Production of V Particles by 3-Bev Protons*

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With a well-collimated beam of 3-Bev protons and a hydrogen-filled diffusion cloud chamber a search has been made for V particles from p-p collisions. The rarity of such events leads to the conclusion that the V-production cross section is probably less than 0.2 mb. This value is significantly smaller than the $\sim$1 mb V-production cross section observed for π^--p collisions at comparable center-of-mass energies. At the same time a cross section of 7.4±1.5 mb is obtained for iron (per nucleus). A direct comparison of p-p and p-Fe interactions under essentially similar conditions allows us to conclude that an interaction with an iron nucleus is at least 4 times more effective in producing V's than is an interaction with a free proton.

I. INTRODUCTION

THE reactions $\pi^-+p\rightarrow Y+K$ have been investigated extensively since the final state has only two particles and is kinematically simple to study. The cross section for these reactions is about 1 millibarn.[1] Examples of the production of V particles in free nucleon-nucleon collisions have been observed,[2] but are not numerous. Experiments in which V particles are produced by neutron and proton beams incident on iron, lead, or other nuclei have not yet yielded detailed information on production in nucleon-nucleon collisions, though there is some evidence that the production cross section is smaller than in pion-nucleon collisions.[3]

In the present experiment, proton-proton collisions were observed in a hydrogen-filled diffusion cloud chamber. The same chamber as that used for the π^--p production work was employed. A well-collimated beam was passed through the chamber in order to increase the number of protons traversing the chamber per photograph. This procedure at the same time decreases the definition of the events and obscures a small but significant volume in the chamber. A 0.043-cm thick iron (Fe) foil was also placed in the visible portion of the chamber to make possible a direct comparison between the production in H and in a heavy element.

Our data indicate that the cross section for producing strange particles is significantly smaller for p-p than for π^--p collisions, for a comparable available energy in the center-of-mass system. The probability of an associated production event in Fe per inelastic collision is considerably larger than for a free proton-proton collision. Implications of this result and a comparison with other recently reported data[4,5] will be discussed.

II. EXPERIMENTAL PROCEDURE

The external proton beam of the Cosmotron has a maximum density of about 10^9 protons per cm^2 per pulse. It could thus, in principle, supply an extremely well-defined beam of $\sim$1000 protons per pulse which would produce one p-p interaction in the chamber per photograph. With such a well-defined beam passing through the central region of the chamber, events could be found and identified almost as well as if individual tracks were passing through. If, for example, the V event cross section were $\sim$1 mb, one would expect to observe about 100 such events per day with a 5 second chamber repetition rate.

At these energies direct collimation of the beam is impractical. The thickness of such a collimator is so great that scattering and production in the walls of the collimator will not only spread the beam spatially, but will introduce an undesirable contamination of lower energy pions and protons. In order to avoid these difficulties, a method was attempted which makes use of the "optical" properties of the external beam.[6] The schematic arrangement of the apparatus is shown in Fig. 1. The protons of the circulating beam enter the magnet $M1$, which deflects them outward through the Cosmotron field. A system of magnetic shims partially corrects the strong defocusing effect of the fringing field of the Cosmotron which would otherwise be present. The Cosmotron-shim magnetic system, taken as a whole, is such that it produces a beam approximately parallel in the horizontal plane at the output of the shim system. In the vertical plane there is a relatively sharp crossover located in the external shim system. The method we used was to place collimators at the entrance to magnet $M1$ and at the exit of the shims.

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[1] See for example: Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955); W. D. Walker and W. D. Shephard, Phys. Rev. **101**, 1810 (1956); Budde, Chretien, Leitner, Samios, Schwartz, and Steinberger, Phys. Rev. **103**, 1827 (1956).

[2] Block, Harth, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **99**, 261 (1955); Wright, Saphir, Powell, Maenchen, and Fowler, Phys. Rev. **100**, 1802 (A) (1955).

[3] Walker, Preston, Fowler, and Kraybill, Phys. Rev. **97**, 1086 (1955); E. Mosburg, thesis, Yale University, June, 1956 (unpublished); Cookson, Bowen, Tagliaferri, Werbrouck, and Moore, Bull. Am. Phys. Soc. Ser. II, **1**, 19 (1957); Blumenfeld, Boldt, Bridge, Caldwell, Pal, and Leavitt, Bull. Am. Phys. Soc. Ser. II, **1**, 19 (1957).

[4] D. Berley and G. B. Collins, Bull. Am. Phys. Soc. Ser. II, **1**, 320 (1956).

