p$ group have gone into an analysis of the elastic scattering of K^- by protons, with particular emphasis on the determination of the sign of the real part of the $K^- - p$ scattering amplitude. This can be determined from the interference with Coulomb scattering. The most useful momentum region is 100 to 200 Mev/c. Above that, the interference occurs at too small an angle, and one worries about scanning efficiency. Maximum interference takes place when the Coulomb amplitude equals the nuclear-scattering amplitude. This occurs at a momentum transfer of about 45 Mev/c, so the proton recoils are just invisible. With approximately 500 events now available we can begin to see the effects of this interference. The magnitude of the real part of the nuclear-scattering amplitude was evaluated from two pieces of data: the total cross section and the nuclear (i.e., isotropic) part of the elastic scattering. In Fig. 9 the alternatives of constructive and destructive interference using this magnitude are compared with the observed angular distribution. The experimental points qualitatively favor constructive interference; however, for quantitative conclusions we must wait for an error analysis which takes into consideration the statistics of the points shown and the uncertainties of the "given" curves representing the alternative hypothesis.*

Our data on $K^- p$ elastic scattering are summarized in Fig. 7 (as a function of momentum) and in Figs. 8 through 12 (angular distributions at five momenta). By 400 Mev/c there is a very large anisotropy.

K^- - p Interactions at High Energy

In the high-energy range, the total K^-- p cross section has been measured by two counter groups, and a more detailed study has been made in the 15-inch bubble chamber during the "Ξ run." The total cross sections are given in Table VII and are plotted in Fig. 13.

Table VII

Total K^- - p cross sections

P (Bev/c)	Cross section (mb)	Source
0.9	52 ± 9	Cork et al. (counters) Phys. Rev. 106, 168 (1957).
1.17	48 ± 5	Alvarez et al. (Hydrogen bubble chamber)
1.4	36 ± 5	MIT group (counters)
1.7	44 ± 5	Armenteros et al. (counters)
2.8	25 ± 5	

*Note added Aug. 28, 1959:
Given more time, an error analysis has shown that the magnitude of the real part of the scattering amplitude is not well determined from the calculation outlined above. Each of the two curves of Fig. 9 should instead be wide bands which in fact overlap. If we analyze the data differently, using only the angular-distribution information, the data favor a positive value for the real part, but the uncertainties still allow small negative values.

The counter results at 0.9, 1.4, and 1.7 Bev/c have already been published, but the high-energy point is from new work of Rafael Armenteros, Charles Coombes, Bruce Cork, Glen Lambertson, and William Wenzel, of Berkeley, and the 1.17-Bev/c datum is from unpublished work by Luis Alvarez, P. Eberhard, Myron L. Good, W. Graziano, Harold K. Ticho, and S. Wojcicki. The latter group is also submitting the preliminary cross sections for individual processes listed in Table VIII. These cross sections are based mainly on a visual examination of the events; at present only a small fraction of the events have been analyzed in detail.

Table VIII

Partial cross sections for K^- - p at 1.17 Bev/c

Reaction products	Cross section (mb)
$K^- + p + (n\pi^0)$ $K^- + \pi^+ + N + (n\pi^0)$	24.2 ± 4.6
$\tilde{K}^0 + N + (n\pi^0)$	7.8 ± 1.1
$\bar{K}^0 + p + \pi^- + (n\pi^0)$	1.8 ± 0.3
$\Sigma^0 + \pi^0 + (n\pi^0)$ $\Lambda^0 + \pi^0 + (n\pi^0)$	4.6 ± 0.7
$\Sigma^0 + \pi^+ + \pi^- + (n\pi^0)$ $\Lambda^0 + \pi^+ + \pi^- + (n\pi^0)$	5.8 ± 0.7
$\Sigma^- + \pi^+ + (n\pi^0)$	1.8 ± 0.3
$\Sigma^+ + \pi^- + (n\pi^0)$	1.7 ± 0.3
$\Sigma^- + \pi^+ + \pi^- + \pi^+ + (n\pi^0)$	0.08 ± 0.03
$\Sigma^+ + \pi^- + \pi^+ + \pi^- + (n\pi^0)$	0.15 ± 0.05
$K^- + p + \pi^- + \pi^+ + (n\pi^0)$	0.06 ± 0.06
$\Xi^0 + K^0$	≈ 0.024
$\Xi^- + K^+$	$\lesssim$ 0.014

Here $(n\pi^0)$ means that extra π^0's are energetically possible; their presence can be sorted out only by kinetic analysis.

Pomeranchuk has shown that at high values of γ the total cross sections for particle and antiparticle should converge to a single value. This is observed for pions, but antiprotons of sufficient energy are not available for test. Now the new point of Armenteros et al. shows that the 20-mb $K^- \sigma_T$ is almost down to the $K^+ \sigma_T$, which has stayed almost constant at 17 mb from the lowest to the highest energies.

A few qualitative observations can be made concerning the individual cross sections.

1. In the absence of the K-K-π interaction proposed by Pais in his theory that the charged and neutral K's of a given "isotopic spin doublet" have different intrinsic parity, two pions must be interchanged in a reaction involving K's, so the effective radius of interaction is only $1/2 \; \frac{\hbar}{m_\pi c}$. A perfectly black sphere of that radius has an area of 16 mb and will have a total cross section $\sigma_T \leqslant 32$ mb.

2. The diagrams leading to hyperon production involve the exchange of a K meson, so their "σ_{geom}" $= 63 \text{ mb} \left(\frac{m_\pi}{m_K}\right)^2 = 5$ mb. The observed cross sections are surprisingly large, considering these constraints.

3. The cross section for cascade hyperon production is exceedingly small compared with that for ordinary hyperon production, of the order of only 1/1000 as great. The cross section for Ξ^- production by K^- - p comes from unpublished (and unsubmitted) work by the Berkeley 30-inch propane bubble chamber group of Wilson Powell et al. They exposed their chamber to the K^- beam set up by members of our group, and in private conversation have spoken of two Ξ^- made on protons (out of about 12 Ξ^- made on carbon plus protons).

When the events have all been measured and processed by our kinematics program, it should be possible to remove the brackets, and also, in many cases, to specify the number of neutral pions emitted and their directions of emission. The main source of error in the total cross section is due to uncertaintly in the pion contamination.

K^- charge-exchange scattering on protons has been a continuing study in our group, and a summary of the data from all runs to date has recently been published (P. Eberhard, A.H. Rosenfeld, F. T. Solmitz, R.D. Tripp, and M. Watson, Phys. Rev. Letters **2**, 312 (1959)). It may also be recalled that earlier this year, two teams from our group reported independently that the neutral member of each K doublet was about 4 Mev heavier than its charged counterpart. (The theory of this anomalous splitting will be discussed by Professor Salam.) The associated production reactions

$$\pi^- + p \rightarrow K^o + \Lambda \quad \text{and} \quad \pi^- + p \rightarrow K^+ + \Sigma^-$$

showed that the K^o was heavier than the K^+, and the charge-exchange reaction $K^- + p \rightarrow \overline{K}^o + N$ showed that the K^o was heavier than the K^-.

This of course explains the otherwise puzzling fact that in the early runs we saw no convincing examples of charge exchange at rest, as one does in the case of pions. (It had been assumed that the neutral mesons would be lighter than their charged counterparts, as in the pion case.)

Figures 14 and 15 are from the letter referred to above, and show the dependence of the charge-exchange cross section on momentum, and the angular distribution as a function of momentum. If it were not for the K^o mass excess, one could use this experiment as a sensitive test of the Pais assignment of odd relative parity for the K^- and $\bar{K}^o$. With no mass difference odd parity, $\sigma_{ch.ex}$ should vary initially as p^2, and then fall off slowly, while for even relative parity, the cross section should be large at low momentum. The energetic threshold for the reaction eliminates the interesting low-momentum region; so the predictions of either sign of relative parity fit the data adequately. The predicted behavior of the angular distribution with either an S-wave effective-range theory or the Pais theory fit the data equally well (or poorly) with a χ^2 probability for either being about 5%. So another possible test of the Pais hypothesis has given an inconclusive answer.

$K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$

This reaction is of interest because it could eventually determine the K-p-Λ parity. Other suggested ways, such as

(a) $K^- + d \rightarrow \Lambda + N$, looking at the correlated polarizations of the two outgoing baryons (Spitzer);

(b) $K^- + He$ (Dalitz);

(c) Associated production ($\pi^- + p \rightarrow K^o + \Lambda$) with polarized targets (Bilenky and Ryndin); or

(d) $p + He^4 \rightarrow He^4 + \Lambda + K$ with polarized protons (Bilenky and Ryndin)

are either more difficult or subject to some uncertainty.

The test involving $K^- + p \rightarrow \Lambda + \pi^- + \pi^+$ (suggested by Okun and Pomeranchuk) consists of looking at the momentum of the Λ with respect to the pion relative momentum, or the Λ polarization normal to the production plane defined by the three particles. Knowing as we now do that the capture at rest is from the S state, we recognize that the Okun-Pomeranchuk conditions are as follows: if the parity is even, then there is isotropy and no polarization; if odd, then there will be a cos θ term in the angular distribution, or polarization of the Λ, or both. Furthermore, if the parity is odd the reaction should be less frequent, and the matrix element should increase as p.

Unfortunately these arguments apply only right at threshold although the reaction is exothermic by 38 Mev even when the K^- has come to rest, so that momenta up to 130 Mev/c are involved. It may not then be safe to assume that terms of order $(p/m_\pi)^2$ are really negligible compared with unity. This parity test, therefore, requires reasonable statistics; however, the reaction is strongly supressed by phase space. So far 10^4 K interactions have yielded only twelve $\Lambda 2\pi$ events, and only four of these are from captures at rest. A more intense K^- beam, for which design is in progress at present, may bring this experiment into the realm of possibility.

III. K^- - d INTERACTIONS

This work is due to Nohmin Horwitz, Donald H. Miller, Joseph J. Murray, Melvin Schwartz, Horace Taft, Orin Dahl, Vincent Monara and Paul White. I wish to thank Dr. Miller for supplying most of the following data in such a form that they could be inserted directly into this report, with only minor editing. The experiments were carried out in the same 15-inch chamber and in the same K^- beam as was used in the K^- - p experiments at the Lawrence Radiation Laboratory (LRL).

Considerable progress has been made during the past year in understanding the nature of the K^- - meson absorption process in deuterium--in fact, the theoretical and experimental advances during the past year lead us to the point where the details of the branching ratios and momentum spectra may soon be quantitatively related to the structure of the deuteron and the general features of the low-energy interactions between strange particles and nucleons. To date, the group has accumulated a total of 10,000 interactions of low-energy K^- - d interactions in addition to an exposure at 300 Mev/c. This report concerns a systematic study of 1700 interactions obtained early last year. Since the analysis has not been completed, the numbers will be subject to small changes.

To eliminate difficulties due to inhomogeneity of illumination, escape of hyperons before decay, etc., only those interactions occurring in a preselected fiducial volume of the chamber were accepted for analysis. From the classes of events which could be identified with a high degree of certainty, the LRL group has estimated the total number of absorptions preceeding through the channels listed in Table IX. The major corrections applied to the data were those deduced from the known hyperon branching ratios.

In general, detailed kinematic fits could not be made to the events--the Λ - π^- - p events are an important exception and will be discussed separately--therefore an attempt was made to estimate the in-flight contamination from a statistical analysis of the momentum distribution of the K^- mesons which interacted in the chamber. For each incident K^-, the momentum ratio R = p (via range)/p (via curvature) was plotted against the length of the K^-. If all interactions occurred at rest, the points would show Gaussian distribution about the value unity. By examination of the non-Gaussian tail corresponding to p (curvature) > p (range) it is estimated that 15 to 20% of the interactions occur at momenta greater than 150 Mev/c. Another 5% interact in the 0- to 150-Mev/c momentum interval, leaving 75% to be captured from orbitals. Therefore if we assume a nonpathological behavior of the branching ratios with momentum, the data represent to a high degree what happens when K^- mesons are captured at rest.

Table IX

Numbers of events in various K^--d interactions

Event type	Number
(1) $\Sigma^- \pi^+ n$ [a]	353 ± 19
(2) $\Sigma^+ \pi^- n$	354 ± 30
(3) $\Lambda \pi^o n + \Sigma^o \pi^o n$ [b]	474 ± 22
(4) $\Lambda \pi^- p + \Sigma^o \pi^- p$ [b]	425 ± 21
(5) $\Sigma^- \pi^o p$ [c]	53 ± 6
(6) $\Sigma^- p$	8
(7) Λn or $\Sigma^o n$	7

[a] 68 events in which only the two π's were visible have been called decays of $\Sigma^\pm$ after zero distance, and have been divided equally between Reactions (1) and (2). One then assumes

$$(\Sigma^+ \to \pi^+ + n) / (\text{All } \Sigma^+) = 0.48 \pm 0.2.$$

[b] A 2% correction for escape and scanning efficiency is included. The branding fraction $(\Lambda \to \pi^- + p) / (\text{All } \Lambda) = 0.63 \pm .03$ is used.

[c] These events are easily confused with K^--d scatterings. This number is the best estimate based upon detailed analysis of the scattering events.

Charge Independence

The implications of charge independence for K^--meson absorption in deuterium have been emphasized in many places. If strange-particle interactions possess this property, the reaction rates for production of Y-N final states may be expressed in terms of three independent complex matrix elements. The reaction rates may be written in the form

$$\Sigma^- \pi^+ n = \lambda/3\,|G_o|^2 + \lambda/6\,|G_1|^2 + \frac{\sqrt{2}}{3}\,|G_o||G_1|\cos\theta,$$

$$\Sigma^+ \pi^- n = \lambda/3\,|G_o|^2 + \lambda/6\,|G_1|^2 - \frac{\sqrt{2}}{3}\,|G_o||G_1|\cos\theta,$$

$$\Sigma^o \pi^o n = \lambda/3\,|G_o|^2,$$

$$\Sigma^- \pi^o p = \Sigma^o \pi^- p = \lambda/3\,|G_1|^2$$

$$\Lambda \pi^- p = 2\,\Lambda \pi^o n = 2/3\,|F_1|^e,$$

where the subscript refers to the isotopic spin of the π - Y subsystem. In principle, then, since the seven hyperon channels have been described in terms of only four parameters (three amplitudes and a phase), there are three independent tests of charge independence. Although it has not proved possible to separate all these channels by direct measurement, several tests of the hypothesis are accessible. It is apparent from the equations above that simple addition indicates that:

$$1/2 \text{ Rate (all charged pions)} = \text{Rate (all neutral pions)}.$$

This is a completely general relation, applying to any isotopic spin-1/2 system interacting to produce pions. From the data of Table I, one finds

$$\frac{\text{Rate (charged pions)}}{2 \times \text{Rate (neutral pions)}} = \frac{(1132 \pm 26)}{2(533 \pm 26)} = 1.06 \pm .05 ,$$

in good agreement with the hypothesis. A more sensitive test consists in determining whether the observed branching ratios may be fitted by a solution of the equations in which $|\cos\theta| \leq 1$.

