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EVIDENCE FOR THE REACTION  $P + P \rightarrow E_0 + A$

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EVIDENCE FOR THE REACTION  $\bar{P} + P \rightarrow \bar{\Sigma}^0 + \Lambda$

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April 18, 1960

EVIDENCE FOR THE REACTION  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda^*$

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We have found an event which may be interpreted as the reaction  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda$ .<sup>1</sup> The event was produced in the 72-in. liquid hydrogen bubble chamber. A highly purified beam of antiprotons of  $1.99 \pm 0.03$  Bev/c was produced by using three velocity-selecting spectrometers. The approximate composition of this beam under normal operating conditions was  $1.0 \bar{p} : 1.5 \pi^- : 1.9 \mu^- : 0.015 K^-$ . A description of the beam will be presented in a later publication.

Figure 1 is one of the three camera views of this event. Table 1 summarized the measured momenta and directions of all the tracks. The table also summarizes the "best-fit" values obtained by assuming that (a) tracks 2, 3, and 4 correspond to a  $\Lambda$  and its decay fragments  $\pi^-$  and  $p$ , respectively, and (b) that tracks 5, 6, and 7 correspond to a  $\bar{\Lambda}$  and its decay fragments  $\bar{p}$  and  $\pi^+$ , respectively. The  $\Lambda$  is produced at an angle of  $10.6 \pm 0.4$  deg and the  $\bar{\Lambda}$  at an angle of  $4.6 \pm 0.3$  deg with respect to the incident antiproton.

\* Work done under the auspices of the U. S. Atomic Energy Commission.

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Table I

## Track momenta and directions for event # 265-608

Track No.	Particle	Measured Values			Fitted values from V decay		
		Momentum (Mev/c)	Azimuth (deg)	Dip (deg)	Momentum (Mev/c)	Azimuth (deg)	Dip (deg)
1	$\bar{p}$	2019 ± 20	89.6 ± 0.1	0.7 ± 0.1			
2	$\Lambda$		79.3 ± 0.1	-0.4 ± 0.8	506 ± 9	79.4 ± 0.1	-0.7 ± 0.3
3	$\pi^-$	107 ± 4	25.0 ± 1.6	39.7 ± 1.9	107 ± 2	25.3 ± 1.4	40.2 ± 1.4
4	p	463 ± 13	86.8 ± 0.4	-9.3 ± 0.5	470 ± 8	87.7 ± 0.2	-9.2 ± 0.3
5	$\bar{\Lambda}$		92.35 ± 0.1	4.6 ± 0.3	1384 ± 15	92.34 ± 0.03	4.7 ± 0.1
6	$\bar{p}$	1180 ± 15	88.5 ± 0.1	8.0 ± 0.1	1164 ± 13	88.6 ± 0.1	7.9 ± 0.1
7	$\pi^+$	271 ± 10	110.7 ± 0.4	-11.3 ± 0.6	245 ± 2	110.5 ± 0.2	-11.0 ± 0.3

Both V's were fit by least-squares methods to the three different hypotheses of  $\Lambda$ ,  $\bar{\Lambda}$ , or  $K_1^0$  decay. The values of the resulting  $\chi^2$  functions are tabulated in Table II. The number of degrees of freedom (and therefore the expected value of  $\chi^2$ ) is three. The  $\chi^2$  values clearly indicate that tracks 2, 3, and 4 correspond to a  $\Lambda$  decay rather than a  $K_1^0$  or  $\bar{\Lambda}$  decay. Likewise, tracks 5, 6, and 7 are clearly the decay of a  $\bar{\Lambda}$ , rather than a  $K_1^0$  or  $\Lambda$ .

The next step was to decide to which of the following hyperon - antihyperon reactions this event corresponded:

- (a)  $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$
- (b)  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} + \gamma$
- (c)  $\bar{p} + p \rightarrow \Sigma^0 + \bar{\Lambda}, \Sigma^0 \rightarrow \Lambda + \gamma$
- (d)  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Sigma^0, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} + \gamma, \Sigma^0 \rightarrow \Lambda + \gamma$
- (e)  $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda + \pi^0$ .