[5] Harris, Orear, Taylor, and Baumel, Bull. Am. Phys. Soc. Ser. II, **2**, 221 (1957), and private communication.

[6] Piccioni, Clark, Cool, Friedlander, and Kassner, Rev. Sci. Instr. **26**, 232 (1955).

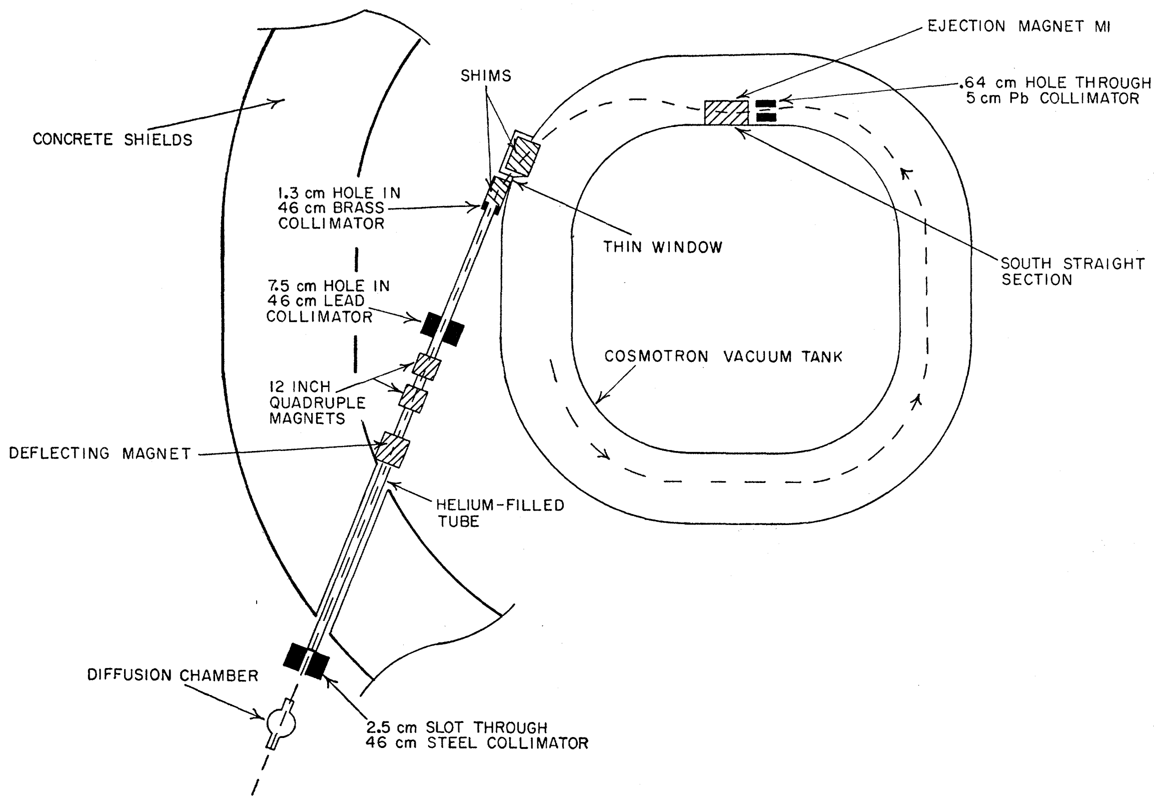

FIG. 1. Schematic drawing of the experimental arrangement for producing the proton pencil beam at the Cosmotron. See Sec. II for details.

By thus "stopping down" the Cosmotron-shim lens system, we hoped to reduce the aberrations. An external quadrupole lens was then suitably adjusted to produce an image at the chamber of a horizontal object at infinity and a vertical object at the vertical cross-over in the shim system. No appreciable momentum selection takes place after the beam leaves the shim system other than that supplied by the quadrupole lens. The collimators beyond the shims do not obstruct the main beam, but serve only to limit the aperture available to stray particles. A 5-cm thick Pb collimator with 0.64-cm diameter hole was used at $M1$, the long magnetic path serving to eliminate particles passing through the material by virtue of their decreased momentum. A brass collimator 46 cm long was used at the shims with an opening of 1.3 cm. It could be aligned very accurately with the beam. A helium-filled bag was used in the flight path; the beam passed through a 0.008-cm Dural window at the exit of the Cosmotron vacuum system.