The group has made a least-squares fit to the data and finds for the four parameters the values

$$\lambda/3\, |G_0|^2 = 315,$$
$$\lambda/3\, |G_1|^2 = 59,$$
$$\lambda/3\, |F_1|^2 = 178,$$
$$\cos\theta = 0 ,$$

with $\chi^2 = 1.5$, in excellent agreement with the hypothesis.

$\underline{Y - \pi^- - p}$

This group of events is of particular interest, since an energy-momentum balance applied to the interaction vertex generally leads to a separation of the Λ and Σ^0 hyperons. The fitting constraints also ensure a high degree of accuracy in the determination of the momenta of the reaction products. This fitting program has been completed, and the results may be best illustrated by considering the momentum spectra of the pions and nucleons. In Fig. 16 we see a histogram of fitted pion momenta for those events which did not result from the decay of a Σ^0 hyperon. The shape of the higher-momentum peak agrees with what is expected if the reaction is between the K^- and the neutron, with the proton simply playing the role of a spectator. The lower-momentum peak is roughly what would be expected for the reaction $K^- + d \rightarrow \Sigma^0 + \pi + p$, again with the proton playing the role of a spectator. The striking result here is that the lower peak appears for events in which a Λ rather than a Σ^0 emerges. This result suggests that a two-step process is occurring. First the K interacts with one nucleon to form a Σ and π^-, and second, the Σ interacts with the other nucleon and converts to a Λ, via the reaction $\Sigma + N \rightarrow \Lambda + N$. Further evidence for the two-step process is provided by the momentum distribution of the protons from the events comprising the lower peak. This spectrum is shown in Fig. 17. The large momentum in these protons comes from the energy released in the Σ - to - Λ conversion.

The group has also examined the momentum distribution of the protons accompanying the directly produced Λ's . In Fig. 18 this distribution is compared with the deuteron internal momentum distribution. Once again, there are too many high-momentum protons. Here, the final-state interaction occurs in a single isotopic spin state (I = 1/2), and if the K - Λ parity is odd, the two baryons are probably in the triplet S state. With better statistical accuracy, then, this kind of reaction will yield direct information on the Λ - N scattering amplitude.

The final separation for these events is summarized in Table X.

Table X

Numbers of events in Y - π^- - p reactions

Event type*	At rest	In flight
(1) Σ^0 - π - p	37	16
(2) Λ - π^-- p	228	45
(a) Direct	96	27
(b) Indirect	132	18

*There were 5 $\Sigma^0 \pi^-$ p and 1 $\Lambda \pi^-$ p events that were ambiguous with respect to the interaction momentum. They were divided in the ratio of those whose classification was certain.

Branching Ratios

If we now accept the validity of the charge-independence hypothesis, it is possible to use the fitted values of the parameters to obtain the best values of the relative reaction rates for all channels. The results are given in Table XI, where they are compared with the analogous results for hydrogen.

It is apparent that although there are strong differences to be accounted for, the general features are similar to these observed in hydrogen. If the final-state interactions are neglected for the moment, the absorption appears to be dominantly through the K-N I = 0 isotopic spin state. Approximately equal numbers of Σ^+, Σ^-, and Σ^0 are observed, while the direct production of Λ's , which must occur in the I = 1 state of the K-N system, is substantially suppressed.

Table XI

Comparison of K^--d and K^--p absorption

	Deuterium	Hydrogen
$\Sigma^- \pi^+ n$	344	44
$\Sigma^+ \pi^- n$	344	22
$\Sigma^0 \pi^0 n$	315	27
$\Lambda^0 \pi^0 n$	178	7
(a. Direct)	(81)	
(b. Indirect)	(97)	
$\Sigma^- \pi^0 p$	59	
$\Sigma^0 \pi^- p$	59	
$\Lambda^0 \pi^- p$	357	
(a. Direct)	(161)	
(b. Indirect)	(196)	
$\Sigma^- p$	8	
$(\Sigma^0$ or $\Lambda^0)$ n	7	

These results, together with the small amount of nonmesonic hyperon production, suggest that analysis in terms of impulse-type models which include final-state interactions possess a high degree of validity. However, it is clear that (a) the possibility of absorption off the energy shell, and (b) strong final-state interactions which change the phases of the elementary production amplitudes and influence the charge states of the reaction products, make a superficial interpretation of the data rather precarious.

Momentum Spectra

It is of interest to see whether an impulse-type model is adequate to account for the pion spectra observed when K^- mesons are absorbed. It is expected from this model that final-state Y-N interactions will influence these spectra only slightly--in general, insufficiently for detection with the momentum resolution available. In Figs. 19 and 20 our group has plotted the spectra for those $\Sigma^- - \pi^+ - n$ and $\Sigma^+ - \pi^- - n$ events which had a high probability of occurring at rest (p (via range)/p (measured) > 0.90). Only pions for which the momentum-measurement error was less than 10% have been plotted (average error 7%).

To compare the results with the impulse model, the integrals obtained by Fujii and Marshak for S-wave capture were evaluated for these reactions and the momentum resolution folded in. We see that this model is adequate to explain the pion spectrum for the $\Sigma^- - \pi^+ - n$ channel, but there seems to be some deviation at the low-momentum end for the $\Sigma^+ - \pi^- - n$ channel. For the latter reaction the π - n system is in an I = 3/2 state. Scattering might become important.

Search for Decay Asymmetries

Fujii and Marshak have used invariance arguments to derive a general form for the transition amplitude when slow K^- mesons are captured in deuterium. They find that when baryon recoil terms contribute to the transition amplitude, both S and P waves are present in the final state. It is usually assumed that such contributions are small; however, the hypothesis may be tested by looking for effects due to the presence of a p-wave amplitude in the final state.

If baryon recoil effects are present, the hyperons may be polarized perpendicularly to the plane of production (the deuteron internal momentum allows a plane to be defined when K^- are captured at rest). Up-down asymmetries have been looked for in the reactions

$$
\begin{aligned}
K^- + d &\rightarrow \Sigma^- \pi^+ n, & \Sigma^- &\rightarrow \pi^- + n, \\
&\rightarrow \Sigma^+ \pi^- n, & \Sigma^+ &\rightarrow \pi^+ + n, \\
&\rightarrow \Sigma^+ \pi^- n, & \Sigma^+ &\rightarrow \pi^0 + p, \\
&\rightarrow \Lambda \pi^- p, & \Lambda &\rightarrow \pi^- + p.
\end{aligned}
$$

In each case the distributions were statistically consistent with isotropy. Since it is known that $\Lambda \rightarrow p + \pi^-$ and $\Sigma^+ \rightarrow p + \pi^0$ constitute good analyzers, we may conclude that very little polarization is present.

Search for Hyperfragments

The calculations by Pais and Treiman have shown that it is to be expected that if the Y-N system possesses a bound state of energy greater than a few hundred keve, considerable hyperfragment production will occur when K^- mesons are captured in deuterium. However, they point out an important exception to this statement. If the $K - \Sigma$ parity is odd, the capture process will probably involve very little spin-flip amplitude. Therefore, if the system is found in the singlet S-state, $\Sigma^- - N$ hyperfragments will not be produced when K^-'s are captured at rest. It is apparent, then, that the observation of Σ^- N hyperfragments in some other process at once fixes the parity and the spin state.

The group has carried out a systematic search for events that might involve hyperfragment production. It is convenient to discuss the possible Y-N systems separately.

1. $K^- + d \rightarrow (\Lambda n) + \pi^0$.

The Λ n hyperfragment will have a momentum of 265 Mev/c. Two charged decay modes must be considered:

(a) $\Lambda n \rightarrow \pi^- + p + n$. If the hyperfragment is loosely bound, the event will appear an ordinary Λ production in which the Λ has a momentum of 143 Mev/c, therefore it is not expected that these events will be readily identified by inspection.

After measurement, all Λ's observed in the fiducial volume were processed by an IBM 650 program which applied the energy-momentum constraints to the decay process. For each event, a "goodness of fit" parameter was calculated. Decays kinematically capable of arising from hyperfragments were examined in detail. In the few cases of a poor fit, the difficulty could be attributed to obvious local distortion, a scattering of the Λ or one of its decay products. In no case was it necessary to invoke the hyperfragment hypothesis.

(b) $\Lambda n \rightarrow \pi^- + d$. Since the hyperfragment momentum is unique, it is readily determined that only decays in which the positive prong is less than 4.2 cm could fit this interpretation. This group of events was reprocessed with the IBM program modified for this interpretation. Although several events gave an acceptable fit to the hypothesis, only two fitted better than when considered as ordinary Λ decays. An examination of the χ^2 distributions leads to the conclusion that the data are consistent with assumption of no hyperfragments decaying via this mode. (The group wishes to thank Professor M. Kaplon for pointing out the possible existence of this decay mode.)

2. $K^- + d \rightarrow \Lambda p + \pi^-$

This hyperfragment should be easily detected. The π will be collinear with the line of flight of the hyperfragment, and then there should be a decay in which a π^- and one or two protons are visible. No such events were found.

3. $K^- + d \rightarrow (\Sigma^- n) + \pi^+$

The hyperfragment has a unique momentum of 178 Mev/c and a maximum range of 0.29 cm. If (as assumed) the lifetime is essentially that of the Σ^-, 75% will travel at least 1 mm, 55% at least 2 mm, and 35% will come to rest and be captured. All events for which the range was greater than 1 mm on the scanning projector were examined visually for collinearity. Deviations of 5 deg or more could be detected even for such short tracks. It is estimated that the over-all efficiency for finding such events was at least 50%. No events were observed that satisfied both the range and collinearity requirements.

One can therefore conclude

$$\frac{\text{Rate }(\Lambda n + \pi^0)}{\text{Rate (all }\Lambda n\pi^0)} < 2\%\ ,$$

$$\frac{\text{Rate }(\Lambda p + \pi^-)}{\text{Rate (all }\Lambda p\pi^-)} < 1\%\ ,$$

$$\frac{\text{Rate }(\Sigma^- n + \pi^+)}{\text{Rate (all }\Sigma^- n\pi^+)} < 2\%\ .$$

Scattering of K Mesons in Deuterium

Some preliminary data on the scattering of K mesons are available. The separation into elastic and inelastic is not always possible because the charged recoil particle is frequently short or unobservable. A scattering was generally considered elastic if it was consistent with the elastic scattering kinematics. It is therefore expected that the inelastic scattering has been somewhat underestimated, but it certainly does not exceed 50% of the total cross section. The measured absolute values of the total cross section are compared with some recent calculations of Day and Sucher. In Fig. 21 their predictions for elastic scattering, using a pure impulse model, have been plotted. The two dark circles represent the calculated values for the total scattering cross section at 200 Mev/c laboratory-system momentum when multiple-scattering corrections are included. If the Dalitz (a) and (b) solutions used are not modified too strongly by the latest hydrogen data, we may conclude that, though statistically poor, the deuterium data are in good agreement with the predictions using the (b) solution.

K^o Interactions

Although there is very little to say on this subject now, it will no doubt grow into one of the most important topics within the next year or two. In fact, only one contribution has been submitted formally to the conference. A paper by J. Litvak, B. de Roederer, and J. Roederer of Argentina reports the presence of particles of negative strangeness originating in an emulsion stack exposed at some meters from a Bevatron target, in a neutral beam.

The reason such beams of K_2^o mesons will probably be used more in the future is the following: of the three kinds of strange particles that have long enough lifetimes to allow them to be produced in an internal target, and subsequently to interact in a bubble chamber, the K^+ mesons are rather "sterile," in view of their positive strangeness, and the K^- mesons can produce a great variety of strange particles, but the ones that do not interact clutter up the pictures because they are charged. In contrast, half of the K_2^o mesons can interact as $\overline{K}^o$, in which case they have most of the advantages of the $\overline{K}$, but without causing useless background. (It may turn out in practice that the neutron contamination in all K_2^o beams will cause more background than the passive $\overline{K}$ tracks, but that remains to be seen.)

Oreste Piccioni, working with the Powell propane bubble chamber group at Berkeley, late this spring completed an exposure to a carefully prepared θ_2^o beam, in an effort to clarify several points in the Pais-Gell-Mann particle-mixture scheme. In particular, the group was looking for regeneration of θ_1^o by diffraction from heavy nuclei. (The θ^o component is largely unaffected in passing through nuclear matter, while the $\overline{\theta}^o$ component is absorbed. The resulting small-angle diffracted wave is then almost pure θ^o, of which half should decay by the θ_1^o mode). A preliminary progress report was made on the experiment by Piccioni at Berkeley just before I left, in which he expressed some satisfaction with the search for small-angle θ_1^o decays. However, since he has not submitted any official report, I mention this only to give him the chance to elaborate on his success, in the discussion period, or to affirm that his preliminary report was not for publication.

The reaction $\theta_2^o + p \rightarrow \Sigma^+ + \pi^o$, which I reported last year at Geneva as a detailed example of the particle-mixture hypothesis, has a substantial cross section (which I don't have available), and has been seen on many occasions in our chambers. Many experiments have been proposed to measure the $\theta_1^o - \theta_2^o$ mass difference, but a proposal that has been made to measure the distribution of Σ^+ hyperons with distance "downstream" from $\pi^- + p \rightarrow K^o + \Lambda$ reactions appears at the moment to be the most promising. It is planned as the next experiment to be tried in the 72-inch bubble chamber.

Hyperon-Nucleon Interactions

A recent publication by Frank S. Crawford, Jr., Marcello Cresti, Myron L. Good, Frank T. Solmitz, M. Lynn Stevenson, and Howard K. Ticho, Phys. Rev. Lett. 2,174 (1959), quotes cross sections for the Λ-P interactions from the 10-inch hydrogen chamber. In the range 500 to 1000 Mev/c, the cross section for elastic scattering, $\Lambda + p \rightarrow \Lambda + p$, is 40 ± 20 mb. The corresponding cross section for the reaction $\Lambda + p \rightarrow \Sigma^+ + N$ is 30 ± 20 mb.

Σ^--p interactions have been studied extensively in the K^--p experiments, by J. Peter Berge, Arthur H. Rosenfeld, Ronald R. Ross, Frank T. Solmitz, and Robert D. Tripp.

Σ^- hyperons produced by K^- capture at rest have a moderation time of 3.45×10^{-10} sec in a hydrogen bubble chamber, so 10% are expected to come to rest. Roughly this many are seen, so the capture times must be less than 10^{-10} sec. The reactions possible are $\Sigma^- + p \rightarrow \Sigma^0 + N$

$$\rightarrow \Lambda + N.$$

of 73 Σ^- captured at rest, and yielding a charged decay of a Λ, 49 were produced directly, and 24 came from the decay of Σ^0. With escape corrections, these numbers become 51 and 25, so the ratio is $\Sigma^0 / (\Sigma^0 + \Lambda^0) = 0.33 \pm 0.05$. Global symmetry predicts that the ratio should be 1/2, if the Σ and Λ masses were equal. The mass differences enhances the Λ-phase space by factor of 4, but the transition (matrix element)^2 for Λ production (assuming Λ and Σ have the same parity) is only about 1/4 as great, owing to its smaller wave function in the interaction region, so the two effects roughly cancel. Since the second of these two effects cannot be calculated with certainty, the experimental result is not in contradiction with global symmetry.