The most descriptive way found of displaying the dynamical differences between these reactions was to plot the possible values of the laboratory production angle versus the laboratory momentum of the  $\Lambda$  or  $\bar{\Lambda}$  for each reaction. These were calculated by using the measured incident-beam momentum, 2.03 Bev/c, and are shown in Fig. 2. The solid line of Fig. 2A is a contour of allowed values of  $\theta_\Lambda$  or  $p_\Lambda$  for the reaction  $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$ . The shaded area is the region of allowed values for both the  $\Lambda$  and  $\bar{\Lambda}$  if the reaction were  $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda + \pi^0$ . On all figures, 2A through 2C, we have plotted the fitted values of  $p_\Lambda$  and  $\theta_\Lambda$  as well as  $p_{\bar{\Lambda}}$  and  $\theta_{\bar{\Lambda}}$ . The size of the black points indicates the size of the errors. Fig. 2B displays the production and decay dynamics of  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda$ . The shaded area is the region in which the  $\bar{\Lambda}$  from  $\bar{\Sigma}^0 \rightarrow \bar{\Lambda} + \gamma$  decay may fall. The solid line is the contour of allowed values of  $\theta_\Lambda$  and  $p_\Lambda$  for the directly produced  $\Lambda$ . We have

Table II

Values of  $\chi^2$  for various hypotheses

Decay				Production (and sigma decay)		
Tracks	Interpretation	$\chi^2$	Degrees of freedom	Interpretation	$\chi^2$	Degrees of freedom
2, 3, 4	$\Delta$	3.1	3	$\Delta \Sigma^0$	13	2
	$\bar{\Delta}$	no fit	3	$\Sigma^0 \bar{\Delta}$	17	2
	$K^0$	450	3	$\Delta \bar{\Delta}$	560	4
5, 6, 7	$\bar{\Delta}$	6.2	3	$\Delta \bar{\Delta} \pi^0$	90	1
	$\Delta$	no fit	3			
	$K^0$	140	3			



also drawn a dotted line for  $\Lambda$  values corresponding to the best-fit beam momentum for reactions (b) and (c) obtained by fitting the production process. A similar set of curves exists for  $\bar{p} + p \rightarrow \Sigma^0 + \bar{\Lambda}$ , where we have  $\bar{\Sigma}^0 \rightleftharpoons \Sigma^0$  and  $\Lambda \rightleftharpoons \bar{\Lambda}$ . The experimental points, of course, remain unchanged. Fig. 2C shows the allowed region for the  $\Lambda$  or  $\bar{\Lambda}$  coming from the decay of a  $\Sigma^0$  or  $\bar{\Sigma}^0$  produced in the reaction  $p + p \rightarrow \bar{\Sigma}^0 + \Sigma^0$ .

On the basis of these plots alone, we conclude that the most likely reaction is (b)  $p + p \rightarrow \bar{\Sigma}^0 + \Lambda$ . Reaction (c) appears next most likely. The other reactions are clearly ruled out.

There is additional information not shown on these graphs which may be gained by plotting this event on a stereographic projection or Wolff plot. Figure 3 is a reproduction of such a plot and shows that the two V's are not coplanar with the incident  $\bar{p}$  track (track number 1). If we assume that the reaction is  $\bar{\Sigma}^0 + \Lambda$ , then point " $\Sigma^0$ " would be the predicted direction of the  $\bar{\Sigma}^0$ . Its momentum would be  $1485 \pm 20$  Mev/c. The angle  $\theta_{\bar{\Lambda}\Sigma}$  ( $3.0 \pm 0.2$  deg) and the observed  $\bar{\Lambda}$  momentum ( $1380 \pm 15$  Mev/c) are consistent with the decay of a  $1485$  Mev/c  $\bar{\Sigma}^0$ . A similar analysis can be made assuming the event to be  $\bar{p} + p \rightarrow \Sigma^0 + \bar{\Lambda}$ . Figure 4 is the resulting stereo projection. The predicted direction of the  $\Sigma^0$  is given on this plot by the point " $\Sigma^0$ ", and its momentum is  $580 \pm 3$  Mev/c. The angle  $\theta_{\Lambda\Sigma}$  ( $7.5 \pm 0.6$  deg) and the observed  $\Lambda$  momentum ( $520 \pm 9$  Mev/c) are consistent with the decay of a  $580$  Mev/c  $\Sigma^0$ . Therefore, on the basis of decay either reaction (b) or reaction (c) could fit the observed angles and momenta.