The proton beam, as seen in the diffusion chamber, had a small dense core containing most of the protons and a lower density "fringe." The beam obscured 2.3 cm of the chamber, and decay points within this region could not be recognized. A V event is shown in Fig. 2 to illustrate the appearance of the beam.[7] The average number of protons passing through the chamber was approximately 800 per pulse with a 30-second repetition rate, or about ten times more protons per hour than with a normal spread-out beam on a 5-second repetition rate. This technique, however, suffers considerably from the fact that the width of the beam tends to obscure a volume of the chamber in which V decays are likely to occur. This is especially detrimental since it is difficult to determine accurately what fraction of the produced V particles decay in this obscured volume.

III. PRODUCTION CROSS SECTION

The beam intensity was measured continuously by a scintillation counter telescope. The total number of useful beam protons was 5×10^6. The thickness of the Fe target was 0.36 g cm^{-2}; the thickness of hydrogen was 0.070 g cm^{-2}.

Proton-proton collisions would, in accordance with the conventional selection rules, be expected to result in the production of hyperons and K mesons by reactions (1) to (7).

$$p+p\rightarrow\Lambda^0+K^++p, \tag{1}$$

$$p+p\rightarrow\Sigma^0+K^++p, \tag{2}$$

[7] The chamber was described by Fowler, Shutt, Thorndike, and Whittemore, Rev. Sci. Instr. **25**, 996 (1954).

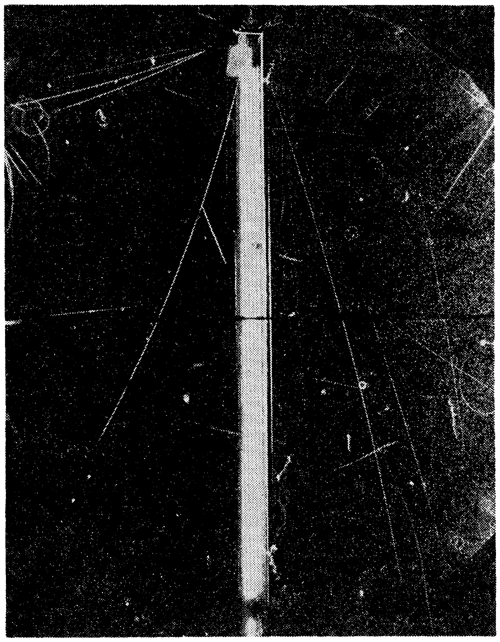

FIG. 2. Photograph which shows a neutral V particle produced in the iron target at the front edge of the diffusion chamber. The dense pencil of protons is seen passing through the center of the chamber.

$$p+p\rightarrow\Sigma^{+}+K^{+}+n, \quad (3)$$

$$p+p\rightarrow\Sigma^{+}+K^{0}+p, \quad (4)$$

$$p+p\rightarrow K^{+}+K^{-}+p+p, \quad (5)$$

$$p+p\rightarrow K^{0}+\bar{K}^{0}+p+p, \quad (6)$$

$$p+p\rightarrow K^{+}+\bar{K}^{0}+p+n. \quad (7)$$

In addition to (1), (2), (3), and (4), corresponding reactions with an additional π meson are energetically possible, but are considered less probable since 3 Bev is barely above threshold for them. Similarly (5), (6), and (7) have thresholds close to 3 Bev. It is therefore likely that (1), (2), (3), and (4) have the largest yield. The lifetime of the K^{+} is so long that there is no appreciable chance of observing its decay in our chamber. Therefore reactions (1) and (2) would be recognized by observing the decay of a Λ^{0}, reaction (3) by observing a Σ^{+}, and reaction (4) by observing Σ^{+}, K^{0}, or both simultaneously.

In the iron target, hyperons and K mesons can also arise from p-n collisions and from π-nucleon collisions of secondary pions produced in the same nucleus. As in the case of p-p collisions, there is little chance of observing a K^{+}, but K^{0}, Λ^{0}, Σ^{+}, and Σ^{-} should sometimes be observed to decay in our chamber.

A. Comparison of Production in Iron and Hydrogen

23 V^{0}, 5 V^{+}, and 1 V^{-} particles were identified which originate in the Fe foil. Compared to the total of 29 events observed in Fe, only one case, a V^{+} particle, was identified which could have originated from a free p-p collision. This single case is, moreover, somewhat doubtful in that the V^{+}-particle trajectory intersects the beam at its bottom limit. Thus, it might well belong to a group of 18 observed background events which clearly originate from collisions in the alcohol or solid material of the chamber.