Five Σ^- disappeared in flight to yield an absorption cross section of 170 ± 80 mb at an average momentum of 150 Mev/c. For the same path length, two elastic scattering of Σ^- were observed.

A plot of the energies of the indirect Λ's from $\Sigma^- + P$ yields two results. Its end points give the Σ^0 mass, in the way the Panofsky first measured the π^0 mass, and its constant population is consistent with an isotropic decay of the Σ^0 and so with the hypothesis that the spin of the Σ^0 is 1/2. A maximum-likelihood calculation of the $M_{\Sigma^-} - M_{\Sigma^0}$ - mass difference gives $(M_{\Sigma^-} - M_{\Sigma^0}) = 4.45 \pm 0.40$ Mev.

Σ^- + d Interactions

Day, Snow, and Sucher have tried to relate the Σ^0 / Λ branching ratio in deuterium to that observed in hydrogen by means of a phenomenological interaction operator. They find that for any values of the parameters involved, the exceedingly small Q value for the reaction drastically suppresses the production. Using the value $M_{\Sigma^-} - M_{\Sigma^0} = 4.45$ Mev for the reaction

$$\Sigma^- + d \rightarrow \Sigma^0 + N + N + 0.92 \text{ Mev},$$

they calculate that the ratio $\Sigma^0/(\Sigma^0 + \Lambda)$ lies between the limits 1/40 and 1/1500. The larger value for this ratio corresponds to having maximum nucleon spin flip amplitude in the reaction $\Sigma^- + p \rightarrow \Sigma^0 + n$.

Thus far, the LRL group has analyzed 145 events for the type $K^- + d \rightarrow \Sigma^- + \pi^+ + N$ in which the Σ^- was captured before decaying, and the resulting Λ decayed via the charged mode. The measured Λ-momentum spectrum has been plotted in Fig. 22. The solid curve rep-sents the momentum spectrum predicted by an impulse-type model (the 5% momentum resolution has been folded in) for absorption on a single nucleon. There appears to be a distinct group of events at low momenta which cannot be attributed to a tail on the high-momentum spectrum. The momentum interval in which Λ's resulting from Σ^0 decay may be expected is indicated on the figure. The limits on the Λ momenta are also indicated for the old mass value. The spectrum lends support to the new mass value reported by the LRL hydrogen group. The LRL group concludes that these are indeed Λ's resulting from Σ^0 decay, and place an upper limit of $-0.04 \pm .02$ on the $\Sigma^0/(\Sigma^0 + \Lambda)$ branching ratio.

EMULSION STUDIES OF THE INTERACTION OF K^- - MESONS WITH NUCLEI

(Supplementary report)

E. H. S. Burhop

Several groups have submitted material on the interaction of K^- - mesons at rest with emulsion nuclei. A group from the Kernphysikalisches Institut, Berlin, have separated capture in flight by light and heavy nuclei, using techniques previously used for π-meson capture stars. They conclude that 25% of all K^- capures at rest occur in light nuclei and 75% in heavy nuclei. They obtain a value $38.4 \pm 2\%$ for the frequency of emission of π mesons from K^- stars at rest, a value in good agreement with that recently published by the European collaboration, [$39.2\ (+1.3) \pm 2$]%. The frequency of π emission, as well as that of Σ emission, we found to be the same for both light and heavy nuclei.

The European collaboration has submitted a study of the emission of fast Σ hyperons of energy greater than 60 Mev as a result of K^- capture at rest. Hyperons in this energy range are not produced in interactions between a K^- meson and a single nucleon. Their presence indicates a primary interaction between a K^- meson and two or more nucleons. This work refers to an analysis of 6862 K^--capture stars and its results confirm the conclusions presented at the Geneva Conference last year, based on much smaller statistics. At least 15% of all Σ^+ hyperons and 25% of all Σ^- hyperons are emitted in nuclei nucleon processes. Of all the primary K^- - capture processes at least 15% take place with two or more nucleons and result in the production of a Λ hyperon. At the same time it has been found that not more than 70% of all K^- - capture processes can be accounted for as one-nucleon processes. It is possible therefore that a futher 15% of the capture processes takes place with two or more nucleons and results in the production of a Λ - hyperon.

Differences are found between the prong distribution of stars accompanying fast Σ^+ emission and those accompanying fast Σ^- emission (Fig. 23). Although fast Σ^+ hyperons are often emitted without other prongs, fast Σ^- have always been observed to be accompanied by other prongs, including usually a fast proton. When these processes are interpreted on the simplest bases in terms of an interaction between a K^- meson and two nucleons, it appears that the processes

$$K^- + P + P \rightarrow \Sigma^+ + N \qquad (1)$$

and

$$K^- + P + N \rightarrow \Sigma^- + P \qquad (2)$$

both occur, but

$$K^- + N + N \rightarrow \Sigma^- + N \qquad (3)$$

does not. When charge independence is assumed, the nonoccurence of (3) enables one to estimate the rates of the process

$$K^- + P + P \rightarrow \Sigma^0 + P \qquad (4)$$

to be half that of (1), and that of

$$K^- + P + N \rightarrow \Sigma^0 + N \qquad (5)$$

to be half that of (2).

In describing the two nucleon processes leading to Σ production three independent (complex) amplitudes are needed, viz $a(3/2, \lambda)$, $a(\lambda/2, \lambda)$ and $a(1/2, 0)$, where the first number in the brackets gives the total isotopic spin and the second the sum of the isotopic spins of the two nucleons. The nonobservation of (3) and the observation that the transition rate for (2) is about 50 % greater than for (1) would imply the following relation between the transition amplitudes:

$$|a(3/2, 3/2)|^2 = 0; \ |a(\lambda/2, \lambda)|^2 = 3/2 \ |a(\lambda/2, 0)|^2 .$$

A study of hyperfragment emission following K^- capture by emulsion nuclei has been submitted by J. Sacton (Brussels), based on an analysis of 2236 K^- stars at rest. He obtains for the fraction of such stars emitting hyperfragments, $4.2 \pm 0.5\%$, that hyperfragments of charge 3 are most probable, and that the ratio of nonmesic to mesic decay of hyperfragments is 3.0 ± 1.0. Assuming nonmesonic decay to result from the stimulated Λ-decay process, $\Lambda + N \rightarrow N + N$, and assuming the presence of a fast proton in the decay star to indicate proton stimulation, he finds the neutron-to-proton stimulation ratio to be 0.9 ± 0.3. From the spectrum of π mesons accompanying the emission of a hyperfragment and the mean number of stable prongs in such K stars, he concludes that in 25 to 35% of the cases of hyperfragment production the Λ was produced directly, while in the remaining cases a Σ was produced directly and then interacted with a nucleon to produce the Λ.

In 34 cases in which a fast proton was emitted from the hyperfragment star the angle between the direction of emission of the hyperfragment and the line of flight of the fast proton was measured. A marked anisotropy in the distribution of the angle was found. The forward-backward asymmetry is $(F - B/)(F + B) = -26/34$. This would appear to indicate a rather strong correlation between the hyperfragment emission direction and the line of flight of the Λ hyperon.

Davis (University College, London), Jones and Zakrzewski (Bristol), and Bizzeti, Lagnaux, and Rene (Brussels), working in the European Collaboration, have observed three cases of the inelastic scattering of a Σ hyperon by an emulsion nucleus. In one case the interaction star contains one other (proton) prong and in the other cases two other prongs, in addition to the re-emergent Σ.

Two other such cases of Σ - inelastic scattering by emulsion nuclei have been reported in the literature: Fry et al. (Phys. Rev. 100, 935 (1955); and Glasser et al. (Phys. Rev. 107, 277 (1957)).

These five examples are set out in the table:

Observers	Sign of Σ	Incident energy (Mev)	Energy of emergent Σ (Mev)	Identification of emergent Σ
European Collaborators	Σ^+	191^{+30}_{-20}	78^{+4}_{-3}	$\Sigma \to P$ decay in flight
- " -	Σ^+	69^{+9}_{-7}	2.6	$\Sigma \to P$ decay at rest
- " -	Σ^-	52.4	4.4	One-prong Σ-star + Auger electron
Fry et al.	Σ^+	40	1.5	$\Sigma \to \pi$ at rest
Glasser et al.	Σ^+	60	15	$\Sigma \to P$ at rest

It is interesting to note that all these events are characterized by a large change of the Σ momentum at the interaction.

The three new interactions reported here have been found in a scan of approximately 70 cm of Σ track of energy greater than 50 Mev.

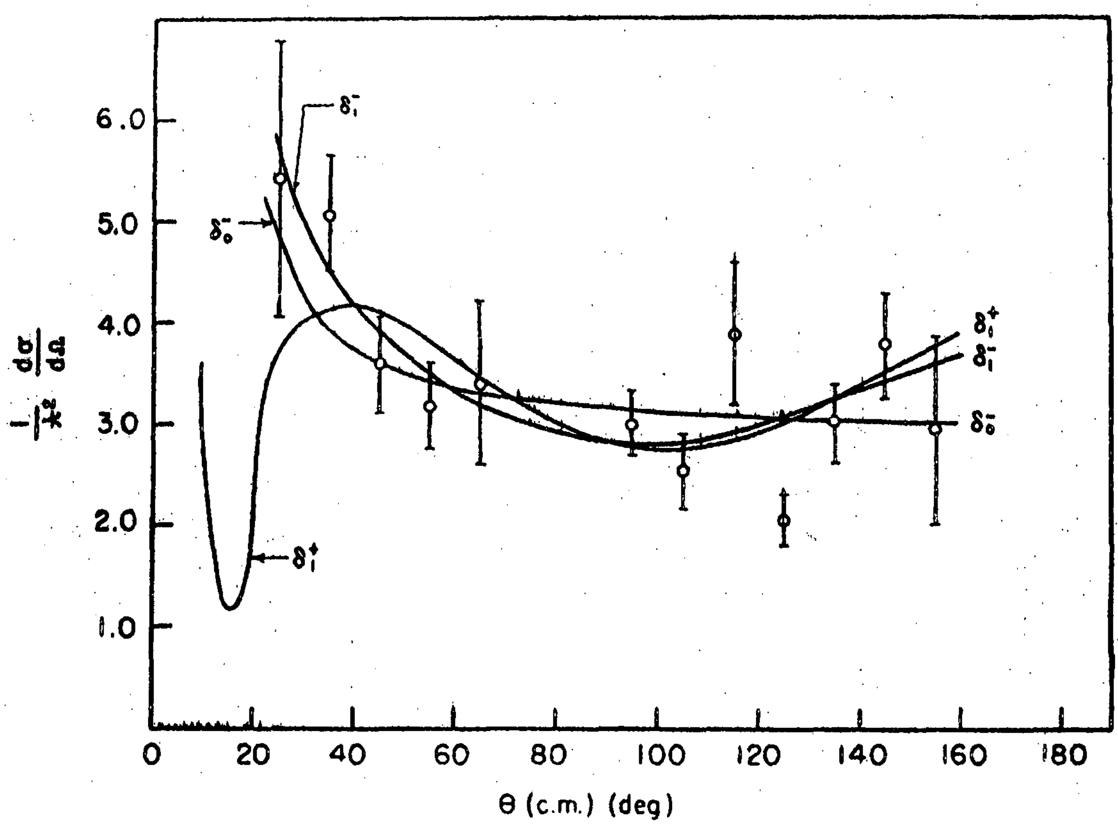

Fig. 1. Angular distribution for $K^+ - P$ at 225 Mev.