In order to summarize the relative likelihoods of reactions (b) and (c), we have constructed  $\chi^2$  functions for the production process plus the decay of the antisyigma or sigma. With the use of fitted values from the  $\Lambda$  and  $\bar{\Lambda}$

decays, the number of degrees of freedom for this combination is two. For the reaction (b), the composite  $\chi^2$  is 13, and for the reaction (c), the composite  $\chi^2$  is 17. Admittedly obtaining a  $\chi^2$  of 13 or 17 when the expected value is 2 indicates that reactions (b) or (c) are not very likely. However, before we attach significance to the actual magnitude of  $\chi^2$ , we must thoroughly understand the assigned measurement errors. At the present time, our information regarding systematic errors in the 72-in chamber is fragmentary. We mention  $\chi^2$  only as an indication of the relative likelihood of the various hypotheses. In Table II, we have summarized the composite  $\chi^2$  for the reactions that we could treat with our present techniques. It is clear that on the basis of  $\chi^2$  we cannot decide between reaction (b) and reaction (c). However, the two rates must be equal if CPT invariance is not violated by these strong interactions. On this basis, the observation of reaction (b) is evidence for reaction (c) and vice versa.

We have observed only one  $\Lambda \Sigma^0$  (or  $\bar{\Lambda} \Sigma^0$ ) reaction in  $\approx 6000$  antiproton interactions. Since  $2/3 \times 2/3 = 4/9$  of the reactions yielding  $\Lambda \bar{\Lambda}$  will give an observable pair, we conclude that on the basis of one event, the frequency of production is about  $1/3000$ . The known total cross section is about  $90 \text{ mb.}^2$  This indicates that the  $\Lambda + \Sigma^0$  cross section is about  $30 \mu\text{b.}$

We have also considered the possibility that this event is the reaction  $\pi^- + p \rightarrow K^0 + \Lambda + \pi^0$  where the  $K^0$  decays via the leptonic mode of decay in such a way as to look like a  $\bar{\Lambda}$  decay. We have, therefore, calculated on the basis of dynamics alone the probability for a  $K_2^0$  to decay giving the  $V$  that we have interpreted as  $\Lambda$  decay. It is impossible for  $K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$  to fit. However, it is possible to obtain a fit for the decay modes  $K_2^0 \rightarrow \mu^\pm + \pi^\mp + \nu$  and  $K_2^0 \rightarrow e^\pm + \pi^\mp + \nu$ . But when we estimate the number of events of this type that we should expect to see on the basis of the known  $\pi^- + p \rightarrow \Lambda + K^0 + \pi^0$

background events and the conditions for ambiguity in  $K_2^0$  vs  $\bar{\Lambda}$  decay, we find less than  $10^{-6}$  of an event.

It is also dynamically possible for the reaction  $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda + \gamma$  to give rise to the observed event. This, however, is very unlikely because of the small probability of radiative production with a  $\gamma$ -ray of 75 Mev/c.

This experiment would certainly not have been possible without the stimulation and foresight of Professor Luis W. Alvarez. An experiment of this difficulty owes its success to a great many people. Graduate students Morris Pripstein and Ngyen H. Xuong have contributed long and tiring hours both in the development and in the operation of the antiproton beam. One can hardly over-emphasize the indebtedness we owe to the people who built and operated the 72-in. bubble chamber, notably James D. Gow, Paul Hernandez, and Robert Watt. Members of Professor Burton J. Moyer's group contributed to the electronic aspect of the beam development and operation. Our thanks go to Drs. Margaret Alston and Hugh Bradner and the scanners for their contribution to the experiment. We are greatly indebted to Jon Peter Berge for assistance in the IBM analysis of our events. Finally we wish to thank the Bevatron crew who had the difficult task of producing the high-flux, short-spill beam that was necessary for this bubble chamber experiment.

REFERENCES

1. Janice Button, Bull. Am. Phys. Soc. 5, 54 (1960).
2. R. Armenteros, C. Coombes, B. Cork, G. Lambertson, and W. Wenzel (to be published).

## LEGEND

- Fig. 1. One view of the event  $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda$  or  $\bar{\Lambda} + \Sigma^0$  found in the 72-in. hydrogen bubble chamber.
- Fig. 2. Contours of  $\theta_{\Lambda}$  vs  $p_{\Lambda}$  or  $\theta_{\bar{\Lambda}}$  vs  $p_{\bar{\Lambda}}$  for all possible antihyperon production reactions yielding  $\Lambda$  and  $\bar{\Lambda}$ . Momentum of the incident  $\bar{p}$  is the measured value of 2.03 Bev/c. Fitted values of observed  $\Lambda$  and  $\bar{\Lambda}$  of the sigma-lambda event are indicated by black dots. In B, the dotted curve represents  $\Lambda$  kinematics for the fitted 1.97 Bev/c incident momentum.
- Fig. 3. Stereographic plot of the  $\bar{\Sigma}^0 + \Lambda$  interpretation.
- Fig. 4. Stereographic plot of the  $\bar{\Lambda} + \Sigma^0$  interpretation.