All photographs were scanned twice and the scanning efficiency is estimated to be $\sim$90%. The efficiency for detecting events from p-p collisions is probably slightly less than from the Fe target for three reasons. First, the target is near the front of the chamber, so the particles have a somewhat longer average path in which to decay. Second, the Fermi momentum of the nucleons in iron may tend to increase the average angle of emission. Third, V particles may undergo scattering in the nucleus. These effects are estimated to be fairly small.

Using our data and the known p-p and p-Fe inelastic cross sections, we may compare the efficiency with which an associated production event is produced *per interaction* in H and Fe. We take 680 mb for the inelastic cross section in Fe and 40 mb in H. For our target thicknesses, we then expect 1.55 times as many inelastic events in Fe as in H. We have observed 20 hyperon events in Fe for which the average detection efficiency is 0.15 (see the following section) and one event in hydrogen for which the average detection efficiency is 0.11. The probability of an associated production event in Fe per interaction is greater than that in hydrogen by a factor of $(20/1.55)(0.11/0.15)\cong 10$. It is to be noted that this ratio is insensitive to the assumptions made in deriving the efficiency factors. A statistical fluctuation could reduce this ratio; for example, there is $\sim$10% probability that the ratio is as small as 4.

There are at least two possibilities for understanding this large ratio. (a) The cross section for direct V production by p-n interactions may be much larger than for p-p interactions. (b) In p-nucleus interactions π mesons can be created directly in p-nucleon interactions with sufficient energy to produce V particles in the same nucleus. Conceivably both (a) and (b) could contribute appreciably to the p-nucleus V-production cross section.

Alternative (b) has been discussed theoretically by several authors.[8] These discussions depend upon several interaction cross sections, some of which are poorly determined experimentally; hence the conclusions which indicate that (b) contributes appreciably to the production of V particles in p-nucleus interactions must be considered as tentative until further information is available.

We investigate (a) and assume the following: (1) if an

[8] See, for example, Fowler, Taft, and Mosburg, Phys. Rev. **106**, 829 (1957); G. T. Reynolds and S. B. Treiman, Bull. Am. Phys. Soc. Ser. II, **2**, 221 (1957), and private communication; R. Jastrow, Phys. Rev. **97**, 181 (1955); E. Mosburg, reference 3; M. M. Block and R. Jastrow, Phys. Rev. **99**, 619 (1955) (A).

interaction occurs in the iron nucleus, it occurs with a single nucleon and the cross section for V production is the same with the bound nucleon as with a free nucleon; (2) the total cross sections for p-p $[\sigma_T(p,p)]$ and p-n $[\sigma_T(p,n)]$ interactions are both 40 mb; (3) for each interaction with an iron nucleus, the relative probability for the incoming proton to strike a proton or a neutron is proportional to the number of protons or neutrons in the nucleus. Let $\sigma_V(p,p)$ and $\sigma_V(p,n)$ be the V-production cross sections in p-p and p-n interactions, respectively. Then the fraction f_A of V's produced per interaction in a nucleus having Z protons and $A-Z$ neutrons is

$$\frac{\sigma_V(p,p)}{\sigma_T(p,p)}\left(\frac{Z}{A}\right)+\frac{\sigma_V(p,n)}{\sigma_T(p,n)}\left(\frac{A-Z}{A}\right)=f_A. \qquad (1)$$

Inserting appropriate values in Eq. (1) for iron and again for hydrogen, one obtains

$$\sigma_V(p,n)/\sigma_V(p,p)=f_{\mathrm{Fe}}/f_{\mathrm{H}}=10. \qquad (2)$$

We see that this analysis leads to a very much larger V production by p-n than by p-p interactions. The effect on the ratio in Eq. (2) of a large error in the number of p-p V events can be seen by arbitrarily taking 4 times as many V events from p-p interactions. This leads to a value of about 4, still a surprisingly large ratio.

B. Absolute Cross-Section Determinations

1. *Detailed Efficiency*

The main problem in finding the absolute cross section is that of determining the probability of observing a hyperon or K meson when one is produced, that is, our efficiency for observing them.

There are three general ways that a V particle may escape detection: (a) It may be overlooked due to carelessness in scanning, though actually visible. We estimate that 90% are found. (b) It may decay through a long-lived mode, such as the $\theta_2{}^0$, or may produce only neutral particles, such as $\Lambda^0\rightarrow n+\pi^0$ or $\theta_2{}^0\rightarrow\pi^0+\pi^0$. We have made use of the most recent results from the Columbia hydrocarbon bubble chamber to correct for these unseen events.[9] (c) It may decay in such a position that the vertex is obscured by the beam or may not decay until outside the sensitive region of the chamber. This type of inefficiency can be estimated roughly from the geometry of the chamber, provided assumptions are made concerning the momentum spectra and angular distributions of the θ^0, Λ^0, Σ^+, and Σ^-. We have assumed that the momentum spectra are statistical and that the angular distributions are isotropic in the center-of-mass system. We note here that (c) is the main reason for our low efficiency in detecting V particles.