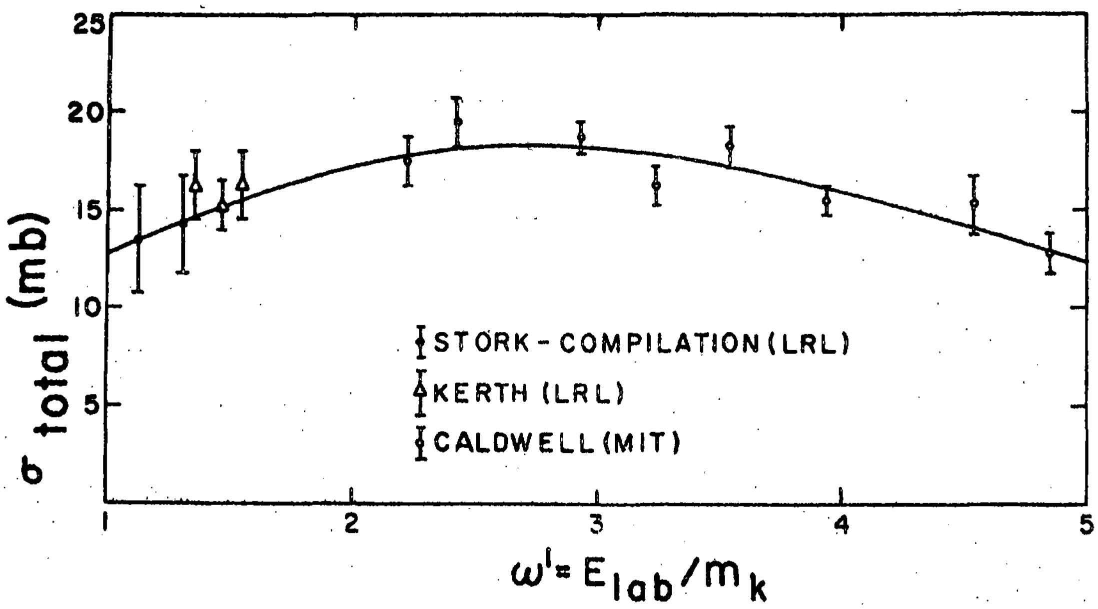

Fig. 2. Energy dependence of total $K^{+}-P$ cross section

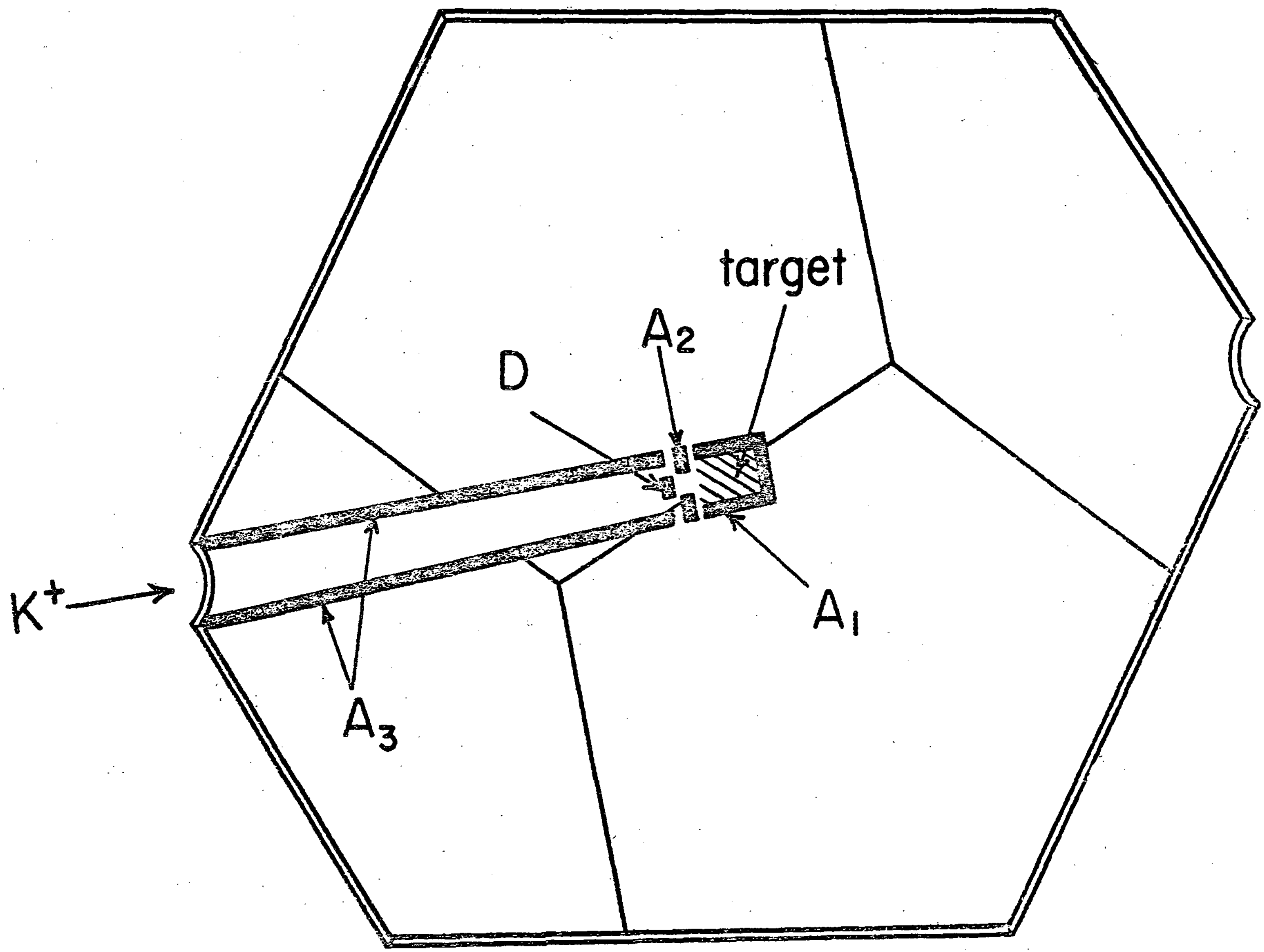

Fig. 3. Experimental arrangement for $K^{+}n$ charge-exchange counter experiment.

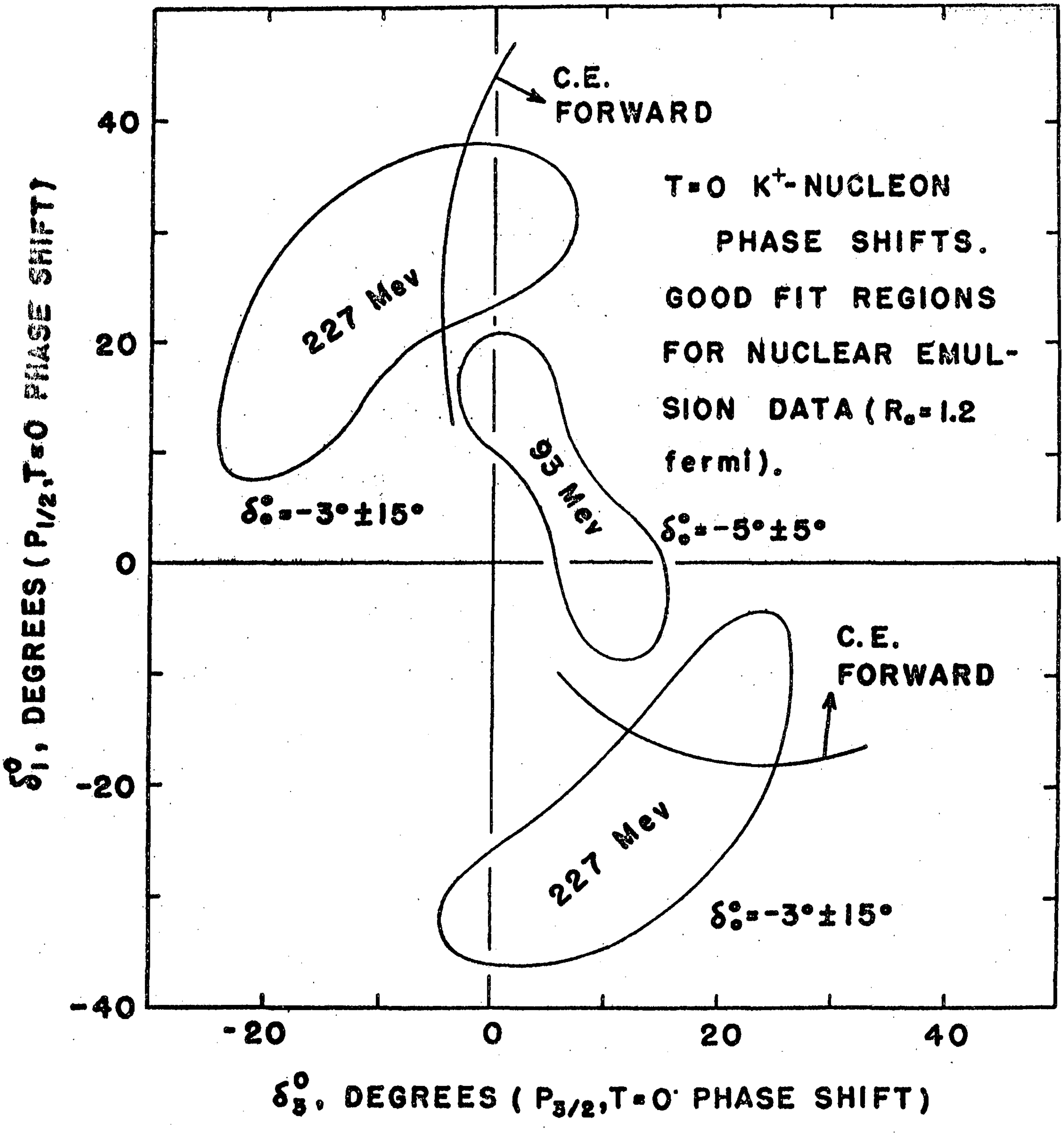

Fig. 4. Phase shifts from UCLA emulsion data

16 July 1959

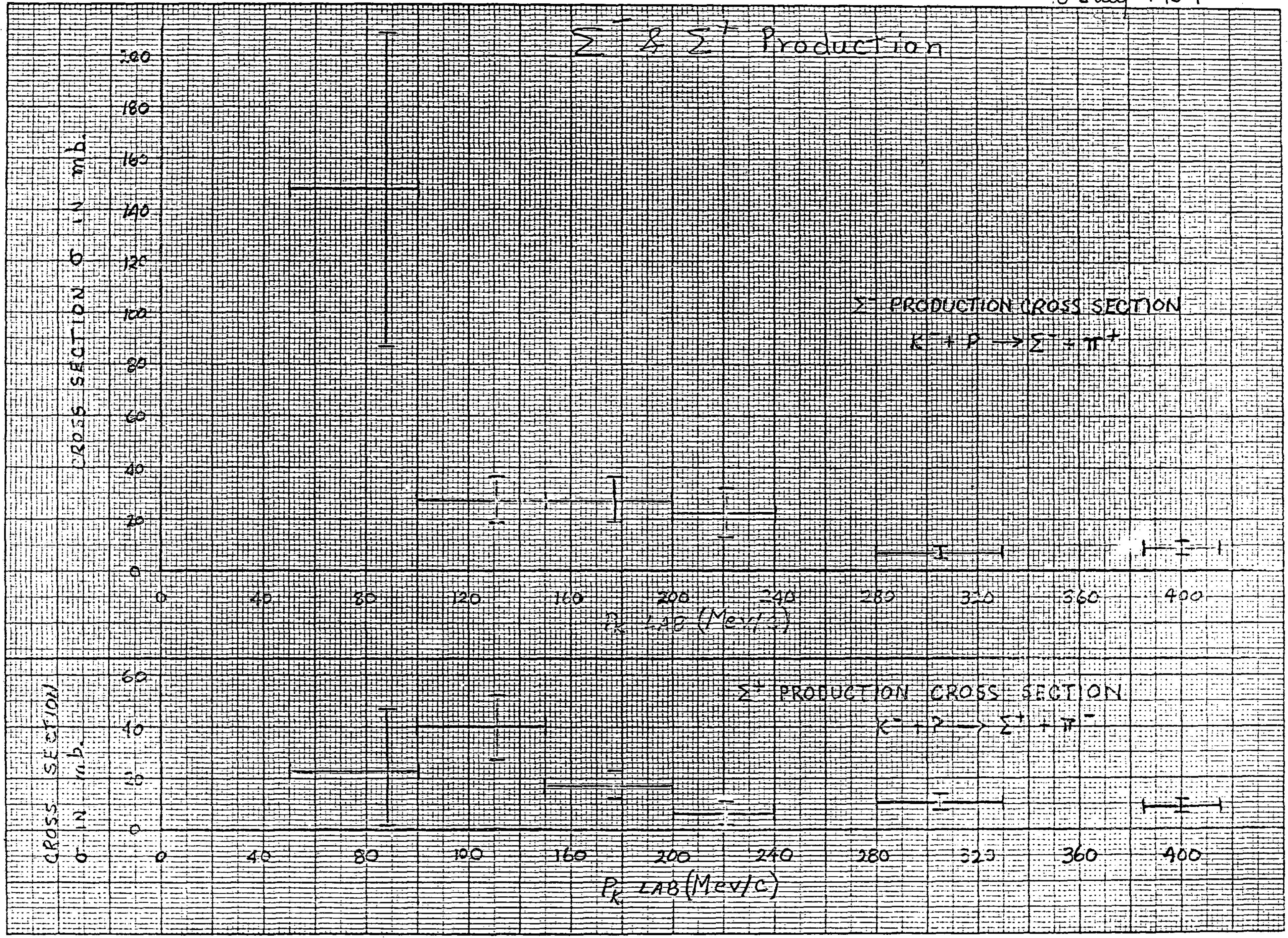

Fig. 5. Hyperon production in flight.

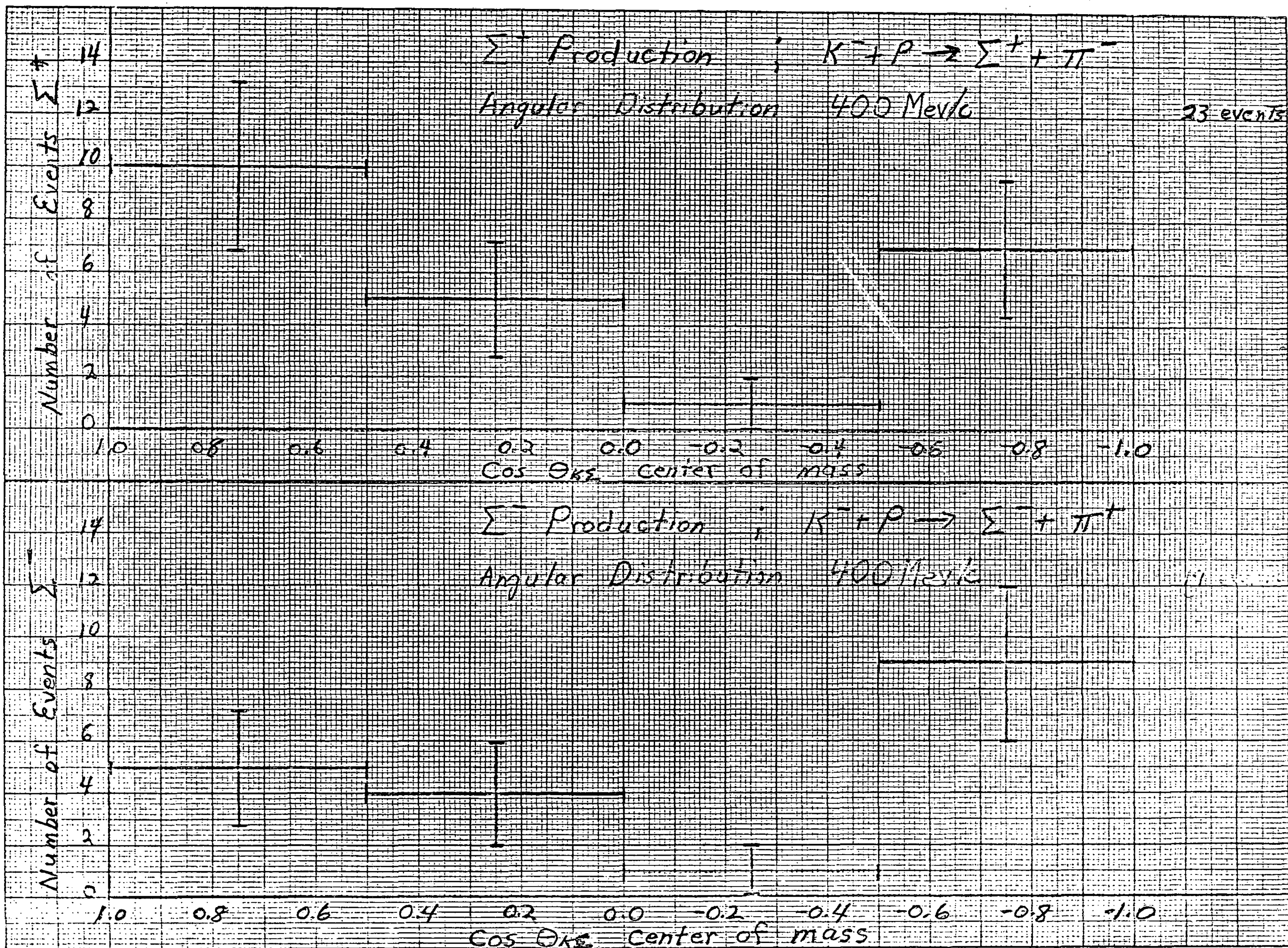

Fig. 6. Angular distribution of Σ^+ and Σ^- at 400 Mev/c.