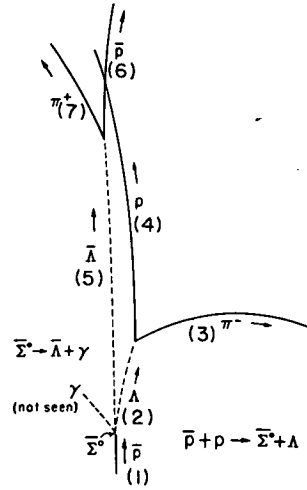
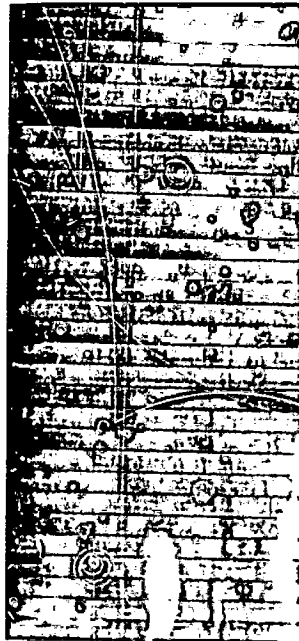
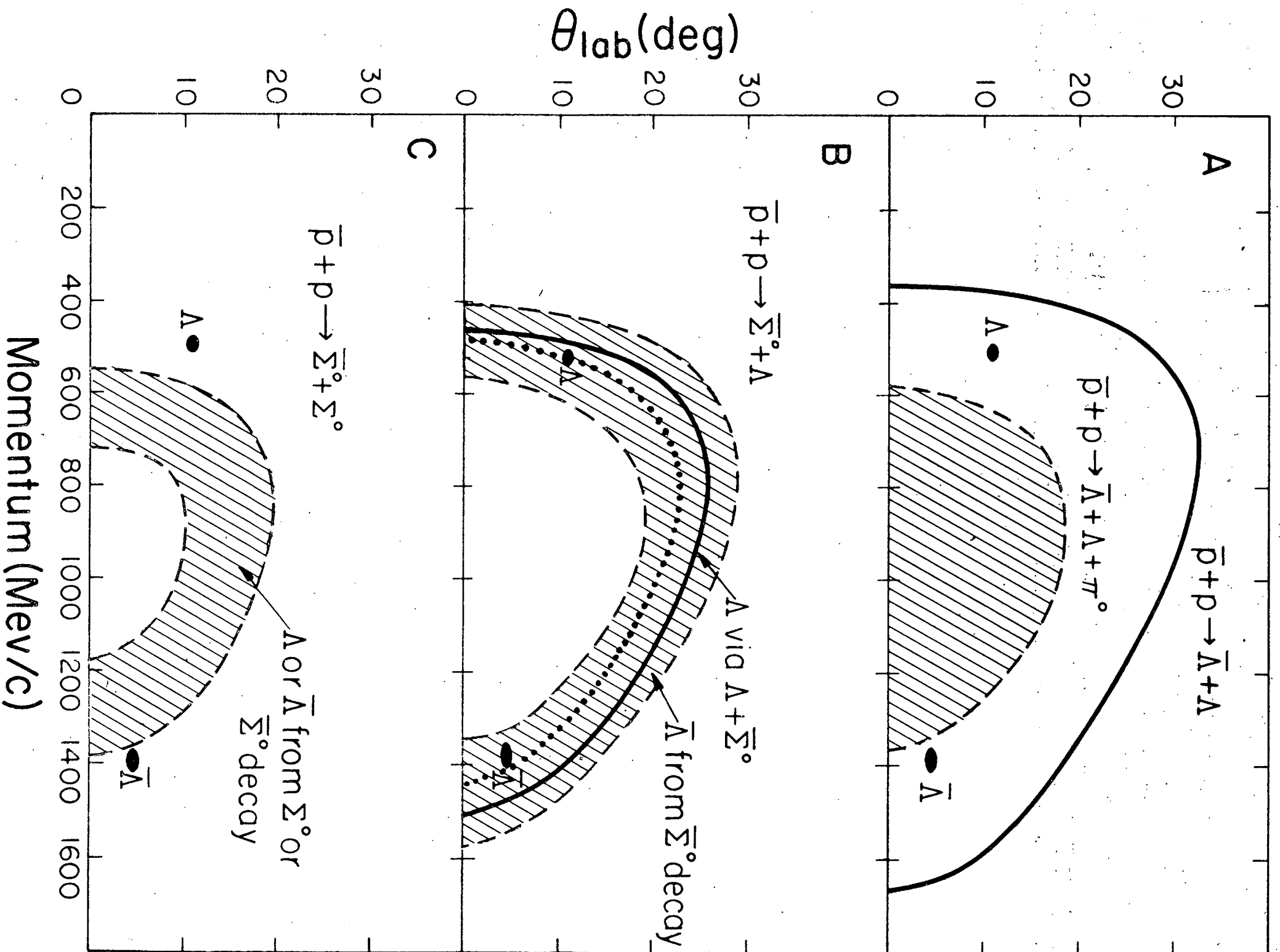