[9] Plano, Samios, Schwartz, and Steinberger (to be published).

2. *Absolute Cross Section in Hydrogen*

Under the above assumptions the detection efficiencies for V particles produced in hydrogen by our proton beam are 0.11 for Λ^0, 0.09 for θ^0, and 0.12 for Σ^+. Since we do not know the actual frequencies of reactions (1), (2), (3), and (4), we simply average the three efficiencies to obtain 0.11 as the geometrical efficiency from the beam. Accepting the one doubtful event from the beam, we obtain a total cross section of 0.04 millibarn. This low value may obviously result from a statistical fluctuation, but it would require an unlikely statistical fluctuation if the cross section is larger than 0.2 millibarn.[10] This conclusion, however, is based on an efficiency which assumes an isotropic angular distribution in the center-of-mass system. If the angular distribution is peaked forward and backward, our efficiency could be still further reduced, since more events would be obscured by the beam, and one should then make a higher estimate for the total cross section.

It should be possible to detect the presence of some of the neutral V events that are obscured by the beam in the following way. One observes a positive and negative track emerging from the beam with positions such that they could have come from a common vertex. One checks the angles and momenta to see whether they are kinematically consistent with a Λ^0 or θ^0 produced in the beam, and computes the apparent Q value. There will be a large background of associated tracks from the beam due to reactions like $p+p\rightarrow p+p+\pi^++\pi^-$ with only two prongs visible. These should have a wide distribution of Q values. If genuine Λ^0's or θ^0's are present, peaks should occur superimposed on this background. There are 5 events that are kinematically consistent with Λ^0 and another 5 consistent with θ^0. These are among 23 events in each category which are more or less uniformly distributed over a wide range of Q values. The number of cases is too small for a peak to be distinguished from a statistical fluctuation. It is certainly unlikely that all of them are genuine V events and quite possible that none may be. The upper limit for the cross section based on these 10 events is 0.4 millibarn. We consider it highly unlikely that all the events counted are really V^0 events and stress the fact that this is a poorly determined upper limit for the V^0 production cross section.

3. *Absolute Cross Section in Iron*

The cross section for iron can also be determined from these data. As noted earlier, the efficiency for detecting V events from the target is somewhat higher than that for V's from the beam. Calculated efficiencies are 0.15 for Λ^0, 0.11 for θ^0, 0.18 for Σ^+, and 0.25 for Σ^- produced

[10] Using Table VIII.1 of R. A. Fisher and F. Yates, *Statistical Tables* (Hafner Publishing Company, New York, 1948), third edition, one finds that if the cross section is really 0.17 millibarn the probability of observing 1 or 0 events would be 0.1; if 0.32 millibarn, the probability would be 0.005.

TABLE I. V-particles from target.

Particle	No. identified	No. with unidentified cases added	Total after correction for efficiency
Λ^0	11	14	104
θ^0	7	9	91
Σ^+	3	5	31
Σ^-	1	1	4

from the target. The number of events seen is given in Table I. An event is considered "identified" if the measurements are more consistent with one identification than another.[11] The five V^0's that could be either Λ^0 or θ^0 are assumed to be divided between Λ^0 and θ^0 in the same proportion as the identified events. The two V^+ that could be either K^+ or Σ^+ are assumed to be Σ^+, since most K^+ would not decay in the chamber. The final column is corrected for geometry and 90% scanning efficiency.

Since hyperons are assumed to be produced in association with K mesons, the total cross section should be based on the number of hyperons in Table I, not counting the θ^0's. The corrected total number is 139 and the cross section derived is 7.4 ± 1.1 millibarns per iron nucleus.