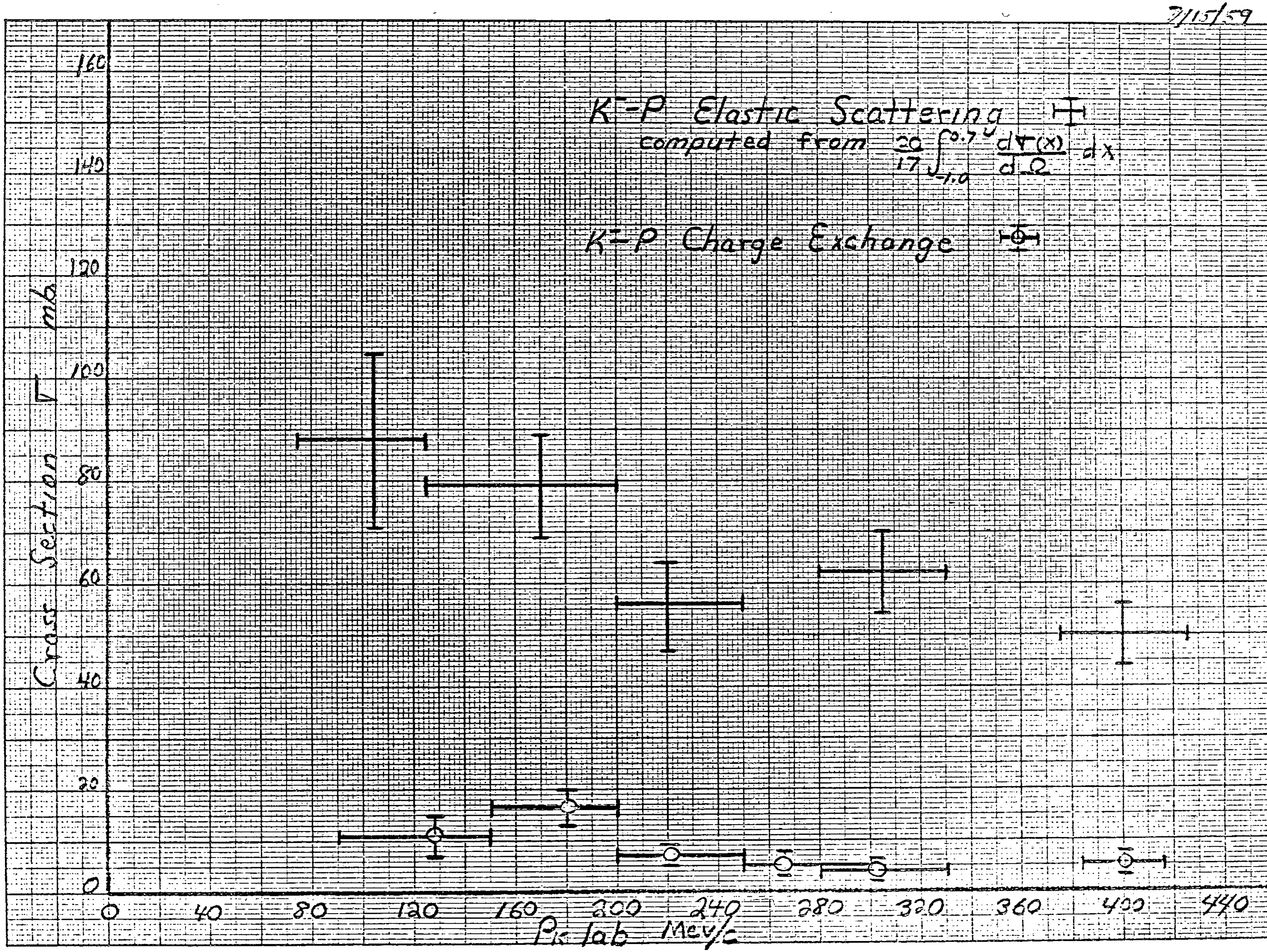

Fig. 7. Elastic and charge-exchange cross sections for K⁻-p vs momentum.

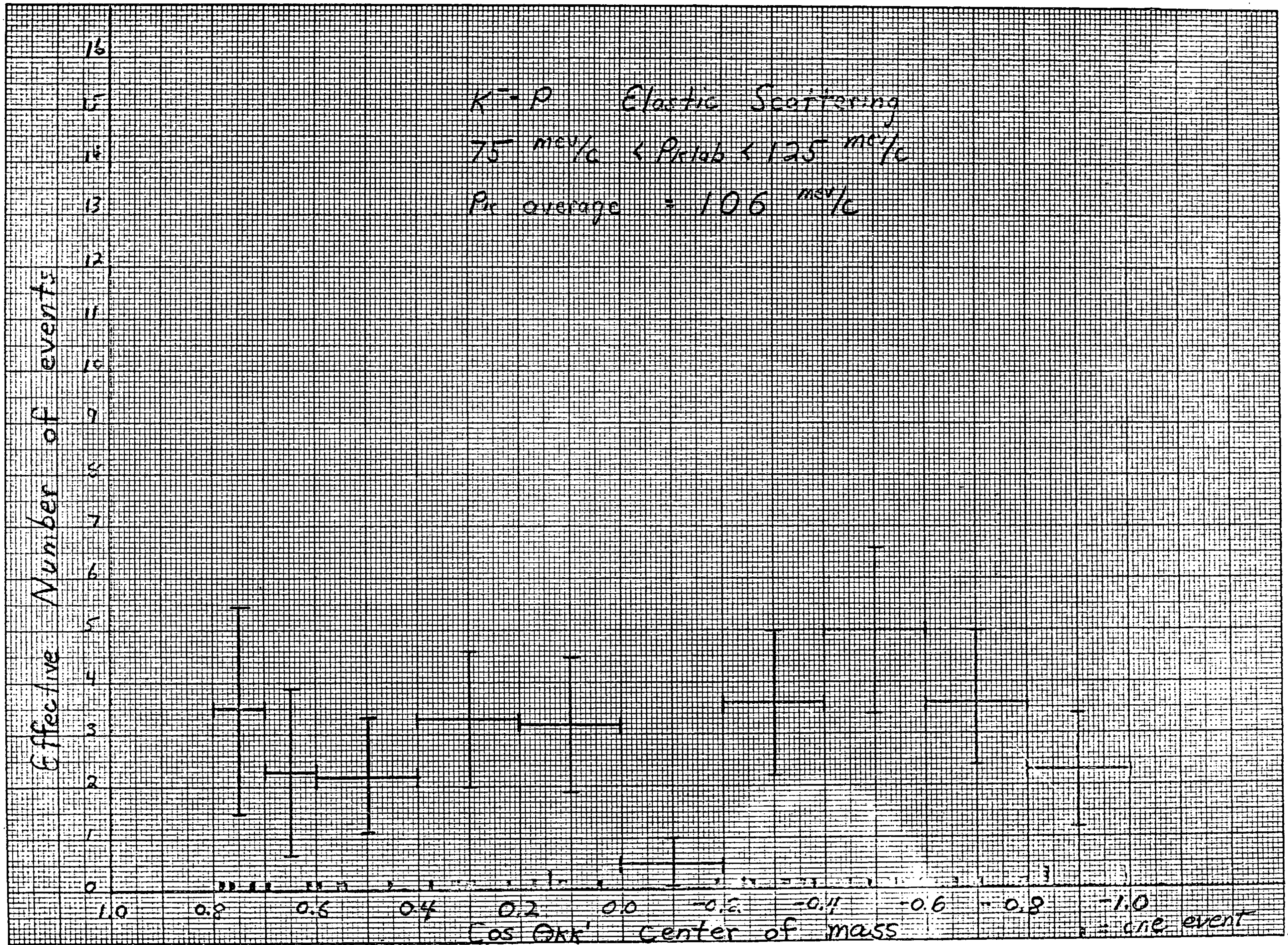

Fig. 8. Angular distribution for K⁻-- elastic scattering at 106 Mev/c.

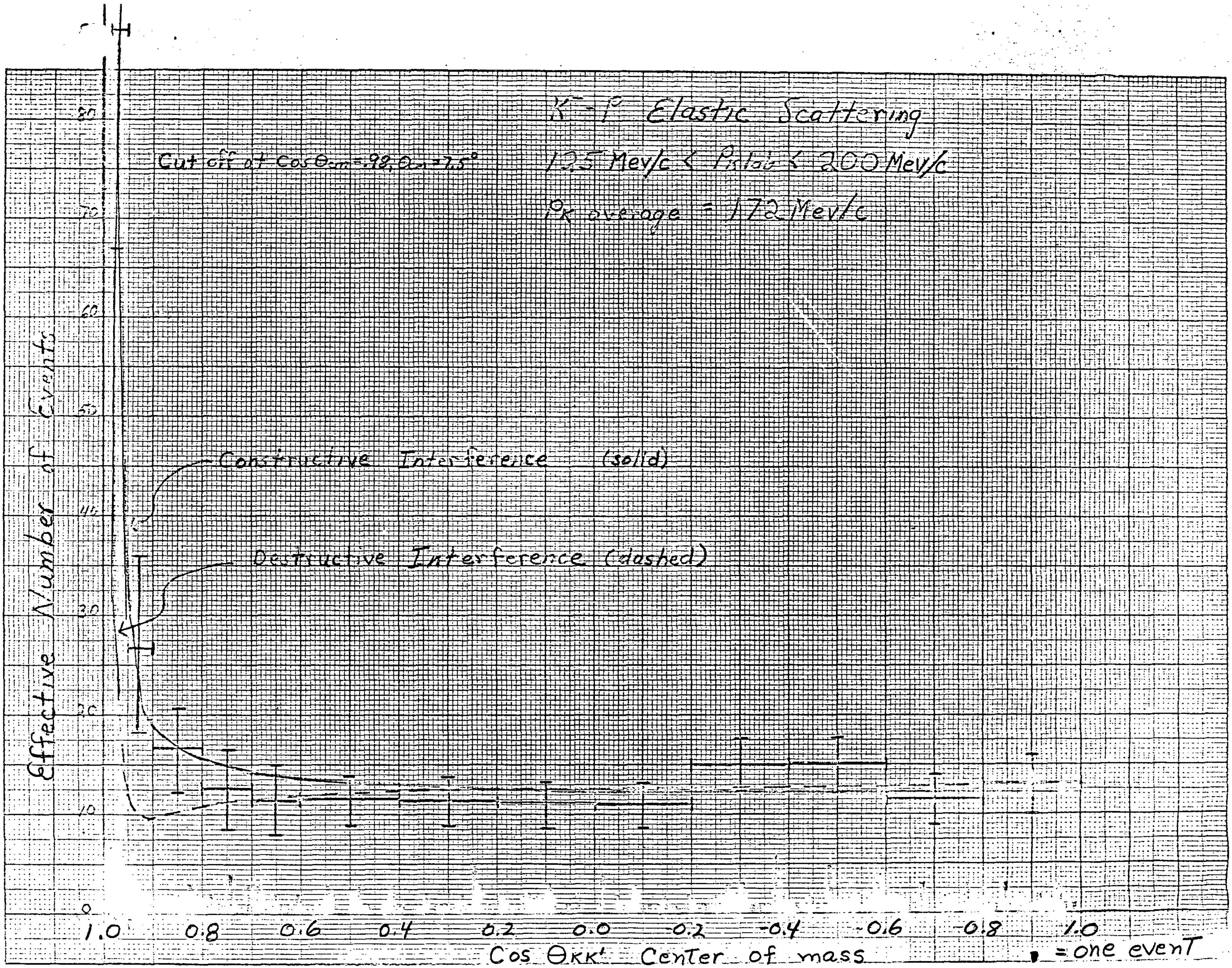

Fig. 9. Angular distribution for K^--p elastic scattering at 172 Mev/c.

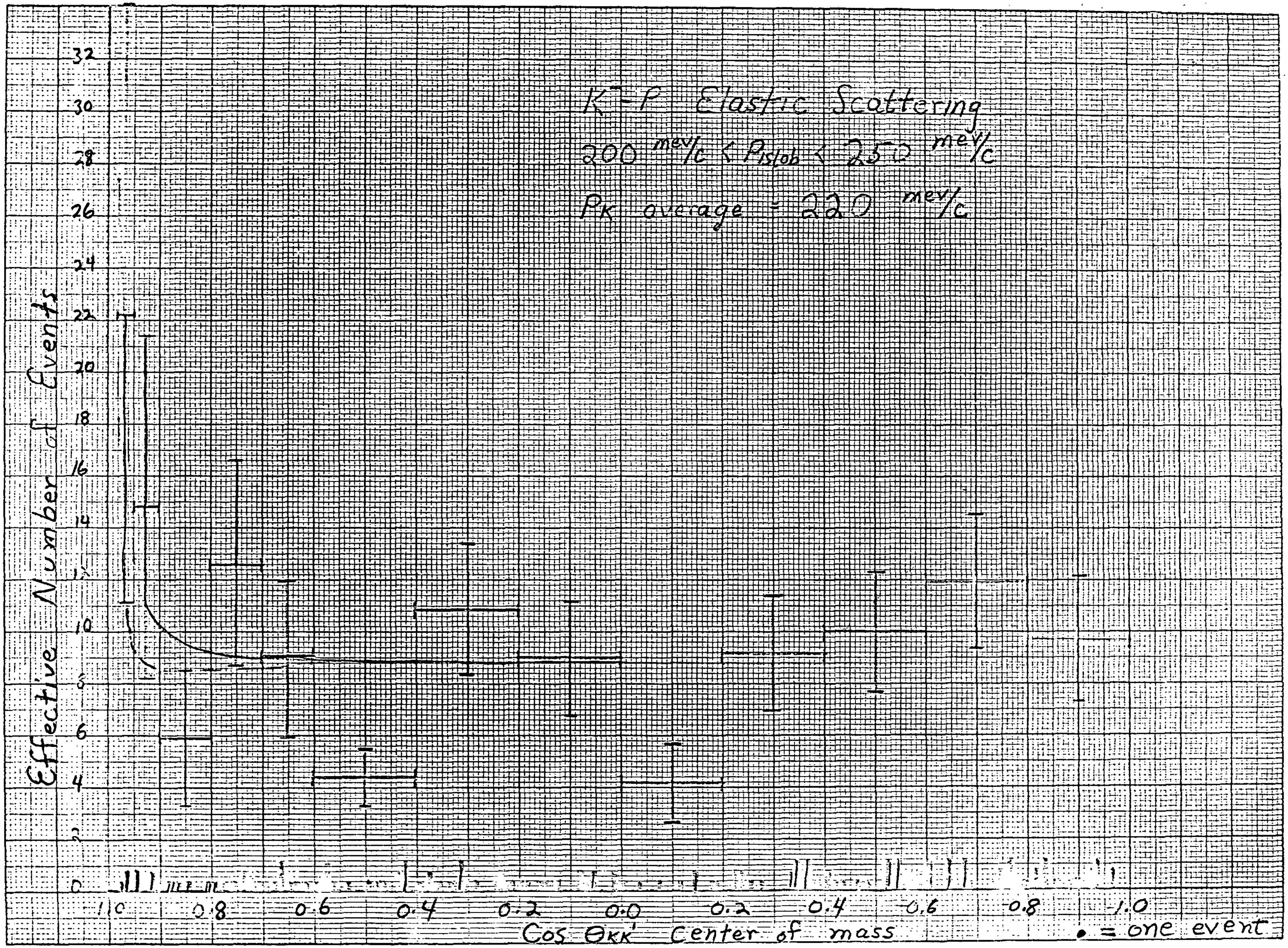

Fig. 10. Angular distribution for K^--p el ic scattering at 220 Mev/c.