Fig 1



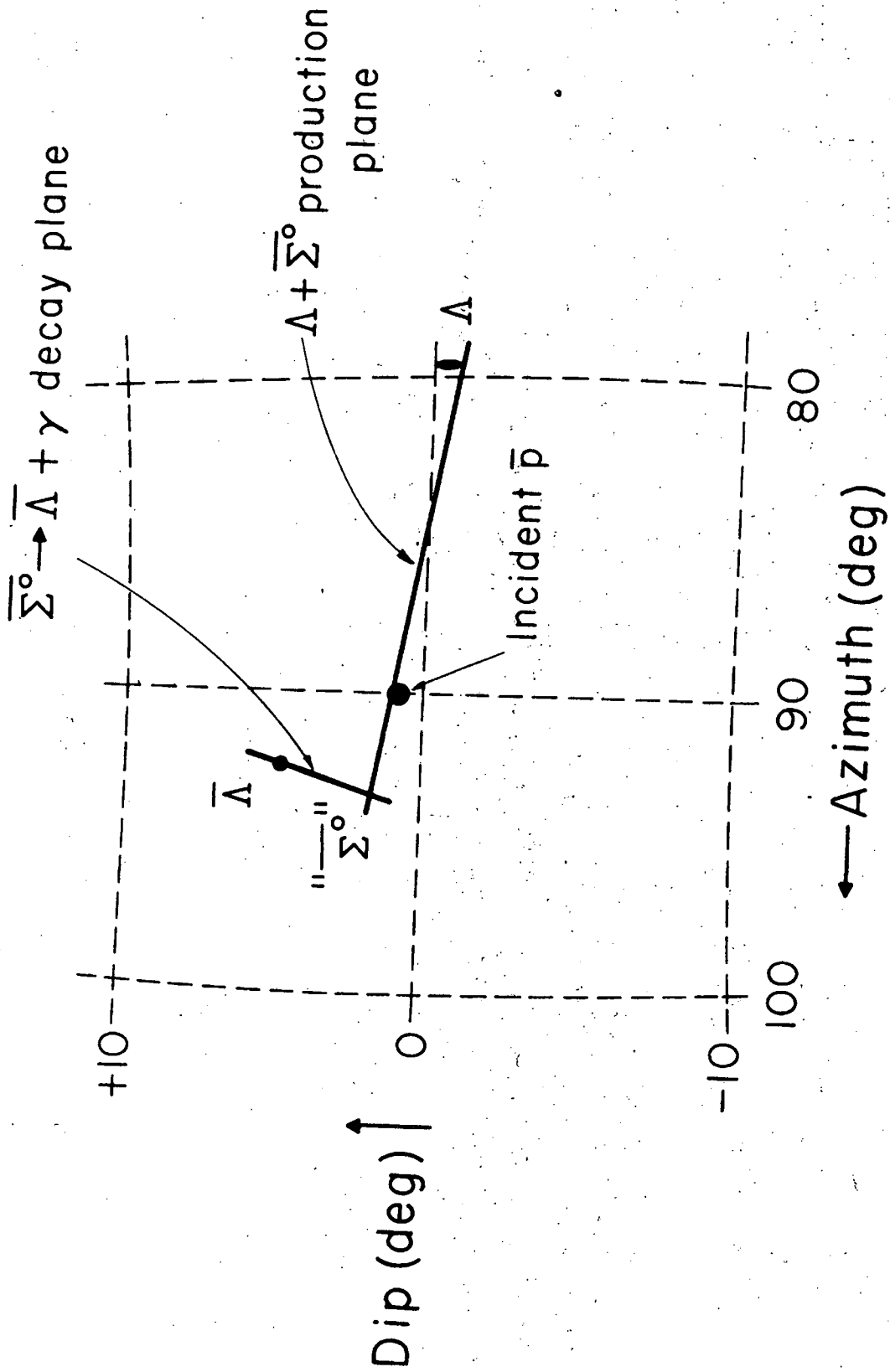