IV. DISCUSSION

Early preliminary experiments[2] on nucleon-nucleon production of strange particles hinted that this cross section might be considerably lower than the corresponding π^--p cross section, which is approximately constant at 1 mb up to π-meson kinetic energies of 1.5 Bev. Our value of $(0.04_{-0.04}^{+0.1})$ mb is additional evidence for such a low cross section. Serber[12] has shown that for 3-Bev p-p interactions and 1.5-Bev π^--p interactions, for which the available energy in the center-of-mass system is comparable, the fraction of phase space available for strange particle production is essentially the same in both cases; thus differences in available phase space can be ruled out as an explanation for the substantial difference in cross sections. Fowler, Kraybill, and Lea,[13] using the same equipment and beam geometry as described here, but with 1.95-Bev protons, have found a cross section of about 0.06 mb, again based on a single production event. Harris, Orear, Taylor, and Baumel,[5] using an emulsion technique, have observed K^+ mesons, with momentum 275 Mev/c at 0° in the lab system, produced by protons on a liquid hydrogen target. Using the differential cross section measured under these conditions, they have integrated over a statistical momentum distribution and an isotropic angular distribution and have calculated a total cross section of 0.2–0.3 mb. This value is somewhat larger than that from our experiment.[14] However, in both experiments the assumptions used to estimate absolute values are severe and may not be completely correct. For example, the angular distribution of the strange particles produced has been assumed isotropic. If in fact a forward and backward peaked distribution is correct, the value of the cross section found in our experiment would tend to be larger while that found by Harris *et al.*[5] would tend to be smaller.

For the absolute total cross section for the production of strange particles in iron, we obtain 7.4 ± 1.5 millibarns per nucleus. This value is based on 29 events. We emphasize here once again that the calculation of the efficiency factor is very important in this determination and is subject to the same criticism as for the hydrogen determination. Cookson *et al.*[3] and Blumenfeld *et al.*,[3] using Wilson cloud chambers with iron plates, have reported preliminary results on the production of strange particles by protons on iron which seem roughly in agreement with our result. Harris *et al.*[5] have observed K^+ mesons from p-copper interactions using nuclear emulsions and obtain a cross section which may be a factor of two larger than our value.

The direct comparison of our hydrogen and iron results is much less sensitive to efficiency corrections. We find that the probability of an associated production event per interaction is apparently significantly larger for a p-iron interaction than for a p-p interaction. A similar result has been obtained by Berley and Collins[4] using counter techniques. On the other hand, Harris *et al.*[5] find that the probabilities for producing a K^+ are essentially equal for Cu and Fe. From our result, we conclude that either the p-n cross section is significantly larger than the p-p cross section or that π mesons produced in p-iron interactions produce in the same nucleus a significant number of V particles.

In conclusion we would like to acknowledge valuable assistance in this experiment from A. Abashian, H. Courant, J. W. Cronin, R. M. Lea, O. Piccioni, R. P. Shutt, and W. J. Willis.

[11] Among the 11 "identified" Λ^0 events is one V^0 with positive track of 560 Mev/c, density estimate 2–3 times minimum, which has a measured $Q(p,\pi)$ of 53_{-4}^{+5} Mev. This may actually be some anomalous type of V^0.

[12] R. Serber, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957).

[13] Fowler, Kraybill, and Lea, Bull. Am. Phys. Soc. Ser. II, **2**, 222 (1957), and private communication.

[14] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **105**, 1931 (1957), have performed a counter experiment to detect K^+ mesons produced in p-p and p-copper interactions. These authors do not quote cross sections, but give K^+/π^+ ratios. This ratio is 2.5 times greater in copper than in hydrogen.

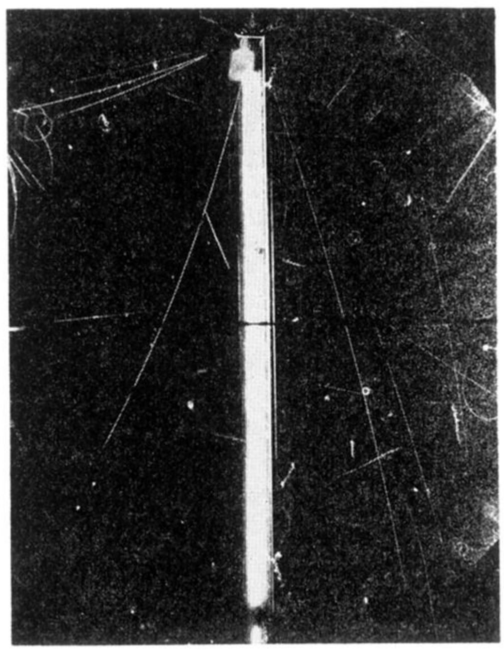

FIG. 2. Photograph which shows a neutral V particle produced in the iron target at the front edge of the diffusion chamber. The dense pencil of protons is seen passing through the center of the chamber.