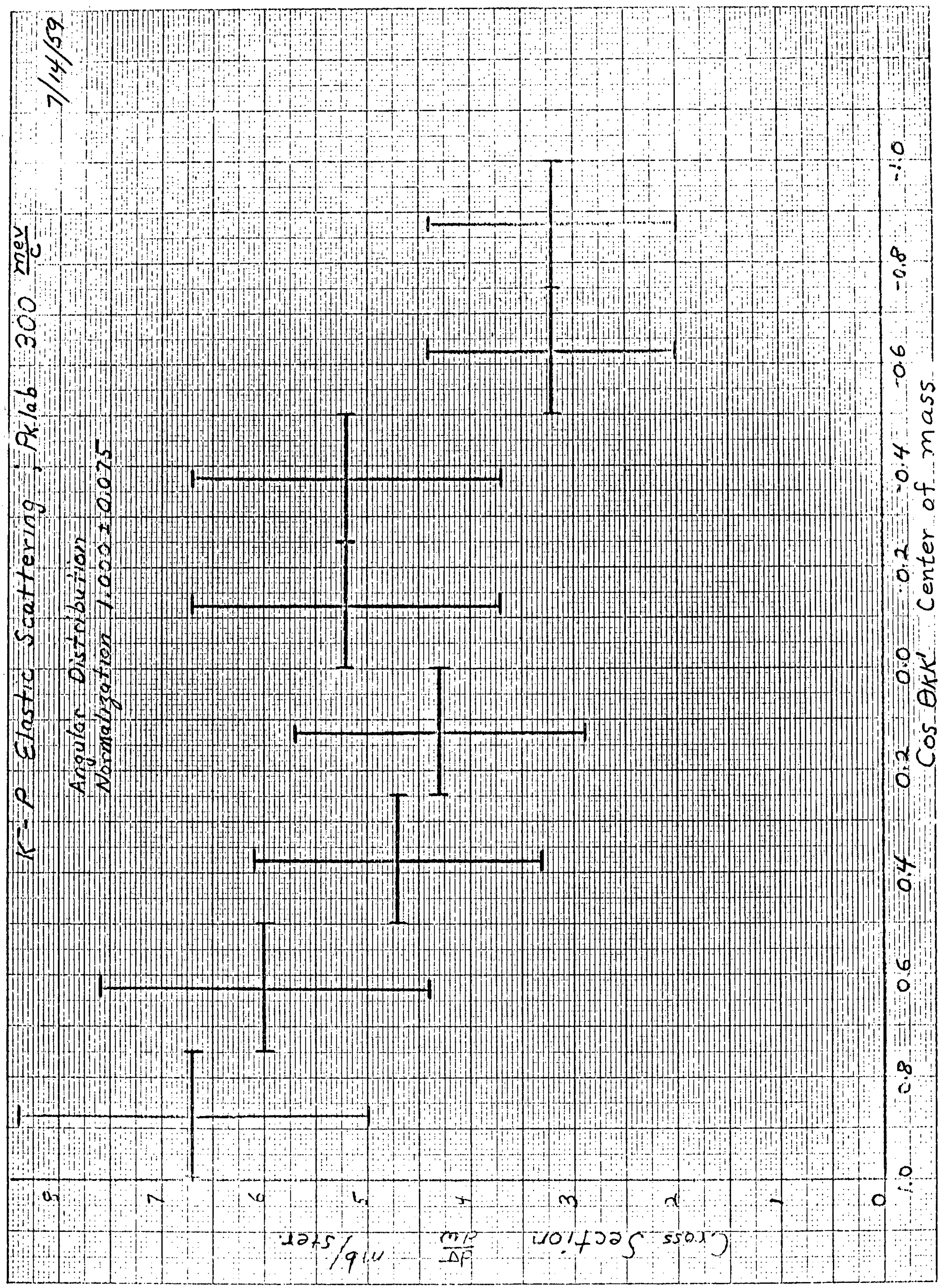

Fig. 11. Angular distribution for K^--p elastic scattering at 300 Mev/c.

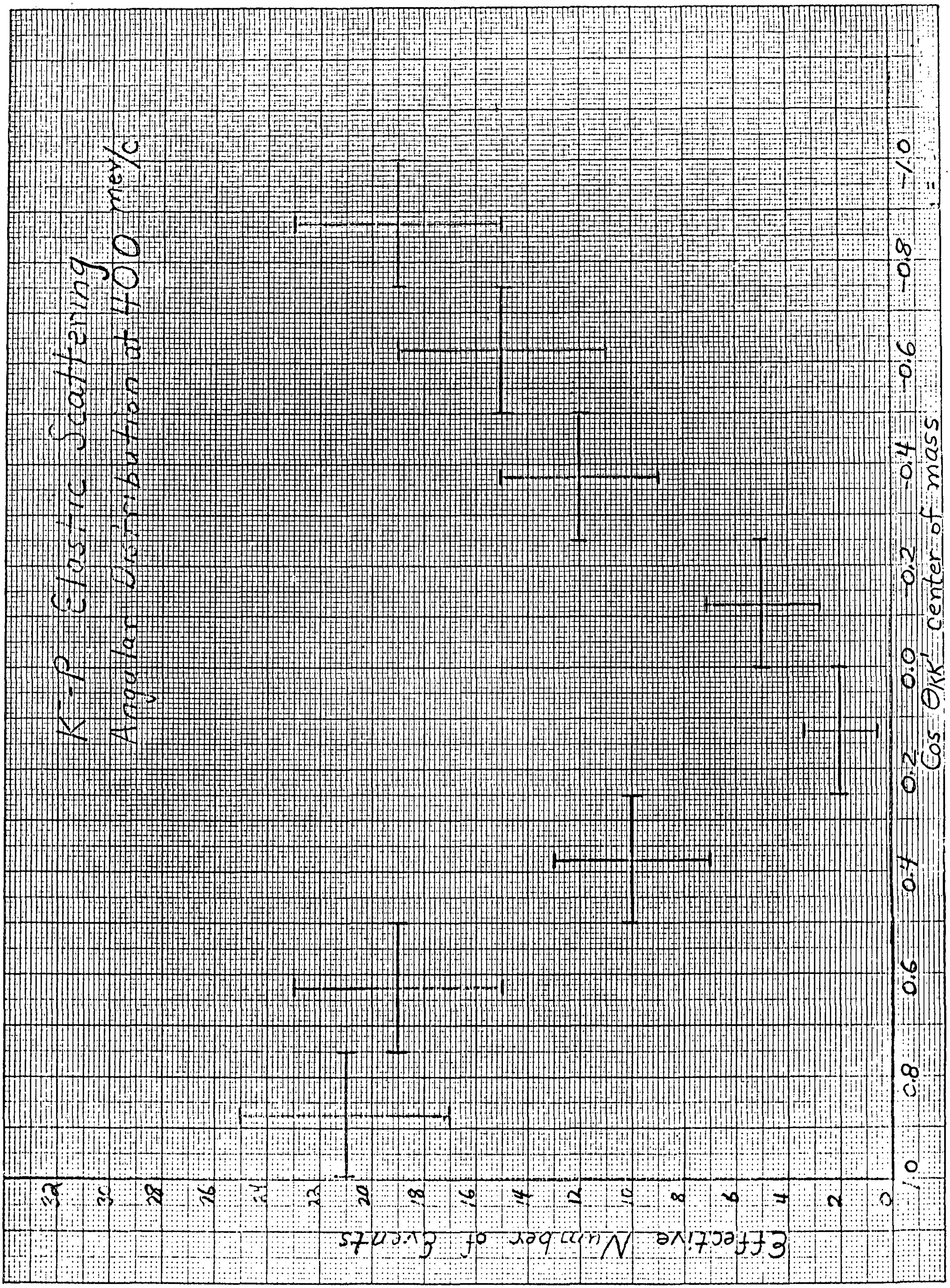

Fig. 12. Angular distribution for K$^-$-p el   ic scattering at 400 Mev/c.