Fig 3



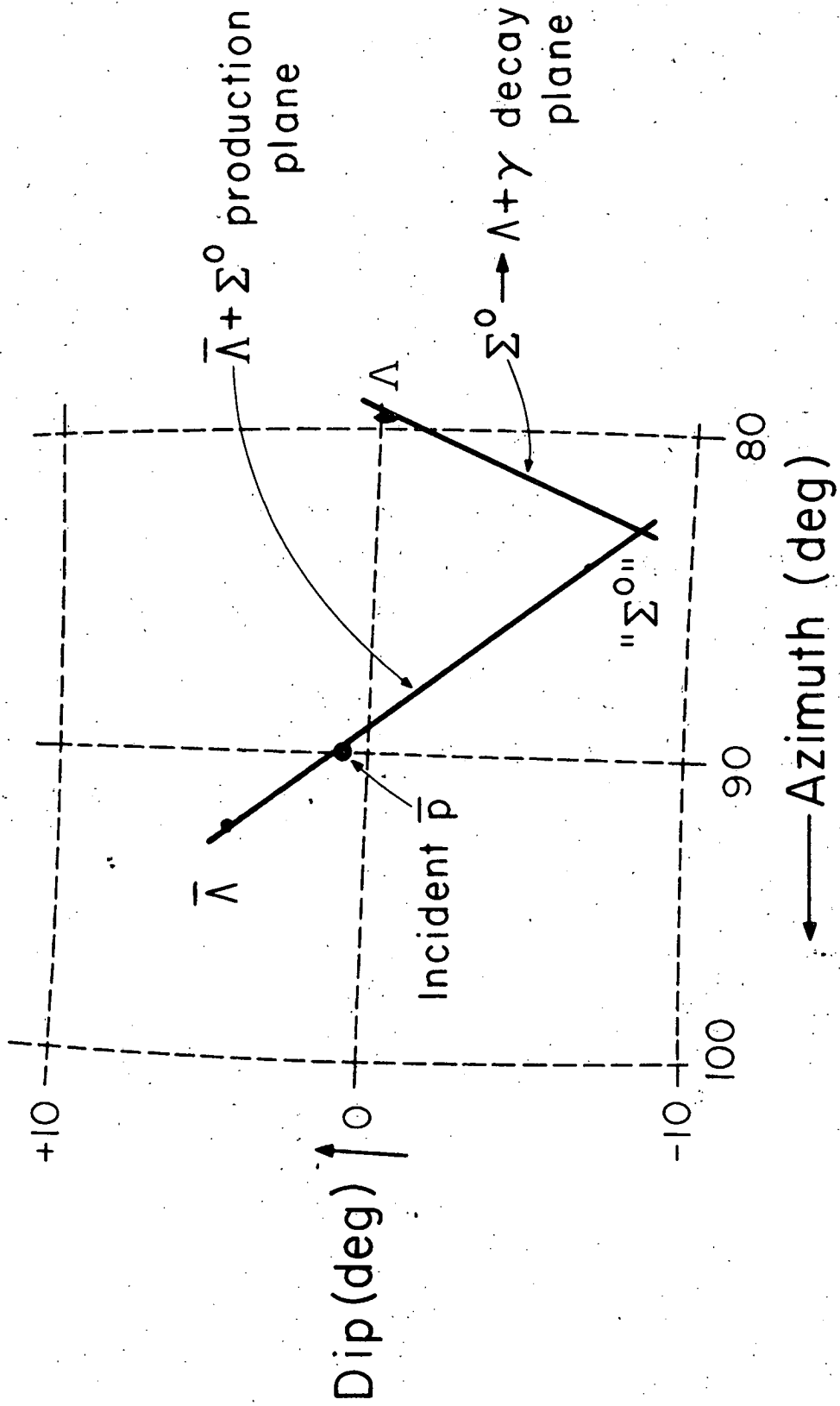


Fig 4