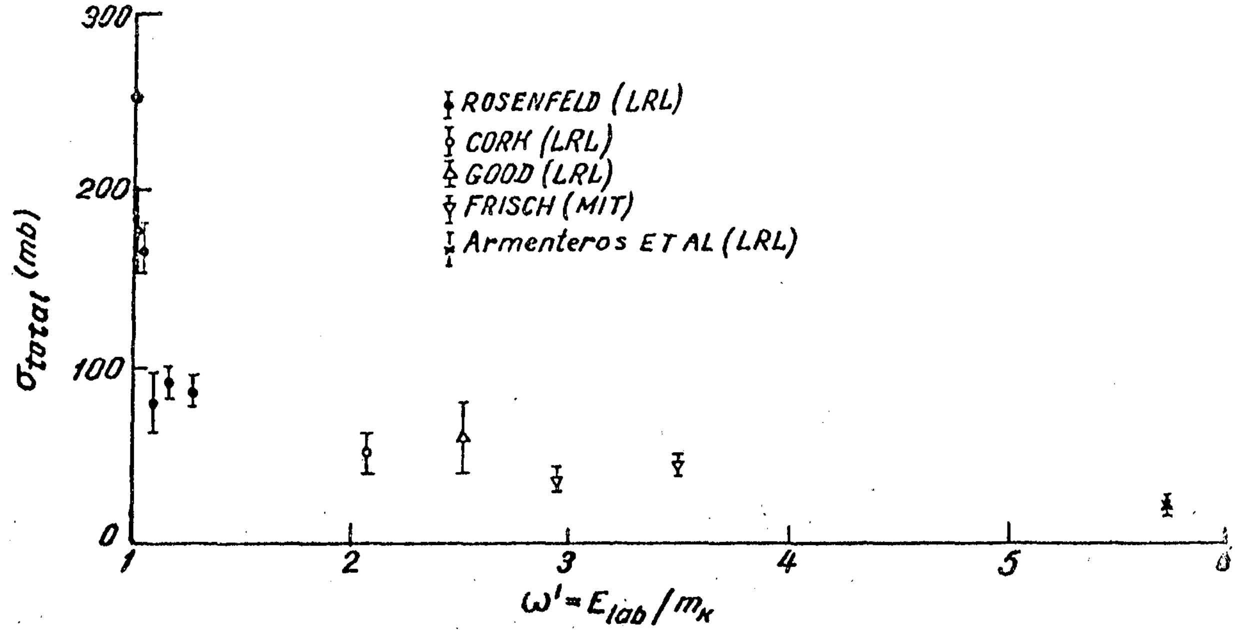

Fig.13. Energy dependence of total K^--P cross section

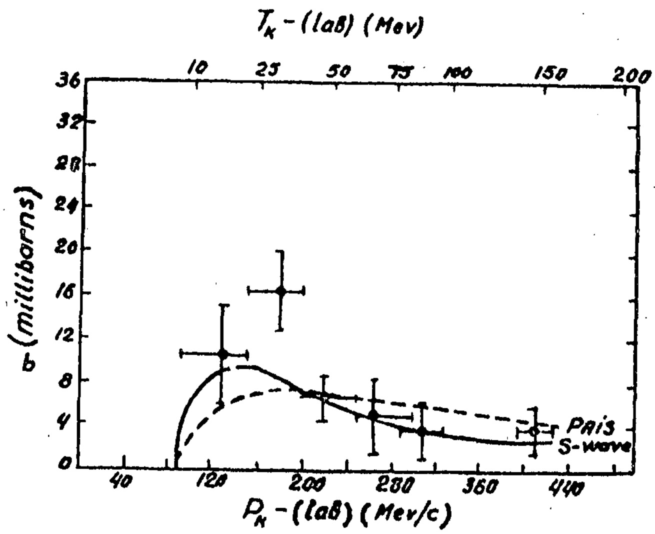

Fig.14. $\sigma(K^-P \rightarrow \overline{K^o}n)$ as a function of momentum

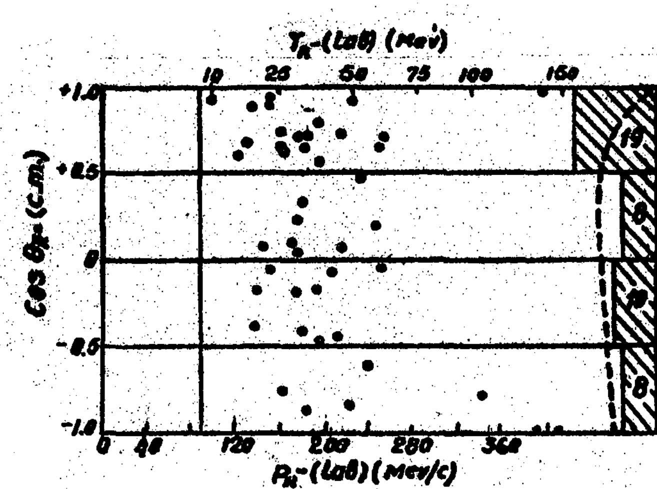

Fig. 15. Angular distributions for K^- - P charge exchange vs. momentum

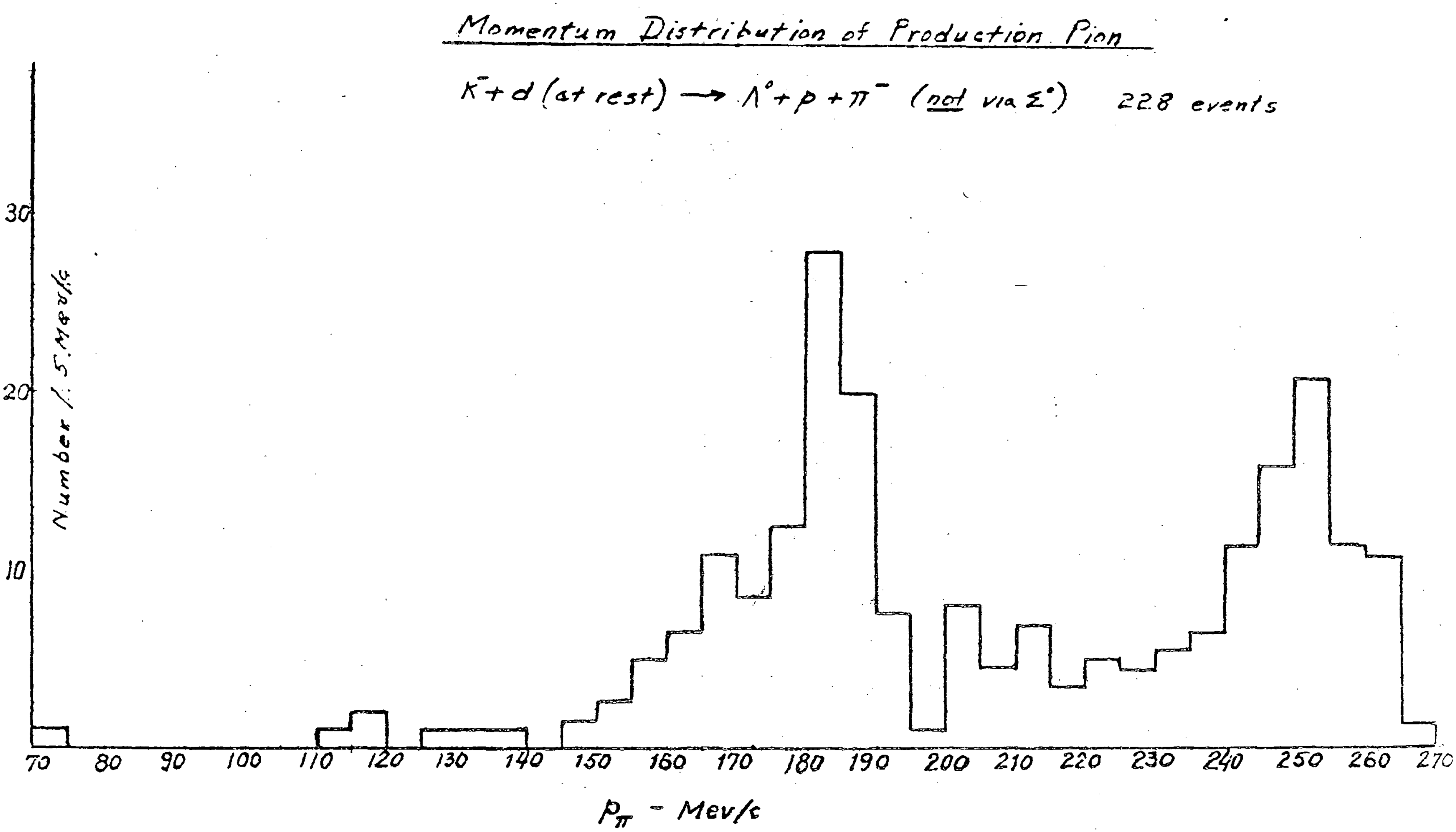

Fig. 16 . Momentum distribution of production pion

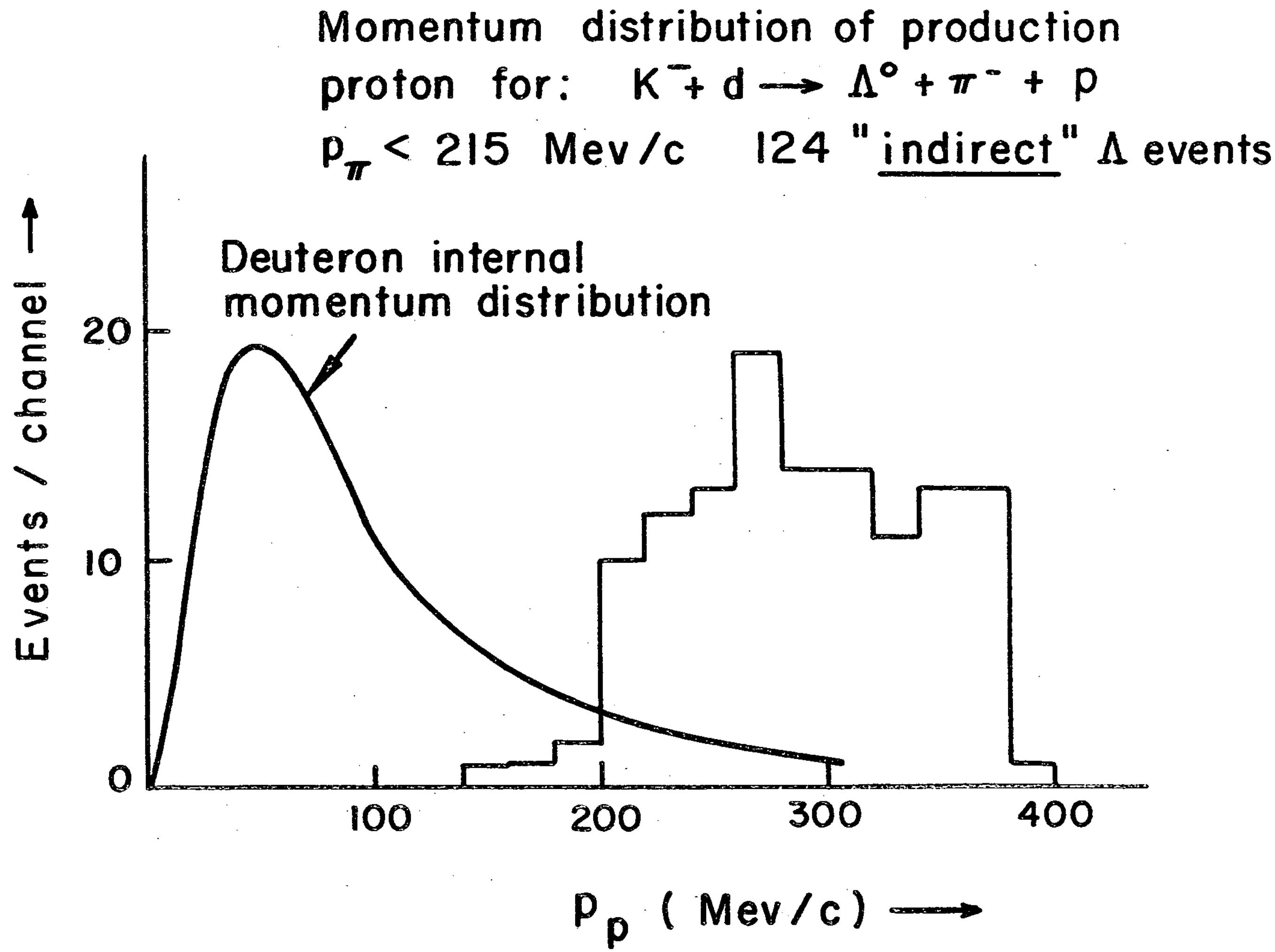

Fig. 17. Momentum distribution of production proton.

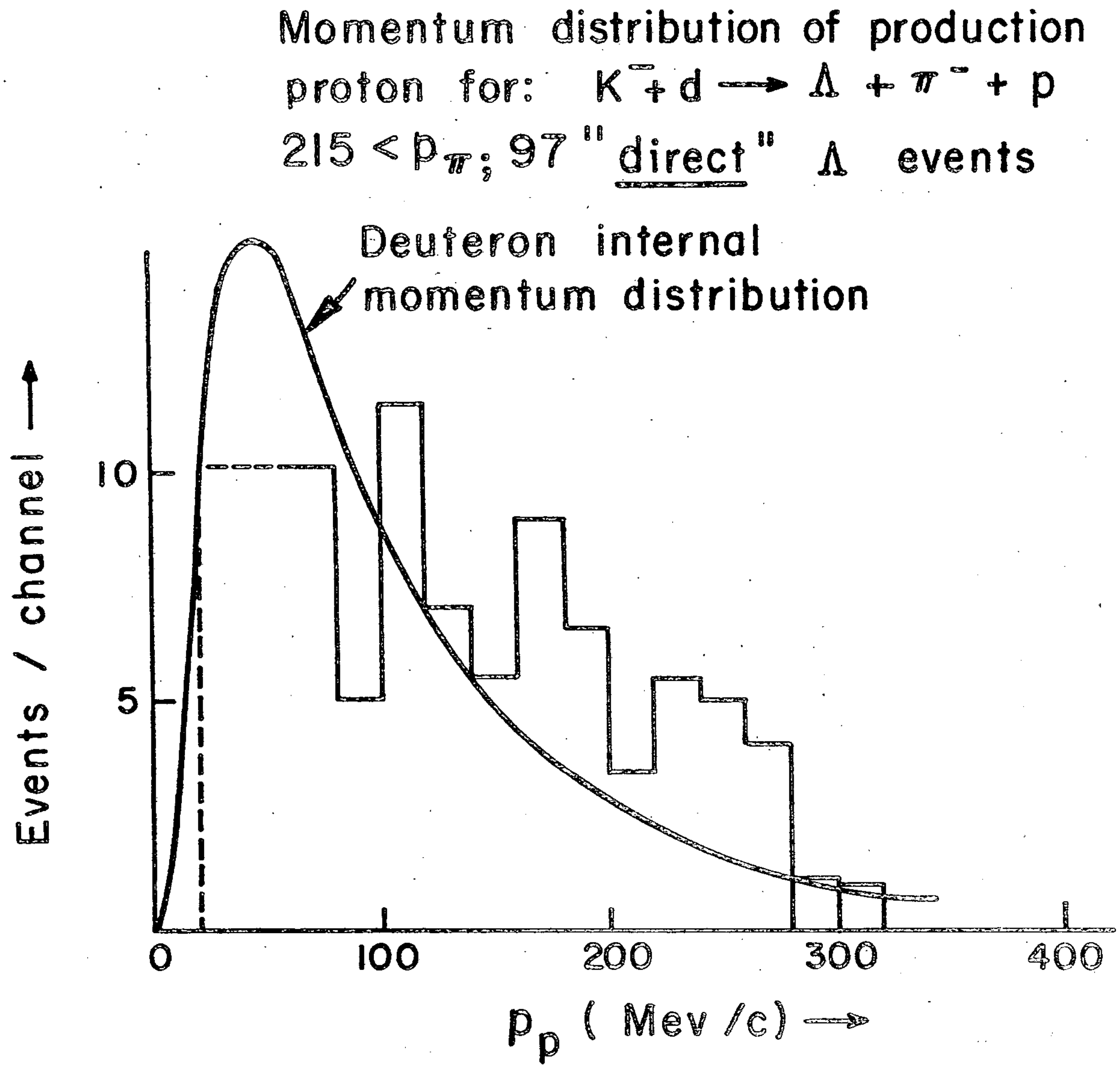

Fig. 18. Momentum distribution of production proton.

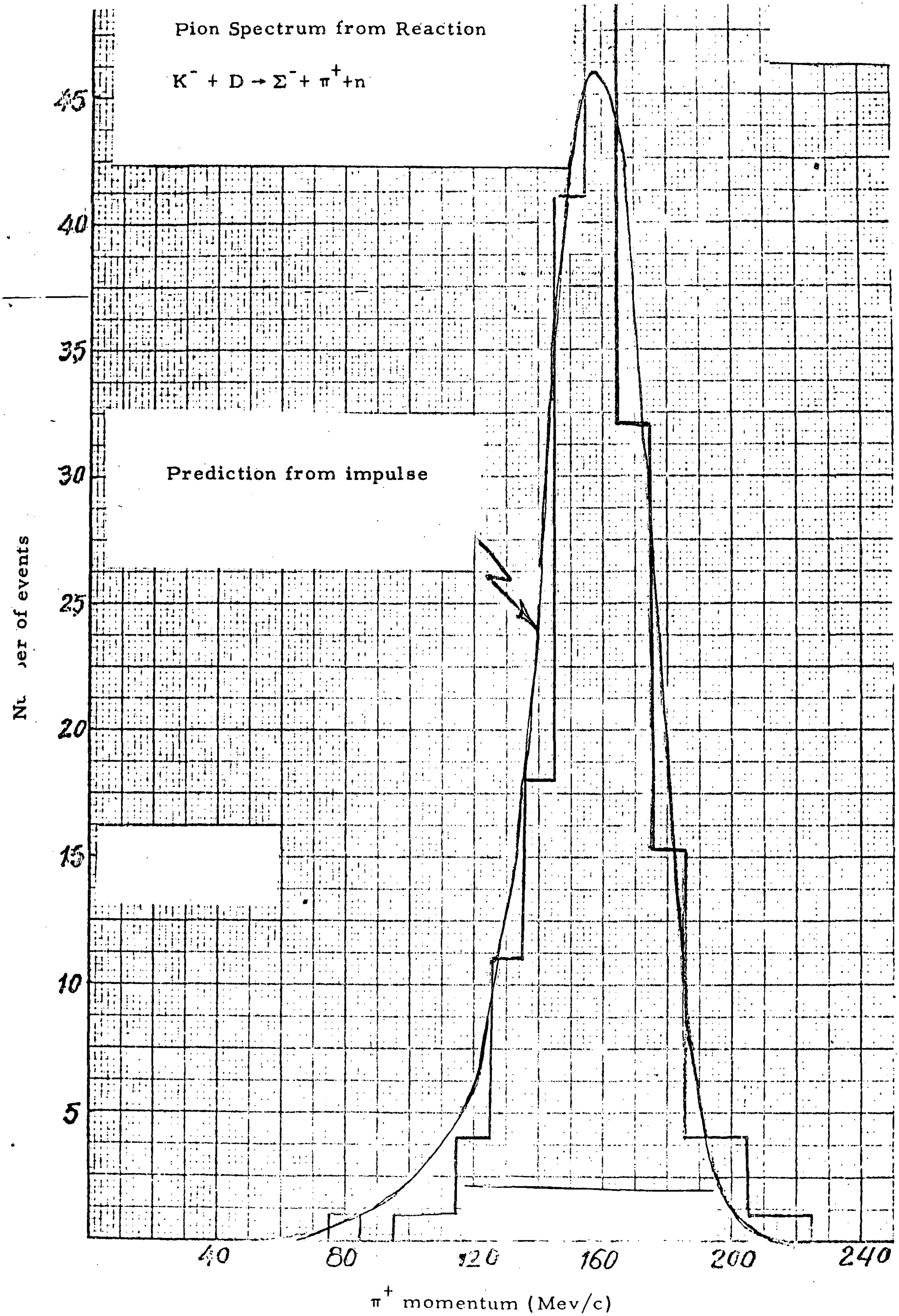

Fig. 19. Pion spectrum from reaction $K^- + D \rightarrow \Sigma^- \pi^+ n$

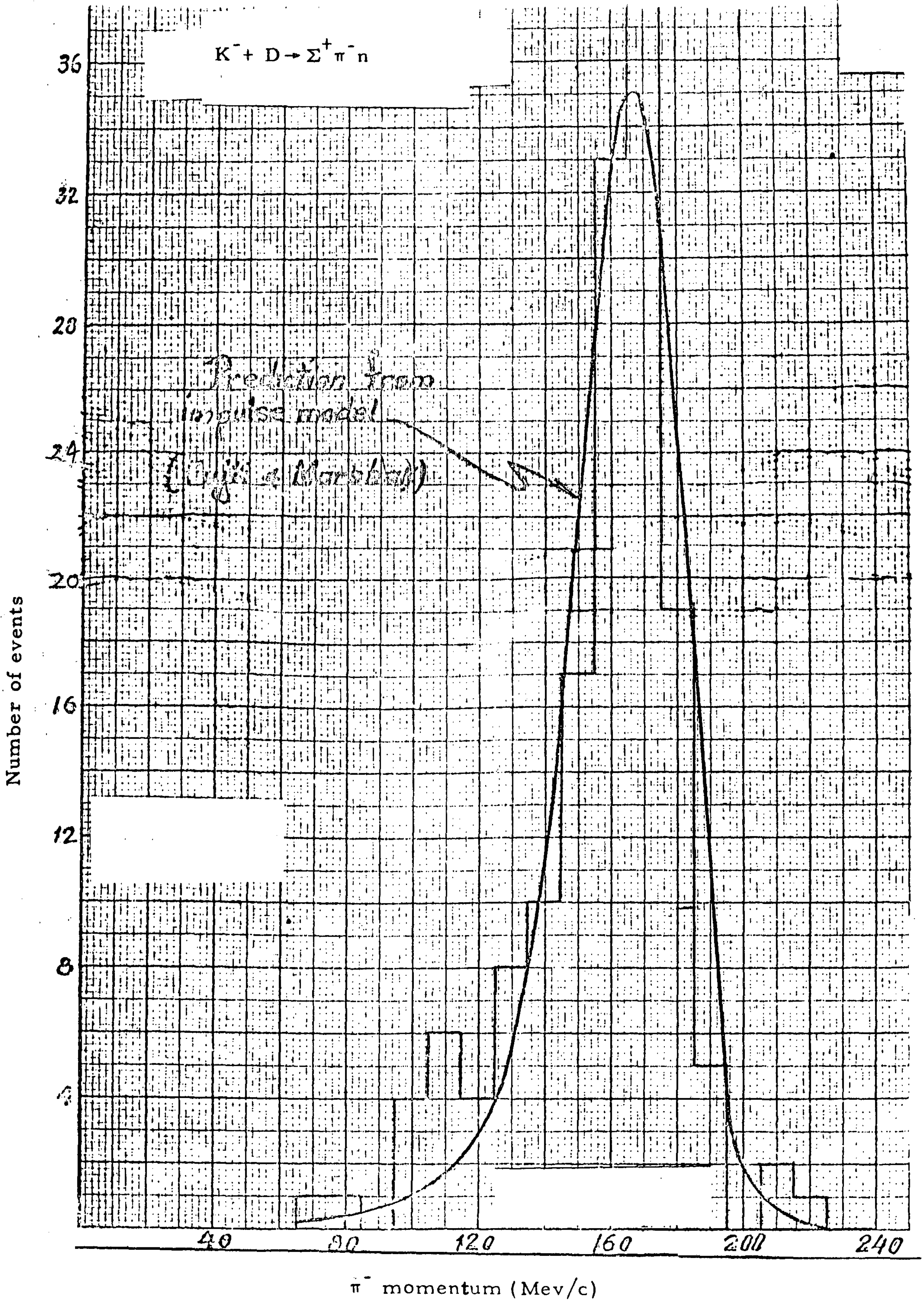

Fig. 20. Pion spectrum from reaction $K^{-}+D \rightarrow \Sigma^{+}\pi^{-}n$.

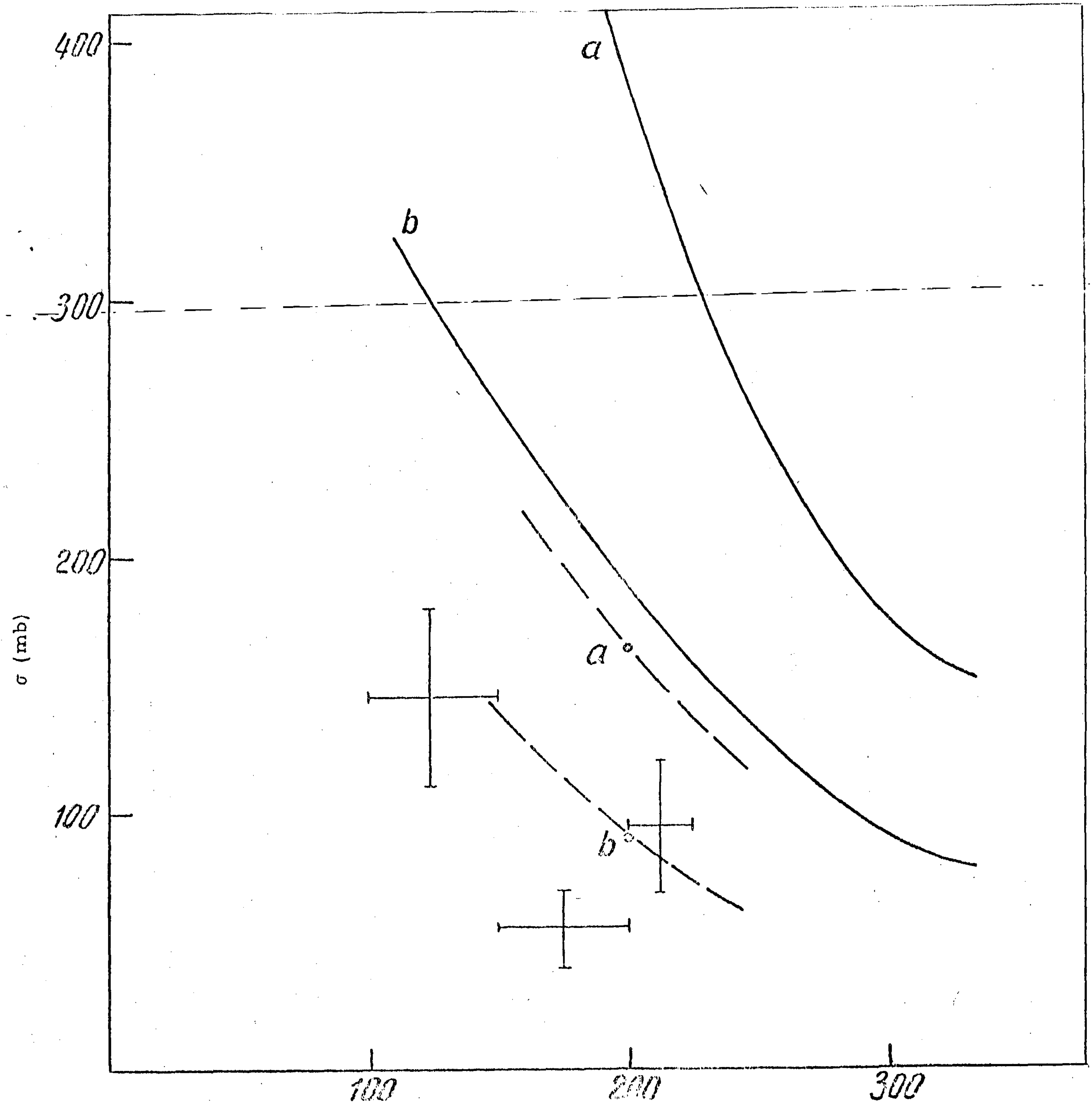

Fig. 21. K⁻-meson scattering in deuterium.

Solid Curve - prediction of pure impulse model for elastic Scattering.

Dashed Curve - prediction of impulse model, including multiple scattering corrections for the total (elastic plus in elastic) scattering cross section.

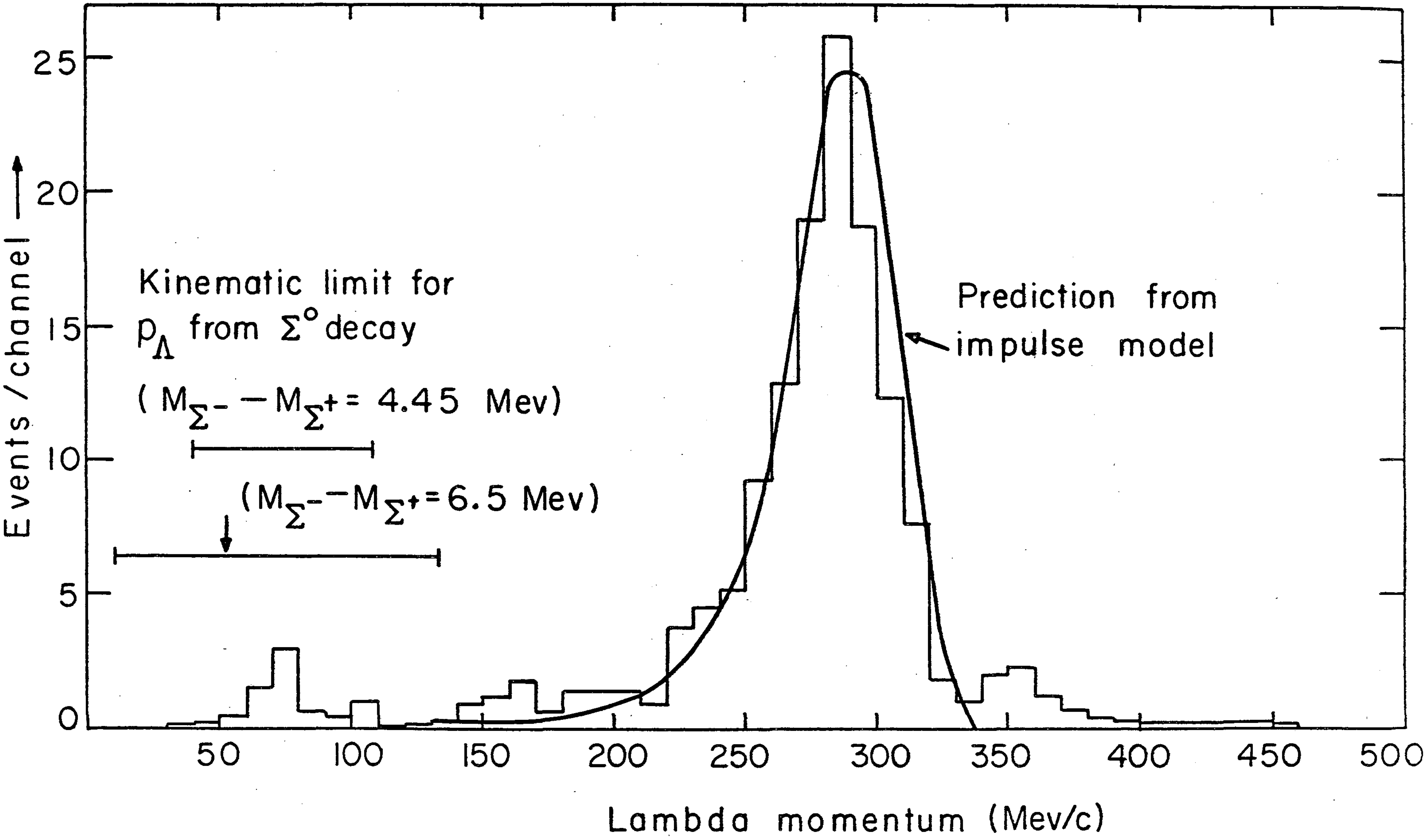

Fig. 22. Spectrum of Λ from $\Sigma^- + D \to (\Sigma^0 \text{ or } \Lambda) + 2N$.

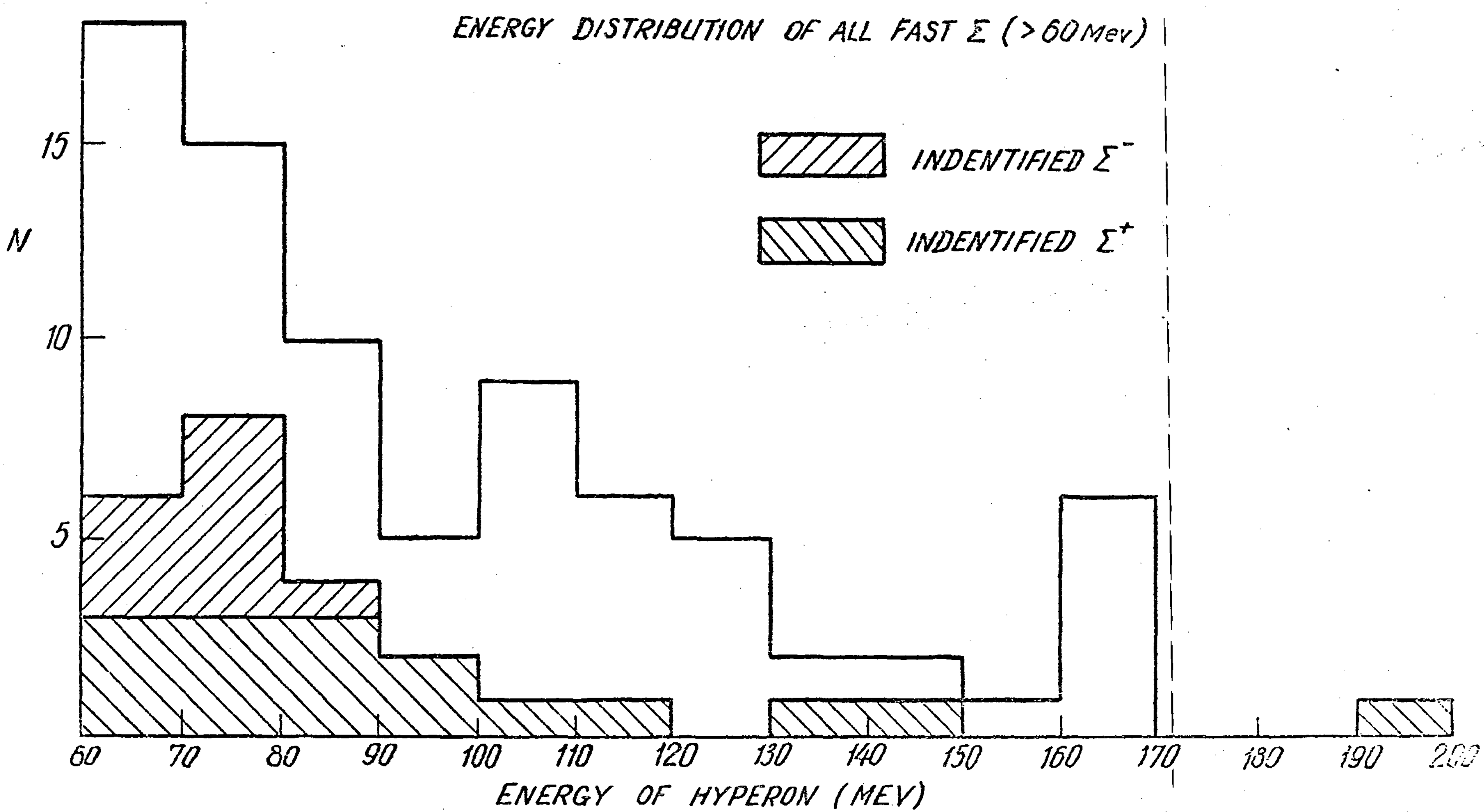

Fig. 23. Energy distribution of all fast Σ (> 60 Mev).

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